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LONG-RANGE ASPECTS OF A LARGE SCALE SPACE PROGRAM
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The theme of the special session on Lunar Utilization is the exploration of the possibilities and means for exploiting the lunar materials for the benefit of mankind. Dr. Gerard K. O'Neill of Princeton University has proposed a bold plan to utilize the lunar resource for the production of power generating satellites to serve the energy needs of man's terrestrial society (Ref. 1). This paper describes the long-range need for materials in space for the power satellites rather than directly exploring the possibilities and payoffs of utilizing the lunar resource. A study at Johnson Space Center is characterizing a possible power satellite network and the supporting space transportation and habitation systems based upon materials of terrestrial origin. This paper describes one potential large scale market for lunar materials should the establishment of lunar mining facilities and space manufacturing facilities prove to be economically attractive when compared to the costs of launch services from the Earth.

BACKGROUND

Why are we interested in power satellites? This question must be addressed in two parts. First, our dominant energy source at present and for the last few generations has been petroleum and natural gas. The Statistical Abstract of the United States (Ref. 2) provides tabular data on energy production and consumption. In the past 10 years, the quantity of imported oil has increased by almost a factor of 3 (Fig. 1) and is expected to increase annually. The financial impact on the United States has increased in this same span of time by more than a factor of 13. The 1974 cash outflow for purchased foreign oil exceeded the total FY 1975 disbursements by the Department of Defense to their top ten contracting firms. Obviously, the unavoidable further growth of imported oil will constitute an increasingly severe monetary burden upon the United States.

Second, and of perhaps even greater significance than that of the dollar outlay is the projected availability of this vital resource in the quantities demanded. From whom will we obtain increasing quantities of petroleum? As a historic example, our ability to cope with the 1973 oil embargo was due, in part, to the relatively small percentage of our imports originating from the Arab states. Canada, Venezuela, Nigeria, and Iran supplied almost 2/3 of the 1973 imported petroleum. The government of Canada has since announced that their petroleum reserves

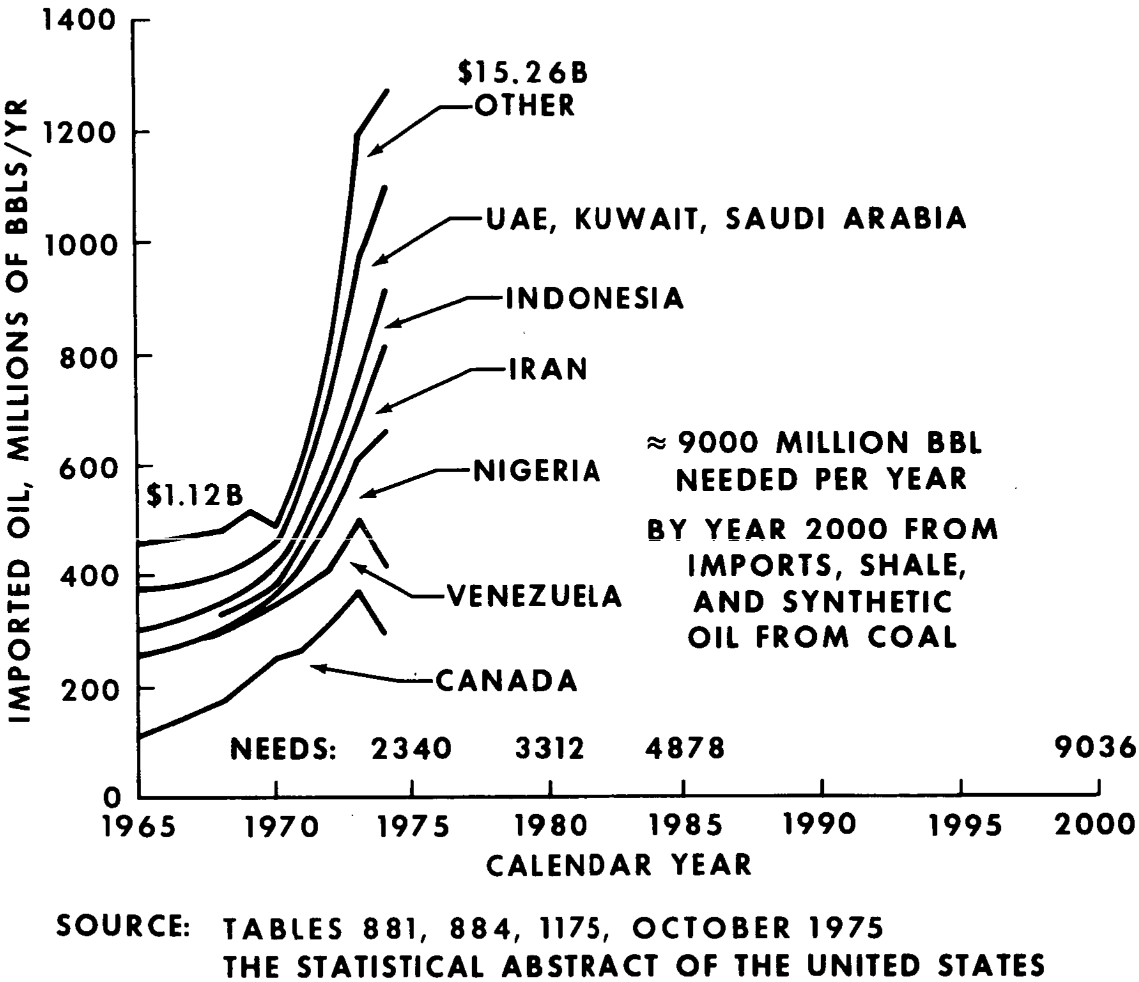


Figure 1. United States Oil Imports

will be dedicated, understandably, to the further development of the Canadian economy rather than to export. This policy was first reflected in thereduced quantity received from that nation in 1974. The U. S. technology of oil exploration and extraction is unmatched in the world and has permitted the U. S. to enjoy, in the past, the desired access to oil from less well developed nations. Hopefully, continued application of this unique technology and expertise will permit us to obtain for use by the United States a large fraction of the "new oil" yet to be discovered. Examination of these historical data and forecasts of comsumption does, however, lead to the disquieting thought that oil in the quantities needed by the U.S. beyond 1990 may not be available at any price. It is for this reason that we are on the leading edge of a major national program led by the Energy Research and

Development Administration (EDRA) to reduce the consumption of energy through conservation and to develop new energy sources, including solar energy in several forms.

SPACE POWER SATELLITE CONCEPT

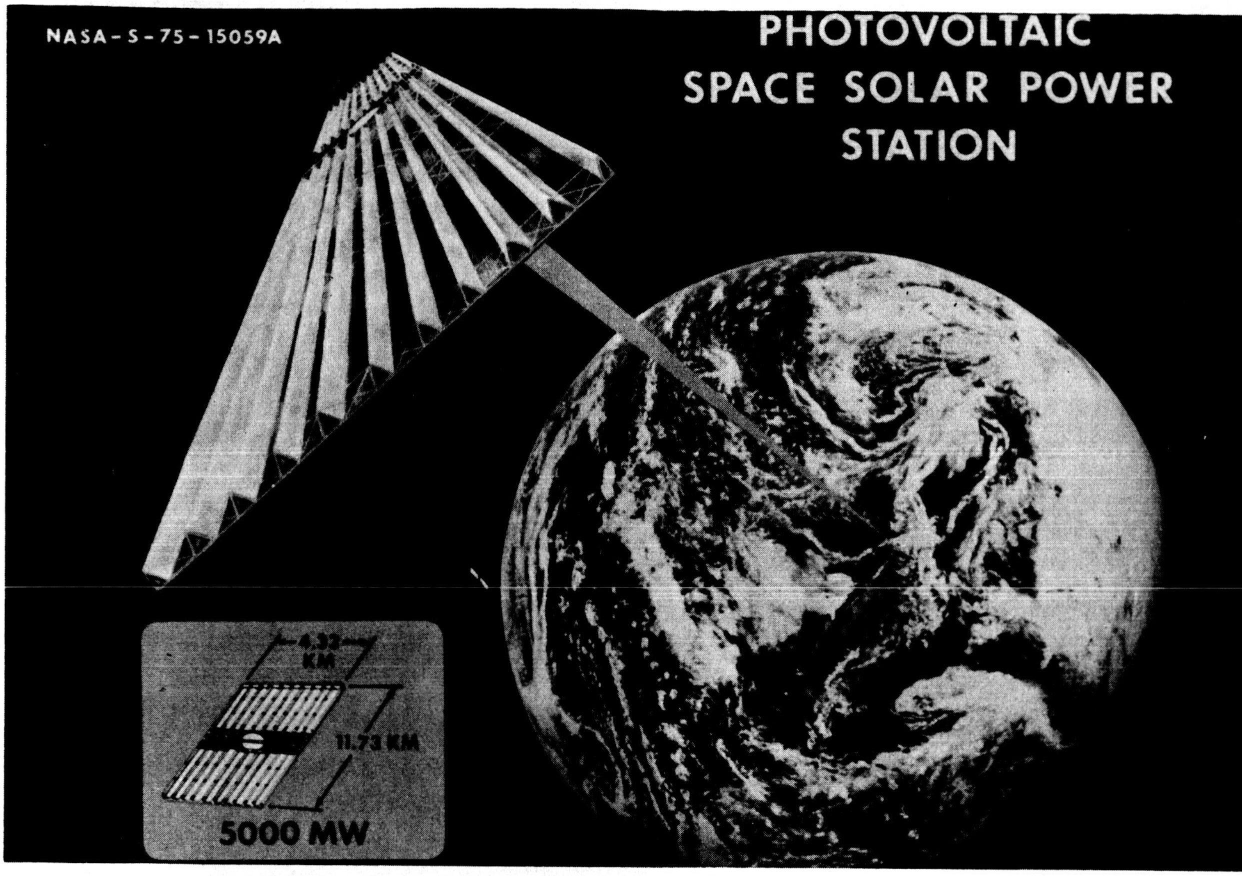
As first defined by Dr. Peter Glaser of A. D. Little, Inc. (Ref. 3) the space power satellite (SPS) concept is one attractive means of employing solar energy to provide the highest quality of energy--electrical energy into the existing national distribution network. The main premise of this proposal is the ability of the satellite to employ the nearly continuous, unattenuated sunlight in geosynchronous orbit (GEO) to produce "base load" electrical power. The terrestrial central solar electrical plant may find first application as a "peaking" system for daytime use. If it is to be utilized for base load power, the terrestrial solar plant requires large energy storage devices and additional plant capacity to sufficiently charge the storage system during sunlight hours, overcome the storage placement and extraction inefficiencies, and simultaneously provide the daytime base load power. The advantage of the satellite is therefore that it need produce only a fraction of the power required of the terrestrial solar electrical gnerating system to serve the same base load requirement. The issue is whether or not the costs of space transportation, construction and operations of this space-based solar power source may be accomplished within the inherent margin of advantage provided by its full time availability.

A photovoltaic space solar power station concept (Fig. 2) has been defined for NASA in an ongoing study of the economics of space solar power (Ref. 4). This satellite has an expanse of over 50 km^2 and a weight estimated to be over 22,000 kg. Obviously, structures of such a scale must be constructed in space. The similarity of the new operations necessary for space power satellite construction is compared on Figure 3 to activities which were necessary to open the conduit to the Alaskan North Slope. To date, no insurmountable barriers to space construction of the scale required have been identified. On the contrary, the absence of gravitational effects upon the orbiting construction site is expected to greatly enhance the productivity of both men and machines, perhaps several hundred-fold compared to terrestrial construction sites.

The SPS concept includes a microwave power transmission system whose feasibility was demonstrated in a Jet Propulsion Laboratory test in the summer of 1975. To simulate the microwave transmission of power from space to Earth (Fig. 4), the Venus Tracking Site antennae at Goldstone was used to illuminate a receiving antennae. This energy transport mode appears to be technically feasible as microwave to DC recption efficiencies above 80 percent for power levels of about 30 kW have been demonstrated.

SPACE TRANSPORTATION AND CONSTRUCTION

Studies have begun on the nature of LEO and GEO operations required to



to build the huge structures in space necessary to collect and convert solar energy to a more directly useful form of energy. Various operations and levels of assembly work of the space power stations components may be delegated to Earth, low orbit and geosynchronous orbit.

The JSC study is examining only Earth-originated materials for satellite power station construction and exploring both low and synchronous orbits as construction sites. The scope of construction and placement options are illustrated on Figure 5.

One option would involve the maximum prefabrication of the parts for the geosynchronous power satellite on Earth and the launch of tightly folded elements into LEO where they would be deployed and assembled into major power producing elements weighing from 200 to 20,000 tons. These elements would then be propelled by electric propulsion devices, drawing power from the payload itself, to the geosynchronous operating orbit. There these major power producing elements would be docked to one another and to the microwave

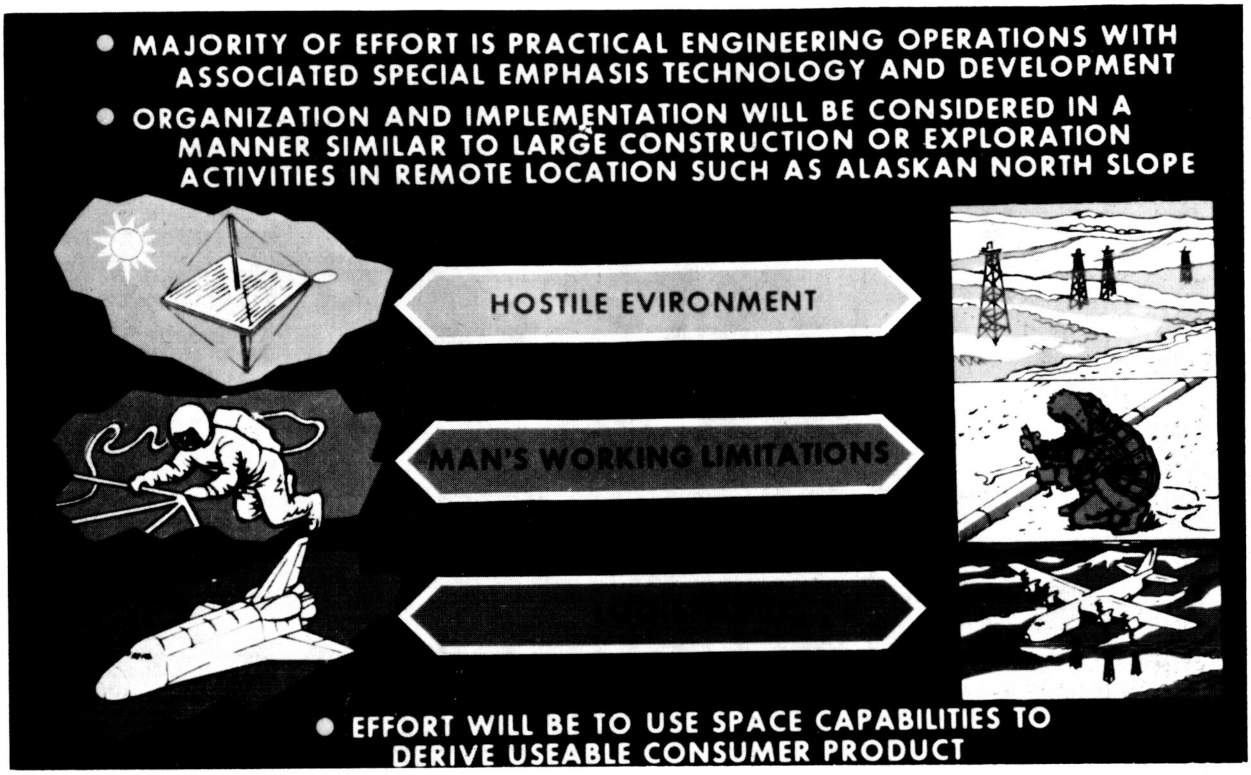
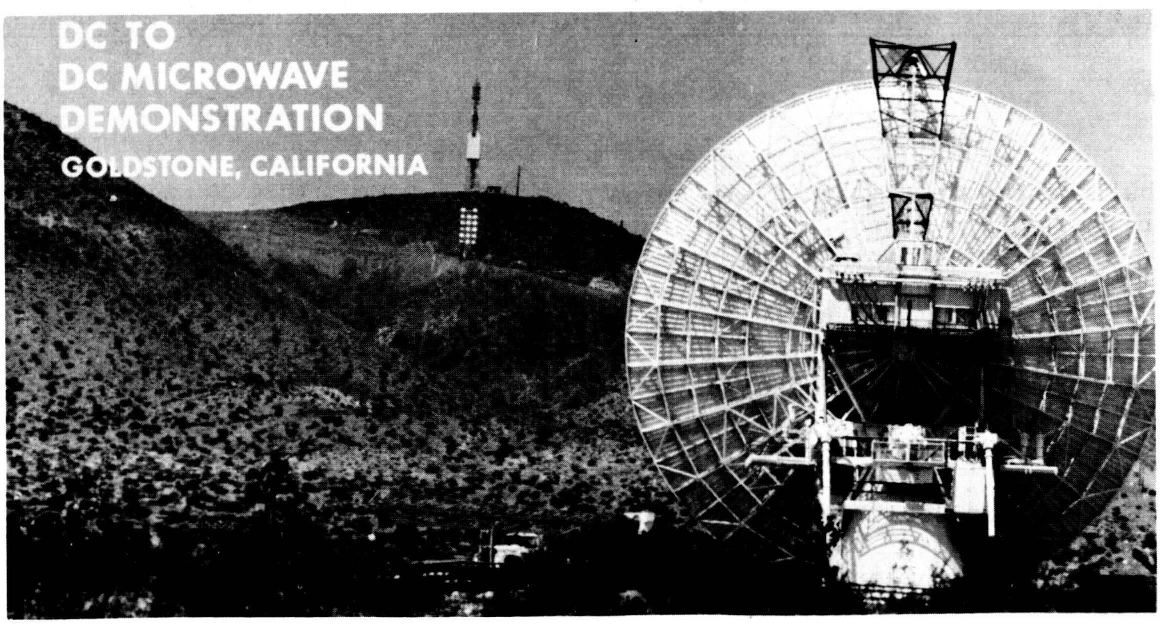


Figure 3. SPS Program Approach



- TRANSMITTER DIAMETER - 26 m
- MICROWAVE FREQUENCY - 2388 MHz
- RANGE (TRANSMITTER TO RECEIVER) - 1.5 km
- SYSTEM EFFICIENCY - 82.5%

Figure 4. Microwave Power Transmission Test

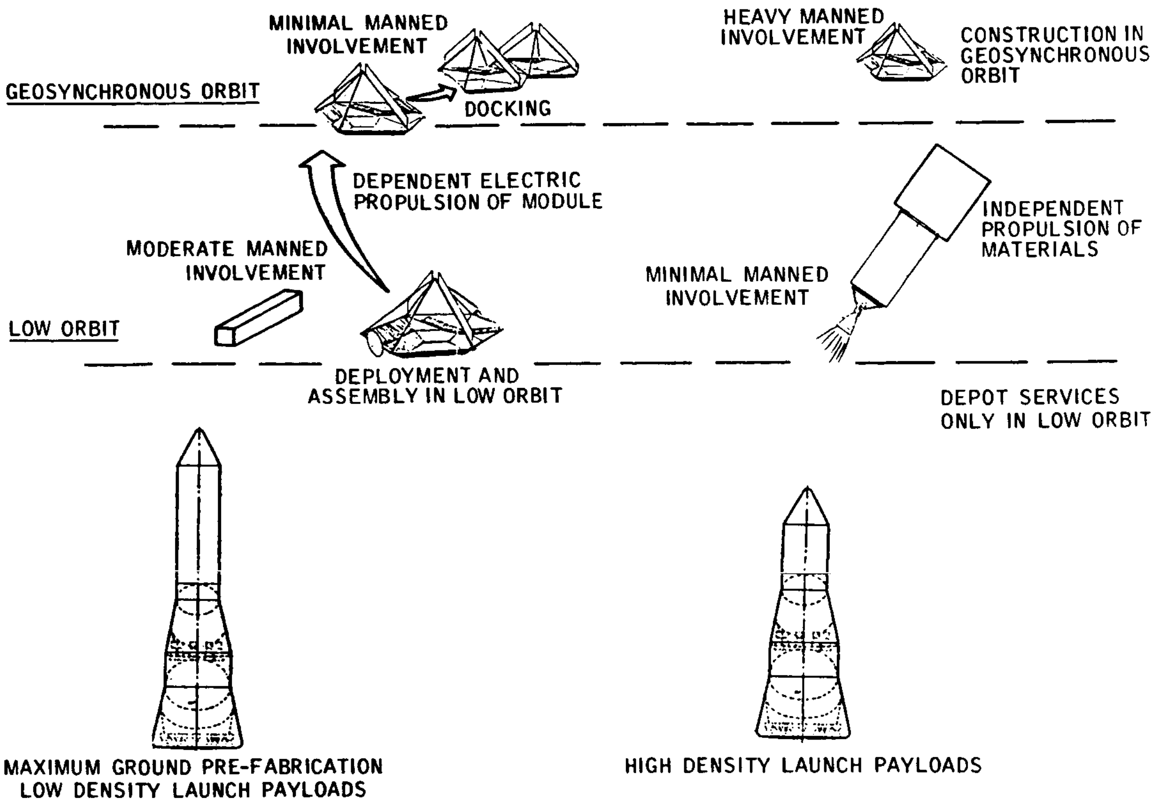


Figure 5. Scope of Construction and Placement Options

transmitting antenna to comprise the power station. This operating mode would involve a moderate degree of manned involvement in the deployment and assembly process of the ground prefabricated subassemblies in LEO. Manned involvement would be held to a minimum at GEO, as the primary operations to complete the power stations would be the the final docking and initialization. The penalty associated with this mode is that the folding of finished subassemblies can proceed only so far, yielding low density payloads. The launch vehicle must then accept very large payloads and be capable of safely housing the low density payloads through the exit from the atmosphere of the Earth.

The other operating mode option would involve launching of high density payloads, consisting of construction materials and piece parts, to LEO where they would be transferred to a propulsive vehicle for delivery to GEO. The only payload function performed in low orbit in this instance would be to offload the payload from the launch vehicle and onload it to the orbit transfer craft. The geosynchronous orbit station would then be utilized to manufacture structural and power generator elements from "strip stock" to construct the power satellite. This would, of course, entail a large facility and a high degree of manned involvement to perform both component manufacture and assembly at the geosynchronous orbit.

A number of intermediate options may also be utilized. The options for cargo transportation from LEO to GEO are illustrated on Figure 6. In the 1970's, the Atlas-Centaur vehicle has been used for placement for many of

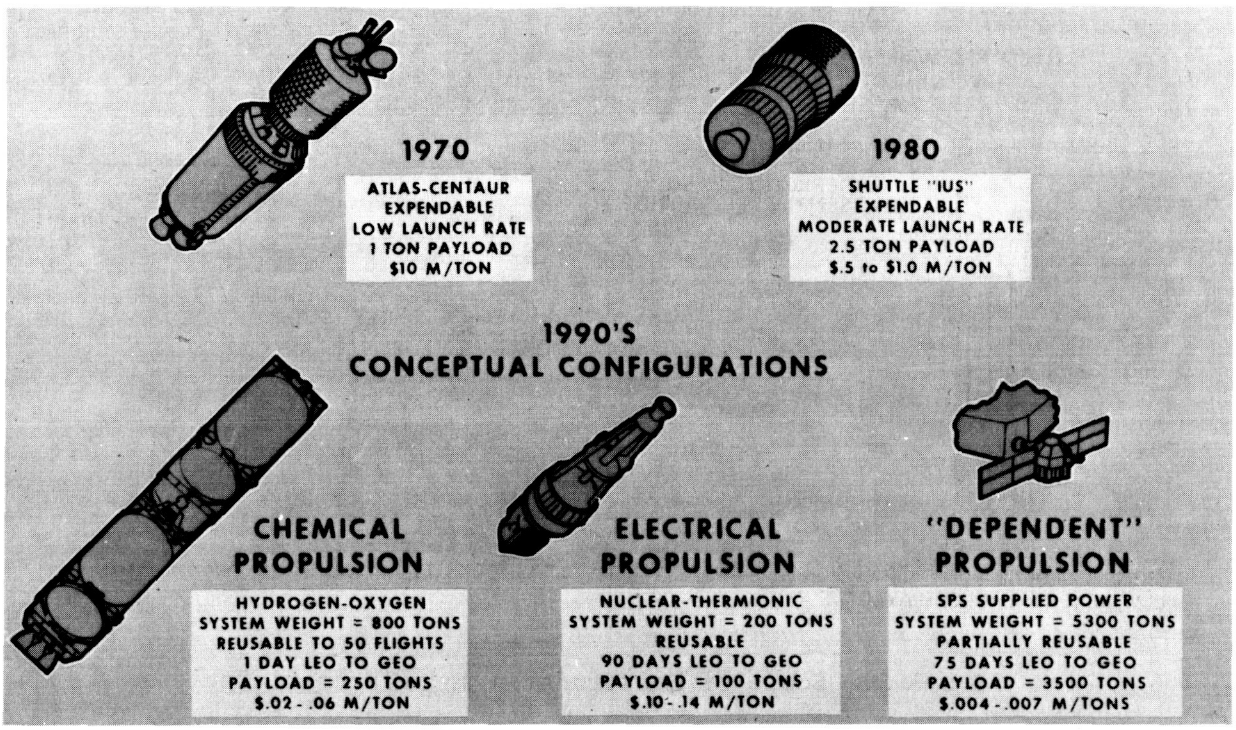


Figure 6. Cargo Transportation--LEO to GEO

the larger geostationary satellites such as Itelsat IV. The Atlas launch vehicle depends upon the Centaur upper stage to complete the insertion into low Earth orbit, hence the Centaur begins the synchronous transfer with less than a full load of propellants. In this operating mode, the Centaur has a payload capability of approximately 1 ton to GEO and results in a cost of LEO to GEO transportation of approximately 10 millions of dollars per ton. The Space Shuttle with the Interim Upper Stage (IUS), to be flown beginning in the 1980 time frame, will improve upon these capabilities. The Interim Upper Stage is a solid propellant two stage expendable rocket vehicle that will be flown at a moderate launch rate of perhaps 20 flights per year. The payload capability is approximately 2.5 tons to geosynchronous equatorial orbit and results in an estimated cost of LEO to GEO transportation of 1/2 to 1 millions of dollars per ton, an improvement by a factor of 10 to 20 over the current Atlas-Centaur. The increased capability and projected lower specific launch costs of the Space Shuttle compared to previous launch vehicles offers promise that the portion of the development of satellite power technology which can only be done in space may be economically conducted and that further development of space transportation technology and systems can achieve the necessary reduction in space flight costs for the operational power satellites placement at the GEO from the Earth's surface.

The time frame of interest for the space power satellite is the 1990's and beyond, and the number of options available to provide this orbit transfer function is much greater and their performance/cost parameters are less well understood. Figure 6 illustrates three of the possible options. The vehicle at the lower left indicates a chemical propulsion system conceptually similar to the Centaur, except that it is used as a two stage vehicle and is much larger in size. This vehicle is presumed to be reusable up to 50 flights, with refueling occuring in LEO upon its return from GEO. The round trip transfer time for resue in low orbit is less than 1 day. The chemical propulsion system shown has a payload yield in GEO of approximately 250 tons and results in an estimated cost of LEO to GEO transportation of between 20 and 60 thousands of dollars per ton. A promising concept suggested by the Jet Propulsion Laboratory is the electrical propulsion scheme utilizing a nuclear reactor power source for energy supply of the electric propulsion thrusters. The start burn weight shown is approximately 200 tons. The payload yièld is approximately 100 tons, an improvement of more than 50 percent in payload yield, but the preliminary cost estimates are increased to 100 to 140 thousands of dollars per ton because of the higher cost of the nuclear reactor system. The Boeing Company, in a study funded by NASA, (Ref. 5) encolved an innovative scheme for the transportation of satellite power station elements. The "dependent" propulsion system utilizes the payload itself built to a sufficient level of assembly to supply power to the electrical thrust system for the outbound transportation. The indicated system weight is 5300 tons. It is partly resuable because the propellant tankage is left behind in the high orbit but the thrusters, power conditioners, and guidance systems are returned to low orbit for reuse. It has a 75 day trip time from LEO to GEO and yields a payload of approximately 3500 tons; a quite favorable payload fraction. The transportation cost of this system must be considered more speculative than the other alternatives, but now appears to be in the vicinity of 4 to 7 thousands of dollars per ton.

Due to current uncertainties of the cost of the orbit transfer, the question of where the assembly of power satellites should take place, low Earth orbit or geosynchronous orbit, must remain open. The basic operational feasibility of assembling a large structural element representative of the space power station needs has been studied in detail by the Martin Company in Denver (Ref. 6). The device chosen for this study was the substructure of the 1 kilometer diameter microwave transmitting antenna (Fig. 7) as defined by a previous study based upon the satellite design concept suggested by Dr. Glaser. This study revealed that the Space Shuttle could conduct repetitive flights to deliver to orbit truss members and orbital assembly tools known as "mobile assemblers" that would permit the assembly of this structure in a period of approximately 1 year. The "mobile assemblers" are similar in concept to the Shuttle remote manipulator system being provided to the Space Shuttle program by the Canadian government.

SPS PROGRAM ASPECTS

The question of how many satellites would be produced is basically one relating to the market economics. If studies during the next 3 to 5 years show power from space to be produced at only a marginally attractive rate, the program may not receive a go-ahead. If, however, in its time frame, it appears to be attractive in comparison with the other alternative means of supplying electrical power, it may be given a go-ahead to a pilot plant stage. Subsequent market penetration of operational power satellites will depend almost entirely on how attractive the economics and environmental effects of power from space prove out relative to the competitive power systems. One possible scenario calls for the power satellite concept capturing approximately 50 percent of the new and replacement U. S. power plant installations beginning in about 2010. In that situation, the number of satellites to be constructed in space would exceed 110 by the year 2024 (Fig. 8). It is this illustrative implementation schedule that might be utilized to explore the applicability of lunar materials to the construction of a satellite network. This task has not been accomplished by the JSC study or is it being currently planned.

The distribution of elemental materials required to fulfill the scenario of over 110 power satellites by 2024 based upon the materials distribution reported by ECON, Inc. (Ref. 4) is illustrated on Figure 9. These data may be useful in envisioning the potential scale of a lunar materials plant. Note that large amounts of aluminum, silicon, and oxygen are needed. Most of the oxygen, all of the hydrogen and argon are used to achieve the low Earth to geosynchronous transfer and would be a different set of numbers for lunar surface to geosynchronous orbit transfer.

The Earth resides in a quite deep "gravity bucket" and to overcome the Earth's gravitational field and achieve low Earth orbit poses a large transportation task. The alternative of supplying materials from the lunar surface does appear, if viewed solely on an energy basis, to be very a attractive. Figure 10 illustrates that approximately 4.3 kilometers per second are required to be added to achieve the Earth geosynchronous orbit from the surface of the moon. Over 13 kilometers per second are necessary to be added to acquire geosynchronous orbit from the surface of the Earth. There is an inherent advantage from a transportation view point of utilizing lunar surface materials. The problem resides in the "front end" costs associated with developing the mining, and manufacturing infrastructure necessary to transform the regolith material into useful metal and ceramics and then into finished satellite power stations. Such an analysis would be interesting and perhaps it will be conducted in the months to come.

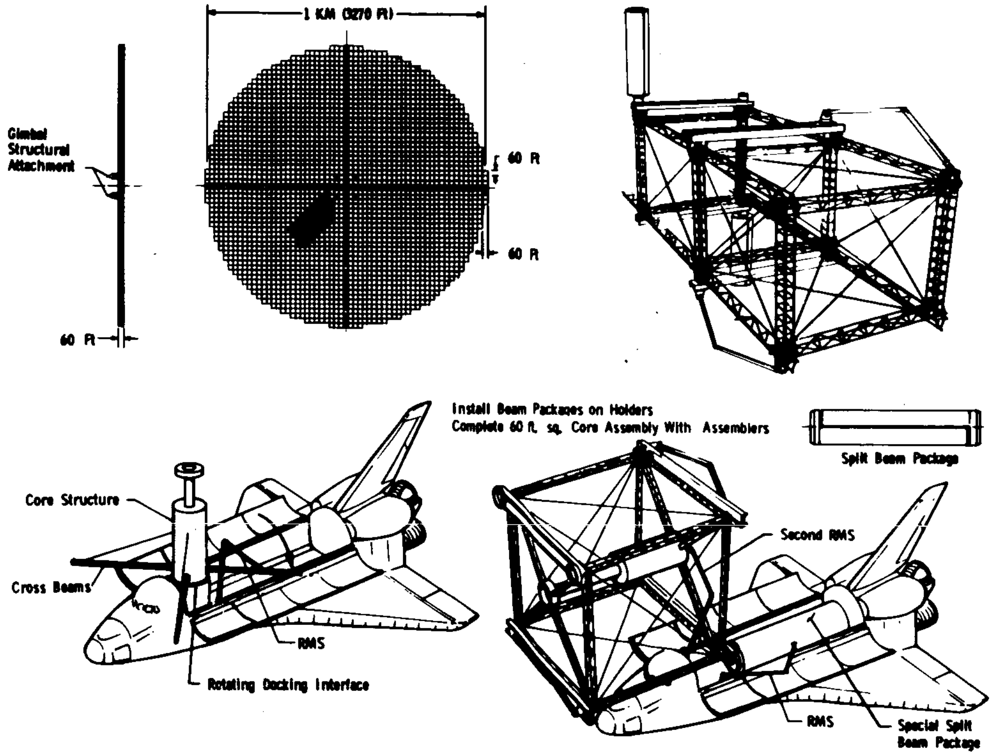


Figure 7. Space Construction of Microwave Antenna

CONCLUDING COMMENTS

In conclusion, the space power satellite program now appears to be one of several very attractive alternative energy sources that must be thoroughly reviewed before the fossil fuel supplies begin to run out. The space power satellite program poses a massive Earth to low Earth orbit transportation task. This task does appear to be both technically and economically feasible, utilizing current and near term state-of-the-art for the large launch vehicles required. The low Earth orbit to geosynchronous orbit transportation option choice interacts with the choice of the construction site and is a complex problem marked by having many options for the transportation system. In the construction arena, more study and development are required to define the techniques and machines to economically achieve the large scale construction in orbit. Decisions need to be reached relative to how much actual manufacturing effort is conducted on Earth and how much is reserved to the space environment and what the productivity of personnel and equipment can be expected in this operating regime. The NASA baseline approach is to utilize materials exclusively from the Earth. The two options

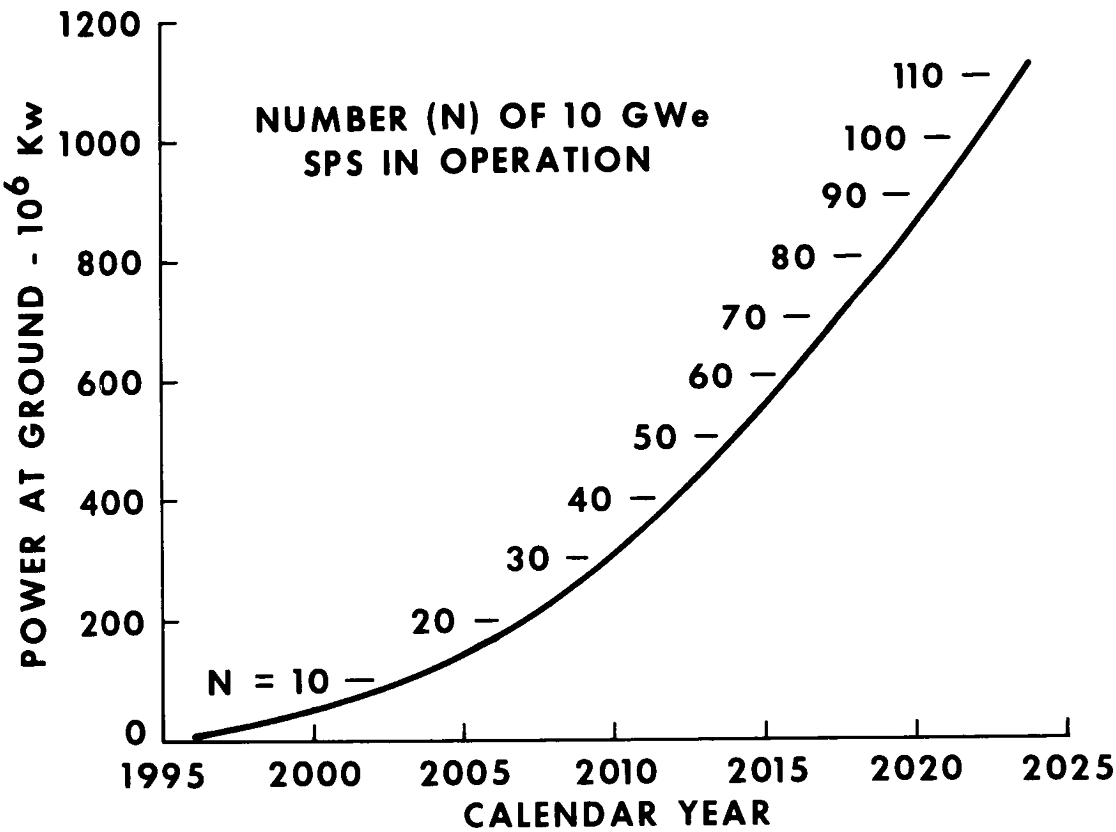


Figure 8. Illustrative SPS Program Scenario

for construction would be the low Earth orbit and geosynchronous Earth orbit. The lunar surface material source is available, as Dr. Gerard K. O'Neill has pointed out in his proposal, to support space power satellite construction at the L-5 Lagrangian libration point in a large space colony. Alternatively, lunar surface materials could be used with the bulk of the construction activity taking place on the surface of the moon or perhaps in orbit about the moon.

REFERENCES

1. Dr. Gerard K. O'Neill, "The Colonization of Space," Physics Today, September 1974.

2. The Statistical Abstract of the United States, October 1975.

3. Dr. Peter Glaser, "The Satellite Solar Power Station: An Option for Energy Production on Earth," Arthur D. Little, Inc., April 24, 1975.

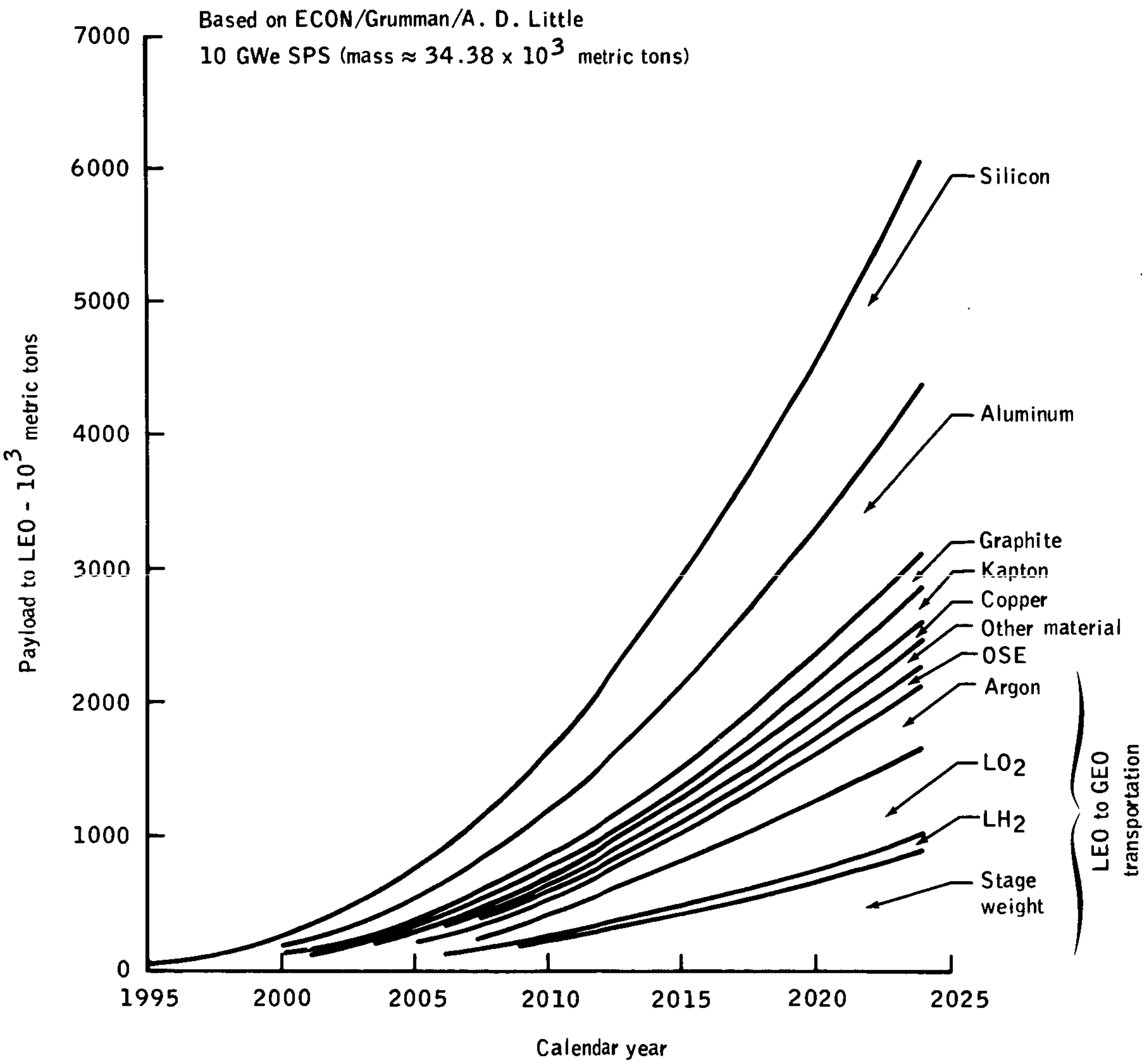


Figure 9. SPS Program LEO Mass Requirements

4. ECON, Inc., "Space Based Solar Power Conversion and Delivery System Study," Contract NAS 8-31308.

5. Boeing Aerospace Company, "Payload Utilization of SEPS (PLUS)," Contract NAS 8-31444.

6. Martin Marietta Corporation, "Orbital Assembly and Maintenance Study," Contract NAS 9-14319.

MISSION		KM/SEC	
EARTH →	LOW EARTH ORBIT	8.99	13.23 km/sec
LOW EARTH ORBIT →	GEOSYNCHRONOUS ORBIT	4.24	
LOW EARTH ORBIT →	EARTH (USING SHUTTLE TPS)	0.09	
LOW EARTH ORBIT →	LUNAR POLAR ORBIT	4.08	
LOW EARTH ORBIT →	L-5	4.08	
LUNAR POLAR ORBIT →	LUNAR SURFACE	2.19	
LUNAR SURFACE →	LUNAR POLAR ORBIT	1.86	
LUNAR POLAR ORBIT →	L-5	0.69	4.29 km/sec
L-5 →	GEOSYNCHRONOUS ORBIT	1.74	

Figure 10. Transportation Options Delta-Velocity Requirements

DISCUSSION (Davis Paper)

SPEAKER 1: Could you say something about the economic rationale for producing this type of power system? Why wouldn't you spread these things out in the Arizona desert? Wouldn't it be cheaper?

DAVIS: Well, the solar terrestrial central powerplant, of course, is a very attractive option. It's one that's being studied by ERDA today and the thing that you're working against here is the fact that in geosynchronous orbit you have 6 to 15 times the solar insolation available that's available on good locations such as the Tuscon area, Saudia Arabia on Earth. This is a consequence of the day-night cycle and the attenuation of the atmosphere. So what you're trying to see is whether or not within that factor of 6 to 15 you can pay for the incremental costs of the space transportation and assembly. Does that respond to your question, sir?

G. ARRHENIUS: The atmospheric attenuation is only 20 percent, isn't it?

DAVIS: Well, someone else will have to answer that. I've seen the numbers but I don't have immediate recall of them. There is a very elegant buildup in the AIAA assessment of solar power on where this factor 6 to 15 comes from. You might wish to review that.

(Editor: The factors of day/night (½), cosine (0.707) and attenutation in the atmosphere are multiplicative and give a minimum diurnal loss of $[(\frac{1}{2})(.7)(.5)]^{-1} \simeq 6$).

SPEAKER 2: I wonder if you have any feel for the best way to transport large systems assembled in low-Earth orbit to geosynchronous orbit and perhaps you could specifically comment on the use of carbon arc resistor jets with hydrogen propellant.

DAVIS: I certainly don't have any idea at all of what's best. I have an idea today of what some of the options are and the carbon arc, hydrogen arc jet is one of the options I was reviewing just before I came here today but it's only one of a number. I have no idea of what's best at this moment.

SPEAKER 3: No matter how small the attenuation of the microwave beam coming down is, it's still on the order of a couple of gigawatts total power, where you're losing a couple percent of that. Do you have any idea what the environmental consequences - or is anybody looking into the environmental consequences of attenuation in the atmosphere?

DISCUSSION (Davis Paper)

DAVIS: Yes, there have been some reviews made of that and that as it happens is the criterion that sizes the relationship between the spaceborne and the groundborne antennas: The desire to keep the beam density as it passes through the ionosphere within the safe boundaries - if memory serves - something like 35 milliwatts per square centimeter. So there is a great deal of attention being paid to the environmental effects of it. As a matter of fact, the environmental effects of the space power option is one of the features that makes it very attractive. It's one of the few occasions in which you beat Carnot cycle looses in that the losses consequent to the power generation are dumped not into the biosphere but into deep space by space radiators. You have no particulate effluents as you will in the case of coal and the heat generated by the rectenna is now estimated to be less that the heat density over any populated city area. The ground beneath is shielded by the receiving antenna itself and should be usable for agricultural purposes. So we think it's environmentally an attractive system. For that reason we are encouraging environmental trades between this and the other options.

SPEAKER 4: What happens if you're not quite pointing this thing in the right direction?

DAVIS: There is a reverse conjugate control scheme for the phased array antenna that has its transmitter for the control signal located in the middle of the receiving antenna on the ground and, should the beam drift for mechanical reasons or others, the beam goes incoherent and the energy density dissipates very rapidly to a communication signal level type of intensity. So we think it's got fail-safe control features.

SPEAKER 4: Well, I'm thinking in terms of the emergency cooling systems for nuclear and the concerns about those.

DAVIS: I'm not aware of any equivalent to the nuclear reactor "guillotine failure mode" present in the satellite power station.

SPEAKER 4: It doesn't kill any people or anything like that?

DAVIS: The phased array becomes incoherent and the energy density of this beam, although it's perhaps a 12- or 14-million-kilowatt beam, becomes incoherent with the loss of the pilot signal that's generated at the ground receiving antenna. As a consequence, the energy is spread over such a vast area that it is no longer of any concern. In addition, I understand that there is no easy way to convert this microwave power beam into a weapon.

SPEAKER 5: What if you fly through the beam in an airplane or something like that? Do you get zapped?

DISCUSSION (Davis Paper)

DAVIS: If it's a metal airplane, the answer is pretty clearly no. You're protected by the Faraday cage. I don't know about the fabric and wood airplanes just yet and that's one of the things we'd have to run some tests on. There is concern about birds as well, and there's two very distinctly contrasting opinions relative to birds and the influence of the current radar type microwaves upon them. One school of thought is that it attracts them because it keeps their body warm and they like it and they cluster around it. The other is that it can kill them. My friend who runs the microwave reception test at JPL has assured me that he has never ever found a dead bird beneath their receiving antenna, but he quickly added, "But, of course, we have coyotes."