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TAP 2

IEEE/WAS/WSE SOLAR ENERGY LECTURE IV

APRIL 4



ELECTRIC POWER FOR SPACE SATELLITES

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CHARLES MACKENZIE has been responsible for the development of technology and systems for the generation of power for satellites and space vehicles at NASA-Goddard Space Flight Center since 1962 and has pioneered the system design approach for space power. He has written a number of papers in the field of space power and serves as consultant to several of the European space projects. He received his B.S. degree in electrical engineering from Northeastern University.

The development of electric power systems for satellites has been an evolutionary process requiring the integration of three elements: (a) power generation; (b) power storage; (c) power control and distribution. The interplay of these elements leads to the formation of a power systems design discipline where a power subsystem becomes a complete unit optimized within itself. The growth of space electric power systems is traced from the early missions of NASA to the current technology. Capabilities and limitations of the various elements and systems are discussed together with their impact on future technological growth. Parallel problems will be faced in adapting Solar Energy to meet the growth rate of Terrestrial Electric Power.

**Sponsored by IEEE, Washington Academy of Sciences,
and Washington Society of Engineers**

WASHINGTON SECTION-MARCH-APRIL-MAY 1974

(NASA-TM-X-66808)
SATELLITES (NASA)

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32 P HC \$3.75 CSCI 21C

N75-23678

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ELECTRIC POWER FOR SPACE SATELLITES

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For the past three weeks you have been listening to Mr. Cherry talking on solar energy conversion with references to solar energy conversion directed toward the production of electricity. You heard Gene Ralph from Heliotec, the maker of solar cells, talk about photovoltaic conversion of solar energy into electricity. You heard Dr. Glaser talk about using these techniques to put a generating station in space, transmit the energy to earth to help solve the terrestrial problem. All of these lectures have one thing in common, that is the emphasis on electricity. I am going to continue that emphasis tonight, the last that you will hear on the emphasis of electricity as I view the program.

It is our predominant use of energy here, it is the one we most feel because we walk over to the wall and flip a switch, therefore, it means something. You have heard three scientists talking from the scientific approach of probleming, talking of concepts, what might be done in the future. I represent a little bit of the other side of the fence. I am the engineer and my job is to talk a little bit about history, to use that history to make the dream of the scientist practical and usable to you. In that light tonight I am going to place my emphasis on history, what has been done specifically, what has been done in the area of photovoltaic conversion of solar energy into the form of electricity. I do this in the firm belief that the past is prologue and that what you see here are the steps leading toward the technique I think that will prove most beneficial, but also is the most far-fetched and that's Dr. Glaser's technique.

Electrical power systems in space, our emphasis here has been low weight because we didn't have theumph to get them up there, at least for a good many years. We started off with the push to get something up there quickly even if it worked for a few days. Then we wanted to extend the life, and as

ORIGINAL PAGE IS
OF POOR QUALITY

the program grew the higher the power level grew. We essentially had batteries on our early missions, they were too short life, too heavy. The solar cells came along and they formed the basis of the entire space program. About 90% of the missions or more have been flown using solar cells, and this is the area I will concern myself with tonight because it is the most practical in form. We have flown fuel cells on the Apollo Program. We have flown a few radioisotope generators, and if I don't mention JHU/APL the Hopkins Applied Physics Laboratory has flown a couple on Transit. We've flown a couple in Nimbus, and we did fly a nuclear reactor. A small one that lasted for about 50 hours. The big one unfortunately was much too costly.

Space programs began back in 1955 when President Eisenhower said it would be a nice thing for this country to launch a satellite in honor of the International Geophysical Year. The project was assigned to the Navy, it was called Vanguard. Unfortunately for the American prestige, the Russians came along and launched a small grapefruit called Sputnik in October of 1957, and this put several people in this country to shame. The Navy was having a little bit of trouble with the Vanguard Program and Wernher Von Braun combined with the Jet Propulsion Laboratory produced America's first satellite in February of 1958, called Explorer I. Since we are interested in power, that was the Explorer I power system. It was made up of 7 to 8 of these cells to get the required voltage. There were two batteries on board. We had a peak power of 1/2 watt, which was to last from two to eight weeks, and a weight of approximately 1 pound.

The Navy did come through about a month later and on March 17, launched Vanguard I. This was the first solar cell power system on a satellite, even though we had launched a few experimental solar cells on some rockets at White Sands, this was the first satellite to use them in a power system. Power system for Vanguard I consisted of these P on N type solar cells, 2 centimeters by 1/2 centimeter, connected in single power form. There were six panels, 18 cells per panel, and they gave us a power of approximately 1/2 watt. The life time was now measured in years, determined only by the degradation, and the weight of that power system was about 1/3 pound. There was also a small battery system on board, the main transmitter was powered off the solar cells and continued to work until the satellite's demise in 1964.

Then we got ambitious and we started the entire space program with the Explorer series of scientific satellites and you noticed they had solar cells in all types of configurations on paddles, body mounted on the end. Also in here was the Tyro series which was the start of our weather satellite program, and the Relay series which was the start of our communications program. The interesting thing about these early satellites as I call them is the power ranged from 10 to 40 watts. We continued to be ambitious, the more advanced missions came along. The Nimbus satellite, a weather satellite with an oriented array, the paddles turning to always face the sun. The large CGO satellite for scientific purposes around the earth. The OAO astronomy satellite for observing stars. The power levels in this series were ranging up to 500 watts.

Along came the higher power emissions, two of which have become realities, two of which are still on the drawing boards. The large communications satellite which is now represented by ATSF, is a slightly different configuration, but with an average power out of the array of 550 watts. We talk about solar electric propulsion and we are talking in the kilowatt range of power systems. The manned planetary which has been shelved temporarily again using kilowatts and the manned orbital space flight which culminated in Skylab again in a different configuration. The last and largest of these, of course, was the Skylab Program with the Apollo telescope mount and its four solar arrays. The orbital workshop area with its two solar arrays, unfortunately, it had to limp along on one.

We are talking 1973, 15 years later from Explorer I. The ATM array is a 12 kilowatt array, it will produce an average system power of 5 kilowatts, it will weigh 4,000 pounds. The orbital workshop array would produce 13 kilowatts for about the same system average. I have rounded off the numbers at 5,000 pounds. The life of the satellite is given as 18 months, and that is the design criteria that sets the end of life power. The end of life power is exactly that power required to produce the 5 kilowatts system load. The life obviously is much longer than that if you work below the 5 kilowatts. But in 15 years we have gone from 10's of watts to kilowatts, and we have gone from pounds to the early tons. The end of life in our design definition is that power required to sustain the satellite at full load at the end of its design life. It will actually live much longer. There is nothing

that will really take the solar cells down to zero except a complete failure, but definition is you must supply the system load at the end of the design life of the satellite and we matched that point and design our degradation factors that way. So that is why we have an end of life figure and you hear that. Two terms which we use very much are beginning of life, which is 12 kilowatts, and end of life which is the 10.5, the difference is the degradation due to radiation and such.

Having seen where the systems have gone, I think it would be very good to take a look at the considerations that went into their design and some of the factors that we had to contend with. On this basis we talk about the hazards from our standpoint associated with outer space. The first is the vacuum. Now it is no problem for our solar cell, it is not going to hurt us at all, but any supplementary power that uses liquids or gases must be in a hermetically sealed container or we will lose those systems. Even with our solar cells we must be careful of out-gassing caused by the vacuum because the products of this out-gassing could condense on other parts of the satellite ruining coatings or even disturb our own optical coating. The ultraviolet light doesn't bother us down here on earth because we have the atmosphere, but upstairs it is a real hazard to materials because it degrades them, it changes their thermal and optical properties and this effects our system design. The temperature extremes, parts of the satellite are in the sun and parts are in the shade. If it is a spinner, it is pretty much averaged out, but the parts that are in the shade get very cold, parts that get in the sun get very warm, and as you rotate on orbit those temperatures change and we must accommodate to that large change.

Energetic particles discovered by Explorer I, the Van Allen belts will degrade solar cells if they are not protected. The fact is if there is no covering on a solar cell, they will seriously degrade the junction and we will lose tremendous amounts of power within a day. Micrometeoroids are an abrasive property, we must watch them to make sure they do not disturb our efficiency.

(Question) The glass cover is determined as a buffer and they are small enough that they don't abrade the surface and disturb the optical transmission. We don't shock them away, we just put something on it so they don't damage the thin junction of the solar cell.

Another factor that we had to contend with in our space design is the solar intensity versus sun. I think the number quoted here for solar intensity, 14 watts per meter square, is the high end of the limit. The official number is 135.6 or somewhere in that ballpark. The interesting thing about this slide is you can see the difference in solar intensities for Earth, Venus, and Mars, but if we confine ourselves to the Earth area, you notice there is a variation about Earth. It's about $\pm 3\%$, and as you consider terrestrial power you will see that $\pm 3\%$ and you will probably have to compensate for it.

As we continue our look at the space problem, we have the problem of geometry of satellites in the near earth field. One of the things we have is for any satellite orbit plane, the angle of the sun with the plane will change over a yearly basis, $\pm 23\frac{1}{2}^\circ$ above and below the Earth's equator, and that incidence angle if not compensated for will effect our power and you will have the same problem on the terrestrial load. Also if we chose an orbit plane that should pass through the Earth's shadow, our dependence on solar energy is gone and we must have some form of power to supplement the solar power system to cover that period if we want to maintain our satellite.

Another problem we face in space is we get crazy load profiles. We see normalized to one, it varies all over, and it's obviously very impractical to design a system to handle a peak load and waste all this energy in here. If we optimize a system and design for here, then we must have a buffer power system to protect against the peak load. Again, the terrestrial problem is similar. Consider your own home and the load profile on that home. You must design your terrestrial system to compensate for the difference and you will not want to pay the price for the peak load.

So what we get to is a power system that we have termed in our work, the solar energy chemical storage type power system. It consists of a solar generator, it consists of a storage element to handle all those loads and to handle the shadow problem. It consists of processing and control electronics to match the characteristics of the two devices and the load system. It contains distribution where it goes to the individual loads where the conditioning occurs. I drew this slide specifically from my old division chief who happened to be a metallurgist and understood what conditioning meant. That's the conversion for each of the individual loads such as your washer, your TV circuit, etc. System design by our definition stops at

distribution. Even though our expertise covers the electronics for power processing and control and conditioning, we do both, we optimize a system using the knowledge in both, but the system design stops here.

The Nimbus R&D weather satellite has two solar paddles that rotate around this axis so that they are always normal to the sun picking up full solar energy. The control system is here, struts and experiment ring that always faces the Earth. That is a 550 watt solar array at 55°C. The power demand profile for such a satellite looks something like that. We have an earth day load which is the television cameras viewing the earth. We have an earth night load which is the IR sensor viewing the earth, and we have a peak load which is a data playback mode taking all the data accumulated here and here on a tape recorder and playing it back to earth over Alaska. Our array is sized for here, the battery handles the peak load. The power system is a bit more complicated, but the theory is the same. This is a negative voltage system for those who watch the convention of diodes.

Power is generated by the array, surplus power is bleed off in the auxiliary loads which are programmed to match the array to the system, thereby dissipating excess power. Power from the array is fed through a regulator to the spacecraft load bus, where it supplies the fuse loads, the experiments, the unused loads which are the same as the essential loads. A feedback device is used to control the regulator voltage. Charges also come through the charge rate limiter, through the battery and it is controlled by voltage sensing devices and temperature sensing devices. A voltage limiter is used to clamp the array for the excess voltage condition that could occur on the cold array, and I will have some figures to show you on that.

That is one module and the interesting thing about Nimbus is there are seven such modules in addition to this one connected in parallel. We have a modular type system in parallel which gives us our redundancy and this is exactly the same type of system that is used in the ATM and the OWS system, where 18 battery modules are connected in parallel to form the system.

Since you are a little tired of looking at block diagrams, this is what the power system engineer goes through in his life cycle. Starting off with conception, he goes through many hurdles to a design approval, many more hurdles and he breaks his design down into the arrays, the batteries, the power conditioning. They supervise putting together a system and they deliver

it to integration, and if they have goofed anywhere along the line the penalties are numerous to loss of time which reflects in loss of money, a loss of time and money in the form of junk hardware. Many more hurdles to launch. The evaluation in orbit which is a firm part of the designers life because if he doesn't see what he designed and see if it is working properly, he loses the whole concept and he doesn't know what to do better next time, and he starts again. You will have to use this iterative approach on your terrestrial problem. Otherwise you will spend more money than you have.

I think having looked at the system and following along with the previous lectures, you would like to see a little more of the generator and how it works and what are its characteristics, and on this basis there is the heart of our generation system. The silicon solar cell. The Nimbus cells is a 2 x 2 M on P silicon cell. It produces 57 to 60 milliwatts at 25°C. The size is about the size of that postage stamp, but believe me the price is not. \$3.50 each in quantities of 20,000. It takes approximately 10,000 of those cells to light five 110-watt lightbulbs.

The process is not quite as simple as I make it, but essentially photon energy from the sun hits an NP junction in a silicon wafer, excites the electrons. The energy in those excited electrons if connected to an external load will produce current and transfer electrical power. This is the equivalent circuit. It is a little simpler than Dr. Ralph used. I did not show the shunt capacity, but that is the device that we are working with.

Where does it get its power? Well up in space outside our atmosphere, we have a condition we call air mass zero. We have a spectro irradiance curve from the sun over these wavelengths, and we have an optical device that will absorb energy over this solar cell response. You notice the device is not optimized for the peak. We have had trouble getting there and we have not gotten there yet. But the combination of areas is what is converted and what produces the 10% to 11% average efficiency obtained by the common solar cell today. You have heard of the violet cell which is a later development. The violet cell did not shift the peak. It did raise the lower end of the curve and because it raised the lower end of the curve, it encompassed more area and, therefore, we have a 14% efficient cell that is what you might say in pre-production.

The electrical characteristics of this device, if you look at the open

circuit voltage as a function of the intensity, you see you get most of your voltage very early in life, and there is some change but not much. Your current is a linear function of the illumination and because of this fairly flat characteristic, the power is approximately a linear function of the illumination. A fact you will use in your terrestrial application. If you take a look at the curve between the open circuit voltage and the short circuit current, you define these series of curves with varying illumination, and I specifically want to point out the difference in current, the difference in power which occurs in this region for varying intensity. That's what you might see when you go from a bright sunny day to a cloudy day, and that's considerable change for your terrestrial system.

Another factor we have to consider is the maximum power that we can get out of this little device as a function of incident angle. You notice you start off with a relative power at one at normal incidence, you drop to about 50% as the cosine law which approximately matches the loss drops to 60° . We must size our array for the worst condition and this produces some deviations in solar power systems and in array sizes. Remember, you will see a terrestrial variation of approximately 8% in power over a year's time just due to the tilt of the earth's axis as it rotates around the sun and you will swing from one to nothing as you go from sunrise to sunset. The one occurring, of course, at noon.

This is a small satellite called OSO. Its average power at least on OSO I was around 18 to 20 watts. OSO VII is close to 100 watts, but it is a very small array because the array is always pointed normal to the sun.

The OAO power system, on the other hand, is a very large solar array because the satellite points anywhere in space. Therefore, while we have 1,400 watts available from the array when it is normal to the sun where they want to use it the most and at 60° off we have 740 watts. Oversized because of use.

Continuing our look at characteristics, the solar cell power output versus temperature is given by this curve. The 100% point is at our 28°C standard. You will notice we have about a 15% variation as we go from 0° to 40°C , and that's only 32° to 104°F , that's about the temperature swing that my wife tells me she grew up in in Arkansas. So you will see a 15% variation on the ground in certain parts of the country, greater in others,

less in others. But in space it is horrible. Here is a typical Nimbus array, you can see the swing is almost 105° . The array most of the daytime is in this region with a large drop at night, and you have a short portion of the day while it is in transition. You have to compensate for that by electronics in space. The problem is not as bad on the ground. Materials stressing is our major problem there.

This gives you an idea of how the power varies due to that temperature variation. As you can see, we drop from a little over 700 milliwatts down to a little over 400 milliwatts as we go from the cold case to the hot case. You will also notice this large shift in voltage characteristic due to temperature, which again must be compensated for. Going back to our basic IV curve, you can see we have a wide swing of voltage, we have the maximum power points here and we have a small variation in current. Therefore, the normal practice is to design for the hotter A which we have for $2/3$ of the daytime, allow margins and protect against this voltage variation. Just to give you a quite simplistic idea of how a system goes together in that configuration, there is the design of the Nimbus system where we start off at a regulated bus which is equivalent to 110 in your house. We have to allow for some electronics drops, we have to allow for the working range of the battery, we have to allow for some margin of degradation due to the array in space, and there is the maximum power point for our end of life design. Then we must compensate for this power that occurs in the orbit as we come out of the shadow into the sun with a very cold and drop quickly to a warm array. We will not get large temperature changes of this magnitude on terrestrial, but if we can with our storage systems take advantage of the cold case in that transition we can store a lot of energy, and electronically we can do this in space and on a system like Nimbus it means 20% more average power.

What does the device look like and what do we have to do to get it upstairs and make it work? This is a section of a typical module that we fly with solar cells. The basic cell is here, the interconnect is here. The cover slide is our protection from micrometeoroids and the radiation damage to protect the junction which lies along here. Not shown on the cover slide is an anti-reflective coating for optical transmission and on the bottom of the cover slide a UV filter to protect the cement from UV degradation. Underneath the solar cell we have the basic contacts, the substrates. Now we will not

have to build such a module here on earth of this complexity and of the complexity of the arrays that I will show you in a little bit. You will need some form of cover to protect against dust. You will not have the UV problem that we have. You can use simpler interconnects and if we can get very cheap cells, we can do something on the roof for electricity, but the storage element is vital because you are going to produce that electricity during the daytime and you need it at night.

This is how we build our solar array. The solar cells modules glued down substrate, printed circuit underneath. Specifically designed to compensate for magnetic problems with the current flow so we can fly very sensitive magnetometers, insulation in the basic substrate of the paddle. This is typical of the hardware we use and it is costly.

There is an engineering model, IMP paddle, with solar cells and with glass to simulate weight. This model is used for vibration purposes.

Here is a spiral mounted panel that was used as a test showing silicon solar cell area. That panel will probably produce about 50 to 70 watts normal to the sun. A set of four of these panels will cost today \$187,000. The Nimbus paddle which is a 500 watt paddle costs \$500,000.

I talked a lot about the solar cell and I have given you some idea of its characteristics and what Gene Ralph is going to put up with on earth when he gets to using them on earth. I can't neglect the rest of the system. I have to say a few words about the batteries. We use three primary types of batteries in space. The workhorse is the nickel cadmium battery because of the life factor. We need life in space. We sacrifice life for non-magnetic characteristics using the silver cadmium and if we want a primary battery that doesn't have to be recharged or just to handle the peak loads, we use silver zinc.

These energy densities are very low in use and the battery is a weight problem. You won't have the same weight problem on earth, but I think we need a better storage element than batteries, for electricity I am not sure what that is yet. These are typical nickel cadmium cells sized in ampere hours. We connect these in series parallel combinations to form a battery. The most popular at present is the 12 ampere hour cell.

These are typical electrical curves, the discharge and the charge. Note the 10 to 1 ratio in time. We can charge them as quickly as we discharge them

without destroying the cell. Also note the difference in voltage level between charge and discharge which is an efficiency in the system. The watt hour efficiency of the system is about 61%.

This is a typical battery pack. The one in question is for OSO. You notice 22 cells connected in a series combination for car storage element. We have some power conditioning and I just brought a couple examples of those. This is a programmable high voltage supply to be used on an experiment for OSO. It's multivoltage in the kilovolt range between 2 and 4, programmable by digital control from the ground. That is a small converter package for one of the IMP satellites on an experiment. That is a decoder converter which is part of our telecommunications system.

As I said, we have flown a few RTG (Radioisotope Thermionic Generator) systems. The problem with RTG systems is safety. It requires a presidential signature to launch them from a safety standpoint. Nevertheless, they give you a reasonably constant power output, they eliminate your storage problem. You have a peak load problem, and if the peak load to average load is very high, you have to argument with batteries.

We had one flying on the second Nimbus B for three years. What essentially you have is down the center of this cylinder a capsule with plutonium in there as a heat source. Around it in circular fashion you have these little semiconductor modules that transfer that heat to electricity at a conversion efficiency of approximately 5% and ship it out and the radiators reflect the waste heat. It is a very costly device because the fuel alone for this particular generator was over a million dollars to produce 50 watts of electricity.

(Question: How long?) That 50 watts lasted three years until something happened to the satellite and we lost our telecommunications that told us, but there is no reason why it shouldn't go on because the half year life is about 90 years. So you have a nice long decay curve.

The fuel cells, the oxygen systems, the problem here we can get kilowatts out of fuel cells but the design life of this hardware right now is less than a year. Of course, if something can be done by using electric energy to generate the hydrogen we have talked about, and we can get long life fuel cell materials, this is a possible alternative and this is a possible answer to the storage problem.

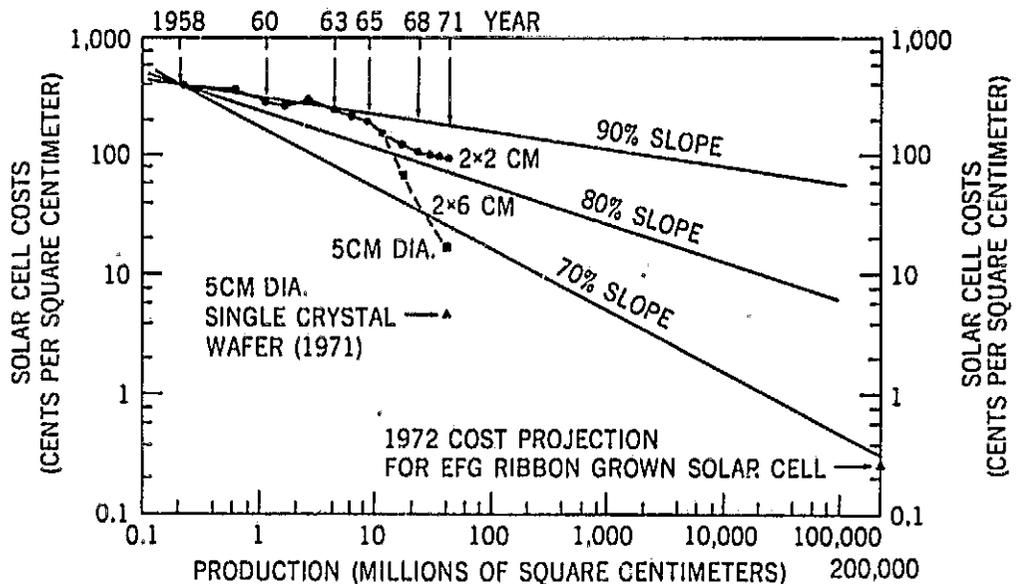
I think you have seen or had enough of the feel of hardware and some of the problems that we have had in space power. The question is what does it all mean? I can give you our opinion from the space power side, and I want to give you some things to think about. The first, it is a systems approach. If you are going to make it economical you have to consider the whole system, you just can't consider the day portion or the night portion. You have the storage problem. I don't quite see right now a clear good way to get around the terrestrial problem. We are still experimenting, but we do need some good storage and we do need some good interconnections.

Systems design is going to have a field day. One of the most depressing things is the progress we have made in solar cell efficiency over the years. Starting off at 1%, getting into silicon. Long, slow, painful rise to eke out the barest percent increase in efficiency and along come Dr. Lindsayyer and he came up with a 14% cell, and we are still way off from the 22% cell. We need a breakthrough. Quite frankly, if we are really going to make this thing work and not brute force it, we are going to need a breakthrough to narrow that gap or we are going to need a new invention to get directly from sunlight into electricity.

I talked to you about the intensity and I showed you Johnson's curve at air mass zero, but let's take a look at air mass one which is where we are today on a nice bright sunlight on the earth. You notice the curve is down, you notice the absorption bands. Now Gene Ralph said we had a 14% cell at air mass zero, but it looks really good because it is 16% at air mass one. Well that might be real good, I'll take 14% of 139 against 16% of only 98. So the silicon efficiencies even though they are high and the numbers are getting close to the theoretical limit, hit the atmosphere absorption problem which takes down the intensity, so you actually get less power out for that 2% increase in efficiency. If you push that just a little bit more you have air mass one, air mass two, all the way down to air mass five, which represents the period five to one and back to five, sunrise to sunset. You add this into the fact that you put an array on a house and you don't track it, you now have the combination of the intensity way down and the incidence angle way off and you get very little power. The answer is oversize the system. Oversize the system is cost.

Looking over from what we see from a space view, and we admit that maybe we are a little prejudiced, the best hope of achieving electric energy for the terrestrial problem from space is exactly what Dr. Glaser promised, to generate it out in space where the incidence problems are minimal, where we do not have the large storage problem and where because of the large space we have we can afford inefficiencies and we take 100% sunlight and come down with 60% or 50% of it to electrical energy and not bother us too much here. So our message is, it's correct, it's going to be long, we can do it with photovoltaics, it is going to be costly unless we get a breakthrough and to get the costs down, we need production.

SILICON SOLAR CELL COST PROJECTIONS



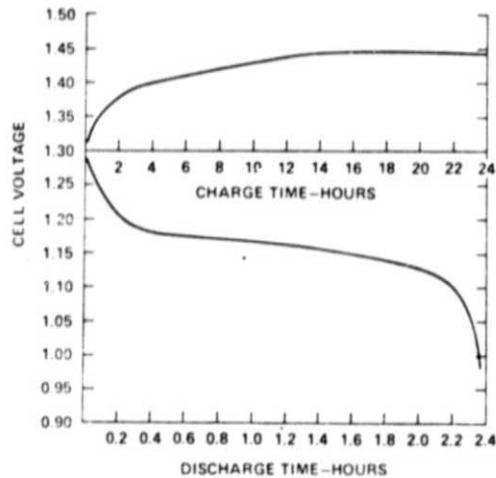
**TYPICAL PERFORMANCE PARAMETERS
FOR THE THREE SECONDARY BATTERY SYSTEMS**

PERFORMANCE PARAMETER	SILVER-ZINC	SILVER-CADMIUM	NICKEL-CADMIUM
ENERGY DENSITY (W-HR/LB):			
THEORETICAL	208	120	107
ACTUAL PEF CELL (2-HR RATE)	40	20	12 TO 15
FLIGHT-PACKAGED CELLS	30	14	9 TO 10
USABLE IN FLIGHT ^a	7 TO 8	4 TO 5	2 TO 3
CYCLE LIFE ^b (1000 CYCLES)	.4	3	12 TO 18
RANK IN USAGE FOR SCIENTIFIC SATELLITES	3	2	1

^aESTIMATED VALUES DEPENDENT ON SPECIFIC APPLICATION AND MISSION REQUIREMENTS

^bBASED ON NEAR-EARTH ORBIT AT 25-PERCENT DEPTH OF DISCHARGE AND 20° C.

NiCd CELL ELECTRICAL CHARACTERISTICS



QUESTIONS & ANSWERS

- Question:** On this space station, it is going to be out of stationary orbit and there is going to be a time though when it will go into earth's shadow. How often and for how long?
- Answer:** It goes into earth's shadow at the equinoxes. It's a 45 day period. The shadow period starts off at zero and goes in for 72 minutes and then comes back down to zero in a 45 day period. I believe Dr. Glaser said that really occurred about midnight anyhow so that the load power would be down and if there were two of these things placed in orbit, they could be so placed that one could take over from the other if you wanted a continuous load. But that only occurs twice a year and two 45-day periods at the equinox.
- Question:** What number of stations was he talking about?
- Answer:** I think he was talking two or three, but I am not sure.
- Question:** Also would these be quite vulnerable if somebody had a sizable amount of the power demand in the country met if some enemy operation could knock one of these out?
- Answer:** It is even much more effective to shut off the supply of oil. Anyone can do that at any time and that's par. Well, I think cost wise to even try something like this we are going to have to go into international cooperation. The fact is we are now space wise co-operating with the Europeans. We have a common program called ISEE where they will be launching one satellite, we'll be launching a satellite and we'll be working together. Our favorite program right now in my area is the IUE (International Ultraviolet Explorer) where they are essentially my contractor on the solar array and they are furnishing me a solar array for an American satellite. We are working very well with these people, we've worked five years with them and we have been swapping technology back and forth, and I specifically have not stunted on the basis that the way their

programs are going and their developments are going, they are behind us and I see the technology coming back.

Question: There's a lot of things floating around up there in space and what are the probabilities of something that floats around smashing into this?

Answer: With all the people putting up communications satellites, are they going to bump into each other in synchronous orbit. Now with all the stuff we have had in space, I think there was only one known record of a collision between two of them. Morris can you shed any light on that?

Floor: No, except to say that it is a problem of growing concern especially in communications satellites where there is quite a large crop of them that they launched in the past 18 months and it's a parking space problem. It is a fairly major issue.

Answer: Okay, the problem is more communications right now than it is physical space. Because you are at 22,000 miles out and on a circumference, that's a pretty big area.

Question: Glaser's concept used concentrators. Have any of the satellites currently projected or in orbit used concentrators?

Answer: Not to my knowledge. Boeing proposed a program using a similar type concentrator for the Jet Propulsion Lab. The difficulty we have found with concentrators are the finish on the concentrator in a space environment deteriorates. As a result, you do not get the proper reflection and you do not get the complete energy you want and you may be better off just putting in more cells and laying them flat. The hope of the concentrator is really to cut down the number of solar cells and thereby cut the costs. The problem we have in space is we can't fail. We spend a couple of orders of magnitude for a piece of space hardware and if we haven't done the job right the first time, it's junk. It's a pretty tense environment because you cannot afford to make a mistake and you have to take out all kinds of insurance. The Nimbus array, let me give you numbers right now. The Nimbus array is a 550 watt array and it costs approximately \$500,000 and it only lights five lightbulbs on earth. I can cut that cost by \$150,000 by just getting rid of that substrate underneath

which has a structural requirement. I can get rid of another \$100,000 or another \$150,000 by getting rid of the environmental test, the vacuum simulation and the thermal simulation I have to do to make sure that thing won't fall apart when I get it in space. So starting right there I have a cost out of 50%. Now those things I can pull out, space costs, but where I really have got to cut the cost is on the basic cell itself. To do that I need large production quantities, and I need a whole new technique of manufacturing to get the cost down in the cents area from the \$3.50 it is now.

Question:

Answer: That's right, well I can get some bad cells in here and I can cull them out when I get my terrestrial thing built and put into repair and very cheaply effected. I can't afford that in space so I have to grade all my hardware and doubly inspect it and that's costly.

Question: Is that where the hang-ups in to the main fact of these cells is that most of it has been oriented towards space operation and went to terrestrial applications providing they have the demand and you could meet the production? Right now it would probably reduce the cost considerably.

Answer: Well if you put the demand in there you can cut the cost. But you can only go so far when you are back to basic material and processes costs based on what they are doing now. I think the interesting thing here about the solar cell manufacture is, and we ran a survey on this about a year ago because one of them was in trouble and getting ready to go out of business. The capability of production and there are only two vendors in the country, is somewhere in the neighborhood of 3 to 4 million cells a year. The NASA demand is only about 500,000 a year, and each company to break even needs an order of 350,000 a year just to keep the thing going at its lowest effective economical rate. Now if the Air Force doesn't come along and fill up that void and COMSAT and a few other people, we are going to lose a vendor, and we have come very close to losing one. But the demand isn't there, and until it is he can't do much on cost.

Question: Who are the two?

Answer: Heliotec, Mr. Ralph's company and Central Lab, which is in the process

of being bought out by Dr. Lindmyer of COMSAT who produced the violet cell. Those are the only two. Texas Instrument was in the business, they couldn't make a go of it. RCA Mountain Top was in the business, and they found out very quickly because they were on the same floor with the transistor making setup that they could make more money by making transistors than they could with solar cells, so they just converted their equipment over.

Question: What is the government doing as far as helping one of these companies develop their solar cell?

Answer: NASA is not doing a lot. We are doing very little. Our total solar budget is less than a million and a half.

Question: From what I understand NSF contracted in space?

Answer: Yes, and we are limited right now as to how far we can go in R&D with the dollars, because we still have not branched out on our so-called energy part of our chart. The fact is I believe there is a bill in Congress to clarify that and get NASA more into the energy field. The people who are starting to push the solar cells right now are NSF (National Science Foundation), and they are getting ready, I think Bill said to pump \$50 million into it. This is solar energy conversion, not photovoltaics specifically, but solar energy conversion in the next year. NASA regrets that the violet cell which is our latest improvement of 3% is not a NASA product, but it was produced by COMSAT because they really went into it. Now we are looking at a multi-junction cell so that we can get more than .46 out of one cell, but that has not born fruit. They have looked at a multi-layer cell to see if with many junctions in there they could pick up more efficiency. They have not been successful in that, and it is a slow process, because the government has to put all the money in, the contractor will not invest until he sees a commercial market and a profit for himself.

Question: What does the concentrator do to the cell?

Answer: All the concentrator does is increase the intensity.

Question: Why does the concentrator not function in outer space?

Answer: After a period of time, the abrasion of outer space effects the reflecting surface and the reflection coefficient goes down so the

amount of intensity on the cell drops over a period of time. Therefore, the efficiency of the whole system falls. One concentrator design took the illumination hitting the cell up to 1.4 times normal, but over a period of time it degraded back to 1.1 time normal, so we lost the increase. The current is a linear function of intensity and the power is essentially a linear function of intensity so as that intensity drops, of course, the power goes down. It's a matter of material finish in a space environment where you have small particles and small micrometeorites hitting that highly polished surface and dulling it.

Question: It doesn't do any damage to your cells then?

Answer: No, the cell is all right, but the light hitting the cell changes because of the reflectance change on the surface. It's the same thing with a highly polished mirror that you put a cloud of spray over. The intensity off that highly polished mirror falls down that reflected off.

Question: Am I to understand that that's the best fraction you can get in the country, 1.4?

Answer: I believe that was the design I saw. As you get it up further the light starts falling off the cell and there's a match in between the two and the number I saw was about 1.4

Question: How do you keep the heat from being concentrated to the long red rays?

Answer: You don't. There is a U-V coating and there's a red coating that they put under the cover glass that cuts off that spectrum, but it still doesn't stop the heat and, of course, as the cell heats up you lose power that way and what you want is a cell on something that is radiating so the back of that cell is as cold as you can get it to get the heat out. If you could run these arrays in space at -55 all the time, we could have the size of a solar array for any one satellite. But we just can't keep it down.

Question: Have you used lenticular lenses for concentrators?

Answer: No. We haven't done any work on that at all. There may have been some work. There was a sunflower concentrator that was used that got efficiencies way up. They have used thermionics with concentrators to try to generate electricity on that. All of that work now is being done at JPL, but it is a very low level effort.

Question: If one of these cells failed does it fail open or closed?

Answer: We have not seen a solar cell fail. What fails is the interconnects. The connection from one cell to another. The cell itself with its voltage current characteristic, you put in series to get voltage you want and you run them out in parallel to get the current and power you want. The interconnects are multi-redundant. In other words, on some cells there are four or five connections, physical connections, wiring from one cell to the next. It is done by a silver mesh process, where you use the diamond mesh, the points on the diamond to make it, and because you have so many of those you can afford two or three and you don't lose any circuit.

Question: What makes them fail, thermal stress?

Answer: Thermal stress, continually working that joint as you go through that 105° swing, and it is actually bigger on some of the satellites that go into the shadow for longer periods. We get down to -160 , -180 on some satellites.

Question: On the central solar power station what is the temperature variation you expect to keep a thermal constant temperature?

Answer: If it goes into the eclipse, the array radiates to outer space with no heat input at all and it is going to go very cold. To make it lightweight, it is going to be very thin, because if it is very thin it is going to get rid of its heat fast. So the temperature is going to go like that.

Question: But he is planning on that not happening too often.

Answer: It is going to happen 45 times every 6 months, but it will not go to its lowest point till the middle of those 45 times. In other words, you just take a little cut for 2 minutes, 4 minutes, 6 minutes, 8 minutes. When he goes through the 72 minutes, it will get the lowest and it will probably be in the area of -180°C . But he has got to live through that thermal stress, and if he is using thin structure for weight, he's got a real problem.

Question: Does the cost of storage make the entire terrestrial system unattractive as opposed to the solar orbiting system?

Answer: It's the storage problem physically, also you get the energy at the wrong time. Your peak load if you think of your home is at sundown.

Question: But the reason it is not attractive economically or practically is basically the problem of storing to match your load curve.

Answer: Some of these things have been proposed. During the day when you have the solar energy pump water to a high reservoir, let it out at night. Use solar energy to process and make hydrogen then turn around and burn the hydrogen at night.

Question: One of the problems where you have a high voltage string and get one cell shaded, the whole voltage would appear across the shaded cell?

Answer: That is right. Remember if you shade one cell, it essentially open that cell and the rest of the array depending on how it is corrected tends to drive that cell, so you force it way back. If you have a real high voltage system, you can force that curve so back that there is a heating problem and the heat can't get out of the cell and that eventually causes the failure.

Question: It isn't a failure due to voltage breakdown but rather heat that destroys the interconnections.

Answer: Yes.

Question: How about Bell Labs and Western Electric, are they making solar cells for their own applications?

Answer: They were, I think they still are now, but they are not commercially available.

Question: Your peak power is during the sunlight during the summer months I think?

Answer: For air conditioning yes. That's started the term of balance, but again the winter months is when you get the best sunlight in the northern hemisphere, when you get the best incidence angle, when you get the clearest days and the solar cell system on cloudy days is a rough system.

Question: Would you care to comment on other materials besides silicon?

Answer: I would like to but I'm a systems type, I'm not a solar cell specialist. Gallium arsenide people have been looking at that for a long time. Its potentialities have been very good since 1962 and the engineer will be very happy to use and pick up all the efficiency they talk about. It's not there. We were told cadmium sulphide

cells, large area, thin cells would come along and you could take them at 5% and use many more of them instead of the 10% silicon. They haven't got that process down yet. They have turned away and turned the money off on the process because they don't see it coming out the way they said it would. So to make this thing go we either need a breakthrough in our own efficiency on silicon or we need some new invention.

Question: What about shifting the peak of the response curve downward, have any of the materials shifted to speak?

Answer: I can't answer that. I know they have been unable to shift it where they want in silicon and the only way they have been able to get the efficiency up is to raise that blue end by optical matching techniques between outer space and the cell itself.

Question: You've been working with APL?

Answer: We work with both APL and JPL. The general research on solar cells has been done at JPL. Our research is more applications oriented. JPL has pushed gallium arsenide and terrestrial application. At Goddard Bill Cherry is about the only one working in terrestrial power because the Goddard charter has not been set. I expect that to change but the main work on terrestrial power has been at JPL.

Question: Is anybody really looking at the terrestrial systems applications market?

Answer: For photovoltaics, probably Gene Ralph. Because he makes the cells and it is a ready market for his product, but I don't think any one has really pushed the system.

Question: Mr. Cherry in his talk seemed to indicate that solar energy funds particularly for terrestrial applications seemed to be lagging.

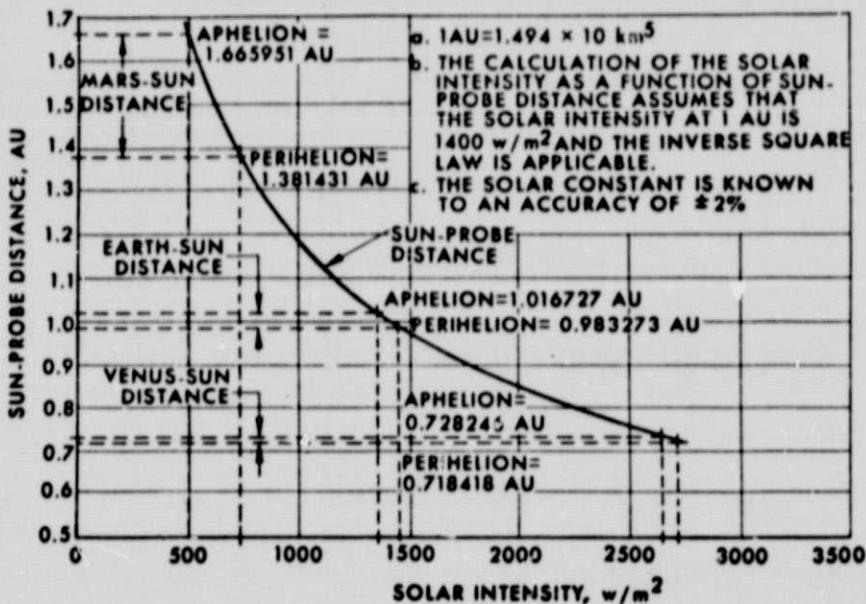
Answer: Bill has worked in the silicon area for many years. The fact is it was he who really started N on P work at Fort Monmouth and I believe the P on N cells that flew on Vanguard actually came out of Fort Monmouth. They would always like to do more because it is their speciality and they have had to fight for funding for many years with NASA Headquarters. One of the big things they have had to fight about has been the SNAP 8, and that program is so large

and the reactor problems are so big that garbled up 80% or 90% of the ART money in power and propulsion. They don't have much margin to move in. 22 is the limit and when you get half way there, the other half comes very tough.

Question: I was really referring to the terrestrial applications as a means of relieving the present short and long term energy problem here.

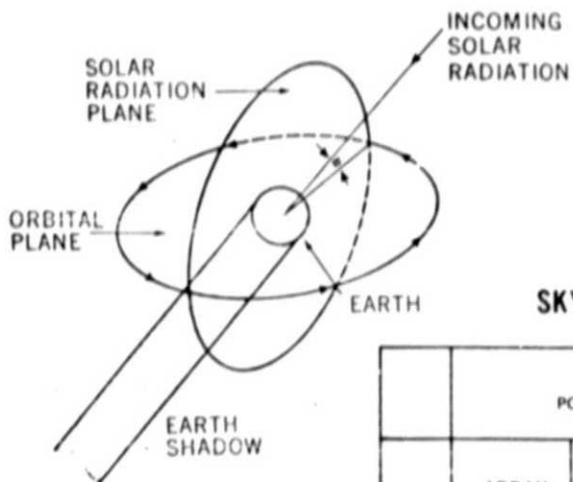
Answer: We're fighting the AEC, and that's a pretty big fight, and you're not going to come out second best with that type of organization already in and already pushing the breeder reactor.

SOLAR INTENSITY vs SUN DISTANCE



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ECLIPSE GEOMETRY OF SPACECRAFT ORBITS

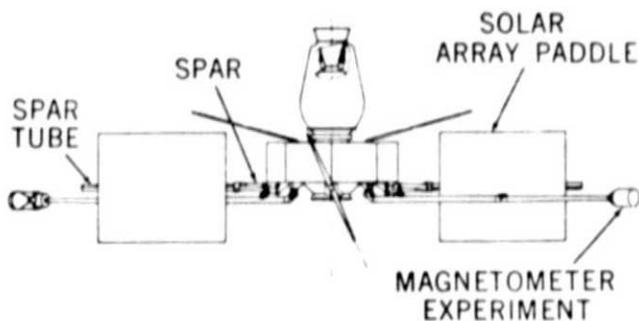


SKYLAB POWER SYSTEMS

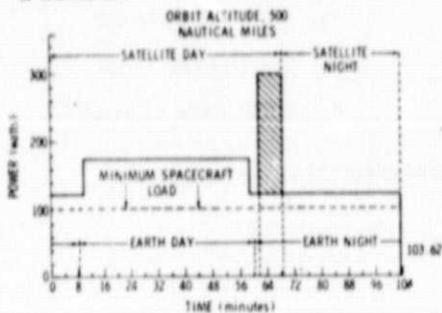
	POWER			WFIGHT	LIFE
	ARRAY	SYSTEM	E.O.L.*		
ATM	12KW	5KW	10.5KW	4,000 LBS	18 MONTHS
OVS	13KW	5KW	10.5KW	5,000 LBS	18 MONTHS

* END OF LIFE POWER AT 55°C

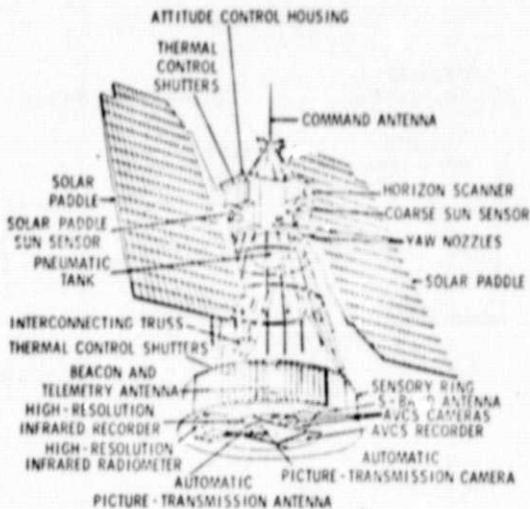
EXPLORER XXXIII (AIMP)



NOTE
 CROSS-HATCHED AREA REPRESENTS AVERAGE INTERROGATION
 LOAD. DURATION OF THIS LOAD IS VARIABLE. FOR A GIVEN 24-HOUR
 PERIOD THERE ARE 16 ORBITS AT 300 NAUTICAL MILES. OF THESE
 8 ORBITS HAVE A 8-MINUTE INTERROGATION PERIODS (ORBIT HAS
 AN 8-MINUTE INTERROGATION PERIOD WITH RESPECT TO S-BAND
 TRANSMISSION - PREDOMINANTLY 4 CONSECUTIVE ORBITS CANNOT
 BE INTERROGATED).

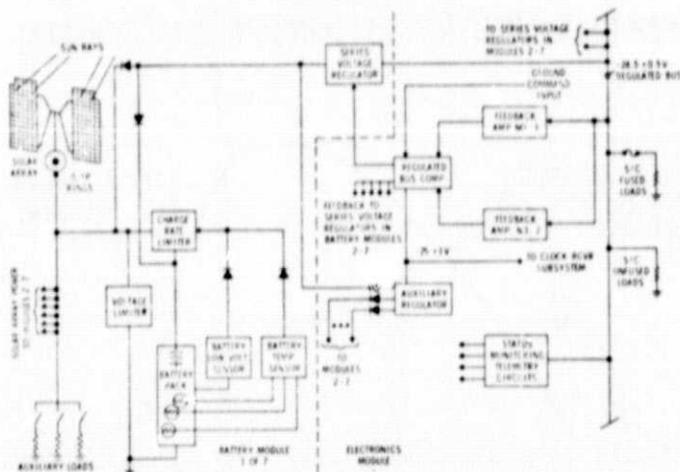


NIMBUS II
 POWER DEMAND PROFILE



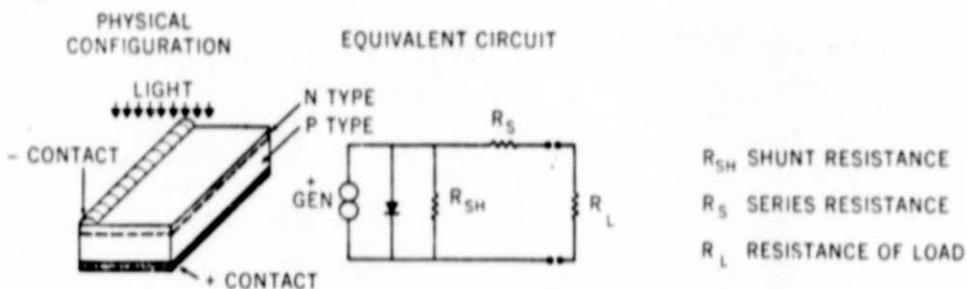
NIMBUS SPACECRAFT

NIMBUS II POWER SYSTEM

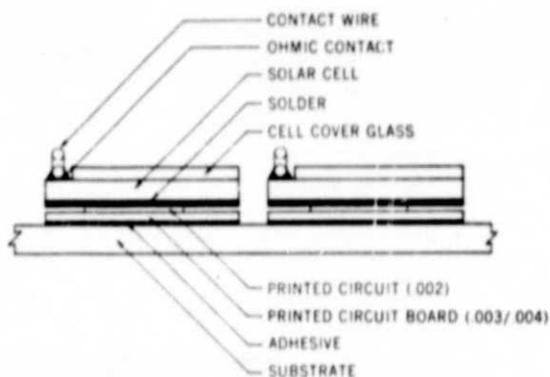


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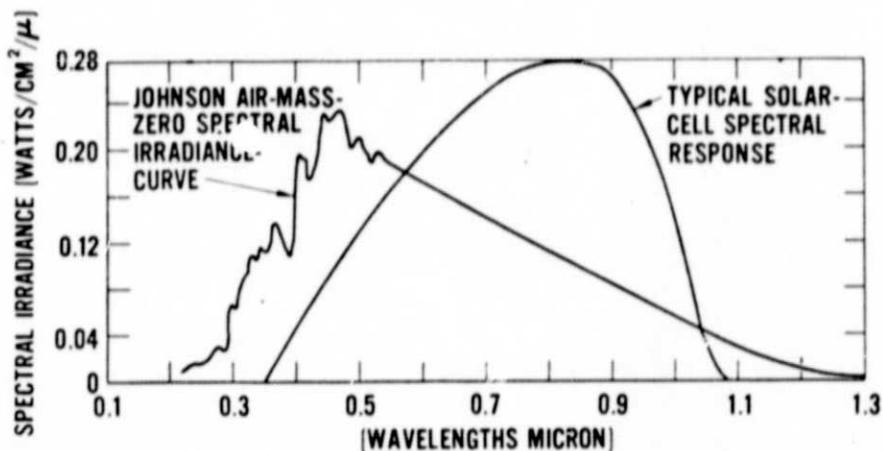
SOLAR CELL



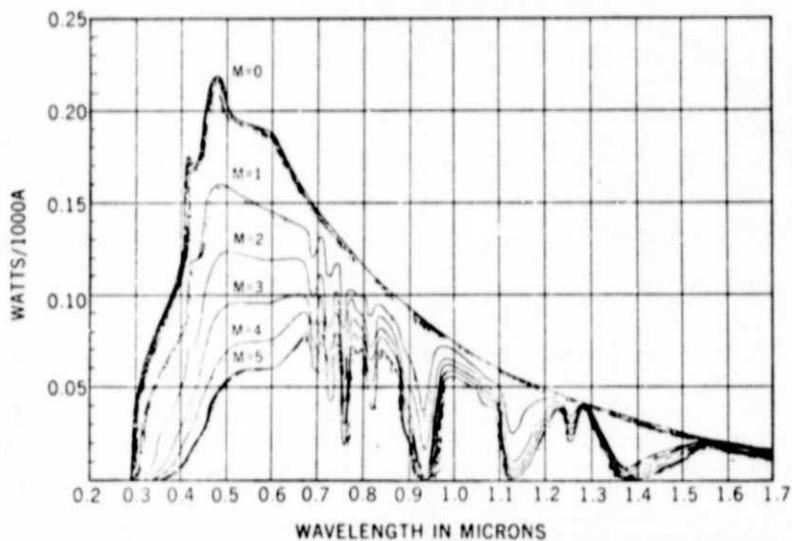
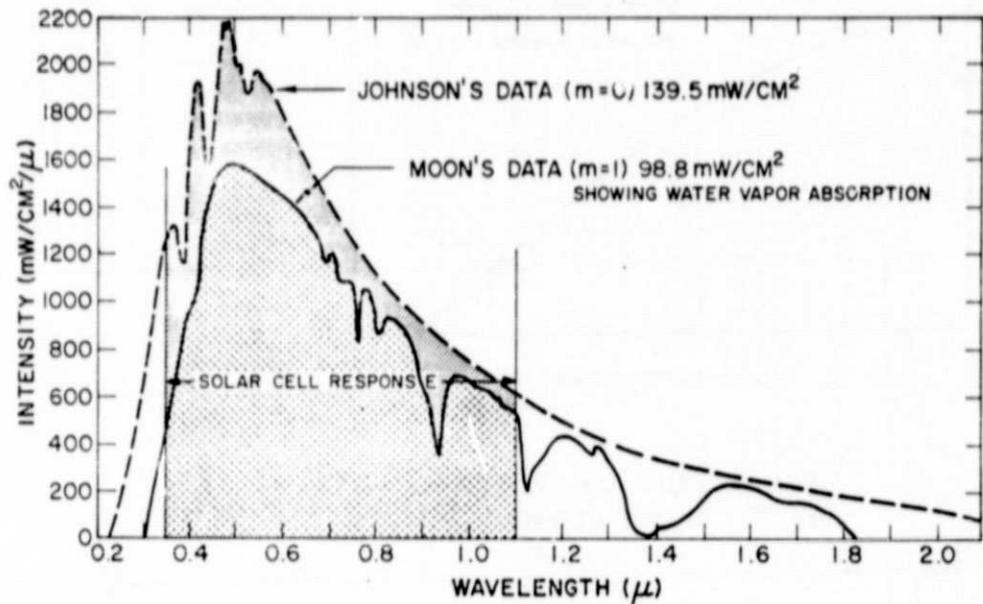
SECTION OF TYPICAL PRINTED CIRCUIT SUB-MODULE



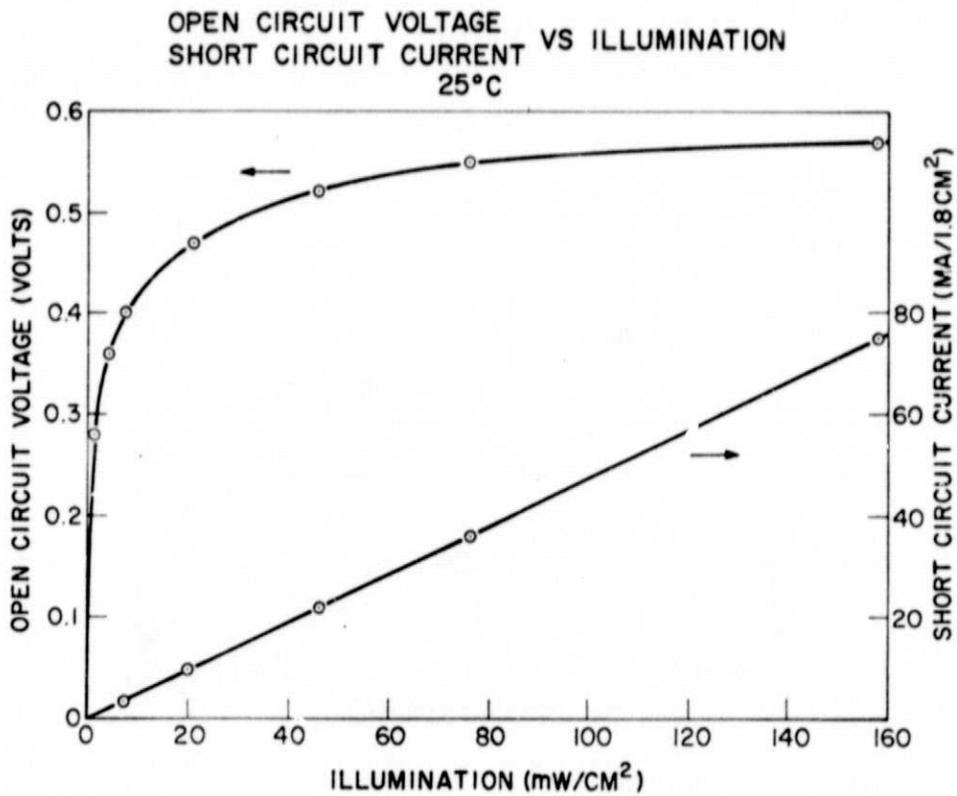
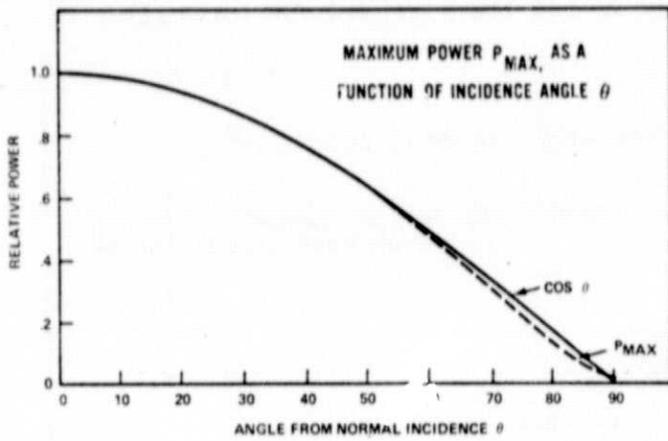
BARE-SOLAR-CELL SPECTRAL-RESPONSE CHARACTERISTIC

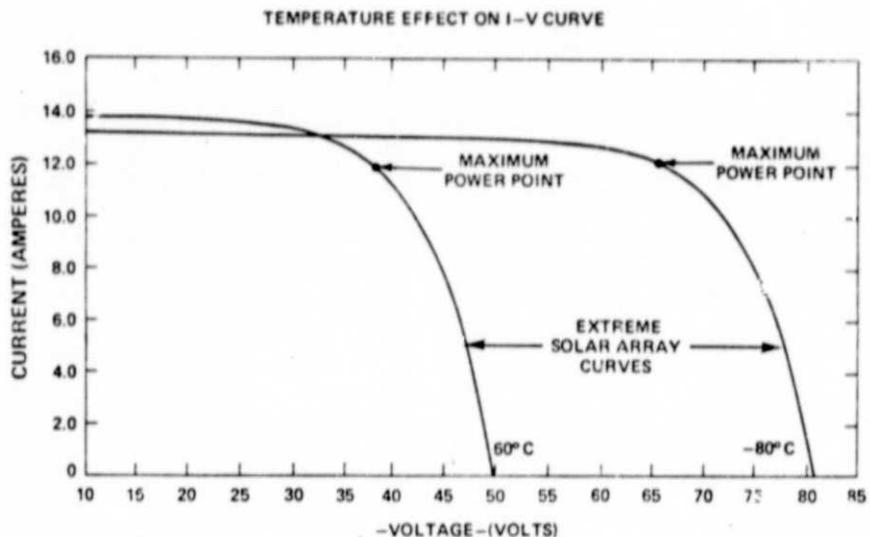


SOLAR SPECTRUM AT AIR MASS ONE AND AIR MASS ZERO



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SILICON SOLAR CELL EFFICIENCY VS TIME

