APPENDIXES

Appendix A

ALTERNATIVES TO THE REFERENCE SYSTEM SUBSYSTEMS

Solar-Thermal Power Conversion

The basic operational principle involved in solar-thermal-electric power systems is identical to that of virtually al l conventional ground-based powerplants, with a solar furnace replacing the fuel-fired furnace or nuclear reactor normally used to heat the power-cycle working fluid. The 10-MW demonstration plant at Barstow, Calif., is such a solar-powered thermal cycle. Virtually all components of such power systems have been extensively used and/or tested on Earth, and hence solar-thermal systems for potential space applications in the SPS time frame would enjoy the availability of a large body of applicable technology, hardware, and experience. Significant problems are foreseen, however, in reducing the mass and complexity of space-based powerplants to levels that make them competitive with the reference system photovoltaic power source.

The basic rationale for considering thermal power cycles is their inherently high energy conversion efficiency. High-performance thermal cycle power generators on Earth routinely attain overall efficiencies of more than 40 percent, as compared with the 17-percent projected efficiency for the reference-system photovoltaics, and it is quite probable that material and component developments during the next decade or two could extend overall operational thermal-cycle efficiencies for terrestrial units to over 50 percent. Unfortunately, however, the space environment is such that these efficiency levels, even with advanced-technology power-conversion hardware, are extremely difficult to achieve. The fundamental problem is that of heat rejection; that is, in accordance with the dictates of the Second Law of thermodynamics, it is necessary that any heat engine reject to its environment some of the energy it receives (the ubiquitous "thermal pollution" of Earth-based powerplants). On Earth, effective heat rejection at the low temperatures needed for high thermal efficiency is readily accomplished by using vast quantities of cool water or air. In space, on the other hand, all heat rejection must be accomplished solely by radiation, a process that depends on the fourth power of the radiator's temperature. Hence efficient heat rejection in space can be accomplished only at high temperatures, which by the Second Law results in reduced thermal efficiency. The radiators of the space-based thermal powerplant therefore become the key limitation on performance, and counteract the beneficial effect of potentially high-cycle efficiency. The most effective space-based thermal power cycle, then, is generally the one that minimizes the radiator mass.

The Brayton and Rankine Cycles

The two "simple" solar-thermal cycles considered for SPS are the Brayton and Rankine cycles—the cycles used on Earth for gas turbines and steam turbines, respectively. In the Brayton cycle, a compressor compresses a gaseous working fluid, that is then heated by solar energy concentrated into an "absorber" by large, diaphanous thin-film solar mirrors having a concentration ratio of perhaps 2,000-to-l, then discharges its waste heat to a radiator. It then returns to the compressor and repeats the cycle.

The Rankine cycle utilizes the same basic energy source as the Brayton cycle —typically, a 2,000-to-l solar concentrator mirror focused on an absorber – but employs a condensable liquid, or, frequently, ordinary steam. The solar energy impinging on the absorber boils and superheats the steam, which then drives a turbine. The steam then condenses in the radiator at constant temperature. The condensed water is then pumped back up to high pressure and forced into the boiler (absorber) to complete the cycle.

The Brayton and Rankine cycle options were rejected for the reference system, despite their relatively high efficiencies, because of the high radiator mass, the lower projected reliability of rotating machinery, and relative complexity of orbital assembly operations as compared with the photovoltaic options. However, recent developments in high-temperature heat exchangers and turbines, [1] and particularly innovative designs of heat-pipe and other radiators[2,3] now make Brayton-cycle turbines more attractive.

[1] "Review Study of a Brayton Power System for a Nuclear Electric Spacecraft, JPL contract 955-008, Garrett-AlResearch report No 31-1288A Oct 9, 1979

[2] Yale G Eastman, "A Study of the Application of Advanced Heat Pipe Technology to Radiators for Nuclear Spacecraft, " Thermacore, Inc , Lancaster Pa Dec 3, 1975, also see Yale G Eastman, "Advanced Heat Pipes in Aerospace Power Systems,' AIAA paper No 77-501, St Louis, Mo , Mar l -1, 1977

[3] John Hedgepeth and K Knapp, "Preliminary Investigation of a Dust Radiator tor Space Power Systems," Astro Research Corp report No ARC-TN 1054 Mar 1978

Other Thermal Cycles

Other thermal cycles have also been considered,[4 5] to be used independently or in conjunction with the Brayton or Rankine cycles in a combination. The most likely prospects are the thermionic[6 7] and the magnetohydrodynamic (MHD)[8] cycles or the wave-energy exchanger.[9 10 11 12 13]

None of these seems particularly well adapted for use in an independent mode in space, although any one of them may have potential when used in combination with either the Rankine or Brayton cycle. The primary consideration for these cycles is the tradeoff between high efficiency and high radiator mass. Principal areas requiring research and/or additional development are in the high-temperature solar collection and absorption portions of all systems and high-performance heat-rejection devices, as well as extensive testing and pilot operations to establish the required levels of reliability and reductions in cost uncertainties.

Photovoltaic Alternatives

Alternative Materials

Alternative photocell materials considered before selecting the reference system options of single-crystal silicon and gallium aluminure-arsenide were amorphous silicon, polycrystalline silicon, cadreium sulfide, copper iridium selenide, and polycrystalline gallium arsenide. Although all these materials cost less than either of the two selected materials, their efficiencies are low and there is little experience in their production. Other factors considered by the National Aeronautics and Space Administration before selecting the two reference system options were total system mass, materials availability, susceptibility to radiation damage, development status, manufacturing processes, and energy payback. Other potential photovoltaic materials that were rejected due to obvious problems with one or more of the above factors include selenium and various selenides, cadmium telluride, copper sulfide, gallium phosphide, iridium phosphide, and a number of higher order inorganic compounds.

Concentration

Another important parameter is the concentration ratio (CR). The selection of CR = 2 for the reference-system gallium arsenide option was strongly Influenced by cell temperature considerations.[14] Should cell technology develop that would retain high efficiency at elevated temperatures, higher concentrations might prove cost effective, since both the mass and the cost of reflector materials are considerably less than those of photocells.

There is good experimental evidence that the gallium aluminum-arsenide/gal lium-arsenide cells selected for the SPS could utilize much higher concentration ratios to gain higher overall efficiency. There has been considerable development in concentrating photovoltaic subsystems for terrestrial use during the past 2 years, and it is possible that passive rather than active cooling may be possible.

Multicolor Photocell Systems

Photocells respond to only a part of the available solar spectrum that impinges on them. It is possible to achieve more efficient utilization of the solar spectrum by: 1) manufacturing a single photocell from various materials, each responding to a different wavelength band;[15] or 2) using separate cells, each optimized for a different spectral region and using an optical system to split the incident light into the corresponding spectral ranges.

'Daniel L Gregory, "Alternative Approaches to Space-Based Power Generation, " *Journal of Energy 1,* March-April 1977, pp 85-92

[5]William P Gilbreath and Kenneth W Billman, "A Search for Space Energy Alternatives, " in "Radiation Energy Conversion in Space, " *Progress in Astronautics & Aeronautics, vol 61,* AI AA, N Y , July 1978, pp 107-125

[6]G O , Fitzpatrick and E J Britt, "Thermionics and its Application to the SPS, " Ibid, pp 211-221

'(For example), W Phillips and J Mondt, "Thermionic Energy Conversion Technology Development Program, " Progress report No 630-36 (for June-September 1978), Jet Propulsion Laboratory, Pasadena, Calif , Nov 15, 1978

'C V Lau and R Decher, "MHD Conversion of Solar Energy, " in "Radiation Energy Conversion in Space, " K W Billman (ed), Progress *in Astronautics & Aeronautics, vol 61,* AI AA, N Y , July 1978, pp 186-200

"Robert T Taussig, Peter H Rose, John F Zumdieck and Abraham Hertz berg, "Energy Exchanger Technology Applied to Laser Heated Engines, " Ibid, pp 465-478

[10]W E Smith and R C Weatherston, "Studies of a Prototype Wave Superheater Facility for Hypersonic Research ' report No HF-1056-A-I, contract AFOSR-TR-58-I 58, AD207244, Cornel I Aeronautical Laboratory, Buffalo, N Y , December 1958

"Abraham Hertzberg and Chan-Veng Lau, 'A High-Temperature Rankine Binary Cycle for Ground and Space Solar Applications, " in "Radiation Energy Conversion in Space, " K W Billman (ed), *Progress in Astronautics & Aeronautics, vol 61,* AI AA, N Y , July 1978, pp 172-185

"Arthur T Mattick, "Absorption of Solar Radiation by Alkali Vapors, " Ibid, pp 159-171

''AJay Palmer, "Radiatively Sustained Cesium Plasmas for Solar E lectric Conversion," Ibid, pp 201-210

[14]I W James, and R L Moon, "GaAs Concentrator Solar Cells, " *Proceedings of the 11 th Photovoltaic Specialists Conference,* 1975, pp 40,? 408

Richard J Stirn, "Overview of Novel Photovoltaic Conversion Techniques at H igh I ntensity Level s," in "Radiation Energy Conversion in Space K W Billman (ed), *Progress in Astronautics & Aeronautics, vol 61* J uly 1978 pp 136-151

" I aan, Jurisson, "Multicolar Solar Cel I Power System for Space, 'r Ibid, pp 152 158

Although the technology for both approaches is known, it is far from having been proved practical, and will require considerable research and development effort before being considered for future operational systems. The second approach appears to be the most promising in principle. However, it suffers from a lack of basic data on the photovoltaic materials that might be used for it. Despite their attractiveness from the standpoint of efficiency, both systems also require either higher mass or concentrator systems, which may require active cooling. Again, vastly more research is needed to determine the overall effectiveness of these concepts.

Alternative Microwave Power Converters

In addition to the klystron, several other devices may be capable of converting satellite electric power to microwaves and transmitting them to Earth. The solid-state amplifier, based on semiconductor technology, could result in a significant and beneficial change of the entire system. The latter serves as one of the four systems considered in this assessment.

- *Crossed-Field Amplifier.* This device in the term of an "amplitron, " was originally suggested for the reference system in place of the klystron (linear beam amplifier). Another form of this device, the magnetron, appears to have considerable merit, * particularly in reducing the spurious noise and harmonics generation of the microwave antenna. In smaller form (1 kW), this is the familiar unit that powers microwave ovens. The latter devices are reliable and cheap. Whether working devices of the 70-kW capacity needed for the reference system antenna will prove to be cost effective and possess the required signal characteristics must await design and testing, individually and in a phased array.
- Solid-State Devices. The principal motivation for considering solid-state devices" is their extremely high reliability;[17 18] projected failure rates are 100 times lower than those of the reference-system vacuum-tube klystrons or amplitrons.[19] A secondary advantage of solid-state devices is their potential for lower mass per unit area than the vacuum-tube devices. Further, their small size and potentially low unit cost facilitate convenient research and development activities.

The basic problem with solid-state devices is their low-temperature capability, which implies low power, coupled with their low-voltage output. Additional potential problem areas are uncertain efficiency, current high cost for high-performance units, and a host of as yet unresolved transmission, control, and power distribution complexities.[20] However, these devices are still in the early stages of being evaluated for the SPS application, and it is likely that studies of the extent devoted to vacuum-tube devices during the past few years can reduce the present uncertainties associated with sol id-state power conversion and transmission.

A major area for concern with the solid-state devices is the paucity of data and experience on phase control. Although the same generic type of retrodirective control is projected as for the reference system, much research, analysis, and technology advancement will be needed to define its phase control capabilities to the necessary level of confidence.

Photoklystrons

The photoklystron combines the principles of a conventional klystron transmitting tube and the photoemitter in a single device. Sunlight falling on a photoemissive surface generates a current of electrons oscillating in such a way as to emit radio frequency electromagnetic waves. If used on the SPS, the resultant microwaves could be beamed to Earth by using a resonator waveguide.

Potential advantages of the photoklystron over the photovoltaic array/klystron are that it could increase the useful portion of the photoelectric energy spectrum as compared with photovoltaics (it may reach efficiencies as high as 50 percent[21] as compared with 15 to 20 percent for conventional photovoltaics), and that it would greatly simplify the entire space segment of the SPS[22] as compared with the reference system, by (a) eliminating the solar cell arrays altogether, (b) eliminating the need for on board power distribution, (c) eliminating the rotary joint and sliprings, (d) reducing the individual klystron power and heat dissipation requirements (there would now be many more klystrons

*W C Brown, Microwave Beamed Power Technology Improvement PT-5613 JPL contract 955-104, May 1980

[17] G M Hanley et al , "Satellite Power Systems (SPS) Concept Definition Study, " First Performance Review, Rockwell International report No SSD79-0163, NASA MSFC contract NAS8-32475, Oct 10, 1979

[18] Gordon R Woodcock, "Solid-State Microwave Power Transmitter Review, " Boeing Aerospace Co DOE SPS Program Review, June 7, 1979

[19] Ibid

[20] Ibid

[21] Gibraeth and Billman, op cit

[22] John W Freeman, William B Colson and Sedgwick Simons, "New Methods for the Conversion of Solar Energy to R F and Laser Power, " in Space Manufacturing 1 I I,' Jerry Grey and Christine Krop (eds) AIAA, New York November 1979

distributed over a much larger area), thereby increasing the lifetime of individual klystrons, (e) reducing individual klystron cost, and (f) reducing rectenna area requirements, since the transmitting antenna is much larger than that of the reference system.

One suggested system (fig. 10) consists of a large elliptical array of photoklystrons, constituting the collector and antenna. A large mirror (that could also be a concentrator) would reflect sunlight to the photoklystrons. Note that even though the mirror and antenna must rotate with respect to each other to maintain proper Sun-facing and Earth-facing attitudes, as in the SPS reference system, there is no need for a mechanical connection between them; in fact, their relative alinement is not at all critical.

Small working models of photoklystrons exist, but have not yet demonstrated any of the system characteristics needed for a practical and cost- effective SPS. Hence the concept still remains just that: a highly interesting and promising prospect for further intensive study.

Offshore Rectennas

Because siting a rectenna near the coastal population centers that will have most of SPS-generated baseload electricity may prove extremely difficult, it has been suggested that rectennas be located in shallow offshore waters. * The costs of such siting would certainly be higher for a given area than for comparable land-based sites, but the system costs might be cheaper overall because of cost reductions in rectenna size. The considerable body of relevant experience that was developed for offshore airports would be useful for studying this possibility. The land areas that have been considered for offshore airports are comparable to the needs of SPS rectennas (e. g., 50 to 20 km^2).

It may be possible to reduce the necessary area of an offshore rectenna by eliminating most of the buffer zone and "flattening" the power distribution of the beam across the rectenna. Though potentially costly, the option may be taken very seriously by the European community for whom rectenna siting on land would prove most difficult. It may also find uses along the shores of densely populated areas in the United States.

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*Rice University, Solar Power Satellite Offshore Rectenna Study NASA CR 3348, November 1980