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INTRODUCTORY ASSESSMENT OF ORBITING REFLECTORS FOR TERRESTRIAL POWER GENERATION

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SYMBOLS USED IN TEXT

A	area, km^2
A_{abs}	minimal absorber area, km^2
A_{sm}	mirror reflecting area, km^2
a	absorption coefficient
B	angle between ℓ and radius vector from Earth, deg
b	reflection coefficient
C	capital costs, 1976 dollars
C	temperature, Celsius
c	velocity of light, 3×10^8 ms^{-1}
D_m	mirror diameter, km
D_s	beam spot diameter on Earth, km
E	power, kWh yr^{-1}
$\vec{E}$	electric field vector
F	force, N
F_{abs}	radiation force, absorption, N
F_{ref}	radiation force, reflection, N
F_g	gravity gradient force, N
f	$(1 + h/r_e)^{-1}$
f'	effective focal length of mirror, km
G	gravitational constant, Nm^2kg^{-2}
g_o	gravitational acceleration at zero altitude, 9.8 ms^{-2}
H	magnetic field vector
h	altitude, km
I_o	space solar constant, 1.4 kW/m^{-2}

i	inclination, deg
K	error in ground spot position, percent
L	angle subtended by great arc, deg
M	Earth's mass, kg
m'	mass, kg
N_e	reflector points when $\lambda = i$
N'_e	reflector points when $i = 0°$ or $90° \neq \lambda$
N_i	reflector points when mirrors must transit zenith and $i \neq 0°$ or $90°$
N_t	reflector points, minimum theoretical when $i \neq 0°$ or $90°$
$\underline{\hat{n}}$	unit vector along normal to mirror
P	satellite period, hrs
$\underline{\vec{p}}$	wave momentum density, $\mathrm{kgms^{-1}m^{-3}}$
Q	intensity, theoretical, $\mathrm{kWm^{-2}}$
R	distance from Earth's center, km
R_m	satellite mirror radius, km
r	radius, km
r'	rate of return, percent $\mathrm{yr^{-1}}$
r_e	Earth's radius, km
Δr	linear displacement of ground spot, km
S	distance, mirror to ground spot, km
$\vec{S}$	Poynting vector
$\underline{\hat{s}}$	unit vector along Poynting vector
t	elapsed time, s
Δt	orbit raising time, s
u	acceleration, $\mathrm{ms^{-2}}$
W	radiation concentration

W_{3D}	ideal three dimensional mirror concentration
$\bar{W}$	orbit-averaged concentration
y	lifetime, yr
α	angle subtended by sun at Earth, 0.0093 rad or 0.53°
γ	orbit inclination to ecliptic, deg
δ	angle of incidence or reflection, deg
$\Delta\delta$	angular deviation of mirror, deg
$\dot{\delta}(t)$	angular velocity of mirror, rad s^{-1}
$\ddot{\delta}(t)$	angular acceleration of mirror, rad s^{-2}
θ	viewing or elevation angle, deg
$\bar{\theta}$	time average elevation, deg
ℓ	mass separation, km
λ	latitude. deg
ψ	mirror fill factor
ρ	density, kgm^{-3}
σ	areal density, kgm^{-2}
τ	torque, Nm
ϕ	one-half of cone angle, deg
$\bar{\phi}$	zenith angle to mean mirror elevation relative to Earth's center, deg
ϕ_m	ϕ when elevation is 30°, deg
Ω	rim angle, deg
∇	gradient operator

INTRODUCTORY ASSESSMENT OF ORBITING REFLECTORS FOR TERRESTRIAL POWER GENERATION

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SUMMARY

The use of orbiting mirrors for providing energy to ground conversion stations to produce electrical power is shown to be a viable, cost effective and environmentally sound alternative to satellite solar power stations and conventional power sources. This is accomplished with the use of very lightweight metal coated polymeric films as mirrors which, after deployment at 800 km, are placed in operational orbit and controlled by solar radiation pressure. Relations are developed showing the influence of a number of parameters — mirror altitude, orbit inclination, period, mirror size and number, and atmospheric effects — on the reflected insolation that may be received by a ground spot as a function of location. Space technology drivers appear to be the pointing and control of such structures, material lifetimes in space and an advanced earth-to-orbit transport system. The ground station is shown to be the major component of the total system investment, since the cost of reflectors in space is much less than that of the ground station. Some attractive alternative uses of the reflector are briefly discussed as beneficial adjuncts to the system. The environmental issues of principal concern appear to be the possible perpetual twilight that neighboring communities might experience and the land area required, while atmospheric effects are believed to be minimal and perhaps beneficial. Bus electricity costs are shown to range from about 25 to less than 10 mills/kWh, depending on the state of technology employed and the system size. Capital requirements are large for optimum systems, that is, those capable of meeting the U.S. or world power needs. Possibilities are described, however, for adding incrementally to the natural insolation received at existing solar facilities.

INTRODUCTION

The seemingly insatiable need of the world community for energy has recently prompted the examination of many alternate sources to substitute for our increasingly expensive and limited supply of fossil fuel. At first glance, solar energy would appear environmentally attractive and in limitless supply. However, research over many years aimed at exploiting this resource on a large scale for electrical and other high-enthalpy use has not succeeded in replacing the less costly fossil fuel alternatives. This economic disadvantage stems from a number of factors. The first is the "diluteness" or low energy

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density of solar radiation (amounting at most to 950 W/m^2 when the Sun is at zenith) which demands a very large collection area for meaningful system output power. Second, the radiation source is not stationary in the sky, thus demanding, for effective operation, active tracking by the large area collector. Finally, the solar intensity is not constant — varying according to the day-night cycle, the time of day, the seasons, the weather, and local obscuration phenomena — effects demanding energy storage facilities for continuous power output. These latter factors reduce the continuous solar intensity of 1.4 kW/m^2 (one solar constant) available above our planet's atmosphere to a useful yearly time-averaged intensity in the United States of only 0.2 kW/m^2. All of the aforementioned factors conspire against the economic viability of this otherwise desirable source of energy.

To avoid many of these problems, an interesting concept has been proposed (ref. 1) to place the energy collection system in space, either a solar cell array or thermal cycle, which provides an almost continuous supply of electrical energy to a phased-array of microwave generators. This radiation is directed, virtually unattenuated, through the atmosphere to a ground station where a rectenna converts the microwaves to usable electrical output power. This satellite solar power system (SSPS) has received much study (ref. 2). Its most serious detractors point to its reliance on considerable technological advancement to achieve electrical output which is cost competitive with alternate nuclear or fossil fuel derived power, and to possible, though as yet not completely assessed, ecological effects. However, as recently suggested (ref. 3), such a space-related solution to our energy dilemma would certainly represent a bonus payoff from our support of space research of the past.

In this document we have examined another space-oriented concept — the possibility and economic viability of using large mirrors in space to reflect solar energy to selected ground sites where the conversion to electrical energy is made. The intent is to provide, by a minimal number of mirrors placed in suitable orbits, both high solar intensity (i.e., concentration) and continuity, thus eliminating most of the aforementioned factors which normally make "solar farming" economically untenable. Although we have found in the preparation of this document that space mirrors have received limited consideration before (refs. 4-6), to our knowledge such a study incorporating a number of innovations made here and directed to the economic generation of electrical power has not been made. Our main goal here is to (1) make an initial technology assessment of this approach, determining the near-term areas and those which present challenges, and (2) to examine the possible environmental and economic payoffs attendant to its implementation.

GENERAL CONCEPT

Before beginning the technological examination of the subelements of the orbiting mirror system, it is useful to examine it as a whole. The desire is to provide <u>concentrated</u> and <u>continuous</u> insolation to one (or more) ground sites. The concentration can be effected by focussing the image of the Sun, by means of refractive or reflective optics located in space at altitude h, onto the ground receiver. As can be seen schematically in figure 1, both the angular subtense of the Sun, $\alpha = 1.39\times10^6$ km/1.5×10^8 km = 9.27 mrad and the large distances of orbital satellites, provide a lower limit to this image size. If a planar mirror of diameter D_m is used, this minimal size is $D_s = D_m \cos \delta + h\alpha$ where δ is the mean angle of incidence (and reflection) of the solar radiation on the mirror. An improvement in concentration can be made by providing at a given orbit position a three-dimensional array of such planar elements (called a Fresnel Field) spatially arranged and individually pointed in such a fashion that each of the reflected images coincides at the receiver. This focussing system provides a minimal Sun image size of $D_s = f'\alpha$ where, to first order, the focal length is equal to the orbital altitude, $f' \approx h$.

We note two facts from this minimal size. First, the dimension is large — amounting to approximately h/100 or 10 km even for an orbit altitude of 1,000 km. Secondly, if we wish to achieve concentrated radiation in this area, that is in excess of ambient terrestrial peak solar values, we must provide a total mirror collection area in space which exceeds this area. Thus, although we can choose to provide a ground station smaller than D_s (based upon the economics of incremental approach to system set-up), the requirement for concentrated radiation sets the minimal scale for the mirror system in excess of $D_s \approx h\alpha$.

Of course, within limits, large mirror structures are possible in the weightlessness of space. Of particular importance to our study is the recent development of low mass per unit area mirror materials (various plastics) overcoated with reflective metal coatings and the possible development of low mass structural supports and controls. The goal of the Solar Sail Program now being investigated by NASA is to reach with such a system an area density of 3-6 g/m^2. Using such technology, we assume the feasibility of providing a focussing mirror array, which we call a satellite mirror, of the type discussed above and as shown in figure 1(b). The individual mirrors will be "free-flyers," that is, individually controlled and chosen in size to be consistent with near-term technology. The satellite mirror area will, of course, be the sum of these mirror areas.

The insertion of the mirrors into orbit will be accomplished in two or three stages. Earth to low orbit (LEO) lift can be provided by a Shuttle-like vehicle, or perhaps for cost effectiveness, a new Heavy Lift Launch Vehicle, followed by lift to approximately 800-km altitude with an OMS package on the shuttle or by an orbital transfer vehicle (OTV). Finally, the low area density of the mirror will allow the structure to be lifted to final altitude by means of solar sailing. While in orbit, the possible use of radiation pressure for station-keeping as well as mirror pointing is suggested. This multiple use of radiation pressure will hopefully reduce significantly the need and attendant transportation costs, for expendables required by other propulsive techniques.

A critical consideration in the orbiting mirror concept is the choice, of the many possibilities, of the optimum mirror orbit. This is complicated by many opposing considerations such as minimal spot size (h small) yet continuous irradiation (the over-site viewing time increases with h) the many possible orbit inclinations, the number and placement of ground sites, and finally, practicality and economic considerations. Clearly, a full parametric study of this is necessary. We have considered certain cases, as seen in figure 2, such as a geo-stationary orbit which, having a period of one sidereal day, provides simple energy continuity since it remains fixed in view of the receiver.

Lower orbits give smaller image size and thus demand smaller mirrors. However, a complication arises because of their shorter periods. This necessitates the use of more than one satellite mirror so arranged that at any time at least one is over the ground site within a useful observation region (chosen to be a right cone of maximum angle relative to the zenith of 60°). Polar, equatorial and other orbits have been examined. The number of satellite mirrors and their requisite area to provide a reflected, continuous insolation of 1.4 kW/m^2, including atmospheric and geometric effects, has been examined as a function of altitude.

The conversion of this radiation to electrical power is considered by two techniques: the indirect method commonly considered for "solar farming" of a thermal cycle and the direct conversion using a flat array of photovoltaic (cadmium sulfide) solar cells. Both are considered in terms of near-term (1980) technology, allowing realistic cost estimates. Importantly, it is found that even a minimal system will make a significant contribution to the U.S. energy needs and, furthermore, the cost appears competitive with that afforded by fossil and nuclear alternatives.

Finally, the key issues in environmental impact and multiple use aspects of the system are briefly identified. The transmission of solar energy into our ecosphere would appear to be the least obtrusive of possible wavelengths. A positive environmental impact would certainly be to conserve our dwindling supply of fossil fuels as well as to remove the pollution accompanying their use for power generation. These, and similar considerations, would appear to outweigh the possible negative effects of land usage and atmospheric scatter leading to sky-glow in the vicinity of the ground stations. An attempt has been made to examine an attractive feature of this system: its multiple use capability. Thus, in addition to its primary function of producing electrical energy for the industrialized nations, those mirrors which are simultaneously over agrarian countries can be providing concentrated and continuous solar energy for their important needs such as extending the food growth season and yield, and the desalination and pumping of water for irrigation purposes. Such usage may, in fact, be the first as the system is incrementally brought into existence.

ORBIT CONSIDERATIONS

It is apparent from the minimum spot size relation (0.0093 h) that orbits nearer to the Earth's surface will require correspondingly smaller Earth receivers (and, as we will see, less complex orbiter reflectors) and thus, by using these lower orbits one can significantly reduce the magnitude of the required engineering. Besides the lessened capital requirements, transportation and operation costs should be reduced. In this section we consider the relative merits and liabilities of several orbit options. Four classes of orbits considered are shown in figure 2. These are geostationary (GEO), low altitude equatorial, polar (including Sun synchronous) and inclined orbits in general. As the latter class is most useful for mid-latitude ground stations, a large portion of the discussion is devoted to the apparent necessity of an array of equal inclination orbit planes, as shown in figure 3 (termed iso-inclination orbit planes).

An equatorially positioned mirror at GEO has the advantage of being stationary relative to a single ground station and can service it on a continuous basis, except for a 1 percent down time when it is eclipsed by the Earth. Lesser orbits result in shorter periods (varies as the 3/2 power of the radius), decreasing to about 90 min at low Earth orbit (LEO). Since the reflector is not stationary relative to a ground point, it can provide energy to that point only on an intermittent basis, at best only when it is above the local horizon and for practical purposes (as shown below) usually only when its elevation is above 30°. Thus, for continual illumination a number of satellites must be provided. This number depends on the orbit altitude, its inclination, the Sun shadowing period, and the insolation desired.

Although the imaged spot size diminishes with decreasing altitude a lower bound exists, other considerations aside, to the altitude we may employ. This limit is imposed because of atmospheric drag causing orbital decay. The low ballistic coefficient of the proposed structure requires a minimum operation altitude of 1750 km to provide a lifetime of 100 years, an adequate margin for a proposed service duration of thirty years. This is for circular orbits, the option is available of using eccentric orbits, whereby one can achieve 900 km, but with an apogee of 10,000 km, and a 100 year life. Further, as discussed later, solar sailing techniques can perhaps be employed to counter the drag and altitudes as low as 800 km can be used.

Reflectors Required

For energy continuity at the ground spot, it is necessary to establish reflector orbits in such a manner that at least one mirror is in view of a given ground station at all times. Obviously, it is also necessary that this mirror is not shadowed (supportive conditions to this requirement are considered later). Basically, the number required to meet this condition is dependent on the location of the ground station and the orbit altitude. The fraction of sky viewed from one point is limited. Due to a number of effects, discussed later, the reflected radiation received by a ground station diminishes with decreasing elevation angle. An elevation angle of 30° has been chosen as a minimum for receival of useful quantities of radiation and this value will be assumed in the following, unless otherwise stated. Given this angle, θ, fixed the following evaluation can be employed (see fig. 4) to determine the fraction of an orbit (which passes through the station's zenith) that can be viewed from a single spot:

$$\phi = 90° - [\theta + \sin^{-1}(f \cos \theta)] , \qquad f \equiv (1 + h/r_e)^{-1} \tag{1}$$

where ϕ is the angular position of the mirror as seen from the orbit's center, and r_e, the Earth's radius. When $\theta = 30°$, ϕ_m is found to vary from 18.9° to 52.5° as the altitude changes from 2000 to 35,800 km. Thus, ground stations which are fixed relative to a single orbit plane would require only

$$N_e = 360°/2\phi_m \qquad (2)$$

satellites in order to maintain one mirror above 30° at all times. Unfortunately, only at three latitude points is an orbit-fixed ground spot possible. A single equatorial belt with N_e equally spaced mirrors will "fill the sky" above any ground station on the equator as each mirror will rise and set on a true east-west line. Similarly, a single ground station at each pole will be serviced by a north-south belt. At all other latitudes the ground station rotates with respect to a given belt, passing under the belt twice daily, providing that the belts' inclination, i, to the equator is greater than the station's latitude.

Ground stations, located off the equator, could still derive some benefit from a single equatorial reflector belt. However, the mirrors will no longer pass directly overhead, and at stations of increasing latitude the mirrors will be below the chosen elevation minimum of 30° for increasing periods. The latter effect may be compensated for by placing additional mirrors in the belt. For example (as can be found from eq. (3)), ground stations at latitudes of N or S 10° would require nearly two additional mirrors at an h of 2000 km, compared to the 9-1/2 necessary to service equatorial sites. And, for this altitude, at 18.9° N or S each satellite would only be seen for the instant, at 30° elevation, as it passes due S or N of the station, respectively.

As the latitude of the desired ground station becomes larger than ϕ_m, there are two choices.[1] First, the equatorial belt may be retained but the mirrors must be in higher altitude orbits, to increase the cone angle. The equatorial number required for a station at latitude λ may be found from an approximate modified form of equation (2).

$$N_e' = \frac{360°}{2(\phi_m^2 - \lambda^2)^{1/2}} \qquad (3)$$

To reach latitude 32° (southwestern United States, for example) with much effectiveness, h could be chosen as 10,000 km, resulting in ϕ_m of 40.3° by equation (1) and $N_e' = 14.7$, instead of the four mirrors required at this altitude for equatorial stations. From this southwest U.S. location, although a mirror would always be above 30°, a maximum elevation of only 41.6° could be obtained.[2]

The other alternative is to place the reflectors into a number of orbit planes, each with the same inclination but separated inertially by equal

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[1] Similar arguments apply to the use of the polar belt.
[2] The maximum elevation may be found from equation (20), discussed later.

degrees of longitude and by equal degrees of anomaly as shown in figure 3. In this situation as the ground station rotates it will pass under new orbit planes. To make use of the satellites in both ascending and descending nodes, the orbit planes at i inclination would be somewhat greater than the sites' latitude. We immediately see, that the number of mirrors required to meet the 30° viewing elevation criterion, is larger than N_e since in the equatorial case each mirror is employed each time it orbits. With inclined orbits a given mirror will only pass directly over a station twice a day; once ascending and once descending as shown in figure 5. (This is rigorously true only if the orbits are "integer," which can be achieved if a given mirror's period in hours is in integer divisor of 24.[3] Additionally, the orbit altitude and inclination must be chosen such that a "compatibility"[4] exists with the ground site during a later orbit as shown for an example 3 hr orbit period in fig. 5.) The number of mirrors required in an inclined orbit, N_i, is given approximately by the ratio of 24 hr to twice the elevation viewing period — the time each takes to pass through the zenith while transversing the 120° sky angle over a ground station. The period of a circular orbit is given by

$$P = 1.4\, f^{-3/2}\ \text{hr} \tag{4}$$

so that

$$N_i \approx \frac{24}{4\phi} \cdot \frac{360}{P} = \frac{1543}{\phi}\, f^{3/2} \tag{5}$$

N_i is found to vary from about 54 at $h = 2000$ km to a little over 9 at 10,000 km. It can be seen that for latitudes moderately removed from the equator, this process is more effective than that governed by equation (3). The equi-longitude array of satellites has the further advantage over the equatorial belt concept for these removed latitudes in that the average elevation angle of the mirror in the former case is higher.

Equation (5) represents the minimum number of mirrors required with the proviso that each passes overhead. (These orbits may be established to meet this criterion for a particular ground spot; they will also exactly match a number of other stations, related to the first by a longitude-latitude relation. Additionally, at times, there may be other mirrors that pass through the viewing cone of a station but do not transit the zenith. The second orbit pass in figure 5 illustrates this case. Because useful reflected radiation (from above an elevation of 30°) may also be received from these nonzenith passes the size of each mirror, needed to produce a given average insolation at the ground station, may be reduced. An estimate of the number of "extra" mirrors may be found by first dividing the global area covered by the set of iso-inclination orbits by the area of a single viewing circle, that is,

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[3] Integer orbits repeat relative to a ground station in a period somewhat different than a sidereal day due to the effects of oblateness.

[4] Compatibility is defined such that a satellite passes through the zenith above a ground site twice a day.

$$N_t = \frac{4\pi r^2 \sin}{2\pi r^2(1 - \cos\phi)} = \frac{2 \sin}{1 - \cos\phi} \tag{6}$$

Thus, a 2000-km orbit of $i = 40°$, radiating between N and S 40° has $N_t \approx 24$, compared to N_i of 54. N_t is both the theoretical number of ground stations and, at a given instant, the number of mirrors in viewing cones that will pass through stations' zeniths — that is one for each station. $N_i - N_t$ is then the number of extra mirrors while the ratio of this value to N_t is the number of nonzenith passing mirrors within a station's viewing cone on a time-averaged basis.

Orbit Insolation

A real consideration for a reflector providing illumination is the eclipsing effect of the Earth — at times most orbits will be shadowed. This problem can be dealt with in two ways. First, by development of relay techniques which permit sunlit mirrors to reflect their received radiance to other mirrors and thence through a "master" to the station of interest. This concept is explored in the next section. And, second, we may select orbits that will minimize the shadowing problem.

Orbit elevations providing continuous insolation may be found from the relation

$$h \geq r_e (\csc\gamma - 1) \tag{7}$$

where γ is the inclination of the orbit relative to the Earth-Sun line, as is indicated in figure 6. Since this line will vary ±23.5° relative to the equator it is apparent that a polar orbit, for example, may have a γ as small as 66.5°, providing that its east-west axis is maintained roughly normal to the Sun's radiation (i.e., in a Sun synchronous orbit). Any such Sun-synchronous near-polar orbit above 575 km will satisfy equation (7). Although such low orbits provide smaller ground spots which is very advantageous from an initial investment's standpoint, the lifetime is short because of drag. (The drag problem can be circumvented by using an orbit with its perigee, at the pole, of 900 km and an apogee of 10,000 km, but then it services only one pole and the effects of Earth oblateness will gradually shift the line of apsides away from the polar orientation. Alternatively, solar sailing can be used to counter drag down to about 1000 km if mirror usefulness is to be retained.) Higher orbits would permit service to ground stations at much lower latitudes, below the 60th with orbit altitudes of 10,000 km, as much the same arguments apply here as with the equatorial belt case. It is important to emphasize that polar belts, although only passing directly over the two stations, have the great advantage by equation ([illegible]) of being continuously sunlit. Actually, to achieve this they must be in zero solar drift rate orbit planes — the regression of the orbit plane due to the Earth's oblateness just balances the motion of the Earth about the Sun. Such Sun synchronous orbits do not exist for the polar inclination but only for somewhat higher orbit inclinations (retrograde), as may be determined from

$$h + r_e = 12349 \cos^{2/7} i \,, \quad \text{in km} \tag{8}$$

A 1400-km orbit, with an inclination of 101.43°, is the minimum altitude orbit that satisfies both equations (7) and (8). Although this belt is not fixed with reference to a given ground point, continuous illumination can be provided to the polar points and other near regions where a mirror from the belt is always above the local horizon. More areas could be reached if the belt were higher. Because at greater altitudes the oblateness has a decreasing effect, a maximum Sun synchronous altitude of 5972 km is the limit (the inclination must also increase to maintain Sun synchronous conditions). Besides higher orbits, other possible options exist for continually illuminating the ground station. Partially shadowed planes can be chosen and multiple belts used. Orbits of various solar drift rates as fixed by altitude and inclination can be chosen. The added variable of equal time (longitude) mirrors discussed earlier in this section must also be analyzed for the shadow effect. As can be appreciated, a good deal more study must be done before we can optimize the orbits and the number of mirrors required to service one or more ground stations. (In actuality, even without specially selected orbits the magnitude of the eclipsing effect is not large. For example, with $i = 40°$, 13 percent and 6 percent of the total orbit is shadowed at 4000 and 10,000 km, respectively. Since this is for the whole of the orbit, if only ground stations are considered at the extreme of orbit trace (i.e., $\lambda = 40°$) then the percent occultation is much less than these values.)

ORBITAL REFLECTOR CONSIDERATIONS

The success of this program rests very strongly, of course, with the ability to engineer optimized space mirrors. Fortunately the technology appears within the near-term although the scale is large and in some instances the effects of the space environment have not yet been fully researched.

Solar Concentration

Solar concentration in general becomes necessary when high temperatures are wanted, or when, as in the case with photovoltaic cells, the cost of the absorber is much higher than the cost of the mirrors. From our economic considerations it will be seen that it is indeed desirable to concentrate, that is, use mirror areas which exceed those of the ground spot area, the latter being found approximately from (normal incidence)

$$D_s = f'\alpha \approx h\alpha \qquad (9)$$

where D_s is the spot diameter, f' the effective mirror focal length, h the orbital altitude, and α the subtense angle of the Sun.

The fundamental problem of radiation concentration can be stated as follows: How can radiation which is uniformly distributed over a range of angles, 0 to $\pm\alpha/2$, arriving from the sun and incident on a mirror aperture of area A, be concentrated on a smaller absorber area A_{abs} and what is the value of the concentration $W = A/A_{abs}$? The second law of thermodynamics can be used to set an upper limit on W, namely for an ideal three dimensional concentrator (set of mirrors in our case), the maximum is $W_{3D} = 1/\sin^2(\alpha/2)$, which for $\alpha = 9.3$ mrad is 1.52×10^8. We are interested in much lower concentrations, namely those sufficient to make up for the losses encountered by passage of the reflected radiation through the atmosphere (absorption and scattering) and for the geometric effects associated with the angle of incidence of the solar radiation onto the mirror elements (δ) and the ground station θ and the fact that the position of the ground station may deviate somewhat from the focal plane of the mirror ($S \neq f'$). (The geometry has been shown in fig. 4.)

Consistent with the concept discussed previously, we assume that a number of small "free-flyer" mirrors will be suitably arranged (clustered) in space to approximate a parabolic, focussing satellite mirror. Thus the smaller mirrors are individually oriented to reflect the Sun's image onto a common ground spot. It can be shown that the concentration for such an array is

$$W = \psi \left[\frac{\cos(\Omega + \alpha/2)\sin\Omega\cos\delta\cos\theta}{\sin(\alpha/2)}\right]^2 \qquad (10)$$

where ψ is the "fill factor," that is, the fraction of available mirror aperture actually filled with mirror elements and Ω is the "rim angle" of the mirror array. Because the small mirrors must be separated in space to allow for motion and to prevent shadowing, ψ will be of order 1/2,[5] given by $\psi \cong A_m/\pi R_m^2$ where A_m is the actual area of coated plastic and R_m is the radial extent of the satellite mirror. The rim angle is given by R_m/S, S being the distance to the ground station as seen in figure 4, namely $S = \sin\phi/f\cos\theta$.

In principle the value of W can be evaluated as a function of time (using eqs. (1) and (4)) given the orbital altitude h of our assumed circular orbit, the latitudinal position λ' of the ground station, and the allowed viewing angle cone specified by ϕ_m. However, in this initial exploratory assessment, we have chosen some representative orbits and evaluated the time averaged values of ϕ, $\bar{\phi}$, the mean mirror elevation angle, and the time averaged distance S to account for out-of-focus spreading at the ground site and atmospheric absorption. The average ground site insolation can then be related to the average concentration by

$$Q = I_o\bar{W}\Sigma \qquad (11)$$

where Σ is a product of transmissive loss factors which will be discussed later. It will be appreciated that all of these considerations set the scale of the effective mirror array. The choice of the mean reflected ground insolation value is one of these — we will choose it to be 1 solar constant (1.4 kW/m^2) in this paper, however, the possibility of lower insolation (or higher) for specific end use will correspondingly decrease (or increase) the large mirror areas derived from the above relations.

Generally then we are considering mirror <u>arrays</u> whose size exceed those of the ground spot ($\alpha h \approx 100$, 200, and 300 km for $h = 10^4$, 2×10^4 and 3×10^4 km,

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[5] Since Ω varies with ψ the fill factor selected has little effect on W.

respectively) and which, because of this scale, will need to use component mirrors, as large as is technically feasible. We will consider some restrictions to these dimensions shortly.

Relay Possibilities

A further reduction in mirror size is possible if a "relay" system, as shown schematically in figure 7, can be developed. Here each mirror (or mirror cluster) individually collects solar radiation and relays a focussed beam to its neighbor mirror in the orbital band of satellites encircling the Earth. The neighbor mirror collects solar radiation directly as well as that from the prior mirror and again relays this to the next satellite. Ultimately this relayed power collected by n satellites is sent downward to Earth by a master transmitter, which is suitably over the receiving site of interest. Hence, to achieve a solar constant of radiation in the spot, the required individual mirror area will approach 1/n of that demanded by the single reflector scheme times a reflector distance factor which accounts for beam spread. This technique is particularly cost effective, not only in allowing a reduction in the mirror mass to be placed in orbit, but, especially for continuous insolation orbits, to allow all of the orbiting satellites to simultaneously be performing useful work independently of their being over the horizon of the intended receiver sites. It should be cautioned, however, that the exact passive mirror system which accomplishes the dual functions of collecting, relaying, and, when it is over the site, downward transmitting still remains a challenge to the optical designers. It may be necessary to use refractive optics, active optical techniques, or even to incorporate amplifier techniques in some manner similar to those contemplated in lengthy optical communications lines.

Mirror Structure

Some prior work has considered large mirror structures in space. Orberth (ref. 4) originally proposed a mirror constructed on radial and crosslinked guy lines held rigid by the centrifugal forces provided by rotation of a centrally located spaceship. Very thin reflective material, namely, sheet sodium metal prepared in the vacuum of space, was then stretched over and affixed to this frame. Sodium was chosen because of its low density and its ready availability (in the salt of the oceans, etc.). Interestingly, he also suggested the desirability of obtaining structural material from the Moon and from asteroids, a concept which has received much recent study by O'Neill et al. (ref. 7) as a possible means to lower the costs associated with the conventional power satellites. More recent examination of mirrors in space has been made (ref. 5) on the solar concentrators necessary to solar-drive the Brayton Engine power satellite. Concepts examined all made use of low density (Kapton, Mylar, etc.) thin plastic substrate material suitably coated with thin metal films, such as aluminum. Configurations studied have included inflatable, inflatable-rigidized, petal, and faceted mirror types. A problem with the inflatable configuration is gas leakage produced by micrometeorite holes, etc. If the structure can be rigidized quickly after inflation, by polymerization or other techniques, this problem may be avoided. In general, however, it appears that faceted mirrors, that is, those constructed of a large number of (redundant) individual tensioned plane sections, probably of hexagonal shape, are most consistent with low mass/area, high strength, assembly in space, and long lifetime or, if necessary, maintenance. A schematic configuration is illustrated in figure 8. The facets can be oriented to approximate a parabola with a low mass stressed cable and boom structure. Finally, NASA has recently begun an examination of the possibility of "solar sailing" in interplanetary space (to be discussed later) which has evolved new concepts, such as possible mirror configuring with electrostatic forces, and new demands on the development of low mass/area mirrors, structures, and control and guidance systems. Preliminary work indicates a presently available technology-achievable value for this in the range of 3-6 g/m^2. In the calculations of this section, we shall assume the system mass/area to be $\sigma = 6\ g/m^2$. The metal overlayed 25-μm film (Kapton, Paralene, etc.) for the solar sail program should be capable of operating continuously with solar intensity of 10 solar constants (14 kW/m^2) at temperatures of 350° C, and should provide specular reflectivity in excess of 85 percent. The solar sail mirror is targeted to be an 800 m × 800 m square mirror. With some modification, the low mass axial mast-spars-and-stays structural configuration of the square solar sail mirror appears usable for the cluster mirrors discussed above.

Orbit Environment Effects

One may well ask whether the environmental demands on such a large structure are compatible with present day materials and technology. Prime concerns are those forces associated with (1) gravity gradient forces, (2) centrifugal forces associated with rotation of the structure, (3) stresses introduced by nonuniform temperatures (such as occur when the structure rotates through the shadow of the Earth), etc. A few calculations have eliminated some concerns here, but further study associated with <u>specific</u> structure designs is necessary.

Gravity gradient forces arise because various elements of a structure are at different distances R from the center of the Earth and hence are subject to forces varying with $1/R^2$. Thus, if for simplicity we consider two mass elements at radii R and $R + \delta R$, there will be a net force

$$F_g = \frac{dF}{dR} \cdot \delta R = \frac{2GMm'}{R^3}\,\delta R \qquad (12)$$

acting on the center of mass of the two-mass system, and in general producing a torque about this center of mass given by $\tau \approx F_g \ell \sin B$ where ℓ is the mass separation and B is the angle between ℓ and the radius vector extending from the center of the Earth. At times these gravity gradient forces can be used to advantage, for example, to keep structures always in a particular orientation relative to the surface of the Earth ("gravity gradient stabilization"). Here we examine how the strength of available materials limits the structural size. If we consider a rod-like structure with $B = 0$, that is, all mass elements lie along their common radius vector, then the gravity gradient stress on the rod is approximately

$$\frac{\rho \ell^2 g_o r_e^2}{2R^3} \qquad (13)$$

where ρ is the material density, g_o the zero altitude acceleration due to gravity, r_e the Earth radius, ℓ the length of the structural member, R the distance between Earth center and the closest mass element. For structural integrity, we must demand that this stress does not exceed the "yield stress" for the material, that is, the stress beyond which it inelastically deforms. Considering the possible low density aerospace materials, Ti (6Al-4V) alloy, Al (2024) alloy, and composite $[0°]_{8S}$ laminate, it is found that the gravity gradient stress will not be excessive. In fact, if one computes the "yield lengths" ℓ allowable, they all exceed the conceivable upper-limit mirror structure dimensions (≈2 hα) by more than a factor of eight at all altitudes. Similar analysis must also investigate the effect on mirror materials. Corresponding calculations were not performed on the gravity gradient torques and temperature effects since, of course, they are closely related to the exact structural mass configuration. However, a successful mirror design (i.e., one which will remain intact and whose figure will remain — by passive or active methods — within tolerance) must incorporate these torques and stresses and their variation.

The durability of such mirrors in space is of some concern. Some experience was attained from the Echo I satellite which was an inflated sphere of 12.5-μm Mylar overcoated with 0.22 μm of aluminum. After 4 years, its reflectivity decreased only by 4.7 percent. This loss can be attributed to meteor cratering which removes available reflective area, sputtering by high energy particles in the Van Allen belts and especially blistering caused by the trapping of low energy protons from the solar wind which produce hydrogen bubbles at the plastic-metal interface. Boeing Aerospace Co. (ref. 5) has estimated the meteoroid damage to be minimal for a system at GEO, 3 percent area lost per 30 years. However, the sputtering erosion and hydrogen effects are much less certain. They believe a minimum unattended lifetime of 8 years is achievable; however, further testing is necessary. Hopefully such tests will take place within the year on the materials being assessed for the Solar Sail Program. In any event, it will appear reasonable to assume it desirable to provide an <u>in situ</u> technique to recoat the mirrors. A metal evaporator situated at each end of the boom normal to the mirror face should easily, periodically re-evaporate new coatings to both sides of the mirror surface in the ideal vacuum of space. In this way a much longer maintenance-free lifetime, depending only upon micrometeorite area removal and substrate degradation, will ensue.

Another lifetime which must be considered is that presented by the atmospheric drag on such a low ballistic coefficient-structure. As will be discussed later, a reasonable scheme to putting a mirror into space involves the placement of partially constructed structures into low Earth orbit (LEO), assembly or deployment for cluster-mirror size, and then solar sailing the mirror to final altitude. The latter avoids the development of new ion thruster vehicles and the requisite expenditure of fuel. However, the orbital decay because of atmospheric drag puts a lower limit on the altitude where this process may begin. For $\sigma = 6$ g/m^2, the ratio of drag force to radiation force is ~0.1 at 800 and ~0.001 at 1000-km altitude. Thus, if rapid deployment is possible, a starting altitude of 800 km appears reasonable. Because of the drag, orbit raising will then begin slowly, ideally reaching 1000 km in ~2 days, 5000 km in 23 days, and, if desired, geosynchronous orbit (GEO) of 35,800 km in 64 days.

Solar Sailing

As can be seen from the previous discussion, it is anticipated that solar radiation pressure will play a significant part in the solar mirror concept. For this reason, it is desirable to discuss the characteristics of this phenomenon. As predicted by Maxwell, electromagnetic radiation has been shown to carry momentum: The momentum density of the wave being given by $\vec{p} = \vec{S}/c^2$ where $\vec{S} = \vec{E} \times \vec{H}$ is the Poynting vector (watts/m^2) associated with the wave, $\vec{E}$ and $\vec{H}$ are the electric and magnetic field components of the wave, and c is the wave propagation velocity. In general, the momentum imparted to a material will depend upon its absorption a and reflection b coefficients, where $a + b = 1$. Absorbed radiation will impart momentum in the direction $\underline{\hat{s}}$ of $\vec{S}$, while reflected radiation inputs momentum normal to the surface, along $\underline{\hat{n}}$, as shown in figure 9. The corresponding forces will be

$$\vec{F}_{abs} = (aI_0 A \cos \delta/c)\underline{\hat{s}} \tag{14}$$

and

$$\vec{F}_{ref} = (2bI_0 A \cos^2 \delta/c)\underline{\hat{n}} \tag{15}$$

where A is the area irradiated, δ is the angle between $\vec{S}$ and $\underline{\hat{n}}$, and I_0 is the intensity of the incident radiation in watts/m^2. Clearly, these forces are small since we do not notice them in our daily experience. But they are finite (a few mg/m^2) and become important when the area is large. Thus, if we consider an object with area mass density σ kg/m^2, and neglect absorption ($a = 0$, $b = 1$), the resultant acceleration is seen to be $u = F/\sigma A = 2I_0 \cos^2 \delta/c\sigma$. For our mirror structure $\sigma = 6\times10^{-3}$ kg/m^2 and for solar intensity of 1.4 kW/m^2 incident at $\delta = 45°$, $u \approx 8\times10^{-4}$ m/sec^2. If we compare this with gravitational acceleration at orbital altitude h, $g = g_0(1 + h/r_e)^{-2}$, we obtain $u/g = (2I_0 \cos^2 \delta/\sigma c g_0)(1 + h/r_e)^2$ which at an altitude of 10^3 km is only a maximum of 9.2×10^{-5}. For this reason, the orbit raising discussed above proceeds very slowly at the beginning of the process. In this regard, it can be shown that the maximum increase in altitude per revolution (neglecting drag) is very nearly obtained by rotating the mirror at one-half the orbital revolution rate. Then the solar force, averaged over one orbital period, is about one-half of the maximum attainable radiation force (i.e., for $\delta = 0$). The time necessary to attain a final altitude h_f, starting at altitude h_0 in a low thrust spiraling orbit can be shown to be, in this approximation,

$$\Delta t = [\sigma c(g_0 r_e)^{1/2}/I_0](f_0^{1/2} - f_f^{1/2}) \tag{16}$$

Actually, because eclipsing of the mirror will occur for most orbits (except Sun synchronous) the orbit raising times will generally exceed this minimal value, in some cases by a factor of 2.

Control

Finally, another area needing study is that of pointing and tracking of such large structures in space and the resultant torques which must be exerted and energy expended in this task. For the intermediate Earth orbit altitudes, as discussed earlier, the mirror sweeps across the ground site in a fraction of an hour. Using the nomenclature defined earlier (see fig. 4) the mirror rotates in its orbit at altitude h with a period $P = 1.40\ f^{3/2}$ hr, where $f \equiv (1 + h/r_e)^{-1}$, and constant orbital angular velocity $\dot{\phi} = 2\Pi/P$. As this rotation occurs, of course, the mirror angle δ, measured between the incident rays of the Sun and the mirror normal, must vary so as to continuously reflect radiation onto the receiving station. This angle is related to the elevation angle θ by $\delta = \theta/2 +$ constant, where the constant is determined by the position of the Sun relative to the orbital plane and the factor of 1/2 arises because the angle of incidence of the Sun's rays onto the mirror equals the angle of reflection. The angle θ, measured relative to the horizontal, varies between 0° and 180° as the satellite moves across the sky. The elevation angle is related to ϕ by the expression

$$\phi = 90^\circ - [\theta + \sin^{-1}(f \cos \theta)] \qquad (1)$$

and thus we have the necessary expressions to evaluate the angular velocity of the mirror, $\dot{\delta}(t) = \dot{\theta}(t)/2$, and angular acceleration $\ddot{\delta}(t)$. In addition we can evaluate the time t the mirror takes to move between θ_0 and θ. These rather complicated expressions will not be given here, however we can state some typical results.

At an altitude of 8000 km, $\dot{\delta}$ is of the order of 10^{-4} rad/sec while $\ddot{\delta}$ is of the order of 10^{-8} rad/sec^2. This appears to be a moderate requirement although one must be mindful of the very large structures involved. To avoid centrifugal loading it may be desirable to individually rotate mirror facets. This would also minimize the rotational kinetic energy which must be supplied by substantially reducing the mirror moment of inertia. On the other hand, certain orbits and arrangements of ground stations may allow a simple integral, almost constant rotational motion so that after the initial investment of the large rotational kinetic energy, very little additional energy would be needed for fine-tuning the mirror angle.

The necessary pointing accuracy of the mirror can be assessed by noting that an angular deviation of the mirror $\Delta\delta$ produces a beam spot center motion of $\Delta r = 2h\Delta\delta$ on the ground. A reasonably tolerable beam spot error on the ground is $\Delta r/r =$ constant, that is, for large receiver stations we tolerate larger (in absolute value) wander. Since the spot radius is $r = h(\alpha/2)$, we then obtain

$$\frac{\Delta r}{r} = \text{constant} = \frac{2h\Delta\delta}{(1/2)h\alpha} = \frac{4\Delta\delta}{\alpha} \qquad (17)$$

Thus if the tolerable percentage error in the ground spot position is 10 percent, $\Delta\delta = 250$ μrad, independent of the mirror altitude. Further study will be necessary to assess the pointing accuracy attainable with such structures as those being considered here.

One concept that seems appealing, and needs further analysis, is the possible use of radiation pressure to effect mirror steering. Here one could imagine flywheels, as were shown in figure 8, of composite (low mass but high strength) material affixed to the extreme ends of three mutually orthogonal axes of the structure. The wheels could slowly be accelerated to nominal rotational velocity using radiation pressure before the mirror becomes operational. By braking action, rotational torques could then be applied conveniently to the mirror. Subsequent renewal of the flywheel kinetic energy would be made during a nonuse portion of the mirror's orbit around the Earth. If successful, such orientational techniques using radiation pressure could effectively negate the need for thruster fuel, a significant maintenance or initial payload problem associated with other power satellite schemes.

It should be noted, however, that radiation pressure, which heretofore has been used to advantage for orbit raising and mirror orientation, does present some potential difficulties. These are related to the facts (1) that the radiative force is proportional to the cosine of the angle of incidence of the solar radiation onto the mirror and (2) that in general, the Sun's rays will be at some constant angle relative to the plane of rotation of the mirrors. The first must be carefully assessed for any potential mirror configuration to assure that uncontrollable torques are not produced when the mirror slew angle is changed. There appear to be some simple methods to avoid this situation. The second radiation pressure effect mentioned can lead to a combination of drag, orbit raising, and orbit precession torques. In the special case of the Sun and mirror orbit being in the same plane, and the mirror being rotated to always direct the beam of radiation down normal to the Earth's surface, there is a net average radiation force per revolution acting to perturb the orbit. This, of course, is the force used in orbit raising, as previously discussed. It can also be used to compensate for drag when using low orbit mirrors. However, it will in general lead to an ever increasing orbit radius unless properly compensated. One solution, which appears simplest, is to dedicate part of the mirror rotation cycle (perhaps when the mirror is in the southern hemisphere) to station keeping, namely, rotation of the mirror to provide compensating radiation pressure drag. A similar situation develops for the sunlight making a nonzero angle of incidence onto the orbit plane. In general, a torque will be produced which will precess the orbit plane. The analysis of this, and how to compensate or perhaps use it, is difficult, but Oberth (ref. 4) has concluded that it can be negated by appropriate mirror orientations during the unused portion of the rotational cycle.

An interesting possibility exists that such a precessional torque could be used to obtain Sun synchronous orbits, that is, those for which the orbit plane precesses with a period of one sidereal year and which, therefore, can be arranged so that the mirrors in these orbits are never eclipsed by the Earth. As discussed elsewhere, this presently can only be accomplished by using the oblateness of the Earth as a perturbative torque on the satellite and the inclination of the plane of rotation must be carefully matched to the orbital altitude. This restraint may be removed if radiation pressure can be used to supply the precessional torque, thus, opening up many new continuous insolation orbit possibilities which are more attractive from the viewpoint of the desired small spot size and the surface location of the ground stations.

GROUND STATIONS

In considering the ground station requirements for receiving and converting the reflected sunlight, one must first assess the solar intensity available in both spacial and temporal dimensions. To increase the efficiency of conventional solar plants, they are designed to concentrate the incident solar radiation to increase the input to output temperature ratio of whatever heat engine is employed in the conversion process. Consistent with this it appears to be most cost effective to use a relatively high intensity from our orbiting reflectors. Such high fluxes would reduce the ground area requirement, the receiver equipment needs and it is also possible that intense beams would prove more penetrating in light cloudiness and fog situations.

Loss Factors I

A number of factors work to reduce both the intensity and total energy received at the ground station. An effective ground receiver must be optimized (design and location) to minimize these effects. Further, the reflector area must be increased to compensate for these losses. As some of these factors require considerable analysis and study, we can at present only point out the effects, their rough magnitude and some possible corrective measures.

1. A number of losses due to geometric factors and absorption, as described above, occur during the in-orbit collection, concentration, relay and reflection, all requiring an increase in mirror area to maintain a given ground-spot intensity. An analysis of the effect of imperfections, waviness and figure deviation in the mirror on ground spot intensity and continuity needs to be performed.

The orbiting mirror, in order to reflect directly to the ground station, cannot be normal to the Sun's rays and thus it intercepts less than a solar constant intensity. The compensating size required is a function of the final design and orbit choice; and, is of lessened importance if some relay technique can be found. At worst (when the Sun is directly overhead, i.e., at noon) it appears that a secondary mirror, approaching the primary in size might be required to maintain a reflected solar constant input to the ground receiver. But, at times these could both serve as primary reflectors producing nearly two solar constants. Thus, the net effect on the energy received by the station may be roughly proportional to the area of the added secondary. As yet we have not determined the increased mirror area required to compensate for this factor. Fortunately, as shown later, in most scenarios the mirror and its transportation to operational orbit is a minor element in the overall system cost.

2. We have already mentioned the spot-size relation to mirror configuration and altitude and the limits on orbits. In general, the mirror will not be at the ground spot's zenith which will result in a beam path length longer than h and a spot size that is proportionally larger. The path length, S, for the beam can be related to the elevation, θ, by

$$S = (r_e^2 \sin^2 \theta + 2r_e h + h^2)^{1/2} - r_e \sin \theta \ , \qquad (18)$$

where r_e is the Earth's radius. At 50°, roughly the time average elevation, this factor increases the path length of mirrors at orbit altitudes of 2000, 5000, and 10,000 km by approximately 20, 15, and 10 percent, respectively.

The minimum spot size for a flat reflector is $D_m + 0.0093S$. For a parabolic dish the optimum figure occurs when it is in focus for the distance at the average viewing angle. At higher angles the receiver is in front of the focus and for smaller angles, after the focal point. There is the possibility that with the parabolic mirror a controlled figure technique could be employed to fix the spot size during the reflector's arc over the station.

3. Except for zenith reflections, the beam from a round reflector will be elliptical (and rectangular from a square), elongated in the direction of the image source. This elongation will be equivalent to $1/\sin \theta$ and thus at our average mirror elevation a 1/3 elongation and dilution will be experienced. Obviously, it would be beneficial to mount our collectors normal to the ray source and actually track the mirror, as is done in the more efficient conventional type solar collection systems. However, as an assist in increasing the amount collected, this does not accomplish much since: (i) even the minimum beam is so wide that we can't construct beam normal collectors tall enough to significantly reduce the land area and fringe collector needs if we are to intercept the total beam. (It is true that such an arrangement can reduce the individual collector size and their area density but this would then leave holes when the reflector is near the zenith, losing energy in those periods. Nevertheless, depending on the ultimate design and conversion method, modified beam normal collectors may prove cost effective.) And (ii) it is likely that this system would be designed to collect energy, a high fraction of the time, from multiple mirrors at different vectors and during most daylight hours from the Sun directly. Such multidirectional collection requirements greatly reduce the value of tracking collectors.

4. Absorption and reflection losses in the clear atmosphere allow transmission of only 64 percent of the beam at the zenith and 54 percent at a 30° elevation. This is direct light; there will be a diffuse contribution from low angle scattering that will increase these energy ratios by a few percent at the beam center.

5. Cloud cover seriously affects the amount of transmitted radiation because of water droplet scattering effects. Rough estimates of this effect can be determined from $1/2 \sin \theta$ which gives the insolation received, relative to clear days, for conditions of complete overcast as a function of elevation angle. This relates to lower altitude cumulus formations while corrostratus clouds would have about half the effect and fog nearly twice as

great. This empirical relation for the Sun's radiation includes diffuse contributions and is certainly an upper bound for the beam value in the reflector case. As water does absorb 10 percent or so of the beam energy, there may be some hope of evaporating and thus, dispersing the otherwise interfering droplets, especially in the case of intense beams. It should be noted that the historical direct insolation data for a site is probably the most important factor in its evaluation. Sites can perhaps be selected where clouds will have about a 10 percent influence on reflector produced insolation. As the occurrence of clouds is independent of conditions 200 km distant, it is effective to establish a power grid containing several separate stations that the reflector would have a choice of powering, depending on local conditions.

6. Dust, smog, nitrogen oxides, and other pollutants act to either absorb or scatter the radiation. Again the avoidance of such areas is important in site selection.

7. The time of year will influence the insolation at the receiver station. First, the Earth-Sun distance causes a ±3 percent variation in the amount of energy intercepted in orbit. Also, the Earth's equatorial inclination to the ecliptic produces significant differences in the daylight period and if the collectors depend on the ambient sunlight for some of their energy input, then a corresponding variation can occur. Lastly, there is an indirect effect in that the cloud cover over most areas is seasonally variable.

8. We saw that the Earth eclipsing effect on the orbit belt may shadow the mirror, on average, a small fraction of the time. Hopefully, this effect can be avoided by either the relay technique or by proper orbit selection. We will neglect this factor until further analysis can better fix its possible magnitude for a chosen orbit and ground station combination. If, for example, the relay technique which would greatly reduce space reflector needs does not prove viable then short term storage facilities would probably have to be installed at the ground station.

Site Selection

These are the principal factors acting to reduce the ground insolation and which influence mirror and station requirements. Proper site selection for the ground station can lessen the impact of some of these factors. A high-desert area at the equator removed from pollution causing industrial/urban areas would be ideal. Unfortunately, since such areas are unattractive places to live and work, the power needs there are minimal. In this country maximum insolation is found in the New Mexico/Arizona region and here, land for large receiving areas would be relatively inexpensive. These advantages would have to be balanced against the transmission costs of power to the users. (The availability of inexpensive power and low land costs would eventually attract many industries.) If a central generating station for the whole United States were located in this area, it would be necessary to develop super-conducting, long-range power lines or go through an electrolysis energy conversion and pipe power as hydrogen. This latter option would be invaluable in damping the input and demand difference problem discussed below. In selecting a site, consideration should also be given to ocean based stations. Although the construction costs at such a site might be higher, the acquisition cost would be low. Cooling water for a Rankine or Stirling cycle plant, for example, is abundant, the absence of land features provides a maximum horizon, airborne pollution could be low, and the station could be located close to population centers (e.g., off of Long Island). Studies should be made to see if cloud cover is a deterrent to such a sea-based endeavor.

Loss Factors II

Taking the above enumerated factors into account and assuming that we are using a fairly optimum ground site, what sort of reflector produced ground insolation can we expect and how will this influence the mirror and station design? In factor (7), the insolation variation due to changes in the Earth-Sun cannot be avoided unless the orbit height or mirror size is changed seasonally; however, this effect is small. Factor (8), because of the lack of proper analysis at this time and its apparently small contributions, will be neglected. Factor (6) with the proper site will cause minimum difficulties and (1) we will assume has been compensated for by relay, or primary-secondary combinations so that the final mirror is reflecting the equivalent of a solar constant for a mirror of diameter 0.0093 h. Factors (4) and (5), absorption and scattering, act to reduce the total energy. If the mean cloudiness is equivalent to complete cumulus overcast 15 percent of the time, then the two factors combine to transmit from 61 to 49 percent of the beam as the reflector moves from zenith to 30°. To compensate for this, the reflector size can be increased — approximately doubled. Factors (2) and (3) act to spread the beam and reduce the intensity. The beam spread due to the mirror distance differing from the orbit altitude is given by $(S/h)^2$ and the elongation due to nonzenith elevations is $1/\sin\theta$, so, in order to collect all of the energy the atmosphere transmits requires a ground area of

$$\frac{(0.0093)^2\,\pi S^2}{4\sin\theta} \qquad (19)$$

This relation varies by nearly a factor of 5 between the extreme conditions.

Since the intensity and energy inputs depend strongly on the elevation angle and altitude of the reflector, it is necessary, before proceeding further, to determine, at least approximately, what the reflectors' time averaged position, $\bar{\theta}$, may be. These averages vary depending on the orbit option chosen. There are four distinct situations (in each analysis we consider only those mirrors 30° above the site's local horizon): (1) For a geostationary equatorial mirror its elevation, $\bar{\theta}$, remains fixed for a given site latitude and can be determined from a rearranged form of equation (1), in which latitude is substituted for ϕ.

$$\theta = \tan^{-1}\left[\cot\phi - \frac{1}{[(h/r_e) + 1]\sin\phi}\right] \qquad (20)$$

(2) For sites depending on a fixed equatorial or polar belt of reflectors the mean elevation is, to a very good approximation, the average of 30° and θ_{max}. Where θ_{max} is the highest elevation achieved and is the solution to equation (20) when L, the great circle degrees between the ground spot and the belt's nearest nadir (the spot under the point of apparent highest elevation), is substituted for ϕ. (3) For a site directly under a belt of mirrors which rise and set the mean, $\bar{\theta}$, is again from equation (20) but by substituting 1/2 ϕ (i.e., 1/4 of the cone angle) for ϕ. And (4) if the mirrors are in a family of iso-inclination orbits separated by equal longitudes, two subcases will exist. (a) At any given moment one mirror, the prime one, is on a visible path which takes it directly overhead and its average elevation will very nearly be that value found in situation three (it will differ slightly because the ground spot is now moving with respect to the orbit plane so the elevation period will vary slightly). And (b) recalling from the redundancy argument that on the average there will be more than just the prime mirror in view and in fact there will be $(N_i - N_t)/N_t$ (symbols as defined in eqs. (5) and (6)). If these are random in our mirror viewing hemisphere (a somewhat flattened hemisphere because its origin is the Earth's center) then the $\bar{\phi}$ boundary bisecting our viewing area can be found from setting the ratio of the sphere areas, above $\bar{\phi}$ and above ϕ equal to 1/2, or

$$\bar{\phi} = 1/2 \cos^{-1}[1/2(\cos 2\phi + 1)] \qquad (21)$$

where ϕ is from equation (1) when $\theta = 30°$. On solving equation (21), $\bar{\phi}$ is converted to the site's frame of reference, $\bar{\theta}$, by equation (20).

Table I presents six orbit examples encompassing these four situations and shows the average elevation for both the single or prime mirror cases and for the random mirrors, the latter as discussed in situation four. Additionally, the loss factors associated with the prime or single mirror, only, are also given. First, the energy transmission factor and then the ground spot area as compared to area for a zenith reflection. These values are used later to develop system costing.

Power Plant Design Criteria

Two problems are central to the design, cost and efficiency of the ground station; both are common to any solar energy plant. Ideally, the generating capacity of the plant should be slightly greater than the demand. The first difficulty making this ideal unobtainable is that the demand curve is quite variable, depending as it does on a mix of residential and commercial customers with differing power, air conditioning, and heating requirements on a daily and seasonal basis. The usual practice with power companies is to have a major energy source provide the base load and, at much higher rates, an auxiliary system to meet peak demands. Second, conventional solar conversion plants have the added difficulty of being tied to a very irregular fuel source. These plants are thus very cost sensitive to the need of using energy storage to provide power on a continuous basis. A plant using orbital reflectors for a solar source would always have some input — being minimal at night during periods of heavy fog and maximum with the reflector directly overhead at the summer solstice.

Several techniques and options are available which will tend to ameliorate the problem of variable energy input in the proposed scheme. A major problem is the factor of three difference in the apparent reflected intensity between a mirror at zenith and at 30° elevation. First, the station may be made larger than the zenith projected spot size requirement, so although the intensity still varies the collected energy remains more constant. Because of the cost of the ground receiver facilities, there are practical cost effective limits to this solution. (Beyond the cost-effective station range, one may make use of the spill-over, to, for example, enhance crop (fuel or food) yield or provide all-year recreation areas.) Second, a large number of reflectors, but with the same total surface area, would ensure that several were in view at a given period, thus averaging the intensity. As discussed in the orbital consideration section, even a system that is designed to have one in view will frequently have more. It may even be worthwhile to collect the radiation, although weak, coming from below the 30° elevation criterion. The weakness will be made up, in part, by the increased number and viewing times available. And third, since the satellite excursions are relatively rapid, the generating or steam plant connected to the receiver can be ballasted to produce an even output.

Unless the primary orbital collector/reflector is made very much larger than the ground receiver so that several or more solar constants are received, the normal Sun radiation (up to 0.7 solar constants) will contribute a significant and largely variant fraction of the total energy received. If a sizable portion of the plant load is not for air conditioning purposes, then much more energy will be received at noon or early afternoon than can be directly used. As peak demand often occurs at dusk, short-term storage facilities could be installed to better utilize this overage. Another option is the use of excess power from this noon period to generate hydrogen to meet long distance transmission needs or to use it simply as a portable fuel.

The design and even the type of solar conversion plant most compatible with orbital reflector delivered energy is at present unknown. Preliminary assessment shows thermal and photovoltaic conversion to be competitive in the present situation. Analysis of thermal conversion techniques using direct solar input shows the central receiver concept to be, currently, the most cost effective by a margin of at least 20 percent (ref. 8). In this concept a field of solar reflectors (heliostats) redirect the radiation to a cavity or boiler, situated on a high tower, which power a large heat engine. Such systems are predicted to operate at 25 percent overall efficiency (ref. 8). This system, along with others operating at similar efficiencies, employs two-axis tracking. As discussed above, tracking, if we have multidirectional inputs as is the case if the ground stations are at mid-latitudes, is of little benefit. (One should note, however, that the tracking ground station would be of clear value in the early stages of implementation, when only a few satellite mirrors are placed in an inclined belt. These few mirrors could be used to supplement normal insolation at, say, dusk, or to lessen energy storage requirements in a conventional system.) Flat plate and nontracking systems are far less efficient. In these systems the collectors represent a major portion of the system cost. Because of this high fraction of energy-independent costs large cost reductions in \$/kWe are possible with the reflector system in which the average insolation is six times greater than in conventional systems. The photovoltaic option is quite attractive, both because of its predicted estimated costs and promised low maintenance. In this scheme, flat arrays would be used and direct energy conversion is achieved with a large reduction in the need for moving parts, fluids, plumbing, and other high-maintenance components. Two alternative devices are considered in the costing section: (1) the silicon solar cell with its ERDA projected costs and efficiency, and (2) the cadmium sulfide-cuprous sulfide "spray on" cell which has a present efficiency of 7.8 percent and quite low price.

ECONOMICS

The economic evaluation of the space-based reflector solar power concept as presented below is very preliminary. Two factors are responsible. First, the text was introductory in nature, not containing an in-depth analysis but merely presenting a number of technical options, suggestions, possible problem areas and scenarios related to the development of such a system. Optimization of the orbit possibilities, transportation options, reflector design, materials, structures and control, relay concepts and the ground station configuration requires a systems analysis of considerable magnitude, even to bound the problem. Second, even given the optimum system it is, at this time, impossible to cost the component items with certainty, since many critical areas are virtually unknowns — for example, future transportation and space operation costs are probably not known within a factor of 2. In the following discussion we have attempted to err on the conservative side and to deal with technology growth not breakthroughs.

Reflectors

It is assumed that the solar sail technology which is being developed for application to missions in the early 1980's will prove viable and materials of similar properties will be readily available and applicable for reflector use in the 1990 timeframe. This material, aluminized Kapton or Paralene with the necessary structural support and control, has an area density of 0.003 to 0.006 kg/m^2. We will assume the latter as a conservative number for this section. (Mylar or an even less expensive material would likely be employed in the present application which calls for differing thermal and lifetime properties than the solar sail application.) Based on information developed in a recent systems overview of the SPS, it appears that the hardware and construction costs of such reflective materials, structural support and controls will be about \$1.50/m^2 (ref. 9).[6]

Transportation

It should be appreciated that to obtain equivalent ground bus power the mirror system needs about 1 percent of the orbital mass of the SPS. Therefore, the transportation cost per unit mass to LEO is likely to be somewhat higher than the amortized (development plus operations) transportation component costs for the SPS (ref. 9). Although the transportation requirements will be less in the present case they are still, in order to meet the world's energy needs, between 2000 and 2025, equivalent to 5000 flights of the present day version on the Shuttle. Clearly, the development of an SSTO (single stage to orbit) if not a HLLV (heavy lift launch vehicle) would be cost effective. This would probably mean \$55/kg to LEO compared with the SPS cost estimates of \$33/kg (ref. 9). Orbital transfer costs by TUG or shuttle OMS (orbital maneuvering system) to achieve elevations of 800 km might reasonably add \$30/kg to the system costs. At this altitude solar sailing (following deployment or construction) would be employed to take the reflectors to operational orbit. It is anticipated that the costs, due to the solar sailing option, will be fairly insensitive to the final operation orbit altitude. The transportation costs for crews and supplies would add about \$5/kg to the above. These total to a conservative estimate of \$90/kg, compared with the \$108/kg for the SPS to GEO. This payload cost equates to \$0.54/m^2 of reflector. As transportation costs are very sensitive to the areal density of the system, it seems prudent to provide an overrun factor and accept \$1/m^2 as a nominal value.

Ground Station

The central receiver configuration appears to be the most competitive terrestrial solar thermal-electric plant possible and requires capital costs of roughly \$1500/kWe, while the flat plate collector system, which may prove more optimum for reflected insolation, costs \$2000/kWe (ref. 8). With the reflected solar power concept presented herein, several significant reductions, overall perhaps a factor of 5, in these costs are likely. First, the expected average intensity is at least six times greater. Second, since the station will be several orders of magnitude larger than the conventional counterpart, the economics of mass productions should prevail. And third, the necessary short term (overnight) energy storage in a conventional system can be responsible for about half of the total system cost — longer storage needs scale directly (ref. 10). Quite similar conversion costs are the goal of ERDA which has set a target of \$500/kWe in 1985 and hopes to reach a market price of \$100 to \$300/kWe by the year 2000 for efficient photoelectric devices — most likely silicon cells.

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[6] The referenced report, prepared by Johnson Space Center, is a thorough evaluation of orbital solar conversion and microwave transmission systems. It is conservative in its analysis, relative to other studies in this area, and arrives at bus power costs for the SPS about double those given elsewhere.

Additionally, the CdS cell holds considerable promise for achieving low cost solar conversion. Following the analysis of DeMeo (ref. 11), it appears that shortly solar conversion ground stations for the reflector system could be built for \$300 to \$400/kWe. By 1985 technology is expected to double the efficiency of these cells, while achievements in other areas coupled with the truly large scale usage envisaged with the present concept would greatly reduce even these figures.

It appears from the above that there are two likely cost scenarios for the 1985 time frame for ground stations in support of the reflector concept. One leading to facility costs around \$400/kWe and probably based on thermal conversion, but possibly by the silicon photovoltaic. And, the other with costs of about \$200/kWe and derived from the CdS cell. We will employ both of these models in the system costing. In both models the cost may be conveniently divided into two elements; collection of sunlight and conversion (or conditioning in the case of the CdS) to bus power of the proper cycle and voltage. The following relations are used to derive ground system costs.

Model 1 (thermal) $\$25/\mathrm{m}^2 + \$300/\mathrm{kWe}$

Model 2 (CdS) $\$30/\mathrm{m}^2 + \$70/\mathrm{kWe}$

These costing models are simplified versions derived from reference 11 and use a 15 percent conversion efficiency and 1.65 $\mathrm{kW/m}^2$ time averaged input (1.4 $\mathrm{kW/m}^2$ reflected and 0.25 $\mathrm{kW/m}^2$ direct solar insolation). The 15 percent efficiency is quite reasonable as it is much less than the 25 percent that could now be achieved with a thermal system using tracking with mirrors in a polar or equatorial belt, or fixed plates with a geostationary mirror cluster. On the other hand, if we are at a mid-latitude station and must use an inclined orbit belt with inputs from several directions simultaneously, 10 percent overall conversion may be the lower bound if technology does not significantly advance. Finally, as shown in the costing models, intensity is a strong cost driver which points to the value of using additional mirrors to produce higher concentrations of reflected sunlight.

Design, Development, Test and Evaluation

DDT&E costs encompass all funding from technology development until start of construction of the first reflector. For the SPS, this cost is estimated (ref. 9) to be \$50B. For the reflector system (station, transportation, and orbital construction facilities), because of much lower complexity and lesser transportation needs, DDT&E is expected to be at the lower part of a \$10 to \$20B range. However, as a conservative estimate, we will use the higher figure.

Operation and Maintenance

O&M costs for the SPS are estimated to equal 3 mills/kWe (ref. 9) and as a better analysis is lacking, will be accepted for the reflector system also.

As shown below for the optimal systems, this number is responsible for a large share of the power costs. Thus, its contribution must be carefully analyzed in the future.

System Characteristics and Investment

Table II presents estimates of system characteristics — size, power output and costs — for several different orbit options in accord with the previous discussions. In order to ascertain what the attendant costs might be for each orbit option, we first determined the total area of reflector needed to produce one added solar constant over a 0.0093h diameter ground spot and then what collector (ground station) area was required to intercept a substantial portion of this radiation — for we have seen that the time averaged beam may be much larger than 0.0093h. Table I and its supportive equations and discussion answers these two questions. There are cost option mixes which will optimize the required reflector and station areas for each orbit but for the purposes of this initial comparison (and the complexities encountered when other variables are added later) we will do the following: The reflector area given in Table II is that needed to provide one solar constant over a $(0.0093h)^2\pi/4$ area, on average. It is based on the mean transmission efficiency of the single or prime plus random mirrors as described earlier. The total reflector area in orbit is the product of the cluster area and N. Thus, one or more mirror clusters of equal area provide a coincidental image at the station at a given moment which produce, when averaged with other mirror cluster inputs at other times of day, the requisite power. Due to beam spread, the intensity is less than I_0. The ground area given is that needed to intercept roughly 2/3 of the beam energy or that found using the diameter 0.0093h, whichever is larger. The total area of all stations that could be effectively serviced by a single orbit option is the product of the individual area and N_t. Generated power, in gigawatts for the single station was determined from the average reflected and direct solar incidence on the station, assuming a 15 percent conversion efficiency. Investment capital required was derived from the cost per unit area and unit output power relations determined earlier. The hardware, construction and transportation costs for the reflectors are totaled as the components are relatively invariant with orbit choice — transportation is 40 percent of the total. It should be recalled that all the satellite reflectors are required for a given orbit choice whether one or all the stations are put into operation.

Power Costs

Table III presents cost estimates of the various components using four orbit options as examples. Capital recovery data was generated from equation (22) assuming 15 percent return, 30 year lifetime and a 70 percent plant (load) factor.

$$\left[\frac{r'}{1-\left(\frac{1}{r'+1}\right)^{y}}\right]\frac{C}{E} = \$/\text{kWh} \tag{22}$$

where r' = rate of return, y = lifetime in years, C = capital costs in dollars, and E = power output in kWh/yr. DDT&E dollars were not discounted but spread over the power produce by a given option in a 30-year life. Costing is provided for both the single and complete ground station situations. Total costing is given for the four possible cases — for single and multiple receiver stations and thermal and CdS photovoltaic conversion — for each orbit where they are applicable. The inexpensive photovoltaic conversion option and full station use produce about equal benefits, each reducing power costs by about 5 mills/kWh. And, because space reflectors appear to be a low cost element in the analysis, ground station improvements are the drivers for reducing power costs. Since present baseload power generating facilities (fossil and nuclear) have bus costs ranging from 12 to 30 mills/kWh, the present concept is more than competitive, as is shown by figure 10. The projected cost range of the various options developed from the orbiting reflector power concept is presented on this figure, taken from reference 9. To put the data illustrated here in context the reader needs to realize several points. First, by around 1990 gas and oil, due to their scarcity, will only be available for electrical power generation at large premium costs. Second, because of expected further social resistance, it is likely that coal- and nuclear-powered plant costs will continue to escalate at several times the rate exhibited by capital, construction, and manufacturing costs — making the advanced systems considerably more attractive (ref. 9).[7] And third, the cost range shown for conventional plants are for those presently in operation, newly installed facilities give overall costs at the top or above each range. Figure 10 presents the present concept in a very attractive light relative to other alternatives and to be fair, we must again stress the one great potential disadvantage, that is, the orbiting reflector power system can only apparently be optimally established on a large scale. Its greatest potential is realized when all possible ground stations, for a given orbit, are installed. As such, we are speaking of large quantities of power, enough to meet new generating needs for many years. Nonetheless, we must not forget that the capital investment necessary to purchase this large capacity is great (see fig. 11). Since this fact is especially true for the high orbit options it is expected that the lower orbit cases will enjoy an initial advantage even though their unit power cost is somewhat greater.

Selecting one orbit option, 4000 km and 40° inclination, figure 12 provides some cost sensitivities as a function of the development scenario selected. This orbit is chosen from among those of Tables II and III because it provides a reasonable balance between investment and power costs and could provide a majority of the world's electrical needs in the year 2000. Additionally, it is at an inclination which would service the United States as well as most of the other developed nations (i.e., the power users). The area of the "pies" represent unit power costs while the slices indicate contributions from the various cost elements in each scheme. Four of the options shown are from the Table III material and illustrate the reduced costs possible from improving the baselined (solar thermal and a single ground station) system. It is clearly shown that in most cases the cost stemming from the

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[7] In passing, it should be noted that the reflector technique, by increasing ocean insolation, can remarkably enhance ocean thermal power prospectives.

ground station is of overriding importance. Thus, ground station improvements even at the expense of increased mirror sizes are probably effective. The last pies show the result of increasing the area of the mirrors in orbit by a factor of 5 — producing about five solar constants, average, to the ground station. The results are beneficial because: (1) power output is five times larger, thus keeping the unit power costs for the mirror and transportation elements about constant, and (2) at the ground station we are, basically, only increasing the energy conversion cost component — not all the collection elements.

APPLICATIONS

It is not the purpose of this report to investigate all of the possible uses of this system which provides solar energy with average high intensity and with minimal diurnal variation. Some possibilities are shown in figure 13. Such uses of solar energy are nicely delineated in a recent book (ref. 12) and include processes which <u>are</u> in use, such as water distillation (desalination) and heating, crop drying, water pumping, heating and cooling of buildings, and those of a more limited usage such as small scale electric power generation, bioconversion into fuels and chemical feedstocks (alcohol, etc.) and industrial process heat. It is generally true that most of these processes could be enhanced by the space mirror system; however, this usage would need to be economically justified when compared with possible large scale electric power generation. One should note that since reflecting area is much less costly than ground power stations, many other applications may be quite attractive.

It is interesting to note, however, that the usage for electric power generation does not necessarily preclude the above applications which can use low temperature heat. Thus, if a number of national energy facilities were located throughout the country, with the primary purpose of "solar farming" the radiation for electrical output, these would in general reject ca. 50 to 80 percent of the incident energy because of the electrical or thermal inefficiencies of the conversion process. Rejection temperatures of high temperature cycles could easily exceed 150° C, thus providing the surrounding communities and industries, which will surely locate near these facilities, with the energy source needed for a community scale total energy system. In addition, the "overload" of electrical energy produced during low electrical demand periods, could well be stored by hydrostorage (pumping reservoirs) or electrolysis of water to produce hydrogen.

There are other applications of a more novel nature in which the mirror system could be applied. Oberth (ref. 4) has discussed some of these such as providing artificial illumination of large metropolitan areas or disaster areas at night. It should be noted, with respect to the recent severe winter and the corresponding shortage of heating fuel, that continuous insolation could also possibly be used to increase the temperature of certain regions. Of particular import may be the prevention of frost on expensive or important crops such as citrus groves, etc. Oberth has suggested the practicality of irradiating frozen navigational waterways; again, this concept must await an engineering and economic analysis. Water evaporation from the oceans is also a real possibility, thus providing, at least on a local scale, the necessary clouds to provide rain. Alternatively, local heating of the atmosphere may be capable of dissipating high pressure regions which prevent the flow of such naturally occurring moisture from the oceans to the drought area.

It is obvious that some applications mentioned will not survive scientific and economic studies, failing for example because the number of mirrors necessary to achieve the requisite intensities or spot size are unrealistic. However, the point to be made is that the mirror system can be used in a number of useful ways, whereas the normal SPS microwave system can only generate electricity. There are many nations in the world which do not have the insatiable demands on electric power made by the industrial countries. Their needs are more basic: food, desalinated water for drinking and irrigation, and fertilizers. It appears reasonable that the mirror system can provide such items, by extending the insolation period on crops, solar distillation and pumping of water, and perhaps the production of nitrogen compounds, while the mirrors are over these countries. Simultaneously, the companion mirrors can be producing the (exportable) commodity: electrical power for the industrialized nations. It is this multiple use which is unique and attractive with the orbiting mirror system. Further study will be necessary to fully assess the benefits mankind may derive from it.

Incremental Approach to Total Mirror System

This brief discussion on applications should also include some relevant considerations on the time ordering of such application arising from the incremental implementation of such a large system. Clearly the first mirrors placed in space will be used for proof-of-concept studies — to ascertain the technology readiness — and will therefore serve no "external" need. However, as mirrors are added (see fig. 14) definite use can begin before complete system deployment. The first of these would appear to be those not associated with electrical production but rather providing low level artificial illumination or meeting agrarian needs. Because of the capabilities of solar sailing, it should be appreciated that opportunities exist for moving the mirrors into different configurations for different tasks as time progresses. For example, providing continuous illumination would likely use a low reflector density above the Earth's surface. However, these mirrors could then be brought together to a composite cluster or focussing satellite mirror for the possible task of supplying higher insolation to an existing ground thermal station for a short period of time. This may be useful for simply extending the effective energy collection time of the ground station near dusk; a peak load period for the power grid and a time during which contemplated, conventional solar installations must rely solely on stored energy. If the single mirror orbit is chosen properly, it will be possible to effect this dusk or peak-load-following insolation to a number of stations around the world sequentially in synchronism with the terminator. The flexibility inherent in this system as a result of solar sailing, making mirror spacing and altitude (or orbital period) changes possible, is hence a system virtue opening many possible interim uses. Such possibilities have barely begun to be explored and need further study.

Of course the major cost factor in the system — the solar farm — can also be incrementally implemented. The reasonable approach here seems to be that of installing small farms on the outer edges of the useful illuminated ground spot. This allows most of the radiation to impinge unused on the central region but, if suitably located, this "power grid" would probably ensure the nonsimultaneous obscuration of all farms by clouds. As revenues are accumulated, of course, the expansion of these farms, possibly using more advanced conversion methods which were developed in the interim, could be made inward to completely use the available radiation.

The efficacy of completing a single large U.S. ground station, of course, will have to be carefully assessed with respect to electrical transmission losses, the reliance on a single, vulnerable power source for much of the nation's power needs, etc., but in principle this would constitute the next step on the ground. This would simultaneously be accompanied by an expansion of the number of mirrors to the full complement of N satellite mirrors corresponding to the orbit desired.

Finally, the full complement of ground stations would be installed, again very likely at a rate consistent with revenues obtained by the sale of power from the earlier stations. Using nothing more than reasonable guesses at this point in our investigation, the possible dates associated with the series of incremental steps outlined above have been shown in figure 14.

ENVIRONMENTAL IMPACT

As with any technological system of the magnitude of the solar mirror scheme, a critical assessment of its environmental impact must be made. We have begun this task and report here on some crucial areas; others will undoubtedly be discovered. Our conclusion is that there appear to be no major environmental impediments.

In such an assessment it is well to consider both the positive environmental impacts as well as the negative counterparts. Certainly the main system output will be electrical power, although as mentioned above, other beneficial outputs are possible. Hence, the first positive effect will be to conserve fossil fuels which are currently used for electrical power generation. In addition, if the system is large enough, such power may well be used for other applications, such as in transportation, where, again, fossil fuels are presently the only economically viable option. Conservation of fossil fuels would also occur if some of the system were devoted to direct thermal heating, such as for desalination of water, crop frost prevention, the enhancement of rain, or the production of chemicals.

On the negative side, however, the questions of (1) solar heat input, (2) disturbances to the ionosphere, (3) atmospheric photochemistry, (4) land usage, (5) light scattering, and (6) continuous insolation all must be considered.

It is frequently stated that, despite the inefficiency of solar farming techniques, the rejected heat is not an added burden to the Earth's ecosystem since the solar radiation would have deposited that energy on the equivalent area anyway. One must be cautious here, however, since (1) the albedo of the area has been modified (dark solar panels), (2) the rejected heat is now in a concentrated form, and (3) we are here considering a system to bring down solar radiation which would not usually reach the earth. To the first problem we must consider the global scale involved. Even the largest area mirror system considered here (GEO) uses a total ground area of 8.7×10^4 km^2. This must be compared with the total area of the Earth: 5.1×10^8 km^2. In addition, other larger areas are now artificially altered — the cultivation of soil in the agricultural regions of the world — without apparent significant albedo-related effects. However, and this is connected to the second possible problem, the existence of large national energy facilities or solar farms, could possibly influence the heat balance locally. As indicated earlier, a properly engineered facility would make use of the rejected heat for community power systems — thus dispersing the energy concentration. Finally, the third question again appears to disappear when considered on a global scale, if effective dispersal is made.

Possible disturbances to the various "-spheres" of the Earth's atmosphere have not yet been analyzed. Again, two facts would appear to obviate problems. Firstly, the transmission of sunlight through these layers is nothing new — it occurs naturally. Secondly, it is again a matter of global scale — assuming no nonlinear effects, this should be a negligible contribution to the average temperature, etc. of these layers. One concern, the possible deleterious effect of removing certain molecular species from the region of the transmitted beam and thus allowing a larger fraction of the ambient sunlight to pass through this region and reach the Earth, is not troublesome. In fact, the best estimates are that the rate of ozone production would be enhanced by the mirror system, thereby making a positive (albeit small) contribution to environmental quality.

The question of land usage is a serious one. In all likelihood the desert regions of the world would be the most advantageous sites. However, if the larger spot sizes discussed in this report (for GEO) were used, it has been estimated that a minimum of 50,000 people would be displaced in any region selected in the U.S. for the solar farm. As discussed earlier, it appears reasonable that the lower orbit schemes would be used, thus demanding little displacement for regions in the Southwestern U.S. and Mexico or possibly allowing the sites to be located over existing water masses. The latter scheme seems, in fact, to be an ideal location based upon other considerations for the technical operation of the solar farm. A typical spot size in this case would roughly occupy the area of the Salton Sea in California. As has also been pointed out, the present increasing area of the world's desert regions, due in part to a lack of irrigation water, could possibly be halted by use of the mirror system. We can, perhaps, look at the desert or over-water area usage of the solar farm as the initial investment on conserving land in the long run. Of course, it is very likely that some displacement of people will be necessary. This unfortunate fact will have to be balanced against the environmental gains the system provides and, in particular, the long-term continual supply of energy to them and their descendants.

Finally, the general area of light scattering will need careful study. Particulate and Rayleigh scattering of the transmitted beams may lead to the observability of these beams in the night sky even though the observer is many miles from the ground receiver station. A general "night glow" could possibly develop. The seriousness of this would, of course, be a subjective matter. Those living in the northern regions of the Earth have, in fact, lived comfortably with six months of even more intense perpetual daylight per year. It would not appear to be a serious psychological problem to most of us based upon this experience. However, to the astronomer this may indeed present an insurmountable obstacle to his research! Hopefully, study will prove this concern not to be real. But if it is, and the project is carried out, it may necessitate a large scale use of space-based telescopes for the future endeavors of this scheme.

CONCLUSIONS

We have attempted a preliminary assessment of the solar mirror system; its various orbital options, technology needs, uses, environmental effects, and economics. The commitment of the nation, or the world community, to such a means toward ultimate energy self-reliance would be a major undertaking. As such, we should not end this report before considering some of the salient points of comparison between this concept and the other solar alternative — the SPS.

It was shown that the costs of power derived from the reflector system could be much less than that from current fossil and nuclear sources. It also appears that such costs will be 10 to 50 percent of that envisaged with the SPS designs to date. (A similar advantage is shown over other popular advanced systems — wind, conventional ground solar thermal, and ocean thermal.) Further, although the initial investments for the minimal systems (DDT&E, one station and the required satellites for the respective systems) are nearly equal, the reflector system has the edge since it would generate several times more power, thus decreasing the payback period. Also, once the mirrors are in place for the first station, power costs from further stations are much less. It was mentioned that besides producing power the subject system could even be used to improve the environment while the necessary SPS microwave power relay may cause problems. The SPS is only an interim solution to our energy needs since it can provide only several TW to the U.S. due to filling of GEO equatorial belt (other countries in our hemisphere may also demand space in this prime region). One of our reflectors at that orbit could provide 16 TW and leave room in that orbit for many others. Additionally, there are many other orbits available for use with the reflector system. It is of interest to also compare the technical requirements of the reflector system with the SPS. Although both systems require advanced transportation, the traffic demands of the reflector are about 100 times less. Thus, much reduced R&D is required in this area. It does appear that more difficulties will arise with the mirror concept in the areas of tracking, pointing, and station keeping, which will require advance technology to overcome. The solar cell SPS system requires a two to three order of magnitude reduction in cell prices to make its system economically attractive while the mirror system could actually use state-of-the-art reflectors. This point has additional importance since the error in costing the reflector system is likely to be much less. At this time structural requirements, simply because they haven't been studied, appear more formidable in the reflector case. In balance it appears that power could be derived from the reflector system at least 5 years prior to that of the SPS simply because the technology is much more in hand.

Of course, as can be seen in a recent interesting book (ref. 12), the history of solar energy usage is filled with the ultimate condemnation afforded each attempt: it is too expensive. In general, the cost of work produced by a solar process is a factor of five over its counterpart fossil fuel alternative. It is frequently stated that this ratio will decrease when the cost of fossil fuels increases; however, since labor and materials costs are closely coupled to fuel costs, the cost of solar systems als rise proportionately. Only when solar techniques become the dominant source of energy and supply, such as would be the case if the solar mirror concept were adopted, will this correlation fail.

If one searches for the more obvious reasons for this excess cost of solar generated power, one finds it intimately tied to the "diluteness" or low solar energy content per unit area, its variation in incidence direction, and its temporal variation. The latter allows few hours per day during which energy may be profitably used and, more important economically, demands expensive thermal storage to prevent the loss of this energy at night. All of these factors lead to (1) low (when compared with fossil fuel driven processes) cycle efficiency and (2) rather large and elaborate opto-mechanical structures. Both combine to give not only a capital intensive system but also one which produces power at costs which are higher than alternative sources.

Our intent here was to make a first assessment of the impact of the solar mirror system on this rather bleak picture. Could it provide higher intensities and less temporal variation consistent with reasonable cost? Could it be effected with present or very near term technology? Finally, would it be environmentally, as well as economically, attractive, especially when compared with other near-term energy solutions?

Obviously, the ultimate answers to these questions will depend upon more complete studies. Crucial technology areas have been delineated to the best of our knowledge, but others may be found. The development of a suitable scheme for relaying energy from mirror to mirror would have a profound effect on the system, especially upon capital investment. It is our belief that the techniques of using radiation pressure for orbit raising, station keeping, and mirror pointing may allow not only substantial cost reductions but also initial and operational energy investment savings as opposed to the SPS which must use propulsive fuels. Finally, a detailed study of the benefits (complexity reduction, increased efficiency, lower costs) which may accrue for solar farms when they can operate with this effectively new source of solar radiation should be illustrative and sharpen an assessment of the solar mirror concepts.

In spite of some uncertainties at this time, we believe the technique outlined here appears feasible with near-term technology, is cost competitive with alternate sources, and it provides an abundance of energy sufficient for our foreseeable needs. In addition, it has the unique possibility of alternate use for needs other than the generation of electrical power.

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TABLE I.- CHARACTERISTIC MEAN REFLECTOR ELEVATIONS AND ASSOCIATED LOSS FACTORS

Orbit		Random mirror	Prime mirror		
Altitude, km	Inclination, deg	Elevation, deg	Elevation, deg	Transmission efficiency	Image area, relative
2,000	40	43.00	54.07	0.55	1.68
4,000	40	44.92	55.96	.56	1.50
10,000	40	47.55	57.92	.56	1.33
35,800	0		52.75	.55	1.34
2,000	0		54.13	.55	1.67
1,400	101.43		34.48	.50	4.00

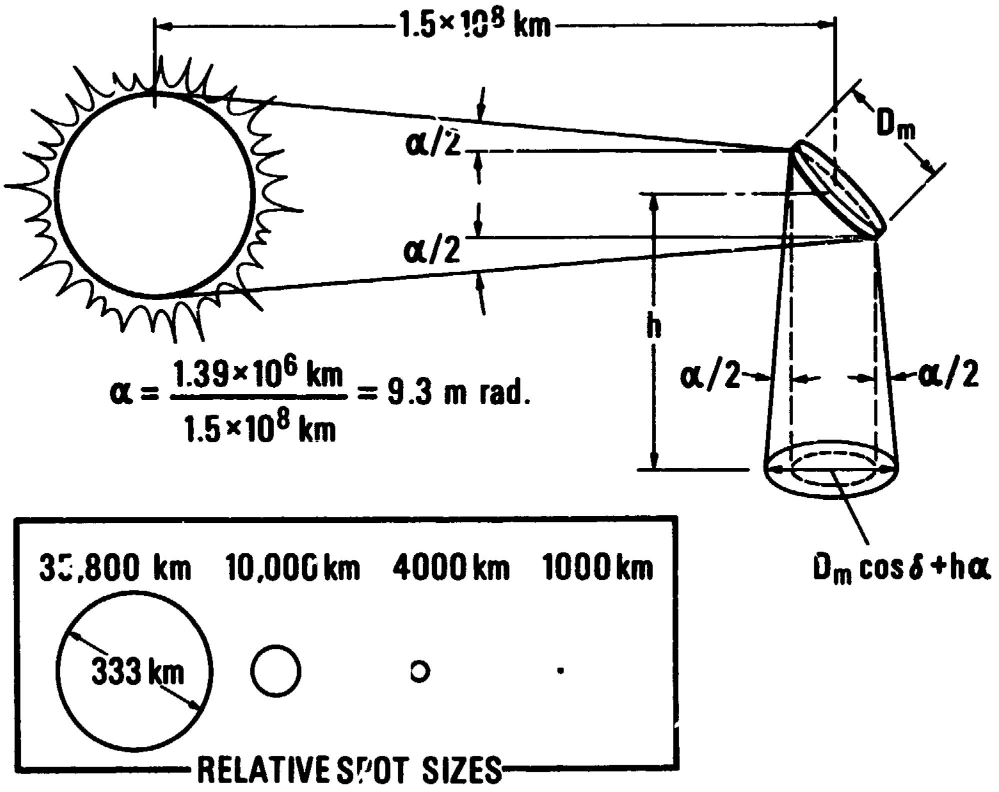
TABLE II.- COMPARISON OF REFLECTOR POWER SYSTEM CHARACTERISTICS

Orbit		Mirror clusters		Ground stations		Bus power	Capital costs,[a] $ Billions		
							Each ground station		N clusters
Altitude, km	Inclination, deg	No. req'd, N	Area of each, km^2	Area of each, km^2	Potential no., N_t	Each grd. sta., GW	Model 1 solar-thermal	Model 2 CdS	Mirrors and transportation
2,000	40	54	220	370	24	48	24	14	30
4,000	40	27	830	1,300	11	185	88	52	56
10,000	40	9	7,300	6,800	5	1,170	520	285	165
35,800	0	1	158,000	87,000	1	16,250	7100	3750	395
2,000	0	7	500	300	7	46	21	12	8.6
1,400	101.43	19	265	355	2	41	21	13.5	12.6

[a] DDT&E amounts to an additional $20B.

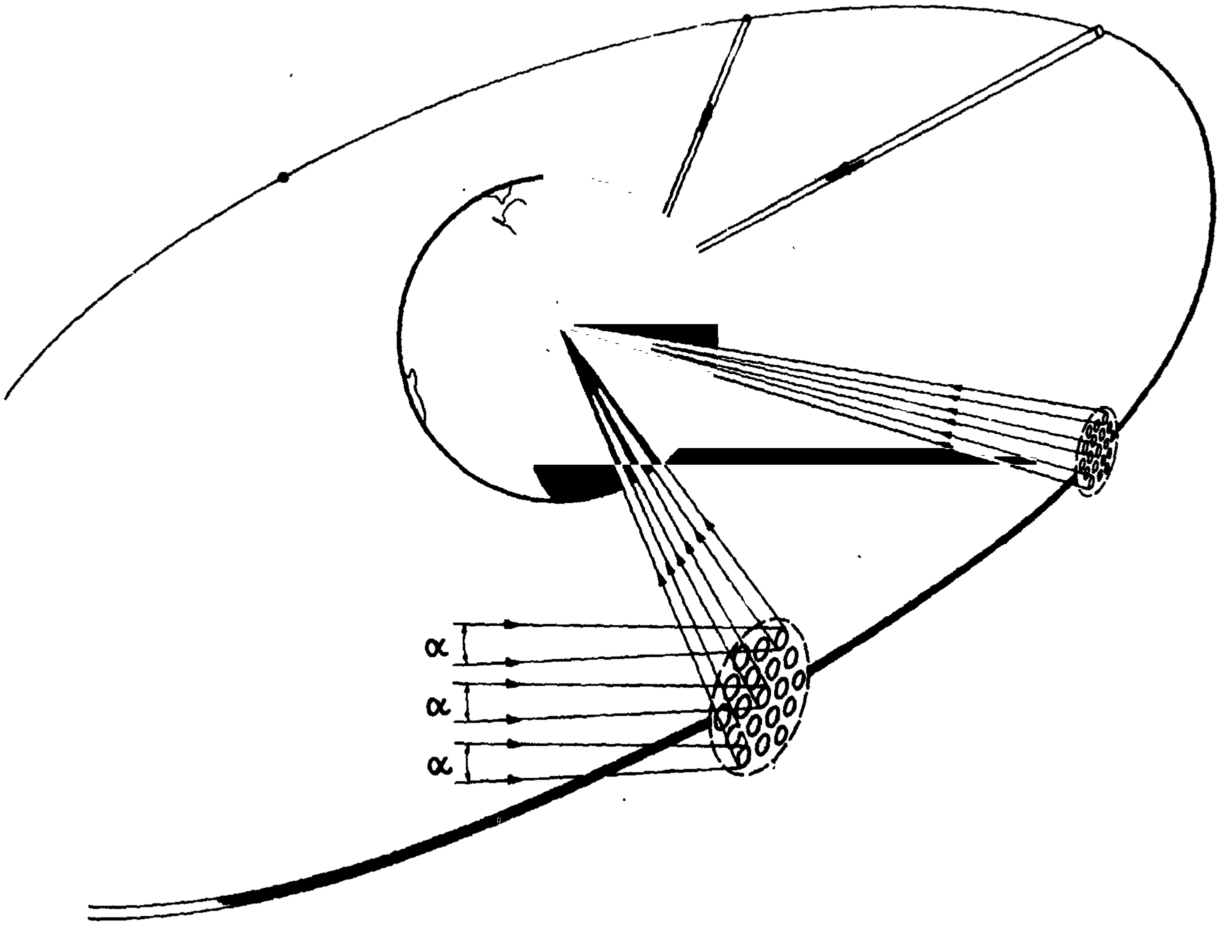
TABLE III.- BUS POWER COSTS OF ORBITAL SOLAR REFLECTOR SYSTEM, MILLS/kWh

ORBIT	4000 km, i = 40°		10,000 km, i = 40°		Geo sync equat.	1400 km polar, sun sync	
Ground stations used	1	11	1	5	1	1	2
Component							
Reflectors and transportation	7.5	0.7	3.5	0.7	0.6	7.6	3.8
DDT&E	0.6	---	0.1	---	---	2.6	1.3
O&M	3	3	3	3	3	3	3
Receivers solar thermal	11.8	11.8	11.0	11.0	10.8	12.7	12.7
Photovoltaic, CdS	7.0	7.0	6.0	6.0	5.7	8.2	8.2
Totals							
Thermal	22.9	15.5	17.6	14.7	14.4	25.9	20.8
Photovoltaic	18.1	10.7	12.6	9.7	9.3	21.4	16.3



(a) Illustrates the angular subtense of the Sun and its effect on spot size with a nonfocussing (planar) mirror.

Figure 1.- Limitations on the minimal ground spot size arising from the angular size of the Sun.



(b) Illustrates how a focussing mirror can be simulated with an array of properly positioned and oriented mirrors.

Figure 1.- Concluded.

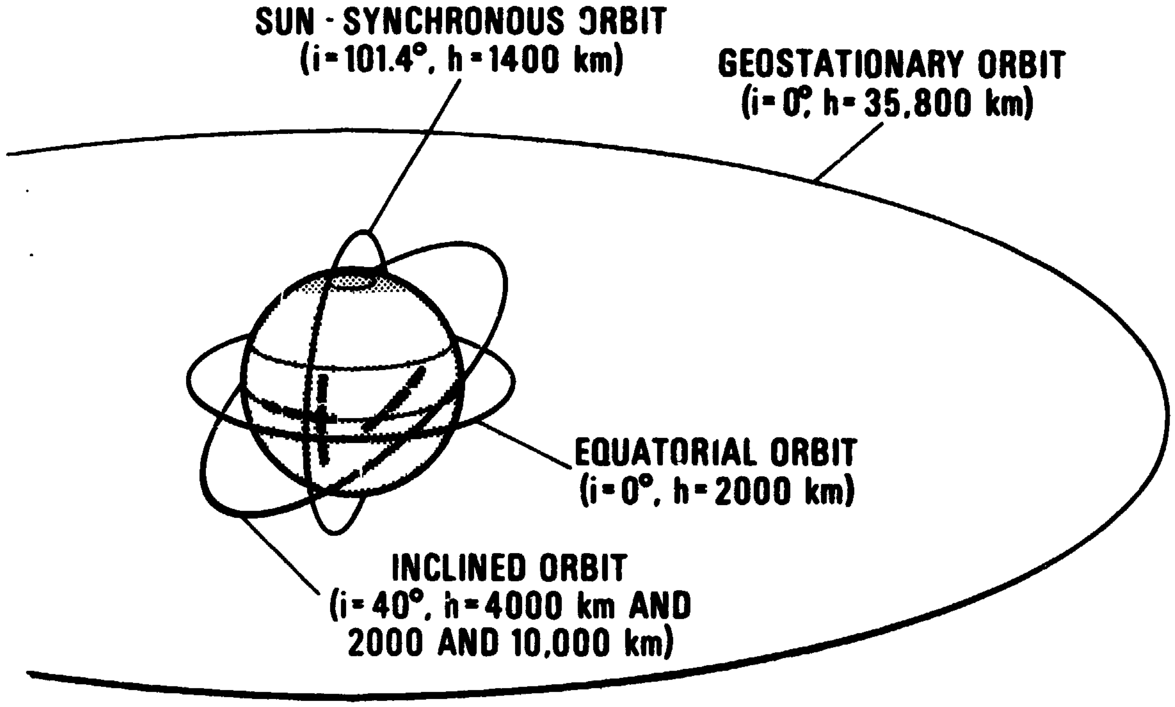


Figure 2.- Orbits examined in this report. Dashed lines indicate partial radial projections onto Earth's surface. For clarity, the geostationary orbit size is shown below scale.

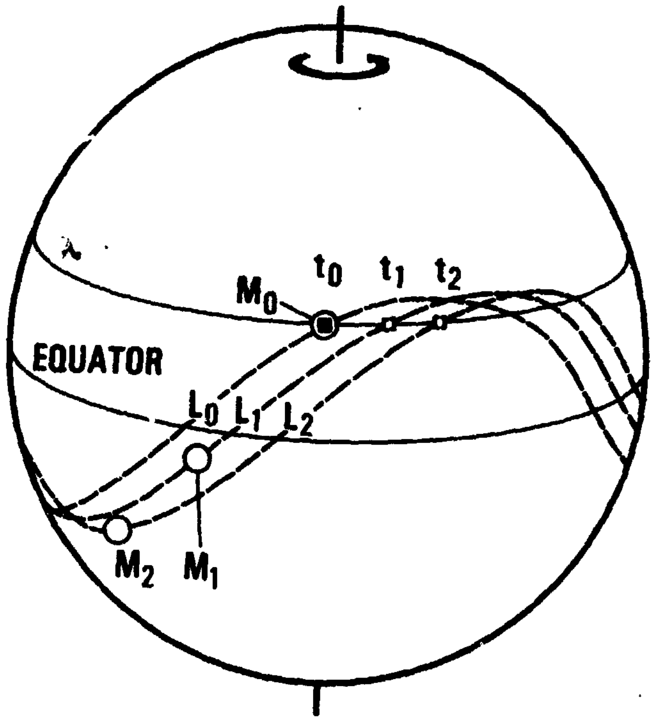


Figure 3.- Ground trace of three equi-longitude (L_0, L_1, and L_2) iso-inclination orbits in view hemisphere, each containing a satellite mirror M_0, M_1, and M_2, respectively. Mirror locations shown at time, t_0 and staggered so that a ground station at latitude λ will be intercepted by M_1 at t_1, M_2 at t_2, etc. Proper integer orbits insure mirror passage through station's zenith twice daily.

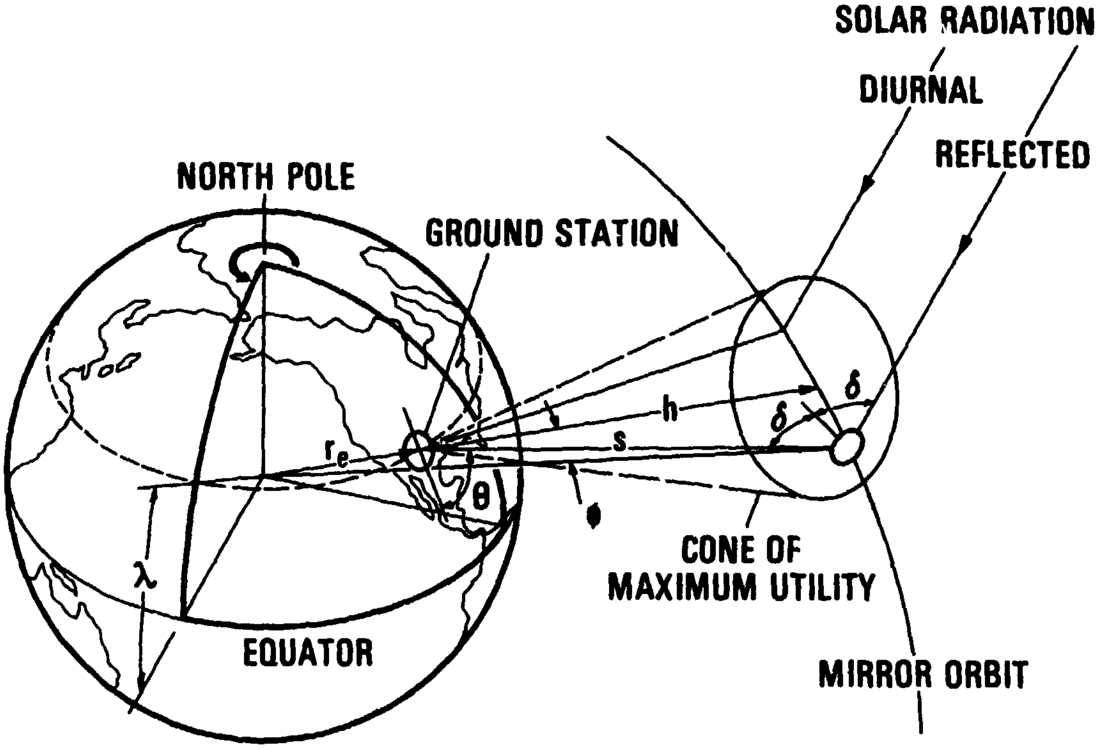


Figure 4.- Orbital geometry. The satellite mirror is described by distance coordinate $r_e + h$ and angle coordinate ϕ measured from the center of the Earth. Corresponding coordinates measured from the ground station, situated at latitude λ, are S and θ, respectively, where θ is measured relative to the local horizon. The orbital altitude, measured from the Earth's surface is h. A cone of maximum utility (defined in the text) is shown; it is characterized by a viewing elevation angle $\theta = \pm|\theta_{min}| = \pm 30°$ in this report, and a corresponding angle ϕ_m which is a function of θ_{min} and h.

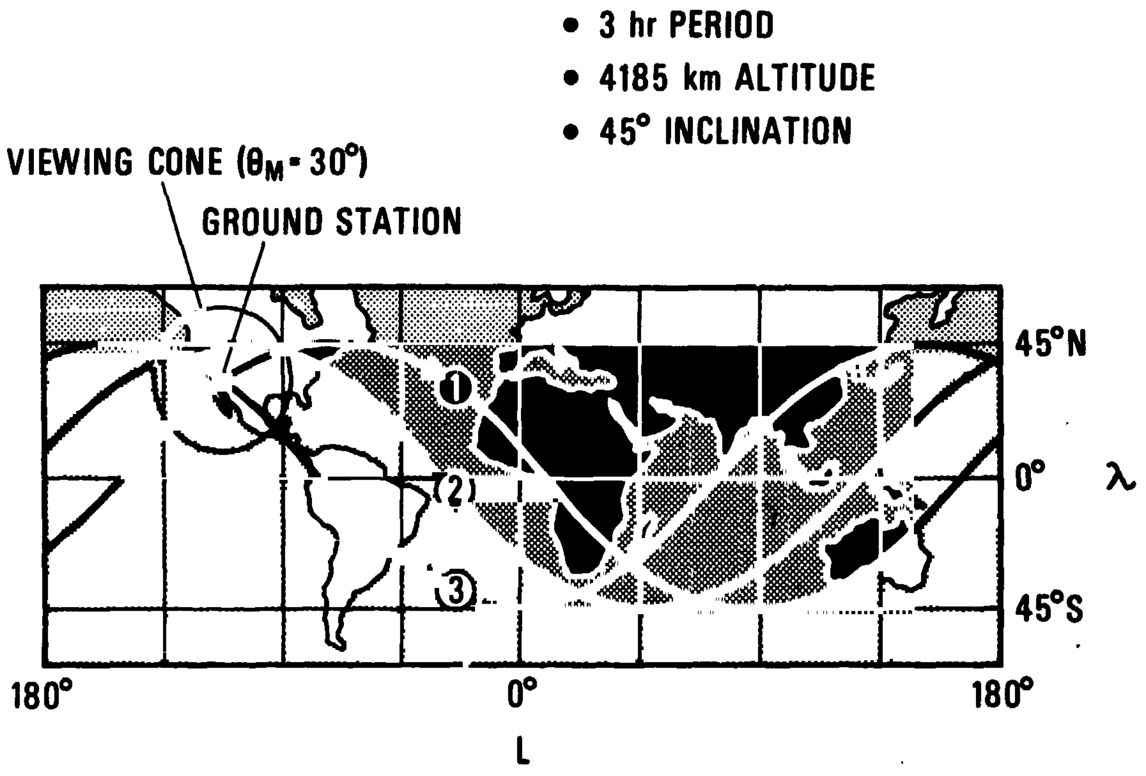


Figure 5.- Ground traces from three successive passes of an integer orbit mirror with a three hour period (45° inclination and 4185-km altitude). As shown, in a 24-hour period, three of the eight orbits will be in view of the ground station and two will pass through its zenith.

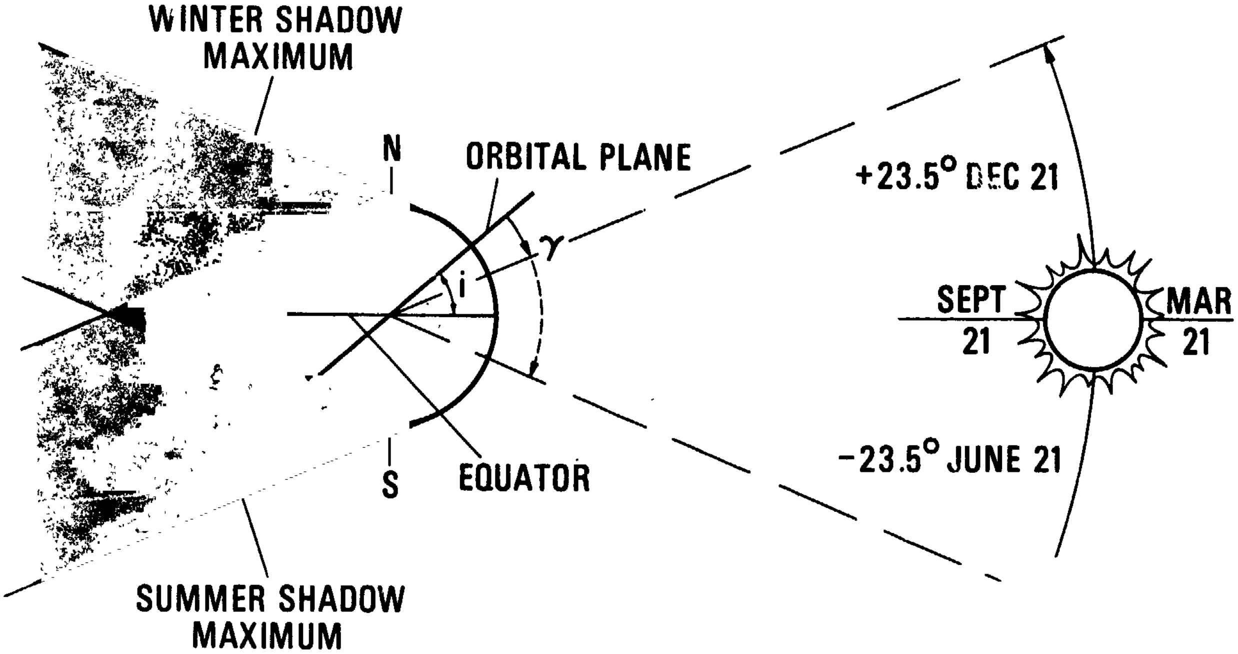


Figure 6.- Orbit relations to Earth and Sun with Earth reference showing apparent seasonal movement of the Earth-Sun line causing the orbit angle γ to change resulting in various fractions of that orbit being eclipsed by the Earth. The orbit inclination, i, to the equator is, to a first order, fixed.

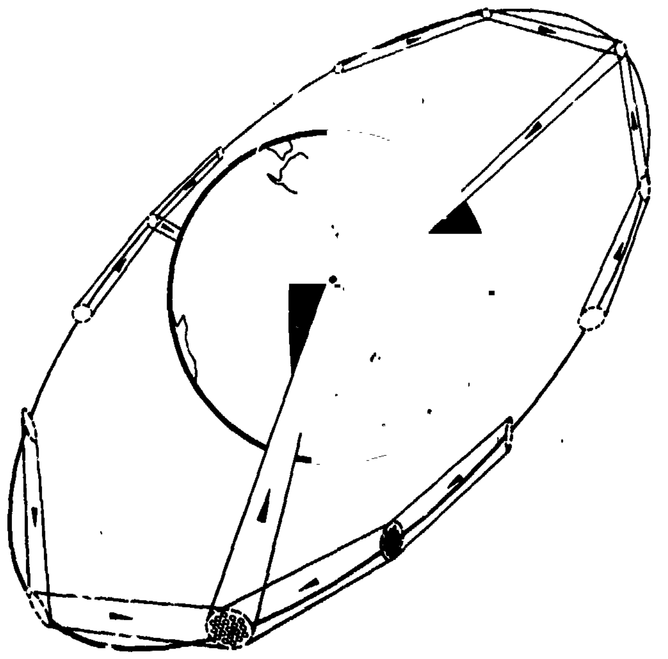


Figure 7.- Relay mirror concept, allowing full utilization of all mirrors for a limited number of receiving stations and a possible reduction in individual mirror size and total system mirror area.

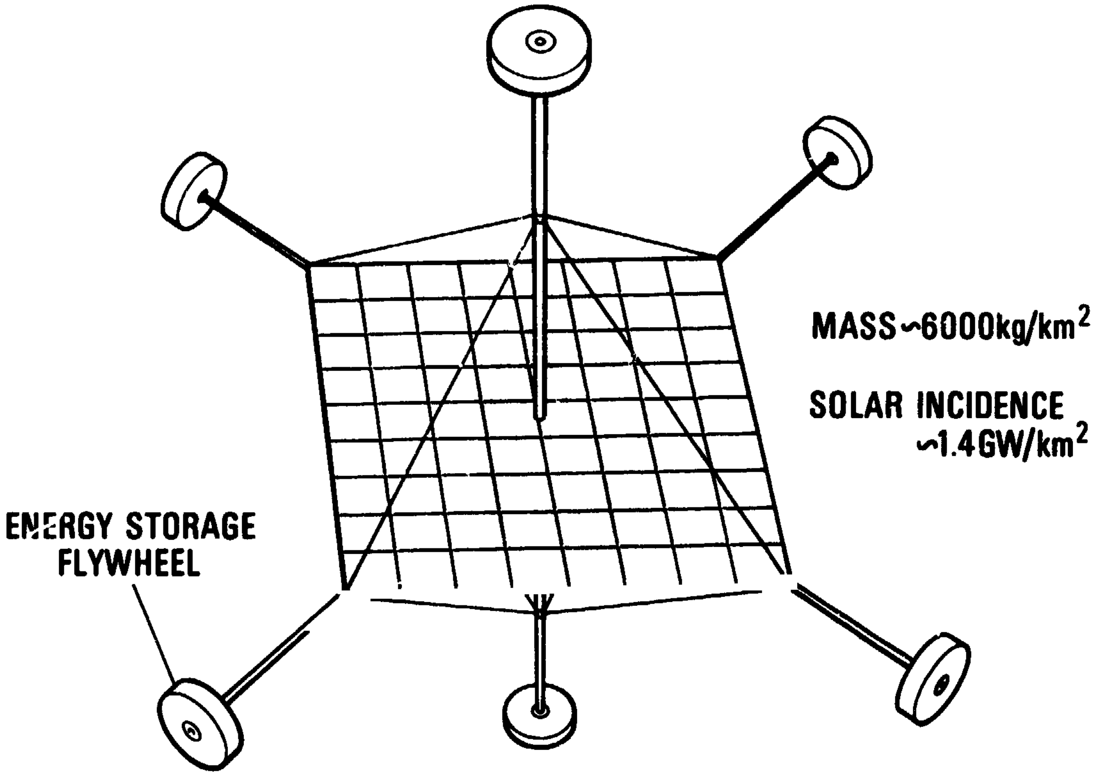


Figure 8.- Schematic of a cluster mirror. Mirror is one of the "free-flyers" which comprise the total array or satellite mirror. Tensional, probably hexagonal mirror elements, form the surface shown. The structure is a low-mass, high strength (probably composite material) boom-stays- and guys-arrangement similar to that under development for the Solar Sail Program. Composite material flywheels, at the ends of the booms, may be used to provide orientational (pointing) torques. Such a structure would be deployed at approximately 800-km altitude and solar sailed to its operational altitude.

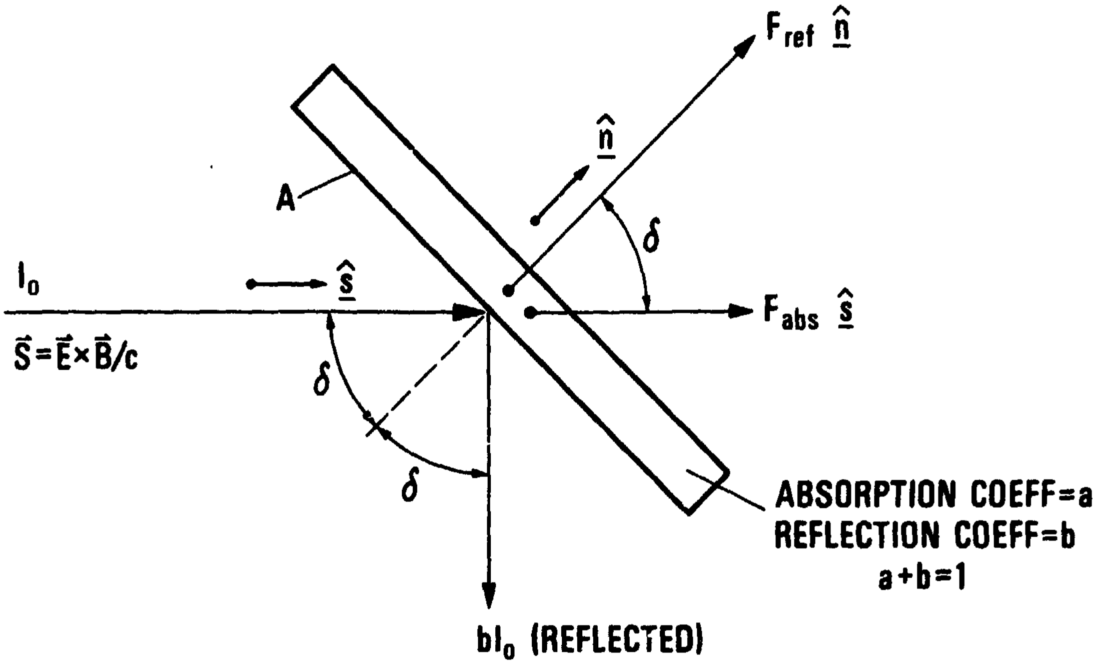


Figure 9.- Radiation pressure forces exerted on a partially absorbing and reflecting material sheet.

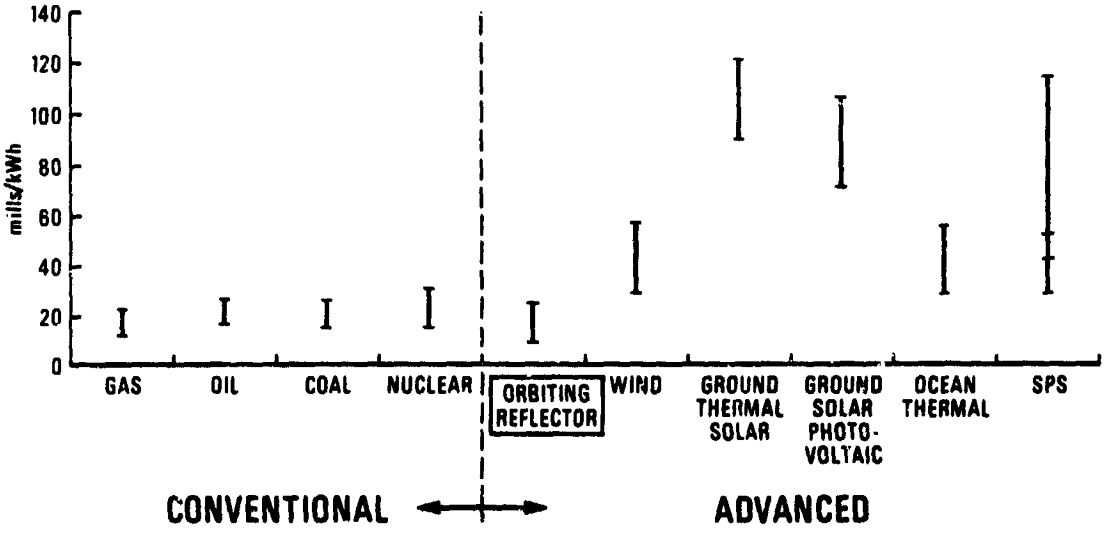


Figure 10.- Comparison of conventional and advanced electric power generation system costs.

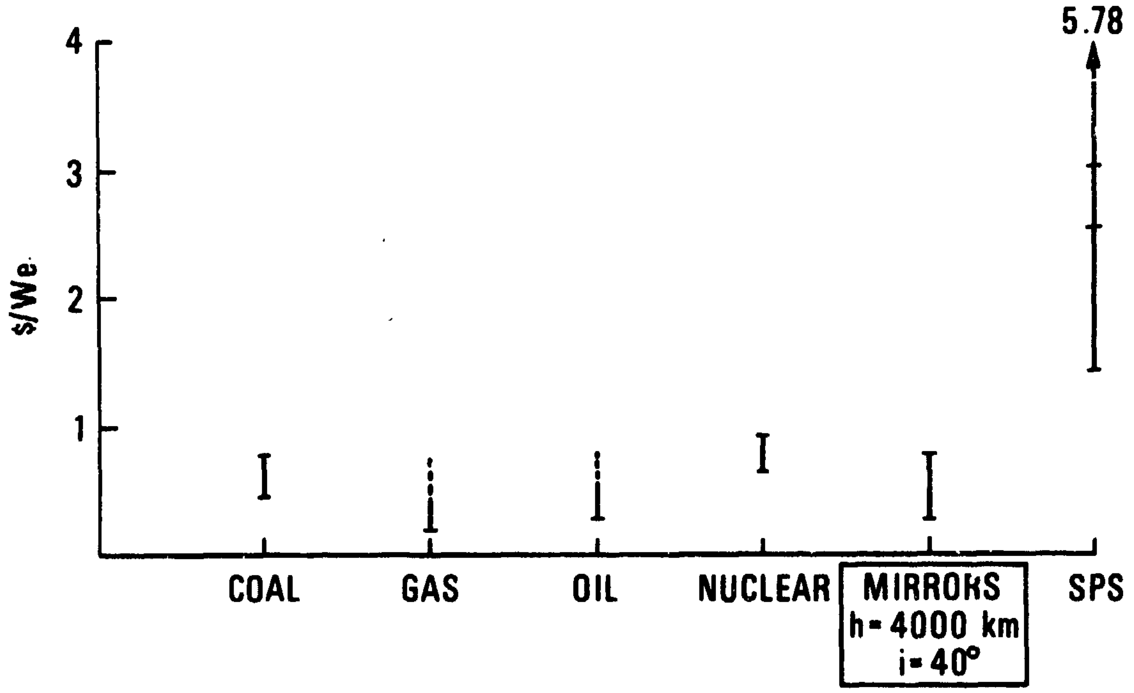


Figure 11.- Capital costs for electric plants in 1976 dollars. Does not include R&D costs.

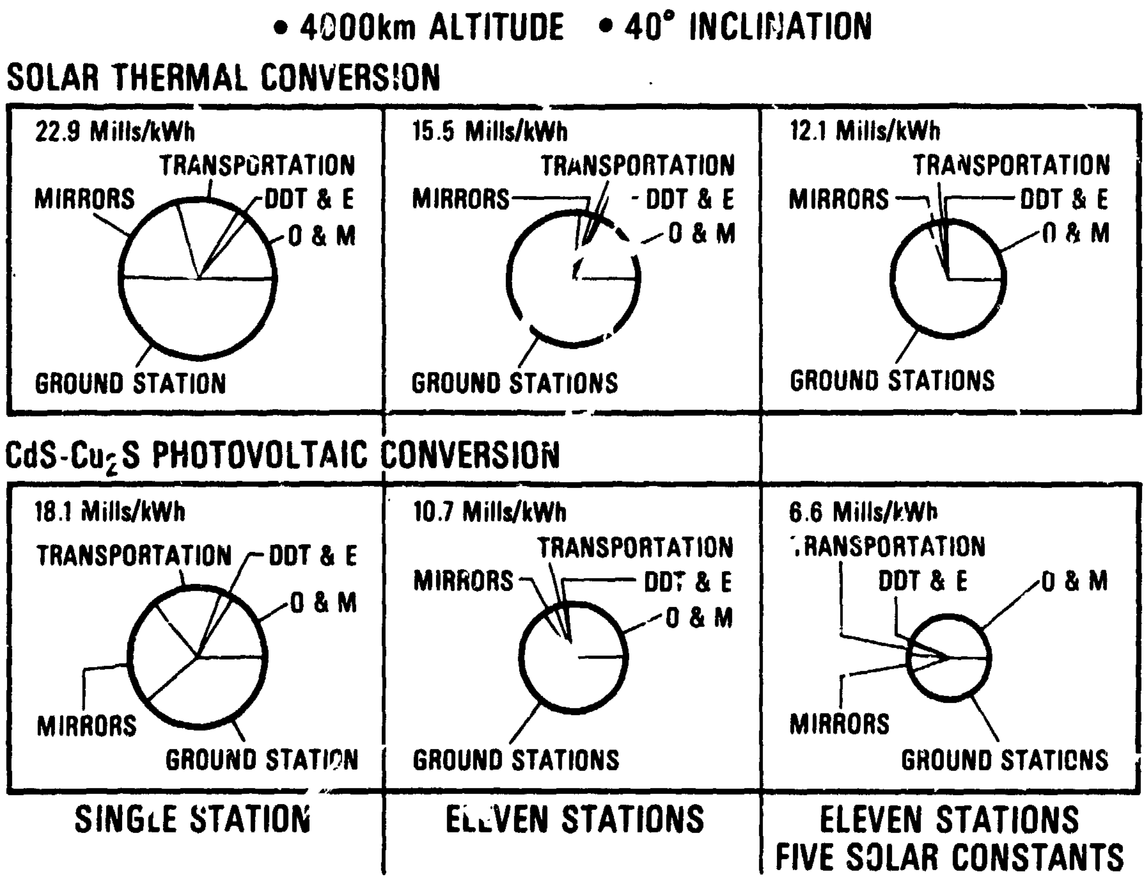


Figure 12.- Cost breakdown for a typical orbit option, 4000-km altitude and a 40° inclination. The effect of multiple ground stations, radiation conversion option and reflected intensity on total bus power cost and its costing elements is shown.

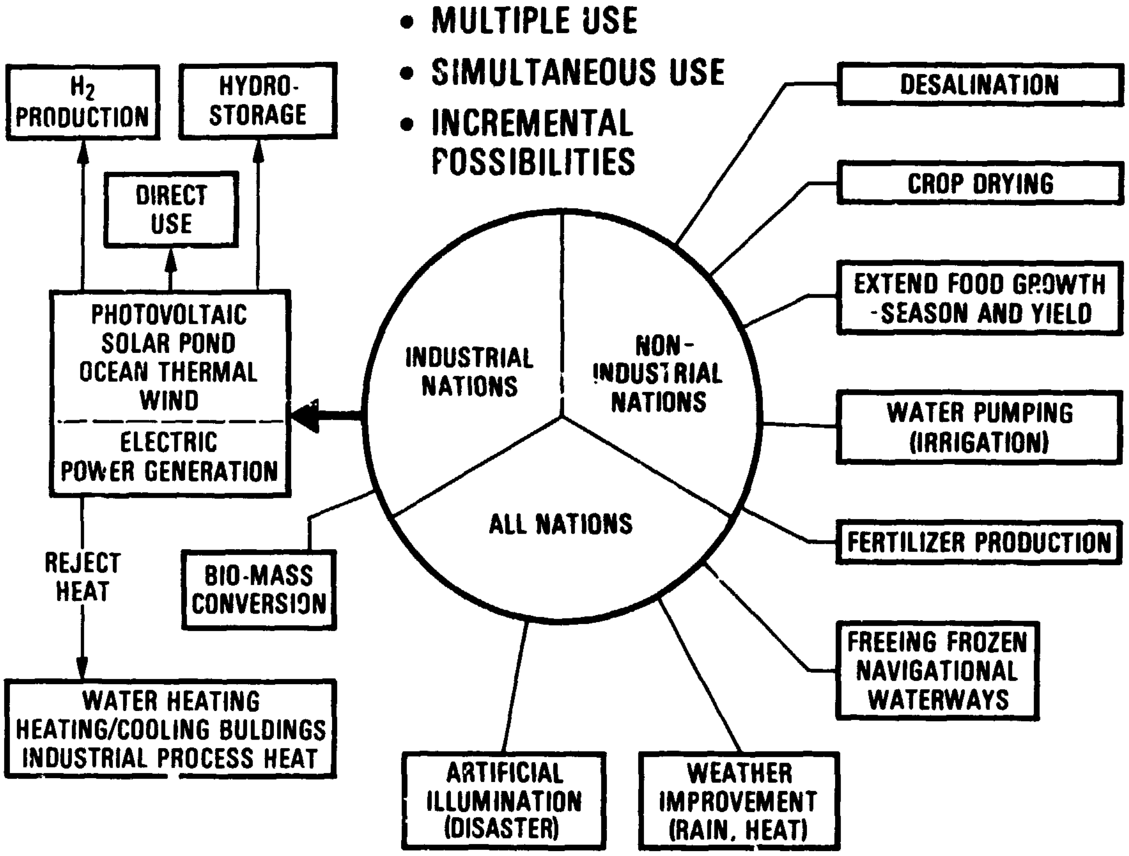


Figure 13.- Mirror system applications, illustrating the multiple use, the simultaneous use, and the incremental possibilities of this system which are not possessed by other solar satellite energy schemes.

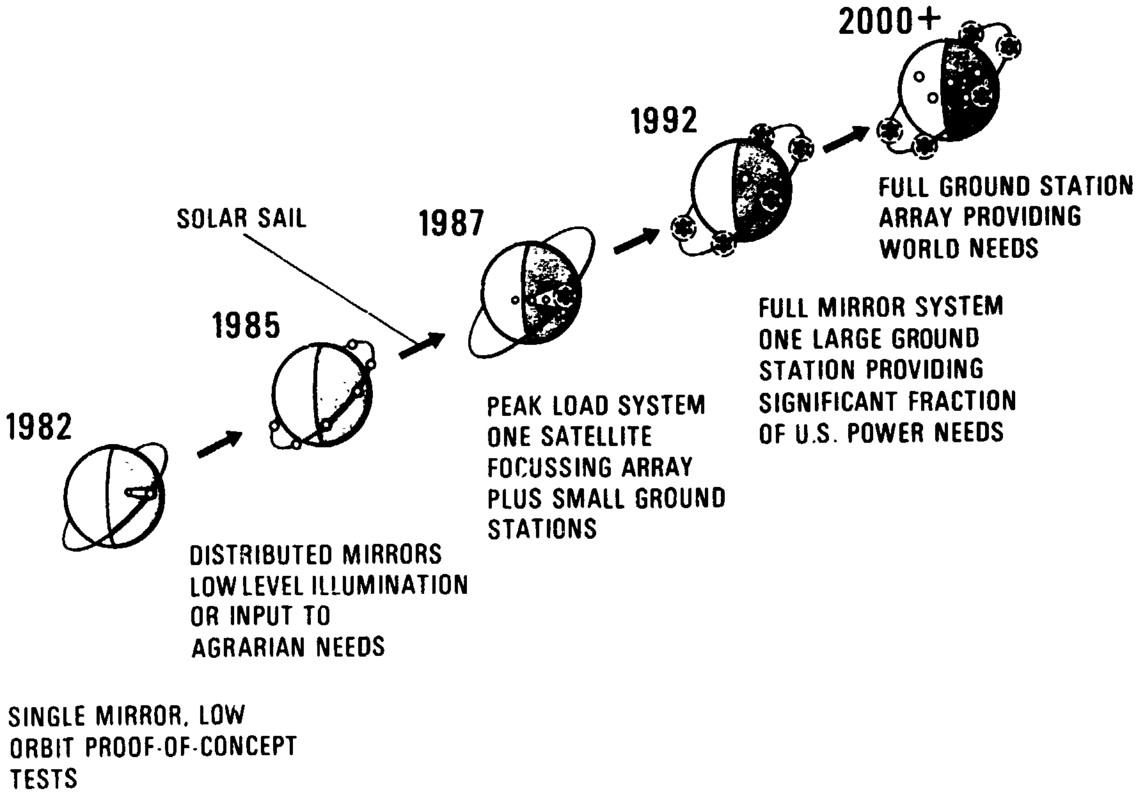


Figure 14.- Incremental implementation approach. Best-guess estimates of how technology readiness, R&D, and economic-political considerations would allow the system employment to attain full supply of world energy needs.