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 2000 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 μW/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 geographical 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 reradiative 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 miniscule compared with natural processes.

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.

REFERENCES

1. Szego, G. C., *et al.*, "The U.S. energy problem," Report for RANN NSF, No. C645, Intertechnology Corporation, Warrenton, Va., Nov. 1971.

2. *World Energy Supplies*, United Nations.

3. *Handbook of Geophysics*. New York: MacMillan, Sec. 16, 1961, pp. [illegible].

4. Ralph, J. E., and Hewitt, J. G., Jr., "Large terrestrial solar arrays," *Proc. 1971 Intersociety Energy Conversion Eng. Conf.*, pp. 15-23.

5. Glaser, P. E., "Power from the sun: its future," *Science*, vol. 162, pp. 857-861, Nov. 22, 1968.

6. *J. Microwave Power*, vol. 5, special issue on "Satellite solar power station and microwave transmission to earth," Dec. 1970.

7. Mockovciak, J., Jr., "A systems engineering overview of the satellite solar power station," *Proc. 1972 Intersociety Energy Conversion Eng. Conf.*

8. Briefings before the Task Force on Energy of the Committee on Science and Astronautics, U.S. House of Representatives 92nd Congress, Second Session, Vol. II, U.S. Gov't Printing Office 73-902-0. "Satellite Solar Power Station: An Option for Power Generation." Testimony by: A. D. Little, Inc., Grumman Aerospace Corp., Raytheon Co., Textron Inc.

9. *Ad Hoc* Panel (Paul Rappaport, Chairman) on Solar Cell Efficiency, National Research Council for National Academy of Sciences, "Solar cells, outlook for improved efficiency," available from Space Science Board.

10. Woodall, J. M., and Hovel, H. J., "High efficiency $Ga_{1-x}Al_xAs$–GaAs solar cells," *Appl. Phys. Letters*, vol. 21, p. 379, Oct. 15, 1972.

11. LaBelle, H. E., Jr., "Growth of controlled profile crystals from the melt: Part [illegible], Edge-defined, film-fed growth (EFG)," *Materials Res. Bull.*, vol. 6, pp. 581-590, 1971.

12. "Development of thick film silicon growth techniques," JPL contract No. 953[illegible] with Tyco Labs, Inc., Waltham, Mass.

13. Currin, C. G., Ling, K. S., Ralph, E. L., Smith, W. A., and Stern, R. J., "Feasibility of low cost silicon solar cells," *Proc. Ninth IEEE Photovoltaic Specialists Conf.*, Johns Hopkins University, Silver Spring, Md., May 4, 1972.

14. Brown, W. C., "Transportation of energy by microwave beam," *Proc. 1971 Intersociety Energy Conversion Eng. Conf.*, pp. 5-13.

15. Okress, E. C., *Microwave Power Engineering*, vol. 1 and 2. New York: Academic, 1968.

16. Okress, E. C., Brown, W. C., Moreno, T., Goubau, G., Heenan, N. I., and George, R. H., "Microwave power engineering," *IEEE Spectrum*, vol. 1, pp. 76-100, Oct. 1964.

17. Robinson, W. J., "Wireless power transmission in a space environment," *J. Microwave Power*, vol. 5, Dec. 1970.

18. Brown, W. C., "Progress in the efficiency of free-space microwave power transmission," *J. Microwave Power*, vol. 7, Sept. 1972.

19. Goubau, G., "Microwave power transmission from an orbiting solar power station," *J. Microwave Power*, vol. 5, Dec. 1970.

20. Goubau, G., and Schwering, F., "On the guided propagation of electromagnetic wave beams," *IRE Trans. Antennas and Propagation*, vol. AP-9, pp. 248-259, May 1961.

21. Li, T., "Diffraction loss and selection of modes in maser resonators with circular mirrors," *Bell System Tech. J.*, vol. 44, pp. 917-932, May-June 1965.

22. Degenford, J. E., Sirkis, M. D., and Steir, W. H., "The reflecting beam waveguide," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-12, pp. 445-453, July 1964.

23. Special issue on "Active and Adaptive Antennas," *IEEE Trans. Antennas and Propagation*, Mar. 1964.

24. Brown, W. C., "High power microwave generators of the crossed-field type," *J. Microwave Power*, vol. 5, Dec. 1970.

25. Brown, W. C., "The receiving antenna and microwave power rectification," *J. Microwave Power*, vol. 5, pp. 279-292, Dec. 1970.

26. Brown, W. C., "Experiments involving a microwave beam to power and position a helicopter," *IEEE Trans. Aerospace and Electronic Systems*, vol. AES-5, pp. 692-702, Sept. 1969.

27. Brown, W. C., "Progress in the design of rectennas," *J. Microwave Power*, vol. 4, pp. 168-175, 1969.

28. *Perspective on experience*, Boston Consulting Group, Boston, Mass.

29. Michaelson, S. M., "Human exposure to non-ionizing radiant energy—potential hazards and safety standards," *Proc. IEEE*, vol. 60, pp. 389-421, Apr. 1972.

30. Special issue on "Biological Effects of Microwaves," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-19, Feb. 1971.

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.

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 . . .

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 . . . 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 . . .