III. CONVENTIONAL AND THIN-FILM SOLAR CELLS

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INTRODUCTION

At present, there appear to be four major trends in research and development on solar cells for space power:

(1) Improved cell fabrication methods
(2) Radiation damage resistance
(3) Film cells
(4) High-power arrays

Much work has been done and is being done on improved methods of silicon cell fabrication. The principal objective of this work is to lower the cost of cells; this kind of work includes the use of dendritic silicon to fabricate solar cells, the use of ion bombardment to produce the junctions in the solar cells, etc. Solar-cell power systems that must operate in the Van Allen belt are subject to damage by electron and proton radiation. Consequently, research on improving the resistance of solar cells to radiation damage is an important area. Thin-film solar cells such as those made from cadmium sulfide or cadmium telluride show promise of low-cost, lightweight solar cells that might be suitable for large solar power arrays. High-power arrays that use silicon cells are being seriously considered in powers up to 50 kilowatts. No attempt is made herein to cover all the work that is being done in these four areas. Instead, only the work of special interest to the Lewis Research Center is discussed, namely, radiation damage to solar cells, film cells, and high-power arrays.

RADIATION-DAMAGE-RESISTANT SILICON CELLS

The improvement of the resistance of silicon cells to radiation damage has been a major theme of the silicon cell research at Lewis. An effort is being made to improve the radiation-damage resistance by improving the blue response of the cells (refs. 1 and 2). The blue response is the current produced by the cell in response to the blue part of the solar spectrum. Figure III-1 shows why it is desirable to improve the blue response of the solar cell in order to improve its resistance to radiation damage. This figure shows the effect of radiation damage on the solar spectral response of a silicon cell. The current density yielded for a 0.1-micron interval of the solar spectrum is plotted against the wavelength of the solar spectrum. The effect of radiation damage is to reduce the current produced in the cell by the red wavelengths of light, 0.7 to 0.9 micron. The response of the cell to the blue part of the solar spectrum, 0.4

to 0.6 micron, is not changed. If the response of the cell to the blue part of the solar spectrum can be increased, the radiation-damage resistance of the cell will also be increased.

The reason that the blue response of the cell is only slightly affected by radiation damage can be explained by recalling some of the elementary features of a silicon solar cell. Figure III-2 shows a cross-sectional diagram of a typical n-on-p silicon solar cell. It consists of a thin layer of n-type silicon in contact with a thick layer of p-type silicon. The junction between the n- and p-type is located quite close to the surface. In most solar cells, it is about 0.5 micron deep. Each photon of sunlight produces a useful current carrier in the silicon. These current carriers diffuse through the silicon to the junction. When they cross the junction, they become excess current carriers, and thus produce a voltage. Figure III-3 shows that the depth at which light is absorbed in the silicon varies with the wavelength of the light. The absorption coefficient of red light in silicon is low, so that the percent of light absorbed changes slowly with the depth in silicon. A depth of 8 to 10 mils is required to absorb all the red light. Red light is absorbed deep in the body of the cell, far from the junction. Blue light has a high absorption coefficient and is absorbed almost completely at the surface of the cell, close to the junction.

The primary effect of radiation damage on the solar cell is to reduce the diffusion length of carriers in the crystal. The diffusion length is the distance that current carriers produced by light can diffuse before they are lost. The current carriers produced by red light must diffuse a long distance to the junction, so that the yield of these carriers is affected considerably by radiation damage. The current carriers produced close to the junction by blue light must travel only a short distance to reach the junction and, consequently, are affected little by radiation damage.

It is interesting to see what gains are theoretically possible in improving the blue response. In figure III-4 the actual response of a commercial silicon solar cell is compared with the theoretical response, which is calculated by assuming a 50-percent quantum efficiency. The actual response is seen to be close to the theoretical maximum response in the red part of the spectrum but falls far short of the maximum possible response in the blue part of the spectrum. Evidently, there is the possibility of a real gain in the response to the blue part of the spectrum; consequently, there can be a real gain in the radiation-damage resistance.

What can be done to improve the blue response of the cell? One thing is to bring the junction closer to the surface of the cell. Since the blue light is absorbed close to the surface, the closer the junction is to the surface, the more current that can be collected from blue light. There is considerable difficulty in moving the junction very close to the surface of the cell. When ordinary boron-doped crystals of silicon are used to make shallow-junction cells, the efficiencies of the cells are below acceptable values for space power systems. Figure III-5 shows that, when aluminum-doped oxygen-free silicon is used to make the cells, it is possible to make good junctions even though they are very shallow. The current output of the cell is the same whether boron-doped or aluminum-doped material is used. However, the aluminum-doped material yields a much superior junction characteristic and as a result, gives a higher open-circuit voltage, and an efficiency of 11.5 percent in space sunlight. The reason that aluminum-doped silicon is superior in this application is probably that aluminum introduces less strain into the silicon crystal lattice than boron does. Oxygen acts as an electrical damage center within the junction, and its removal is therefore beneficial. As a result, the crystal of oxygen-free aluminum-doped silicon contains fewer defects and imperfections than a boron-doped silicon crystal. This means that a better quality junction can be made in the aluminum-doped material.

In addition to requiring the use of oxygen-free aluminum-doped material, shallow junction cells have other special construction requirements. One of these is the alloy contact to the cell. The conventional titanium-silver contact, which is used commercially to make contact to the cells, contains a material that diffuses into the shallow junction and poisons it. As a result, it was necessary to develop a new contact alloy in which cerium was used in place of titanium. Cerium does not contain harmful impurities, so that a silver-cerium alloy can be used to make contact with the shallow junction cells with considerable success. In fact, the silver-cerium contact has proved to be superior to the silver-titanium contact in terms of strength.

Solar cells require cover glasses in space power supplies for two reasons. One reason is to protect the cell against radiation damage, and another reason is to increase the infrared emissivity of the cell in order to lower its operating temperature in space. The cement used to attach the cover glass was undesirable for use in space because it degrades when illuminated in space sunlight, and then absorbs blue light. It was necessary, therefore, to devise a means of attaching the cover glass to the shallow junction cell without the use of cement, as shown in figure III-6. The cover glass has been provided with an evaporated silver-cerium pattern that exactly matches the top contact pattern on the cell. The cover glass and the cell are then clamped together, placed in a furnace, and heated. The solder on top of the contact pattern on the cell wets the silver pattern on the cover glass and bonds it firmly in place. After furnace brazing, the cover glass is firmly bonded to the cell without the use of light-absorbing cement.

Also shown in figure III-6 is one other effect of using a very shallow junction and that is the large number of grid fingers on the top contact. Ten grid figures are used to collect current from the top of the cell, rather than the five or six which are commonly used. Having a shallow junction raises the electrical resistance of the surface layer of the cell. To avoid electrical losses due to this extra resistance, a greater number of grid fingers than usual must be applied.

The gain in blue response from the shallow junction is shown in figure III-7. Here, the response of a commercial type cell with the junction depth of about 0.5 micron is compared with the response of a cell with a junction depth of about 0.25 micron. This cell, of course, is an aluminum-doped cell with silver-cerium contacts. The improvement in the blue response of the shallow-junction cell is evident. However, there are still more gains to be made in the response, as can be seen by observing the theroetical maximum response, also shown in this figure. There is a way of improving the blue response still further by improving the antireflection coating of the cell. A two-layer antireflection coating is excellent for reducing reflection in the blue part of the spectrum. This coating consists of a layer of magnesium fluoride on the usual silicon monoxide antireflection layer. With this coating, reflection losses in the 0.4- to 0.5-micron region can be reduced. Thus, there is a considerable gain in the blue response of the cell (fig. III-8). The gain in blue response from the antireflection coating is about equal to the gain in blue response produced by using a shallow junction.

The result of these efforts in terms of radiation-damage resistance is shown in table III-1. Here a conventional cell is compared with the best Lewis cell that includes all the improvements discussed previously. The efficiency of the conventional cell and of the Lewis cell is about the same. The blue response has been improved, but this improvement has been accompanied by some loss in total active surface area of the cell, with the result that the efficiencies are about the same. However, the resistance to radiation damage of the high-blue-response cell is about 3 times that of the conventional 10 ohm-centimeter n-on-p cell. This represents a considerable improvement in radiation-damage resistance. Use of this cell in place of a conventional cell will allow either a reduction of the array weight by use of thinner cover glasses, or an extension of array lifetime with the same thickness of cover glass.

THIN-FILM SOLAR CELLS

A thin-film solar cell can be defined as a solar cell made from a thin polycrystalline semiconductor film rather than from a single crystal of semiconductor, as is the silicon solar cell. Figure III-9 shows a cross section of a typical film cell. The cell shown happens to be a cadmium sulfide film cell, but a basic similarity exists for all film cells. The cell consists of a layer of polycrystalline semiconductor, cadmium sulfide here, which has been deposited on an electrically conducting substrate. On top of the polycrystalline semiconductor, there is barrier layer which is similar to the surface p- or n-layer in a silicon cell. In this case, the barrier layer is copper sulfide. The p-n junction in this solar cell is formed between the two materials, copper sulfide and cadmium sulfide. On top of the barrier layer a metal grid is placed to collect the current from the barrier layer. The cell is usually covered with a layer of transparent plastic that performs the same function that the quartz cover glass does for the conventional silicon cell.

Table III-2 shows a summary of the film cell research being done at present. RCA (ref. 3) has been working on gallium arsenide film cells. In these film cells, the semiconductor layer is gallium arsenide and the barrier layer is cupric selenide, or platinum. They have achieved efficiencies of 3 to 4 percent, but only in small areas - 1 centimeter square or so. Harshaw has been working on cadmium sulfide thin-film cells for many years (ref. 4). Their efficiencies in production are 3 to 4 percent in areas of 50 square centimeters. The Clevite Company (refs. 5 and 6) has also been working on cadmium sulfide cells. They have achieved production efficiencies of 4 to 5 percent in 50-square-centimeter cells. Their cells are not sensitive to moisture, remaining unchanged for long periods of time in moist atmospheres. Lewis has also been working on cadmium sulfide cells and has achieved efficiencies of 4 to 5 percent, but in small areas. The work here is aimed primarily at understanding the mechanism of the cell. The General Electric Company (ref. 7) has been working on cadmium telluride cells made from films of cadmium telluride with a barrier layer of copper telluride. They have achieved efficiencies of 4 to 5 percent, and occasionally somewhat more. These cells are reported to be insensitive to moisture but do appear to be damaged by exposure to moderate temperatures. The most advanced of the thin-film solar cells appears to be the cadmium sulfide cell, so the status of this cell is discussed in considerable detail.

Radiation damage is a serious problem for silicon cells, but this is not the case for cadmium sulfide cells. Data for radiation damage to cadmium sulfide film cells is shown in figure III-10 (ref. 8). The relative maximum power for film cells is shown as a function of radiation dose.

For electrons with energies of 0.6 to 2.5 million electron volts, there is not measurable damage to the cells up to doses of 10^{17} electrons per square centimeter. Proton damage can be detected but it is small and amounts to only 5 to 10 percent with doses of 10^{14} to 10^{15} protons per square centimeter. These are very large doses of electrons and protons. The largest doses shown here correspond to times in the Van Allen belt of 10 or more years. This means that the cell is extremely resistant to radiation damage and does not require the heavy cover-glass shielding required for conventional silicon cells.

The film cells do require a covering or encapsulation to protect their surfaces from abrasion and moisture, as well as to increase their infrared emissivity. Coverings are discussed in more detail subsequently, however the most successful coverings have been plastic films. The bombardments previously described were performed by using plastic-encapsulated cells. Kapton plastic encapsulation was not noticeably affected by the largest radiation doses given. Mylar plastic encapsulation darkened very slightly and became brittle after the maximum doses quoted previously. Delamination of the plastic did not occur for either plastic encapsulant.

It is interesting to look at the weight of cadmium sulfide film cells. The layers of cadmium sulfide, copper sulfide, plastic, etc. can be made very thin, so that the cells can be made very light. In figure III-11, cell weight is plotted in terms of pounds per square foot of cell against time in years. Several years ago, cell weights of 0.2 to 0.3 pound per square foot were observed. At this time, the cells were formed by depositing cadmium sulfide on 2-mil-thick molybdenum substrates. Most of the molybdenum substrate could be etched away to remove much of the unnecessary metal and reduce the weight to about 0.1 pound per square foot. More recently, Kapton plastic has been used as the substrate. This material allows further reduction in cell weight to the vicinity of 0.06 pound per square foot or about 1 ounce per square foot. It is interesting to compare these cell weights with the weight of silicon cells. The thinnest state-of-the-art silicon-solar-cell - cover-glass combination weighs about 0.17 pound per square foot, so that cadmium sulfide cells are presently about 3 times lighter than the lightest silicon cell.

While cadmium sulfide cells are superior to silicon cells with respect to weight per unit area and their resistance to radiation damage, silicon has a higher conversion efficiency. Figure III-12 shows the mean production efficiency that was observed for 3- by 3-inch cadmium sulfide cells shown as a function of time in years. The early film cells were very inefficient. From time to time during the past few years, the Clevite Company has achieved mean production line efficiencies of 5 percent at air mass one and 25° C.

Two hundred cells were delivered to NASA by Clevite in the period from July to September 1966. These cells were half the pilot production of plastic-substrate cells, with every other cell in the exact order of fabrication delivered to Lewis. Of this lot of cells, the average efficiency was 4.9 percent, with 68.5 percent of the cells having efficiencies from 4.5 to 5.5 percent, 8.5 percent with efficiencies from 5.5 to 6.0 percent, 20.5 percent from 4.0 to 5.0 percent, 1.5 percent from 3.5 to 4.0 percent, and 1 percent from 6.0 to 6.5 percent. While the highest cell efficiency in this period was less than 6.5 percent, several 50-square-centimeter cells showing efficiencies up to about 8 percent have been reported by Clevite (ref. 6). This fact is indicated in figure III-12 by a point at 8 percent. Cells with efficiencies in excess of 6.5 percent have not been stable, dropping in a few days to efficiency values near 6 percent.

At Lewis, a small 4-square-centimeter cell was made with an efficiency of 7 percent. In

6 months of desiccated storage, the efficiency had dropped to 6 percent. It should be mentioned that cell efficiencies reported at Lewis are based on airplane-flown standard cadmium sulfide cells.

At present, an efficiency of 5 percent at air mass one for the 3- by 3-inch size plastic-substrate cell is the value that is consistently available from a pilot production line. Further improvements in cell technology may eventually bring average efficiencies into the 6- to 6.5-percent range, where now only about 1 percent of the plastic-substrate cells fall.

It is interesting to make a point-by-point comparison of the cadmium sulfide cell with the silicon cell. In table III-3, the largest and lightest state-of-the-art cells are compared. This comparison considers only the cells and does not include any other parts of the solar array. It would be desirable to compare entire arrays of cadmium sulfide and silicon cells, including the supports and extension mechanisms for the arrays. In the author's opinion, however, insufficient information is available about the kinds of supports and extension mechanisms needed for an array of cadmium sulfide cells to make a valid comparison at this time. It appears naive and premature to assume that these factors should be identical for cadmium sulfide and silicon cells because of the greater flexibility and mechanical strength of the film cell, which should allow different methods of array construction.

When the weights per unit area are compared, the cadmium sulfide cell is about three times lighter than the silicon cell. As a result, in spite of the low efficiency of the cadmium sulfide cell, the weight per unit power of cadmium sulfide is less than the weight per unit power for silicon; 14 pounds per kilowatt for cadmium sulfide against 15 pounds per kilowatt for silicon. This difference is small enough so that it is really not significant in a discussion of this kind. It simply indicates that the weight per unit power is comparable for the two cells. The area per unit power shows clearly the low efficiency of cadmium sulfide relative to silicon; 220 square feet per kilowatt are required against 87 square feet per kilowatt for silicon. Another interesting feature of cadmium sulfide is the number of cells required to generate unit power. Cadmium sulfide requires 3400 cells to generate 1 kilowatt of power, while silicon requires 20 000 cells to generate 1 kilowatt of power. Consequently, the labor costs involved in assembling an array of cadmium cells will be much less than the cost to assemble an array of silicon cells.

Another advantage of the cadmium sulfide film cells is flexibility. A cadmium sulfide film cell array can be easily rolled to occupy a very small volume. Another desirable feature of the cadmium sulfide cell is its probable low cost of production. For example, the current price of cadmium sulfide cells is such that the cost of power is about $125 per watt. This price is substantially the same price as power from silicon cells. However, this is the price for laboratory produced cells. In production, it is possible that the cost might drop to $10 to $50 per watt in units of 10 to 100 kilowatts production per year. If the production rate were increased to several million watts per year, the cost could probably be reduced to about $1 per watt (ref. 6). With these advantages in mind, one may wonder why a number of large cadmium sulfide film cell arrays have not been constructed. The answer to this is that all the problems have not been solved that remain before the cadmium sulfide film cell can be used by the spacecraft power engineer.

The primary remaining problem of cadmium sulfide is that of stability. The major areas where stability is a problem for cadmium sulfide cells are as follows:

(1) Storage degradation
(2) Humidity damage
(3) Thermal cycling failure
(4) Ultraviolet-light damage

In some cases, the cells degrade during storage. This problem seems to be under control except for high-efficiency cells. The damage to the cell by moisture has been, until recently, a severe problem. The cadmium sulfide cell is constructed of many different materials, and the thermal stresses that appear in the cell as a result of temperature changes as the cell goes in and out of sunlight can damage it considerably. Ultraviolet light causes damage to the plastic used to cover the cadmium sulfide.

The two main factors that control the stability of cadmium sulfide cells are the gridding of the cell and the encapsulant of the cell. The parts of the cell to which these refer are shown in figure III-9. The gridding of the cell refers to the metal screen grid electrode used to collect current from the barrier layer or surface of the cell. The encapsulant refers to the layer over the grid that serves to protect the surface of the cell from moisture, mechanical damage, ultraviolet light, and low-energy electrons.

The various techniques used for applying current-collecting grids to cadmium sulfide cells are shown in figure III-13. The oldest and simplest method uses a screen grid which is laid on the surface of the cell and is held in contact with the cell by pressure applied during lamination of the plastic. More recently, the screen grid has been held in place by a gold-filled epoxy cement. Grids can also be prepared directly on the surface of the cell by electroplating. In still another technique, the grid is bonded to the surface of the cell by heat and pressure to produce a compression-bonded screen grid.

The effect of these various types of grid on the stability of cadmium sulfide cells is shown in table III-4. Here are shown the various grid types and how they compare in stability against thermal cycling, moisture, and storage. The original pressure grid with a molybdenum substrate is poor in thermal cycling. The pressure grid with a plastic substrate seems to be quite good in its resistance to thermal cycling, but it is poor in its resistance to moisture. When the grid is cemented in place with a gold-filled epoxy cement, there is good resistance to moisture but problems with thermal cycling. The electroplated grid is very resistant to damage by thermal cycling, but it does not provide much resistance against moisture. The compression bonded grid is resistant to thermal cycling, but not much good in other respects.

The second factor that affects the stability of cells is the method used to encapsulate the cells. Three principal methods used for encapsulating cells are shown in figure III-14. The oldest method is the use of plastic and nylon cement. In this case, the grid is covered with a very thin layer of nylon plastic, which is covered by a thicker layer of another plastic that might be Mylar or Kapton. The whole assembly is laminated under heat and pressure. The nylon melts and flows, cementing the plastic cover to the grid and cadmium sulfide. In a variation, epoxy cement is used in place of nylon plastic. In this case, the heat and pressure of the lamination process cures the epoxy. The third type of encapsulation requires a grid that is electroplated or compression bonded. This coating, a transparent inorganic coating, does not provide any mechanical strength toward holding the grid in place.

Compounds such as silicon monoxide, aluminum oxide, and magnesium fluoride have been used for these transparent inorganic coatings. These encapsulants are compared in table III-5 with respect to their effects on cell stability. The Mylar-nylon encapsulant is poor against moisture. It is very poor in its resistance to ultraviolet damage, because the Mylar becomes brittle when exposed to ultraviolet light (ref. 9). If nylon is replaced by epoxy, the moisture stability is good, but the ultraviolet stability is still poor. The ultraviolet problem can be cured by using Kapton plastic film (ref. 9). This produces a cell that is good in all respects, except that the use of Kapton is accompanied by a 20-percent penalty in efficiency due to light absorption by the Kapton. This problem can be circumvented somewhat by using Mylar and coating it with a thin layer of Kapton. In a sense, Kapton acts as a sunburn cream and reduces the damage to the Mylar by ultraviolet light. After approximately 1 year of exposure to simulated space sunlight in a vacuum of 10^{-8} torr, Kapton coated Mylar cells were still flexible and undarkened. Still, a 5-percent efficiency loss is incurred as a result of light absorption in the Kapton layer. This is a good coating because it is resistant to moisture damage, stable in storage, and appears to resist ultraviolet damage. The inorganic coatings have been disappointing, primarily because they do not resist moisture probably because of small cracks in the film.

In summary, it appears that the problem of stability of these cells in use has not been solved. However, a solution seems imminent and in the author's opinion, a year or two more of work should yield stable space-worthy cells with efficiencies of 5 percent at air mass one. It is conceivable that the cadmium sulfide film cell might be useful for building large high-power arrays because of its expected low cost in production, its flexibility, and its lightweight.

HIGH-POWER ARRAYS

Presently, there are serious efforts to design, and eventually to construct solar power arrays that yield power up to 50 kilowatts (ref. 10). These high-power arrays use silicon cells. Silicon cells, of course, have the advantage that they are efficient, stable, and proven in the space environment. High-power solar arrays have definite disadvantages. First, there is their cost. They will be very expensive. The cost of a 50-kilowatt array is estimated to be $20 million. Second, the arrays cannot be built for much more than 0.1 gravity, so that any propulsive maneuvers of a spacecraft equipped with a high-power array must be very slight. The principal advantages of high-power solar arrays are the facts that no major development problems must be solved for construction of such arrays, and the lifetime and reliability of solar arrays have been proved to be very good. A summary of some of the high-power solar arrays that are currently under active study is shown in table III-6. The largest of these is a 50-kilowatt array that has an area of 4500 square feet and uses very thin silicon cells as well as a number of lightweight construction features. The final array is expected to yield a specific weight of 50 pounds per kilowatt. This array is a folding semirigid structure in which the cells are mounted on rigid panels. A 1/4 segment of this array is under construction. Another large array is being studied by RCA. This array will yield approximately 20 kilowatts of power, and again it is a folding semirigid construction. Some smaller experimental arrays are also listed in the table because they use a flexible rollup style of construction, rather than a folding semirigid style. The flexible rollup arrays can be easily expanded to larger powers, or adapted for thin-film solar cells.

CONCLUDING REMARKS

Solar cells have provided electric power on almost every satellite launched since the beginning of the space program. It appears that this state of affairs will continue for several years especially with the development of high-power arrays and high-radiation-damage-resistance cells. It is possible that, in the future, the use of film solar cells can reduce the cost of large high-power arrays to a relatively low price, accompanied by the disadvantage of increased array area. Insufficient information is now available to determine whether or not large film cell arrays can be made lighter than large silicon arrays.

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TABLE III-1. - RADIATION-DAMAGE RESISTANCE

Cell	Efficiency, percent	Relative radiation-damage resistance
Best conventional 10 ohm-cm	10 to 12	1
Best Lewis	10 to 12	3

TABLE III-2. - FILM CELL RESEARCH

Organization	Material	Approximate efficiency, percent	Remarks
RCA	Gallium arsenide	3 to 4	Small area
Harshaw	Cadmium sulfide	3 to 4	Moisture sensitive
Clevite	Cadmium sulfide	4 to 5	Moisture stable
NASA Lewis	Cadmium sulfide	4 to 5	Small area
GE	Cadmium telluride	4 to 5	Heat sensitive

TABLE III-3. - COMPARISON OF CADMIUM SULFIDE CELL WITH SILICON CELL

[Temperature, 50° C; space sunlight at 1 AU]

Cell	Weight per unit area, lb/ft^2	Weight per unit power, lb/kW	Area per unit power, ft^2/kW	Cells per unit power, cells/kW
Cadmium sulfide[a]	0.065	14	220	3 400
Silicon[b]	0.168	15	87	20 000

[a] Plastic substrate, plastic covered; 50-cm^2 cell; 5 percent efficiency at air mass one and 25° C.

[b] 8-mil-thick 4-cm^2 cell with 4-mil cover glass; 10.5 efficiency at air mass zero and 25° C.

TABLE III-4. - EFFECT OF GRID TYPE STABILITY ON CADMIUM SULFIDE CELLS

Grid	Stability against-		
	Thermal cycling	Moisture	Storage
Pressure (molybdenum substrate)	Poor	Poor	Fair
Pressure (plastic substrate)	Good	Poor	Fair
Cemented (plastic substrate)	Poor	Good	Good
Electroplated (molybdenum substrate)	Good	Poor	Good
Compression bonded (molybdenum substrate)	Good	Poor	-----

TABLE III-5. - EFFECT OF ENCAPSULANT ON STABILITY OF CADMIUM SULFIDE CELLS

Encapsulant	Stability against-		
	Moisture	Storage	Ultraviolet light
Mylar-nylon	Poor	Fair	Poor
Mylar-epoxy	Good	Good	Poor
Kapton-epoxy[a]	Good	Good	Good
Kapton-coated Mylar-epoxy[b]	Good	Good	Good
Inorganic (SiO, Al_2O_3, MgF_2)	Poor	Fair (?)	Good

[a] Efficiency loss due to light absorption by Kapton, 20 percent.

[b] Efficiency loss due to light absorption by Kapton, 5 percent.

TABLE III-6. - DEPLOYABLE HIGH-POWER SOLAR ARRAYS CURRENTLY UNDER ACTIVE STUDY

Nominal power, kW	Nominal area, ft^2	Silicon cell type	Company	Construction style
50	5000	0.008-in. thick	Boeing	Folding, semirigid
20	2000	Conventional	RCA	Folding, semirigid
0.5	50	Dendritic Conventional	Hughes Ryan	Rollup, flexible Rollup, flexible
0.2	20	Conventional	Fairchild-Hiller	Rollup, flexible

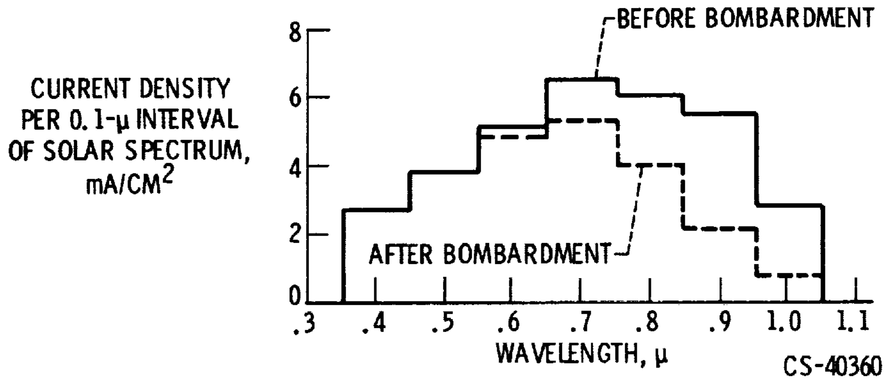

Figure III-1. - Effect of radiation damage on solar spectral response. Radiation dose, 10^{16} 1-million-electron-volt electrons per square centimeter; shallow junction; silicon oxide coated silicon cells.

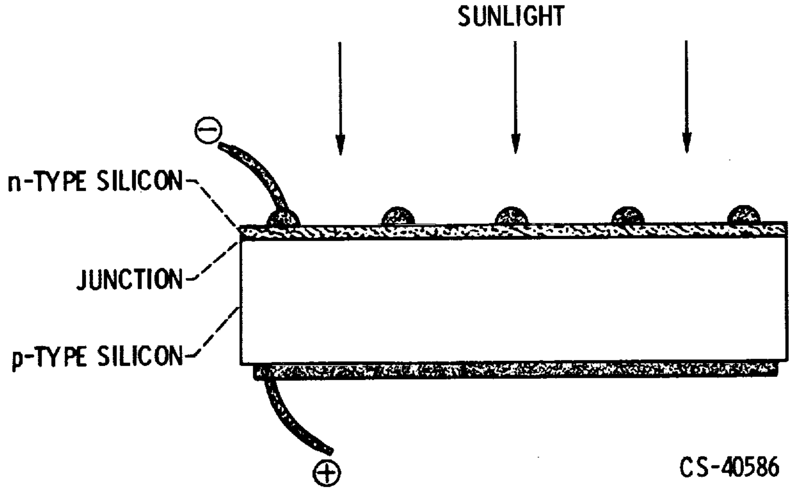

Figure III-2. - Cross section of silicon solar cell.

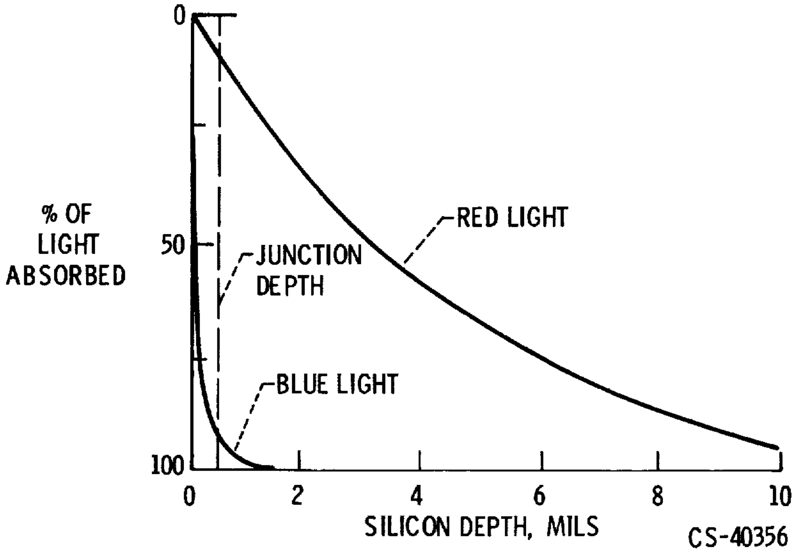

Figure III-3. - Dependency of absorption depth on wavelength in silicon.

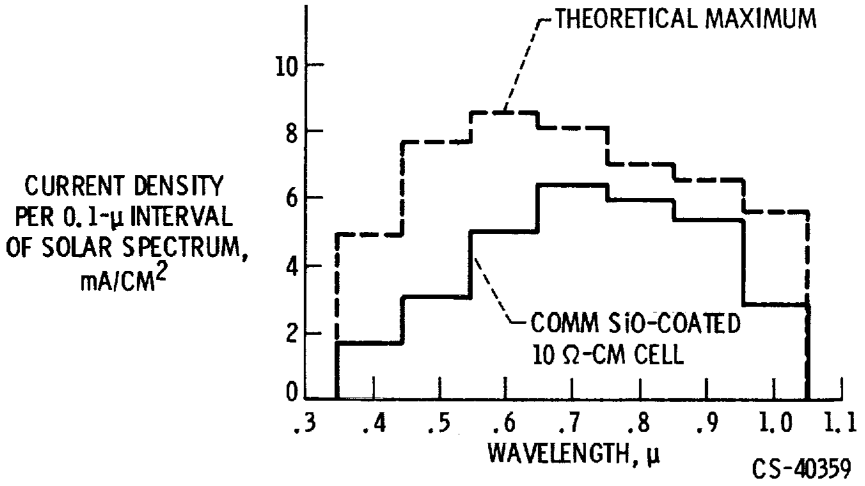

Figure III-4. - Comparison of actual response with theoretical solar spectral response for silicon cells.

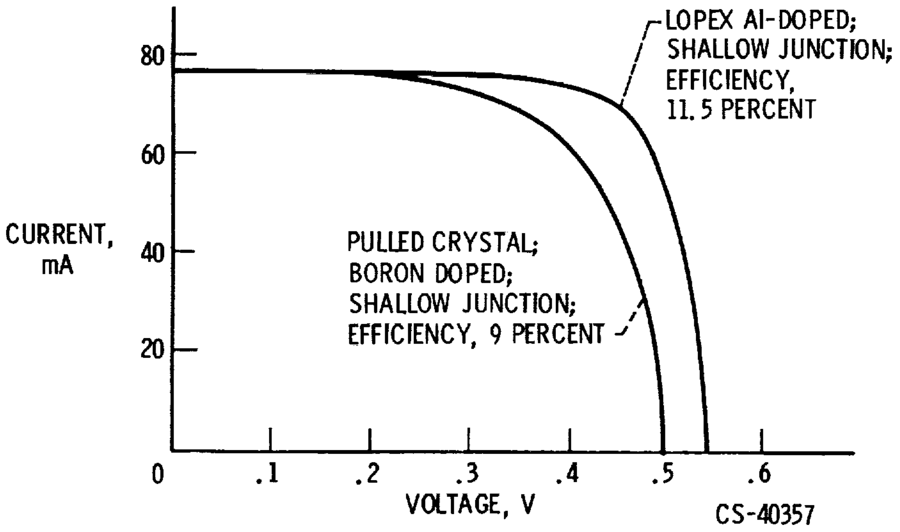

Figure III-5. - Effect of dopant on efficiency of shallow-junction cells. Current-voltage curves under simulated space sunlight. Cell area, 2 square centimeters.

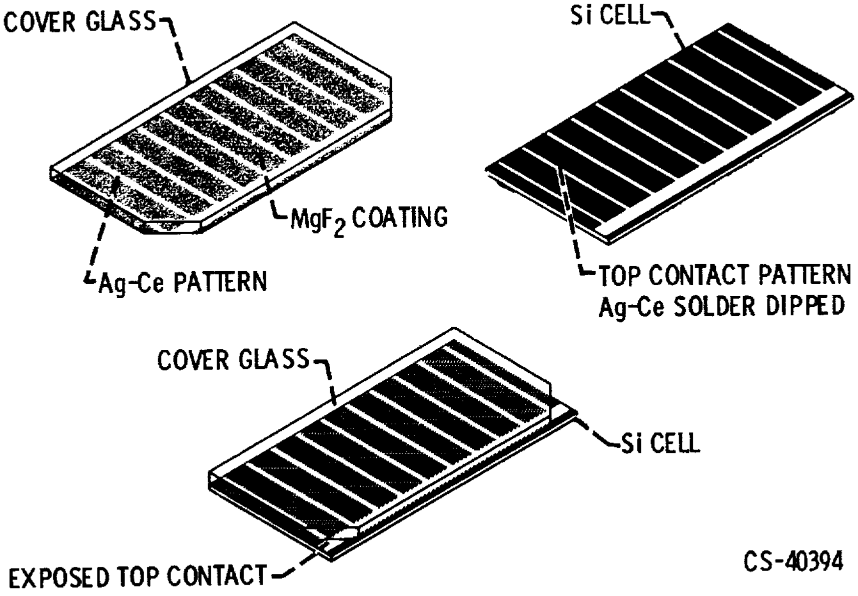

Figure III-6. - Lewis cover-glass attachment.

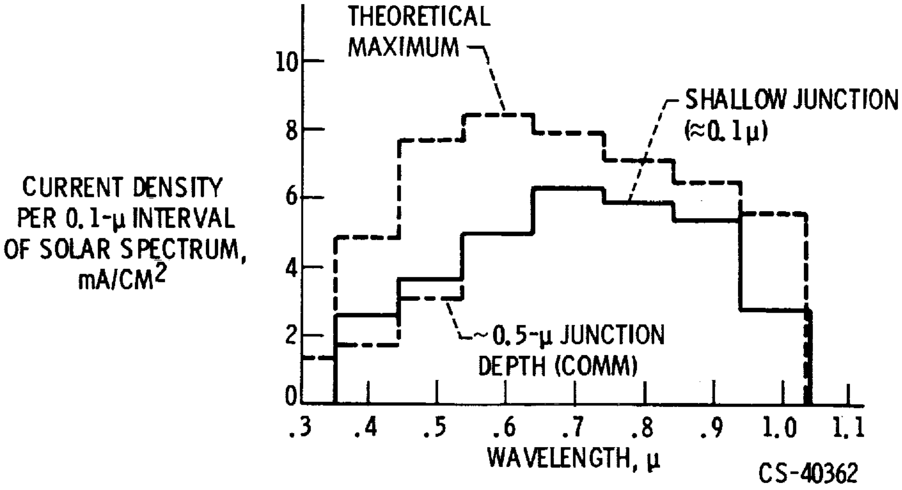

Figure III-7. - Effect of junction depth on solar spectral response for silicon oxide coated cells.

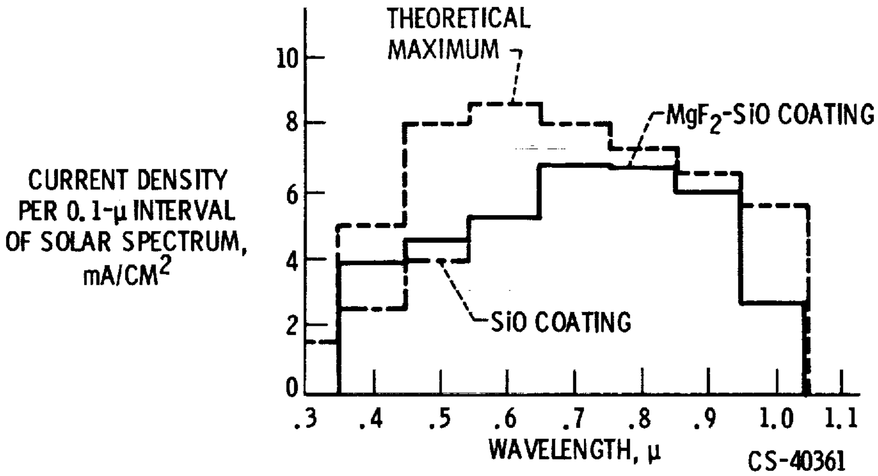

Figure III-8. - Effect of antireflection coating on solar spectral response for shallow-junction cells.

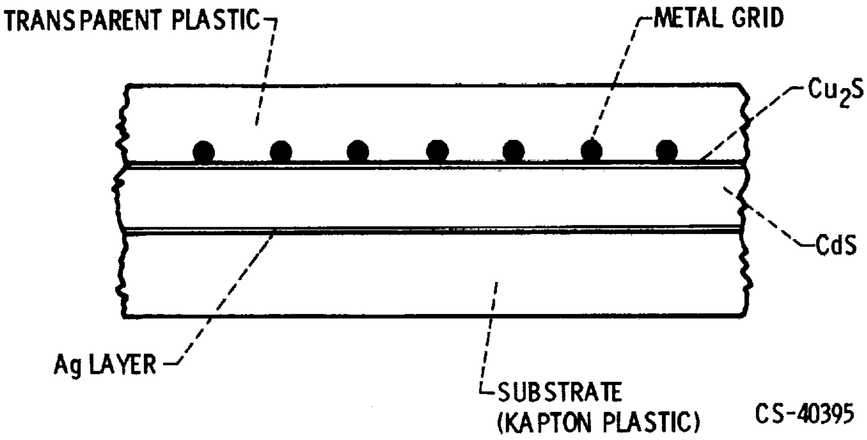

Figure III-9. - Cross section of typical cadmium sulfide film cell.

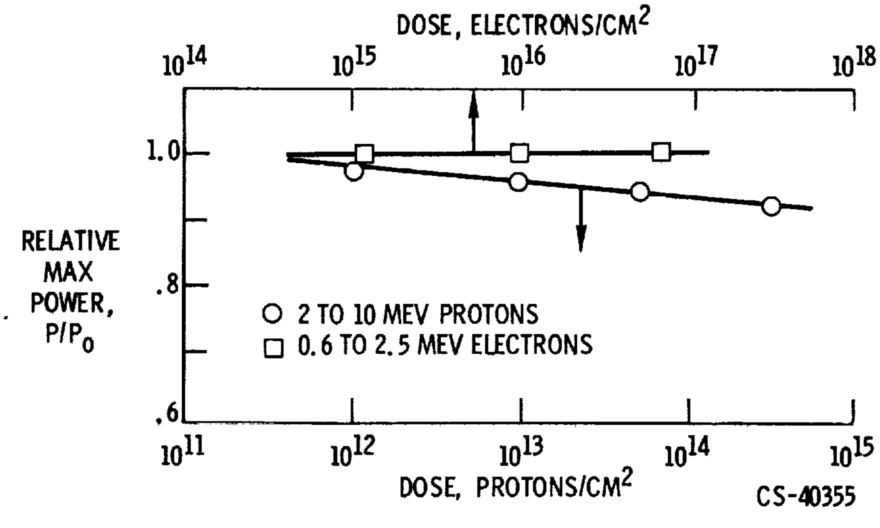

Figure III-10. - Radiation damage to cadmium sulfide film cells.

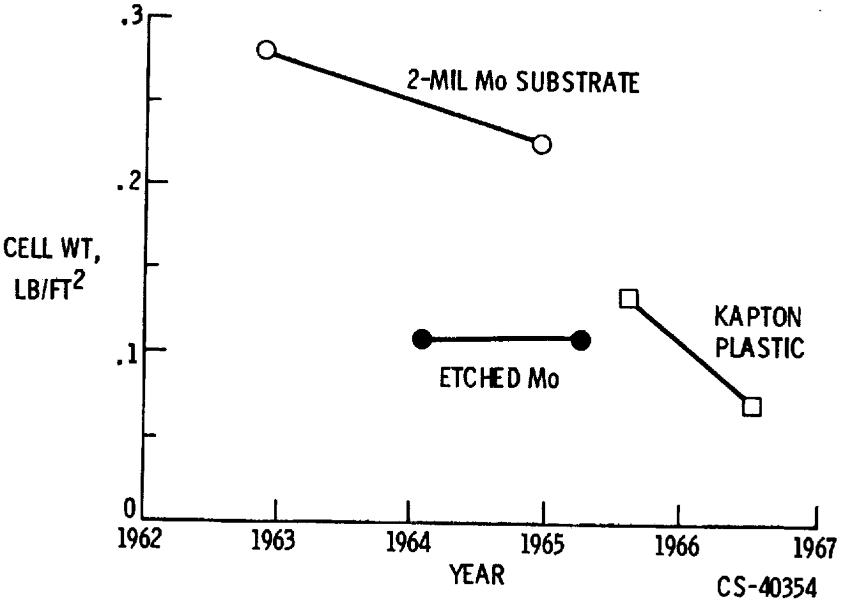

Figure III-11. - Improvements in cadmium sulfide cell weights.

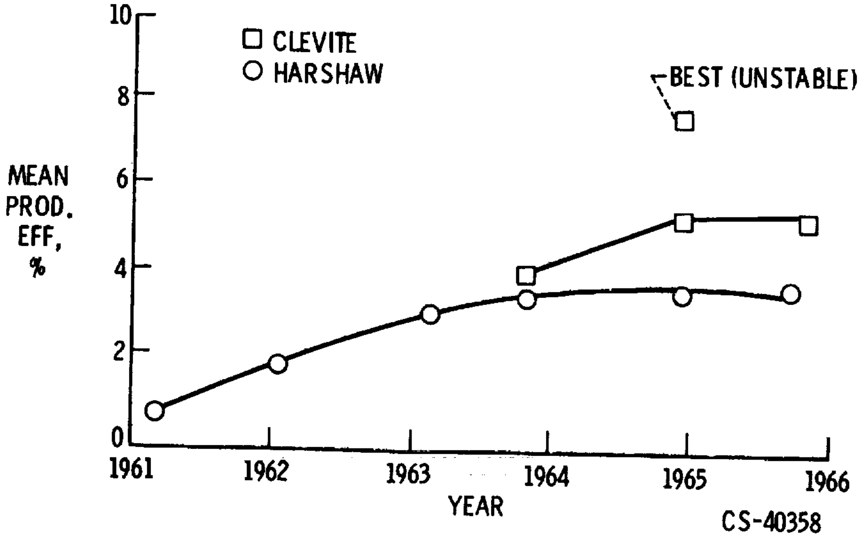

Figure III-12. - Efficiency improvements in cadmium sulfide film cells. Cell area, 50 square centimeters; air mass, 1; temperature, 25° C.

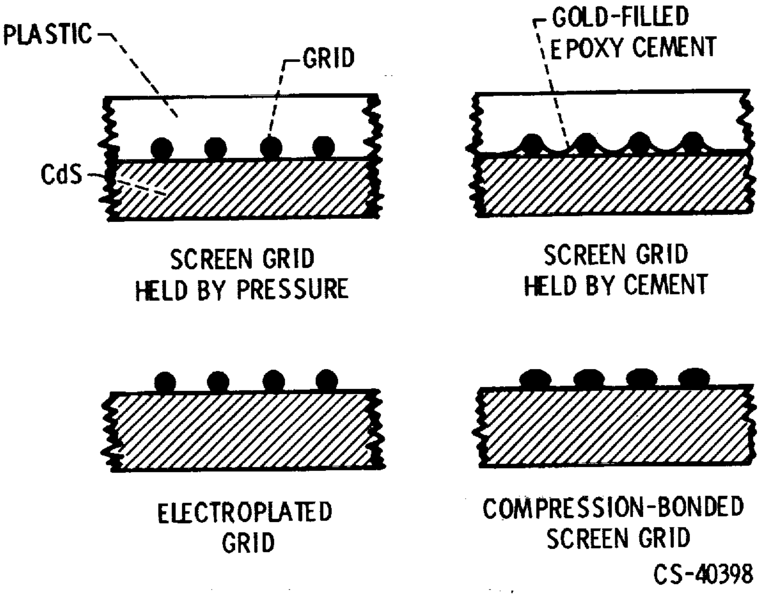

Figure III-13. - Gridding techniques for cadmium sulfide cells.

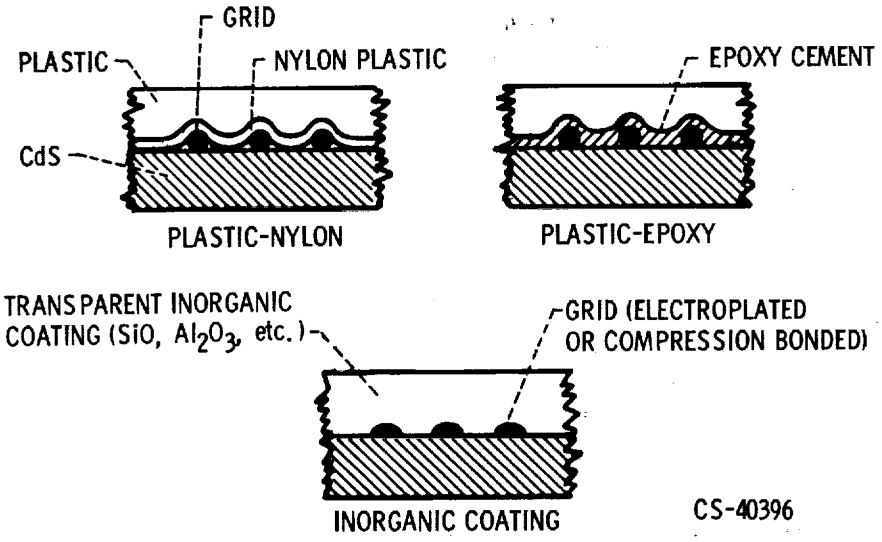

Figure III-14. - Encapsulant techniques for cadmium sulfide cells.