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METHODS FOR FABRICATING CdS THIN-FILM SOLAR CELL MODULES

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ABSTRACT

Two methods for the series and parallel interconnection of CdS thin-film solar cells into modules have been developed and evaluated. Either soldered or conductive-epoxy bonding methods can be used with either of two electrical paralleling methods to produce modules having low joint resistivity, low weight, high mechanical strength, and maximum area utilization. Sample submodules of each method have exceeded the requirements of specialized dynamic, tensile, and vacuum thermal-cycling tests. Processes and tooling have been developed and used for the efficient fabrication of both soldered and bonded modules of 25 cells each. The soldered modules weigh 0.3447 kg/m^2 and the bonded modules weigh 0.3055 kg/m^2.

A solder-type joint for interconnecting modules was also devised. It affords easy module replacement and incorporates the same principle of stress-free electrical connection used to connect cells in the soldered module.

INTRODUCTION

The results of a program (ref. 1) to develope and evaluate methods for joining CdS thin film solar cells into modules are summarized.

The program was divided into three phases: development and screening of candidate joining methods, choosing and evaluating the two best methods through a series of specialized tests, and fabricating 8 modules of 25 cells each. In addition, module fabrication equipment was designed and built and was used to fabricate the 8 modules. The final report (ref. 1) contains all experimental data, discussion of test results, and module fabrication equipment drawings and fabrication procedures.

Electrical Connections

Soldered electrical series connections for CdS thin film solar cells had been used at the Lewis Research Center (ref. 2) and undoubtedly elsewhere for some time prior to this module development program. In anticipation of a contractual program, three other connection methods were briefly evaluated at Lewis. These were: hot pressure welding, ultrasonic welding, and an experimental mixture of General Electric Company SMRD 745 epoxy and silver flake.

The hot pressure welded connections proved difficult to make over large areas. Although the connections fabricated were satisfactory from an electrical standpoint, they had very low mechanical strength and would have been difficult to handle during manufacture. Later, attempts to make such connections were unsuccessful and the method was eliminated from consideration.

Several attempts at ultrasonic welding proved unsuccessful and this method was also eliminated from further consideration. The results of the SMRD 745-silver flake experiments appeared very encouraging. As a result of this preliminary information, the effort was concentrated on soldered, conductive epoxy bonded, and parallel gap resistance welded connections.

Joint Configurations

Two general methods of cell-to-cell electrical parallel connection were evaluated. One designated the Tab Inline method (fig. 1) uses a separate conductor to bridge the gap between cells in series. The other, designated the Staggered Cell method (fig. 2), involves staggering cells in series by a half cell and thus achieving the paralleling function through the use of the cells' tabs. The "half cells" at the ends of alternate rows are obtained by cutting a whole cell in half.

Two general methods of reinforcing the joint between cells were evaluated. One, the common substrate method, involved mounting electrically connected cells on a 1 mil sheet of Kapton using G.T. Schjeldahl Co. GT100 thermoplastic adhesive strips. For this method, the 1 mil Kapton substrate is the load carrying member. The other method, designed the the butt joint method, uses a mechanical reinforcement of the electrical connection in such a way that the cell substrates become the load carrying members.

Screening Tests

Three tests were used to screen the electrical connections and mechanical joints fabricated during the screening phase of the program; conductivity, less than 8 milliohms per series connection per cell; roll strength, at least 100 cycles over a 9.08 cm (2") dia. roller; and, ultimate tensile strength. The conductivity of all joints was monitored during

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all tests.

For the roll tests, cells with sample joints were cycled back and forth over the 9.08 cm diameter roller 100 times at a speed of 0.305±0.09 m/sec (1±0.3 ft/sec) while under a constant tensile load of 2.27 kg (5 lb)/cell-width (fig. 3). There were two types of roll test, primary and secondary. They differed in that the cell active surface faced away from the roller for the primary test and toward the roller for the secondary test. In practice a common substrate sample of a particular connection method was fabricated and rolled in the two fashions. If the connection did not degrade, the substrate was cut away and the same sample rolled again as a butt joint sample.

Ultimate tensile strength tests established strength comparisons between candidate methods. This test was performed by incremental loading of sample joints (fig. 4). Ultimate tensile strengths were obtained on specific ultimate tensile strength test samples and on most roll test samples following roll test. Since most roll test samples survived 400 roll cycles, the tensile strengths of these samples showed the strength of the joints following considerable flexure.

Series Joint Connections

To achieve the greatest area utilization, i.e., ratio of active cell area to overall area, all of the joining methods considered required that the cell positive grid tab be folded back 180° when joined to the next cell's negative cell substrate tab (unreinforced butt joint, fig. 5). This simple joint subjects the electrical connection to peel-type loading. It also transfers all the mechanical load through the positive tab and into the cell. This type of joint must, therefore, be reinforced, even in the common-substrate configuration.

Reinforcing the simple butt joint results in the partially reinforced butt joint (fig. 6). This type of joint was selected as the basic configuration for all connection and joining methods. To increase the mechanical strength of the partially reinforced joint, it can either be attached to a common substrate (common substrate method) or the immediate area of the partially reinforced butt joint can be reinforced with a piece of tape (reinforced butt joint method, fig. 7).

Parallel Joint Connections

Reinforced soldered and conductive epoxy bonded Tab Inline parallel connections were made using (1) a copper tab identical to the cell positive tab, (2) flexible photoetched tabs used successfully with silicon cells, and (3) a 0.475 cm × 7.62 cm (3/16" × 3") piece of G.T. Schjeldahl Co. Schjel Clad L5550, a copper coated mylar. Samples using the copper tab failed during roll test and samples using the photoetched tab displayed erratic conductivity during roll test. The samples using the Schjel Clad tab met all the screening requirements. The edges of the cells for all Tab Inline methods were joined by GT100 adhesive and a 0.95 cm (3/8") wide strip of Kapton running the length of the cell.

The Staggered Cell parallel connection makes use of the cell's tabs as parallel conductors. In theory, Staggered Cell paralleling offers a potential 6 percent module weight reduction. Part of the weight reduction comes from the cells' tabs acting as the parallel conductors. This function saves the weight of a paralleling tab. The other part of the weight-saving results from the staggered mechanical joints along a series string of 2 or more cells in parallel. The nature of the mechanical joint at the parallel connection makes it possible to omit it any other mechanical connection between cells along their edges. Handling experience showed, however, that the resulting module does not have good sheet characteristics.

The Staggered Cell samples did pass the screening tests once the cell edges were joined as for the Tab Inline method.

Electrical Performance

The series resistance of all three electrical connection methods - conductive epoxy bonding, soldering, and resistance welding - were less than the series resistance limit of 8 milliohms per cell connection. The series resistance only for the Tab Inline and Staggered Cell paralleling samples were also less than 8 milliohms per connection. Series resistances ranged from about 0.5 milliohms for soldered connections to about 1.4 milliohms for welded connections. The soldered and conductive epoxy bonded samples showed no electrical connection degradation during the entire sequence of roll tests. The welded sample did show a slow but definite degradation in the first roll tests (primary and secondary common substrate). It, therefore, was not subjected to the butt joint roll tests.

No parallel resistance limit was specified. Instead, performance comparable to the series connections was adopted as a goal. The combined series and parallel resistance of Tab Inline connections using either solder or conductive epoxy was less than 8 milliohms. The combined series and parallel resistances of 2 1/2 cell wide Staggered Cell samples were about 43 ohms. The high Staggered Cell resistances result from the high resistance of the cells' negative tabs (about 83 ohms per cell) which form part of the parallel current path.

Mechanical Performance

Minimum measured ultimate tensile strengths in the series direction were 9.07 kg (20 lb)/cell-width for the partially reinforced soldered butt joint, 20.87 kg (46 lb) for the reinforced soldered butt joints, and 24.95 kg (55 lb) for the conductive epoxy bonded butt joint. Partially reinforced soldered butt joints were acceptable. However, the reinforced soldered butt joint was the preferred soldered type joint since its mechanical strength was more comparable to the higher strength conductive epoxy bonded joint.

Final Selection

The criteria for selecting two connection and joining methods for evaluation included; conductivity, roll strength, ultimate tensile strength, manufacturability, total joint thickness, and overall module weight. Also, substantially different methods were desirable in order to provide an independent alternate should one method fail and to allow a choice for subsequent array designs. Taking all these factors into consideration, the conductive epoxy bonded and the reinforced soldered butt joints (fig. 8) were selected as the two best methods for final evaluation and module fabrication.

Table I shows the overall evaluations of all the candidate methods. Tab Inline was selected as the preferred paralleling method with Staggered Cell a suitable alternate.

Evaluation Program

Three major tests comprised the evaluation program; ultimate tensile strength, roll tests, some of which were followed by ultimate tensile strength testing, and vacuum thermal-cycling and dwell (fig. 9). The ultimate tensile strength and roll tests were the same as those described under "Screening Tests".

The vacuum thermal-cycling tests were performed in a vacuum of 10^{-6} torr. Thermal cycling was accomplished by means of a high intensity carbon arc lamp operating at air mass zero intensity and liquid nitrogen cooled walls in the vacuum tank. All energy transfer to and from the solar cells was radiative.

The test samples were subjected to 24 thermal cycles of 8 minutes each. The cell temperature extremes for each cycle were $+55^{\circ}$ C and -70° C. Following thermal cycling, the test samples were subjected to 8 continuous hours of lighted operation; that is, $+55^{\circ}$ C at 10^{-6} vacuum. Electrical connection performance was monitored during all tests and, in addition, solar cell performance was monitored during vacuum thermal-cycling and dwell.

The evaluation test schedule, i.e., the number and types of samples subjected to each of the various tests, was tailored to complement confidence levels reached during the screening tests. Mechanical strengths, both in roll and pure tension, were comparable to the screening test results. Thus, modules and arrays fabricated using the developed techniques require no additional support and, indeed, may even serve as tension members in an array.

With the exception of the combined series and parallel resistance of the Staggered Cell samples, all connection resistances were less than 8 milliohms. Also, there were no indications of joint degradation during the vacuum-thermal testing. Although the low temperature extreme (-70° C) was not as low as would be expected in space (less than -150° C), tests at the Lewis Research Center on both conductive epoxy (SMRD 745 + Ag) bonded joints and joints using GT100 adhesive cycled between -150° C and $+65^{\circ}$ C show no degradation when loaded at 0.816 kg (1.8 lb)/cell-width.

Fabrication Equipment

The multiple steps necessary to fabricate both types of joints required a fixture on which a module could be built up. Since the fabrication process for both the reinforced soldered and conductive epoxy bonded methods requires that the cells be aligned and that the positive tabs be bent, a fixture was designed on which to perform these steps. The resulting assembly fixture is shown in Fig. 10. Modules formed by conductive epoxy gonding remain on this assembly fixture during epoxy cure.

Experience soldering connections during the development and screening phase pointed out the need for a piece of equipment capable of making multiple solder connections and long GT100 bonds. A design patterned after the joint fabrication apparatus used at the Lewis Research Center during exploratory work and at the General Electric Company during the screening phase resulted in the soldering/bonding machine shown in Fig. 11. Although the module fabrication equipment was designed to fabricate modules of 25 cells each (5 series × 5 parallel), it can be used to fabricate modules from 2 to 5 cells wide (in parallel) to any number of cells long (in series).

Fabrication Procedures

The general procedures for fabricating both soldered and bonded type modules were worked out during fabrication of both development and evaluation samples. Since the assembly fixture and the soldering/bonding machine were available near the end of the evaluation program, the last evaluation samples were fabricated using this equipment. This afforded an opportunity to define the procedures which were then refined and finalized during module fabrication.

Basically, the fabrication of soldered modules involves building up connected rows of cells in parallel on the assembly fixture. After the entire module has been electrically connected and joined along the series/parallel joints, it is turned over on the assembly fixture. The series joint reinforcing strips and strips of Kapton used to join the "series columns" of cells along their edges are then bonded to the backs of the cells with GT100.

Conductive epoxy bonded modules are formed by placing and aligning all the cells for the module on the assembly fixture. The electrical connection and joining surfaces are then exposed and the conductive epoxy brushed on. The faying surfaces are then brought together and any excess epoxy squeezed out. A piece of foam is placed over the module followed by a metal plate and the whole assembly is clamped together and put in an oven to cure. Following cure, the edges of the "series columns" are joined together as for soldered modules.

Module Fabrication

The culmination of the contractual effort was the fabrication of 8 modules, viz., 4 reinforced soldered, and 4 conductive epoxy bonded.

Figures 12 and 13 show the front and back of one of the reinforced soldered modules. The fronts of the soldered and bonded modules are identical. The back of the bonded module, however, does not have the Kapton reinforcing strip over the length of the electrical connection.

Having proved the soundness of the joining methods during evaluation, it remained for the manufacturing phase to prove the fabrication equipment and procedures. Engineering and manufacturing technician labor hours directly applicable to the fabrication of each of the 25 cell modules were recorded. The fabrication times, shown in Fig. 14, show that a stronger learning effect was present with the reinforced soldered modules than with the conductive epoxy bonded modules. The curve for the soldered modules seems to indicate that only a slight decrease in fabrication time in possible with the present equipment.

The curve for bonded modules should, however, be extrapolated with some caution. Using present equipment, indications are that fabrication time will level off at or slightly above that for soldered modules. Some additional equipment and process modifications offer the possibility of time savings for both methods.

Looking ahead to array fabrication, the present module design provides for the interconnection of modules by using a slightly modified reinforced soldered butt joint (fig. 15). This joint affords the same electrical connection stress protection as does the reinforced soldered butt joint for individual cells. Additionally, it has the important advantage of repairability. The connection of modules along their edges would be accomplished the same as for cells within the module.

Conclusions

Two different and proven methods are available for connecting and joining CdS thin film solar cells into modules. Module fabrication equipment and procedures are developed and can be used to fabricate modules using reinforced soldered or conductive epoxy bonded joints.

Joint design yields modules having the maximum ratio of active to total surface area using present cell design. Joint mechanical strength is sufficient to eliminate the need for any array substrate or additional supporting structure.

The specific weight of the reinforced soldered modules is 0.3447 kg/m^2 (0.0706 lb/ft^2) and of the conductive epoxy bonded modules, 0.3056 kg/m^2 (0.0626 lb/ft^2). Using present cell efficiencies of just under 3 percent in space, these module weights translate to between 90 W/kg (41 W/lb) and 112 W/kg (51 W/lb). These numbers do not include structure weights.

Improvements in overall joint strength, although there is no apparent need for any now, could only result from adhesives of greater strength. Present module fabrication times, although reasonable, could be improved slightly with minor equipment additions and process modifications.

REFERENCES

1. F. A. Blake and M. R. Stahler, "Thin Film Solar Cell Module Development, CdS Cell," General Electric Company, Report 68SD4233, April 1, 1968.

2. H. W. Brandhorst, Jr. and A. E. Spakowski, "A 23.4 Square-Foot (2.17-SQ-M) Cadmium Sulfide Thin-Film Solar Cell Array," NASA TM X-1519, April 1968.

TABLE I. - OVERALL EVALUATION OF JOINING METHODS

Electrical	Mechanical	Overall evaluation
Conductive epoxy	Butt joint	Excellent
Solder	Butt joint-Kapton and GT100 reinforced	Very good
Solder	Butt joint-GT100 reinforced	Good
Parallel gap resistance weld	Butt joint-Kapton and GT100 reinforced	Good
Conductive epoxy	Common substrate-GT100	Fair
Solder	Common substrate-GT100	Fair
Solder	Butt joint-unreinforced	Poor
Hot pressure weld	Butt joint-unreinforced	Very poor
Ultrasonic weld	----------------	Unsuccessful

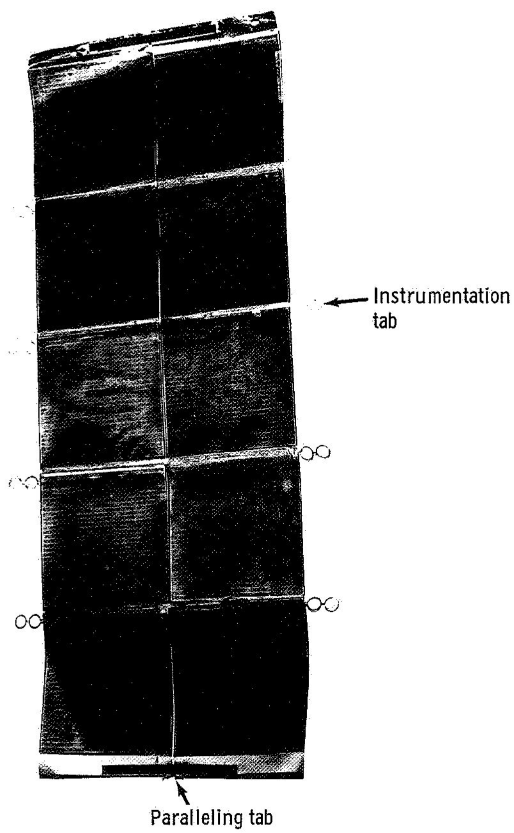

Figure 1. - 2 Cell parallel x 5 cell series test sample, "Tab-connected Inline" paralleling method.

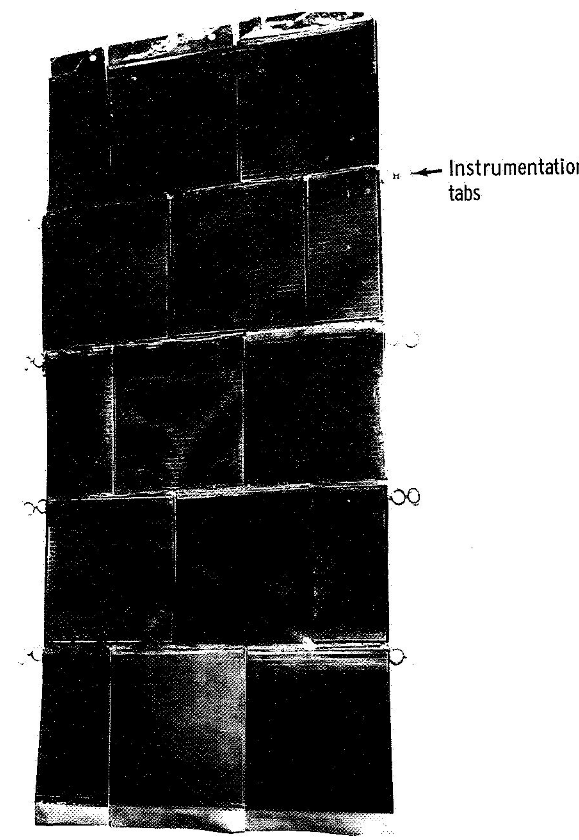

Figure 2. - 2-1/2 Cell parallel x 5 cell series test sample, "Staggered Cell" paralleling method.

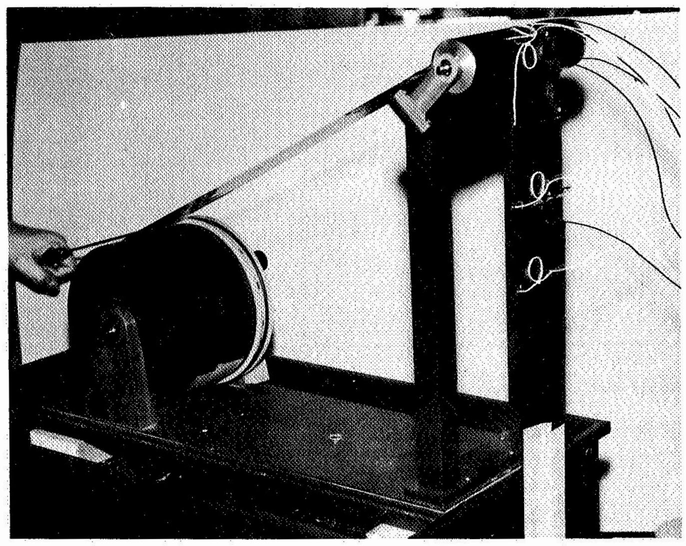

Figure 3. - Roll test apparatus with test sample.

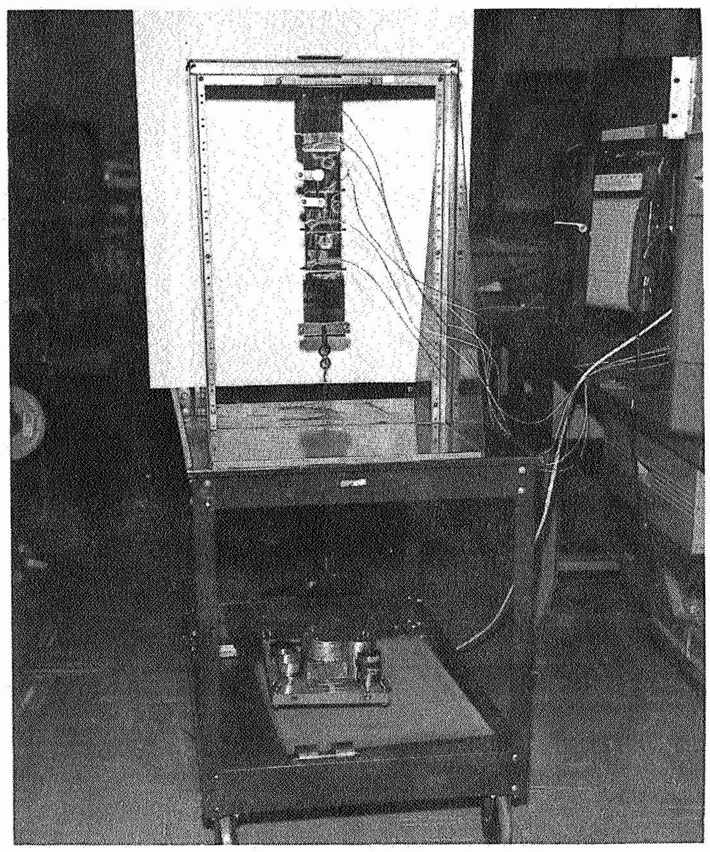

Figure 4. - Ultimate tensile strength apparatus with test sample.

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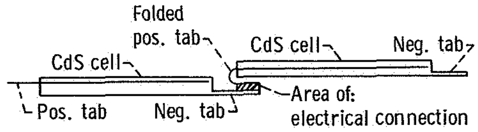


Figure 5. - Unreinforced butt joint.

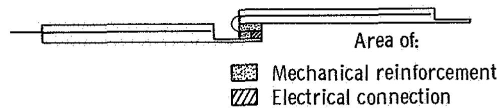


Figure 6. - Partially reinforced butt joint.

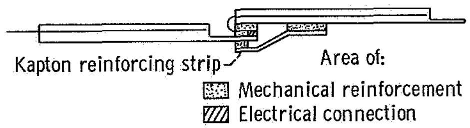
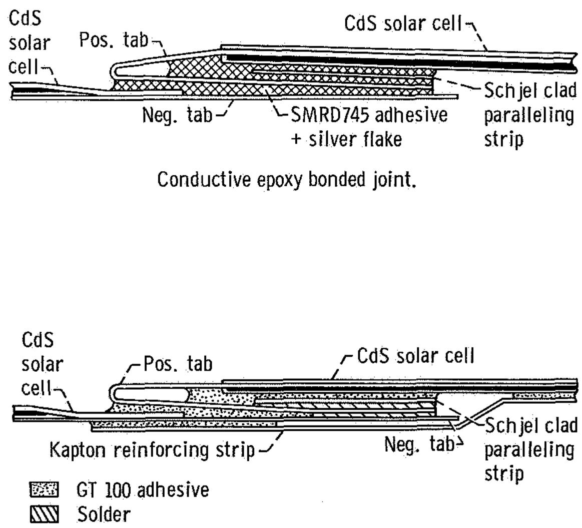


Figure 7. - Reinforced butt joint.



Conductive epoxy bonded joint.

Reinforced soldered joint.

Figure 8. - Optimum cell-to-cell joining methods.

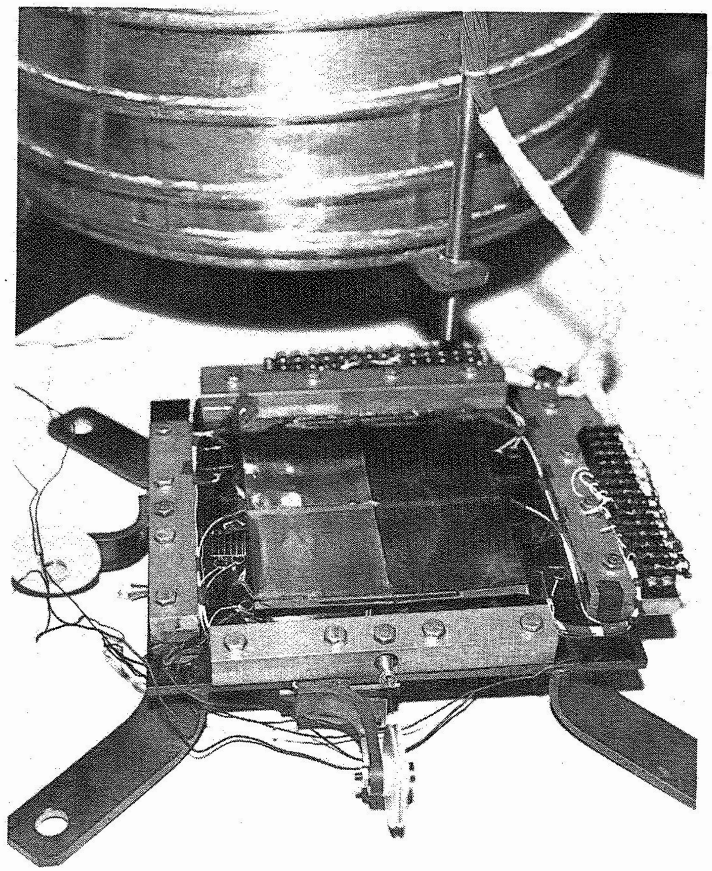


Figure 9. - Vacuum thermal-cycling test sample mounted on test fixture.

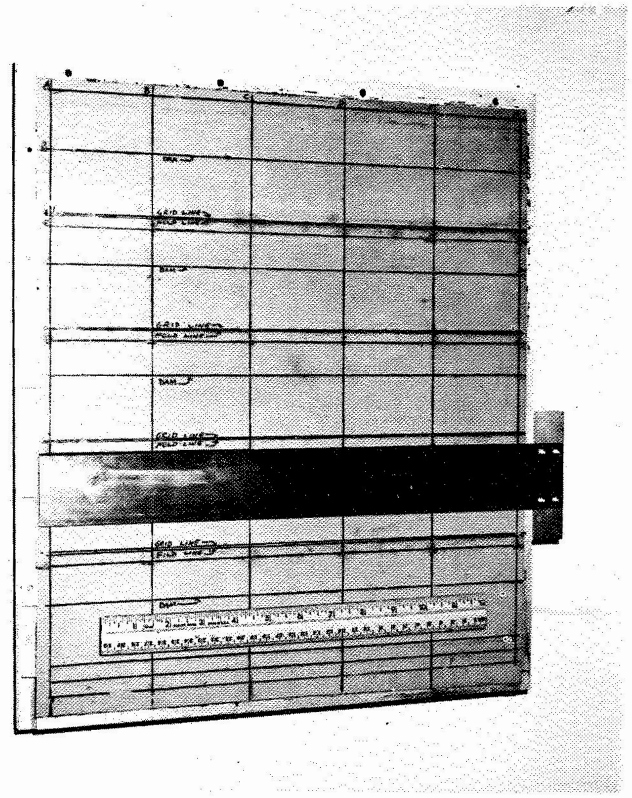


Figure 10. - Module assembly fixture.

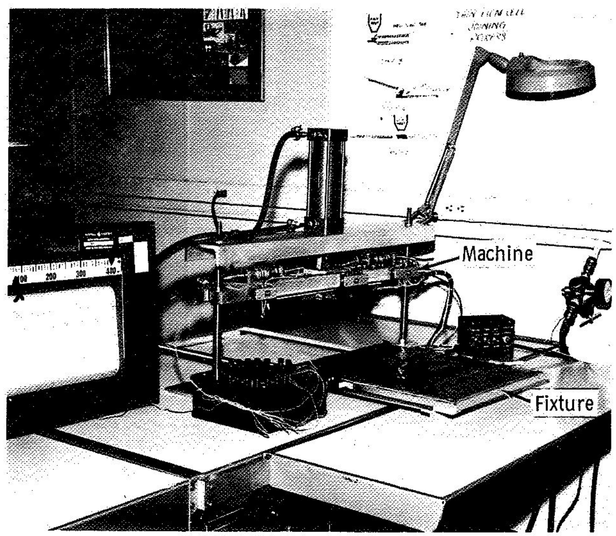


Figure 11. - Thin film solar cell soldering/machine and module assembly fixture.

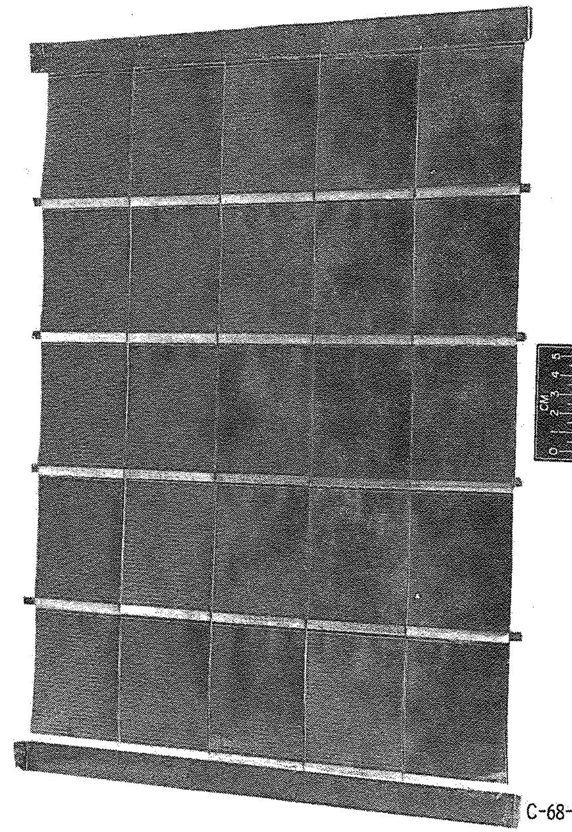


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Figure 12. - Reinforced soldered module (front view).

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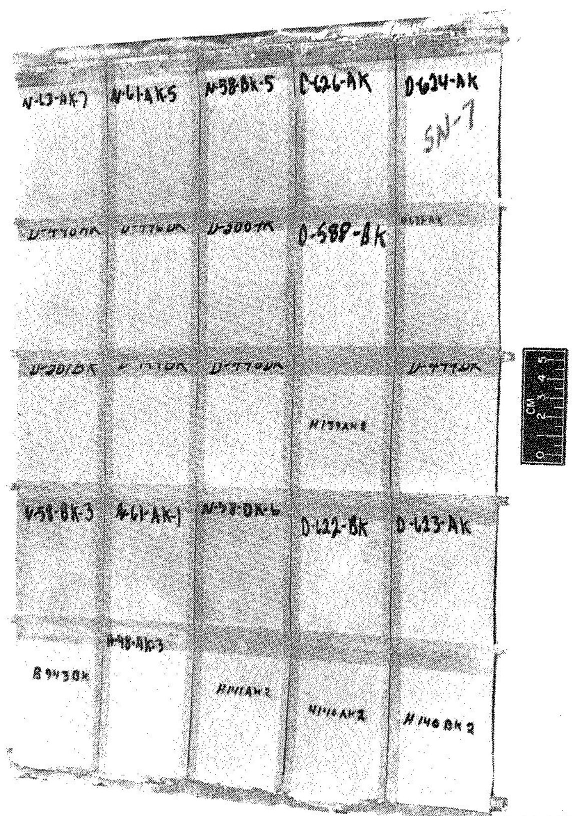

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Figure 13. - Reinforced soldered module (rear view).

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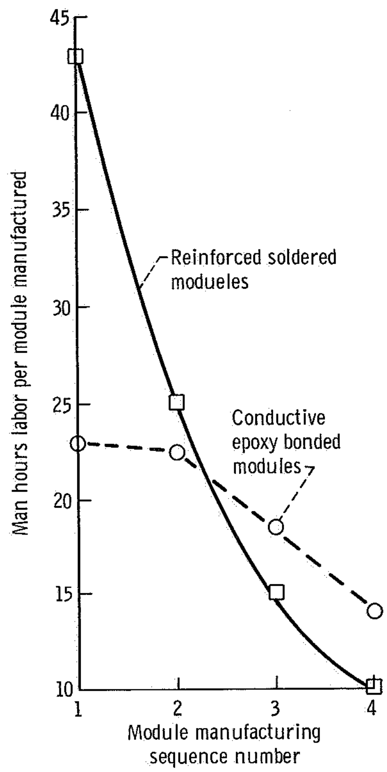

Figure 14. - Learning effect on module fabrication time, 25 cell CdS cell modules.

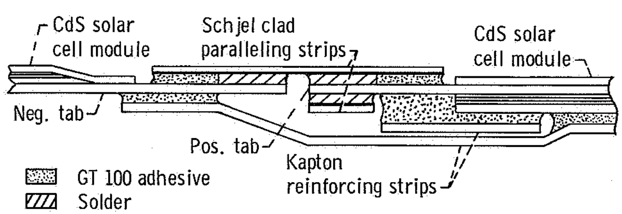

Figure 15. - Method for joining CdS solar cell modules.