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Regional And Global Energy Transfer Via Passive Power Relay Satellites

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REGIONAL AND GLOBAL ENERGY TRANSFER
VIA PASSIVE POWER RELAY SATELLITES

by

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INTRODUCTION

The movement of energy is a basic requirement of our industrial
civilization. Therefore, power transmission is a component of the energy
confrontation concerning this country. It is an even more important
aspect of mankind's global energy future.

The reason for this is that the development of new power sources and
improvements in the distribution of conventional sources depend on the
extent to which energy can be moved freely from its primary source to the
load centers. There is no lack of energy in this country or on this planet,
if nuclear, solar, geothermal and other primary sources are taken into con-
sideration.

But it becomes increasingly desirable to remove nuclear and fossil power
plants from heavily populated or biologically sensitive areas and to utilize
geographically less conveniently located solar or geothermal energy sources.
Such developments require, or at least are facilitated by, the ability to
transfer energy economically and reliably over large distances, including
wilderness areas, large bodies of water or mountain ranges, at little or no
interference in, or threat to, the regional ecology.

The Power Relay Satellite offers interesting possibilities as a feasible,
Shuttle-compatible method of transferring energy over continental or global
distances. This method can be operational in the 1980s.

ENERGY TRANSFER

There are three major forms of moving energy: by electric transmission, in
material form (as chemical or nuclear material) and by electromagnetic
radiation.

In the existing fossil economy, energy is moved in chemical form over regional and global distances. Presently, nuclear material is shipped as natural or U-235 enriched uranium. In the longer run--that is, within the next 30 years or so--a growing portion of the nuclear material will be plutonium-239, extremely poisonous and a far more potent nuclear explosive than enriched uranium.

Electric power transmission is efficient and practical over about a thousand miles and is subject to constraints of terrain or large bodies of water. Limitations in electric transmission would make global or even hemispherical export of electric power unfeasible. Superconducting lines are limited as to the distances across undeveloped terrain or bodies of water because of the need for helium refrigeration. The presently existing transmission network, which represents an enormous capital investment, also contributes importantly to keeping fossil and nuclear power stations in *high-burden areas*--that is, areas in which the burden level on land, fresh water resources and air is already high owing to population density, industry and intensive agricultural cultivation.

A typical example is the distribution of existing and planned nuclear power plants in the United States (Fig. 1) (1). The distribution follows closely that of the major load centers. It would indeed be highly desirable if these *Primary Electric Power Plants* (PEPPs) with their *high burden quotient* (chemical, nuclear, thermal waste per kilowatt-hour) could be located in an otherwise less burdened environment and be replaced in high-burden areas by power plants of low burden quotient, hooked into the existing transmission system.

Such arrangement becomes feasible if the energy is transferred by electro-magnetic radiation, specifically by microwave beams, to be received by *Electromagnetic Power Plants* (EMPPs)--collector-converter stations whose burden quotient is extremely low[1]. The same stations can receive beamed energy from different sources. PEPPs will change in time from fossil to nuclear to solar or geothermal. Their location may change significantly.

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[1] Chemical waste/kwh = 0; nuclear waste/kwh = 0; thermal waste/kwh ~ 0.1 $kwh_{thermal}$/kwhe, or about one-sixth of that of a highly efficient PEPP.

As of Jan. 31, 1973

■ PLANTS IN
OPERATION: 29
KILOWATTS: 14,683,000

▲ PLANTS BEING
BUILT: 57
KILOWATTS: 50,125,000

● PLANTS
PLANNED: 76
KILOWATTS: 79,549,000

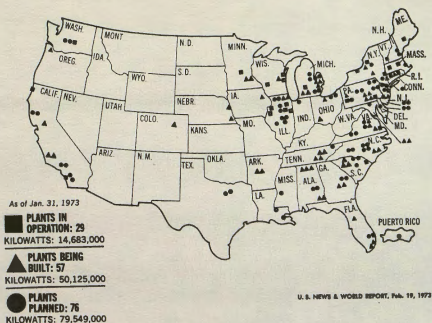U.S. NEWS & WORLD REPORT, Feb. 19, 1973

33MS21315

Fig. 1 America's Nuclear Power Plants

Still, the same EMPPs and their local distribution networks remain usable.

This is an important economic advantage of microwave beam transmission. Primary energy source and load centers are decoupled in the electric transmission network and can freely be recoupled without geographic constraints. by means of connectors in geosynchronous orbit--the *Power Relay Satellite* (PRS).

THE POWER RELAY SATELLITE CONCEPT

The Power Relay Satellite (PRS) concept is illustrated schematically in Fig. 2. Outlined briefly in an earlier publication (2), the concept is based on the premise that space technology can be used to move energy from one point of the globe to another. The basic principle is simple. A microwave reflector is placed into geosynchronous orbit to redirect energy beamed from a power generation system (power source) to a receiver at great distance from the power source. There the microwave energy is converted back to electricity for local distribution. The figure shows, highly schematically, the five principal components of the global power distribution

system. At left is the Primary Electric Power Plant (PEPP) consisting of
power station and microwave transmission facility. At transmission midpoint
is the PRS. At the right is the Electromagnetic Power Plant (EMPP), consist-
ing of microwave receiver facility and reconversion to electricity. The
transmission "line" is a microwave beam, the "distributor" is the reflecting
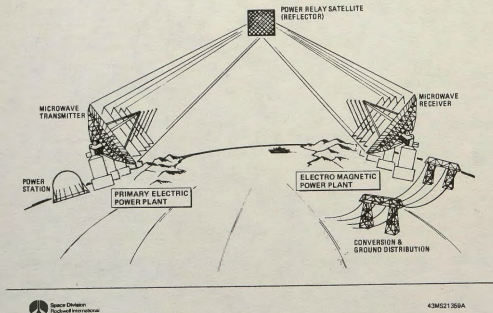PRS. The reconverted electricity is fed into the local ground distribution
system.

Fig. 2 Satellite Power Relay System (Schematic)

Figure 3 depicts the three main components--PEPP, PRS and EMPP--of the space
relay system and their major subsystems. The heavy arrows delineate the
energy flow.

As overall transmission efficiency η_T of the system we define the ratio of
electric power output of the EMPP to electric power input into the microwave
generator subsystem in the PEPP. Its value is determined by major efficiency
elements

$$\eta_T = \eta_{EM} \, \eta_{But} \, \eta_R \, \eta_{Bdt} \, \eta_{Aut} \, \eta_{Adt} \, \eta_{ME} \tag{1}$$

η_{EM} = efficiency of conversion from electricity to microwave power
   (MW power generation efficiency)

η_{But} = geometric beam transmission efficiency, up-transmission

η_R = efficiency of reflection at the PRS

η_{Bdt} = geometric beam transmission efficiency, down-transmission

η_A = atmospheric attenuation, up- and down-transmission

η_{ME} = efficiency of conversion from microwave power to electricity
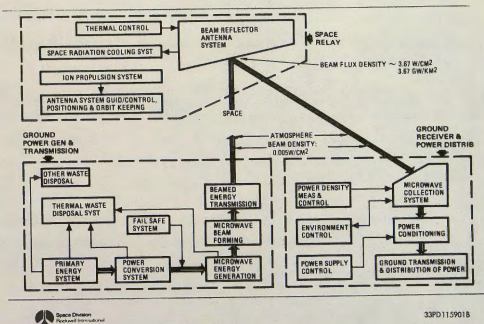   (collection and rectification efficiency)

Fig. 3 Space Power Relay for Global Distribution

Primary energy is converted first to dc-power, then to microwave power which is radiated from the transmitter antenna in the form of a highly directive beam. The beam is aimed at the PRS where it is reflected to the collectors of the EMPP and rectified, that is, reconverted to dc power. The collector-rectifier combination is also referred to as rectenna (3). The format of the transmitter antenna determines to a large degree the required operating power level of the microwave generators. Therefore, the transmitter antenna is discussed first.

THE TRANSMITTER ANTENNA

Because of large amounts of power involved, and the power flux density must be kept low for safety reasons, the beam area at transmitter level measures

many square kilometers. A single giant parabolic or cassegrainian antenna is therefore not practical. It is necessary to use a large number of smaller antennas as elements, combined to an array. The elements are driven by microwave generators. To generate the type of narrow beam required for power transmission, the antenna array must be highly directional; that is, it must be phase-coherent. This requires very accurate phase control to avoid beam scattering and associated scattering losses. Thus, phase control is important in the operation of an array, since the phase relation between the currents in the various elements determines the directional quality of the antenna. Coherence is obtained by using a continuously running oscillator as driver, feeding its output to amplifiers which, in turn, feed the output circuit of the array elements. If many microwave generators are used, each feeding their power into several elements, it follows, therefore, that these microwave generators must be the amplifiers, controlled from one central frequency source for phase coherence.

A suitable arrangement consists of an array of half-wave dipoles, straight half-wavelength antennas placed in rows with the current in each element having the same phase.

For very large antenna apertures, such as in the case of multi-gigawatt power transmission levels, the transmission efficiency of a phase-coherent microwave beam is, or approaches, 100 percent--i.e. all beam energy is received by the receiver. Radiation side lobes are very small. It has been shown by Goubau (4) that in this case, the power distribution across the beam--hence, across the face of transmitter and receiver--approaches Gaussian distribution.

In a Gaussian distribution, the power density p_ρ (power per unit area) at a distance ρ from the beam center follows the relationship

$$p_\rho = p_o \exp(-\rho/\rho_{63}) \qquad (2)$$

where p_o is the (peak) power at beam center and ρ_{63} is the radius of the beam within which 63 percent of the overall beam power is contained. This relationship applies equally to transmitter and receiver antennas. Therefore, the subscrips t and r are not required until dimensional differences enter into the consideration.

Integration of Eq. (1) between $\rho = 0$ and $\rho = \infty$ yields the overall beam power

$$P = P_0 \pi \rho_{63}^2 \tag{3}$$

Equations (2) and (3) are plotted in Fig. 4 out to 2.5 ρ_{63} from the beam center within which 99.8 percent of the overall beam power is contained.
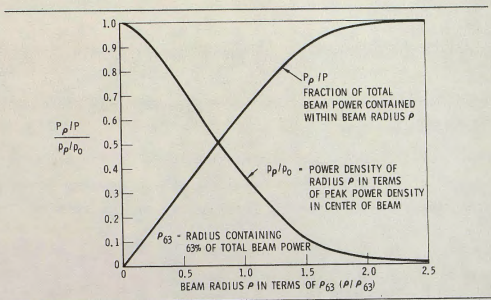
Fig. 4 Microwave Beam Power Profile Characteristics
at Gaussian Distribution

The power density contour p_ρ/p_0 corresponds to a beam transmission efficiency of 100 percent. A lesser efficiency flattens the power density contour. But for high efficiencies (≥ 90 percent), the deviation is small. For a given beam power P, the peak power density in the beam follows from Eq. (3),

$$P_0 = \frac{P}{\pi \rho_{63}^2} \tag{4}$$

Assuming an antenna radius, or side length in the case of a quadratic aperture of

$$\rho = 2.5 \; \rho_{63} \tag{5}$$

the peak power density can be expressed in terms of ρ

$$p_o = \frac{P}{0.16 \, \pi \, \rho^2} = 1.99 \, \frac{P}{\rho^2} \tag{6}$$

The value of p_o must be compatible with human and animal tolerances. In determining the safety limit for p_o, it must be kept in mind, however, that safety for long-term residence is not involved, but rather the safety of birds and people crossing the beam--where, in the latter case, it is perfectly feasible to follow flight routes that avoid the central region of the beam inside, say, ρ_{63}.

For high-efficiency ($\geq 90\%$) beam transmission, the Gaussian distribution applies to the beam at transmitter (t), PRS (s) and receiver (r), so that the respective areas are proportional to the square of their respective ρ_{63} values,

$$\frac{A_t}{A_s} = \left(\frac{\rho_{63t}}{\rho_{63s}}\right)^2 \; ; \; \frac{A_s}{A_r} = \left(\frac{\rho_{63s}}{\rho_{63t}}\right)^2 \tag{7}$$

It furthermore follows from Eq. (4)

$$\left(\frac{\rho_{63a}}{\rho_{63b}}\right)^2 = \frac{P_a}{P_b} \frac{P_{ob}}{P_{oa}} \tag{8}$$

where subscripts a and b may stand for t and s or for s and r. With (8), the area ratios can be expressed in terms of the particularly important peak power densities

$$\frac{A_a}{A_b} = \frac{P_a}{P_b} \frac{P_{ob}}{P_{oa}} \tag{9}$$

where the difference between P_b and P_a results from transmission losses.

In view of the Gaussian distribution, the power density is highest in the center and falls off rapidly toward the edges of the array. Thus, most of the microwave power must be fed into the central portion of the transmitter antenna. Microwave power generation is closely associated with the antenna design.

MICROWAVE POWER GENERATION

The technology of converting electricity to microwave power was advanced greatly with the development of crossed-field devices. They operate on the principle of electron motion in a crossed electric and magnetic field.

A rod-shaped cathode is surrounded by a cylindrical anode with a circuit of the desired radio frequency (rf). An electric field is generated by applying a potential. The negative terminal of the power supply is connected to the cathode. The positive terminal generates an rf wave in the anode circuit. The cathode emits electrons which tend to "fall" through the potential field, hitting the anode at great speed and heating it. The kinetic energy of the electrons equals the potential energy which, in turn, represents the electric energy fed into the generator.

To generate microwave power, the potential energy of the electrons at the cathode must not be converted to kinetic energy, but to energy of the rf field. This is accomplished by the use of a static magnetic field whose lines of force run parallel to the cathode, i.e. vertical to the direction of electron fall from cathode to anode. The magnetic field lines force the electrons into a curved path of motion between cathode and anode. At the proper potential of the electric field the speed of the orbiting electrons is such that their cyclic motion becomes synchronized with the rf wave in the anode circuit. The electrons begin to interact with the rf field and convert potential energy to rf field energy; that is, they convert electric to microwave energy of the desired frequency. As they lose potential energy, the electrons spiral outward, moving closer to the anode. Eventually they strike the anode, where their remaining energy is converted to heat.

The rf energy flows into the converter output and is radiated away by the antenna. The heat generated at the anode constitutes part of the energy loss at conversion and is carried away by cooling devices as waste heat. It

determines the electronic efficiency. Other elements of the overall converter efficiency are the rf circuit efficiency and electron back-bombardment losses--that is, losses due to electrons which return to the cathode because of path deflections caused by equal charge interactions in the electron flow.

Crossed-field technology provides converters of high efficiency and long life. One of these is the magnetron, the other the Amplitron (5,6,7,8). Both use the same conversion principles but differ in their anode structure and in the method of startup of the initial electron flow. The Amplitron combines the high efficiency, light weight and low operating voltage with the ability to amplify signals over a wide band of frequencies. The latter is not a very relevant virtue in a system that is strictly frequency controlled. However, the efficiency of the Amplitron circuit, which has an input and an output, is higher than that of the magnetron whose rf circuitry forms a resonant system (the circuit is closed in itself or re-entrant and therefore the magnetron needs only a signal input). Moreover, the Amplitron is an amplifier device and can handle a wider range of power levels. The magnetron is a self-oscillator.

Because, neither converter tube can handle the overall power levels involved, many tubes are required to feed an antenna array. Adequate phase control. requires high phase stability. Thus the generator must be an amplifier whose individual output frequencies must be very accurately adjusted with respect to each other and must not vary in time. These characteristics make the Amplitron particularly suitable for the transmission of large amounts of power via a multiple-fed antenna array (8).

Amplitrons presently have been tested at 3 gigahertz (Ghz) and between 200 and 400 kw (849 Amplitron) and in pulsed mode at 3 megawatt (Mw) (622 Amplitron). The electronic efficiencies of the 849 and the 622 Amplitrons were 84 and 80 percent, respectively; the overall conversion efficiencies 78 and 75 percent (8). As stated in (8), the microwave power generated per unit anode area (kw/cm^2) equals the heat dissipation density (thermal kilowatt, kw_{th}/cm^2) divided by $1-\eta$, where η is the overall conversion efficiency.

In terms of dissipation density, terrestrial converters--particularly in cold-sited PEPPs--have a significant advantage over space-based converters, because the cooling problem is comparatively simplified. Dissipation densities of up to 8 kw_{th}/cm^2 have been achieved (8). Assuming that this value can be doubled with further development, then, the Amplitron power generated is almost 107 kw/cm^2 at 85 percent overall conversion efficiency and 160 kw/cm^2 at 90 percent. Even at a dissipation density of 12 kw_{th}/km^2, the generated power is 80 and 120 kw/cm^2, respectively, at the above efficiencies.

The losses due to electron back-bombardment and circuit efficiency range from 6 to 9 percent (8). It is therefore, important to raise the electronic efficiency as high as possible. Values up to 95 percent have been reached with the RCA 8684 magnetron[1] at 915 Mhz frequency and 30 kw power level.

As pointed out in (8), the electronic efficiency depends on a parameter B/B_o, where B is the strength of the magnetic field and B_o is a parameter which is determined by frequency and the geometry of the cathode-anode interaction area. The larger B/B_o, the higher the electronic efficiency. A high value of B/B_o means a low value of B_o; and this, in turn, requires a high quality of the magnetic material in terms of its ability to accept coercive forces due to the field, and resist demagnetization. Also, since B_o increases with the operating frequency, a lower frequency reduces the demands on the quality of the magnetic material; hence, the cost. On the other hand, lower frequency requires larger antenna areas, so that here is a trade-off to consider for terrestrial installations. In order to achieve an overall conversion efficiency of 90 percent with an Amplitron whose non-electronic losses are about 5 to 6 percent, it is necessary to reach an electronic efficiency of at least 95 percent, or a B/B_o of at least 11. The highest value used so far is 10 (in the RCA 8684 magnetron). The values used in Amplitrons range from 4 to 8. The use of lower cost materials (ferrites and an aluminum-nickel-cobalt (alnico) alloy, in the order of decreasing quality) results in large magnets for high values of B/B_o. A superior alternative is a very costly platinum-cobalt alloy. In 1969, a rare earth alloy, samarium-cobalt was developed, the strongest known permanent magnet material, twice as

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[1] In terms of electronic efficiency, magnetron and Amplitron are closely comparable, since both are crossed-field devices.

strong as platinum-cobalt. Its cost is less than that of platinum-cobalt, because of the high cost of platinum. But, with a samarium price (1969) of $135 to 195 per pound of high-purity metal, the samarium-cobalt magnet is still much more costly than alnico or ferrites. For space applications, its use is mandatory because of extreme weight sensitivity. In terrestrial transmitters its use is no doubt desirable. But weight is not a driving factor on Earth. Moreover, perhaps slightly less than categorical emphasis on the last ounce of efficiency--an important consideration in space, to minimize cooling system weights--may be permissible if it has adequate cost advantages. These two factors provide a measure of trade-off latitude for an optimum cost-efficiency combination for terrestrial installations. This is true particularly for the Amplitrons in the outlying areas of the array where the power density is less (due to the Gaussian beam power distribution) and some reduction of efficiency may be acceptable in return for a sizeable reduction in installation cost. This question remains to be decided by more detailed studies which may include geographic location (cold sited nuclear PEPPs versus desert location of solar PEPPs) as an influence factor.

The operation of high-power Amplitrons in the non-vacuum terrestrial environment raises problems associated with the output window. It also increases surface erosion due to sputtering by unavoidable residual gases in the tube. These problems limit the maximum desirable power level of the Amplitrons used. On the other hand, the problem of low-weight heat dissipation in space limits the power level of Amplitrons of given efficiency in orbiting power plants. Thus, if a perhaps characteristic Amplitron power level of 800 kw is used in a terrestrial PEPP, a microwave antenna array radiating 12 GW_R requires 15,000 Amplitrons.

Each Amplitron feeds an array sub-module, containing a certain number of dipoles (4). Because of the Gaussian power distribution required for high beam transmission efficiency, these sub-modules are larger at the outsides, becoming smaller toward the center. In fact, depending on the power limitations of the Amplitron, the ratio may be down to one dipole per Amplitron in the central region of the antenna. The optimum sub-module distribution depends also on the increase of internal losses with panel size. This, in turn, determines the individual power level of the Amplitrons consistent

with the limiting power level. Thus, a given transmitter antenna array may look as indicated schematically in Fig. 5. Phase control must take the particulars of the antenna array arrangement into account.
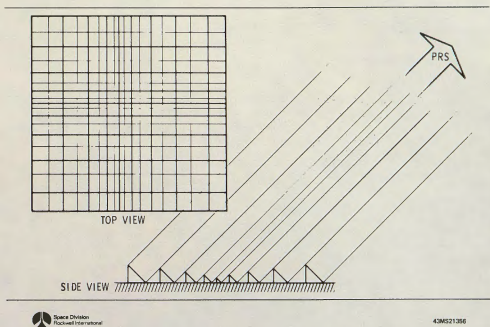

Fig. 5 Submodule Size Variation of an Antenna Array in
Frontal and Side View (Schematic)

MICROWAVE BEAM TRANSMISSION

If the transmitter antenna were an isotropic radiator, that is, would radiate in all directions, the energy would be dissipated in proportion to the square of the distance ("inverse square law"), as illustrated on top of Fig. 6.

In this case, the PRS would intercept only a tiny fraction of the original energy. The losses between transmitter and receiver would be prohibitive.

With parabolic antennae, that is, antennae of high directivity, the microwave beam may be focused to a spot smaller than the diameter of the transmitter antenna (Fig. 6, center). Thus, in the near field of the antenna, the beam can be made to converge. Beyond the focal plane, in the antenna's far field, the beam is divergent again. The near field is of little
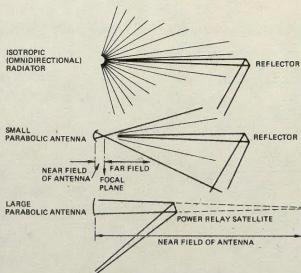
Fig. 6 Geometry of Power Relay Satellite Reflection

practical interest in present radar operations, because of its small extent
for conventional antenna apertures. Even for a 10-meter (33-ft) antenna
operated at a frequency of 3 Ghz, the near field extends only 2,000 meters
from the antenna aperture.

However, if very large apertures are used (Fig. 6, bottom), the near field
can extend far out into space—to geosynchronous orbit and beyond. The
directivity of the transmitter antenna determines the extent of the near
field in which the microwave beam can be focused by proper beam shaping.
The distance of the Fraunhofer region or focal zone separating the near
field from the far field is, in the first approximation, given by

$$R_F = \frac{2\,D_t^{\,2}}{\lambda} = \frac{8\,A_t}{\pi\,\lambda} = 2.547\,\frac{A_t}{\lambda} \tag{10}$$

where D_t and A_t are the effective diameter and area, respectively, of the
transmitter antenna, and λ is the wavelength.

In the Microwave Power Generation Section, the ratios between the various beam areas--hence, antenna areas--were given as function of power density or other parameters (Eqs. (7), (9)). The beam area at a given distance can be adjusted according to the maximum desired power density at beam center by controlling the degree of convergence of the beam. But there is a lower limit for the beam diameter, corresponding to the maximum focusing capability of the antenna. The beam diameter D_b in the near field of the transmitter antenna as function of range is given by

$$D_b = \frac{3\lambda R}{D_t} \tag{11}$$

The transmission distance R = 36,700 km is given by the distance of PRS in geosynchronous orbit from the PEPP[1]. The principal parameters are, therefore, λ and A_t.

The choice of wavelength is determined by atmospheric interference, by the effect of frequency choice on the existing user spectrum and, to a certain extent, by the effect of wavelength on the design and mass of the PRS. Minimal atmospheric interference is a particularly important requirement for two reasons. Power losses increase installation and operating costs; and a high degree of independence of variations in atmospheric humidity, clouds and rain are mandatory for assuring reliable power delivery to the receiver. It is also important that beam distortions by the ionosphere are minimized because of the long transmission path after the beam traverses the atmosphere on its way to the PRS.

The microwave beam traverses the lower atmosphere and the ionosphere on its outbound path and traverses it again in reverse order on the way back. At wave lengths larger than 5 cm, oxygen is the principal cause of gaseous transmission losses. Calculations of the transmission losses versus wave length for a dry atmosphere (9) are shown in Fig. 7 for PRS elevation angles of 90 degrees and 30 degrees, corresponding to a meridian position of the PRS for a PEPP located at the equator and at 60 degrees northern or southern latitude, respectively. At 10 cm wavelength and equatorial position, 99 percent of the beam energy reach the PRS; 60 degrees the efficiency is 98.1 percent.

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[1] Nominally, this is the distance measured from the equator. For a PEPP located at latitude θ, the distance is given by R = 36,700/cos θ (km).
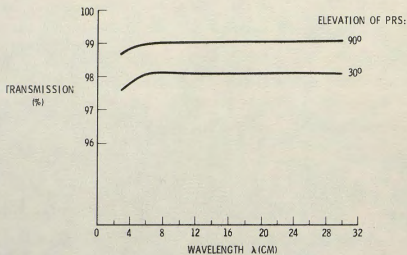
Fig. 7 Transmission Efficiency Through a Dry Atmosphere
from PEPP Location at Equator and 60 Degrees Latitude

Clouds and rain cause losses by absorption and scattering. Since drop
sizes in clouds are generally much smaller than the wavelengths under con-
sideration, absorption is the main cause of attenuation and the water con-
tent is more influential than the distribution of droplet sizes (9).
Moreover, attenuation from ice clouds is much smaller than from water
clouds--which is a bonus for PEPP locations at northern latitudes.

The greatest energy loss is caused by rain. Based on db-losses given in
(10), the calculated transmission efficiency versus wavelength is shown in
Fig. 8 for the given condition.

A precipitation rate of 50 mm/hour is very heavy and extends rarely over a
path length of 10 km. However, only under these severe conditions do the
beam losses at λ = 10 cm reach values of the order of 7 percent. At larger
wavelengths the losses vary less with precipitation rate. But, since
transmitter and receiver antenna areas increase with the square of the
wavelength, it is desirable to limit the wavelength as much as possible to
reduce land use and associated costs, particularly at the receiver terminal.
Moreover, ionospheric disturbances are reduced at smaller wavelength (see
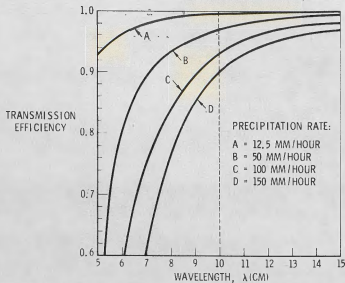below).

Fig. 8   Absorption and Scatter Losses Caused by Rain at Given
Precipitation Rate Averaged Over Beam Cross Section
At 10-Kilometer Path Length Through the Rain

When passing through the ionosphere, the beam is laterally displaced and
the polarization plane is rotated. Horizontal gradients in electron density
can cause a tilting of the phase fronts by a small angle adding to the beam
displacement. All effects are small, but tend to increase with the square
of the wavelength and with the slant angle (deviation of beam direction from
the vertical).

For transmission from orbit to Earth the ionospheric effects appear insig-
nificant. However, space relaying is more sensitive to ionospheric distur-
bances of the outbound beam, since their effect is magnified by the long
transmission path to the PRS and to the EMPP. The potential problem of
ionospheric disturbances is emphasized further by the fact that little is
known regarding irregular variations of the ionospheric electron content.
Here is an important problem area demanding further theoretical and experi-
mental investigations. It is possible that ionospheric effects impose
certain limitations on the beam path length through the ionosphere and there-
with on the highest acceptable latitude of the PEPPs.

Taking all factors into consideration, a frequency of 3 Ghz, or $\lambda = 10$ cm, appears at this time close to an optimum choice. Moreover, the 3-Ghz frequency—which can be controlled to an accuracy of a few khz and, therefore, does not cause a "pollution" of the microwave spectrum—is not heavily used, compared to lower and higher frequencies (there is a radio navigation band of 2.9 to 3.1 Ghz for ground-based radar). Communication satellites operate at higher frequencies. The selection of a 3 Ghz seems to interfere comparatively little with other users.

The size of the beam depends on the power density at given power level. The presently accepted safe power level for humans and animals is set at 10 milliwatts per square centimeter (mw/cm^2), although this value has recently been questioned, at least for prolonged exposure (see the section on Microwave Beam Safety Aspects).

Assuming a *mean effective power density* of 5 mw/cm^2, it follows that one square kilometer emits 50 Mw and a beam power of 12 Gw requires an area of 240 km^2 (15.49 x 15.49 km). Then, using $R = 3.67 \cdot 10^4$ km and $\lambda = 10^{-4}$ km, the beam diameter at geosynchronous distance follows from Eq. (11) to be 0.71 km or about 0.5 km^2. The corresponding average power density, using $P_s = 11$ Gw is 22 Gw/km^2 or 2,200 mw/cm^2. Adapting Goubau's analysis of the Gaussian beam, the transmitter antenna area can be computed from the rela-relation

$$A_t = \frac{2P}{P_o} \tau \qquad (12)$$

where τ is a quantity related to the geometry of the beam transmission efficiency (i.e. not counting atmospheric losses)

$$\tau = \frac{A_t \, A_s}{\lambda \, R} \qquad (13)$$

where A_t is the area of the beam at the PEPP transmitter aperture and A_s the area of the PRS. With $A_t = 240$ km^2 and $A_s = 0.5$ km^2, $\tau = 2.98$. For a quadratic aperture, $\lambda = 10$ cm and geometric beam transmission efficiencies of $\eta = 90$, 95 and 100 percent, the values of τ are 1.65, 1.95 and 2.72, respectively. Thus, taking the Gaussian distribution into account, it

appears safe to even reduce the size of the PRS to $0.5 (2.72/2.98)^2 \sim 0.4 \text{ km}^2$. For weight reasons—hence, also for cost reasons—it is desirable to make the PRS as small as practicable, consistent with thermal load limitations and phase control tolerances (including ionospheric effects).

If an area of $A_t = 240 \text{ km}^2$ is selected, on the basis of a mean effective power density of 5 mw/cm^2 (0.05 Gw/km^2), it is of interest to determine the associated maximum power level in the center of a Gaussian beam. This value follows from Eq. (12), using $\tau = 2.72$, to be $p_o = 0.272 \text{ Gw/km}^2 = 27.2 \text{ mw/cm}^2$. For 95 percent transmission efficiency, $p_o = 19.5 \text{ mw/cm}^2$. While these values are too high for prolonged exposure, there appears to be no evidence that it would harm birds crossing the beam. It follows from (3) that, for $p_o = 27.2 \text{ mw/cm}^2 = 0.272 \text{ Gw/km}^2$, $\rho_{63} = 3.74 \text{ km}$. For a quadratic aperture with a side of almost 7.5 km, this represents an inner beam shaft of 56 km^2 area. It follows from Fig. 4 that the central beam diameter in which the mean power density is approximately 95 percent of the maximum, is about 0.2 ρ_{63}, corresponding to a relatively small area of 5.6 km^2. At ρ_{63} the power density is down to 37 percent of maximum or 10 mw/cm^2.

The Gaussian beam area at PRS distance can be determined by the relation

$$A_{b,s} = 2\pi\tau \, \rho_s^{\,2} = \frac{(\lambda R)^2}{2} \, \frac{p_{o,t}}{P_s} \, \tau \tag{14}$$

where R and $p_{o,t}$ express the interconnection of the transmitter plane and the plane at R by the beam whose dimension is determined by $p_{o,t}$. Assuming a geometric beam transmission efficiency and atmospheric transmission efficiency combined of 5 percent, it follows that $P_s = 11.4 \text{ Gw}$. From this one finds with $P_{o,t} = 0.272 \text{ Gw/km}^2$ and $\tau = 2.72$, $A_{b,s} \approx 0.4 \text{ km}^2$. From Eq. (9) the maximum power density is found to be 570 times the maximum value at the transmitter aperture or $p_{o,s} = 155 \text{ Gw/km}^2 = 15,000 \text{ mw/cm}^2 = 155 \text{ kw/m}^2$.

Assuming again an overall transmission efficiency from PRS to EMPP yields a beam power of $P = 10.8 \text{ Gw}$. Using a maximum power density at the the receiver end of $p_{o,r} = 27 \text{ mw/cm}^2 = 0.27 \text{ Gw/km}^2$ and $\tau = 2.72$, the receiver area, according to Eq. (12), is $A_r = 218 \text{ km}^2$.

MICROWAVE BEAM SAFETY ASPECTS

Microwave radiation occurs in nature only at very low intensity levels. Microwaves can be absorbed by organic matter and constitute, therefore, a health hazard if radiation levels are too high and exposure too long. Prolonged exposure to 1000 mw/cm^2 can be lethal. The Bureau of Radiological Health of the Department of Health, Education and Welfare has evidence that power densities of 100 mw/cm^2 produce damage to the eyes in the form of cataracts. Experiments with small test animals exposed to 10 mw/cm^2 indicated the potential for disturbing testicular functions even at a relatively low level. Reliable human data on damage through cataract formation or otherwise are not yet available. The problem is, therefore, that at the present time a safe, generally agreed-upon upper limit of radiation density (power flux) cannot be defined. HEW has set new legal standards, effective January 1971, which reduced the allowable emission of new microwave ovens to 1 mw/cm^2 measured 5 cm from the oven's surface. Of course, these standards assume daily exposure over prolonged time periods. This is not true for the power beam. The outbound beam, in particular, generates no ground effects. So, most of the subsequent observations apply to the incoming beam.

The controlled power beam does not "pollute" the environment with microwave radiation, although it introduces radiation not otherwise present. The beam is rather comparable to a freeway or a power line--strictly controlled and defined. It is not comparable to an oil spill or an effluent spreading into water or air. Outside the beam and even at its periphery, in the outer 10 percent of the beam area, the power density is less than 1 percent of its peak value (Fig. 4). If the peak value in the beam's center is taken as 30 mw/cm^2 or less, the value in the outer 10 percent of the beam area--which, for an antenna of 220 km^2 (85 sq. mi) corresponds to a strip over 2000 feet wide--the power density is 0.3 mw/cm^2 or less. At the edge of the beam, the power density is 0.03 mw/cm^2 or less. Nobody has any business wandering around in the center of the beam any more than wandering on the freeway or doing gymnastics on power lines (maintenance personnel work in special protective enclosures).

Birds can cross a 30 mw/cm^2 beam center within minutes without harm. Certainly, no provisions (trees or otherwise), inviting them to light, linger or nest, will be provided inside a safe peripheral band.

Airplanes need not cross the beam. But if they do, it will have no consequences for the people in them, due to the protection afforded them by the plane's highly reflective metallic enclosure and the brief crossing time. In fact, the beam should be off-limits for aircraft. Crash landings in the receiver near the beam's center are undesirable for many reasons, including health of the survivors who may have to linger waiting to be rescued. But it would be harmless compared to hitting power lines. Beam deflections for any reason, causing the beam to drift away from the rectenna--which then loses power generation capability anyway--would immediately produce a signal to the transmitter via PRS and independent communication satellite back-up link. The signal would cause the transmitter antenna to disperse the beam by eliminating phase control. Thereby, any possibility of accidental irradiation of population centers would be avoided--even for brief and basically harmless irradiation periods.

THE POWER RELAY SATELLITE

If the outbound beam is converging, the beam reflected by a planar surface is converging also. This, of course, would be delightful from the standpoint of minimizing land purchases for the EMPP; but it would result in unacceptably high power densities. There are several ways to avoid this and cause the beam to be diverging to the desired power density. They are depicted in Fig. 9.
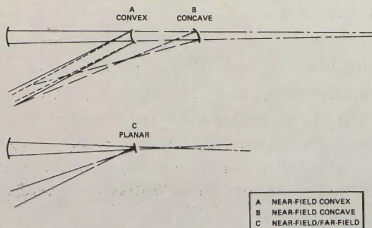

A	NEAR-FIELD CONVEX
B	NEAR-FIELD CONCAVE
C	NEAR-FIELD/FAR-FIELD

Fig. 9 Power Relay Satellite Arrangement For
Low-Power-Density At The Receiver

One relatively simple approach is to give the reflector a slightly convex shape (case A). Another possibility is to use a concave reflector with a short near field, reducing the flux density in the far field (case B). But in this case it might be simpler to reduce the distance of the focal area (case C). By this method, the same effect as in case B can be obtained with a more planar reflector of small size. However, since case C places the reflector closer to the beam's focal plane, thermal load limitations on the reflector structure due to power concentrations may reduce the maximum amount of energy per unit time transferrable by the beam. On the basis of simplicity, case A appears to be the most attractive alternative. The convex curvature is very small in view of the large distance involved. The radius of curvature is, in the first approximation, equal to the distance from focal plane (beyond the PRS) to the PRS. For $\lambda = 10$ cm and $D_t = 16$ km the distance of the Fraunhofer region from the transmitter aperture is $5.1 \cdot 10^6$ km. Since the distance of the PRS from the aperture is of the order of $0.037 \cdot 10^6$ km, the radius of curvature of the reflector is, in this case, of the order of $5.1 \cdot 10^6$ km. The reflector is almost a flat plate.

The PRS is envisioned as an interrupted-surface reflector. Reflection is provided by a wire mesh surface, stiffened by a light-weight rigid framework, thereby reducing the weight below that of a solid-sheet reflector. Figure 10 shows the transmission loss at the reflector as function of mesh size for a wire diameter of 0.1 cm and for two frequencies. The computation is based on a monograph developed by Mumford and presented in (11).

For a PRS weight estimate, a design point with a mesh size of 0.4 cm for 3 GHz and a basic design concept shown in Fig. 11 was assumed. The reflector consists of modules, each equipped with a deployment mechanism and a diagonal framework to pull the mesh membrane tight. The diagonal framework is somewhat heavier than a chessboard rectangular framework but was nevertheless chosen for reasons of better transportation in folded condition and easier mechanical unfolding in orbit, reducing the work of the erection crew.
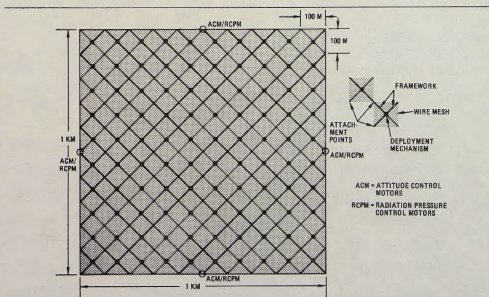
The modules can be connected to each other at the end points of their diagonal frames. Thus, a reflector of the desired size can be put together
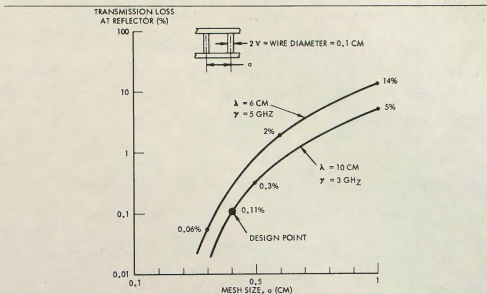
Fig. 10 Transmission Loss at Reflector Satellite vs. Mesh Size

Fig. 11 Power Relay Satellite Basic Design Concept

by attaching the required number of modules to each other. The frames are strong enough to provide the necessary overall stiffness.

Table 1 summarizes a first-order weight breakdown of a 1 km^2 PRS. The wire mesh is coated with a highly reflective deposit for thermal control and maximum microwave reflectivity. The first-order weights are conservative, since the system is not weight-optimized.

Table 1
FIRST-ORDER WEIGHT DATA OF 1 km^2 POWER RELAY SATELLITE

Wire Mesh

Mesh size	0.4 cm
Number of meshes per km^2	250,000 + 250,000 = 500,000
Equivalent length of each wire strand	1 km
Wire diameter	0.1 cm = 1 mm
Material	Chromel-R
Weight of wire knit	0.031 kp/m^2 = 0.0062 lb/ft^2
Weight with 20% contingency added	0.037 kp/m^2 = 37 tons/km^2

Frame

Length per module (100x100m)	283 m
Length per km^2 (100 modules)	28,200 m
Material	Aluminum tubes (0.5 kp/m)
Frame weight	14.2 tons 15 tons
Deployment mechanism and misc.	0.8 tons
Weight with 20% contingency added	18 tons
Attitude control system and propulsion	5 tons

Overall weight = 37 + 18 + 5 = 60 tons/km^2

The PRS does not have to be both Earth- and Sun-oriented, as must solar reflectors and solar (thermal or photovoltaic) orbital power stations. The PRS is exclusively Earth-oriented. This simplifies positioning requirements and the associated dynamic control. However, the impingement of a Gaussian beam generates the possibility of dynamic interactions between PRS and microwave beam (see the section, A Satellite Power Relay Reference System) not present in a uniformly illuminated structure, because of non-uniform radiation pressure distribution.

Radiation pressure, p_r, on a reflecting surface is given by the relation

$$p_r = (1+\rho) \frac{R*}{c} \cos^2 \alpha (\text{force/length}^2) \tag{15}$$

where ρ is the reflectivity, $R*$ the radiation constant, c the velocity of light and α the angle between incident ray and normal to the irradiated plane. With $\rho \sim 1.0$ and $\alpha \sim 0°$, p_r reaches its maximum value.

With a space solar constant of 1.35 kw/m^2 = 137.7 mkp/m^{2}s, the solar radiation pressure at vertical incidence on a 100-percent reflective solid surface is 0.9 kp/km^2 (5.14 lb/sq. mi.). For the PRS of above described mesh size, the maximum solar pressure is less than one third of this amount, about 0.29 kp/km^2 (1.49 lb/sq. mi).

The principal radiation pressure is exerted on the PRS by microwave beam reflection. Referring back to the 12 Gw beam at transmitter aperture (see section on Microwave Beam Transmission) and assuming an overall beam transmission efficiency of 0.95, the beam power at the PRS is 11.4 Gw. At a PRS area of 0.4 km^2, this corresponds to a mean effective power density of 26 Gw/km^2 = 26 kw/m^2 = 2.6 w/cm^2 = 19.2 solar constants. The maximum radiation pressure ($\rho = 1.0$; $\alpha = 0°$) is, therefore, 17.3 kp/km^2 (9.87 lb/sq. mi).

This pressure would exert a radially outward directed force vector on the PRS. To neutralize this pressure, it is necessary to generate an opposing thrust force of equal magnitude--that is, 17.3 kp/km^2. An electric thruster system of this performance and a specific impulse of 6400 sec consumes 85 t/km^{2}yr (t = metric ton). For the PRS size of 0.4 km^2 this amounts to 34 t or 75,000 lb annually. The exhaust jet power corresponds to 5.3 Mwj/km^2. At 90 percent conversion efficiency from electric power input to jet power output, the electric power requirement is 5.9 Mwe/km^2 or, for a PRS of 0.4 km^2, about 2.4 Mwe--about 0.02 percent of the 11.4 Gw impinging on the PRS. The electric radiation pressure compensation thrust system can, therefore, be powered by electric energy drawn from the beam without causing significant power transmission losses.

MICROWAVE RECEPTION AND RECONVERSION

The heart of the electromagnetic power plant (EMPP) is the receiver
antenna (collector) and microwave–dc conversion system. W. C. Brown has
shown that a combination of half-wave dipole antenna elements and solid-
state diodes offers presently the highest promise (12,13,14). The collec-
tor system can be designed to offer a high degree of insensitivity to the
direction of the incoming beam and to beam amplitude and phase coherence
distortions suffered by the beam's traverse through the ionosphere.

This has several important advantages. The first and most obvious one is
to harden the power transmission process against diurnal, seasonal and
solar-activity related variations in ionospheric electron densities. The
second advantage is that directional insensitivity reduces the selectivity
requirements for the real estate on which the rectenna can be located--such
as degree of flatness, sloping, etc.--thereby presumably permitting the use
of less valuable real estate. The third, and by no means least advantage,
also a consequence of low directional sensitivity, is that the EMPP can
receive power from Power Relay Satellites stationed at different
points of the geosynchronous orbit.

Each antenna element is attached to a solid-state diode rectifier whose dc-
current output is fed into a common load. This radiation collection and
power conversion by thousands of antenna-diode elements reduces the
rectenna's sensitivity to damage.

The rectenna is presently the comparatively least advanced link in the
transmission chain. Brown points out that the measured efficiency of indi-
vidual rectenna half-wave dipole elements, each with a rectifier attached
to it, is 70 percent. The efficiency of multiple element rectenna arrays
is given by Brown as presently only 50 to 55 percent. However, improve-
ments due to intensified development work over several years are expected
to raise the efficiency of large rectennas in the 3 Ghz regime to 85 percent.

A SATELLITE POWER RELAY REFERENCE SYSTEM

Based on the discussion in the preceding sections, the data for a design
point reference system can be summarized. The system is depicted in
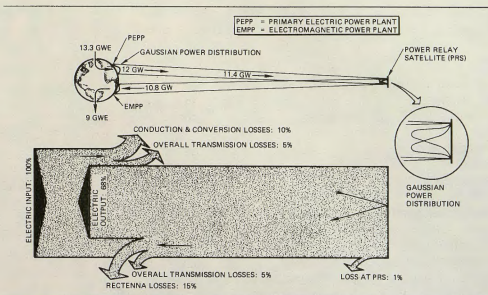Fig. 10.

Fig. 10 A Satellite Power Relay System

First-order values for the efficiency contained in Eq. (1) can be assumed to be as follows:

EM power generation efficiency: $\eta_{EM} = 0.9$

Overall beam up-transmission efficiency: $\eta_{But} \, \eta_{Aut} = 0.95$

Reflection efficiency: $\eta_R = 0.99$ (reflectivity: 0.995)

Overall beam down-transmission efficiency: $\eta_{Bdt} \, \eta_{Adt} = 0.95$

Collection and reconversion efficiency: $\eta_{ME} = 0.85$

Therewith the overall transmission efficiency is of the order of $\eta_T = 0.68$. Not counting the collection and reconversion efficiency, the transmission efficiency is 0.8. Improving the rectenna efficiency is, therefore, of particular significance. An additional 5 percent improvement to 90 percent would raise the overall efficiency by 4 percent to 72 percent.

On the basis of these efficiencies, Table 2 summarizes the data of the preceding sections for a relay system delivering 9 Gwe at the bus bar of the EMPP. The table points out two additional areas for future investigations not previously mentioned. Both are associated with the PRS. One is the thermal load. The other concerns the effect of Gaussian power distribution in the beam on the PRS dynamics.

Table 2

REFERENCE SYSTEM DATA FOR A POWER RELAY
SATELLITE SYSTEM TRANSMITTING 9 Gwe

PRIMARY ELECTRIC POWER PLANT (PEPP)

ELECTRIC POWER OUTPUT	13.3 GWE
MICROWAVE POWER GENERATION EFFICIENCY	90%
MICROWAVE	3 GHZ; λ = 10 CM
ONE-WAY TRANSMISSION DISTANCE	36,700 KM
TRANSMITTER POWER	12GW
AREA OF TRANSMITTER ARRAY	240KM^2 (15.49 X 15.49KM) (93 SQ. MI.)
POWER DISTRIBUTION	GAUSSIAN
MEAN EFFECTIVE POWER DENSITY	5MW/CM^2
POWER DENSITY AT BEAM CENTER	p_0 = 27.2 MILLIWATT/CM^2 (MW/CM^2)
BEAM CORE AREA WITH POWER DENSITY $\geq 0.94\, p_0$	5.6KM^2
BEAM CORE CONTAINING 63% OF BEAM POWER	56KM^2 (ρ_{63} = 3.74KM)
POWER DENSITY AT DISTANCE ρ_{63} FROM BEAM CENTER	10MW/CM^2
POWER DENSITY AT PERIPHERY OF ANTENNA ARRAY	0.052MW/CM^2

POWER RELAY SATELLITE (PRS)

OVERALL BEAM TRANSMISSION EFFICIENCY PEPP TO PRS	95%
BEAM POWER IMPINGING ON PRS	11.4 GW
PRS AREA	0.4KM^2 (0.632 X 0.632KM) (4.3·10^6 FT^2)
MEAN EFFECTIVE POWER DENSITY	2.6W/CM^2 = 26KW/M^2
POWER DENSITY AT BEAM CENTER	15,500MW/CM^2 = 155KW/M^2
BEAM CORE CONTAINING 63% OF BEAM POWER	0.094KM^2 (ρ_{63} = 0.153KM)
REFLECTION EFFICIENCY	99 %
POWER DISSIPATION REQUIREMENT FROM PRS	11,400KW
STRUCTURAL WEIGHT OF REFLECTOR	24 TONS
OVERALL WEIGHT OF REFLECTOR	26 TO 28 TONS (NOT INCL CONSUMABLES)

ELECTROMAGNETIC POWER PLANT (EMPP)

OVERALL BEAM TRANSMISSION EFFICIENCY PRS TO EMPP	95%
BEAM POWER IMPINGING ON RECTENNA	10.8 GW
RECTENNA AREA	218KM^2 (14.76 X 14.76KM) (84 SQ MI)
MEAN EFFECTIVE POWER DENSITY	5MW/CM^2 = 0.05KW/M^2
POWER DENSITY AT BEAM CENTER	27.2MW/CM^2 = 0.272KW/M^2
BEAM CORE CONTAINING 63% OF BEAM POWER	50.4KM^2 (ρ_{63} = 3.55KM)
RECTENNA CONVERSION EFFICIENCY	85%
ELECTRIC POWER OUTPUT	9 GWE
LOCAL WASTE HEAT RELEASE	2 MILLION THERMAL KW (KW$_{TH}$)
LOCAL CHEMICAL POLLUTION	NONE
LOCAL RADIOACTIVE MATERIAL HANDLING	NONE
LOCAL WASTE HEAT FROM FOSSIL POWER PLANTS[1]	13 TO 16 MILLION KW$_{TH}$
LOCAL WASTE HEAT FROM NUCLEAR POWER PLANTS[1]	14 TO 19 MILLION KW$_{TH}$

[1] For comparison purposes, assuming a set of fossil or nuclear power
plants generating 10 Gwe.

Of the assumed overall power loss of 1 percent at the PRS, 0.5 percent or 57,000 kw is estimated to be converted to thermal energy in the structure. The thermal load is highest in the center of the PRS. In the area containing 63 percent of the beam power, 63 percent of 57,000 kw or about 36,000 kw must be dissipated. This area has a size of 0.094 km^2 or 94,000 m^2. The thermal load is, therefore, 0.38 kw/m^2 or about 28 percent of the space solar constant (1.35 kw/m^2). This suggests that the thermal load should not represent a significant problem. However, the overall beam energy is so high that a reduction in reflectivity can readily escalate the thermal load to a critical level.

Therefore, it is necessary to maximize the satellite's microwave albedo at the selected frequency. The durability of the reflectivity (especially of coatings) must be established. The durability of the coating may be affected by the intensity of the microwave beam. If so, power density, i.e. beam concentration and PRS size must be traded off against durability of the coating. Other factors that could, in time, degrade the albedo include solar wind and ultraviolet radiation as far as coatings are concerned. Structural damage caused by meteorites could lead to local distortions resulting in local hot spots which, in turn, could cause further damage.

Due to the Gaussian power profile, 63 percent of the beam power—hence, 63 percent of the microwave radiation pressure—are exerted on about 24 percent of the area. In other words, the 63 percent core of the beam exerts an almost three times larger radiation pressure on the area it illuminates than does the rest of the beam. Eccentric impingement, therefore, causes a moment, disturbing the attitude of the PRS. This possibility emphasizes the need for high beam pointing accuracy, for coupling beam and PRS so that the beam follows slight drifts of the PRS, and for sensitive and fast responding attitude control.

These and other potential problems are recognized. They are emphasized here in an attempt to present a balanced appraisal of the pros and cons of the PRS concept, as well as of space power generation alternatives (see Section The Shuttle Compatibility of Space Relaying and its Comparison with Space Power Generation). All of the above mentioned problems can be avoided by proper identification and engineering approaches, resulting in the optimum compromise of size, mass, reliability, durability and safety of operation.

As Table 2 shows, the mean effective power density of the microwave beam illuminating the rectenna is 0.05 kw/m^2. At a 90-percent load factor, this means the energy transmitted annually is about 395 Gwh/km^2. At 85 percent conversion efficiency, the electric energy production is 336 Gwhe/km^{2}yr. From the global map of solar radiation energy distribution shown in the Energy Sources and Primary Electric Power Plants (PEPPs) in the United States section (Fig. 15), it follows that high-insolation areas are offered about 2000 Gw/km^{2}yr in the form of solar radiation energy. At a representative value of 25 percent solar power plant conversion efficiency, the electric energy production is 500 Gwhe/km^{2}yr.

Thus, the energy productivity per unit area of the rectenna is 67 percent of that of a solar power plant. The EMPP area is not considerably larger than the area required for a solar power plant, as one might be led to believe on the basis of the beam's mean effective power density which is only 5 percent of the nominal terrestrial solar constant of 1 kw/m^2. The reasons are, of course, the diurnal irradiation of the EMPP and the much higher conversion efficiency to electricity from microwave radiation than from solar radiation.

In turn for the somewhat larger area requirement, the EMPP offers greater flexibility of siting, rather independently of climatic conditions.

ENERGY SOURCES AND PRIMARY ELECTRIC POWER PLANTS (PEPPs) IN THE
IN THE UNITED STATES

A wide variety of primary energy sources can be taken into consideration. PEPPs can be located so as to better meet demographic, ecological and environmental compatibility criteria.

Starting at home, our country is rich in fossil and non-fossil primary energy resources, and in land. In spite of large population and extensive industrialization, the United States still has at its disposal low-burden areas of larger size than the entire territory occupied by many sizeable nations. Through the Power Relay Satellite, the Space Shuttle and space technology in general, both can become valuable assets--within the relatively short time span of 15 years--contributing to higher quality of life and improving the nation's posture on the international energy market. This country has the capital, technological know-how and industrial capabilities to begin using its assets in this manner by about 1985.

Because of the transparency of the atmosphere to microwaves in the S-band, geographic latitude is not a significant criterion in locating PEPPs in the United States. However, air humidity and particulate content can have some effect. Among all atmospheric constituents, these are relatively most effective in absorbing or scattering microwave energy--although even they generate transmission losses only in the order of a few percent of the beam's power flux. Figure 11 suggests that the far Middlewest and large parts of the West are preferred regions in terms of low-humidity.

□ AVERAGE ANNUAL TEMPERATURES BELOW 40°F

▨ SEMI-ARID (STEPPE)

■ ARID (DESERT)

Space Division
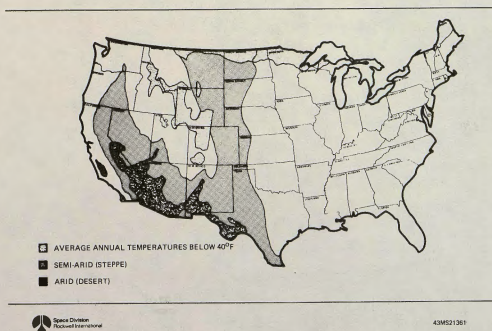Rockwell International   43M521361

Fig. 11 Dry Regions and Low Temperature Areas

The same is true as far as precipitation is concerned. Due to a low level of industrialization, the air over these regions is also rather free of atmospheric particles.

Additional undesirable weather conditions include tornadoes and thunderstorms. Figures 12 and 13 show that, again, the western parts of the country show preferable conditions.
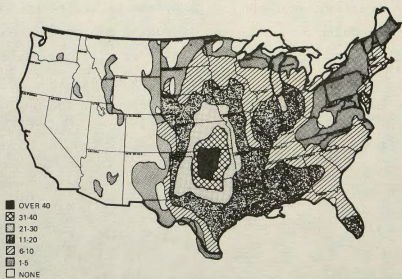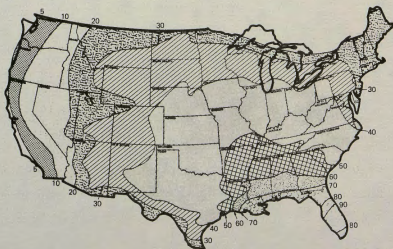
Fig. 12 Number of Tornado Days per Year Over Equal Areas

Fig. 13 Average Number of Thunderstorms per Year

Thus, it is fortuitous that meteorological criteria clearly favor location of PEPPs in the Central and Western United States where, generally, land is in greater supply. The bulk of the non-fossil non-nuclear energy resources is also located in the Central and Western U.S.

The *nation's solar energy resources* are concentrated in the southwest, with an average number of more than 220 clear days (Fig. 7).

■ MORE THAN 220 DAYS
▧ 180–220
▨ 140–180
□ < 180
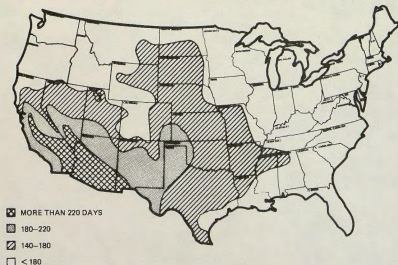
Space Division
Rockwell International   43MS21364

Fig. 14 Average Annual Number of Clear Days

In this region, the average annual insolation energy ranges from 1.9 to 2.3 terawatt-hours per km^2 (4.9 to 5.9 Twh/mi^2)[1]. The solar thermal energy input offered to a high-insolation area at 1,900 Gwh/km^2yr corresponds to a mean effective solar power influx of 0.433 Gw/km^2 based on an average daylight period of 12 hours per day, hence, on a nominal number of 4,380 sunshine hours per year. At 25 percent conversion efficiency to electricity, the mean effective power generating capacity is 0.018 Gwe/km^2 or 9.2 km^2/Gwe (3.6 mi^2/Gwe)[2]. The attainment of high-conversion efficiency (20–30 percent) is of decisive importance. Subsequently, a goal of 25 percent is assumed.

_____
[1] 1 Twh = 1000 Gwh = 10^6 kwh

[2] For a day/night generating capacity of 1 Gwe, twice this area is required. However, the U.S. annual electric energy consumption is 53% of the available generating capacity. Therefore, 1.06 or ~ 1.1 times the area per Gwe provides the annual Gwhe quantity corresponding to the diurnal generating capacity of 1.1 Gwe or 9.2·1.1 ~ 10.1 km^2. The actual area required for all installations is about 1.5 km^2.

5-47

The combination of thermal power plant and transmitter antenna array· in a
solar PEPP has complementary qualitites, as far as the local thermal
balance is concerned. The absorptivity of the power plant collectors is
obviously very high--usually far higher than that of the desert ground.
The large collector area is almost "black". Although, at 25 percent elec-
tric conversion efficiency, 75 percent of the absorbed solar heat is
returned to the local environment (unless part of it is chemically absorbed
in secondary processes) these 75 percent are released from the power plants
in far more concentrated form than they were collected. This does create a
certain local thermal imbalance. The antenna surface, on the other hand,
can be made more reflective than the desert ground. Its high reflectivity
counteracts the higher absorptivity of the solar collectors. Under the
before mentioned assumptions, the electric power-specific area requirement
is 9.2 km^2/Gwe, or some 10 km^2 per Gw transmitter beam power. At a mean
effective power density of 5 mw/cm^2 it takes 20 km^2 of antenna area per Gw
transmitter beam power. Thus, by raising the reflectivity of the antenna
array no more than 50 percent above that of the desert soil, the low
albedo of the solar collectors can be balanced microclimatically.
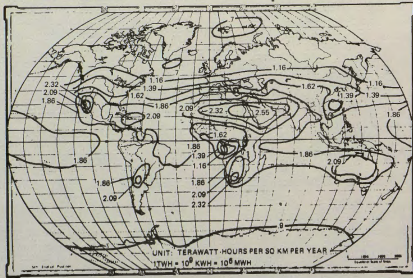
Fig. 15 Average Annual Solar Radiation Energy
on a Horizontal Surface at the Ground

The nation's Southwest includes some of the Earth's maximum-insolation
regions, as can be seen from Fig. 15 which is based on data given in (15).
Its western parts cover earthquake-prone territory. But most of the

available solar energy can be collected in Arizona and New Mexico. The desert area west of Phoenix alone covers some 70,000 km^2 (27,000 sq. mi). Taking the required U.S. annual electric energy consumption in 2000 as 2,000 Gwe, that of the rest of the Western hemisphere as 1,000 Gwe (a much higher consumption in relation to the U.S. than today), 18,400 km^2 (7,400 sq.mi) would satisfy the needs of the United States, 9,200 km^2 (3,700 sq.mi) would meet the needs of the other parts of the Western hemisphere. Thus, 26.3 and 39.5 percent of the desert area west of Phoenix could meet the electric energy needs of the U.S. and the entire Western hemisphere, respectively, in the year 2000.

It may not be practical--and it is not suggested at this point--to cover such a large portion of this particular area. But this area is only a small fraction of the overall usable territory in the Southwest. The above figures illustrate the great solar energy wealth of this country.

This energy can be utilized far more economically than solar energy in space, in spite of the diurnal variations in the operation of a terrestrial solar power plant. Also, many load centers in the U.S.--especially those in the Southwest and on the West Coast--can be supplied more economically by ground transmission than via PRS. On the other hand, for export of power to Central and South America, or to Africa, space relaying is clearly superior to ground transmission.

The supply of the big Eastern and Northeastern load centers represents an intermediate case, and the relative superiority of cryogenic ground trans- mission versus space transmission may depend on whether or not a PRS system or an adequate helium refrigeration system for such large transmission dis- tances is developed. If energy is being exported at the time, at least a partial supply of the distant load centers via PRS will be economically competitive.

Generally, the economic superiority of one method over the other at a cer- tain time in the future depends on the amount of capital invested into the alternatives over the intervening years--provided the alternatives require reasonably comparable investments. The worthwhileness of concentrating the bulk of the available investment capital on the one or other alternative depends on--or at least should be strongly influenced by--the respective

economic potential, the growth potential and the "lastingness" (including
socio-ecologic interference). The PRS system offers a unique potential
for energy export. It offers a considerable growth potential, in terms
of the capability of increasing the amount of energy transferred, and in
terms of ultimate growth to power generation in orbit. It offers lasting-
ness because of its low socio-ecological interference factor and the effec-
tiveness with which it eventually can connect the desert areas of the globe
to mankind's growing load centers.

The *nation's natural geothermal resources*[1] are scattered through
California, Nevada, Oregon, Utah, Colorado, Idaho, Arizona and New Mexico.
A National Science Foundation report estimates that by 1985, geothermal
resources in the U.S. have the potential of supplying 132 Gwe (more than
one-third of the 1970 U.S. power generating capacity) and by the year 2000
could provide 395 Gwe (slightly more than one-sixth of the projected
capacity needed).

There is also evidence that *winds* are a *potential energy source* of not
insignificant magnitude.

14 MPH
12 MPH
10 MPH
8 MPH
<8 MPH

Space Division
Rockwell International   43M521365
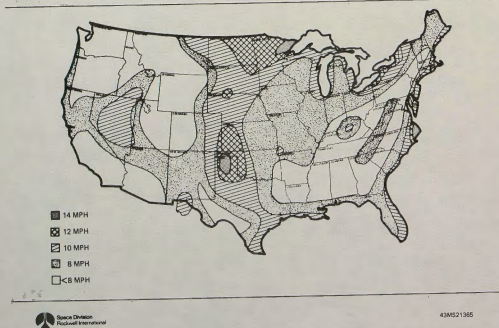
Fig. 16 Average Surface Wind Velocities in High-Wind Regions

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[1] The term "natural" is used here to designate the location of geothermal
sources at lesser depth than corresponding to the average thermal
gradient.

Figure 16 points again at the middle western, northwestern and western regions as the primary sources of wind energy.

Wind, like solar radiation, is a diffuse and variable energy source. Large-scale utilization requires, therefore, more area coverage than the use of other energy sources with the exception of solar power plants, and must cope with intensity variations. It may be feasible to plant wind mills between the transmitter antenna facets, thereby improving the utilization of the land area needed by the PEPP. In contrast to the predictability of the diurnal cycle of solar energy input, the variations in wind energy are more erratic, reducing the reliability of wind power plants below that of any other power generating system. It is, of course, possible to store excess electric energy chemically during high-wind periods, as in large solar power plants, where energy must be stored chemically to provide power around the clock and on cloudy days.

It may be more economical, however, to combine a wind PEPP with a fossil energy PEPP—preferably an oilplex or coalplex plant, generating and using clean fuel gas. Fuel gas production is kept steady, but consumption varies to complement wind power generation. During periods of high winds, the excess fuel gas is stored for later use or sold. As complementary energy source, the wind power could contribute to the conservation of our indigenous fossil resources. Both systems feed the same transmitter antenna array. Because of the freedom in the placement of PEPPs, the location of the combined system could be so chosen that the effectiveness of wind power utilization is maximized.

Desirable sites for *nuclear power plants* are characterized by safe remoteness from high-burden regions—regardless of whether the burden elements are population, industry, intensive agriculture or a combination of these. Significant additional desirable conditions are ample water supplies and a cold climate, because in a cold climate the complex can be ecologically comparatively more effectively isolated, through the use of a recirculating cooling system using cooling towers and cooling ponds, than in warmer regions.

In cold regions, the water is cooled more extensively by "dry" heat transfer (convection and conduction) than by evaporation—that is, the cooling cycle

operates at lower temperature levels. The make-up water requirement is reduced. The cooling system is more nearly a closed one. Less water vapor is released into the environment. More thermal energy is transferred directly into the cold air where it is distributed in the fastest possible way. Whether or not these individual effects are significant, at least they all act in the direction of minimizing the system's intervention in the ecological pattern of the area in which it is placed. In cold climate, the isolation of nuclear power plants from the cyclic bio-environment can be reduced compared to an identical system in a warmer climate.

Population distribution, low average annual temperatures (Fig. 11) and generally low environmental burden levels suggest the northern parts of Montana and North Dakota as meeting the before-mentioned placement criteria more completely than other areas in the continental United States.[1] Water could be available from fresh water lakes on both sides of the U.S.-Canadian border--at least sufficient to support a recycling cooling system.

Therefore, large, integrated nuclear power complexes might be located in these areas. They are large, in order to reduce the capital cost per kilo-watt generating power. They are integrated in the sense that they are made as self-sufficient as possible, including fuel processing and radioactive waste storage. In the case of breeder reactors, the complex includes fuel reprocessing and Pu-239 extraction plants, as well as Pu-239 and radioactive isotope storage facilities, near the power plants. Thereby the transporta-tion of the extremely toxic plutonium over highways and through populated territories is avoided. By storing the plutonium at the more easily con-trolled remote sites--in "plutonium Ft. Knox" storage facilities--the danger of theft and misuse of Pu-239 can be greatly reduced or practically eliminated, using modern control and fail-safe methods as developed for nuclear missile sites. Radioactive waste storage facilities should be included where possible. The waste is a mixture of various radioactive substances whose rate of decay is porportional to $t^{-1.2}$. In other words, after 5 years of storage, the radioactivity of the waste is reduced to 14.6 percent of its original level. This remaining one-seventh of the original amount may be considered for removal from Earth via Shuttle and

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[1] Alaska may not be suitable, as it is an earthquake-prone region, with the possible exception of eastern and northeastern Alaska.

and orbit-launched toward Jupiter to be removed from the solar system via Jupiter gravity assist. This is the least expensive and most Shuttle-compatible method of long-term radioactive waste disposal (16).

Thereby, it is economically possible and environmentally more compatible to utilize, on a large scale, Nuclear Energy through Space Transmission (NEST). Each NEST unit is remotely sited, transpace relayed, integrated nuclear power complex. An example of such a NEST complex is shown in Fig. 17.

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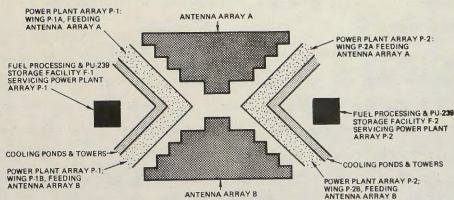
Fig. 17 Remote Sited Transpace Relayed Integrated
Nuclear Power Complex (NEST)

The arrangement is shown in the form of a butterfly pattern. The princi-pal functional components are the:

o Breeder Power Plant Arrays (BPPA)

o Cooling Pond and Tower Arrays (CPTA)

o Microwave Antenna Arrays (MAA)

o Fuel Processing and Pu-239 Storage Facilities (FPSF).

The BPPAs are arranged in two angular strips. The power level of the breeders depends on the overall generating capacity of the NEST complex. Remote siting and transpace relaying encourage large generating capacity for economic reasons--in the order of 100 to 250 Gwe per NEST complex.

Using breeder power plants with 2 Gwe output power each, the two BPPAs contain 50 to 100 plants. The cooling water is circulated through arrays of cooling ponds and/or towers arranged alongside the BPPAs.

The power plants feed their electric output into two microwave antenna arrays. Each MAA consists of a number of phase and amplitude controlled microwaves antenna array modules (MAAM). Each MAAM illuminates a given Power Relay Satellite (PRS) and is, therefore, compatible with its size. If the individual PRS is standardized according to the specifications presented in the section, A Satellite Power Relay Reference System, a nuclear complex driving 20 MAAMs would have the characteristic data summarized in Table 3.

This table compares the ground components of a nuclear PEPP based and a solar PEPP based large space transmission system employing 20 Power Relay Satellites. The energy moved by each of these PEPPs alone corresponds to the electric energy that can be gained from over 2 billion barrels of oil annually. The table shows that the unrivalled flexibility of space transmission must be paid for in comparatively high land requirement. This fact emphasizes, not surprisingly, the continental and global character of the space transmission system. In judging the land requirement, it must be kept in mind, however, that the very character of the space transmission system makes it possible to use low-cost, as well as environmentally low-burdened land tracts—certainly for the PEPP. It is functionally impossible not to locate the EMPP reasonably close to load centers and therefore on somewhat more valuable land—in terms of price due to its greater proximity to highly developed areas (cities, industrial centers, etc.), but not necessarily in terms of agricultural or other high-utility value. It is even conceivable to extend the rectennas off-shore where conditions are suitable, without ecological interference. In terms of land requirements, lines (22) and (23) are therefore more significant than lines (20) and (21).

The area-specific yield is inherently lower for solar than for nuclear PEPPs. But, as pointed out before, collectors and antennas are thermally complementary and therefore, eliminate potential climatic disturbances resulting from large-scale utilization of desert land.

Table 3

COMPARISON OF NUCLEAR AND SOLAR PEPP BASED GROUND
COMPONENTS OF A SPACE TRANSMISSION SYSTEM USING
20 POWER RELAY SATELLITES HANDLING 10.5 Gw EACH

		NUCLEAR	SOLAR
(1)	PRIMARY ELECTRIC POWER OUTPUT	262 GWE	262 GWE
(2)	PRIMARY EFFICIENCY	37%	25%
(3)	REACTOR POWER OUTPUT	710 GW	
(4)	THERMAL WASTE	448 GW	
(5)	NUMBER OF MICROWAVE ANTENNA ARRAY MODULES (MAAM)	20	20
(6)	OVERALL AREA OF MICROWAVE ANTENNA ARRAY (@240 KM2) (MAA)	4,800 KM2 (1,850 MI2)	4,800 KM2
(7)	OVERALL MICROWAVE POWER EMITTED (11.8 GW/MAAM)	236 GW	236 GW
(8)	OVERALL MICROWAVE POWER RECEIVED BY EMPPS (10.5 GW/EMPP)	210 GW	210 GW
(9)	OVERALL ELECTRIC POWER DELIVERED (9 GWE/EMPP)	180 GWE	180 GWE
(10)	ASSUMED ANNUAL DUTY PERIOD	7,884 HR[a]	4,380 HR[b]
(11)	PEPP AREA REQUIREMENT ASSOCIATED WITH GENERATION OF PRIMARY ELECTRIC POWER	600 KM2[c] (232 MI2)	3,600 KM2[d] (1,400 MI2)
(12)	OVERALL PEPP AREA	5,400 KM2 (2,100 MI2)	8,400 KM2 (3,243 MI2)
(13)	PEPP AREA-SPECIFIC MICROWAVE POWER EMISSION, (7)/(12)	0.04 GW/KM2	0.028 GW/KM2
(14)	PEPP AREA-SPECIFIC MICROWAVE POWER DELIVERY, (8)/(12)	0.0356 GW/KM2	0.0249 GW/KM2
(15)	PEPP ANNUAL MICROWAVE ENERGY TRANSFER, (8) X (10)	1.66·10⁶ GWH	0.92·10⁶ GWH
(16)	PEPP AREA-SPECIFIC ANNUAL MICROWAVE ENERGY TRANSFER, (15)/(12)	281 GWH/KM2	109 GWH/KM2
(17)	OVERALL AREA OF 20 EMPPS (@ 250 KM2)	5,000 KM2	5,000 KM2
(18)	OVERALL SYSTEM AREA (PEPP AND EMPP), (12) ÷ (17)	10,400 KM2 (4,000 MI2)	13,400 KM2 (5,174 MI2)
(19)	OVERALL-SYSTEM AREA-SPECIFIC ELECTRIC POWER DELIVERY, (9)/(18)	0.0173 GWE/KM2	0.0134 GWE/KM2
(20)	OVERALL-SYSTEM ANNUAL ELECTRIC ENERGY TRANSFER, (9) X (10)	1.42·10⁶ GWEH	0.79·10⁶ GWEH
(21)	OVERALL-SYSTEM AREA-SPECIFIC ANNUAL EL ENERGY TRANSF (20)/(18)	137 GWEH/KM2	59 GWEH/KM2
(22)	EMPP AREA-SPECIFIC ELECTRIC POWER DELIVERY, (9)/(17)	0.036 GWE/KM2	0.036 GWE/KM2
(23)	EMPP AREA-SPECIFIC ANNUAL ELECTRIC ENERGY TRANSFER, (20)/(17)	284 GWEH/KM2	158 GWEH/KM2

(a) 0.9 X 8760 HR
(b) 365 NOMINAL 12-HR DAYS
(c) INCL AREA FOR COOLING TOWERS, PONDS; LOCATION OF NUCLEAR-POWER PLANTS; FUEL PROCESSING PLANTS AND PU-239 STORAGE FACILITIES
(d) NOMINAL AREA OF 9.2 KM2/GWE INCREASED BY 50% FOR COOLING, ENERGY STORAGE AND POWER GENERATION FACILITIES

It is not in the scope of this paper to evaluate the relative merits of
the different primary energy sources available in the U.S. The technolo-
gies of their utilization are in different states of development. The
flexibility of evolutionary progress in developing this country's energy
wealth is increased by the use of microwave energy and Power Relay
Satellites. Figure 18 illustrates conceptually the scope of this
development.
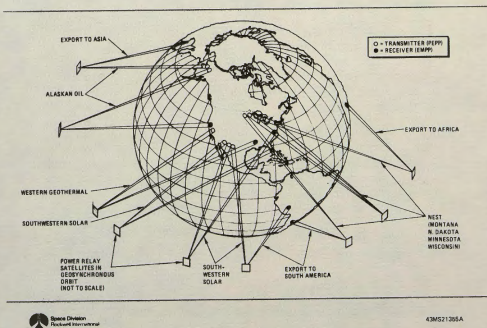
Fig. 18 U.S. Domestic Energy Transfer & Microwave Energy
Export Via Power Relay Satellite

THE GLOBAL ASPECT

On the global scale, the same criteria apply as on the national level.
Since mankind's economic, political and cultural traditions are essen-
tially still sub-global, it is realized that the global approach involves
a longer time constant. Therefore, one must look ahead beyond the immedi-
ate national crisis aspects to understand the global potential. Figure 19
presents a composite picture of present intensive load areas in America,
Europe, Asia and Australia, of the regions containing the vast global
reserves of solar energy and of the equally vast global "heat sink"

regions, north of the 10°C (50°F) annual water isotherm suggesting preferred locations for large heat generating nuclear power stations. The nuclear and solar power regions are mostly separated by large distances, including oceans and extensive wilderness areas from the intensive user areas. Therefore, the ability to move large amounts of energy efficiently over global distances is basic to the establishment of a long-range, non-fossil, environment compatible world energy basis.
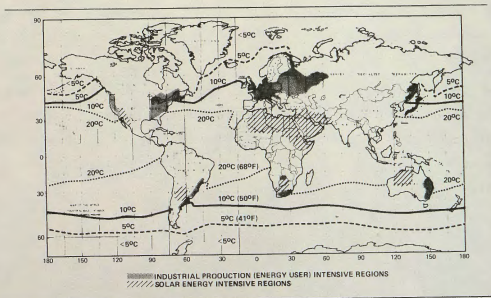

INDUSTRIAL PRODUCTION (ENERGY USER) INTENSIVE REGIONS
SOLAR ENERGY INTENSIVE REGIONS

Space Division
Rockwell International   13PD115959

Fig. 19   Global Heat Sinks, Solar-Intense and High
Energy-Consumption Regions

Figure 19 shows the maximum-insolation areas receiving 2 Twh/km^{2}yr or more, according to Fig. 15. The largest of these areas stretches from southern Iran across Saudi Arabia and the Sahara to northwestern Africa. The second largest area is the Australian desert, followed by the Kalahari desert in Bechuanaland, the Thar desert in northwest India, the southern California and northwestern Mexico desert complex and the Pampa de Salinas in Argentina. Together these "choice areas" comprise more than 11 million square kilometers (over 4 million sq.mi). Between 25 and 30 percent or about 3 million km^2 (1.2 million sq.mi) may be actually usable. They can provide more than 500 times the 6,000 Gwe global electric generating capacity which may be needed by the year 2000.

The U.S. Atomic Energy Commission (17) forecasts for the year 2000 a
nuclear generating capacity of 1,200 ± 300/375 Gwe for the United States,
and estimates this to amount to about 60 percent of the total U.S.
generating capacity of the order of 2,000 Gwe. Its forecast for foreign
nuclear capacities in 2000, estimates 1,460 ± 440/425 for the non-
Communist world and 600 Gwe for the Communist Bloc nations. This adds
up to a projected world nuclear generating capacity of about 3,300 Gwe
and to a world total generating capacity of the order of at least
6,000 Gwe—up by a factor of better than 5 over the January 1970 level
(1,100 Gwe).

Figure 20 shows the growth of electric energy consumption—provided to a
growing extent by nuclear power plants—and the associated waste heat
generation due to conversion and transmission losses. The dashed line
indicates the possible effect of improving efficiencies during the next
40 years.
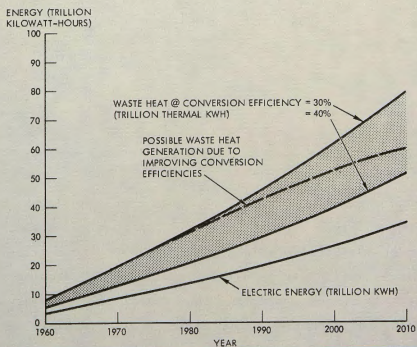
Fig. 20   Electric Energy and Waste Heat Generation – World Level

The magnitude of the waste heat can cause very high thermal burdens, if
concentrated in limited regions of Earth, near major load centers. The
ecological and sociological side effects of these burdens militate against
the buildup of the needed electric generating capacity.

There exists, however, a significant potential for avoiding undesirable
burden concentrations without, as yet, moving power generation into space,
which is beyond the capability of the Space Shuttle presently under
development, if undertaken on a scale commensurate with the need. This
potential becomes apparent if one considers the thermal load per unit
area, if the waste heat could be distributed evenly over the surface of
the globe. The loads are shown in Fig. 21.
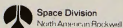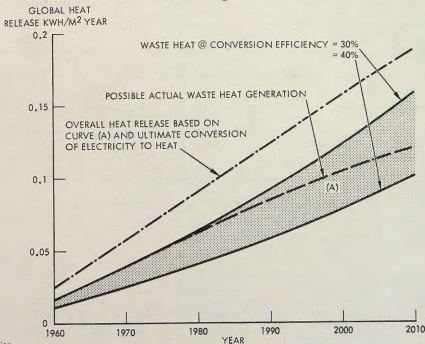
Fig. 21 Annual Heat Release Averaged Over Global Surface

They are seen to be well below 0.2 kwh/m^2yr. By comparison, the average
annual solar thermal energy input into the lower atmosphere and the ground
is 1,000 kwh/m^2, dwarfing the human energy input.

The small global averages show that the environmentally acceptable heat
capacity of the terrestrial environment is far from exhausted. Of course,
such distribution of waste heat cannot be achieved in practice. Not even
the thermal energy influx from solar radiation is evenly distributed. In
spite of these variations, however, the geographic distribution of solar
thermal energy can be regarded as relatively uniform, compared to the heat
release distribution from electric power plants.

Thus, with increasing energy consumption in which extrinsic thermal waste is generated, it becomes more important to strive for a wider geographic distribution of the waste heat. This means that a dissipation of power generation facilities is desirable, particularly into the cold regions at high northern latitudes.

Nuclear breeder facilities are no longer dependent on even the small amounts of uranium-235 enriched fuel resupply (small, compared to the fuel supply for fossil plants) needed by the Light Water Cooled Reactor. Therefore, they can, in principle be located anywhere, consistent with adequate availability of cooling fluid and with economic considerations.

Figure 22 presents a pole-to-pole meridional cross-section which is fairly representative for meridians passing over continental land masses. It shows qualitatively the profile of five parameters of importance in selecting nuclear power plnat sites if distance from the load centers plays no role as far as power transmission is concerned.
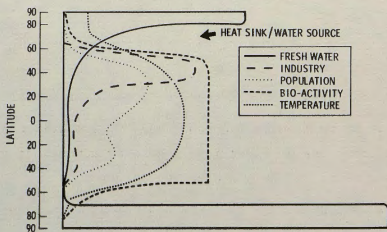

Fig. 22 Meridional Profile of Human and Natural Environmental
Characteristics Over A Continental Land Mass

The fresh water profile is dominated by its accumulation around the poles. Similarly, the other parameters have their "preferred" latitudes. Even land bio-activity drops off at high northern and southern latitudes ("dents" representing deserts in the equatorial belt, are not indicated). Due to the accumulation of population and industry between 30 and 60 degrees northern latitude, the environmental burden tends to be particularly high in this latitude belt. Globally speaking, on the basis of locating large nuclear power facilities as far north as necessary, but not further north than required, the latitude belt between 55 and 70 degrees north appears most suitable, avoiding Pacific coastal regions because of earthquake dangers.

This latitude belt includes the northern Canadian central and eastern territories, southern Greenland, northern Scandinavia and northern Russia. These regions do not lack water. It is even possible to use biologically unused water, ice, to supply the needed cooling fluid. Obviously, the amount of ice requisitioned in this manner would in any case be negligible compared to the ice stored in northern latitudes.

In addition to the preferred nuclear and solar energy regions, the planet is rich in geothermal energy sources and even in as yet unharnessed hydropower, particularly in Greenland. Local fossil reserves and places with favorable tidal and wind energy concentrations can be exploited by the appropriate PEPPs, almost regardless of their geographic location. Figure 23 illustrates the utilization and satellite distribution centers of our planet's energy wealth.

THE SHUTTLE COMPATIBILITY OF SPACE RELAYING AND ITS COMPARISON
WITH SPACE POWER GENERATION

During the past years, the author investigated a variety of systems for large-scale power generation in orbit.[1] The systematic investigation

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[1] As a matter of record, the author stated in 1966 (18): "It is suggested here that the reverse process [to use power beams for interspace purposes] might become of great value. Satellites either in properly inclined low orbits and/or in high orbits can be perpetually in sunlight; or a system of a few satellites can assure that at least one satellite is in sunlight at all times. In large solar collectors, large quantities of energy in the megawatt range can be accumulated and fed into laser beams or high-energy CW transmitters. These energy beams also could power spacecraft or at least provide emergency power. But they could also be directed toward Earth for peaceful purposes, providing, upon request, extra power to remote settlements, expeditions and ships."
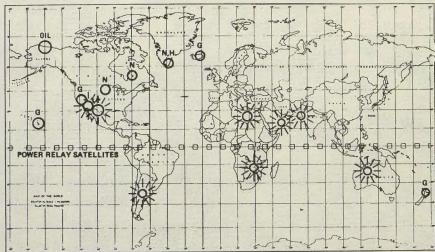
Fig. 23 World Electrification Through Space Transmission (WEST)

of space uses for energy supply began actually with various power generation systems and proceeded from there to space transmission only when it became apparent that the requirements associated with orbital power generation on a relevant scale to terrestrial needs would exceed the transportation capability of the Space Shuttle presently authorized for development and of any interorbital transport presently under consideration (including solar- or nuclear-electric).

The results presented here are based on reference systems worked out for space power generation by the following means: (a) breeder reactor (Rankine cycle using rubidium); (b) solar-thermal (Rankine rubidium cycle); (c) photovoltaic. These systems are compared with the PRS. The fact that the PRS does not generate electricity in space, but merely relays it, does not affect the validity of comparison, because in either case the space installations only are compared. The questions addressed here are those of Shuttle compatibility[1] and cost competitiveness of the space components of either method: power relaying and power generation.

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[1] This term is meant to include transportation into geosynchronous orbit, since the propellant requirements for this part of the overall transportation system must also be Shuttle compatible.

The PRS was described before. The solar-thermal power plant is depicted
in Fig. 24 which shows a four-module power generation system with a two
microwave antenna array.
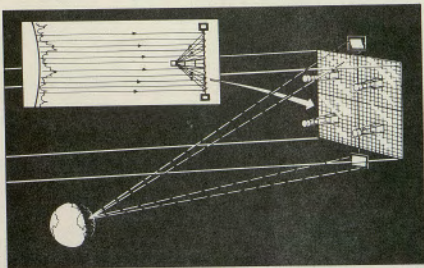
33MS21285

Fig. 24   Solar-Thermal Space Power Plant

The use of two antenna arrays was preferred for several reasons: control
of power input into a given EMPP; supply of two different EMPPs in time
zones of lower power demand while keeping the power plant output at its
maximum for economic reasons; and shut down flexibility for repairs and
maintenance.[1] The size of power generation modules is assumed to be stan-
dardized and their number is presently therefore not of particular
importance. The insert indicates the method of focusing by facets that
can be rotated about two axes to concentrate solar energy on the rubidium
heater driving the turbo-generator system. At a system efficiency of
40 percent, a Carnot efficiency of 25 percent the conversion efficiency
is 10 percent; and at a 3-sigma reflector efficiency of 90 percent, the
overall electric power generation efficiency is 9 percent. It is
important to note that the solar-thermal system is essentially solar
radiation pressure balanced (Fig. 25).

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[1] Each antenna array is independently microwave radiation pressure
balanced.
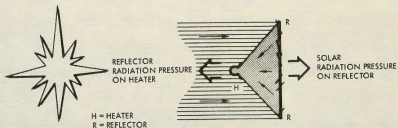
SOLAR RADIATION PRESSURE BALANCE IN SOLAR-THERMAL SYSTEM

THE SOLAR-THERMAL CONFIGURATION IS INHERENTLY SOLAR PRESSURE BALANCED.
THE RADIATION PRESSURE ON THE REFLECTOR IS COUNTERBALANCED BY THE PRES-
SURE OF THE CONCENTRATED LIGHT BEAM ON THE RADIATOR WHERE SMALL SUN-
FACING AREA PRODUCES NO SIGNIFICANT RADIATION PRESSURE. THE BALANCE
IS, OF COURSE, NOT PERFECT, PRIMARILY BECAUSE OF THE REFLECTOR'S ABSORPTIVITY.
BUT THIS REDUCES THE IMBALANCE TO A FEW PERCENT OF ITS ORIGINAL VALUE,
CUTTING THE PROPELLANT CONSUMPTION FOR RADIATION PRESSURE COMPENSATION
FROM 1/20 TO 1/50 PER UNIT AREA OF WHAT WOULD BE REQUIRED BY AN ISOLATED
REFLECTOR, SUCH AS THE LUNETTA.

33MS21309

Fig. 25 Solar Radiation Pressure Balance in
Solar-Thermal System

This has important advantages as far as the annual cost of radiation
pressure control is concerned (consumables). It leaves the emission
reaction force of the two antenna arrays as the primary radiation pres-
sure points. Each is individually balanced by radiation pressure compen-
sation thrusters so that they can be independently deployed. The same
holds for the other systems.discussed below.

The breeder reactor system is similarly built as the solar-thermal system,
except that the large reflectors are not needed, greatly reducing the
system size which now is determined primarily by the radiator areas, the
antenna arrays and shielding arrangements to assure accessibility to
individual reactor-converter systems. The reactor power sizing is based
on an overall electric power generation efficiency of 10 percent.

Two photovoltaic models were investigated, briefly referred to as (c-1)
photovoltaic (P-system) and (c-2) pressure-balanced (with) two solar con-
stant equivalent solar cell irradiation (PB2S). The P-system configura-
tion is shown in Fig. 26.

The solar cells are not supported by reflectors and therefore receive a
power influx of one space solar constant (1S). This system must compen-
sate a significant solar pressure acting on the large collector area, and
the antenna array emission reaction force.
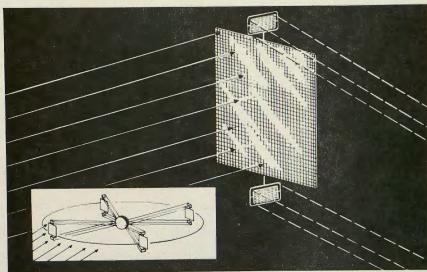
33MS21282

Fig. 26 Photo Voltaic Power Station in Orbit

Because radiation compensation thrust generation--even with electric
thrustors--is a leading contributor to high annual maintenance cost of
all solar devices unless balanced out, the alternative configuration
PB2S was studied (Fig. 27).

T = TRANSMITTER ARRAY
R = REFLECTOR (PR = PRIMARY; SR = SECONDARY)
S = SOLAR ARRAY (PS = PRIMARY; SS = SECONDARY)
R_n = RADIATOR
LG = LIGHT GUARD FOR RADIATOR
1-2-T = PATH OF ELECTRIC CURRENT
        TO MW CONVERTER & TRANSMITTER
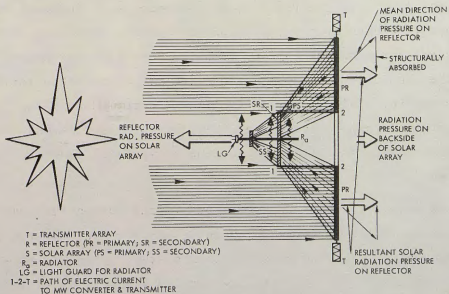
33MS21308A

Fig. 27 Solar Radiation Pressure Balanced
          Photovoltaic Configuration

The reflector-photovoltaic system consists of two mirrors reflecting the radiation on a solar array facing the mirrors. The radiation pressure on the solar array counteracts the pressure on the reflectors. The reflectors are subject to higher radiation pressure than the solar array. The radiation on their surface is not absorbed but bounced back. If the array were a perfect absorber and the reflectors were perfect mirrors, the radiation pressure on the mirrors would be twice that on the solar array. In other words, the ratio of radiation pressure on the reflectors to radiation pressure on the solar array would be 2 to 1. In an ideally pressure balanced configuration, this ratio should be 1 to 1. In that case, the need for spending propellants on solar radiation pressure compensation is reduced to compensate the radiation pressure on the Sun-illuminated side ("backside") of the solar array. There are several factors which tend to reduce this pressure ratio and actually cut it below 1 to 1.

The reflectors absorb 5 to 10 percent of the incident radiation. The array reflects some its incident radiation. These two factors reduce the pressure ratio to a value below 2 to 1, say to about 1.8 to 1. Moreover, the mirrors reflect the light at an angle. This causes the direction of the pressure on the reflectors to deviate from the Sun-reflector plane. The deviations on the upper and lower reflector are equal and opposite. They are absorbed as slight bending moments by the reflector-solar array structure. This leaves only the resultant pressure component in the Sun-reflector plane. If, for example, the mean direction of the radiation pressure on the reflector deviates by an angle of 45 degrees from the Sun-reflector plane, the resultant pressure component in the Sun-reflector plane is only 71 percent of the actual pressure. In that case, the pressure ratio would be reduced to 1.8 times 0.71 or 1.27.

Finally, and most importantly, the reflectors can concentrate the incident radiation on the solar array by using an adjustable-facet design described above in connection with the solar-thermal system. This has several significant advantages. The opposing pressure on solar array is increased. The size of the solar array is reduced. The radiation pressure on its backside, which acts in the same direction as the pressure on the

reflectors, is thereby reduced also. In fact, if perfect reflectors would concentrate the radiation on a perfect absorber of half their area, a balanced pressure ratio of 1 to 1 would be attained--in other words, the original ratio of 2 to 1 would be cut in half. However, the other factors discussed before have already reduced the ratio to 1.27 to 1. Multiplying this value by 0.5 reduces the pressure ratio to 0.635 to 1. But this is not actually an overcompensation. The backside of the solar array must be highly reflective to avoid excessive heating of the solar cells. Taking the resulting radiation pressure into account, balances the overall system almost perfectly (theoretically to an overall pressure ratio of about 0.97 to 1).

In view of the large areas involved, it may well be useful to utilize the backside of the solar array as a secondary reflector, irradiating a secondary solar array. The electricity gained from it can be used to drive an active radiation cooling system for both the primary and secondary array-- that is, one circulating a cooling fluid. Another use for the secondary array output is to drive the electric thrustors needed for the remaining orbit control tasks (microwave transmitter emission pressure, gravitational perturbations and attitude control). Excess energy can be fed into the main production output of the station furnished by the primary array.

The primary's array power output is conducted along structural members and the backside of the reflector from points 1 to 2 to the transmitter. Doubling the irradiation intensity of the array by using concentrating reflectors is not only favorable from the standpoint of radiation balance. It also exchanges solar cell area for cheaper and lighter reflector area. Finally, the fact that the solar array faces away from the Sun protects the solar cells from ultraviolet radiation which tends to degrade their performance and increase their operating temperature, thereby also reducing their output. The reflectors can furnish the array with a more useful radiation spectrum than the Sun. Being turned away from the Sun, however, offers no protection against solar flare protons which follow complex paths in the solar and terrestrial magnetic field and tend to hit the system from all sides.

For the P-system, a 3-sigma conversion efficiency of 15 percent was assumed. The PB2S system, which places the photovoltaic cells into a "Venus-solar environment", was based on the same conversion efficiency, using a fluid-radiator cooling system.

Finally, the PRS is shown in Fig. 28.
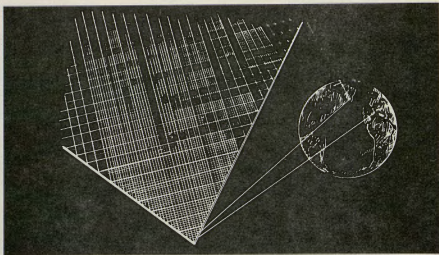
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Fig. 28   Power Relay Satellite

These systems—the nuclear (N), the solar-thermal (ST), the P, PB2S and the PRS system (R)—are compared subsequently. The performance of the power generation systems is standardized to 12 Gw transmitter output. The PRS is based on the reference design (Table 2).

A systematic summary is presented in Table 4. Several characteristics are also grouped together in the subsequent bar charts, based on Table 4. They show the trends particularly clearly. It would exceed the scope and purpose of this paper to discuss the data in detail. Some salient assumptions and conclusions are discussed along with the bar charts.

Figure 29 compares the areas, system weights and procurement costs, based on underlying data listed in Table 4. The basic simplicity and low cost of the space component of the relay system stands out, becuase in this system the lightest, simplest and least maintenance requiring parts are placed in orbit; whereas in the orbital power generation method the most complex and a major

Table 4

FIRST-ORDER COMPARATIVE DATA FOR THE SPACE COMPONENT OF A 10-Gw SYSTEM (STATE OF ART ~ 1990-2000)

Line	Item	Breeder Reactor (Rankine Cycle)	Solar-Thermal (Rankine Cycle)	Photovoltaic (1 Solar Constant)	Photovoltaic with Reflectors (2 Solar Constants)	Power Relay[1] Satellite
1	Area (km²)	4 Ra 2.5 T	90 Re 4 Ra 2.5 T	61 S 2.5 T	31 S 27 Re 2.5 T	0.4 MR 0.0169 S
2	Area-specific weight (tons/km²)	500 Ra 750 T	80 Re 500 Ra 750 T	120 S 750 T	120 S 80 Re 750 T	60 MR 150 S
3	Area-related wt. (tons) (1) x (2)	2,000 Ra 1,870 T	7,200 Re 2,000 Ra 1,870 T	20,120 S 1,870 T	10,230 S 2,160 Ra 1,870 T	24 MR 2.5 S
4	Other major power-related wt. items (tons)	4,000 P @ 3.3 kg/kwe	3,600 C @ 1 kg/kwe		160 Ra	1.5 (El. Drive & Misc.)
5	First-order system weight (3) + (4) (tons)	7,870	14,670	22,000	14,420	28
6	Area-specific cost (10⁶$/km²)	0.75 Ra 80 T	0.02 Re 0.75 Ra 80 T	320 S 80 T	320 S 0.02 Re 80 T	0.5 MR 1,000 S
7	Area-related cost (1) x (6) (10⁶$)	3 Ra 200 T	2 Re 3 Ra 200 T	19,520 S 200 T	10,230 S 0.6 Re 200 T 0.22 Ra	0.2 MR 16.9 S
8	Other major power-related cost items (10⁶$)	2,400 P @ $200/kwe	1,200 C @ $100/kwe	5% of (7)	5% of (7)	0.1 (El. Drive & Misc.)
9	First-order procurement cost (7) + (8) (10⁶$)	2,603	1,405	20,675	10,945	17.2
10	Power-specific cost (9)/10 Gw ($/kw)	260	141	2,067	1,094	1.72
11	Overall wt. to be lifted by the Shuttle, @ 3 tone prop. per ton pld. for NEO-GSO transfer = 4 x (5) (tons)	31,480	58,680	88,000	57,680	112
12	Number of Shuttle flights @ 29.5 t/flight) plus 10% contingency	1,174	2,188	3,282	2,150	5
13	First-order overall placement cost (12)x$8M (10⁶$)	9,392	17,504	26,256	17,200	40
14	First-order overall establishment cost (9) + (13) (10⁶$)	11,995	18,909	46,931	28,145	57.2
15	Orbit control consumables based on elec. prop. @ I_{sp} = 4,500 sec (tons/yr)	70 12.5/km² T	140 0.3/km² Re 12.5/km² T	210 3.5/km² S 12.5/km² T	140 0.6/km² Re 12.5/km² T	10 120 (85)/km² PRS
16	Orbit control consumables (1) x (15) (tons/yr)	90	200	481	189	48 (34)
17	Other consumables & replacements (tons/yr)	240(R)+30(C) +340/60 (WD)	30 C 5 M	9	11	2 (1)
18	Overall consumables & replacements = (16) + (17) (tons/yr)	700/420	235	490	200	50 (35)
19	Procurement cost of consumables	Not considered				
20	Overall weight to be lifted annually by the Shuttle (as (11)) = (4 x (18)) (tons)	2,800/1,680	940	1,960	800	200 (140)
21	Number of Shuttle flights per year @ 29.5t/flight) plus 5% contingency	100/63	34	70	29	8 (6)
22	Annual transp. cost for supply & maint. (21)x$8M (10⁶$)	800/504	272	584	232	64 (48)
23	First-order capital cost of space component for 30-yr operation at 90% load factor (Mill/g/kwh) [(14) + 30(22)]10⁹ Mills / 8,766 hrx0.9x30x10⁹ kwe	15.2/11.4	11.5	27.2	14.8	0.84 (0.63)
24	First-order capital cost per electric kw if ground conversion is 90% (Mills/kwhe)	16.9/12.7	12.8	30.2	16.4	0.93 (0.7)
25	Major cost- and schedule-driving development tasks	Microwave power generation, transmission and reconversion to DC-power must be developed. Microwave power generation & transmission system must be space-rated. Power generation system must be space-rated at low weight & cost.				

Re = Reflector; Ra = Radiator; T = Transmitter; S = Solar Panel; MR = Microwave Reflector;
P = Power Generation System (nucl. reactor & Rankine cycle converter/generator); R = Reactor; WD = Waste Disposal;
C = Converter/Generator System (Rankine cycle); M = Miscellaneous

1) From line 15 on down, the first number is based on I_{sp} = 4,500 sec, number in parenthesis on I_{sp} = 6,400 sec
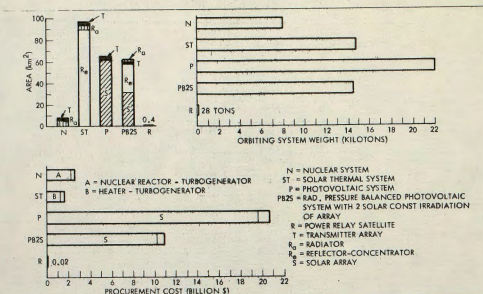
Fig. 29 Power-Related Systems in Orbit (10 Gw Beam Power Delivery) Areas, Weights, Procurement Cost

portion of the overall system weight is located in space. This difference affects not only transportation costs, but the pressure to minimize weight raises the procurement costs as well (not including amortization of the consideration development cost). It also places orbital power generation into a considerably more advanced category, as far as space operations, space transportation *and* power generation methods are concerned.

Among the power generation systems presented in Fig. 29, N requires the least weight, ST the least procurement cost, followed by N as a close second. The main procurement cost component of the photovoltaic systems is the solar array, in spite of the fact that a reduction from present cost figures of the order of 10^6/kwe for the solar array to $2,000/kwe, or $320 $\bar{M}$/km^2.[1] The PB2S shows a significant reduction in both weight and cost, because of large-scale replacement of solar cells by lighter and cheaper reflector area, which are also the main reason for the relatively favorable cost and weight characteristics of the ST system. The reason for the weight equality of the ST and PB2S system is the higher conversion efficiency of the latter.

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[1] For comprehensive summarizations of the outlook for solar cells see refs. (19) and (20).

To the procurement cost shown in Fig. 29, must be added the placement cost. The placement cost is taken as

Placement Cost = Transportation Cost + 10%

The transportation cost from Earth to GSO, using the Shuttle and reusable interorbital transports, consists essentially of the cost of shuttling into near-Earth orbit (NEO) the system weight and the propellant required to lift the system from NEO to GSO,

$$\text{Transportation Cost} = \frac{\text{Syst. Wt. (1 + Interorb. Propell't Factor)}}{\text{Shuttle Payload}} \text{ Cost of Shuttle Flight}$$

The interorbital propellant factor p_{IO} defines the average propellant consumption per unit mass payload delivery from NEO to geosynchronous orbit (GSO)--the value being average, because in the course of a large construction project in GSO, not all payload is placed in GSO. Some loads are returned to NEO. With a reusable chemical tug (O_2/H_2) to transport the load from NEO to GSO, the Shuttle must lift about 6 tons of propellant per ton of load into NEO[1]--i.e. $p_{IO} = 6$. The propellant factor is lowered, if the interorbital part of the transportation system is based on the Swing Station concept (17). This concept provides an orbiting work- and assembly shop (Swing Station) in an intermediate (elliptic) swing orbit (ISO) between NEO and GSO, with high-thrust interorbital transportation between NEO and ISO (near the perigee of the latter and high-thrust or low-thrust transportation between ISO and GSO). Figure 30 illustrates the system for high-thrust interconnections on either end, for which $p_{IO} \sim 3$.

The system is suitable for low-thrust high-specific impulse (I_{sp}) electric transportation between ISO and GSO, because the flight time is greatly reduced compared to spiralling out from, and returning to, the NEO. Using low-thrust connection at the apogee end, the overall transportation requirement is lowered at least to $p_{IO} = 2$, depending on a trade-off between thrust and specific impulse. For an electric tug between NEO and GSO the flight time is longest, but p_{IO} is reduced to values between 1.0 and 0.5.

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[1] It is assumed that the Shuttle does not have to return the Tug to surface; i.e. the Tug is refueled in NEO.

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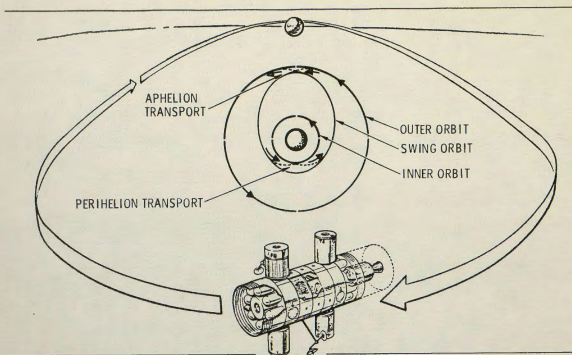
Fig. 30 Swing Station

In computing the transportation cost for system placement, $p_{IO} = 3$ was assumed, because this system can attain the highest weight carrying capability at a lower development cost increment beyond the Tug. This is not intended to prejudice the case against the use of electric drives, especially for the ISO-GSO connection. Moreover, high-I_{sp} engines need to be developed for the control of the power systems as well as of the Swing Station. But the thrust levels for which these control engines must be developed is consistent only with the transportation requirements as needed for the PRS, not for the power generation systems. On the other hand, in view of their large weights involved, it is practically mandatory to use electric interorbital transports. In other words, for the power generation systems, a considerably more advanced interorbital transportation is needed than for the PRS.

The same is true for the Earth-to-orbit Shuttle. The upper bar chart in Fig. 31 shows the number of Space Shuttle flights required, based on the following specifications: Shuttle payload per flight: 29.5t (65,000 lb); number of flights = $1 + p_{IO} + 10\% = 1 + 3 + 10\%$, or 4.4 Shuttle flights per
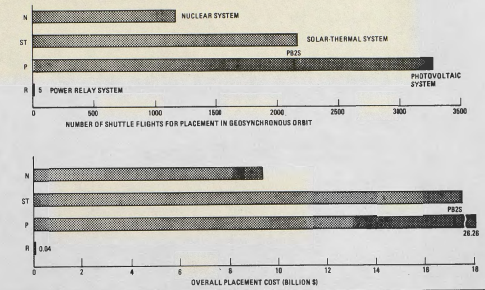
Fig. 31 Power-Related Systems in Orbit (10 Gw at Receiver)
Buildup

ton of payload into the GSO. It is seen that even for 1 + 1 + 10%, in
which case the number of Shuttle flights would be cut in half, between
600 and over 1,000 Shuttle flights would be needed just for a 9 Gwe system.
The lower bar chart in Fig. 31 is predicated on a cost per Shuttle flight
reduced to $8 $\overline{M}$ in the nineties. Considering that any system involving
space components (generating or relaying) must be capable of handling at
least several hundred Gwe if it is to be worthwhile for terrestrial
support, it clearly pays even for the PRS to add $4 to 5 $\overline{B}$ to develop a
fully reusable Shuttle which would reduce the direct cost per flight to
the order of $5 $\overline{M}$ to 6 $\overline{M}$. For the power generating systems, however, a
larger payload capability is required.

Figure 32 summarizes the procurement cost (black bars) and the procurement
plus placement cost (grey bars) per kw radiative power offered to the EMPP.
The grey bars, therefore, constitute roughly the capital costs as far as
the space component is concerned. Among the generating systems, N requires
the lowest capital costs by a considerable margin, followed by the ST. The
photovoltaic systems are highest. Taking the PB2S as the preferred photo-
voltaic system, even half the placement cost would still result in a capital
cost of $1,900/kw. Cutting, in addition, the procurement cost of the PB2S
in half, causes the capital cost to drop to $1,400/kw. But even this is not
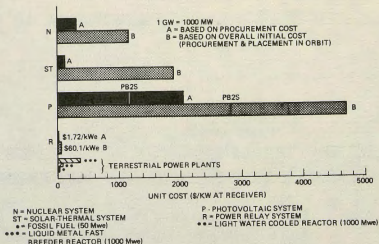
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Fig. 32 Power-Related Systems in Orbit (10 Gw at Receiver)
Unit Cost of Space Components

a competitive level. This is apparent if one compares these figures with
the unit cost of fossil fuel power plants (typically $50/kwe), light water-
cooled reactor power plants ($100/kwe) and the AEC projected value for
future breeder reactor power plants ($350/kwe). Apparently, only the PRS
system can hope to be compatible with these cost levels.

The annual maintenance costs are determined by the relation

$$\begin{matrix} \text{Annual} \\ \text{Maintenance} \\ \text{Cost} \end{matrix} = \begin{matrix} \text{Procurement} \\ \text{Costs} \end{matrix} + \begin{matrix} \text{Transportation} \\ \text{Costs} \end{matrix} + \Delta C$$

where ΔC is the cost delta due to manned inspection and handling flights
and contingency flights. A value of 5% of the procurement and transporta-
tion costs was assumed. The transportation costs are determined primarily
by the supply requirements. Because of the great variety of the supply
materials, it is difficult to fix a mean effective cost value. Moreover,
in most cases the cost per unit mass is small, compared to the transporta-
tion costs. Therefore, in the present comparison, the procurement costs
were not considered.

The supplies can be divided into two main groups--consumables for orbit
control and maintenance supplies.

Propellant is consumed for maintaining the proper orbit (orbit maintenance), for keeping the position of the system in the orbit (station keeping) and for attitude control. Of these three, the first two require the bulk of the consumables because of gravitational perturbations and radiation pressures. Figure 33 shows the radiation characteristics involved--the power densities and the pressures per km^2 caused by solar and microwave radiation.
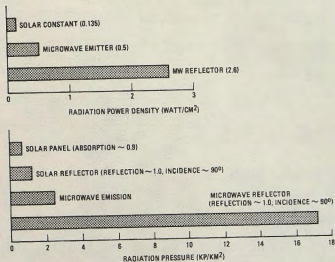
Fig. 33 Power-Related Systems in Orbit
Radiation Characteristics

In Fig. 34, the upper bar chart shows the annual propellant consumption per kw^2, based on the lower bar chart in Fig. 33 and on I_{sp} = 4,500 seconds. This is 71% of the 6,400 sec assumed earlier in this paper. The reduced value increases the propellant consumption by 42%. This weight delta is presently held as a reserve to provide a contingency for the not yet well-defined effects of gravitational perturbations and attitude control and other uncertainties on the overall propellant consumption.

The lower bar chart in Fig. 34 compares the annual supply requirements. They comprise the orbit control consumables, and other consumables and replacements as identified in lines (16) and (17) of Table 4. For the solar-power systems and the PRS, propellant consumables dominate the supply requirements--primarily because of radiation pressure compensation. The bar chart shows that the propellant supply requirements for the ST reflectors would be very
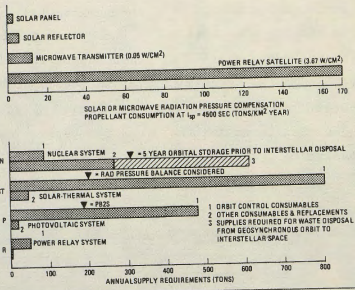
Fig. 34 Power Related Systems in Orbit (10 Gw at Receiver)
Maintenance

large if it were not for the pressure balance provided by concentration
of the radiation on, and absorption by, the heater. Thereby the overall
consumption is reduced from almost 800 t to 200 t. Similarly, a signifi-
cant reduction is achieved by the PB2S design.

Because of its small size and mass, the PRS requires the smallest amount of
consumables--the bulk of it stemming from microwave pressure compensation.
The N-system is a close second. Because of its high power density, the
solar pressure on the N is small, compared to the force of microwave beam
emission. Both PRS and N are separated by a wide margin from the solar-
powered systems, as far as orbit-control consumables are concerned. The
closeness of the PRS value (50 tons/yr) to that of the breeder system
(90 t/yr), in spite of the far smaller mass of the former, shows the power-
ful effect of the microwave beam reflection on the dynamics of the PRS
control.

The only system for which the maintenance supply requirements are markedly
higher than the orbit-control consumables, is the nuclear system. The
heavy maintenance demand stems primarily from four requirements. Fuel
rods must be exchanged. The plutonium-239, or uranium-233, produced by the
breeder must be retrieved. Waste must be processed for recovery of useful

fissile material and radioisotopes. Non-usable waste must be disposed. However, advanced breeders offer greatly improved fuel economy and reduce the replacement requirements accordingly. For example, a typical fuel burnup for today's light water reactors (LWR) of 1000 Mwe capacity is about 18,000 thermal megawatt-days per ton of uranium-plutonium, whereas the burnup target for an LMFBR of equal capacity is 67,000 to 100,000 Mwd/t (U-Pu). These figures suggest a four to five times longer fuel life in the LMFBR. The 1000-Mwe LWR requires an annual supply of about 30 tons of enriched uranium, or 25 to 30 percent of its uranium inventory. The supply requirements for the LMFBR would, therefore, correspond to about 5 tons per electric gigawatt-year (5 t/Gwe-yr). Due to the lower overall efficiency of the space system, this figure is raised to 20 t/Gwe-yr, resulting in 240 tons for 12 Gwe at the space power plant (9 Gwe on the ground). The 1000-Mwe LMFBR's fuel inventory comprises between 1.6 and 2.9 tons of fissile U-235 and Pu-239. The same quantity of Pu-239 is produced in a doubling time of 8 to 12 years. Thus, the effect of breeding on the transportation requirements is very small.

The third major factor to be considered is radioactive waste. Since one Mw_{th}-d corresponds to the consumption of 1.05 g of fissile material, an equal amount of radioactive waste is generated. Thus, one Gw_{th}-year produces 0.3832 tons of waste. In a terrestrial power plant with 37 to 39 percent efficiency, the breeder generates, therefore, about one ton of waste per electric gigawatt-year (Gwe-yr). In a space power plant, lower conversion efficiency (using 10 percent) and the loss involved in power transmission to Earth must be considered (not counting the conversion back to electricity, since the data relating to the other space power plants and to the PRS are also based on the reception of 10 Gw). On this basis, the waste production is 42.2 t/yr for the delivery of 10 Gw to the receiver array. This waste could be stored under controlled conditions in a heavily shielded depository in the GSO for a number of years, to let the shorter-lived isotopes run down. Nuclear waste is a mixture of various radioactive substances and decays at a rate proportional to $t^{-1.2}$. In other words, after 5 years of storage, the radioactivity of the waste is reduced to 14.6 percent, so that only about one seventh of the original amount, or 6 t/yr containing long-lived isotopes would have to be removed from the Earth-Moon system.

The most cost-effective method is disposal in interstellar space. The waste material is inserted into a path to Jupiter and there, via Jupiter gravity-assist, hurled into a minimum-velocity escape path from the solar system. Departure from the GSE would begin with a retromaneuver, injecting the waste-carrying vehicle into an elliptic orbit with a perigee close to Earth but at a safe altitude (e.g. 350 n.mi.). At perigee, the final departure maneuver is executed. Assuming oxygen-hydrogen powered propulsion stages, a total hardware and propellant mass of about 8 tons is required per ton of waste.

Based on the waste disposal of 6 tons annually, 60 tons of consumables would have to be delivered annually. However, safety considerations may prohibit orbital storage. In that case, 42.2 tons would have to be removed annually per 10 Gw delivered to Earth's receiver array, requiring the annual supply of 340 tons to the GSE. The preceding bar chart compares the annual removal to interstellar space based on both cases.

Figure 35 compares the annual maintenance flights (5 percent added to the nominal number as contingency) and the associated annual transportation cost. Comparison of the annual service requirements shows that photovoltaic systems with large area requirements are at a basic disadvantage, unless a radiation-pressure balanced configuration is used. The nuclear fission system is at a disadvantage, because reduced overall efficiency raises the fuel burnup rate, hence the supply requirements.

The waste disposal assumptions place the N-system well in the lead as far as Shuttle flights and annual transportation costs are concerned. Increasing the cost effectiveness of nuclear waste disposal from orbital power stations is therefore one major area of improvement. But even if this cost item is eliminated entirely, the annual maintenance cost is still comparable to that of the P-system. Another significant area of improvement is therefore the reduction of the reactor and converter maintenance requirements assumed here. As far as the P-system is concerned, the obvious direction of improvement is the adoption of the pressure-balanced PB2S-system, thereby reducing the annual maintenance requirement to a level comparable or slightly below that of the ST-system. Again, the R-system requires by far the smallest annual maintenance cost.
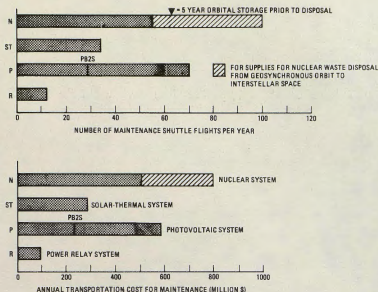
Fig. 35 Power Related Systems in Orbit (10 Gw at Receiver)
Maintenance—II

Finally, the comparison of the capital cost of the space component (in
terms of Mills (0.1¢) per kilowatt-hour of energy transferred to the
receiver of the EMPP) shows that the cost of electricity is highest for
the photovoltaic systems and comparable for the N- and ST-systems, if
the cost of nuclear waste disposal for the N-system is not counted.
However, none of these systems can even approach the Power Relay Satel-
lite, the only approach promising economic viability still in this
century (Fig. 36).

Figure 36 does not take into account the development costs of the dif-
ferent space power generation systems. If they were included, the photo-
voltaic system would be likely to be most costly on that account also,
since, in terms of weight and cost reduction, solar panels have still the
widest development gap to bridge. On the other hand, the breeder will be
developed in any case, since it is the most important answer to the world
power needs in the eighties and nineties. The use of solar-powered
orbital stations suffers from still another handicap which accentuates the

NUCLEAR WASTE DISPOSAL FROM
GEOSYNCHRONOUS ORBIT TO INTERSTELLAR SPACE

▼ = 5 YEAR ORBITAL STORAGE
PRIOR TO DISPOSAL

CAPITAL COST* (MILLS/KWH)

*30-YEAR OPERATION
*COST OF BUILDUP & MAINTENANCE
*90-PERCENT LOAD FACTOR
*COST PER SHUTTLE FLIGHT: $3M
*INTERORBITAL PROPELLANT CONSUMPTION 3 TONS PER TON PAYLOAD

N   = NUCLEAR SYSTEM   P = PHOTOVOLTAIC SYSTEM
ST = SOLAR-THERMAL SYSTEM R = POWER RELAY SYSTEM

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Fig. 36   Power-Related Systems in Orbit (10 Gw at Receiver)
Capital Cost of Space Component

disadvantage of the high cost of photovoltaic system and the high
development cost that must be expended to remove it from the bracket of
economically outright prohibitive approaches. This handicap is a lack of
environmental "returns". An environmental advantage of using solar energy
in space at higher cost, rather than on Earth, ensues only if the so
generated power replaces fossil and terrestrial nuclear power; but not if
it is done in lieu of terrestrial solar power generation, since the latter
generates no extrinsic waste in the first place. Thus, solar power sta-
tions in space must compete with terrestrial solar power stations primarily
in economic terms. Nuclear power stations in space, on the other hand,
have in any case the advantage, over their terrestrial counterpart, of zero
environmental impact. However, even they could not compete economically
with cold-sited integrated nuclear power plants on Earth or with solar
power plants even in remote deserts along with the use of Power Relay
Satellites.

For the above compared space power generation systems, especially the two
photovoltaic types, such advanced state of the art has been assumed that
sizeable further reductions in procurement cost and weight cannot be

expected. Therefore, the capital cost (Mills/kwh) could be lowered
significantly only by major cuts in transportation costs, particularly
in the cost of transfer from near-Earth orbit to geosynchronous orbit.

On the other hand, no allowance was made for the significant improvements
attainable by using superconducting electric machinery. In this case,
non-iron (e.g. niobium-titanium alloy, critical temperature $T_c \sim 8°K$)
superconducting windings are substituted for the use of iron for
magnetic-flux paths. The resulting increase in magnetic flux density
over that of iron-core machines leads to significant reductions in size
and weight of the turbogenerator systems, because the energy produced
in a generator per revolution is roughly proportional to the magnetic
field energy crossed by the conductors. The ST/N-systems contain many turbo-
generators. The savings in manufacturing costs due to the savings in weight
are enhanced substantially by the added savings in transportation costs.
The technology in this field is much farther advanced even today than
the state-of-the-art postulated for the solar arrays in the photovoltaic
systems. Superconducting temperatures can far more readily be sustained
in space than on Earth. Since the converter-generator system is a major
cost item in the ST-system, savings of 30 to 40 percent in overall capital
cost appear attainable, somewhat lesser savings for the N-system. Mass
reduction also reduces the propellant consumption for orbit control,
hence, the annual maintenance costs.

Moreover, among the orbiting power stations the nuclear system is an
exception, because of the growth potential in the advancement from solid
core reactor to gaseous core reactor and fusion reactor. These reactors
have higher power densities, which reduces their size and weight and
reduces the initial orbit placement cost. They deliver more power per
unit mass of fuel. Fewer structural elements must be exchanged, since no
fuel elements are involved. All these factors lower the annual resupply
and maintenance cost. Along with reduced transportation cost, advanced
orbiting power plants using gaseous core reactors or pulsed laser fusion
reactors should be capable of beaming power to terrestrial electromagnetic
power plants at a cost that is compatible to the cost of power delivered
from cold-sited nuclear plants or desert solar plants via Power Relay

Satellite. Neither of these systems is likely to reach operational capability in space prior to some time in the first half of the 21st century. Therefore, it is not useful to conjecture their specific physical and operational characteristics at this time.

The salient conclusion that may be drawn here is that economically viable orbital power stations for the terrestrial market are feasible in the context of a future plateau of more advanced transportation and more advanced nuclear power generation technologies. Its potentially most formidable competitor is the large terrestrial solar power plant. Its most important prospects will be limitations in relaying capacity and the fact that a country's power generation system in GSO overhead reduces or eliminates its dependency on foreign deserts.

OVERALL SYSTEMS COMPARISONS

Table 5 briefly compares the complete space relay system—PEPP, PRS and EMPP—with terrestrial nuclear power plants and orbiting power stations. The comparison is based on a nuclear PEPP, because the cost of its primary electric power plant can be more accurately estimated at this time. Using the system data presented in Table 3, a land area of 5,400 km^2 = $1.33 \cdot 10^6$ acres is postulated for the PEPP, and a combined land area of 5,000 km^2 = $1.23 \cdot 10^6$ acres for the 20 EMPPs. The PEPP power output is 262 Gwe = $262 \cdot 10^6$ kwe, or 1.33/262 ~ 0.005 acres/kwe. The combined power output of the EMPPs is $180 \cdot 10^6$ kwe, or 1.23/180 = 0.007 acres/kwe. Thus, even if the cost of purchasing and preparing the land at the PEPP sites adds up to $1,000 per acre—an unlikely case in view of the remoteness of the PEPP site, the low quality land required and magnitude of the purchase, even if the construction of roads, cooling ponds, planning, fencing, etc. (but no buildings) are included—even then the land cost would add only $5 to the cost of each kwe. At the EMPP site, the land is presumably somewhat more developed and better accessible, requiring less work and lower labor costs than at the PEPP site. In turn, the land will be somewhat more expensive. Assuming a land cost of $1,500 per acre, the cost of land adds about $10 to the cost of the kwe produced. In terms of capital cost, therefore, land does not appear to be a major factor, unless the land costs are five to ten times higher than assumed.

Table 5

OVERALL SYSTEM COMPARISON

	UNIT COST ($/KWE)	TYPICAL CAPITAL COST (30-YEAR OPERATION) (MILLS/KWHE)
• LIGHT WATER - COOLED REACTOR (1000 MWE)	100	
DISTRIBUTION LOSSES: 10%		
COMBINED COST	110	3 TO 4
• LIQUID METAL FAST BREEDER REACTOR (1000 MWE)	350	
DISTRIBUTION LOSSES: 10%		
COMBINED COST	385	~5
• PEPP (262,000 MWE), INCLUDE ANTENNA ARRAY	380	~4
OVERALL TRANSMISSION EFFICIENCY: 68%		
COST PASSED ON ELECTRICAL POWER DELIVERED	560	6
POWER RELAY SATELLITE	60	1.3
EMPP, INCLUDE LAND COSTS	70	0.5 - 1.0
OVERALL	690	~8
• ORBITING POWER STATION (SOLAR - THERMAL)	~1,900	12 - 13
EMPP	70	0.5 - 1.0
OVERALL	~2,000	12.5 - 14

When building large nuclear power complexes as assumed in Table 3, the cost per kwe will be lower. The extent of the reduction is difficult to express generally, but a 20-percent reduction does not appear unreasonable, all things considered. On the basis of LMFB reactors, this means $280/kwe. Adding $100/kwe (or about $110/kw of beam power) for the antenna array, a cost of $380/kwe is indicated for the PEPP. This means, the unit power land cost is in the noise level.

For the GSE the value of $57/kwe in Table 4 is rounded off to $60/kwe. For the EMPP a unit cost of $50/kw of incoming beam power, i.e. $60/kwe appears attainable. Adding to this the cost of land yields $70/kwe. The overall capital cost, normalized to the power output of the EMPP is, therefore, of the order of $690/kwe. This places the cost of space relaying between that of an all-terrestrial nuclear system and a space power system but significantly closer to the former than to the latter. It should further be noted that in the second case (LMFBR, all-terrestrial) the cost implications of handling and shipping the Pu-239 between not-integrated facilities has not been taken into account. Therefore, the actual costs are likely to be higher.

Still, a unit cost ratio of 1.8 and a 30-year capital cost ratio of 1.6 between the LFMBR-PEPP space relay system and the all-terrestrial LFMBR system is not unexpected. It may not be an unreasonable price to pay for greater flexibility in utilizing primary energy sources, in large-distance power distribution and for the attendant socio-ecological quality improvements.

Comparison with Capital Requirements for Oil & Gas Transportation 1971-1985

It has been recently noted by a power company that "transmission limitations are not as limiting as might be inferred" by the emphasis on transmission implied in the Power Relay Satellite concept (22). This is no doubt correct if one looks at power transmission from plants located reasonably close to the load centers.

But the picture changes radically if one takes the overall system into account, particularly in the fossil energy economy. In its summary report (23), the National Petroleum Council (NPC) notes (p. 20) that, by 1975, the electric energy sector is expected to be the largest user of primary fuels of any U.S. energy sector; and that the balance between energy demand and domestic supply of fuels depends decisively on the demands imposed by the electric energy sector. The NPC analyzed four cases of primary fuel supply. Case I is based on fast resolution of environmental issues, intensive government support of energy development, including making government land available, and a higher success rate in discovering new resources than has been the case in the sixties. This case, therefore, is the least likely. Case IV assumes that environmental issues continue to constrain energy growth, that government policies do not provide support and that the exploratory success rate does not improve over that of the sixties. This is, therefore, the most likely case. Cases II and III are intermediate cases in terms of finding new gas and oil reserves and in terms of the rate of building nuclear power plants, where Case II is closer to Case I.

Table 6 compares the resulting conditions. The capital requirements in the fossil energy sector between 1971 and 1985 are listed in lines 1.1 through 1.4 and the import costs for oil and gas (in 1970 dollars) by

Table 6

EFFECT OF ELECTRICITY DEMAND ON ENERGY TRANSPORT
COSTS AND OIL/GAS IMPORT REQUIREMENTS

Supply Case	I	II	III	IV	Notes
1. Oil & Gas (Capital Req'd. 1971-85)					Numbers in
1.1 Exploration & Production	171.8	144.8	135.1	88.0	Billion Dollars
1.2 Oil Pipelines	7.5	7.5	7.5	7.5	
1.3 Gas Transportation	19	24	30	38	
1.4 Tankers, Terminals	2	9	16	23	
2. Imports - Oil	5.4	13.1	20.4	29.1	Numbers in
2.1 (1985 - Nat. Gas & LNG	4.9	5.0	5.3	5.4	Billion Dollars
3. Percent of Imports Consumes					
3.1 by El. Utilities (1985) Oil 60	52	33.6	23.5		Percentages based
3.2 - Gas 66	64	61	59		on "condition 1" (baseline case)
3.3 In Terms of Import $ - Oil 3.24	6.81	6.85	6.84		Billion Dollars
4. In Terms of Capital for Tankers & Terminals (1.4)	1.2	4.68	5.38	5.4	Billion Dollars
5. Oil Imports Req'd. (MMB/d)	3.564	8.701	13.474	19.248	MMB/d = Million
6. Consumed by El. Utilities (MMB/d)	2.138	4.524	4.527	4.523	Barrels per day
7. Number of Power Relay Satellites Equivalent to (6)	6	13	13	13	Based on Energy Transfer Capability: 3 PRS ~1 MMB/d

1985 in lines 2. and 2.1. The electricity requirements consume a high
percentage of oil and gas imports, as seen in lines 3.1 and 3.2.

The largest capital requirements in the fuel import are associated with
oil. The transportation costs of overseas oil can more readily be prorated
than the gas transportation costs which are a mix of capital requirements
for domestic pipelines, underground storage, liquefaction plants, rail cars, and
processing plants as well as liquid natural gas tankers. Therefore, only the
oil scenario is considered in the lower part of Table 6.

Line 3.3 shows the import cost of oil required for the generation of elec-
tricity, based on lines 2.1 and 3.1. Line 4 prorates the capital costs for
tankers and terminals according to 1.4 and 3.1 Line 6, based on lines 5 and
3.1 gives the amount of oil imports needed by the electric utilities. Thus,
in the overall picture, energy transfer is of very great importance both in
terms of transportation costs and import costs.

Three PRS of 0.4 km^2 area, operating 90 percent of the time, transmit
the energy equivalent of 365 million barrels of oil per year, or 1 MMB/
day. Thus, the use of 6 or, in the more likely cases, 13 Power Relay
Satellites transferring nuclear energy or solar energy from remote PEPPs,
would save around 5 billion dollars in tanker and terminal investments
between 1971 and 1985 and over 4 billion dollars annually in 1985 and
thereafter. The savings in tankers and terminals are equivalent to the
cost of developing the Space Shuttle *with* reusable first stage, since no
more than 50 percent of the fully reusable Shuttle development should be
charged to the Shuttle's role in the energy sector. The savings in import
cost would, in less than 5 years, amortize the investments in developing
the microwave technology, the PRS and an adequate interorbital transport
to geosynchronous orbit. The political benefits of the reduced import
requirement cannot be expressed in dollars alone.

Thereafter, in the late eighties and in the nineties, the growth potential
of space relaying for domestic purposes and its export potential are avail-
able to pay still much larger dividends.

SPACE RELAYING AND SPACE SHUTTLE

The Space Shuttle is valuable to the nation not because of what it is,
but because of what it makes possible.

The Power Relay Satellite would not be possible—at least in economic
terms—without the Space Shuttle. The PRS is not a concept developed to
justify the Shuttle but one more expression of the vast potential of a
human action world in which Earth and Space are indivisible. In connection
with moving energy through space from terrestrial sources to load centers
anywhere on the globe, the Shuttle plays the role that pipelines and tankers
play in moving energy in chemical form across continents and oceans.

Figure 37 expresses numerically the relation between electric power
delivered via space relay and the associated number of Shuttle flights.
If the standardized Power Relay Satellites needed to provide the power
relay capability expressed on the ordinate are to be established over a
10-year period, then the annual number of Shuttle flights (abscissa) is
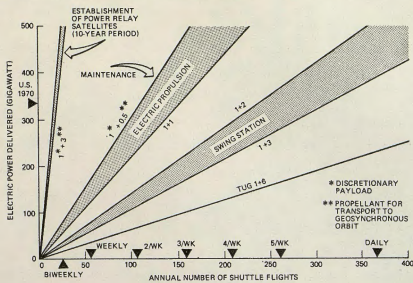indicated by the thin band at the far left, marked "establishment of

Fig. 37 Shuttle Compatibility of Energy Transfer

Power Relay Satellites". For example, in order to establish a space relay
capability of 280 Gwe EMPP output (33 standard PRS), in the span of a
decade, 14 Shuttle flights per year are required--less than one flight
every two weeks, based on a Shuttle delivery of 3 tons propellant per
ton of payload to be placed into GSO.

The maintenance requirements are strongly dependent on the type of inter-
orbital transport. In contrast to the establishment band, the maintenance
correlations refer not to the buildup condition but to the requirements
that exist after the required number of PRS for the performance shown on
the ordinate is established. The correlations also are based on a propel-
lant consumption associated with a specific impulse of 4,500 sec. If
I_{sp} = 6,400 sec is used, the annual number of Shuttle flights are reduced
to 71 percent of the values shown. But, for the Swing Station and for the
electric tug, the number of annual Shuttle flights required for maintenance
remains manageable at least up to about 300 Gwe even for the conditions
shown.

COMPARISON WITH SOME TERRESTRIAL ENERGY TRANSFER ALTERNATIVES

As pointed out earlier in this paper, the principal methods of moving energy on Earth are in electric or material form. The advantage or disadvantage of either method in relation to each other and to the electromagnetic method is so strongly situation-dependent that a "best" method can no more be identified than a "best" power source. An evaluation of terrestrial alternatives relative to space relaying is presently in progress, so that only initial results can be presented here and exemplified on a number of specific cases.

1. Alaskan-Canadian Oil: Conventional Vs. Space Energy Transfer Cost Aspects.

This case exemplifies energy transfer in material form in the case of fossil energy sources found in remote places. It is realized that the PRS is not a practical alternative to terrestrial methods of transporting the oil and gas, unless the construction of the Alaskan pipeline or other means (train) to carry the oil through the wilderness are delayed for another 15 years or so. Therefore, the comparison is made not to suggest the PRS as an alternative in this special case, but to use this case as a basis of comparison for similar situations that may arise in the future.

Table 7 compares the use of railroad-pipeline and pipeline-tanker combinations with the Shuttle-PRS combination. Only energy transfer costs are involved. It is seen that the costs are comparable in terms of Mills/kwhe, although the placement costs are included in the case of the PRS, but the construction costs are not included in the two other cases. It must also be kept in mind that the pipeline and, to a large degree at least, also the railroad are no longer useful after the local reserves are used up, whereas the usefulness of a PRS is not diminished. If one given primary energy source is exhausted, the PRS is allocated to another source.

2. Superconducting Power Transmission.

Cost comparisons are very difficult to make. Superconducting (s.c.) lines are expensive and therefore are considered attractive primarily for underground power transmission in highly developed (urban and industrial) areas where the costs for conventional underground lines are very high

Table 7

ALASKAN-CANADIAN OIL: CONVENTIONAL VS. SPACE ENERGY TRANSFER COST ASPECTS

RAILROAD (RR) - PIPELINE (PL)	PIPELINE - TANKER	SHUTTLE - POWER RELAY SATELLITE (PRS)
• RR PRUDHOE BAY TO TROUT RIVER • PL TROUT RIVER - CHICAGO	• PL PRUDHOE BAY TO VALDEZ • TANKER FROM VALDEZ TO SEATTLE, S.F., L.A.	• MICROWAVE BEAM PRUDHOE BAY TO PRS • PRS TO ANYWHERE – AMERICAS, PACIFIC, JAPAN
$1.07 PER BARREL CRUDE • 1.8 MILLS/KWHE[1] W/O CONSTRUCTION COSTS	$1.30 PER BARREL [1] • 2.2 MILLS/KWHE [1]	• 1.5 – 2.1 MILLS/KWHE (WITH PLACEMENT COST 30 YEARS OPERATION)
• 2,000,000 BARRELS/DAY		• 1 PRS: 71,280 GWHE/YEAR [2]
• 400,000 GWHE/YEAR [2]	⟶	• EQUIVALENT TO ~6 PRS
[3] RR: • 2 TRACKS; 1,240 MILES • 5 YEARS CONSTRUCTION CAPITAL COST $2.4B • MAINTENANCE $194M/YEAR 20 TRAINS DAILY EACH WAY 5 LOCS, 168 TANK CARS PER TRAIN	• PL: $2.5B TANKERS $1.25B	PRS: • 6 AT 4 MILLION SQ FEET • 2 YEARS CONSTRUCTION 12-24 SHUTTLE FLIGHTS CAPITAL COST $0.5B • MAINTENANCE $380-760M/YEAR 32-64 SHUTTLE FLTS/YEAR

(1) 1 BARREL – 1,700 KWHTHERMAL = 612 KWHE (36% CONVERSION EFF)

(2) LOAD FACTOR: 0.9

(3) CANADIAN MINISTRY OF TRANSPORTATION

Space Division
Rockwell International   33MS21320

and overland transmission hindered by unavailable right-of-way. For long-distance transmission, the problems of refrigeration system reliability and low-cost high-vacuum insulated lines remains to be overcome. It is not clear what constraints the need to provide a very low-temperature environment will eventually place on the correlation between economy and transmission distance or even on the correlation between practical feasibility and transmission distance.

An additional complication can arise for long distance lines if, for reasons of reliability, large amounts of copper are necessary for emergency heat conduction in case the conductor becomes temporarily a normal conductor. Copper is a scarce energy-related metal and can become adequate only at about twice the present cost.

Superconducting lines will become feasible in the next decades. Their operational problems can be solved. It is not obvious, however, that they are a viable alternative to space relaying over continental distances; and almost certainly they are not a viable alternative on a hemispherical or global scale.

On the other hand, it appears that superconducting dc-lines could be very attractive as a secondary distribution system from EMPPs which convert the

incoming microwave power to dc-power. The power could thus be distributed to surrounding load centers at greatly reduced transmission losses before being converted to ac-power. This would increase the flexibility in locating the EMPPs in the most suitable—i.e. otherwise least useful—real estate and reduce further the cost and effectiveness of land use for the rectennas.

The PRS concept can be economically competitive and is probably unrivalled in its capability of moving large blocks of power without right-of-way problems and, therefore, its potential for becoming an essential building block in a national power network.

SUMMARY AND CONCLUSION

We live no longer in the closed world of the biosphere and the terrestrial environment at large. Because of space technology and the development of comparatively low-cost space transportation, our world becomes open to the cosmos. The open world is based on the indivisibility of terrestrial and extraterrestrial environments as far as the human activity sphere is concerned. In the open world, limits to industrial growth can be overcome, allowing the human population to level off under conditions of a high average living standard without destroying the natural environment. One of the keystones of open-world development is the continued supply of growing amounts of energy to meet the needs of our growing industrial civilization. In order to assure this supply within the constraints of environmental concerns, the transition from predominantly fossil fuel sources to nuclear, solar and other forms of non-chemical energy in the next 30 to 40 years becomes increasingly desirable. For economic and timing reasons, it is more practical in the initial phase to develop these energy sources on Earth, before advancing to the level where suitable energy sources can be utilized on a globally relevant scale for power generation in space.

Non-chemical energy utilization tends to require far greater flexibility in national and global power plant siting than is the case with conventional fuel power plants. The practicality of the initial phase, therefore, is affected favorably by a flexible system of power transmission that is practically insensitive to transmission distances.

Point-to-point power transmission via satellite relay is the comparatively simplest and therefore least costly of the various methods through which space technology can be applied to the solution of our energy confrontation. It is the only space-related method to offer a realistic prospect of becoming operational in the 1990s. There appears to be no attractive terrestrial alternative to continental, hemispherical or global power transmission. Yet, power transmission over continental and intercontinental distances is an important link in forging the chain of transition from fossil to non-fossil energy base.

The PRS is Shuttle compatible. It can become operative in the second half of the eighties, provided the development of the Shuttle and of two major new technologies--microwave power transmission and large solar-electric, and possibly nuclear-electric, propulsion systems--is given high priority in the seventies and eighties.

Space power transmission via relay satellites makes it possible to capitalize on the extensive efforts invested already on nuclear power plant development, provided that emphasis is placed on the development of what might be called distant siting--the location of nuclear power plants in remote areas. Through space power transmission and remote siting, the development of breeder reactors becomes more promising. The negative implications feared by many are largely removed, due to greatly increased isolation from the natural and human environment. The latter should even facilitate the control--and prevent the misuse--in handling the growing quantities of plutonium-239 (and possibly of uranium-233) produced by the breeders. Thereby, space power transmission improves the prospects that power from nuclear fission can indeed serve as a vital link in the transition from fossil to solar and perhaps fusion energy.

By uncoupling primary energy source and load centers from their present close association by electric transmission increases this country's freedom of utilizing its energy wealth more extensively, regardless of location. This reduces the nation's dependence on foreign fossil resources and leads to the supply of locally "clean" electricity to regions that are heavily burdened environmentally by population, industry and agricultural cultivation.

Moreover, there is no reason why this country cannot become an exporter of energy--microwave energy rather than oil before the end of this century. Because Power Relay Satellites can bridge oceans and continents, it is possible even to export electricity, along with electromagnetic power plants and eventually Power Relay Satellites. Electromagnetic power plants are less expensive to construct and simpler to operate than primary electric power plants and therefore fit better into the economic capacity of developing countries. Electric power, used for socially and economically desired ends, is an effective means for industrially and technologically developing countries to build an economic infrastructure on which to raise their living standards and become more active trade partners of the U.S. and other industrial countries. The socio-economic and geo-political effects of the arbitrary distribution of fossil fuel deposits on this globe can be reduced greatly for the benefit of our growing global society as a whole.

The development of a space relay system is not without problems. But there seems to be no reason to assume that they could not be solved within the next 15 years, given the necessary priority. The potential of the system makes the effort worthwhile, particularly since the required level of effort is well within the scope envisioned as a reasonable and necessary investment in this country's energy future which, along with all other aspects of our future, depend on the pursuit of excellence.

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