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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE PRODUCTION

TASK 4: AUTOMATED ARRAY ASSEMBLY

Quarterly Report No. 4

In Reference To:

JPL Contract No. 955699

Prepared For:

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

15 July 1981

MB-R-81/11

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PREPARED BY: JOHN J. HAGERTY

15 July 1981

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

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ABSTRACT

Good progress has been made on this program during the last quarter in a number of areas:

The Unimate robot was programmed for the final 35-cell pattern to be used in the fabrication of the deliverable modules.

Phases 3 and 4 of this project (mechanical construction of the Automated Lamination Station and Final Assembly Station) were completed on schedule and as contractually obliged by 31 May 1981.

All final wiring and interconnect cables have also been completed and the first operational testing is underway.

The final controlling program has been written and is currently being optimized.

A local fabricator has been contracted to produce the Glass Reinforced Concrete (GRC) panels to be used for testing and deliverables.

A video tape showing all three stations in operation has been produced for display at the 18th PIM this month (July).

INTRODUCTION

The program is proceeding well with good progress being made last quarter, especially on the edge sealing machine and control system.

With all of the equipment being developed, the project has outgrown its original area so the entire equipage (robot, cell preparation station, lamination station with chamber and edge sealing machine) was moved to the adjacent, larger room and re-installed.

All the machines in the system are much more accessible now making them much easier to work on which facilitates development.

Construction of both the Automated Lamination Station and the Final Assembly Station was completed, as required, by 31 May 1981. Also complete is the checkout and installation of the control electronics as well as the various interconnect cables. All of the functions of both stations have been operated under program control by using test routines that operate whole subsystems. These test routines have been grouped together and refined to produce the final control program. This program is now in the process of being refined in preparation for the manufacture of the deliverable panels.

2.0 TECHNICAL DISCUSSION

Progress on each machine in the system will be discussed separately. Following this is a discussion of the other program areas.

2.1 Cell Preparation and Interconnect Station

The Cell Preparation Station has remained essentially unchanged since the completion of its upgrading last December. After being moved, the station was started up and required only minor re-alignments to become operational. Two 3/8" aluminum plate shields were installed to help protect the delicate mechanisms in the event of a robot "excursion" from its normal program (in the two years of our experience on this project, these have been very infrequent and always attributable to operator error).

In preparation for the fabrication phase, the robot was programmed with the final 35 cell pattern to be used in building the deliverable modules. This is a very tedious process on the Unimate 2000 and required over two days to complete.

2.2 Automated Lamination Station

Progress on this machine has centered around the completion of the final mechanical assembly and upgrading to complete construction as contractually required by the end of May (see Section 2.5). The control electronics were also installed and the individual function routines written. These have been grouped into an overall controlling program which is being optimized.

2.2.1 Mechanical

Mechanical completion involves final plumbing and wiring. An enclosure has been installed at the base of the framework (Figure 1) which houses all of the solenoid valves, terminal strips and connectors. The plumbing is completed and terminal strips/connectors have been wired. The numerous interconnect cables that run from the driver boards in the cell preparation station enclosure to the other machines (the Lamination Station , the Automated Lamination Chamber and Final Assembly Station) have also been fabricated.

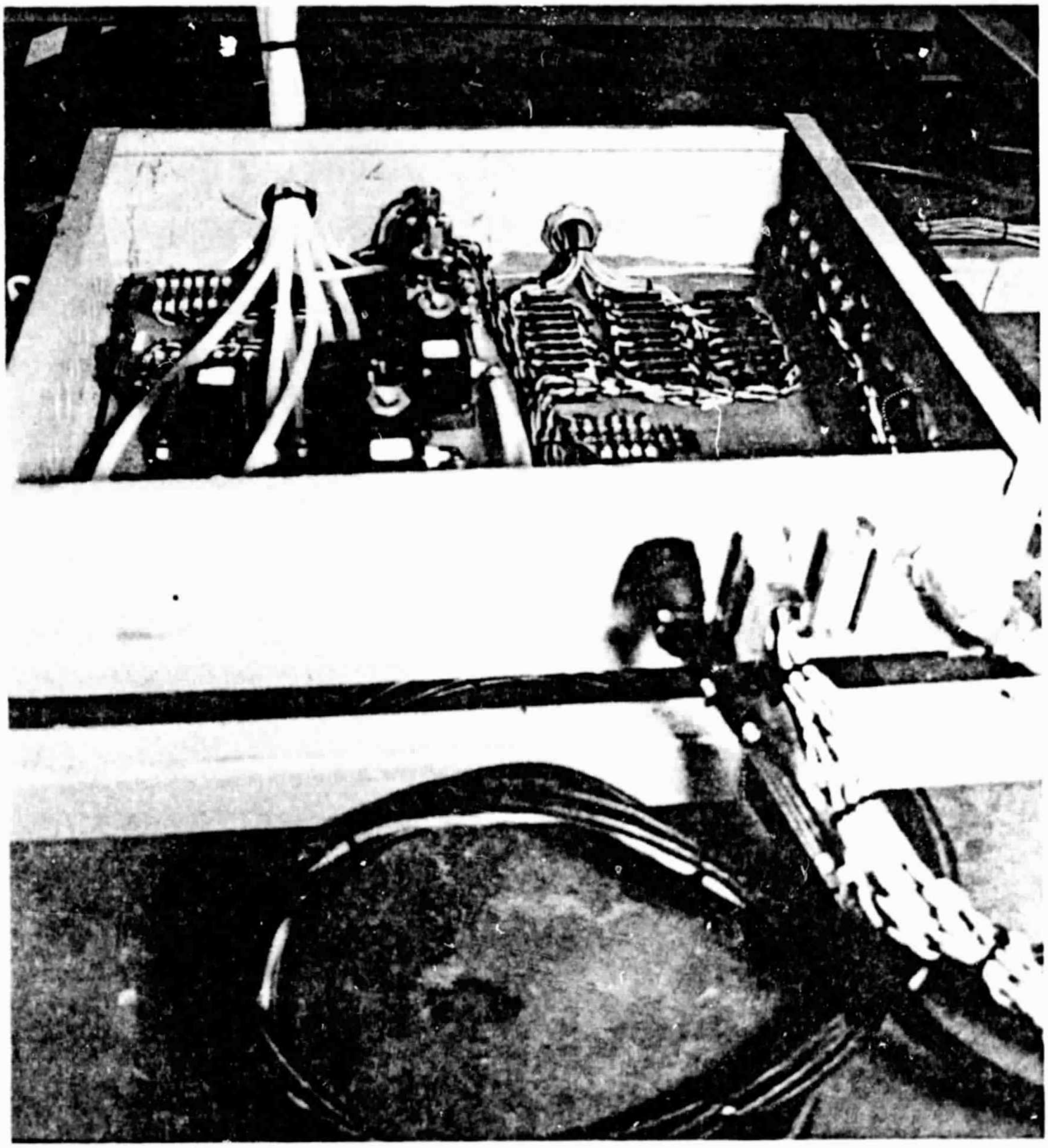


FIGURE 1
LAMINATION STATION JUNCTION BOX

OSHA-style knife guards have been fabricated and installed as a safety precaution.

As mentioned in the previous Quarterly Report (Section 2.1.2.1), the shuttle drive motor was replaced with one of much higher torque to prevent stalling when a load was applied to the web. The new motor was tested using a quickly devised BASIC program. Although the motor ran quite slowly (about 1/4 of its ultimate speed with an assembly language controlling program) its increased torque, plus the new rail-guided free end (see below) make the shuttle literally unstoppable. A load in excess of 50 lbs failed to stop it at which point the cogged drive belt began to slip.

As mentioned, this performance was attributable, in part, to a new guide system on the shuttle's free end. Originally, this was a set of needle bearing rollers placed above and below the frame rail which both supported the shuttle and offered torque reactions to the ball screw. However, it offered no resistance to rotation in the horizontal plane. In fact, a load of 30-40 lbs on the shuttle (well within the range expected for normal operation) would "cock" it severely enough to lock the ball nuts and stop the screw. To correct this situation and to give a more positive location of the encapsulant, the free side of the shuttle was fitted with a floating wheel-and-rail set-up (Figure 2) identical to those in the Final Assembly Station described in the previous Quarterly Report.

2.2.2 Control Electronics

Control routines were written for each individual function on the machine e.g. shuttle drive, shear solenoid, etc. Each function can be operated from the computer keyboard simply by giving the RUN command for the appropriate routine. The generalized controlling program was then created by placing all of the individual function routines in the correct order separated by timing waits. The duration of these waits are determined empirically making this (naturally) a repetitive and time consuming process.

2.2.3 Operational Testing

The results of the first operational tests are quite encouraging with most of the mechanisms working correctly with little or no adjustments.

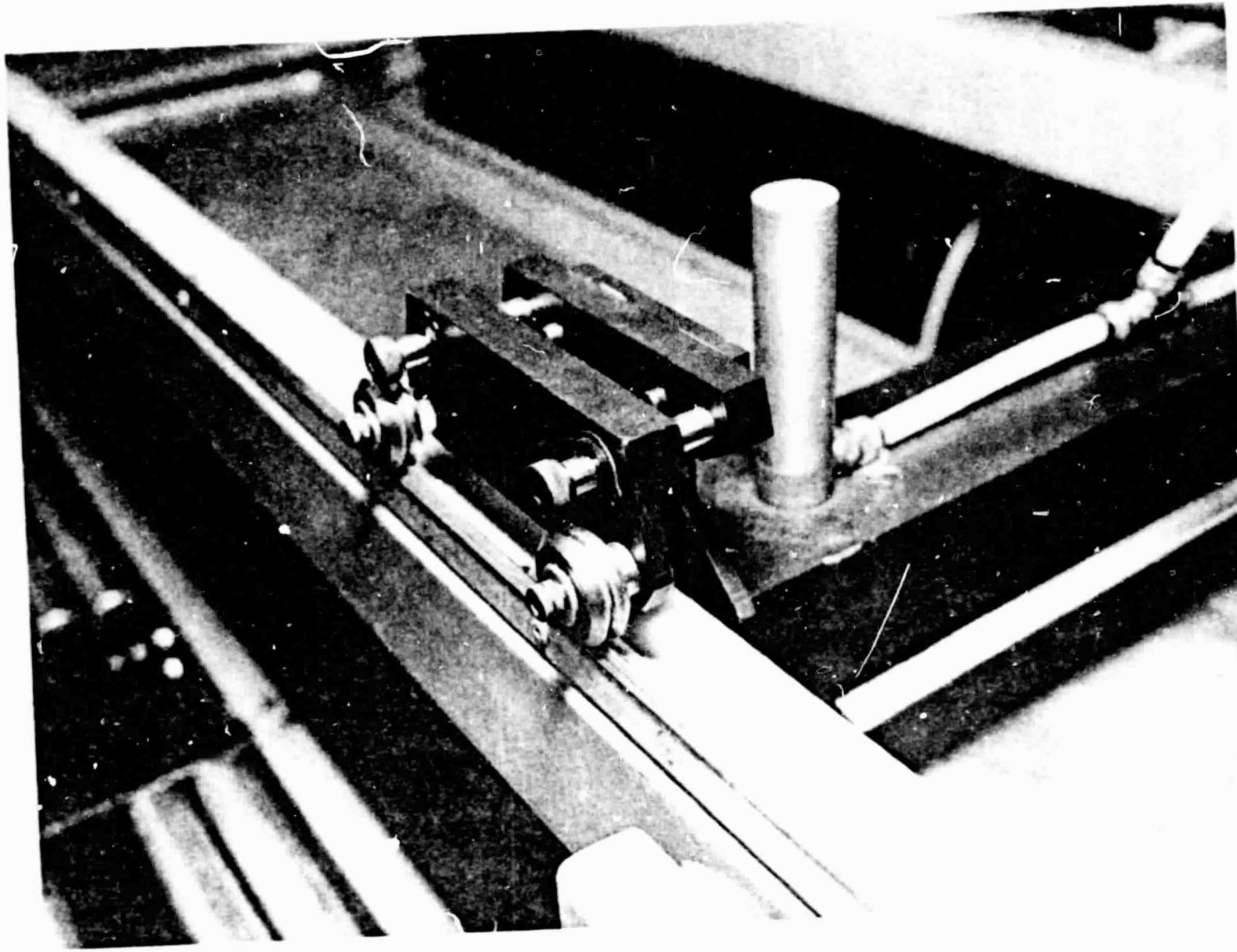


FIGURE 2
SHUTTLE WHEEL AND RAIL ASSEMBLY

An early concern was alleviated when the feed rollers were able to easily feed the encapsulant materials into the shuttle. It was feared that either the motor torque and/or the roller friction against the encapsulant would be insufficient to overcome the brake force. Happily, this was not the case although the very fragile Craneglas web did tear while starting during several tests showing that the brake's holding force was still slightly too high. Lowering the brake preload solved this problem. The shuttle, too, had more than adequate torque for pulling the web against the control brake. However, it appeared at first as if the shuttle's clamp would need some modification. Although the material fed smoothly into the clamp, the clamping force was too low to prevent the material from pulling out of the clamp while it was being drawn out against the brake. The problem turned out to be self correcting since we lowered the brake force as mentioned above. The shuttle now pulls the material smoothly and evenly in both directions.

2.3 Automated Lamination Chamber

The Lamination Chamber has also been complete for some time although there has been a change in the cover seal. Early tests of the original cover (Quarterly Report No. 3, Section 2.2) were quite encouraging showing that a plain rubber sheet could be self-sealing and have good draw-down. Unfortunately, the chamber vacuum could not be pulled below 20 in-Hg with this arrangement, far short of the 27-28 in-Hg required for encapsulation. A rigid frame was built (Figure 3) which is placed on top of the rubber sheet so that the edge of the sheet is compressed between the frame and the chamber walls. However, this means removing the automated cover opening mechanism as the tubular supports would be in the way. This renders the opening and closing of the chamber a manual operation as there is neither time nor budget left in this program to automate this new cover. It should be noted, though, that the new cover design is identical to the original concept as described in the First Quarterly Report (15 October 1980) Sections 2.3.3.2 and 2.3.3.3, and that preliminary designs for automating the cover therefore exist.

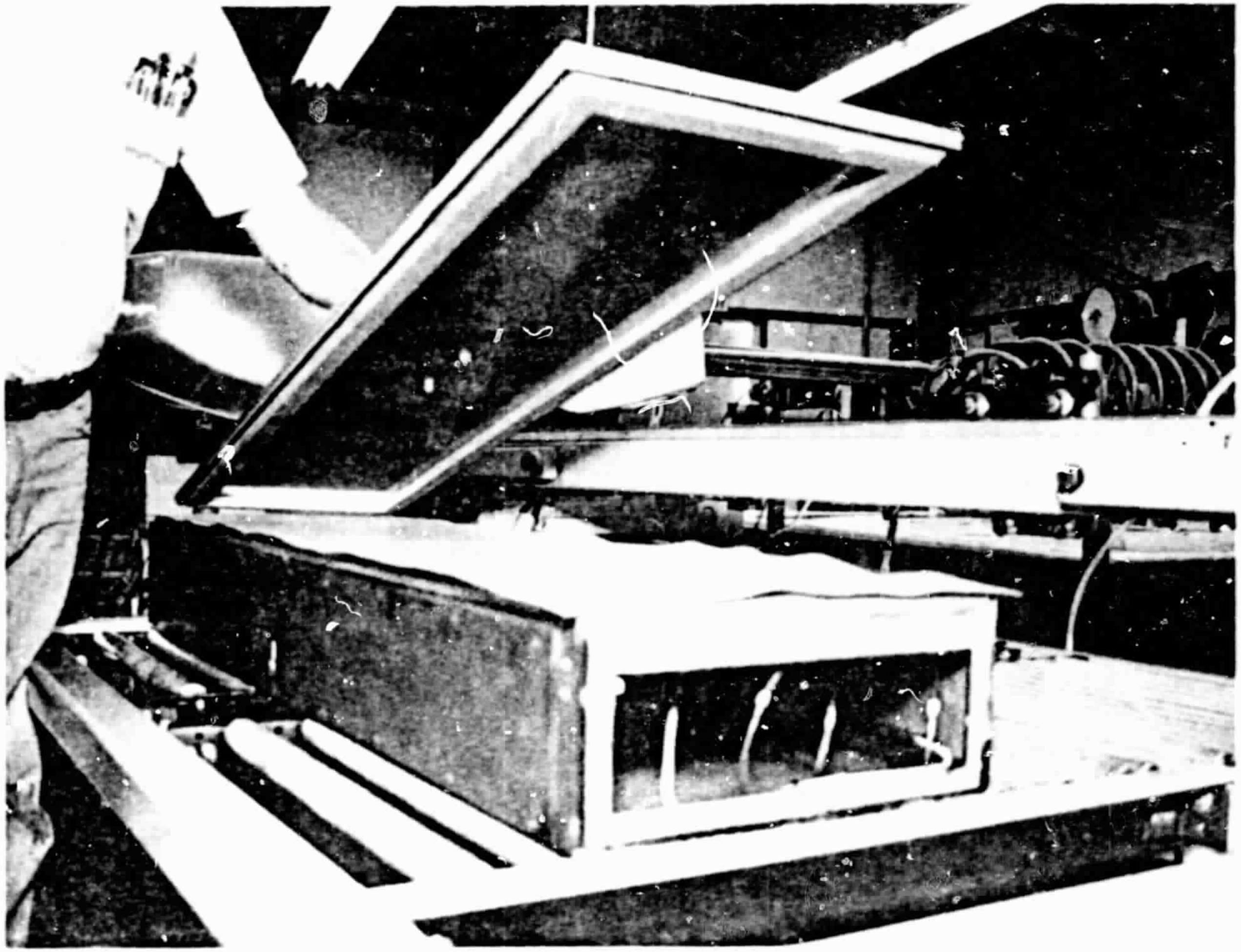


FIGURE 3
LAMINATION CHAMBER RIGID COVER

Even though the chamber cover is no longer automated (actually this was not a contractual requirement, but rather was done in the spirit of the program i.e. totally automating the process) the process cycle is completely automatic. This includes the controlled pumpdown (to avoid cell breakage), rapid heat to cure temperature, holding at cure temperature for the correct duration, cool down and finally vacuum release.

The chamber heaters have not yet been tested due to delays in building and installing the new cover. They are wired into place, however, and full operational testing (vacuum and heat) should be well underway by the end of this month (July).

2.4 Final Assembly Station

Very good progress has been made on this machine with all of the design, machining, assembly, control installation and inital testing being completed during this period.

A method to control the cables as the shuttle moves across the panel has been developed. The two sets of wires (one set for the drive motor and one set for the hot melt gun) are each run through a piece of 1/2" ID coiled air hose. These are then supported in a manner that allows the hose to uncoil as the shuttle travels across the panels (Figure 4). When the shuttle returns, the hose, being self storing, simply coils up out of the way.

Tests have been run that drive the hot melt gun both in rectangles (i.e. running the X axis and Y axis motors individually) and along diagonals (running both motors simultaneously). To expand on that last point; actually the control system cannot run both motors at the same time. Instead, the software routines that run the motors are set up to operate each motor for only one step (1/200 of a revolution or 0.04" of travel) at a time. These are then placed in a loop to control the number and speed of the steps. The speed of the computer's execution is such that the motion is indistinguishable from true simultaneous operation.

The hot melt gun itself has been tested and found to be operating properly. The tests were run to determine two important operating parameters: the extrusion rate of the bead and the consumption rate of the

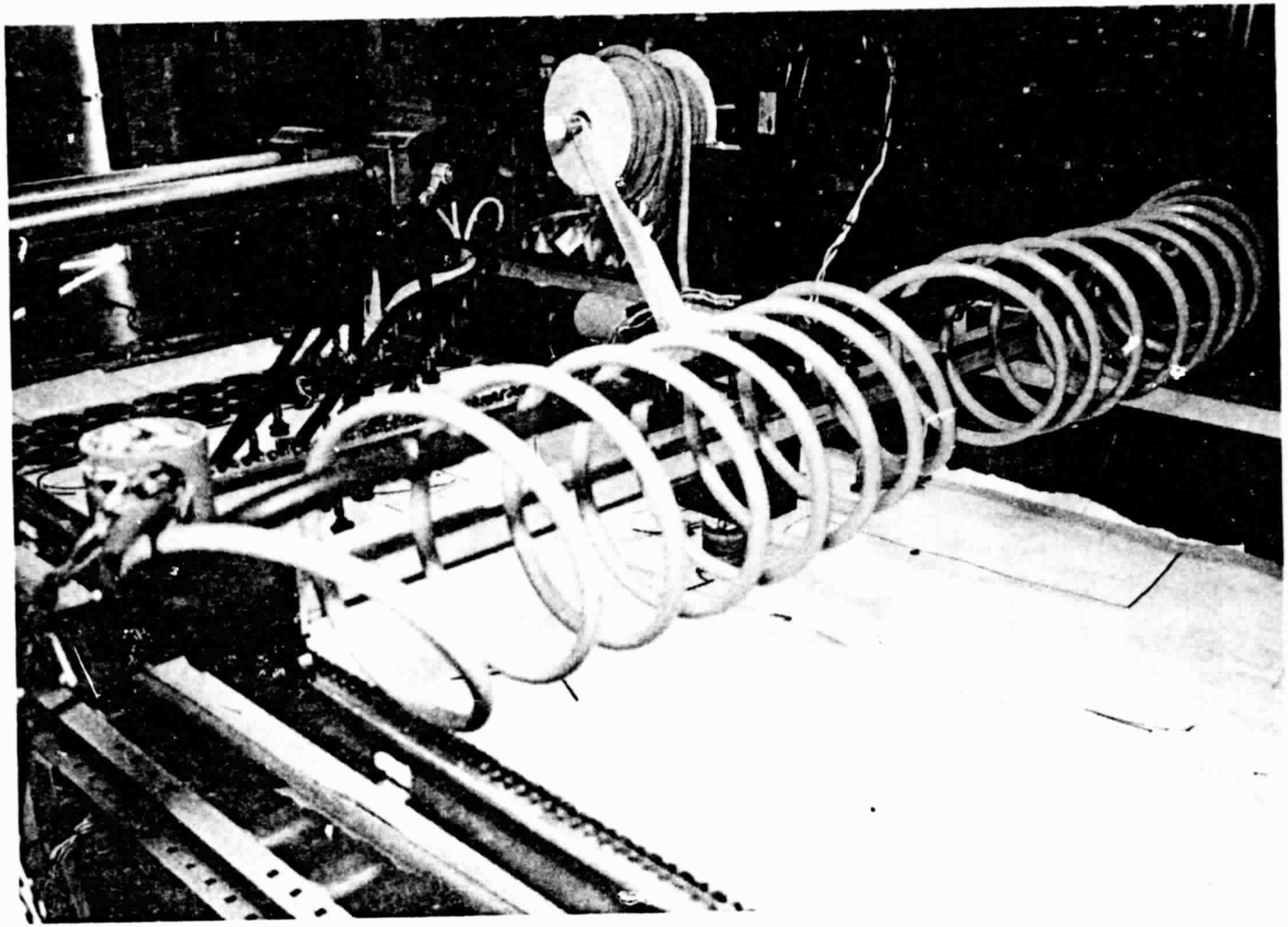


FIGURE 4
EDGE SEAL SHUTTLE CABLE CONTROL

Butyl supply rope. The results turned out to be an almost exact 2:1 ratio with the bead extruded at approximately 2 in/sec and the supply rope being consumed at 1 in/sec. The supply spools are approximately 50 ft. each meaning that 100 ft of bead could be extruded from each spool. This is sufficient to edge seal two 4' x 8' panels consisting of eight 1' x 4' modules each.

2.5 Fabrication of Deliverables

Contractually, the construction of the Automated Lamination Station and Final Assembly Station had to be completed by 31 May 1981. This does not include any tests or adjustments which, for the purposes of this contract, are considered to be part of the three month fabrication phase. In addition to operational testing, this phase includes, naturally, the fabrication of the deliverable modules The contract specifies that these shall be six 4 ft^2 modules produced on the equipment developed in this program.

It was decided early in the program that the module size would be 1' x 4'. In order to demonstrate the multiple-size capability of the Final Assembly Station, these six modules should be laid up on at least two different size GRC substrates. At a recent program review meeting, the final size of the substrates was decided upon. For ease of portability during JPL testing it was decided to keep the overall size small. The final deliverable panels will be a combination of 1' x 4' (one module per panel) and 2' x 4' (2 modules per panel) substrates. The panels have a 1" wide raised lip around their perimeter which acts as an edge frame.

The actual fabrication of these panels has been sub-contracted to a local firm that has GRC spraying equipment and specializes in prototype runs. This should provide a considerable savings to the program as the major cost of any short run GRC fabrication involves the setup and breakdown (and in our case refurbishment) of the spraying equipment. Since this vendor is already set up for short runs, we need pay only for the materials and labor involved with the actual spraying of the panels. The molds to be used in the fabrication were built and checked by MBA and have been shipped to the vendor. Spraying has been scheduled for the middle of July and, with a two week curing time, should be delivered by the end of the month.

All lamination materials are now in house, the polyester covered aluminum foil being the last to arrive. The multi-ply supply spools have been wound using our multi-ply roller described in Quarterly Report No. 3, Section 2.1.2.4. Due to the loose wrapping of this hand operated device, there are only about 250 ft. on a 12" diameter spool. Commercial rewinders, with tighter web tension control, could achieve two or three times that amount for the same diameter.

2.6 SAMICS

Preparation of SAMICS Format A's, with appendices, was performed for the entire process sequence covered by this contract. The sequence was broken into four processes: ROBOTBOND, which represents the cell stringer; ROBOTLAY, which represents the layup of encapsulated materials into the chamber; CURE is the curing of modules using a large number of automated chambers cycling continuously (to get the curing throughput rate to match the layup rate); and ROBOTSEAL which is the edge sealing and framing onto the GRC panels.

A Format B was also prepared which groups these processes together into a company called ROBOTMOD. This company would take the place of MODULECO in the standard SAMICS industry.

These forms are all included at the end of this report as an appendix.

2.7 Drawing Package

The drawing package has, in a sense, been in production for the entire duration of the contract since all of the machining prints used in the assembly of these machines are included.

Now that the machines are completed and operating, however, the assembly drawings can be produced. These have already been done for the Automated Lamination Station and are approximately 50% complete for the Final Assembly Station.

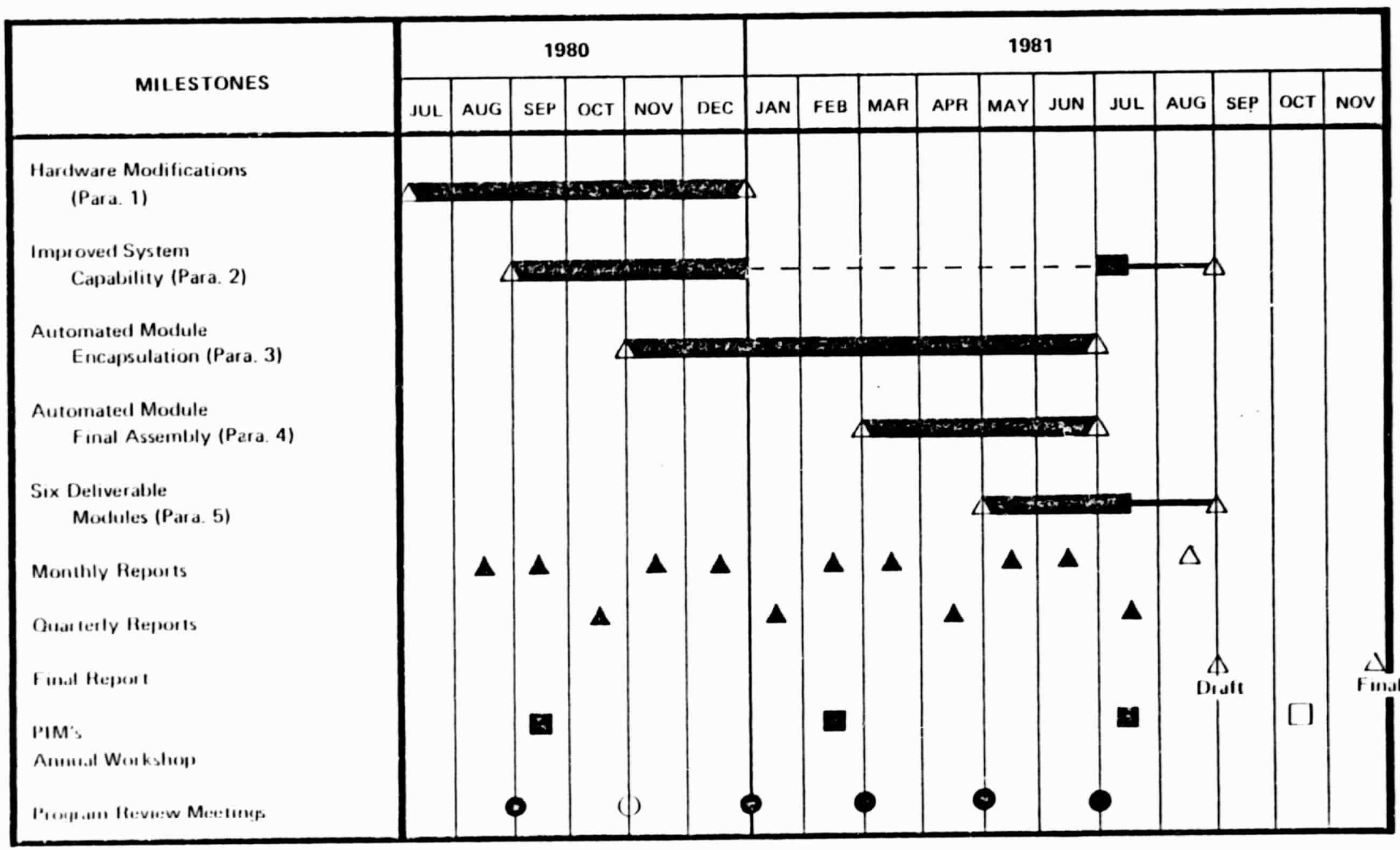
3.0 CONCLUSIONS AND FUTURE WORK

With the completion of the construction phase of this contract, we find ourselves well into the fabrication phase. All of the materials necessary to make the modules: cells, interconnect ribbon, solder paste, EVA (white and clear), Craneglas, polyester/foil and cover glass; are all in house. The encapsulant materials have been slit to width and rolled into spools. The GRC panels have been designed, the forms built, and fabrication by an outside vendor scheduled.

The current major effort involves preparations for the 18th PIM in July. A videotape of all three work stations in operation has been produced which will be on display.

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.



PROGRAM PLAN

APPENDIX A

SAMICS Formats A and B with appendices

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT B — COMPANY DESCRIPTION

Company Referen[ce]: ROBOTMOD

DESCRIPTIVE NAME: Module manufacturing company using industrial robot based assembly equipment

0.	(b)	(Final) Product(s) Produced	PANEL
	(a)	(Final) Process(es)	ROBOTSEAL
	(c)	Ideal Ratio(s) with units	0.125 Panels/module
1.	(b)	Intermediate Product(s)	CUREMOD
	(a)	Process(es)	CURE
	(c)	Ideal Ratio(s) with units	1.0 modules/module
2.	(b)	Intermediate Product(s)	LAYMOD
	(a)	Process(es)	ROBOTLAY
	(c)	Ideal Ratio(s) with units	1.0 modules/string
3.	(b)	Intermediate Product(s)	STRING
	(a)	Process(es)	ROBOTBOND
	(c)	Ideal Ratio(s) with units	
4.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
5.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
6.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
7.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
8.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
9.	(b)	Intermediate Product(s)	
	(a)	Process(es)	
	(c)	Ideal Ratio(s) with units	
		Purchased Product(s)	
		Supplier and Percentage	
		Supplier and Percentage	

PREPARED BY: John J. Hagerty

DATE: 16 June 8[illegible]

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A — PROCESS DESCRIPTION

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California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

A-1 Process [Referent]

ROBOTBOND

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process Placement and soldering of cell string using an industrial robot

PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent] STRING

A-4 Descriptive Name [Product. Name] Interconnected String of Cells

A-5 Unit Of Measure [Product. Units] STRINGS

PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput) 0.1622 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time] 6.1667 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle] 0.97 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day] 3 Shifts

A-8b [Personnel. Integerization. Override. Switch] off (Off or On)

PART 3 – EQUIPMENT COST FACTORS (Machine Description)

A-9 Component [Referent]	ROBOT	CELLPREP	I-HEATER
A-9a Component [Descriptive. Name]	Unimate 2000B Robot	Cell Preparation Station	Induction Heater Generator
A-10 Base Year For Equipment Prices [Price. Year]	1979	1979	1981
A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component)	49,685	56,500	8,000
A-12 Anticipated [Useful. Life] (Years)	4.83	7	10
A-13 [Salvage. Value] ($ Per Component)	24,842	2825	400
A-14 [Removal. And. Installation. Cost] ($/Component)	700	500	200

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 •), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

A-15 Process Referent (From Front Side Line A-1) ROBOTBOND

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)

[Facility. Or. Personnel Requirement]

A-16 Catalog Number (Expense Item Referent)	A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine]	A-19 Units	A-17 Requirement Description or Name
A2064D	125	ft^2	Type A Manufacturing Space
B3752D	0.25	Person/shift	Production machine operator
B3736D	0.0179	Person/shift	Mechanical maintenance
B3688D	0.0089	Person/shift	Electrical maintenance

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

A-20 Catalog Number (Expense Item Referent)	A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle]	A-23 Units	A-21 Requirement Description or Name
E1140D	0.0446	m^2	Solar cells
EA3D	0.0063	lb	Copper ribbon
EG1600D	0.0031	lb	Solder paste
C1032B	0.3083	KW-Hr	Electricity
C2032D	18.55	ft^3	Compressed air

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED None

A-24 [Required. Product] (Reference)	A-28 [Yield]* (%)	A-26 [Ideal. Ratio]** Of Units Out/Units In	A-27 Units Of A-26***	A-25 Product Name

PREPARED BY John J. Hagerty

DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

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FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]
ROBOTLAY

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process: Layup of Encapsulant Materials using an Industrial Robot

PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent]: LAYMOD

A-4 Descriptive Name [Product. Name]: Laid-up module ready for curing

A-5 Unit Of Measure [Product. Units]: Modules

PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput): 1.0 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time]: 1.0 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle]: 0.956 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day]: 3 Shifts

A-8b [Personnel. Integerization. Override. Switch]: off (Off or On)

PART 3 – EQUIPMENT COST FACTORS (Machine Description)

A-9 Component [Referent]	ROBOT*	LAM PREP	
A-9a Component [Descriptive. Name]	Unimate 2000B Robot	Lamination Preparation Station	
A-10 Base Year For Equipment Prices [Price. Year]	1979	1981	
A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component)	33,105	110,000	
A-12 Anticipated [Useful. Life] (Years)	4.83	10	
A-13 [Salvage. Value] ($ Per Component)	16,553	6,000	
A-14 [Removal. And. Installation. Cost] ($/Component)	467	800	

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 •), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

*The robot is used as both an assembly and transfer device between this station and the edge seal station (pages 7 & 8). Its time is split 2/3 here and 1/3 there. The values on A-11, A-13 and A-14 on both forms are pro-rated by that proportion. The same applies to maintenance and direct machine requirements.

A-15 Process Referent (From Front Side Line A-1) ROBOTLAY

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)

[Facility. Or. Personnel Requirement]

A-16 Catalog Number (Expense Item Referent)	A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine]	A-19 Units	A-17 Requirement Description or Name
A2064D	150	ft^2	Type A manufacturing space
B3752D	0.5	person/shift	Production machine operator
B3736D	0.0119+	person/shift	Mechanical maintenance
B3688D	0.0060+	person/shift	Electrical maintenance

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

A-20 Catalog Number (Expense Item Referent)	A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle]	A-23 Units	A-21 Requirement Description or Name
E1828D	4	ft^2	Float glass (tempered)
E1807D	12	ft^2	Crane glass
EP1003	8	ft^2	1 sheet clear EVA
			1 sheet white EVA
EMBA01	4	ft^2	Polyester/foil laminate
C1032B	0.136	KW-Hr	Electricity
C2032D	2.458	ft^3	Compressed air

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A-24 [Required. Product] (Reference)	A-28 [Yield] * (%)	A-26 [Ideal. Ratio] ** Of Units Out/Units In	A-27 Units Of A-26***	A-25 Product Name
STRING	97	1	Modules/string	Interconnected string of cells

PREPARED BY John J. Hagerty

DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

ORIGINAL PAGE IS OF POOR QUALITY

+ See note at bottom of page 3

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SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]

CURE

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process: Evacuate and thermal cycle module for curing

PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent]: CUREMOD

A-4 Descriptive Name [Product. Name]: Encapsulated module ready for edge sealing and framing

A-5 Unit Of Measure [Product. Units]: modules

PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput): 1.0 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time]: 60 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle]: 0.98 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day]: 3 Shifts

A-8b [Personnel. Integerization. Override. Switch]: off (Off or On)

PART 3 – EQUIPMENT COST FACTORS (Machine Description)

A-9 Component [Referent]: CAROUSEL

A-9a Component [Descriptive. Name]: Auto-cycling thermal/vacuum multi-chamber

A-10 Base Year For Equipment Prices [Price. Year]: 1981

A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component): $85,000

A-12 Anticipated [Useful. Life] (Years): 20

A-13 [Salvage. Value] ($ Per Component): 4,250

A-14 [Removal. And. Installation. Cost] ($/Component): 5,000

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 *), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

A-15 Process Referent (From Front Side Line A-1) CURE

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)

[Facility. Or. Personnel Requirement]

A-16 Catalog Number (Expense Item Referent)	A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine]	A-19 Units	A-17 Requirement Description or Name
A 2064D	1014	ft^2	Type A manufacturing space
B 3752D	0.5	person/shift	Production machine operator
B 3736D	0.0064	person/shift	Mechanical maintenance
B 3688D	0.0139	person/shift	Electrical maintenance

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

A-20 Catalog Number (Expense Item Referent)	A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle]	A-23 Units	A-21 Requirement Description or Name
C 1032B	1.1103	KWH	Electricity

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A-24 [Required. Product] (Reference)	A-28 [Yield] * (%)	A-26 [Ideal. Ratio] ** Of Units Out/Units In	A-27 Units Of A-26***	A-25 Product Name
LAYMOD	99	1	Modules/Module	Laid-up modules

PREPARED BY John J. Hagerty

DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]

ROBOTSEAL

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process: Apply edge seal and frame using an industrial robot

PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent]: PANEL

A-4 Descriptive Name [Product. Name]: Completed panel, ready for packing and shipping

A-5 Unit Of Measure [Product. Units]: Panels

PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput): 0.125 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time]: 8.0 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle]: 0.97 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day]: 3 Shifts

A-8b [Personnel. Integerization. Override. Switch]: off (Off or On)

PART 3 – EQUIPMENT COST FACTORS (Machine Description)

A-9 Component [Referent]	ROBOT*	SEAL-STN	
A-9a Component [Descriptive. Name]	Unimate 2000B Robot	Edge Seal and Framing Station	
A-10 Base Year For Equipment Prices [Price. Year]	1979	1981	
A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component)	16,562	50,000	
A-12 Anticipated [Useful. Life] (Years)	4.83	10	
A-13 [Salvage. Value] ($ Per Component)	8,281	2,500	
A-14 [Removal. And. Installation. Cost] ($/Component)	233	500	

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 •), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

*See note at bottom of page 3

A-15 Process Referent (From Front Side Line A-1) ROBOTSEAL

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)

[Facility. Or. Personnel Requirement]

A-16 Catalog Number (Expense Item Referent)	A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine]	A-19 Units	A-17 Requirement Description or Name
A2064D	80	ft^2	Manufacturing space type A
B3752D	1.0	person/shift	Production machine operator
B3736D	0.0060	person/shift	Mechanical maintenance
B3688D	0.0029	person/shift	Electrical maintenance

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

A-20 Catalog Number (Expense Item Referent)	A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle]	A-23 Units	A-21 Requirement Description or Name
EMBA02	4 .0	ft^2	GRC Panel
EMBA03	3.25	ft	Butyl Rope
C1032B	0.0679	KWH	Electricity
C2032D	0.3646	ft^3	Compressed air

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED

A-24 [Required. Product] (Reference)	A-28 [Yield] * (%)	A-26 [Ideal. Ratio] ** Of Units Out/Units In	A-27 Units Of A-26***	A-25 Product Name
CUREMOD	100	0.125	Panels/module	Encapsuled Module

PREPARED BY John J. Hagerty

DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

Appendix for Process ROBOTBOND

A-6→A-7 Cycle time 10 sec/cycle → 6 cycles/min

String has 35 cells + 2 end bus bars = 37 cycles

$$\frac{37}{6} = \underline{\underline{6.1667 \text{ min/string}}}$$

$$\rightarrow \underline{\underline{0.1622 \text{ strings/min}}}$$

A-8 Ribbon and solder paste supplies sized to be changed once per shift, a 5 min. job.

$$\frac{5}{480} = 0.0104 \text{ down fraction } 1 - 0.01 = 0.99 \text{ up fraction}$$

Unimate up time 98% (manufacturer's estimate)

$(0.99)\times(0.98) = 0.97$

A-9→A-14

Unimate 2000B

Purchase Price: $ 49,685. Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate) → 4.83 yrs.

Salvage Value: 50% (manufacturer's estimate) before overhaul → $24,842

Installation and Removal Costs: $700 Based on experience with current robot.

Cell Preparation Station

Purchase Price:

$ 50,000	Construction labor
2,600	Siltec Cassette Unloader
2,300	Computer & Interface
1,600	Enclosure
$ 56,500	

Useful Life: 7 years (Engineering Estimate)

Salvage Value: 5% (Engineering Estimate) → $2825

Installation and Removal Costs: $500 (Estimate)

A-9→A-14

Induction Heater

Purchase Price: $8,000

Useful Life: 10 years (Industrial Estimate)

Salvage Value: 5% (Engineering Estimate) → $400

Installation and Removal Costs: $200

A-16→A-19 Mfg. Space: 125 ft^2 (based on current machine)

Machine Operator: One person can watch four systems

Maintenance:

Scheduled - 6.5 hr/1000 hr (mfg. est.)	→	1.092 hr/wk
Unscheduled (98% up time)	-	3.360
		4.452 hr/wk
	≈	4.5 hr/wk

Required Maintenance 4.5 hr/wk assume 2/1 ratio mechanical to electrical.

$$\text{Mechanical: } 3.0\ \frac{\text{hr}}{\text{wk}} \times \frac{1}{21}\ \frac{\text{wk}}{\text{shift}} \times \frac{1}{8}\ \frac{\text{shift}}{\text{man-hr}} = 0.0179 \text{ person/shift}$$

$$\text{Electrical: } 1.5\ \frac{\text{hr}}{\text{wk}} \text{ - - - - - - - - - - - - - - - - - - } = 0.00893 \text{ person/shift}$$

Appendix for Process ROBOTBOND (Continued)

A-20→A-23

<u>Solar Cells</u>:

100mm = 0.0079 m^2/cell

@ 35 cells/string = 0.2749 m^2/string

@ 0.1622 strings/min = <u>0.0446 m^2/min</u>

<u>Copper Ribbon:</u>

2 types - interconnect & bus bar

Interconnect ribbon is 0.1" x 0.002"

two 7" ribbons per cell = 14 in/cell

@ 35 cells/string = 490 in/string

490 x 0.100 x 0.002 = 0.0980 in^3/string

Bus bar is 0.5" x 0.01"

2 Bus bars per string, 2.25" long

2x2.25 x 0.5 x 0.01 = 0.0225 in^3/string

0.0980 + 0.0225 = <u>0.1205</u> in^3/string

Density of copper = 0.3237 lb/in^3

0.1205 x 0.3237 = 0.0390 lb/string

@ 0.1622 strings/min = <u>0.0063 lb/min</u>

<u>Solder Paste:</u>

Each cell requires 4 solder beads each 3" long

For 0.015" dia. bead: $\left(\frac{.015}{2}\right)^2 \pi \times 3 \times 4$ = 0.0021 in^3/cell

@ 35 cells/string = 0.0742 in^3/string (Includes connection to bus bars)

Solder paste density = 0.2575 lb/in^3

0.0742 x 0.2575 = 0.191 lb/string

@ 0.1622 string/min = <u>0.0031 lb/min</u>

Appendix for Process ROBOTBOND (Continued)

A-20→A-23

Electricity:

Robot	12.0 KW	manufacturer specs.
Induction Heater	5.5 KW	
Preparation Station	1.0 KW	Sum of electrical equipment in preparation station
	18.5 KW	

= 18.5 KWH/hr → 0.3083 KWH/min

Compressed Air:

System contains two model B-100 eductors, each rated @ 20 scfm

1) The prep station eductor runs 5.5 sec of the 10 sec. cycle

$$\rightarrow \frac{5.5}{10} \times 20 = 11.0 \text{ cfm}$$

2) The robot eductor runs an average of 3 sec/cycle

$$\rightarrow \frac{3}{10} \times 20 = 6 \text{ cfm}$$

3) The prep station air table runs 2.5 sec/cycle @ ≈ 1 cfm

$$\rightarrow \frac{2.5}{10} \times 1 = 0.25 \text{ cfm}$$

4) The robot "cell release" air is on 3 sec/cycle @ ≈ 1 cfm

$$\rightarrow \frac{3}{10} \times 1 = 0.30 \text{ cfm}$$

5) 3 small cylinders and 4 solder paste tubes use ≈1 cfm

Total Air:

11.0
6.0
1.0
.25
.30
18.55 ft^3/min.

Appendix for Process ROBOTLAY

A-6→A-7 Machine cycle time = 1 min.

A-8 Bottom Lamina Supply Spool must be changed 4 times per shift (a 2 min. job) ∴ 4x2 = 8 min/shift

Top Lamina Supply Spool must be changed 2 times per shift:

2x2 = 4 min/shift

$$\frac{8\text{x}4 \text{ min down}}{480 \text{ min total}} = 0.025 \text{ down fraction} \rightarrow 1-0.025 = 0.975 \text{ up fractic}$$

Unimate up fraction = 0.98 (mfg. est.)

0.98 x 0.975 = 0.956

A-9→A-14

Robot - Unimate 2000B

Purchase Price: $ 49,685 Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate) → 4.83 yrs.

Salvage Value: 50% (manufacturer's estimate) before overhaul → $24,842

Installation and Removal Costs: $700 Based on experience with current robot.

See note at bottom of page 3

Lamination Station

Purchase Price: Development costs of prototype

Useful Life: 10 yrs (engineering estimate)

Salvage value: 5% of purchase price

Removal & installation cost: 2 man weeks installation

Appendix for Process ROBOTLAY

A-16→A-19

Manufacturing Space: 150 ft^2 (based on current machine)

Machine Operator: The operator divides his time between this machine and the curing chambers in process CURE.

Maintenance: Scheduled - 6.5 hr/1000 hr (mfg. est.) → 1.092 hr/wk
Unscheduled (98% up time) - 3.360

4.452 hr/wk

≈ 4.5 hr/wk

Required Maintenance 4.5 hr/wk assume 2/1 ratio mechanical to electrical.

Mechanical: $3.0 \frac{hr}{wk} \times \frac{1}{21} \frac{wk}{shift} \times \frac{1}{8} \frac{shift}{man\text{-}hr} = 0.0179$ person/shift

Electrical: $1.5 \frac{hr}{wk}$ - - - - - - - - - - - - - - - - - = 0.00893 person/shift

See note at bottom of page 3

A-20→A-23

Machine produces one 4 ft^2 module per minute. Module consists of 1 sheet tempered glass, 3 layers of Craneglas (a mat-type fiberglass) 1 layer clear EVA, 1 layer white EVA, and 1 layer of a polyester-foil laminte back cover. The cell string is obtained in part 6. The polyester/foil was obtained from Gila River Products, Chander, AZ. The cost to us was $200 for a 1500' x 1' roll (0.13$/$ft^2$). This was a special price for some surplus material, but is probably a good number for large production quantities.

Expense Item: EMBA01

Name: Polyester/Foil laminate, expressed in ft^2

Cost: 0.13 $/$ft^2$

Base Year: 1981, Inflation Rate: 8

A-20→A-23

Electricity

Robot = 12.0 KW (mfg. spec.)

Robot 8.00 KW (prorated as per note at bottom of page 3)

Stepper motors & valve solenoids	0.05 KW
Computer/controller	0.10 KW
	8.15 KW →8.15 KWH/hr

8.15 KWH/hr = 0.136 KWH/min

Compressed air:

Vacuum platen has 35 mini-vac MV-75 eductors each rated at 0.125 cfm

35 x 0.125 = 4.375 ft^3/min.

Platen operates for 20 sec each 1 min. cycle (This is only the time spent operating at this machine. Time spent at edge seal machine is entered on page 8).

$$4.375 \frac{ft^3}{min} \times \frac{20 \text{ sec/cycle}}{60 \text{ sec/min}} = 1.458 \ ft^3/\text{cycle}$$

$$= 1.458 \ ft^3/\text{min @ 1 min/cycle}$$

Six small cylinders use approx. 1 ft^3/min

Total air used: 1 + 1.458 = 2.458 ft^3/min

Appendix for Process CURE

A-6→A-7

Our approach to the cure cycle involves using 60 modular thermal/vacuum curing chambers interfacing with a single chamber loading/unloading machine (process ROBOTLAY). At present, a one hour cure cycle to evacuate, heat, hold for cure, and cool seems quite feasible (based on current JPL research).

A-8

Based on a 1 min. unload/load cycle, 60 on-line chambers seem to be sufficient for a complete cycle of: 1 min. unload/load, 50 min. evacuate/heat/cool and a 1 min. wait before re-entering the loading machine. This wait allows the change-out of a defective chamber without stopping the line. A one week maintenance of the chamber carrying carousel once a year yields:

$$\frac{51 \text{ wks. up}}{52 \text{ wks./yr.}}$$

$$= \underline{\underline{0.98 \text{ up time}}}$$

A-11

Purchase Cost:

$1,000 is the estimated cost of a mass produced chamber based on the production costs of the prototype. 60 x $1,000 = $60,000. Another $25,000 is included for the cost of the carousel to carry the chambers, cycle control equipment, power supplies and vacuum pumps.

A-12

Useful Life: 20 yrs. is the life expectancy of the carousel equipment. The chambers are continually refurbished to match this life expectancy (cost covered in maintenance).

A-13

Salvage Value: 5% of purchase cost

A-14

Removal & Installation cost:

As mentioned above in A8, change-out of a defective chamber is considered part of normal operation; therefore, not included here. $5,000 is the estimated removal and installation costs of the carousel and control equipment.

Appendix for Process CURE

A-16→A-19

Manufacturing Space: If the 1 ft. wide chambers are spaced 1 ft. apart, then 60 chambers require (1+1) x 60 = 120 linear ft. of carousel.

A circular carousel with a mean diameter of 40 ft. would do it but the floor area required would be 1520 ft^2 based on an outside diameter of 44 ft.

A straight sided, round ended carousel (such as used for luggage at airports) with 35 ft. long sides spaced 16 ft. apart has sufficient length and occupies only 1014 ft^2 based on outside dimensions. This still leaves a 12'x35' space in the center for control equipment.

Machine Operator: The operator divides his time between this machine and the lay-up machine in process ROBOTLAY.

Mechanical Maintenance: The one-week maintenance of the carousel once a year requires $\frac{1}{52}$ = 0.0192 person/day

@ 3 shifts/day = 0.0064 person/shift

Electrical maintenance - Assume one chamber (essentially an electrical device) per day goes bad requiring an average of 1 hr. to fix

→ 1/24 = 0.0417 person/day

@ 3 shifts/day = 0.0139 person/shift

A-20→A-23

Electricity: Each chamber heater is rated at 2.6 KW

1) In each 1 hr. cycle, the heater runs 15 mins. at full power to heat the chamber followed by 20 mins. at half power to maintain cure temperature.

$$15 \text{ min. } (2.6 \text{ KW}) + 20 \text{ min. } (1.3 \text{ KW}) = 65 \frac{\text{KW-min}}{\text{hr}} = 1.0833 \frac{\text{KWH}}{\text{hr}}$$

$$= 0.0181 \frac{\text{KWH}}{\text{min}}$$

$$\text{for 60 chambers} = 1.0833 \frac{\text{KWH}}{\text{min}}$$

2) The 1 HP carousel motor runs for 10 sec. every min. to index the carousel.

$$1 \text{ HP} \times 0.7457 \frac{\text{KW}}{\text{HP}} \times \frac{10}{60} \frac{\text{sec}}{\text{sec/min}} = 0.1243 \frac{\text{KW-min}}{\text{index}} = 0.0021 \frac{\text{KWH}}{\text{index}}$$

$$@ \text{ 1 index/min.} = 0.0021 \frac{\text{KWH}}{\text{min}}$$

Appendix for Process CURE

A-20→A-23

3) A 2 HP vacuum pump, running continuously

$$2 \text{ HP} \times 0.7457 \ \frac{\text{KW}}{\text{HP}} = 1.4914 \ \text{KW} \rightarrow 1.4914 \ \frac{\text{KWH}}{\text{Hr}} = \underline{\underline{0.0249}} \ \frac{\text{KWH}}{\text{min}}$$

Total Electricity = 1.0833 + 0.0249 + 0.0021 = $\underline{\underline{1.1103}}$ KWH/Min

Appendix for Process ROBOTSEAL

Background: Our system uses Glass Reinforced Concrete (GRC) panels as a substrate. The panels contain a shallow indentation into which the modules are placed. A bead of hot melt Butyl rubber edge sealant is placed around the module's opening just before the module is put in place by the Unimate robot. (The robot is time shared with process ROBOTLAY as per the note at the bottom of page 3).

The modules can be placed in any configuration up to a maximum size of 4'x8'. The configuration chosen for this simulation is eight 1'x4' placed side by side, joined along the 4 ft side.

A-6→A-7 Rate: The hot melt sealant is extruded at the rate of 2 in/sec. It must be applied to three sides of the module opening: the side common to two modules (in our case the 4 ft dimension) and the two sides along the GRC (the 1 ft sides).

$$\text{Total bead length per module} = \left(4\ \text{ft} \times 12\ \frac{\text{in}}{\text{ft}}\right) + 2\left(1\text{ft} \times 12\ \frac{\text{in}}{\text{ft}}\right) = 72\ \frac{\text{in}}{\text{module}}$$

@ 2 in/sec = 36 sec/module

This fits well with our lamination cycle of 1 min/module allowing a time budget of 5 sec to move the hot melt gun into place, 36 sec to apply the sealant, 5 sec to move the hot melt gun out and 14 sec for robot placement of the module.

One min per module means <u>8 min/panel</u> or $1/8 = 0.125\ \frac{\text{panels}}{\text{min}}$

A-8 The hot melt supply spool must be changed (a 30 sec job) every other panel or every 16 min.

$$\text{Up time fraction} = \frac{16\ \text{min up}}{16 + 30/60\ \text{cycle time}} = 0.97$$

Note: Our prototype uses a modified hand-held hot melt applicator which must be reloaded frequently. A true production machine would have remote located heaters and pumps with real-time replenishment which would raise the up time fraction to nearly 100%.

Appendix for Process ROBOTSEAL

Robot:

Unimate 2000B

Purchase Price: $ 49,685. Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate)

→ 4.83 yrs.

Salvage Value: 50% (manufacturer's estimate) before overhaul

→ $24,842

Installation and Removal Costs: $700 Based on experience with current robot

See note at bottom of page 3

Edge Seal Station:

Purchase cost: Based on development costs of prototype

Useful life: Engineering estimate

Salvage Value: 5% of purchase cost

Removal & Installation Costs: One man week installation time

A-16→A-19

Manufacturing space: Based on prototype machine. Does not include space for robot which is covered in process ROBOTLAY.

Machine Operator: Maneuvering GRC panels (both in and out of machine) and reloading hot melt gun (or tending to a more sophisticated remote pump system) make this station a full time job.

Maintenance:

Scheduled - 6.5 hr/1000 hr (mfg. est.) → 1.092 hr/wk
Unscheduled (98% up time) - 3.360
4.452 hr/wk
≈ 4.5 hr/wk

Appendix for Process ROBOTSEAL

A-16→A-19

Maintenance (Continued)

$$\text{Mechanical: } 3.0\,\frac{hr}{wk} \times \frac{1}{21}\,\frac{wk}{shift} \times \frac{1}{8}\,\frac{shift}{man\text{-}hr}$$

$= \underline{\underline{0.0179}}$ person/shift

$$\text{Electrical: } 1.5\,\frac{hr}{wk} \quad \text{- - - - - - - - - - - -}$$

$= \underline{\underline{0.00893}}$ person/shift

See note at bottom of page 3

A-20→A-23

GRC panel: A 4'x8' panel = 32 ft^2

for one panel every 8 min: $\frac{32\ ft^2/panel}{8\ min/panel} = \underline{\underline{4\ ft^2/min}}$

Cost: The GRC panel we are using was developed by MBA for JPL under Contract 955281. The cost for this Expense Item is from the final report for that program, section 7.2

Expense Item: EMBA02
Name: GRC panel, expressed in ft^2
Cost: 3.69 $/$ft^2$
Base Year: 1980
Inflation Rate: 10

Butyl Rope: The hot melt supply rope is ¼" diameter and the required bead is 1/8" giving a 2:1 ratio of bead length to supply length.

The relation for total bead length of a panel is:

L = n(c+2E) +c where

n = number of modules in panel
c = length of the module side common to two modules
E = length of the module edge not in common

For this panel L = 8 (4 + 2(1)) + 4 = 52 ft bead

$$52\ ft\ bead \times \frac{1}{2}\,\frac{ft\ rope}{ft\ bead} = 26\ ft\ rope/panel$$

@ 8 min/panel = $\underline{\underline{3.25\ ft\ rope/min}}$

Butyl Rope: (Continued)

50 ft Butyl rope supply spools are available in our area for $25 = 0.50 $/ft.

Expense Item: EMBA03
Name: Butyl Rope, expressed in ft.
Cost: 0.50 $/ft.
Base Year: 1981
Inflation Rate: 8

Electricity:

Robot = 12.0 KW (mfgr. spec.)

Robot	4.00 (pro-rated as per note on page 3)
Computer/Controller	0.05
Stepper Motors	0.025
	4.075 KW

→4.075 KWH/Hr = 0.0679 KWH/min

Compressed Air:

Vacuum platen (on robot) has 35 mini-vac MV-75 eductors each rated at 0.125 ft^3/min.

35 x 0.125 = 4.375 ft^3/min.

Platen operates for 5 second each 1 min. cycle

$$4.375 \frac{ft^3}{min} \times \frac{5 \text{ sec/cycle}}{60 \text{ sec/min}} = 0.3646 \, ft^3/\text{cycle}$$

for 1 min. cycle = 0.3646 ft^3/min.