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IEEE/WAS/WSE
SOLAR ENERGY LECTURE III

MARCH 28

SPACE SATELLITE POWER SYSTEM

Peter E. Glaser
Vice President and Head of Engineering Sciences
Arthur D. Little, Inc.

DR. GLASER is directing projects on the feasibility of the concept of a satellite solar power station and the potential of solar climate control systems for buildings as a new industry. Since joining the staff in 1955, he has directed research on: methods of generating high temperatures including the construction of solar and arc imaging furnaces, thermal insulation systems, properties of postulated lunar surface materials. He was responsible for the development of scientific experiments for all Apollo landing missions, including measurements of the heat flow from the lunar surface, lunar gravity and the earth-moon distance. Dr. Glaser received his undergraduate training in mechanical engineering at Leeds College of Technology, and Charles University, Prague, and his M.S. and Ph.D. degrees in mechanical engineering from Columbia University in 1955.

The concept of a Satellite Solar Power Station producing about 10,000 MW (sufficient to provide base load of New York City in year 2000 or 3 percent of U.S. generating capacity) has been studied in depth and offers the potential to meet a significant portion of future energy needs, pollution free and sparing of irreplaceable earth resources.

Photovoltaic solar cell arrays convert the sun's optical energy to dc energy which in turn is converted into microwave energy in a large active phased array. The microwave energy is beamed to earth with little attenuation and is converted back to dc energy on the earth.

The economics of the system is an important part of the concept and the basic material requirements for the complete system are minimal as compared with conventional systems for generating electric power. Further, the total amount of electrical energy required to produce the SSPS and to put it into orbit is less than 9 months output of the completed system.

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Solar energy is a very diffuse energy source. We receive here on earth only about 1 kilowatt per square meter. This means that only by covering large areas with solar energy conversion devices can we make a significant contribution to our future energy needs. Solar energy conversion is capital intensive which implies that we have to be technologically sophisticated to be economically competitive. Although solar energy is free, it will be a very challenging and difficult task to convert it into useful forms. There are less technologically demanding ways to use solar energy; for example, for heating and cooling of buildings, but significant effort over the next few decades will be required to obtain electricity from the sun. There are several approaches to achieve this objective. Among the approaches being explored are conversion of solar energy to power based on the use of wind, ocean thermal gradients, solar-powered heat engines and photovoltaic energy conversion.

Photovoltaic energy conversion is not new and suggestions have been made that we place photovoltaic energy converters in sunny areas, particularly the Southwest, and on the roofs of buildings. If the sun shines, we can obtain about 180,000 kilowatts for each square mile, even if we just have a 10% efficient energy conversion device. However, we have to contend with day and night, we have to contend with weather, and we have to contend with absorption in the atmosphere. If we concentrate sunlight we have to contend with the effect of scattering of sunlight in a hazy atmosphere even if it is fairly bright, so all of these effects tend to reduce the economic attractiveness of large scale solar power generation on earth.

Having worked with various mirrors on earth (I constructed a solar furnace at Arthur D. Little in 1955) I was familiar with some of these problems. In 1968 I suggested that we place solar energy conversion devices in a location where the sun is available nearly continuously, where we no longer have to contend with day and night and weather, and where we don't have to expose the solar energy conversion devices to the active environmental influences of the earth environment.

The concept has evolved into the design of a Satellite Solar Power Station (SSPS). The principle is straight forward. We use the technology developed in the space program for silicon solar cells, and we reduce the area of solar cells required by concentrating the sunlight with plastic film reflectors to reflect sunlight onto solar cells. The electricity generated is conducted to microwave generators which form part of a transmitting antenna. The antenna then directs a beam of microwave energy back to earth where it can be converted directly into DC. I will acquaint you with some of the technical aspects of this particular concept and outline where we may go from here.

In synchronous orbit, one has the advantage of a zero gravity environment. Thus very large solar collection areas can be assembled to convert solar energy directly into electricity. In analyzing the geometric optics of transmitting antenna design, we find that the optimum design is a very large satellite, and for our baseline we have chosen a satellite which provides a power output of 5000 megawatts on earth. This size could be typical for a commercial size satelltie. I don't suggest that this is the first step to take, but the size that eventually might be cost effective.

This implies that we require large area solar collectors (about 4.3 kilometers by 11 kilometers) with a transmitting antenna about 1 kilometer in diameter to produce the 5000 megawatts on earth. We can control the solar collector to about $\pm 1^{\circ}$ with reaction control systems. The solar cells form the bottom of a trough with reflecting mirrors on the sides. We can expect this design to evolve as we look at the various technical options available to us.

One of the first things we had to do is ask ourselves the basic question, "if you have a large structure in space can it be analyzed by the techniques available to us now?" We believe that it can, and we have examined various analytical methods. We evolved a basic structural approach starting with an aluminum alloy to make up the first structural element, 3 meters long. The 3 meter element is used to build up the 30 meter structure element until we obtain the final size structure.

The structure has two functions. One function is to provide structural support and the other function is to gather the current supplied by the solar cells and to conduct electric current to the microwave generators.

Solar cell technology has been progressing rapidly over the last few years, the violet cell which was developed at COMSAT, is now available at an efficiency of about 16%. Major changes will take place in the jewelry type assembly process used in our present space program to the mass-production of silicon solar cells. The first step, which gives us reasonable hope that mass production can be accomplished, is a new method for growing single crystal solar cells by ribbon techniques, in which a ribbon of single crystal silicon is pulled from a melt. Recent results indicate that Harvard University, working with TYCO Laboratories, has already been able to measure reasonable good cell efficiencies, about 17% which is an interesting breakthrough.

One of the material's problems, is the choice of die material wetted by silicon which does not react with the silicon and introduce impurities. With the continuous ribbons of single crystal silicon the production of solar cells no longer will take the 58 steps which we have to go through now if we start with an ingot. We can reduce these steps to about 18, starting with the ribbon and ending with a solar cell blanket.

A solar cell blanket was developed at NASA with the silicon single crystal solar cells packaged between plastic films. The thickness of the silicon solar cells can be reduced to between 50 and 100 microns and the efficiencies reach about 18%. Automatic assembly of solar cells using a printed circuit with the appropriate alloy contacts can be developed.

A survey of photovoltaic specialists attending an October 1973 NSF NASA Conference, Cherry Hill, N.J., revealed that 50% of those queried were confident that the cost of solar cells would drop to about a dollar per peak watt by 1985 and about $0.30 per peak watt before the year 2000. We feel that the state-of-the-art, particularly in silicon solar cells, is moving reasonably rapidly and that the costs would reach these levels if volume production is reached.

In synchronous orbit the solar collector always faces the sun, while the antenna will always face the earth. To accomplish this, the antenna must rotate with respect to the solar collector once every 24 hours. The rotary joints are the only moving parts in the satellite. A gimbal adjustment is provided for fine control. The structural approach to the transmitting antenna is the same as in the solar collector structure. We start out with a primary structure and go then to the secondary structure and a tertiary structure which supports the microwave generators.

The weight breaks down into about 81% for the solar array and about 19% for the microwave antenna. In the solar array, the solar cell blankets are over half the total weight and the structure about one quarter. The estimated weight will be about 5 lb. per kilowatt. If you compare any other power generating method now in use or projected, e.g., the 150 lbs. per kilowatt required to construct a nuclear power plant, you appreciate that 5 lbs. per kilowatt as a remarkable low weight. This means that the SSPS is also conserving of materials.

We have now a large object in orbit and that large object will be subjected to various forces: the interaction of the sun-moon system, the fact that the earth is not a perfect sphere, and solar radiation pressure. Solar radiation pressure is the most significant of the forces acting on the SSPS.

If we calculate the effects of the various forces, we find that we will require about 15,000 kilograms of propellant per year for the reaction control systems to maintain the solar collectors pointing to the sun within one degree. That would be a fraction of a space shuttle payload supplied each year, a very reasonable supply mission.

We can interconnect the solar cells to obtain the desired high voltage, perhaps 40,000 volts, to convert the DC into microwaves, form the beam, and then, on earth, convert it back into DC power.

The state-of-the-art of microwave generators is well known and established. As a mechanical engineer, I always think of it as an electric motor where the rotor is the space charge of electrons. We apply our DC power input, amplify the microwave signal and get a microwave output. Obviously there are no moving parts in this generator.

The types of devices that we expect to use are very close to the theoretically attainable efficiency determined by measured values. We presently have the industrial capacity to produce these devices.

If the permanent magnet of the commercially available microwave generator is replaced with samarium-cobalt magnet material which is about 20 times more effective, we get a much smaller device capable of an output of 5 kilowatts.

The production of these devices has reached about a million in the U.S. and about the same amount in Japan, so there is already today the capacity to produce a large number of these devices. For 5,000 megawatts output on earth one satellite would need about 1 million devices. The production can be increased readily to take care of our terrestrial as well as our space needs. The cost for these devices would be about $25 per kilowatt.

Because we are dealing with a very efficient device, we can use space radiators to reject the heat from the cathode as well as the anode. We expect to use a cool cathode, coated with platinum. Experimental results tend to confirm that it will have a long life.

The microwave generators will inject microwaves into a waveguide allowing the microwaves to propagate through the slots in a phased array antenna. IEEE members are familiar with various phased array antenna programs. There is a major phased array antenna five stories high being built in Alaska. The technology that we are talking about is state-of-the-art.

In space we have a tremendous advantage because microwaves are the most effective means for power transmission. If we look at the theoretical predictions and compare them with the actual experimental data, we find that the transmission efficiencies are very high. The efficiency is a function of the area of the transmitting antenna, the area of the receiving antenna, the wavelength, and the distance between them. For those of you familiar with the work of Goubau, these relationships are to a large extent based on his theoretical work.

A very large antenna will be required in space to reduce the diameter of the receiving antenna on earth to obtain the desired microwave power density on earth. This power density and distribution is given by the geometry of the optics of the transmitting antenna.

We can design the phased array antenna to obtain a desired microwave density power distribution across it. For an ideal Gaussian distribution across the microwave beam a receiving antenna about 7 kilometers in diameter will intercept about 90% of the beam power. To accomplish this we will need a 1 kilometer diameter transmitting antenna. The highest power density in the beam, for the ideal Gaussian distribution, is about 870 watts per square meter, for other distributions it reduces to about 500 watts per square meter. The solar energy density on earth, if you want to compare it with the microwave density is about 1000 watts per square meter. At the edges of the antenna the microwave density drops to 100 watts per square meter. This value corresponds to the present U.S. standard for exposure to continuous microwave radiation. Therefore, we are not dealing here with a beam which is expected to give a major problem in terms of safety. We also, of course, have to have a low microwave density because we are transferring power in the most efficient way possible, and wish to avoid significant absorption in the atmosphere. For those who might question why use microwaves and not laser beams, a laser beam is much more concentrated, we don't know how to convert it efficiently and absorption in the atmosphere is high because spectral windows for a laser beam are not as effective.

To direct the microwave beam towards the earth, we can use a precision microwave interferometer of the type which has been designed and tested at NASA Goddard and that has a capacity to provide directional accuracy of ± 1 arc minute.

In addition, we can use electronic steering by having the transmitter at the center of the receiving antenna radiate a coded signal to control the phase front of each 5 meter by 5 meter subassembly of microwave generators in such a way that the microwave beam is locked into the signal. The microwave beam, therefore, cannot be directed by some outside agency away from the receiving antenna, and the electronic steering can be arranged to be accurate to within ± 1 arc second.

This pointing accuracy provides control which we project will maintain the beam to about 200 feet of a desired location of the receiving antenna Remember, the solar collector is controlled to ± 1 degree.

We have used Air Force developed programs to provide data on microwave power absorption in the atmosphere and the ionosphere to indicate the expected absorption losses. At a Northwest location for the receiving antenna at a frequency of 3.3 GHz, we would expect to have an attenuation of about 2% in normal rainfall of 2 mm. per hour-in rainfall of about 12 millimeters per hour about 4% which would occur 1/10 of 1% of the time. In the Southwest in a rainfall of about 35 millimeters of the same probability, attenuation would increase to about 3.3% . Thus, at the low levels of the microwave power density which we have chosen, atmospheric absorption will not cause significant losses even during heavy rainstorms.

We used the computer program developed by AFCRL to test for microwave interactions with the ionosphere. At the low levels of the microwave power density analyses indicated no significant interactions.

The receiving antenna on earth is a stationary antenna which points towards the satellite in synchronous orbit. The antenna consists of an expanded metal mesh on which dipole rectifiers are mounted. The rectifiers are dipoles with Schottky barrier diodes arranged in a bridge configuration and spaced half a wavelength from each other. Each dipole can accept up to 5 watts of microwave power. Of considerable interest is the demonstrated very high efficiency of direct conversion of microwave power into DC. Today already an efficiency of 85% has been reached. This is a rather significant accomplishment, after all there is no thermodynamic process known to man which can reach this high a conversion efficiency.

Instead of discrete electronic components, two dimensional rectifier components could be mass-produced in the quanities required. The view of the Raytheon laboratory indicates how the microwave portion of this system was demonstrated. Receiving antenna costs are about $11.50 per square meter. Depending upon the DC output of the busbar the costs will range from $100 to $50 a kilowatt for the total structure.

From DC in the satellite to DC on the ground, we project about a 70% overall efficiency for the microwave portion of the system. Since we are using solar energy, efficiency is not so much a concern as if a nonrenewable energy source would be used, but it is an economic criterion.

One of the major attractions of solar energy conversion in space is that we need about 1/10 the area if the same device were placed on earth. Furthermore, the receiving antenna can be in any desired location because in a synchronous orbit the satellite will have a 17 degree view of the earth. We have also found that to minimize propellant consumption for station keeping we would prefer to locate the satellite at the minor earth axes. A system of satellites in these orbital locations would allow us to direct the beam to most of the earth sites of receiving antennas.

One of the drawbacks of the satellite is that it cannot be small to achieve a reasonable microwave transmission efficiency. The smallest rectified power output on the earth is about 2,000 megawatts and the largest about 20,000. Based on a favorable power to weight ratio 5,000 megawatts which fell in the middle of the power output range was chosen as our baseline design. The reason for this is that the transmitting antenna should be fed the power required to obtain the desired microwave power density at the receiving antenna as determined by the geometric optics of the transmitting and receiving antennas. That doesn't mean that we cannot build small experimental satellites, but to achieve a high transmission efficiency the commercial version must be a large satellite.

How do we get this large payload into space? The mass of the 5,000 megawatts satellite is about 25 million pounds. The space shuttle being developed would probably not be the best transportation system. The March issue of Aeronautics and Astronautics had on its front cover a second generation space shuttle of the single stage to orbit, mixed mode propulsion type, which allows for return of the booster and payload delivery into low earth orbit. A spacetug which might be either chemical or ion propelled would take the payload into synchronous orbit. These tugs are now being studied by NASA. The present space shuttle uses solid propellants and a nonreturnable booster. Its total payload capacity is about 50,000 lbs. The single stage to orbit space shuttle could be designed to take payloads of around 300,000 lbs. into orbit. Thus less than 100 space shuttle flights would be required for the installation of the satellite. By way of comparison there are 1,000 747's crossing the Atlantic every month.

(Question: What makes up this principal weight?) Primarily the solar cells. The solar collectors represent about 82% of the weight. The satellite will weigh 5 lbs/kw which is still very light weight compared to any other kind of energy production method.

We have used \$[illegible]00 a pound to synchronous orbit for our cost projection. This is the payload cost for the single stage to orbit vehicle as described in Aeronautics and Astronautics Magazine.

We are quite confident that with the technology available to us now, the satellite can be technically feasible. We also believe that with the production potential that industry possesses, we can make the satellite economically competitive. What we need to understand in more detail are the ecological impacts of this approach, its social desirability, its policical implication and its public acceptance. This approach is of international interest particularly to countries like Japan and countries in Europe which do not have an Arizona, or the alternative resources that we have in this country.

For a prototype system based on the use of the current space shuttle, we project costs to be about \$1,500 a kilowatt, which is also the prototype cost of the fast breeder reactor. If we project costs to an operational system, the major cost reduction could be made in the space-transportation-to-orbit costs. We believe that the cost goal of \$1000/kw. for a commercial satellite is reasonable to project. This cost is probably within reasonable range of future energy production methods including the fast breeder reactor.

We did look at environmental impacts. At the receiving antenna the conversion device will be 90% efficient, and therefore, only 10% thermal pollution is expected. This is equivalent to the heat release over an urban area. Thus, we have made a major contribution to lessen the environmental impact. At the receiving antenna we can exclude all RF which has been absorbed by the dipole rectifiers from reaching the ground beneath the antenna. Depending on where we construct the antenna we have to be very careful so that we do not create an adverse ecological effect. As far as materials use is concerned, we have set ourselves a goal; we will not use more than 2% of the resources, such as platinum or cobalt, available to the U.S. We believe that we can meet that goal. We have looked at the energy costs of placing the satellite system into operation and we find that we can pay back in one year the energy required to make propellants, solar cells, roads, steel structures and so on.

One of the major concerns are the biological effects of the microwave radiation. The present U.S. permissible limit for exposure to microwaves is about 10 milliwatts per sq. cm. The Russian limit is about 1000 times less. We can meet the Russian limit at a distance of 15 km. from the beam center. We are confident that we can design the total system to meet international limits for microwave exposure.

We have also examined the effect of radio frequency interference. It is obvious that a satellite which radiates large amounts of microwave power must be designed to minimize radio frequency interference, particularly with services which are important to world communication systems and to science, e.g., radio astronomy. In the chosen 3.3 GHz region the only services which share this frequency and which would suffer interference are amateur sharing, state police radar, and high power defense radar. We have discussed this subject with the Office of Telecommunication Policy. We have been assured that with a system design which avoids RFI with important services international agreement on frequency assignment could be obtained if it can be shown that the satellite will benefit other countries as well, which, of course, I believe this approach can.

I am not advocating that we go all out to build a huge satellite but that the development program during the next 30 years be divided into three phases. In the first phase we can proceed with the development of supporting technology and with experiments to verify the technology both on the ground and in orbit. We propose to construct a 10 kilowatt satellite for a space shuttle payload to test its performance in orbit. This experiment would test all of the functions of the transmitting and receiving antenna on a limited scale but not necessarily direct the microwave beam back to earth. We believe that we can construct a prototype which might produce perhaps 1000 kilowatts in the earth 1990's. By that time either we would have a current space shuttle available for the required number of space shuttle flights, or we would have developed a second generation space shuttle. Before the year 2000, we would be ready, as we were sometime ago with communication satellites to form a government-industry partnership (e.g., SUNSAT) along the lines of COMSAT. Beyond that we would expect to have international commercial ventures utilizing the satellite.

We expect that the life of the satellite in orbit would be well in excess of 30 years. We know a great deal about the environment in synchronous orbit. For example, the micrometeoroid impacts would lead to degradation of about 1% of the solar cells in 30 years.

For those of you who wish to study the subject further, our final report on the feasibility study of the satellite solar power station has been issued by NASA, CR-2347, which can be obtained from NTIS, Springfield, Va.

This briefly then represents an overview of the work which we have been carrying out with Grumman Aircraft, Raytheon Company, and Textron's Spectrolab Division over the last several years. The work was primarily an industry effort, with partial support from NASA.

QUESTIONS & ANSWERS

Question: What happens if you lose control of the beam and it just sort of meanders through our metropolitan areas?

Answer: Well, I tried to indicate that this is an impossibility by the way we have designed it. If some power outside of our control would move the transmitting antenna then beyond a certain point the phase front control signal would no longer be received in the appropriate way and the beam would defocus. It would no longer be a beam directed towards the receiving antenna but the beam would spread over a large area and decrease the communication signal levels on earth. In any case we can instantaneously switch off all power in the satellite because there is no energy storage.

Question: Would you compare again the amount of power that this brings to the earth visavis what the earth normally intercepts from the sun because we're sort of concentrating and adding a lot and this must upset our heat value.

Answer: I would like to suggest the following. We will intercept solar energy which normally would not have reached the earth.

Question: You are sending more energy to the earth than we normally would have received from the sun?

Answer: That's right. However, we can take care of this because we have a manmade structure on earth. We can control its albedo and in a sense we can control the environment because we can reject more sunlight than we receive microwave power. If we wish we can have either a negative or positive energy balance by controlling the albedo of the receiving antenna structure.

Question: You mentioned that the heat at the receiving antenna was a small amount, but all this energy gets converted to heat?

Answer: I am suggesting that at the receiving antenna, solar energy is received and normally would be converted to heat. If the receiving antenna structure rejects the solar energy through albedo control, it can reject more energy than is converted into heat by microwave rectification losses. In other words we can reject as much of the sunlight as we wish to have a desired heat balance at the receiving site.

Question: But only for that small area?

Answer: The receiving site can be a large area. If 80 to 90% of the sun's energy is rejected in this area this would probably have a negative effect on the total energy balance at the site.

Question: Would you compare the figures so what you are sending in here versus what the sun gives us everyday?

Answer: The maximum microwave power density at the center of the receiving antenna is about 40 milliwatts/cm^2. The solar energy density is about 100 mw/cm^2. So at the receiving antenna site we would receive less than about one half the total energy if the sun would be shining.

Question: But you would also receive in the daytime?

Answer: We also would receive in the daytime.

Question: So you are adding what the sun would have in the same area or what the sun has over the whole earth?

Answer: Oh my no. Just over that area. I am only concerned with that area, not the whole earth. By controlling the albedo, we can arrange to reject more energy than is actually received because the sun shines on the receiving antenna. I also submit that if you compare this approach with any other energy production method, if you burn coal, or if you produce nuclear power, heat losses will be far worse, because we can today generate power on earth with 85% microwave rectification efficiency. For nuclear or other thermodynamic processes the efficiency is probably closer to 30% or 40%. We will be at least twice as efficient as any other production method.

Question: Have you looked at the harmonic and subharmonic generation of microwave frequencies at the rectenna?

Question: How do you propose to put this thing together when you get it in orbit? I imagine the construction costs will be fantastic. Are they included in the kilowatt cost?

Answer: Yes they are. We assumed that the construction costs would be of the order of $40 a kilowatt. By the way, the construction would not be done by astronauts using wrenches. We expect assembly will by primarily by an automated system. The methods for assembly of large space structures are now under investigation by NASA.

Question: Do you see any problems in matching polarizations through your transmitting receivers?

Answer: I would say that it is a significant technical problem but we believe it can be done. We are fully aware of the needs to achieve this. We believe that we know how to go about matching.

Question: What is the life expectancy of the microwave generators?

Answer: We haven't yet tested a microwave generator for 100 years, but we believe that with the approach we are using it will have a life in excess of 30 years. We do not use a heated cathode as is done in many other microwave devices.

Question: It looked like a magnetron or similar device?

Answer: Actually it is an amplitron.

Question: And they have that long a life ordinarily?

Answer: Yes, for the device which is being selected for this purpose.

Question: Would it be possible to have that signal be coherent so that it doubles as a broadcast satellite?

Answer: We actually believe that once you have such a large amount of power available in orbit you could combine the functions of communications and broadcast satellites. Whether you would use the same signal, I am not sure, because you may have different area coverage requirements; for example you may want to broadcast TV programs to the Americas, but one satellite can combine a number of functions in addition to power since it is already there.

Question: Have you looked at the energy absorption profile at 3.3 GHz in the atmosphere and determined what the key profile might do to say weather conditions?

Answer: I indicated that we have used the Air Force Analysis Programs to obtain the numbers I displayed to you. We have a lot of computer data from our analysis. Based on these data we believe that atmospheric absorption will be a minor effect. Certainly this needs to be looked at in detail; that is why I said not enough work has yet been done to establish some of the ecological effects. I think this work needs to be done.

Question: Were there any special techniques required to keep your I^2R losses down your copper losses from transmitting this power across the area to the antenna?

Answer: We don't believe that this will be a problem, we have looked at it. We have a lot of stuucrure available to release I^2R losses. For example, the main mast which forms the structural element for the satellite is about 100 meters in diameter. Thus, the electrical power density will be at such a low level that the radiation to space would be able to take care of the heat losses.

Question: What total efficiency are you talking about from DC on a satellite to DC on earth?

Answer: 70%.

Question: Are you serious?

Answer: Of course. I showed you one slide indicating what the expected efficiencies are.

Question: Is microwave about 85%?

Answer: The microwave generator is about 90% efficient.

Question: Now the rectifier efficiency is about 90% to. The total efficiency is about 80% right there plus all the losses?

Answer: We looked at the losses I indicated on that one slide. You can look details up in our report to NASA. The losses indeed are quite small. We lose about 3% going through the atmosphere on a rainy day.

Question: You cast a shadow on earth at some place and don't some people suffer?

Answer: If you analyze the shadow for the size of the satellite at an orbit of 22,300 miles and you take into account that the sun subtends an angle of 32 minutes, you find that no shadow is cast on earth.

Question: Would you expect a solar flare to cause any difference in the amount of energy received?

Answer: A solar flare should not affect the microwave power radiated to earth. I would be concerned with the effects of solar flares on the solar cells. But again that kind of information is being obtained by the various satellites now in synchronous orbit. We have a lot of operational experience to draw on. For example, Intelsat IV solar cells are designed to have an operational lifetime of 10 years. We expect to have a lifetime in excess of that because radiation resistant solar cells are being developed.

Question: Speaking of the human problem again. You have a power density of 400 watts per square meter, and a human being can only stand 1/100 of a milliwatt?

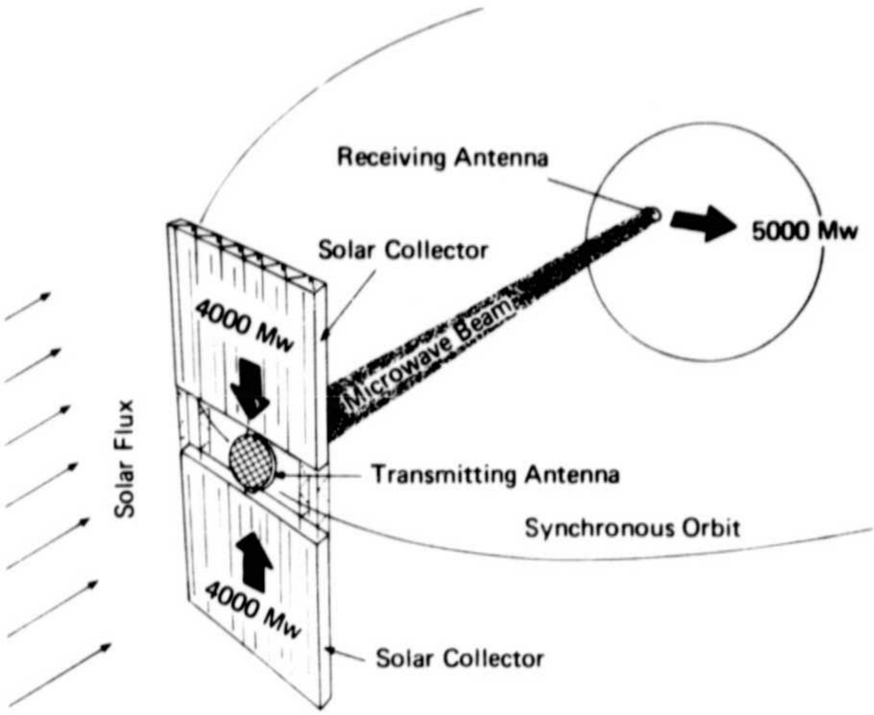
Answer: Let me talk in milliwatts per square centimeter. The present U.S. permissible limit for continuous exposure to microwave radiation is 10 milliwatts. If you buy a microwave oven and you have the door closed, the leakage out of the oven has to be less than 10 milliwatts per square centimeter. This is the expected level of microwave exposure at the edge of the receiving antenna I showed to you. The graph I showed you indicates that beyond the edge of the antenna, about 3 kilometers beyond, a level of 10^{-2} milliwatts per square centimeter is reached which is equivalent to the Russian permissible limit. Nobody expects people to live in the antenna. Therefore, the public would not be exposed to any microwave radiation which would exceed the lowest limit imposed by internationally agreed upon standards.

Question: What is the level at the center?

Answer: 40 milliwatts per square centimeter.

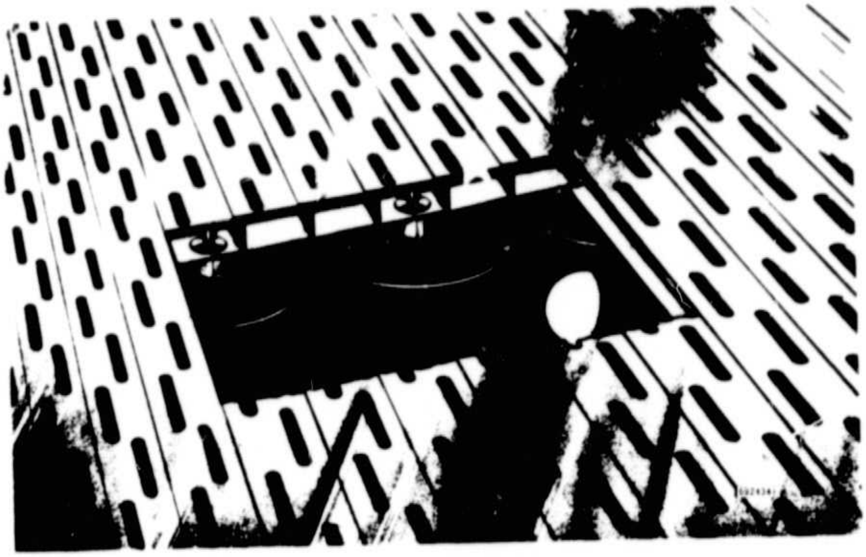
Question: I understand that silicon cell production requires a process in zero gravity?

Answer: No, silicon single crystals are produced in Waltham, Mass,

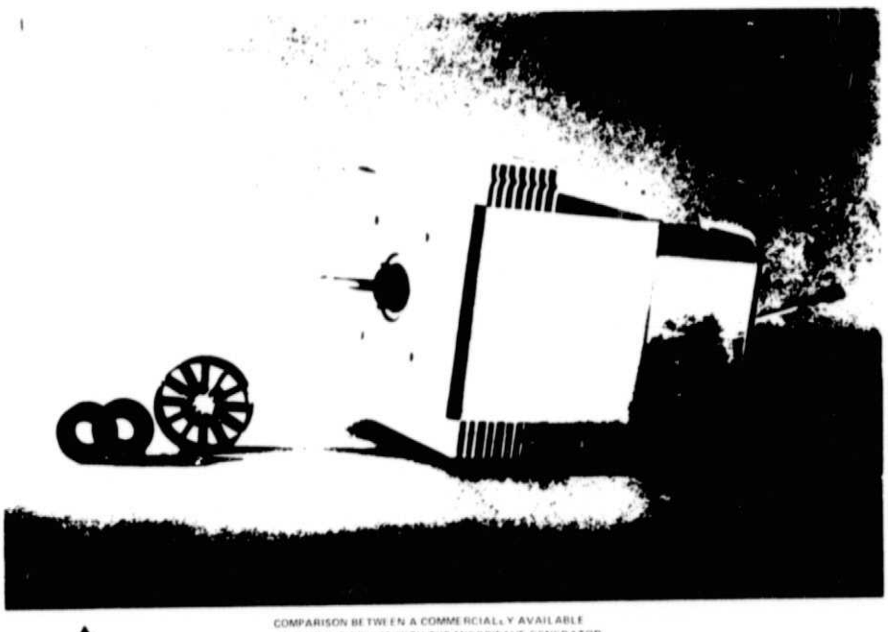


DESIGN PRINCIPLES FOR A SATELLITE SOLAR POWER STATION

Arthur D Little Inc

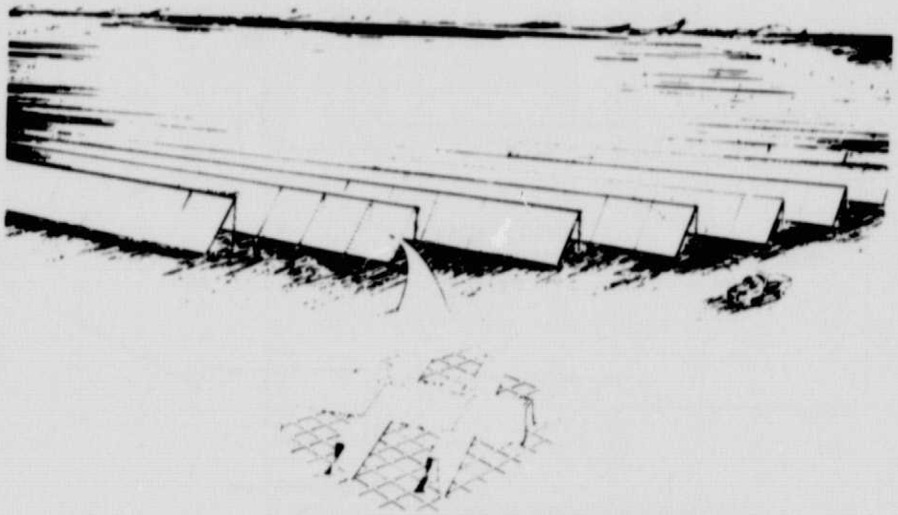


MICROWAVE TRANSMITTING ANTENNA



COMPARISON BETWEEN A COMMERCIALLY AVAILABLE MICROWAVE DEVICE WITH THE MICROWAVE GENERATOR COMPONENTS DESIGNED FOR USE IN SPACE

Arthur D Little Inc. 11440-



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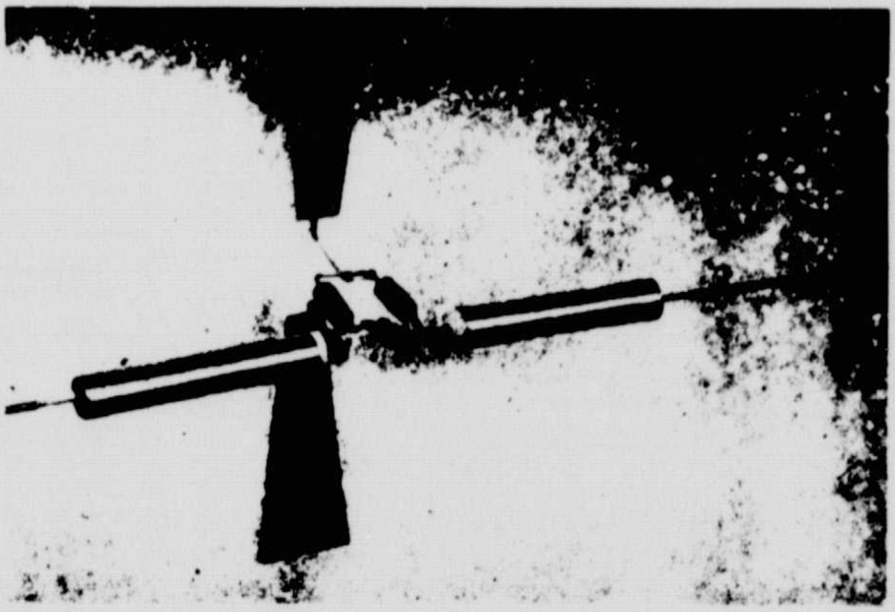
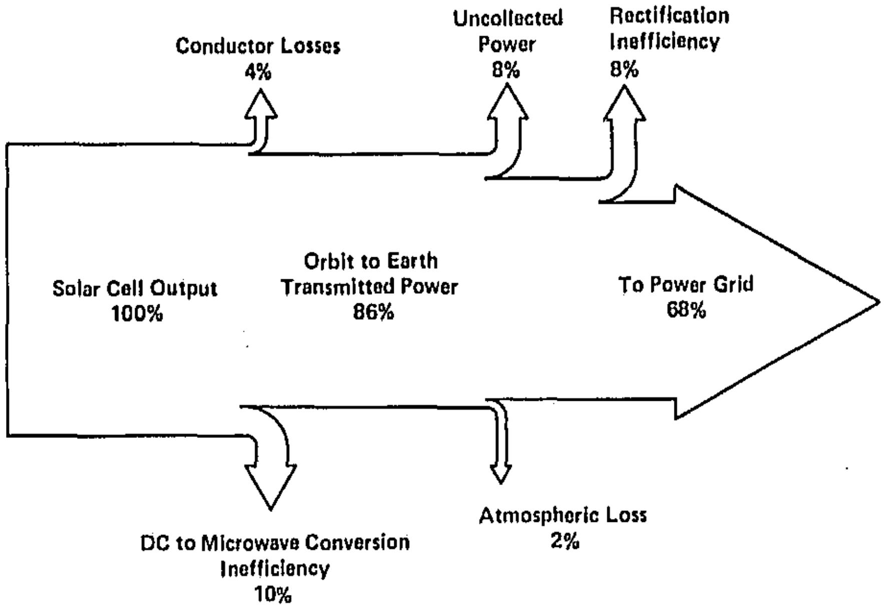
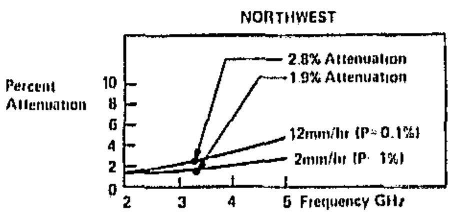
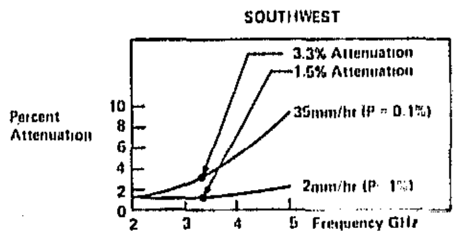
RECTIFYING ANTENNA



DETAIL OF MICROWAVE RECTIFIER ASSEMBLY


Conductor Losses
4%
Uncollected
Power
8%
Rectification
Inefficiency
8%
Solar Cell Output
100%
Orbit to Earth
Transmitted Power
86%
To Power Grid
68%
DC to Microwave Conversion
Inefficiency
10%
Atmospheric Loss
2%


NORTHWEST
Percent
Attenuation
10
8
6
4
2
0
2
3
4
5 Frequency GHz
2.8% Attenuation
1.9% Attenuation
12mm/hr (P = 0.1%)
2mm/hr (P 1%)


SOUTHWEST
Percent
Attenuation
10
8
6
4
2
0
2
3
4
5 Frequency GHz
3.3% Attenuation
1.5% Attenuation
35mm/hr (P = 0.1%)
2mm/hr (P 1%)