Wireless Power Transmission: The Key To Solar Power Satellites

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ABSTRACT

In the years following the OPEC oil embargo of 1973-74, the United States aggressively researched alternative energy options. Among those studied was the concept of Solar Power Satellites — generating electricity in space from solar energy on giant satellites and sending the energy to the Earth with wireless power transmission. Comprehensive system definition studies of the concept were performed under the auspices of the Department of Energy and NASA from 1977 until 1980. The conclusion was that there was no technical reason why the satellite system should not be developed and that the potential benefits were very promising. However, the studies were terminated because of concerns over the validity of the cost estimates and the magnitude of the program.

Much has happened in the fifteen years since the studies were terminated. The solar cell industry has matured; robotic assembly, which has revolutionized the automobile industry, is no longer just an idea but a practical reality; Space Shuttle has proven the technology for reusable space transportation; and wireless power transmission is being planned for many applications. Maturing of the enabling technologies has provided much of the infrastructure to support the development of a commercial Solar Power Satellite program. All of this will reduce the cost by one to two orders of magnitude so development can now be undertaken by industry instead of relying on a massive government program.

Solar Space Industries was formed to accomplish this goal. The basis of their development plan for Solar Power Satellites is to build a Ground Test Installation that will duplicate, in small scale on the earth, all aspects of the power generating and power transmission systems for the Solar Power Satellite concept except for the space environment and the range and size of the energy beam. Space operations issues will be separated from the power generation fixation and verified by testing using the NASA Space Station and Space Shuttle. Doing the developmental testing on the ground instead of in space will result in a low cost program that can be accomplished in a very short time.

Solar Space Industries' concept is to build a Ground Test Installation that couples an existing 100 kW terrestrial solar cell array, furnished by an interested utility, to a phased-array wireless power transmitter based on the subarray developed by William Brown and the Center for Space Power. Power will be transmitted over a 1-1/4 mile range to a receiving antenna (rectenna) and then fed into a commercial utility power grid.

The objective is to demonstrate the complete function of the Solar Power Satellites, with the primary issue being the validation of practical wireless power transmission. The key features to demonstrate are: beam control, stability, steering, efficiency, reliability, cost, and safety. This test will give the utilities confidence in the efficiency, cost, environmental safety, and operating characteristics of a Solar Power Satellite with a very low-cost research program. This installation could be in full operation within two years.

It is time for United States industry to initiate the development of Solar Power Satellites and gain the benefits of abundant, low-cost, nonpolluting energy they will bring.

SOLAR POWER SATELLITE CONCEPT

The concept of the Solar Power Satellite energy system is to place giant satellites, covered with vast arrays of solar cells, in geosynchronous orbit 22,300 miles above the Earth's equator. Each satellite will be illuminated by sunlight 24 hours a day for most of the year. Because of the 23° tilt of the

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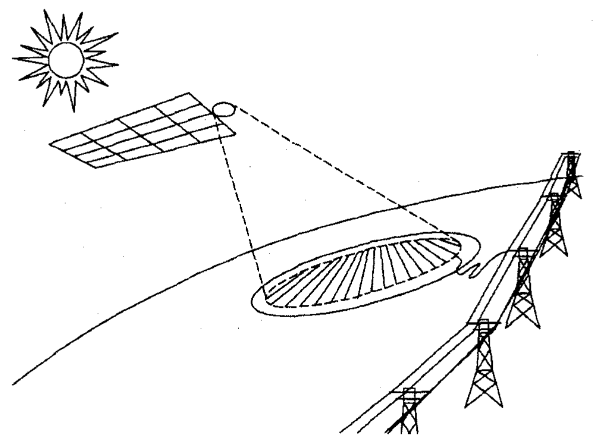


Fig. 1. Components of the Solar Power Satellite System — The Sun, The Satellite, The Wireless Power Transmitter, and the Rectenna — Deliver Electricity to Existing Distribution Grids

Earth's axis, the satellites pass either above or below the Earth's shadow. It is only during the equinox period in the spring and fall that they will pass through the shadow. They will be shadowed for less than 1% of the time during the year. The solar cells will convert sunlight to electricity, which will then be changed to radio-frequency energy by a transmitting antenna on the satellite and beamed to a receiver site on Earth. It will be reconverted to electricity by the receiving antenna, and the power would then be routed into our normal electric distribution network for use here on the Earth. Figure 1 illustrates the concept.

Each satellite will have an output equivalent to the current capacity of a large Earth-based power plant. The great advantage of placing the solar cells in space instead of on the ground is that the energy is available 24 hours a day, and the total solar energy available to the satellite is between four and five times more than is available anywhere on Earth and 15 times more than the average location. Testing has demonstrated that wireless energy transmission to the Earth can be accomplished at very high efficiencies. Tests have also shown that the energy density in the radio-frequency beam can be limited to safe levels for all life forms. The concept is simple; the technology exists.

BACKGROUND

The concept of generating solar energy in space and beaming it to Earth was first proposed by Dr. Peter Glaser of A.D. Little in 1968. The idea was made possible by development of practical wireless power transmission demonstrated by Bill Brown of Raytheon in 1964. After the OPEC oil embargo of 1973-74 NASA initiated studies of the idea. The program, called Solar Power Satellites, was later transferred to the Energy Research and Development Agency (ERDA) as the first step of consolidating all government energy efforts. Consolidation of responsibility was completed when the Department of Energy was formed in 1977.

The Department of Energy developed a comprehensive program that concentrated on four areas: 1) technical feasibility; 2) environmental impact; 3) societal impact; and 4) cost comparison. NASA was responsible for the technical studies and DoE retained responsibility for the others as well as overall program management. Funding for 3 years was $19.5 million.

At the end of three years of studies all participating organizations — the major aerospace companies and their subcontractor teams, the Environmental Protection Agency and their research scientists from universities and research institutes, concerned citizen groups representing organizations both supporting and opposing the concept, research scientists from technology development companies, and economists — assembled in Lincoln, Nebraska, in April of 1980 to report on their findings. The conclusion of the conference was that there was no technical reason why the satellite system should not be developed and that the potential benefits were very promising.

However, by 1980 the oil crisis of 1973-74 appeared to be over and nearly forgotten. Concerns over the size and cost of the program, opposition to the concept from the established energy industry who saw it as a threat to their future, and opposition of the Carter administration to large programs, resulted in the order to stop all further work in the summer of 1980.

Since that time there has been no significant organized system development work on the concept in the United States. The public has forgotten that there is an energy system that could replace oil, coal, and nuclear power; an energy system that would have unlimited capacity, be environmentally clean, and, in time, would result in energy costs much below those of fossil fuels or nuclear. With Solar Power Satellites, the cost of electricity by the year 2050 would be between 15 and 70 times less than with fossil fuels or nuclear.

Development of enabling technologies, such as solar cells and wireless energy transmission, has continued for other applications, making the concept even more technically and financially sound today. Also during this time system definition and design has been initiated in foreign countries. Japan is now committed to the development of Solar Power Satellites with the ultimate goal of producing 30% of global energy needs by 2040, most of it for export.

THE PROBLEM TODAY

Even though energy prices are relatively low today, the problem of where energy will come from in the future, how much it will cost, and how it will impact the world's environment has not gone away. It has two major facets. One is economics and the other is the environment. Energy is deeply enmeshed in both. A look at history and what is happening in the world today illustrates the problem.

Two energy eras have elapsed during humanity's sojourn on Earth: the era of wood and the era of coal. The third (and

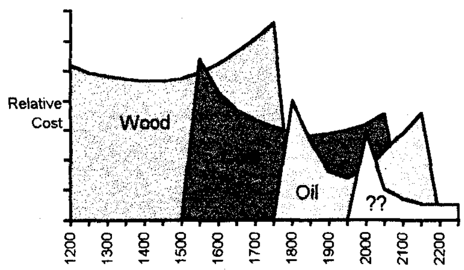


Fig. 2. Each Energy Era Brings Prosperity and Growth—Before the Supply Runs Out. Can we find a nondepletable source for the next energy era?

present) era of oil is waning. Each new major source brings new economies and prosperity to the world.

Wood supported the human race for millennia before expanding population and energy use outstripped the growth rate of trees. It happened first in England centuries ago when they were forced to convert to coal. Coal proved to be a far superior fuel and propelled England to the forefront of the world economy and fueled the Industrial Revolution. Coal made England the dominant economic force in the world for centuries.

At the turn of the last century, oil came gushing out of the ground of Texas, and the United States flowed into the twentieth century on a river of black gold that floated the United States to the top of the world economy. Cheap energy gave Americans the highest standard of living on Earth. However, oil, which once sold for two cents a barrel, is a dwindling resource that now threatens the economy, world politics, and the environment. The United States oil production continues to drop as imports exceed production. Coal, now generating 56% of US electricity, has been forced to take up the shortfall in electrical power generation as oil production dwindled; nuclear power proved unacceptable to the population because of fear of nuclear accidents and nuclear proliferation; hydroelectric has reached its maximum capacity; fusion remains only an elusive hope on the far horizon; and Earth-based renewable sources are still too costly. Atmospheric emissions are increasing as use of coal and natural gas expands. The fear of global warming is a grim specter to the world's future. At the same time, world population is exploding and the underdeveloped nations yearn for the standard of living of the developed nations. Unfortunately that is impossible without sufficient cheap energy. The standard we have reached today has already imposed a severe penalty on the world's environment.

Figure 2 illustrates the three eras of energy the world has experienced. The question is: Can we develop a new energy source for the fourth era?

CRITERIA

The solution to the problems will require a new energy source to replace oil and coal and become the primary energy source for the future. It cannot be a solution only for America, but must be able to solve global problems also. To accomplish this the next energy source must satisfy some very basic criteria. First, it must be nondepletable, so it will not have to be replaced by the next generation. Second, it must be low cost, or it will not be developed to produce large quantities of energy. Third, it must be environmentally clean, so the Earth is not destroyed as we develop. Fourth, it must become available to everyone on Earth if war is to be avoided. Fifth, it must be in a useful form so it can support the developing societies as they emerge as well as the developed nations. These five criteria are simple but challenging to satisfy:

Nondepletable
Low cost
Environmentally clean
Available to everyone
In a usable form

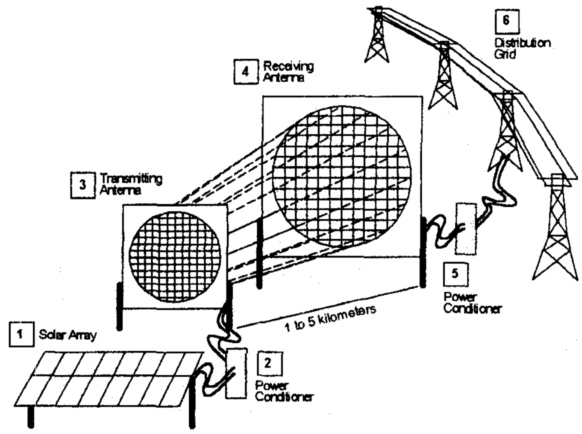


Fig. 3. Components of the Ground Test Program include all parts of the Solar Power Satellite System

SOLUTION

The solution to the problems described above can be accomplished by the development of Solar Power Satellites. The Solar Power Satellite system is the only energy source with known technology that can meet the criteria for a viable major new energy source and move the world into the fourth era of energy.

There are two primary paths that can be followed to develop Solar Power Satellites. One is a government program and the other is commercial development with some government support. In 1980 the only conceivable option was a massive government sponsored and funded program. This was one of the primary reasons the program was stopped. Today that is no longer the case. Advances in the enabling technologies along with significant infrastructure development now make possible commercial development of the program with some government support.

The terrestrial solar cell industry has evolved into a robust growing industry approaching maturity. Cell prices have dropped dramatically as production has increased and more cell types have emerged. The automobile industry has been

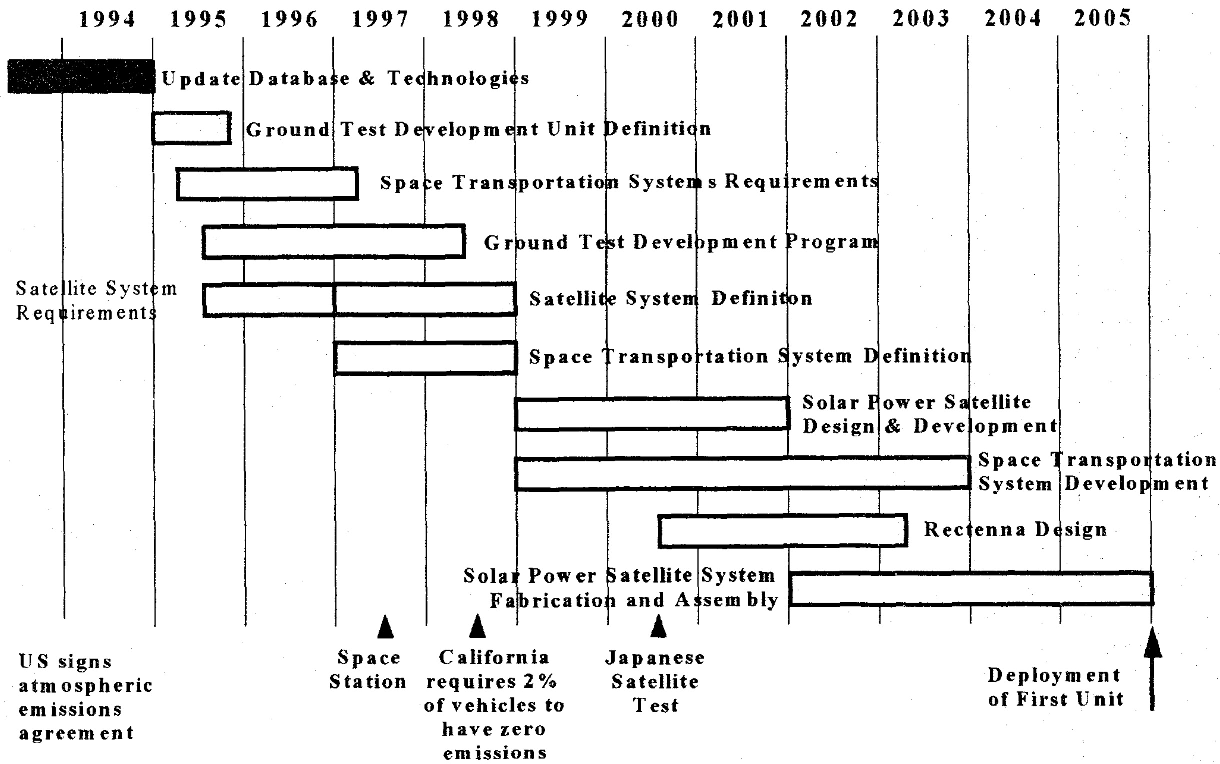


Fig. 4. Solar Power Satellite Development Plan Schedule

transformed with the conversion to high levels of robotic assembly tools. Robotic assembly of the satellites in space is now a practical reality that will limit the requirement for human involvement in most of the in-space assembly operations. Radio frequency generators can be magnetrons that are manufactured by the tens of millions for microwave ovens and commercial dryers.

For commercial development to be successful it will be necessary to demonstrate to the utility industry that the system will perform as predicted and the cost will provide electrical power at a competitive level. To achieve this goal, Solar Space Industries has developed a plan to validate the technology and cost of the system in a step-by-step approach that is based on a Ground Test Program illustrated in Figure 3 (on previous page). This is the first step in the overall Solar Power Satellite development plan shown in Figure 4.

GROUND TEST PROGRAM

The Ground Test Program will use a small-scale terrestrial-based solar cell array coupled to a phased array wireless power transmitter, which would transmit the energy over a short distance to a receiving antenna (rectenna); and feed the DC power output through an inverter/power controller into a commercial AC utility power grid.

The Solar Power Satellite Ground Test Program proposed by Solar Space Industries will test, validate, and verify all steps in the process of bringing power from space to Earth. This program will replicate the processes involved in intercepting the stream of solar energy coming from the sun, converting it to electricity, change it into radio frequency energy, transmitting to a receiver, reconverting back to electricity, and conditioning the power for delivery to the utilities' transmission systems.

Each element of the system will be designed to incorporate several different technology approaches to be tested in the complete end-to-end test installation. The initial array will be a 100 kilowatt terrestrial array procured by a utility to supply solar energy into their commercial grid. During the ground test program, its power will be used as the source of energy for the wireless energy transmitter. Later in the test program, it is planned to test different arrays with different types of cells and different wiring schemes and power controllers.

Testing of the transmitting antenna will start with a small number of 30-inch square slotted wave guide subarrays powered by magnetrons operating in the Industrial Scientific & Medical (ISM) band at 2450 megahertz. This frequency was used for the earlier studies and there is no reason to change the frequency at this point in time. The subarrays will be based on the design developed by Bill Brown in conjunction with the Center for Space Power and Texas A&M University. The initial tests will verify the ability of the subarrays to work together for beam control and steering. As these factors are proven, the number of subarrays will be expanded to form a transmitting antenna approximately 30 feet in diameter that will be able to transmit the full 100 kilowatt output of the solar array. It will have all of the features of a full-sized satellite transmitter including beam formation, retrodirective control, and steering. Later tests will be made on other radio frequency generators with solid state devices leading the list. It will also be desirable to test hybrid transmitter arrangements that use both magnetrons and solid state radio frequency generators on the same antenna.

The receiving antenna or rectenna will also be given special attention. The rectenna is a rectifying antenna that receives the radio frequency energy from the transmitter and converts it directly into DC electricity. The original designs were three-dimensional half-wave dipole antenna elements set in front of a wire mesh backscreen and coupled to a rectifying diode. Later designs use a single diode to receive the energy from several of the dipole elements and have become nearly two-dimensional. Various designs will be tested to determine the best efficiency and lowest cost. The rectenna will be approximately 60 feet in diameter and located about a 1-1/4 miles from the transmitter.

Inverter/power controllers will be integrated into the installation to process DC power from the rectenna into AC power compatible with a commercial utility grid. There are several commercially available systems of different designs that will be tested to verify efficiency and reliability.

The key function of the Ground Test Program is to validate the wireless power transmission system. The ability to transmit energy without wires has been demonstrated many times, but previous tests have not included all of the necessary functions in a total end-to-end operation. Particularly important is demonstration of beam control, stability, steering, feedback and safety. These will lead to validating efficiency, reliability, and cost. There is little doubt that solar cells work well in space with their cost and efficiency now reaching acceptable levels, but efficient, reliable wireless power transmission is yet to be demonstrated. The Ground Test Program will remedy this situation by duplicating all aspects of the power generating and transmission systems for the Solar Power Satellite concept.

More than twenty years ago, NASA certified an overall efficiency of 54% for wireless power transmission in a laboratory test. Since that time major improvements have been made in many of the technical areas. Today overall transmission efficiencies of 65% to 75% can be expected.

DEVELOPMENT PLAN

The Ground Test Program is the first major step in the development program. Its cost for a three year program will be very modest, but it will provide the confidence in the concept to move on to the next phase. The proposed Solar Space Industries development plan for the total Solar Power Satellite system, including space transportation, shown in Figure 4, is based on an industry/government partnership with industry taking the leading role to develop the power plants. The important role for government will be to coordinate international agreements, support the development of high technology multi-use infrastructure, and assume the risk of buying the first operational satellite.

Only government can establish international agreements on orbit slot assignments, frequency allocations, space debris cleanup, space traffic control, and licensing. And there is still the question of whether commercial investors will be willing to finance the development of a new reusable space transportation system for Solar Power Satellites prior to proving the system is economical. It is still also desirable to have the government assume some of the development risk on the first unit and to be the focal point for international cooperation during the development phase, but most of the financing and control can be commercial.

The approach of using a ground-based prototype to do the major development testing has resulted in a dramatic reduction in the projected development cost and is one of the key elements making commercial development possible. Testing for the space oriented aspects of the concept is a logical mission for Space Station. The Space Station is a major piece of the infrastructure needed to develop solar power satellites and is currently being developed as a national investment. By focusing the research conducted on the Space Station to solve the problems of developing the space aspects of solar power satellites, NASA would still be able to accomplish their space research objectives with very little increase in cost. Most of the space research needed for the solar power satellites is also needed for many other space programs. The economic benefits of using the Space Station for developing technology for solar power satellites will give it a clear mission that will more than justify the cost of its development.

The most expensive part of the program will be the development of a new reusable space transportation system. The need for a low cost space transport is not unique to the Solar Power Satellite program. NASA is currently working with industry on the early phases of a program to demonstrate a small scale prototype of a new low-cost reusable system to replace the Space Shuttle. There are several space programs planned that would benefit from a new low-cost launch vehicle. One example is Teledesic's plan to launch 840 satellites for telephone communication. However, none of the planned programs are large enough to justify the cost of a new system. What is unique about the Solar Power Satellite program is it is large enough to justify the development of a new low-cost system by itself. The potential space transportation market is huge. For example, if solar power satellites were only used to replace worn-out power plants, the annual revenue for transporting them to space would be over $15 billion per year. This only takes in the US replacement market. If the total world market is considered, the space transportation revenues would be closer to $100 billion a year. It is certainly a large enough market to entice competitive commercial operations. To be successful however, it is very important that the requirements for transporting the solar power satellite hardware be incorporated into the transportation system development.

The final part of the development plan is a full size operational Solar Power Satellite which proves the validity of all facets of the concept, including the most important — cost. A government owned utility such as Bonneville Power

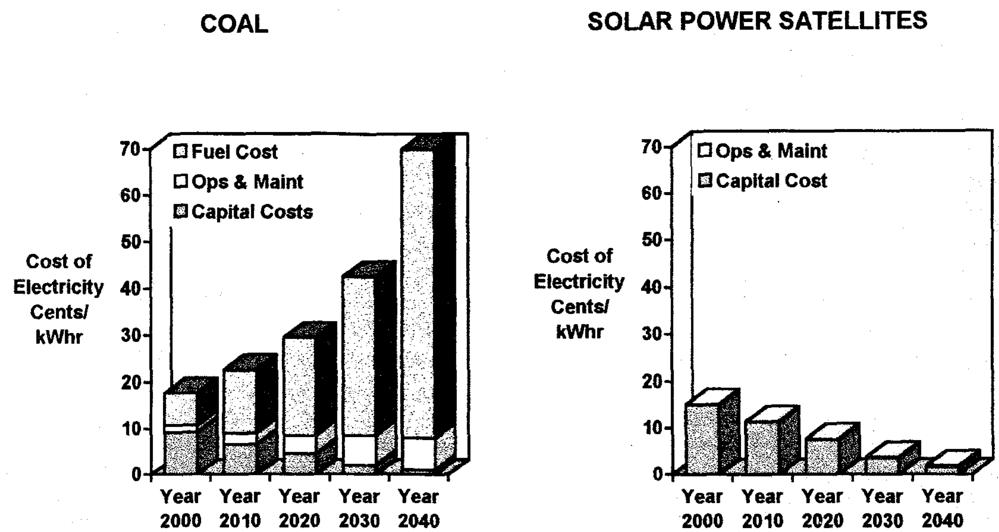


Fig. 5. Cost of Coal Power Escalates with Fuel Cost — Cost of Solar Power Satellite Energy Decreases over Time — There is No Fuel Cost

Administration is the logical buyer of the first unit. Bonneville, with more than 20,000 megawatts of generating capacity, and a large distribution system, is large enough to readily absorb the power from a 1,000 megawatt power plant. In addition, there are sites within their service area where the receiving antenna could be built. The cost will be repaid by the revenue generated by the satellite. The main reason a government utility should buy the first unit is so the government would accept the risk.

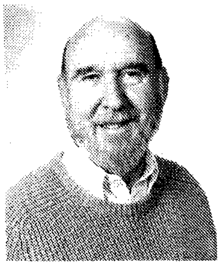
The price of the first unit would cover the cost of the satellite and a portion of the design and development cost. The developing contractors would be expected to recover the remainder of the development cost over the sale of some reasonable number of follow-on orders. This first unit is critical to demonstrate to electric utilities that solar energy generated in space and beamed to the Earth is a viable commercial power source. From this point on, orders for additional power plants can be expected from utilities in the United States and other locations throughout the world.

The potential market for satellites is enormous. Today the world market for electricity is a trillion dollars a year. As demand grows from the developing nations, this market will expand. As fossil fuels are depleted and environmental pressures force conversion to renewable energy sources, the market will shift from fossil fuels and nuclear to Solar Power Satellites.

Figure 5 shows a cost comparison of electricity from coal, which is the only fossil fuel with large reserves, and from Solar Power Satellites based on the DoE/NASA studies. This comparison illustrates the magnitude of the potential cost savings from developing Solar Power Satellites.

The ground rules for the comparison were power plants of equivalent capacity, thirty year payoff of capital costs, 3% inflation, 1-1/2% real cost escalation for coal due to environmental constraints, operation start date in the year 2000, a minimum forty year life, and typical utility financing regulations. Both start at about the same cost, but after that the costs diverge rapidly. The cost of coal generated energy escalates with inflation and environmental constraints while the cost of electricity drops for Solar Power Satellites as the capital cost is paid off. By the end of 40 years, the cost of electricity from coal is over 70¢ a kilowatt hour and the plant is worn out. After the capital cost is paid off for a Solar Power Satellite in 30 years, the cost of electricity has dropped to less than 2¢ a kilowatt hour and the plant should be able to operate for many decades longer because of the benign environment of space. The great difference is because there is no fuel cost with Solar Power Satellites. They are like hydroelectric dams, only they dam sunlight instead of water — both are free.

The key to the feasibility, of gathering solar energy in space for our use on the Earth, is wireless power transmission that makes it possible. The Ground Test Program proposed by Solar Space Industries will validate wireless power transmission with a very small initial investment before large development funds need to be committed. The economic and environmental benefits that will result from this investment will change the world in the new millennium.



Ralph Nansen has been involved in space engineering for nearly 40 years. While with The Boeing Company from 1956 until his retirement in 1987, he was a manager on the Saturn/Apollo program, Space Shuttle definition studies, Manager of the Design-to-Cost Laboratory, and led the Boeing team that developed the overall concept of Solar Power Satellites under the auspices of the Department of Energy and NASA. He is the author of the book *Sun Power: The Global Solution for the Coming Energy Crisis*, published by Ocean Press. This book, written for the general public, defines the great economic and environmental benefits of developing Solar Power Satellites as the next major world energy source.

Mr. Nansen is the founder and president of Solar Space Industries, a company dedicated to the commercial development of Solar Power Satellites. He graduated with a BS degree in Mechanical Engineering from Washington State University.

New Jersey Coast Chapter

Speaker, **Harvey Mantz**, (l) receiving book on *Space Science & Applications* as a token of appreciation for his talk on *"DoD Initiatives for Advanced SATCOM Technology Development"* on February 27, 1995 from **Samuel Segner**, Chairman, NJ Coast Joint AES/EM Chapter

From left to right:
Seymour Krevsky, Past President, EMS;
John Van Savage, Vice Chairman, NJ Coast Joint AES/EM Chapter;
Speaker, **Bernard V. Ricciardi**, Chief Comm. Technology Branch, S&T Directorate CECOM, Ft. Monmouth, NJ, who gave a talk on *"Tactical Low Level Helicopter Communications"* on March 27, 1995; and
Samuel Segner, Chairman, NJ Coast Joint AES/EM Chapter

From left to right:
George Hessel, Treasurer, NJ Coast Joint AES/EM Chapter;
Speaker, **Stephen Rurak** gave a talk on *"Nuclear Hardening for Military Satellites"* on May 22, 1995;
John Van Savage, Member BoG, EM Society;
Leo Labanca, Consultant, SATCOM; and
Samuel Segner, Chairman, NJ Coast Joint AES/EM Chapter