

graphical area for rectenna installation. The side effects associated with RFI are expected to be more important than the biological effects. Since the microwave beam portion of the SSPS system is not intended to handle information, no bandwidth is required for that purpose. However, a transmitter of this power level will inherently generate a large amount of noise, which would be scattered physically outside of the microwave beam. The intensity of this noise would be greatest near the frequency assigned to the SSPS system, just where the use of filters is the least effective. It would be desirable, therefore, to assign a frequency band—perhaps 100 MHz wide—to the system. Initial calculations based upon the measured noise properties of the type of microwave generator proposed for the system and the use of a moderate amount of additional filtering indicate that the CCIR flux density limitation requirement that protects earth-based microwave receivers can be met if a band of 100 MHz is assigned. However, this aspect of the SSPS operation needs a great deal more study.

In the minds of many, it may seem that the proposed use of space for the transmission of power represents a potential intrusion into an area long reserved for the transmission of information and should be permitted only if our future energy problem becomes so great that power transmission through space is an overriding consideration in our system of priorities. But the coexistence of power and information transfer in space should be examined in terms of what communication practices will be in 1990 and 2000—reasonable dates for the first operational SSPS system and for full-scale deployment. The low-frequency end of the microwave spectrum, in which the SSPS would probably be located, is already becoming too restrictive for the large mass of information to be conveyed and, by 1990, almost all land-based communication may be handled in ducted systems using millimeter waves or light waves and spaced-based systems may be using millimeter waves.

It is also observed that, in the past, power and communication have been able to take advantage of a common transmission medium, notably wire transmission, and to resolve the mutual interference problems that have arisen. There may also be a clue to a solution in case interference problems do arise by observing the palliative action that has been taken to override man-made interference in the AM broadcast band by increasing the power level of the transmitter. It is even possible that the synchronous SSPS satellite may become attractive as the physical location for the transmitters of advanced communication systems because of the easy availability of power.

The issue of the microwave beam's impact upon atmospheric disturbances and weather has also been raised. Upon examination, however, it is found that the density of power input to the atmosphere resulting from absorption of microwave energy is typically 20 watts/m². This level is small compared with the density of power absorbed from solar radiation and radiative processes from the earth. It is doubtful if the beam could produce a significant local disturbance. On a global scale the total energy input to the atmosphere from 100 SSPS systems would be minuscule compared with natural processes.

would have to supply about 500,000 MW. This figure corresponds to a quantity of fifty 10,000-MW systems, each requiring about 40 km² for the rectenna and a protective guard ring. The total land requirement would be 2,000 km². This is an insignificant portion of the marginally useful land that is still expected to be available in the year 2000.

Side effects of the SSPS system

The freedom of the SSPS from any pollution in the form of chemical, particulate, or nuclear wastes has been mentioned. It also has a very low thermal pollution as the result of the very high efficiency of the rectenna, the only terrestrially based part of the system. Three possible side effects whose seriousness should be evaluated, however, are biological effects, RFI, and weather modification.

From the viewpoint of general biological effects^{29,30} of microwave energy upon man and other forms of life, the only effect that has been established after many years of investigation and observation is the heating effect, now used beneficially in the home electronic oven and in industrial processing. The heating effect is relatively benign biologically and man has the relatively high continuous-exposure tolerance of 10 mW/cm². The continuous exposure standard in the U.S. is set at that level.

The maximum power density of microwave radiation in the base-line SSPS system is at the center of the rectenna and its value is a little less than 100 mW/cm²—less than that of solar radiation but ten times the density of the U.S. continuous exposure standard. The intensity level falls rapidly near the skirts of the microwave beam and reaches levels of a few μ W/cm² within a few kilometers of the outer edge of the rectenna. A reasonable guard ring and fence around the rectenna should prevent any damage to humans or wild life in the general area. Within the confines of the rectenna area, wild life would probably be excluded and maintenance personnel would take suitable precautions.

The impact of the beam upon metal-skinned aircraft that fly through it should be minimal because almost all of the energy impinging upon the aircraft would be reflected. For fabric-covered planes and plastic cockpit helicopters or airplanes, the occupants would be exposed to the beam for the period of time required to fly through it. The impact upon birds is a special problem that needs to be studied. Location of the rectenna in comparatively desolate areas and away from the migration lanes of birds should minimize this aspect.

In concluding this brief discussion of biological effects of the SSPS, it should be noted that despite the lack of identification of any effects of microwave radiation other than thermal, there is agreement that the study of biological effects of microwaves should be continued, particularly with respect to any long-range or delayed effects. This concern has been recognized by the U.S. Government and is identified with a proposed Government-supported comprehensive study of the nonionization aspects of microwave radiation. The results of this and other studies that may be made would determine the extent of the guard ring around the rectenna and the range of choice of geo-

graphing the 65 to 70 percent projected for the... The achieved efficiencies and those expected to be... are given in Table I. It shows an eventual labor... of about the efficiency of 75 percent. The... reason for the high efficiency is that in the... nearly all of the beam can be intercepted... in practice (this may be theoretical).

lected costs for the SSPS system... Table II gives the estimated capital costs of SSPS... generation in dollars per kilowatt. Various... levels are reflected in the three different... of total cost and principal components cost... The estimates for the solar array were based on a... extrapolation of existing manufacturer... into a highly automated plant that... by the huge production volume. They did not... into account possible breakthroughs in materials... and techniques, such as those already discussed.

The cost for the microwave transmitter stations... "microwaves" in Table II) and the recten... arrived at by a consideration of the bulk an... and a highly automated production... by the large number of identical... The cost of the microwave gen... was based on the very low cost of steady... electronic-oven magnatrons whose... and assembly labor content is similar to the... of the Sabelco factory... The cost of the rectenna was projected on the basis of... basic material content and the use of experience... of the semiconductor device industry.³¹

All component and system costs are assumed to be... average cost associated with the loading for and... of 20 or more nearby identical systems... The development cost of the first prototype... now be estimated accurately. It is assumed... this cost spread over a production of 20 or more... systems represents only a small fraction of the costs... in Table II.

number of SSPS systems and land use... The number of SSPS systems that might be de... is dependent upon their economic viability... of the number deployed and land use... in the context of the year 2000 or... At that time, the projected requirement... of electric power generation... This requirement is staggering but it still does... such distant possibilities in... of local loads for heating pur... to be met by conven... the requirement was to be met by conven... each plant would be required. If... all located offshore so as to minimize im-

1. Microwave power transmission efficiencies

Efficiency	Expected	Present	Additional Development
Efficiency	75.0	70.0	77.0
Transmission efficiency	85.0	80.0	85.0
from output of generator to collector aperture (a)	84.0	78.0	80.0
Generator and rectification efficiency (rectenna) (a)	84.0	78.0	80.0
Transmission collector and rectification efficiency (b)	85.2	79.2	82.0
Overall efficiency (a)(b)	70.2	63.6	70.6

* Frequency of 2450 MHz (12.2-cm wavelength)
 † This efficiency was determined at 3000 MHz and a power level of 300 kW
 ‡ This value could be further easily increased to 85 percent if an efficient generator were available at the same power level at which the 94% efficiency of 60.2 percent was obtained

II. Estimated capital costs of SSPS power generation (\$/kW)

Component	Low	Medium	High
Solar array	0.10	1.00	18.70
Microwave	50	150	180
Rectenna	30	90	70
Transportation	150	450	370
Land	500	1750	2040
Total	1430	2100	2680

Cost Index Factor
 p = 0.25 b = 0.50 d = 0.75

part upon the land environment, there would be an average of one transmitting station approximately every 2 km along the entire U.S. coastline exclusive of Alaska and Hawaii. This should require thousands of acres of land, not only the magnitude of the requirement but the necessity of a variety of approaches to the energy problem. The terrestrially based portion of the SSPS system... of its low pollution and no need for a cool... is well suited to the inland areas of a country. There is, then, a desire to find land areas that are... waterland or at least marginal from an economic... point of view. The land areas may be added... land that may be located within a reasonable... of even our most populous areas. Without... of the present flow of the population from rural... to urban centers, many densely populated... will remain available as sites for recten... in the year 2000. This is particularly true of the... and regions of the Southwest and the Great Plains. To be an important factor in supplying the base... in the year 2000, the SSPS system... all located offshore so as to minimize im-

The side effects associated with the use of the system are expected to be more important than the potential benefits. The microwave beam passing through the atmosphere is expected to be scattered to a large extent, and the amount of power which would be scattered is expected to be of the same order of magnitude as the power which would be received at the ground station. The intensity of the scattered power would be greatest near the horizon, and it would be desirable, therefore, to have the beam directed at an angle of about 10 degrees above the horizon. This would require a large antenna system, and the cost of such a system is expected to be very high. The system is also expected to be subject to a number of other problems, including the possibility of interference with other microwave systems, and the possibility of damage to the atmosphere and the ground station.

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Time scale for the SSPS

Any proposed time scale for the SSPS development must be made in the context of the possible need for the system, when it may be needed, and the difficulty of the development and deployment. From a strictly technological point of view, the development of the SSPS system may well be less of an undertaking than was the Apollo project when it was first initiated in 1961. Most, but certainly not all, of the basic technology and know-how involved are at hand, either from the Apollo project or from other sources.

Will there be a need for the system? This depends upon whether the approach can be made more cost competitive and upon the experience with other approaches to satisfying our future electric power needs. And here the picture is very clouded. Even nuclear fission has a relatively near-term fuel problem whose solution is dependent upon the successful development of the breeder reactor. In the long term, the bulk of all our energy—including electric energy—must come either from a concentration of the sun's diffuse energy or from nuclear fusion.

If needed, when will it be needed? It is clear that the approaches to achieve our electric power needs for the next two decades have already been set in motion. It should become much clearer in the 1980 time frame whether these approaches will also meet our needs in the 1990 to 2010 time frame and whether nuclear fusion will have progressed to the point where we will have confidence in its capability to help supply our energy needs into the future. It appears that it will be the 1980s, when the SSPS option will be picked up, if there is a need for it.

With this discussion as a background, the appropriate near-term action is clear. A thorough systems study of the SSPS should be made to determine the critical and weak points in the system and to assess if they can be dealt with successfully. If the study continues to indicate a viable system, some development effort on a few long-lead-time items should be initiated. Concurrently with the systems study, development effort should go forward in some of the already established critical areas that have a broader range of application than just the SSPS. Two specific technological areas are solar photovoltaic cells and microwave power transmission. With such a near-term program as a background, the 1980 time frame should be arrived at with a well-organized, well-thought-out program to mobilize our resources efficiently and to build and deploy the complete SSPS system if it should be desirable to do so.

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William C. Brown (F) has been with the Raytheon Company since 1940 where he has contributed many innovations to microwave tube technology. He was educated at Iowa State University (B.S. degree in electrical engineering) and Massachusetts Institute of Technology (M.S. degree). For a period of two years prior to joining Raytheon, he was with the Radio Corporation of America. Mr. Brown is a recognized authority on magnetrons and, in 1953, he applied the crossed-field energy-conversion principle to an efficient broadband amplifier device known as the Amplitron, or the reentrant-beam, crossed-field amplifier. In the recent time period, he has devoted his attention to the improvement of the overall efficiency of microwave power transmission and to the establishment of its credibility within the scientific and engineering community. He has also been involved in developing the details of a microwave power transmission system suitable for use in the Satellite Solar Power Station concept. Mr. Brown has had 43 U.S. patents issued to him and is the author of more than 25 technical articles.

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William C. Brown (F) has been with the Raytheon Company since 1955 where he has conducted many projects in microwave tube technology. He was educated at Iowa State University (B.S. degree in electrical engineering) and Massachusetts Institute of Technology (M.S. degree). For a period of two years he worked for Raytheon. He was with the Radio Corporation of America. Mr. Brown is a recipient of the National Defense Science and Engineering Graduate Fellowship and the National Defense Science and Engineering Graduate Fellowship. He has been involved in the development of the overall efficiency of microwave power transmission and to the development of its stability when the modulated signal is transmitted. He has also been involved in developing the details of a microwave power transmission system suitable for use in the satellite communication system. Mr. Brown has had 45 U.S. Patent Office patents to his credit and more than 25 technical articles.

Special report

Energy: Crisis and challenge

After a century of feasting, the U.S. now finds itself facing a fuel famine, with no immediate end in sight

Gordon D. Friedlander Senior Staff Writer

In Chicago, this past winter, Commonwealth Edison was forced to shut down gas fired boilers that delivered steam to a 96-MW turbogenerator. In Iowa, a natural gas scarcity forced farmers to dump their wet corn harvest because their crop dryers could not be operated. In Denver, the city school system was shut down for lack of fuel oil. These are not isolated occurrences: most industries in the western states including electric utility generating plants have been served for many years under an "industrial interruptible" gas schedule, shifting to fuel oil during severe cold spells or shutting down. Along the eastern seaboard and throughout the central states, the fossil fuels, oil and gas, have reached dangerously short supply, barely enough to meet domestic and commercial requirements. Both the states affected and the fuel suppliers were forced to ration reserves.

And throughout this crisis, ironically, the most polluting of fossil fuels, coal, continued in abundant supply.

The seemingly inevitable consequence of this abundance: the United States, the world's wealthiest and most pollution-conscious nation, will undoubtedly be forced to increase greatly the production and use of coal, a fuel which not only is responsible for the pollution of the atmosphere in vast areas of the country, but is obtained primarily through strip-mining, a process not noted for its kindness to the landscape in the 38 states in which the fuel is readily available by this method.

Background to the dilemma

As the world's wealthiest nation, with the highest standard of living, the demand for labor-saving devices, creature comforts, and luxuries in the United States is without parallel. And the kilowatt-hour has been the servant that has abetted this demand. The U.S., like most other technologically advanced nations, has behaved for decades (despite certain recog-

The fuel that, at present, is in critically short supply is natural gas. There is an urgent need for new supply sources and pipelines. There are also sporadic domestic shortages in oil (and a gasoline scarcity may soon be felt) so that . . .

by 1985, more than 50 percent of our petroleum will have to be obtained from overseas sources.

We have sufficient uranium ores for nuclear fission, but . . .

1985, or earlier, may see a number of geothermal power plants on the line, capable of generation in the megawatt range (in addition to three plants presently in operation).

Coal is plentiful—if extensive strip mining is permitted there should be more than ample for . . .

time scale for the 1980s. Any program that would be made in the context of the system when it may be needed. The development and deployment of a new technology may well be faster than the Apollo project when it was first initiated in 1961. Most, but certainly not all, of the work that we do now involves the Apollo project or from other sources.

Will there be a need for the system, the strength of which the approach can be made more competitive and upon the experience will depend on whether the approach is very limited. And here the picture is very limited. Some nations have a relatively near-term fuel problem which solutions dependent upon the amount of the power reactor in the past term. The bulk of all our energy—industrial electricity—must come either from a concentration of the sun's energy or from nuclear fission.

It is clear that the approach to reduce our electric power needs in the next two decades have already been set in motion. It should become much easier in the 1980 time frame whether these approaches will also meet our needs in the 1990 to 2010 time frame and whether nuclear power will have progressed to the point where we will have confidence in the capability to help supply our energy needs into the future. It appears that it will be the case when the SRE's option will be picked up.

With this discussion as a backdrop, the appropriate near-term action is clear. A thorough systems study of the SRE's should be made to determine the critical and weak points in the system and to assess if they can be dealt with successfully. If the study indicates a viable system, some development effort in a few long-lead-time items should be initiated concurrently with the systems study. Development effort should go forward in some of the already established critical areas that have a broader range of application than just the SRE's. Two specific technical areas are solar photovoltaic cells and microwave power transmission. Within a near-term program as a backdrop, the 1980 time frame should be viewed as with a well-organized, well-thought-out program to mobilize our resources efficiently and to build and deploy the complete SRE's system. It should be desirable to do so.

The fuel that, at present, is in critically short supply is natural gas. There is an urgent need for new supply sources and pipelines. There are also sporadic domestic shortages in oil (and a gasoline scarcity may soon be felt) so that . . .

We have sufficient uranium ores for nuclear fission, but . . .

There is a great deal of interest in the potential of geothermal power, but the technological problems are still vast, and harnessing this natural power will be costly, but . . .

Coal is plentiful—if extensive strip mining is permitted there should be more than ample for . . .