Final Report

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COMPARISON AND EVALUATION OF POWER PLANT OPTIONS
FOR GEOSYNCHRONOUS POWER STATIONS

Part 1

Synchronous Solar Power

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INTRODUCTION

Energy sources for the 1990's and beyond can be divided into five general categories: 1) fossil fuels, 2) nuclear fission, 3) nuclear fusion, 4) solar, and 5) others; this last category including geothermal, tides, radioactive isotopes, and other sources which are expected to make only a small contribution to the total world energy supplies. Terrestrial solar energy could provide from 10% to 20% of the world's energy supply by the year 2000 if its development and use is vigorously promoted;[1,2] most of this energy would be used for heating and air-conditioning and supplying hot water for homes and buildings.

There are three major objections to the continued large-scale combustion of fossil fuels: resource depletion, environmental degradation, and the increase of CO_2 in the atmosphere. Fossil fuels, especially oil and gas, are non-renewable natural resources of great value for manufacturing plastics, textiles, fertilizers and a variety of other products on which our society depends. Oil and gas are being burned at such a rapid rate that the world supplies of these valuable raw materials are expected to be depleted in a few decades. After they are gone, future generations will certainly be appalled at our selfish misuse of these resources, just as people today denounce the wanton slaughter and subsequent extinction of the passenger pigeon and other animal species by our ancestors. As the space program develops, it may become possible to mine the moon, astroids and planets for needed minerals, but coal, oil and gas exist only on earth, and cannot be replaced after they are gone.

Most of our air pollution at the present time comes from the combustion of fossil fuels. Recent legislation requiring reduction of pollutant emissions has resulted in control technology being applied to automobiles and power plants which reduce their efficiency, and further increase the rate of usage of these fuels.[3] The disastrous consequences of oil spills and strip mining are well known.

Carbon dioxide is not usually considered a pollutant because it is a natural constituent of the earth's atmosphere. However, it is the only combustion product gas for which a worldwide increase in atmospheric concentration has been measured. Particulates have also shown an increase, but particulate emissions from combustion sources can be reduced considerably by a variety of control devices. Carbon dioxide emissions, however, cannot be removed by any practical process, and will continue to be released into the atmosphere as long as fossil fuels are burned. Several studies have predicted that continued combustion of fossil fuels will double the atmospheric CO_2 by the year 2020 which will result in an increase in worldwide temperatures, melting of the polar ice caps, a 200 foot rise in the level of the oceans, and gradual flooding of the major coastal cities of the world.

Nuclear and solar power do not pollute the air, have little or no environmental impact, do not use up non-renewable natural resources which have other valuable uses, and do not release CO_2 into the atmosphere. Nuclear energy sources consume uranium and deuterium, materials that have no use other than the production of nuclear power. It is or soon will be technologically and economically feasible to supply all man's energy needs with nuclear and solar energy[1,4] so certainly in view of the need for coal, oil and gas for manufacturing and producing food, and the environmental and climatological

implications of continued combustion of these materials, all fossil fuel combustion should be phased out as quickly as possible and replaced by nuclear and solar energy sources, with a minor contribution from geothermal, and tides.

The development of nuclear power is proceeding in three phases: 1) fission-burner reactors which burn the scarce U-235 isotope, 2) fission-breeder reactors which convert relatively plentiful uranium and thorium isotopes into fissionable reactor fuel, and 3) fusion reactors. Fission burner reactors represent only a short-term energy resource since the available uranium will be rapidly consumed. The estimated U.S. demand for uranium is 2.4 million tons for the rest of this century, considerably in excess of the known U.S. uranium reserves of 525,000 tons. The limited supply of uranium fuel is the reason the breeder reactor is being pushed so strongly.

The fuel for breeder reactors is extremely toxic; it has been estimated that a few kilograms of finely dispersed plutonium could wipe out an entire city. Also, much concern has been expressed about the safety of breeder reactors, the fuel reprocessing facilities, the transportation of nuclear fuels and nuclear wastes, and the disposal of radioactive wastes. Another concern is the safeguards problem--preventing fissionable materials from coming into the possession of radical groups who could fabricate an explosive device.

Fusion reactors represent the ultimate in nuclear power, but its feasibility has not yet been proven, and fusion power may not be practical for another hundred years or more. If commercial fusion reactors are developed, mankind will be assured of unlimited energy supplies for the forseeable future, but until the feasibility of such reactors is proven, alternatives to fusion for providing power beyond the 1990's should be pursued. A major alternative to fusion in this time period is the synchronous power plant.

The safety problems of nuclear breeder reactors can be virtually eliminated, and the economics of large-scale solar power generation can be improved, by generating power in synchronous orbit and transmitting it to earth by microwave beam.

The objections to nuclear reactors are virtually eliminated if the large breeder reactors are located far out in synchronous orbit, and the nuclear fuel is reprocessed on site. Various fluid-fueled, particle-fueled and gaseous-fueled reactor concepts have been explored which permit efficient power generation in space and simplified on-site fuel reprocessing schemes. Only non-hazardous fertile materials (depleted uranium or thorium) are shipped from earth to the plant, the toxic breeder reactor fuels are produced and used at the plant, and the final end-product radioactive wastes are projected away from the earth. The decay heat of the encapsulated waste itself can be used to produce the power for an ion engine to drive the capsule into the sun, or into intersteller space. A reactor accident at the plant would have negligible impact on the earth, and accidental reentry of a synchronous power plant is inconceivable because of the large velocity change required for reentry. The safeguards problem is solved also, since theft of fissionable fuels from a synchronous satellite would be an extremely difficult undertaking, and could be accomplished only by a nation with a well-developed space logistics capability. Such a nation would probably already possess the ability to manufacture nuclear weapons, so such a theft would be unnecessary.

The major advantages of solar power generation in synchronous orbit as compared with terrestrial solar power generation are the increased energy availability in space and the fact that this energy is supplied almost continuously. Terrestrial solar plants must be six to fifteen times as large

to collect the same amount of energy, and since this energy is supplied only
when the sun is shining, large energy storage facilities or alternative
power sources must be used to provide power at nighttime and during cloudy
weather. A detailed feasibility study of a satellite solar power station,
funded by NASA, has been recently reported by Glaser et al.[5]

Geosynchronous power plants, either solar or nuclear, can provide un-
limited power to the earth without pollution and at a reasonable cost,
provided a fully reusable space shuttle is developed. When one considers the
adverse economics of large-scale terrestrial solar power, the potential future
hazards of nuclear fission, the uncertainties in the development of fusion,
and the environmental impacts and depletion of fossil fuels, it is apparent
that the synchronous power plant alternative should be pursued, and the space
logistics capability to permit the exploitation of this energy resource
should be developed. This report describes the present state-of-the-art of
the various technologies which may lend themselves to the development of
synchronous power plants.

GEOSYNCHRONOUS SOLAR POWER SATELLITES

The concept of placing a large solar array in geosynchronous orbit 35,800 km from earth and transmitting this power to earth was proposed by Glaser[121, 122] in 1968, and since that time, has received increasing attention as a potential major energy resource for the next century. The basic motivation for placing the solar array in space is the increased availability of solar energy in space, as illustrated below. Up to fifteen times as much solar energy is received by a solar array in space as the same array would

Average Availabilities of Solar Energy[8]

AVAILABILITY FACTOR	AVERAGE ON EARTH	IN SYNCHRONOUS ORBIT	AVERAGE RATIO
Solar Radiation Energy Density	0.11 watts/cm^2	0.14 watts/cm^2	4/5
Percentage of Clear Skies	50%	100%	1/2
Cosine of Angle of Incidence	0.5	1.0	1/2
Useful Duration of Solar Irradiation	8 hr.	24 hr.	1/3
PRODUCT			1/15

receive on the ground, and this energy is received almost, continuously, 24 hours a day. Now that NASA is developing the space shuttle to permit the routine exploitation of the space environment, the economics of geosynchronous power plants are becoming more attractive.

The basic concept is illustrated by Figure 1. Concentrators reflect sunlight onto an advanced, lightweight solar array. The two symmetrically

arranged collectors convert solar energy directly to electricity which powers

microwave generators within the transmitting antenna located between the two

large collecting panels. The 1 Km kiameter antenna transmits the power to

a 7.4 Km diameter receiving antenna on the ground (Figure 2) with an overall

efficiency of about 68%. The microwave transmission system is expected to

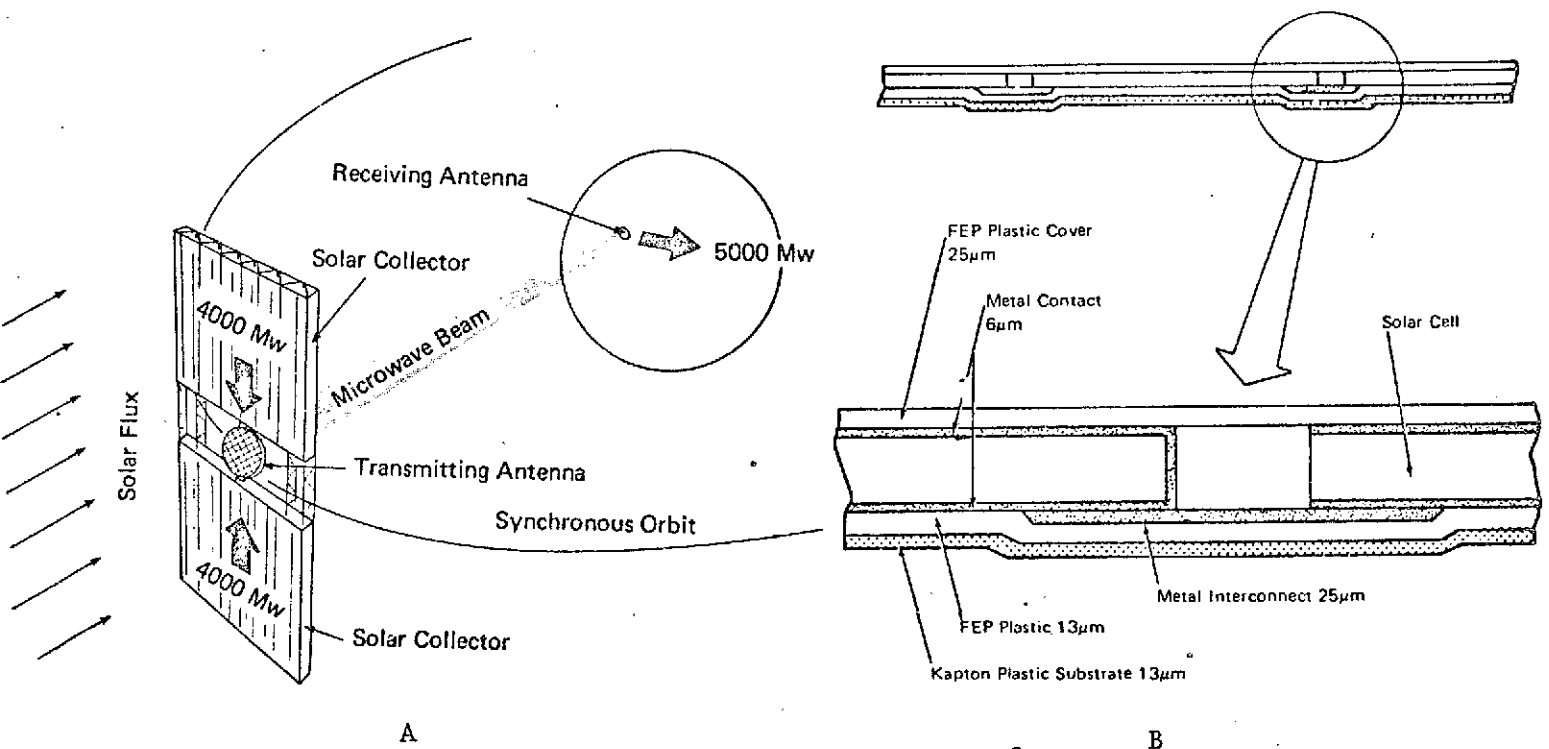cost about \$130/KWe.[10] In order to achieve the necessary coherent transmission,

Figure 1. A) Geosynchronous Solar Power Plant[9]

B) Solar Cell Array Construction[10]

the many separate elements of the transmitting antenna must be phase locked

onto a pilot signal originating from the center of the receiving grid, and

it is impossible to direct the beam away from the receiving antenna. Since

the receiving grid does not block sunshine, the land beneath can be used for

growing farm crops. Microwave intensities reaching the earth are completely

safe.

The solar cells in the array are projected to have an 18% efficiency, 50 micron thickness, and cost $0.38 per cm^2, which should lead to a 950 watt/kg array costing $0.68 per cm^2 and having a 30 year life. The array is expected to suffer a 1% loss of solar cells from micrometoroid impacts over a 30 year period. Glaser[10] gives the cost of a small several hundred megawatt prototype plant, based on current shuttle cost estimates and near-term solar cell technology, as $310/KWe for the solar arrays, $230/KWe for the microwave
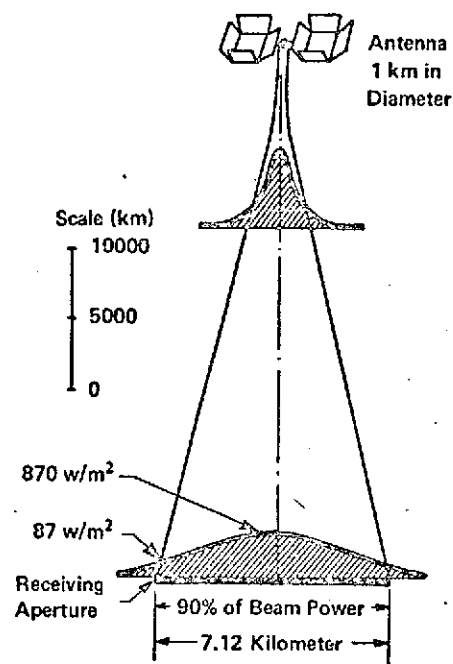

Figure 2. Microwave Transmission to Earth[11]

transmission system, and from $800/KWe to $1380/KWe for transportation to geosynchronous orbit and assembly, for a total system cost of from $1340/KWe to $1920/KWe. Capital cost for a fully operational 5000 MWe plant is expected to be about $800/KWe. The power satellite will produce more energy in its first year of operation than was required to manufacture it and place it is orbit.

Patha and Woodcock[12] explored the feasibility of large geosynchronous solar-thermal plants (Figure 3) operating with a "current technology" helium/xenon brayton cycle, and estimated the capital cost of a 1980 technology plant at $2540/KWe. Since about 80% of this cost is space transportation, this cost should be reduced if a fully reusable space shuttle becomes operational and lighter weight reflecting surfaces become available. They also projected an advanced solar cell system to cost $2950/KWe, slightly more than the solar-thermal system. Brown[13] projected the capital cost of solar cell geosynchronous plants to lie in the range of $1400/KWe to $2600/KWe. Mockovciak[14] reported an earlier estimate of $2100/KWe for a prototype
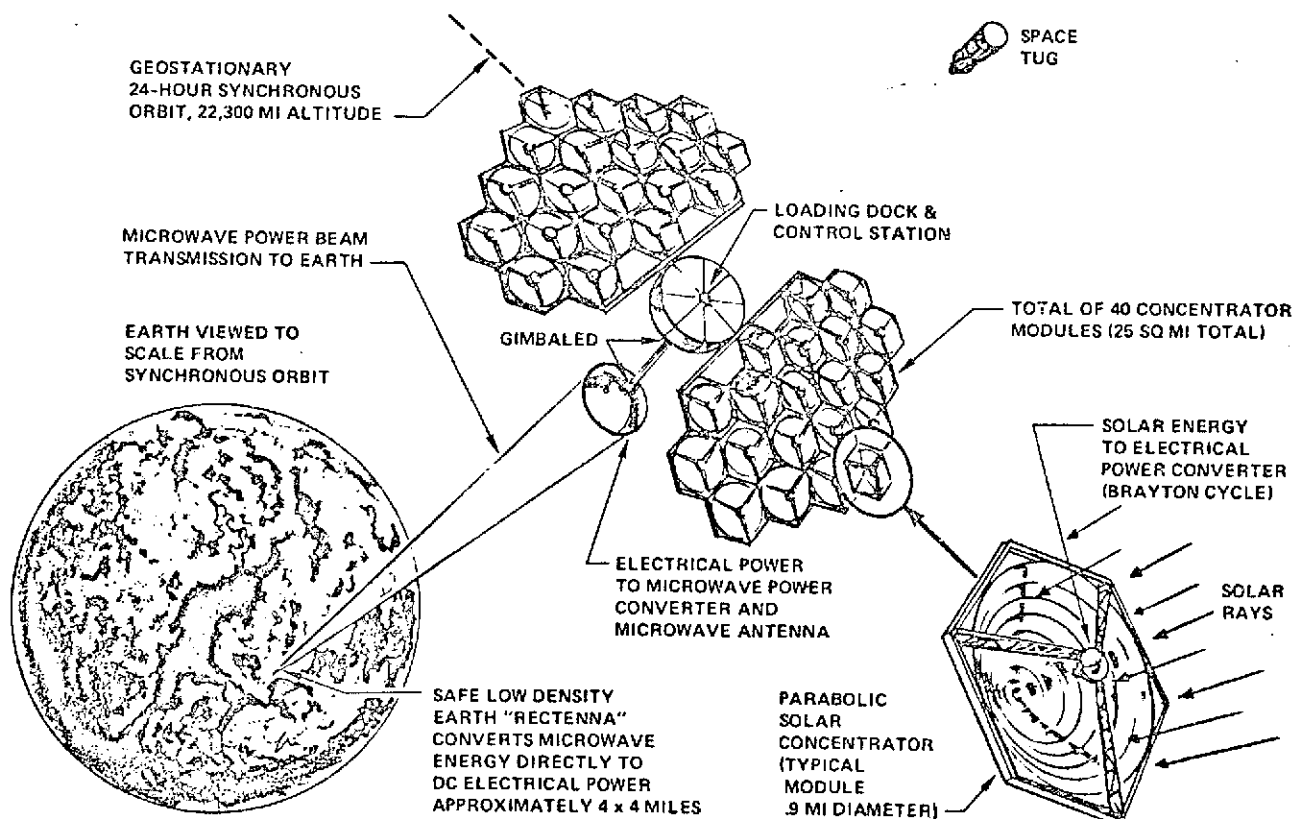

Figure 3. Geosynchronous Solar-Thermal Power Plant

solar cell plant based on a study by the A.D. Little/Grumman/Raytheon/Tex-
tronics team which has been conducting studies of solar cell power satellites
for several years.

Photovoltaic Arrays for Power Satellites

As currently envisioned, a 10,000 MWe power plant system would use channel
concentrators to focus sunlight onto 50 micron thick silicon solar cells.
The solar cells would be sandwiched between thin FEP plastic films with
electrical interconnections between individual cells applied by vacuum-
depositing metal alloy contact materials, as shown in Figure 1. The channel
concentrators consist of thin reflective plastic films stretched over a
supporting frame.

Channel concentrators have been used for terrestrial solar collectors,
and consist of two flat reflecting surfaces at an angle of 30 degrees placed
on both sides of a line of solar cells. The theoretical maximum concentration
ratio is 3. Ralph[15] achieved an actual concentration ratio of 2.25 using
5.08 cm by 5.08 cm silicon solar cells at the base of the V channel. Five
channels with 30 cells each formed a 2.16 Kg, 30.5 cm by 61 cm array producing
12 watts at 12 volts. The concentration ratio is less than the theoretical
maximum because the reflecting sides of the channel are not 100% reflective
and because the 60 degree angle of incidence of the reflected sunlight onto
the solar cells results in greater reflective losses from the front surface of
the solar cells. Another factor to be considered is the reduced efficiency
of the solar cells due to their higher temperature when operating with con-
centrated sunlight. Still, solar cell power outputs per unit cell area can
be increased a factor of 2 or more with channel concentrators, and since
reflective surfaces are much cheaper than solar cells, the cost per watt is
reduced.

Figure 4 illustrates the solar collector configuration as proposed in the recent study performed for NASA.[5] The main structural framework for each solar array consists of a large-diameter coaxial mast transmission bus, four transverse D. C. power buses, and non-conductive struts. Shear loads are transmitted by cables in tension. Figure 5 shows the baseline configuration of the array for a power satellite to provide 5000 MWe to the earth. The microwave antenna is located between the two solar array sections and can be rotated independently to remain pointed toward the earth as the solar arrays face the sun. The structure between the two solar arrays is fabricated of a fiber composite dielectric material so as not to interfere with the microwave beam.

Large, triangular compression struts can be built up from small truss elements as shown in Figure 6. The basic building element is easily manufactured. The electric currents circulate in the antenna structure in such a way that the magnetic fields cancel out, so the satellite is not affected by the magnetic field of the earth. For the baseline configuration (5,000 MWe) 6061 aluminum alloy was selected for the structure because of its high strength per unit weight and high electrical conductivity.

This structure was studied using a finite element structural analysis computer program developed by the Grumman Aerospace Corporation.[16] This program assumes that each structure may be idealized into an assemblage of individual structural components, and the idealized structure is analyzed and the results used to predict the behavior of the actual structure. Dynamic studies were performed using large digital computer programs developed by Grumman and NASA. The weight of the baseline solar array was 8.12 million Kg, including 6.11 million Kg for the solar cell blankets, 1.01 million Kg
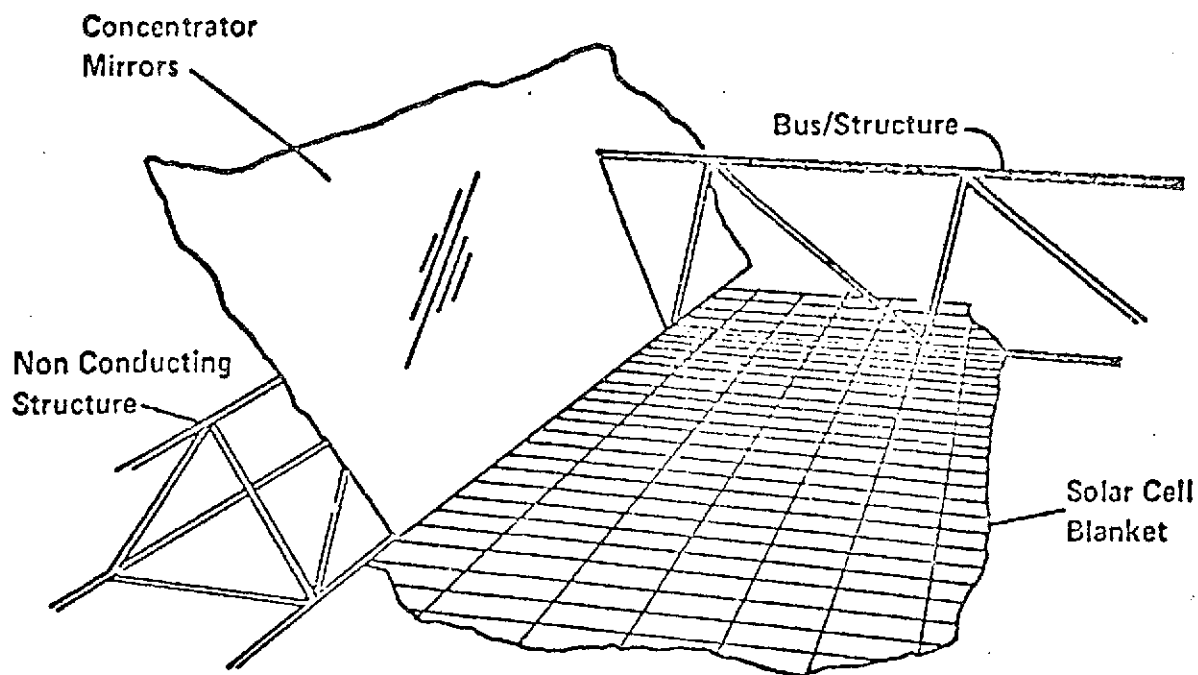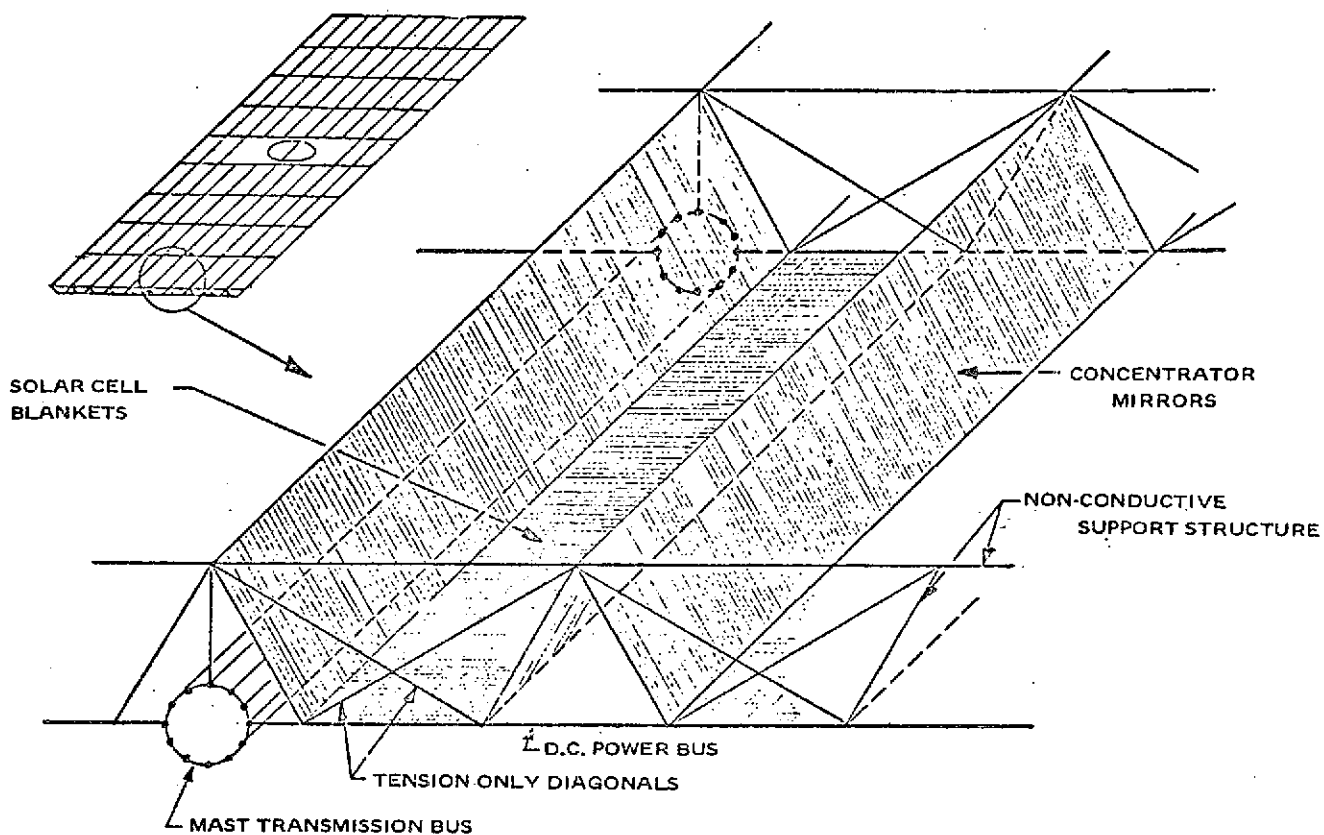
SOLAR CELL
BLANKETS

CONCENTRATOR
MIRRORS

NON-CONDUCTIVE
SUPPORT STRUCTURE

D.C. POWER BUS

TENSION ONLY DIAGONALS

MAST TRANSMISSION BUS

Concentrator
Mirrors

Bus/Structure

Non Conducting
Structure

Solar Cell
Blanket

Figure 4. Configuration of Solar Cell Array
with Channel Concentrators[5]
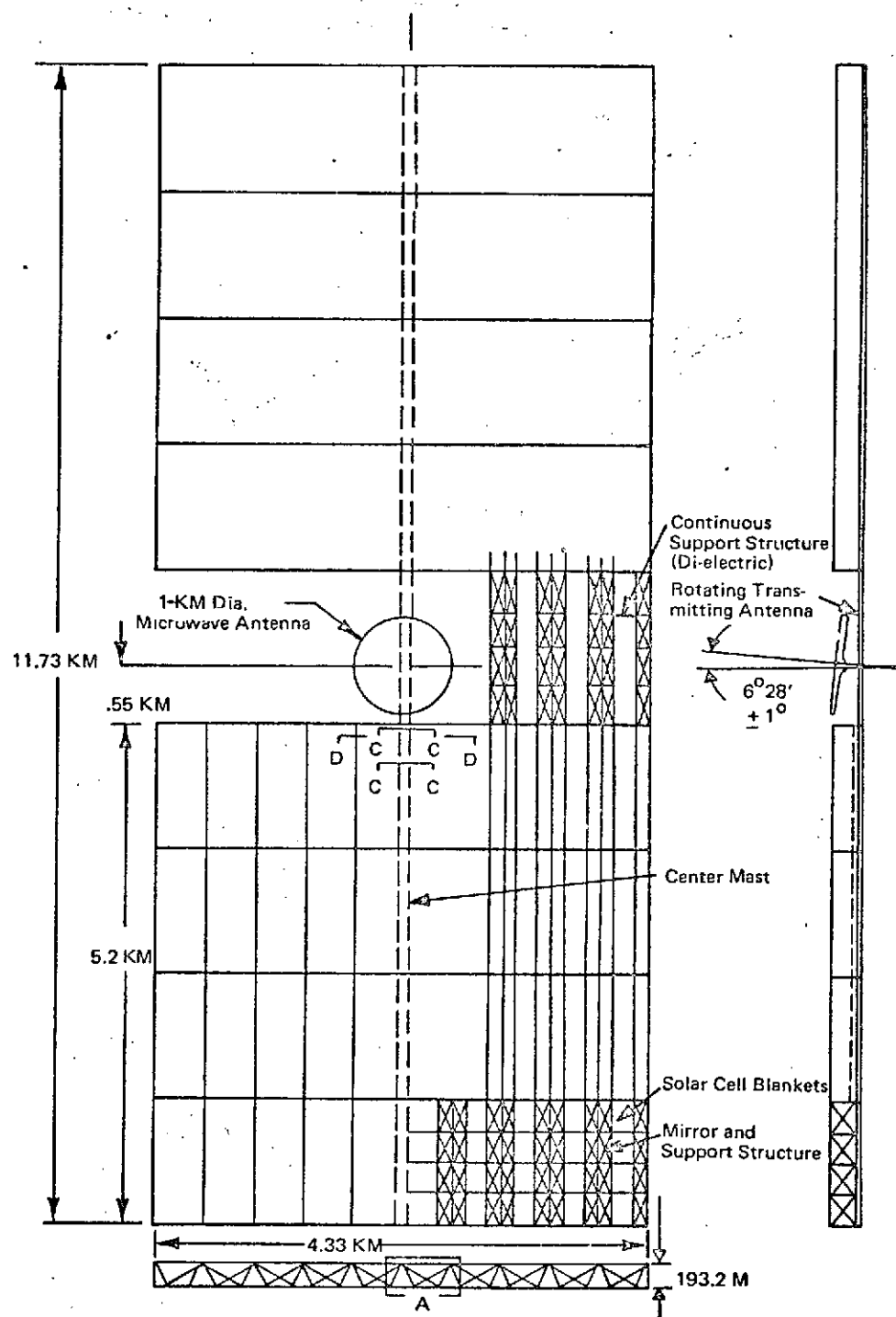
Figure 5. Solar Cell Array with Channel Concentrators
to Provide 5000 MWe to the Earth.[5]

30.5
CM

Basic Building Element

2.5 CM

30.5
CM

30.5 CM

3M

3 M

3 M

30 M

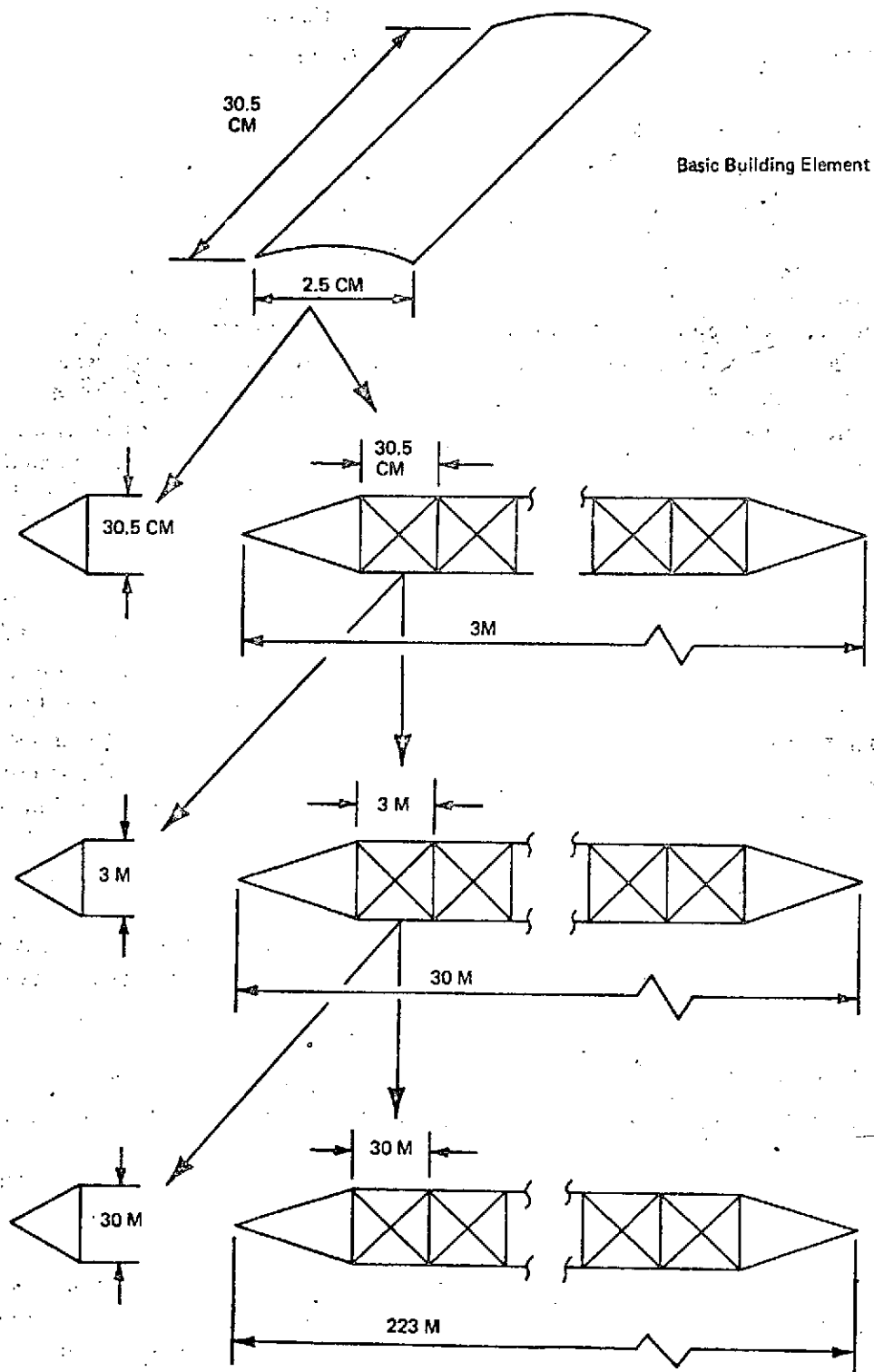30 M

30 M

223 M

Figure 6.   Construction of Compression Strut for
            Solar Cell Array.

for the reflecting films, 0.41 million Kg for the supporting structure, and 0.58 million Kg for the antenna mast. The microwave antenna was projected to weigh 1.98 million Kg, and the rotary joints, 0.32 Kg. This leads to a total weight in synchronous orbit of 10.42 million Kg.

The weight of such a solar array in space is far less, and the type of structure very different, from terrestrial solar collectors of similar size. Thin reflective films cannot be used to concentrate sunlight on earth unless they are rigidly supported, since solar collectors on earth are subject to high wind loadings. Wind and gravity require that terrestrial solar collectors be much more massive, and considerably stronger than collectors in space. Also, the terrestrial collector must be six to fifteen times larger to collect the same amount of energy. Thus, the raw materials consumed in constructing a satellite solar power station can be far less than the raw materials required to construct solar power plants on the ground.

Five external forces act on the power satellite: aerodynamic, magnetic, solar pressure, microwave pressure, and the gradient of the earth's gravitational field (Figure 7). In synchronous orbit aerodynamic forces are negligible, and the magnetic interaction with the earth's geomagnetic field is negligible because the currents in the arrays circulate in such a way that these interactions cancel. The solar pressure on the satellite is 224 newtons (50 lbs), and the recoil of the microwave antenna from the microwave beam leaving it is 18 newtons (4 lbs). The gravitational torque results from the simple fact that if one side of the satellite is closer to the earth than the other, the closer side experiences a greater gravitational attraction than the other, causing a torque on the array. The gravitational torques can be compensated for by ion thrusters applying 45 newtons (10 lbs) of thrust at opposite ends

External Forces

A. Solar Pressure

B. Aerodynamic

C. Gravity Gradient
    Torque
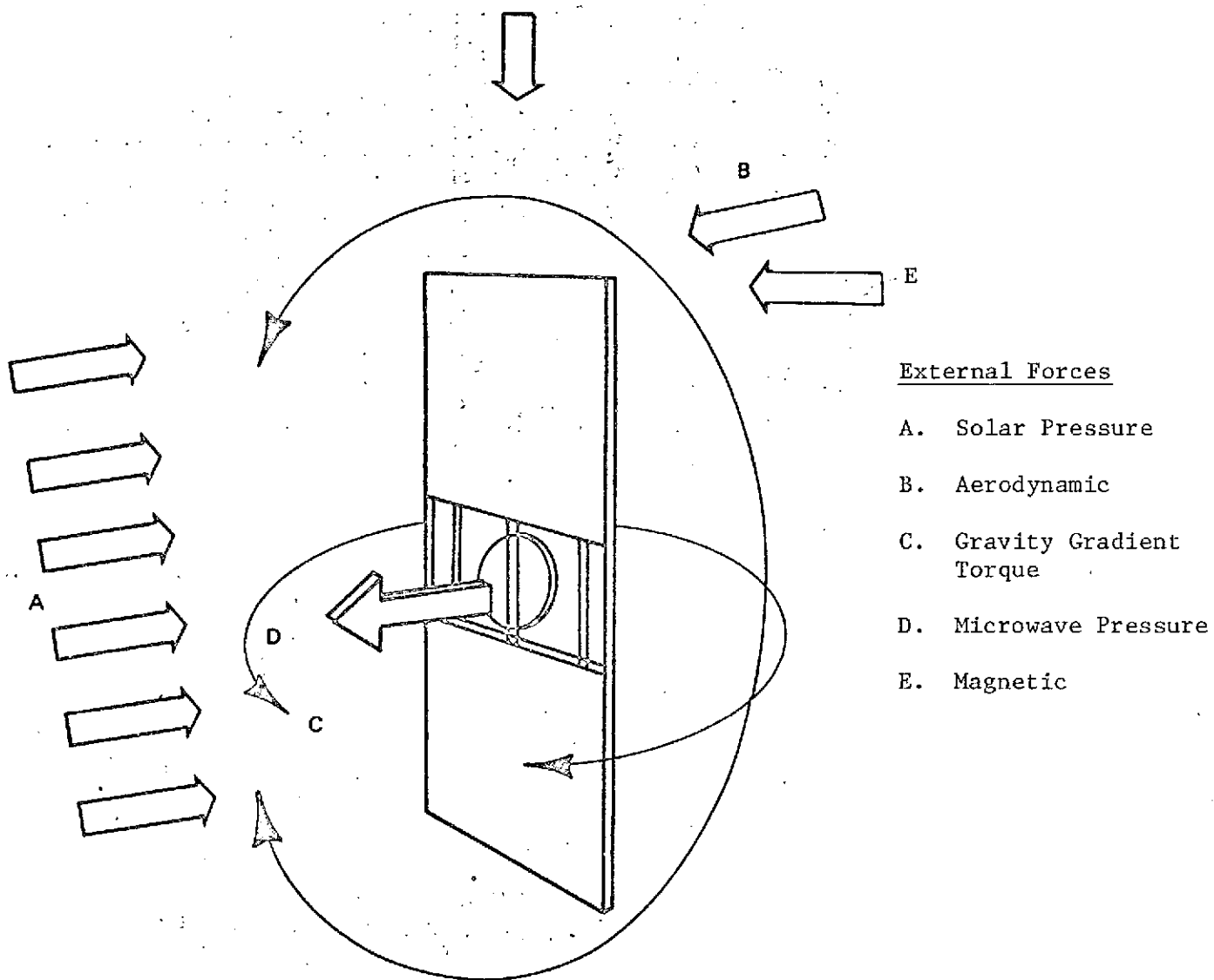
D. Microwave Pressure

E. Magnetic

Figure 7. External Forces Acting on Solar Power Satellite.

of the array to keep the solar arrays toward the sun.

One of the primary obstacles to be overcome before solar cell power satellites can become a reality is the cost of solar cells. At present, solar cells for terrestrial uses cost about $20/watt. These costs will need to be reduced to less than $1/watt and the thickness reduced to about 50 microns. One promising approach to achieving these cost goals is the thin film extrusion process now under study by NSF contractors.[19] This process is known as edge-defined film-fed growth[21] (EFG), as illustrated by Figure 8. The single crystal silicon ribbon is continuously extruded from the molten silicon contained in the RF heated quartz crucible. Silicon ribbons up to 6 feet in length have already been produced. The advantage of this approach is that it lends itself to automated manufacturing processes, so that solar cells can be mass produced at low cost.[22] These thin film solar cells could then be continuously incorporated into the transparent plastic blanket, as illustrated in Figure 9. The blankets can be rolled up for transport.

The size and cost of the solar array (Figure 5) for the 5000 MWe system is based on a solar cell efficiency of 18% and cost of 38 cents per cm^2, leading to a blanket cost of 68 cents per cm^2 and weight of 950 W/Kg, and an array cost of $310/KWe and weight of 1.4 Kg/KWe.

One possibility for reducing the weight of the blanket still further is the use of gallium arsenide instead of silicon solar cells. The minimum thickness of the cell is determined by the optical absorption coefficient of the material. As is shown in Figure 10, the absorption coefficient of GaAs is about a factor of ten higher over the wavelength range of interest than silicon, so theoretically the thickness can be reduced to one-tenth that of
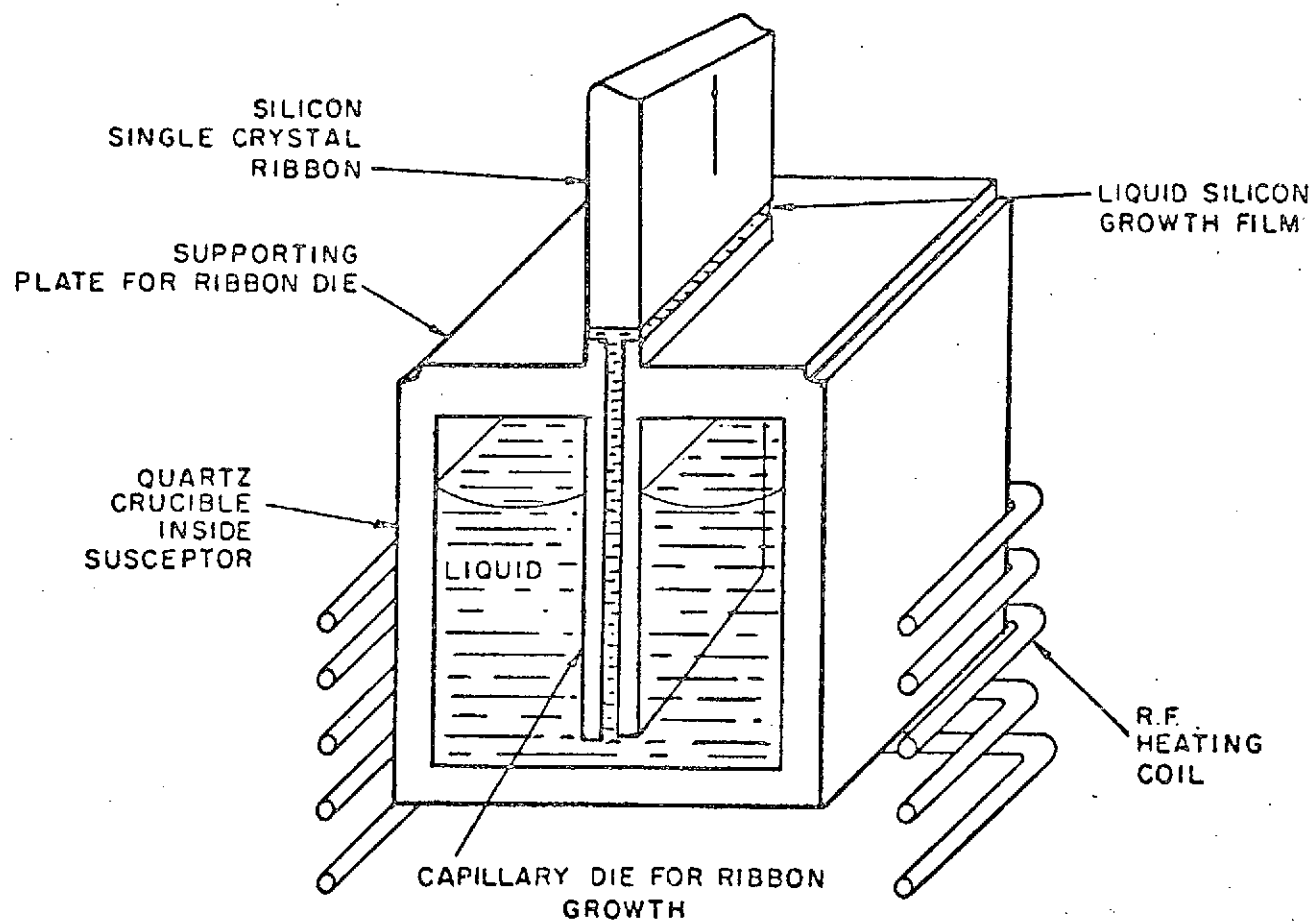
SILICON
SINGLE CRYSTAL
RIBBON

LIQUID SILICON
GROWTH FILM

SUPPORTING
PLATE FOR RIBBON DIE

QUARTZ
CRUCIBLE
INSIDE
SUSCEPTOR

LIQUID

R.F.
HEATING
COIL

CAPILLARY DIE FOR RIBBON
GROWTH

Figure 8.   Technqiue for Producing Edge-Defined Film-Fed
            Growth Silicon Solar Cells.

Load magazine conveyor pickup   Clean for inter-connect   Attach inter-connect   Bond lower FEP and Kapton plastic   Dip in filler bath   Bond upper FEP plastic   Cut for 40 m. length
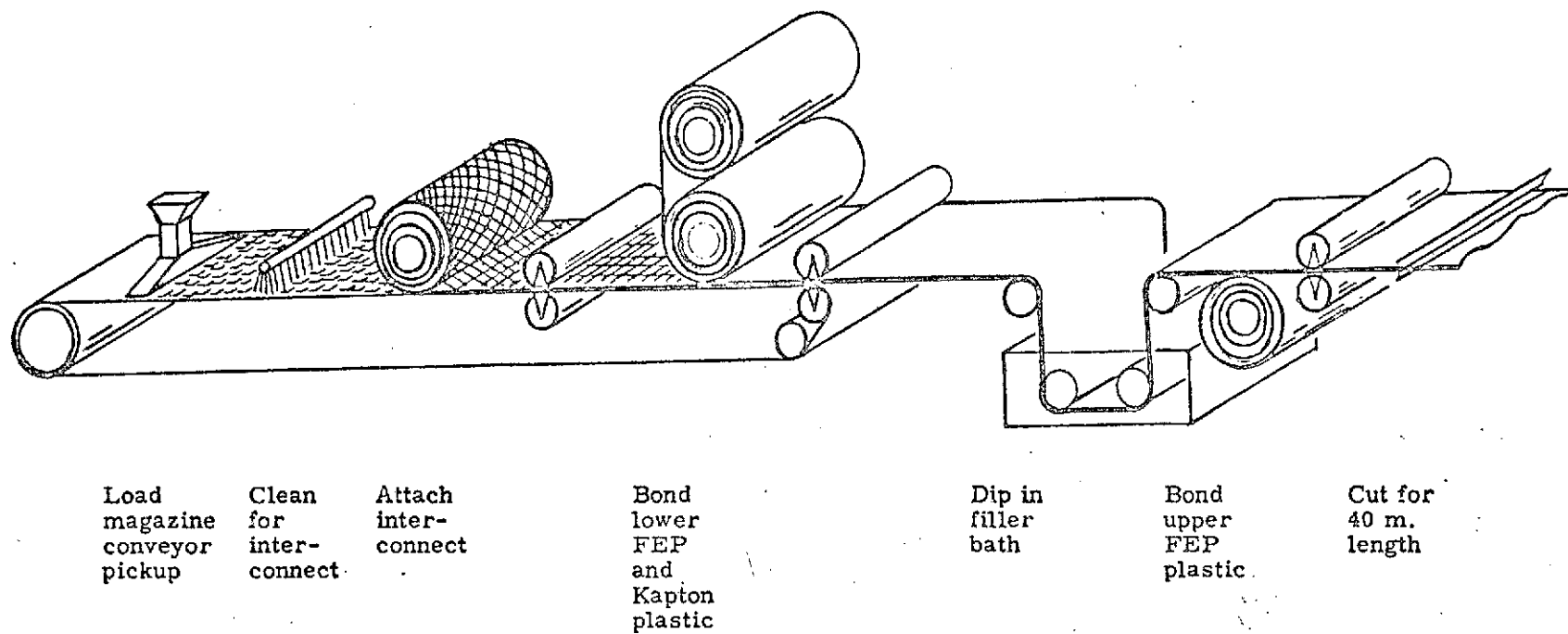
Figure 9. Continuous Process for Fabricating Solar Cell Blankets for Array.
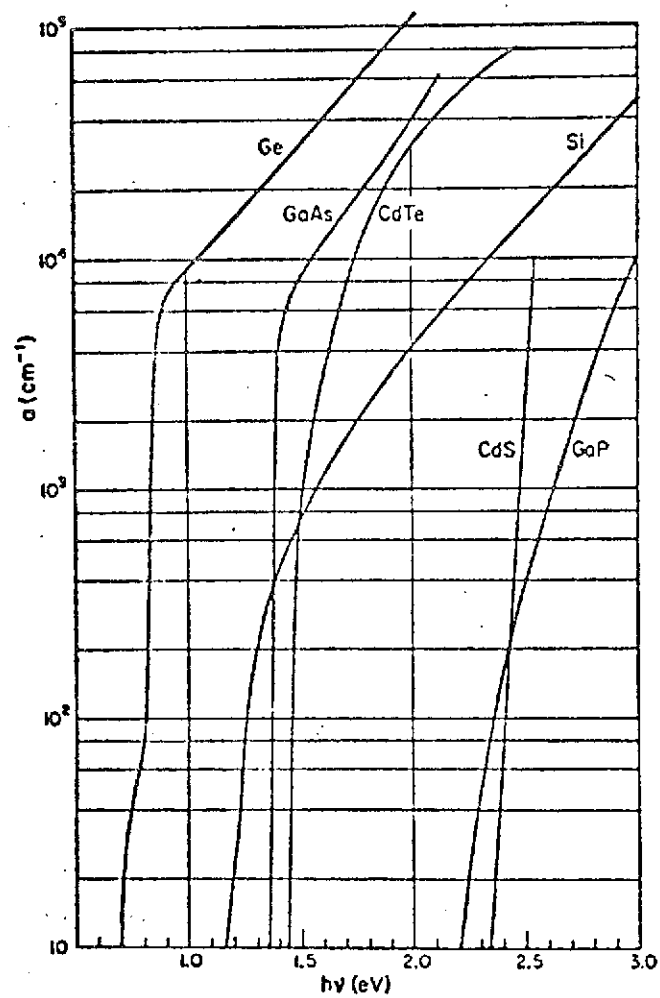
Figure 10. Optical Absorption Coefficient vs. Photon Energy.[23]

silicon, for the same light absorption. Also, as shown in Figure 11, the theoretical efficiency of GaAs solar cells is higher than silicon. An efficiency of 18% for GaAs solar cells has already been demonstrated.[24] The raw materials cost, however, is higher for GaAs. Silicon is the second most abundant element in the earth's crust, and is produced in the United States at an annual rate of 66,000 tons at a cost of about $600/ton. Gallium arsenide has the potential for very lightweight solar arrays, but at present silicon cells are cheaper and their manufacturing techniques are more advanced.

Pritchard and Mead[25] reported an analysis of the solar cell power satellite system conducted by the Aerospace Corporation using a computerized technique they developed for the Business Risk And Value of Operations (BRAVO). Data for this study was collected from the Federal Power Commission, A. D. Little, Inc., Grumman Aerospace, Raytheon, Spectrolab, and NASA. The solar power satellite was sized to produce 20,000 MWe in orbit and provide 10,000 MWe to the ground at the end of a 30 year life. The supporting structure for the solar cells and reflecting mirrors was taken to weigh 90% of the weight of the 50 micron thick solar cells and concentrating mirrors. The total weight of the power satellite was estimated at 86 million pounds, exclusive of the attitude control system.

The space transportation system consisted of a fully reusable space shuttle of 20 million pounds gross weight and a 609,000 pound payload, and a reusable nuclear tug of 360,000 pound gross weight capable of carrying a 170,000 pound payload from low earth orbit to synchronous orbit. Three hundred and sixty-one shuttle flights were projected for deploying the synchronous power plant and providing propellant for stationkeeping. In order to provide for 10% of the U.S. growth in energy demand beyond 1990, the
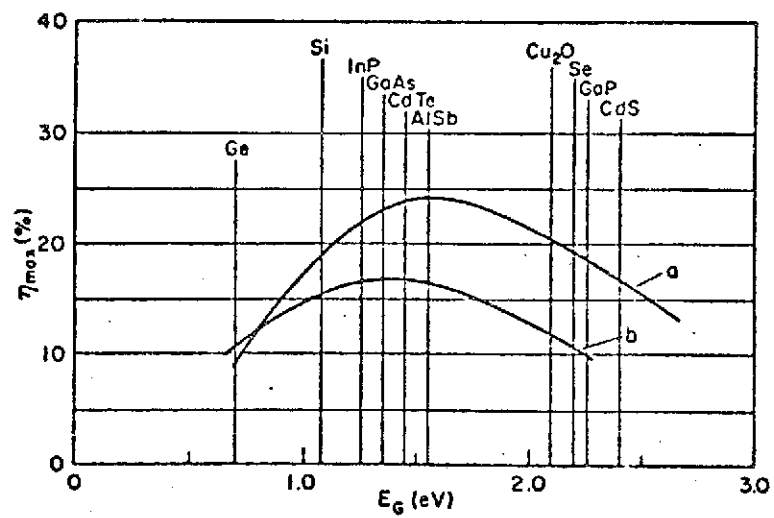
Figure 11. Theoretical Efficiency of Solar Cells[23]
a) Ideal Behavior, b) Non-ideal Behavior.

number of stations and shuttle flights were projected as follows:

TIME PERIOD	STATIONS ADDED	TOTAL STATIONS	SHUTTLE FLIGHTS
1990-94	4	4	1444
1995-99	5	9	1805
2000-04	7	16	2527
2005-09	10	26	3610
2010-14	14	40	4693
2015-18	17	57	6137

The receiving antenna was designed to receive three gigahertz micro-wave radiation, rectify to D. C. and convert this to 60 cycle A. C. for the commercial power grid. Halfwave dipoles feeding Schottky barrier diodes and filter circuits were mounted 1/4 wavelength above a wire mesh ground plane. The 284 dipoles in each square meter of antenna would provide 1.5 watts each. With a suitable series parallel connection the antenna could provide the output power at an extremely high voltage. Since some utility networks are now using high voltage D. C. transmission, the receiving antenna could provide this D. C. power directly for long distance transmission. The size of the antenna to provide 10,000 MWe would be covering a land area of about 130 Km^2 (50 miles^2). Its cost is projected to be \$85/KWe, including a \$3000/acre land cost and \$5/KWe for conversion from D. C. to A. C. If the power from the antenna is transmitted as high voltage D. C., the antenna cost would be \$80/KWe. The total cost of the power system is projected at \$1215/KWe, including \$512/KWe for space transportation.

The solar power satellite was compared economically with nuclear power plants costing \$300/KWe (water reactors) through the 1990's, and \$369/KWe (breeder reactors) for the next century. These costs are low by today's standards, even in 1973 constant dollars. The first demonstration breeder

reactor power plant is expected to cost over $1000/KWe, and future plants may

cost around $600/KWe. Using the lower cost values for nuclear plants,

power from the solar cell satellite power station was projected to cost 2.7¢/KWh

as compared with 0.9¢/KWh for terrestrial nuclear power.

Nuclear power costs have been rising recently much faster than the

inflation rate. Part of the reason is that increasing worldwide competition

for available uranium supplies has driven up prices. Even with these increasing

nuclear power costs, it is unlikely that power from space could ever be

cheaper than terrestrial nuclear power. The reason for building power satel-

lites will not be lower costs, but the elimination of the safety, safeguards

and radwaste disposal problems of terrestrial nuclear power.

Solar-Thermal Power Satellites

Patha and Woodcock[26] have proposed that large reflectors be placed in

orbit to concentrate sunlight onto a heat engine for power generation. These

reflective films, costing a few cents per square meter, are stretched on a

frame to form reflecting facets which concentrate sunlight onto the heat

exchanger of a Brayton cycle engine. Originally an inflatable frame was pro-

posed, but subsequent studies have shown a rigid frame to be more cost-

effective.[27] A cycle diagram of the proposed Brayton cycle is shown in Figure

12 and a schematic diagram of the total power plant is illustrated in Figure 13.

Nuclear powered Brayton cycle electric power generators using a helium/

xenon working fluid have been built for operation in space, and have achieved

power outputs in the range of 2 to 15 KWe.[28] The proposed satellite power

station conversion system would heat the inert gas working fluid to about

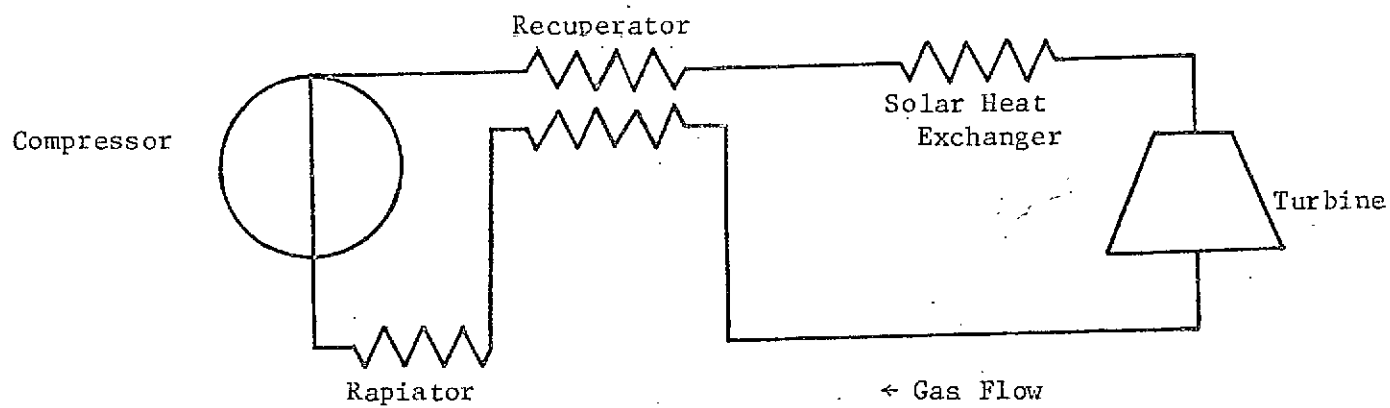1700°C using the intensely concentrated sunlight from the reflector. This

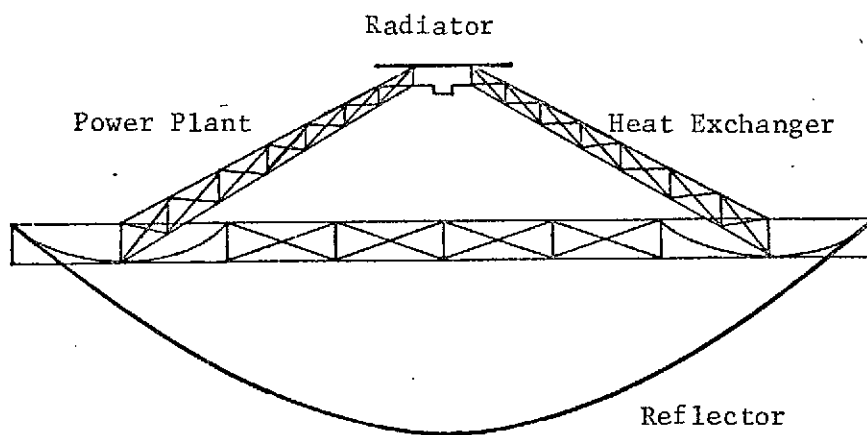Figure 12. Solar Power Brayton Cycle.

Figure 13. Solar-Brayton Power Plant.

gas expands through a turbine, then flows through a regenerative heat exchanger to the 224 meter diameter radiator, which rejects heat at an average temperature of 390°C. The gas is compressed, flows back through the regenerator, which heats it to 1270°C, and then is heated again by solar energy to 1660°C. With 90% turbine and compressor efficiencies, the overall Brayton cycle efficiency is 53%, and the total system sunlight-to-power conversion efficiency is 36%, which is considerably higher than the efficiency achieved by solar cell arrays. The total weight of a 10,000 MWe plant is projected to be 35 million kilograms, or 3.5 Kg/KWe, exclusive of microwave transmission. Turbine-generator weights are based on 1973 technology. The reliability and lifetime of turbine-generators may be considerably enhanced by the weightlessness of space operation and the use of inert gas working fluids. Gas bearings for large rotating machinery should be practical for weightless operation. The lifetime limitation will result from blade creep.

The capital cost of the complete system was estimated to be $2540/KWe using near term microwave transmission cost projections given in reference 29.

POWER TRANSMISSION TO EARTH

At the present the preferred method for transmitting power to earth is by microwave beam. Laser transmission has been proposed but transmission efficiencies are far too low to warrant serious consideration, unless a future breakthrough results in very high efficiency lasers.

Selection of the optimum microwave frequency is based on considerations of antenna size and atmospheric attenuation. Higher frequencies (shorter wavelengths) result in greater atmospheric attenuation, especially during rainstorms, but lead to smaller antenna sizes. There is a minimum practical antenna size based on the requirement for rejecting heat produced by inefficiencies in the conversion of electric power to microwave energy and microwave transmission. From these considerations, it appears that the microwave band between 2 and 4 megahertz (7.5 to 15 cm wavelength) is optimum for microwave power transmission from synchronous orbit, 35,800 Km above the earth's surface.

Transmission of electric power by a microwave beam has been seriously considered for a number of terrestrial applications, since the development of new techniques for the generation, transmission and rectification of microwave power has made possible the efficient transfer of large amounts of power by microwave beam. A considerable effort in the experimental development of microwave power transmission systems has been conducted since the early 1960's.[32-35] Theoretically the microwave beam is capable of transmitting power through space for any distance with nearly 100% efficiency. An efficiency of 99.63% has actually been measured.[37] The theoretical transmission efficiency for a microwave beam is given by Figure 14, where A_t is the area of the
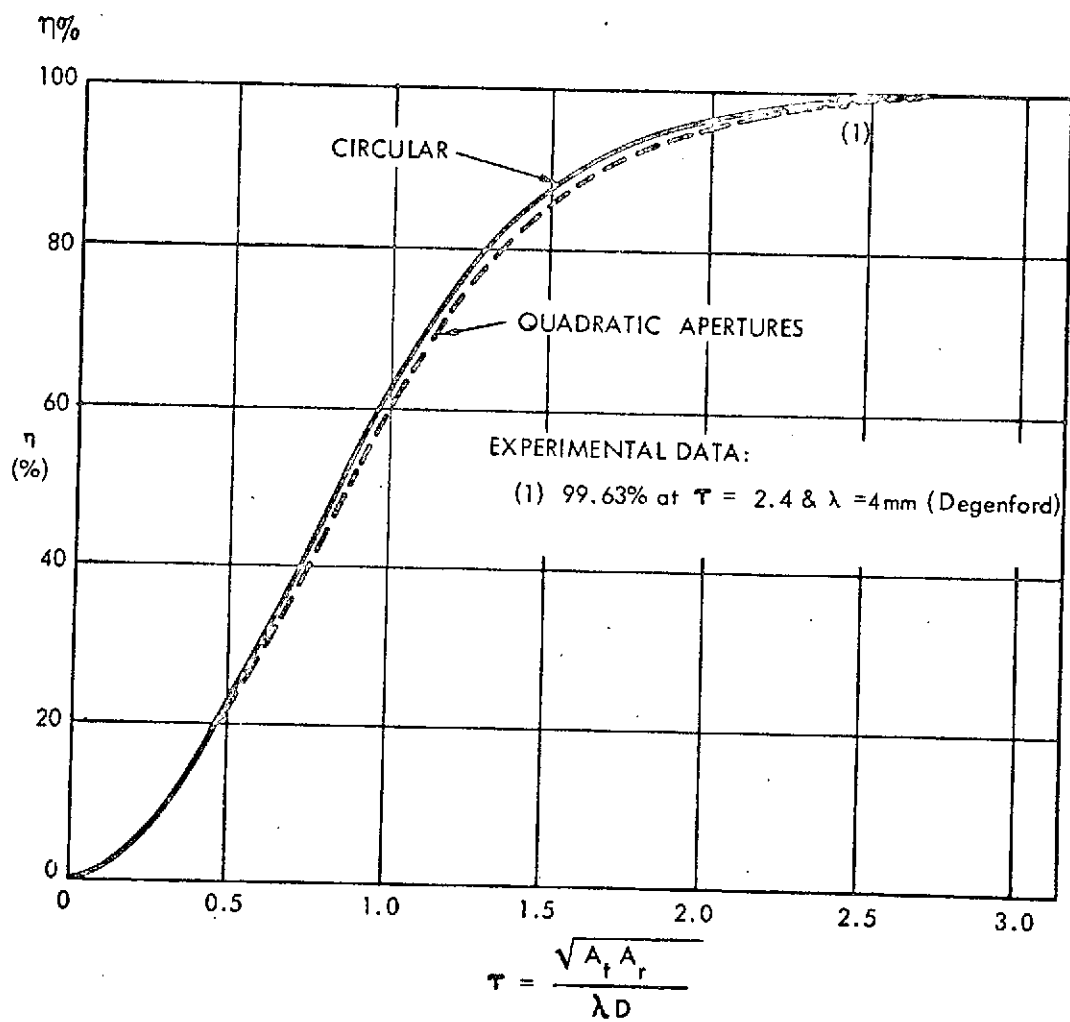
Figure 14. Theoretical Transmission Efficiency for
a Microwave Beam.[36]

transmitting antenna, A_r is the area of the receiving antenna, λ is the wavelength, and D is the distance over which the beam is transmitted. It is seen that if $(A_t A_r)^{1/2}/\lambda D$ is greater than 2.5, the transmission efficiency can be nearly 100%, keeping in mind that this is only the efficiency of transmission of the beam in free space and does not include the d.c.-microwave and microwave- d.c. conversion systems or atmospheric attenuation. The three atmospheric attenuation processes are ionospheric non-linear effects, attenuation by gases such as oxygen and water vapor, and attenuation by clouds and rain. The ionospheric non-linear effects cause less than a 0.1% loss.[36] Attenuation by atmospheric gases and clouds is about 1% for an incoming beam at normal incidence and about 2% for an incoming beam at 60° to the vertical. Moderate rainfall results in a total attenuation of about 3% at a 60° incidence angle.[38]

The microwave transmission system for a synchronous power plant consists of four basic components; the d.c. to microwave conversion system, the transmitting antenna, the receiving antenna on the ground, and the microwave to d.c. conversion system. This d.c. electric power generated in space ends up as d.c. electric power on the ground. The last two components are actually combined into a rectifying antenna, or rectenna, which encorporates rectifying diodes within the antenna structure. In order to achieve a 90% transmission efficiency (Figure 14), the receiving antenna must be 7.44 Km in diameter if the transmitting antenna is 1 Km in diameter, as shown in Figure 2. The receiving antenna subtends an arc of 0.7 minutes from the satellite.

The Transmitting Antenna

The active phased-array transmitting antenna utilizes radiating elements distributed over the antenna structure with the d.c. to microwave converters

incorporated in them. The microwave generators each handle only a few kilo-watts. They are crossed-field devices called Amplitrons which should have high reliability, long life, and reasonably low cost for operation in the hard vacuum of space.[39] They can use modern samarium-cobalt low-weight permanent magnets and omit the glass envelope required on earth, so the weight as compared with terrestrial devices is reduced considerably. Figure 15 illustrates an amplitron with the cathode and anode designed to reject waste heat with passive extended surface radiators of pyrolytic graphite. The cross section A-A shows the essential features of a 17 vane amplitron.[40] Electrical connections, insulating supports and the magnets are not shown. Figure 16 shows several amplitrons located on the transmitting antenna. The microwave power is radiated through the slotted waveguides in the lower surface to form a coherent wavefront leaving the front surface of the antenna, which is the lower surface in Figure 16. Heat is radiated from the circular cooling fins at the rear of the antenna. Figure 17 illustrates the system by which d.c. electrical power is distributed to the amplitrons. The positive d.c. buses are structural members of the antenna, and the negative d.c. bus is the slotted waveguide antenna at the lower part of this figure, and also shown in Figure 16. About a million separate amplitrons would be used for power conversion in the one kilometer diameter antenna.

The width of the microwave beam reaching the earth is minimized if the phase front leaving the transmitting antenna is slightly concave, with the radius of curvature equal to the distance to the earth. This means the center of the phase front should be depressed in relation to the outside edge by 3.56 mm. For an antenna diameter of one kilometer and 10 cm wavelength, the diameter of the spot on the earth with intercepts 96.3% of the total power
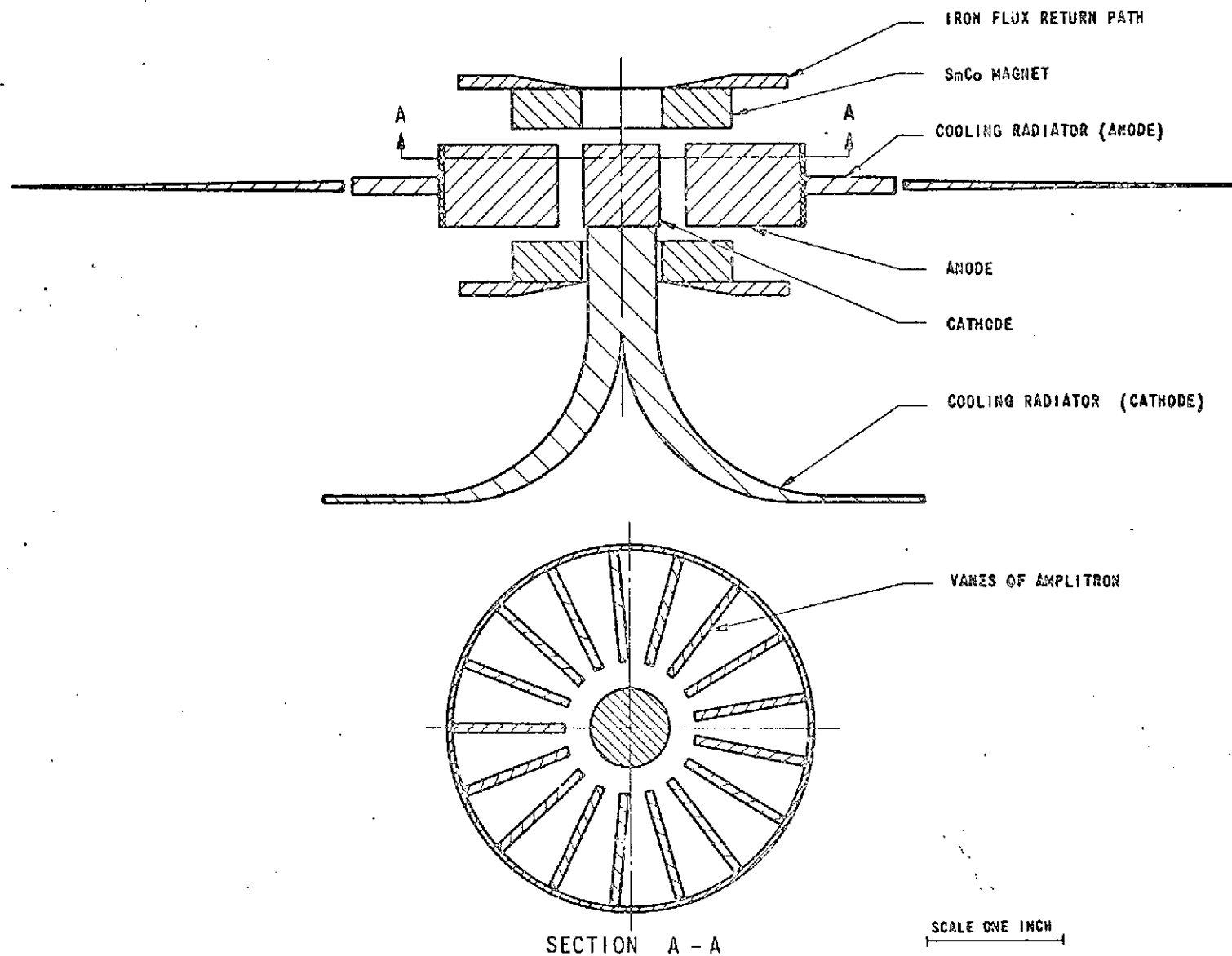
IRON FLUX RETURN PATH

SmCo MAGNET

COOLING RADIATOR (ANODE)

ANODE

CATHODE

COOLING RADIATOR (CATHODE)

VANES OF AMPLITRON

SECTION A - A

SCALE ONE INCH

Figure 15. 17 Vane Amplitron Design for Microwave Generation in Space.[40]
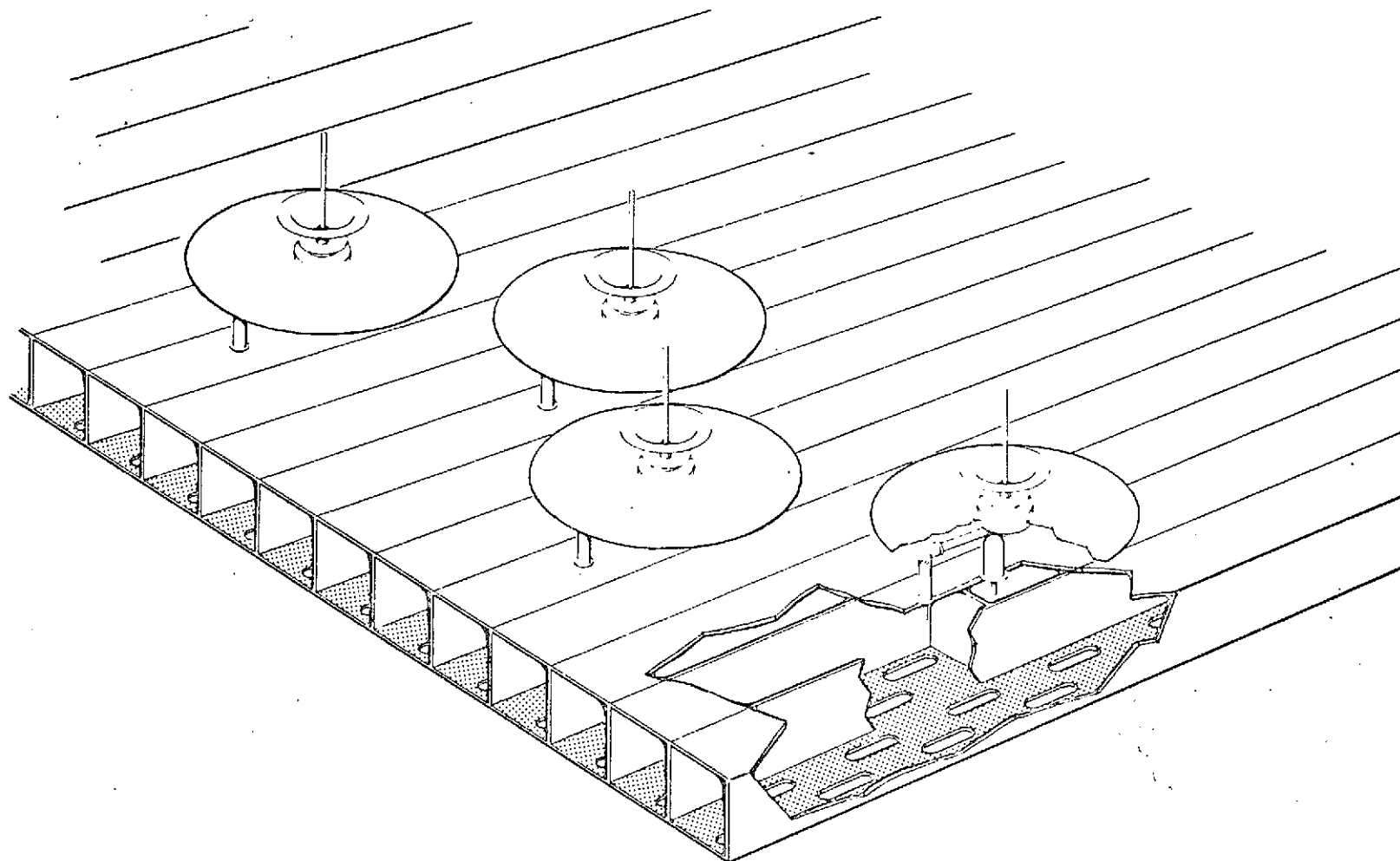
Figure 16. Amplitrons Attached to Transmitting Antenna[41] (microwave radiation emerges downward in figure through slots in waveguides).
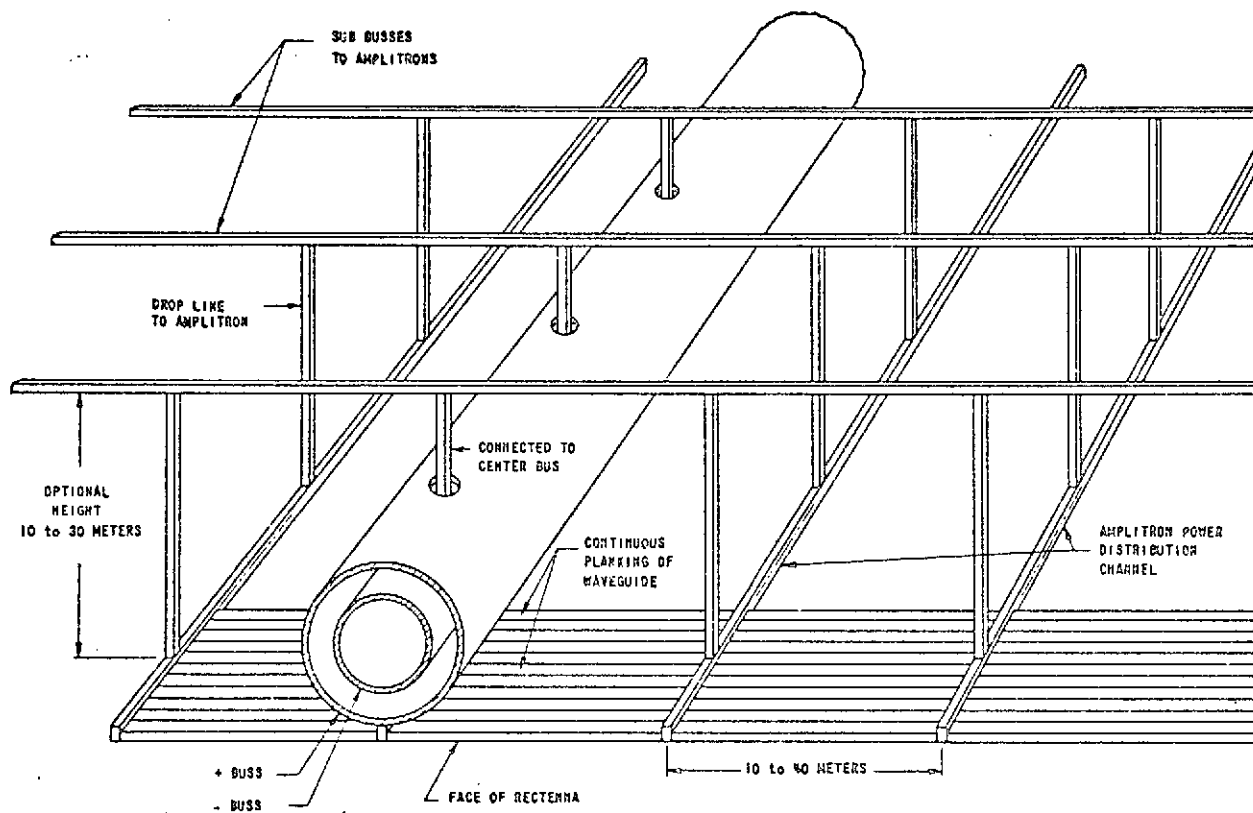
Figure 17.   Schematic Drawing Showing D.C. Power Distribution to the
Amplitrons in the Slotted Waveguide Microwave Antenna.

is 8.72 Km. If the phase front leaving the antenna is flat, the spot diameter

is 9.10 Km, and if the phase front is spherically convex with the center

raised 10 cm with respect to the edge, the spot diameter increases to 17.3 Km.

If the phase front leaving the transmitting antenna is very slightly irregular,

with random fluctuations across the face of the antenna of only 0.5 cm (1/20

wavelength), about 10% of the energy would be scattered from the beam.

It is obviously impossible to construct a 1 KM diameter antenna to such

a close tolerance so as to keep the beam coherently focused onto the receiving

antenna, so a self-phased array is used. This technique requires an incident

beam broadcasted from the center of the receiving antenna on the earth. The

self-phased antenna utilizes this incident wavefront to maintain the proper

phase over the entire transmitting surface by sensing electronically the

physical displacement of local waves on the transmitting antenna and compensating

for any displacement by changing the phase of the microwave radiation generated

at that location. Thus, the transmitting antenna array is subdivided into a

large number of smaller subarrays so that the phase of the microwave output

from each subarray can be controlled independently by the incoming reference

beam to produce the coherent output beam necessary for efficient microwave

transmission to earth. If, for some reason, the reference beam eminating

from the center of the receiving antenna is shut off, the output beam will

become incoherent and radiate in all directions. Also, it is important to note,

that because of the inherent nature of the self-phased-array, it is impossible

to direct the beam to any point on earth except the receiving antenna. For

security reasons, the pilot signal from the receiving antenna can be coded

so as to prevent unauthorized diversion of the beam to another point on earth

by a separate signal source. It may occasionally be desirable to switch the

beam from one part of the U.S. to another by shutting off the pilot signal

from the center of one receiving antenna and turning on the signal from

another. The pilot signal would require a transmitting antenna about 10

meters in diameter and a power level of about 100 KWe. This signal also

makes possible a pointing accuracy of less than one second of arc.

The amplitron is a device that converts high voltage d.c. electric power

into microwave energy by amplifying an input microwave signal, as illustrated

by Figure 18. The d.c. voltage is applied between the anode and cathode,

and the microwave power entering causes electron emission from the cold

cathode. Because of the applied magnetic field, the electrons move in cir-

cular paths around the central cathode. Since the input microwave radiation

causes these electrons to be emitted in short bursts, they are grouped

together, as indicated by the gear-shaped cloud of black dots in Figure 18.

These rotating spokes of space charge extract energy from the applied electric

field (as they move between cathode and anode) while they are also interacting

with the applied microwave field in such a way that the microwave field is

amplified as the electrons lose energy to it. The reason for this amplifi-

cation is obvious if one carefully examines Figure 18. The rotating "spokes"

of negative space charge (electrons) interact with the stator to increase the

amplitude of the microwaves in the waveguide. These space charge spokes act

like the rotor in a conventional generator. The force that spins the rotor

comes from the electrons moving through the voltage gap between cathode and

anode interacting with the applied magnetic field which is at right angles

to the electric field. The electric and magnetic fields combine to force

the electrons to move in circles, the applied microwave field causes them to

form spokes that rotate at frequencies of around 6,000 MHz, which in turn

$$\text{EFFICIENCY} = \frac{\text{MICROWAVE OUTPUT} - \text{MICROWAVE INPUT}}{\text{DC POWER INPUT}}$$
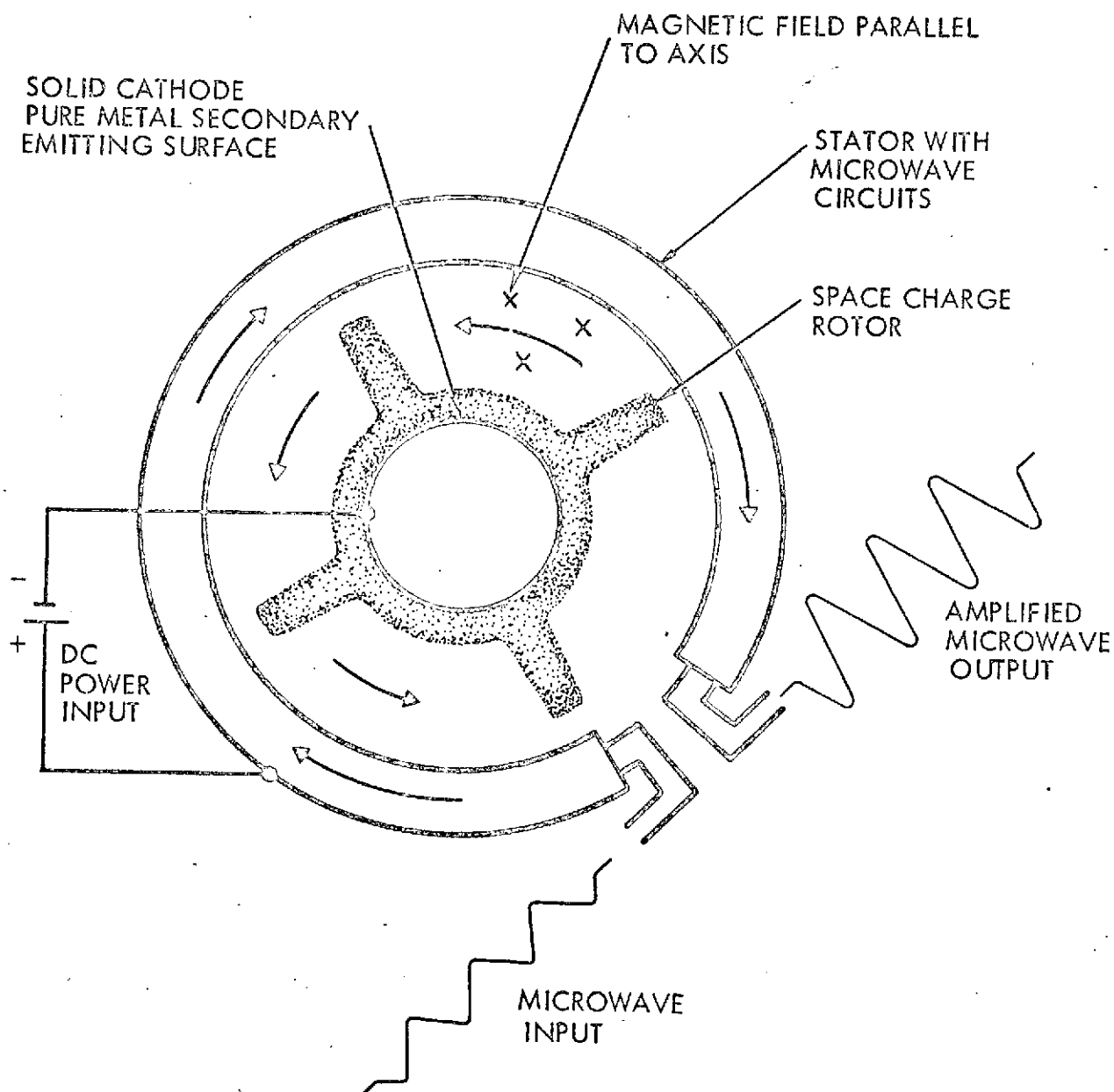
Figure 18. Schematic Program of Amplitron Operation

amplify the microwave field emerging from the amplitron. The result is that d.c. electric power is converted into microwave power.

This device has demonstrated energy conversion efficiencies between 85% and 90%, and efficiencies of 95% should be possible.[39] The efficiency increases as the magnetic field strength increases, and new magnetic materials are making possible higher field strengths with less weight. High efficiency is important since the power dissipated by the amplitron must be radiated to space. It is the heat dissipation that limits the power output of an amplitron.

The choice material for the amplitron radiator fin is pyrolytic graphite because of its low weight and high thermal conductivity. At the amplitron operating temperature of 300°C pyrolytic graphite has a thermal conductivity twice that of copper, and emissivity of 0.92. The weight of the cooling fin goes down rapidly as the amplitron efficiency is increased. The cooling fin for a 95% efficiency amplitron rated at 6KW output is 1/40 that of a 80% efficient amplitron.[40] In the baseline solar cell power satellite design reported by Glaser, et al.,[5] an efficiency of 90% was assumed for amplitrons rated at 5 KWe, in which case each cooling fin weighed 175 grams.

Amplitrons are very similar to magnetrons which are used extensively for microwave ovens and other microwave applications. At present the 1 KW magnetrons used in the microwave home-oven industry are mass produced at a cost of about $30/KW. Amplitrons for space use will not require the expensive vacuum jacket, but will require lighter magnets and cooling fins. For satellite power stations they are projected to cost about $25/KW[41] and weigh about 661 grams.[40]

The radiating elements of the antenna are waveguide sections with slots parallel to the length of the waveguide. The dimensions of the guide are such

that only the lowest order mode propagates, such as 5 cm x 10 cm. Power from an amplitron is coupled into a waveguide at one end, and the remaining power at the other end is used to excite another amplitron whose output is connected to the next waveguide section.

The specific frequency for power satellites is the one between 2 and 4 MHz that will cause the least radio frequency interference (RFI). To study the RFI problem a numerical model was developed which included orbital and ground location, ground power transmission, device characteristics, phase-front control, component efficiencies, the induced RF environment, ionospheric and atmospheric attenuation, the frequency band, specific frequency, typical users in that band, and selected equipment.[44] The result of this study was that 3.3 GHz was selected as the transmission frequency that would cause the least RFI.

The Receiving Antenna

The receiving antenna incorporates GaAs Schottky barrier diodes into its structure so that microwave radiation received by the half-wave dipole antenna elements is converted directly into direct current electric power. Since the rectifying elements are uniformly distributed throughout the antenna, it is called a rectenna (rectifying antenna). It is capable of high collection and rectification efficiency, is insensitive to amplitude and phase perturbation of the incoming beam caused by atmospheric disturbances, and can be constructed economically.[45] The gallium arsenide Schottky barrier diodes have a power handling capability of 6 watts each. Rectification efficiencies of over 75% for these diodes have been reported in the wavelength region of 10 cm,[45-48] and efficiencies from 70% to 75% were measured for the collection and recti- fication of microwave energy by a combination half-wave dipole and rectifying

diode.[49] With improved circuits and diodes, an overall collection and rectification efficiency approaching 90% should be possible.[39]

Figure 19 is an artist's concept of what such a rectenna might look like. The rectenna surface is placed normal to the incoming microwave radiation to optimize capture efficiency and reduce the total area of the rectenna. A single supporting frame of aluminum tubing and a vinyl molding is illustrated by Figure 20, and a closer view is given by Figure 21. Aluminum and vinyl were chosen because of their long outdoor life. The cost of the rectenna is projected to be $11.60/m^2, or $63/KWe.

Efficiency of Power Transmission

The overall power transmission efficiency is the product of the efficiencies of the various power conversion and transmission efficiencies. At the present time a microwave generation efficiency of 76.7% has been demonstrated at 3000 MHz with a power level of 300 KW, a transmission efficiency of 94% was measured at 2450 MHz, and a collection and rectification efficiency of 64% has been measured, again at 2450 MHz. Combining these three efficiencies (separate experiments) would lead to an overall efficiency of 46% as having been demonstrated. Brown[43] believes that with present technology equipment one could achieve an overall efficiency of 60% at this frequency, and with additional development this overall conversion/transmission efficiency could be increased to 77%.
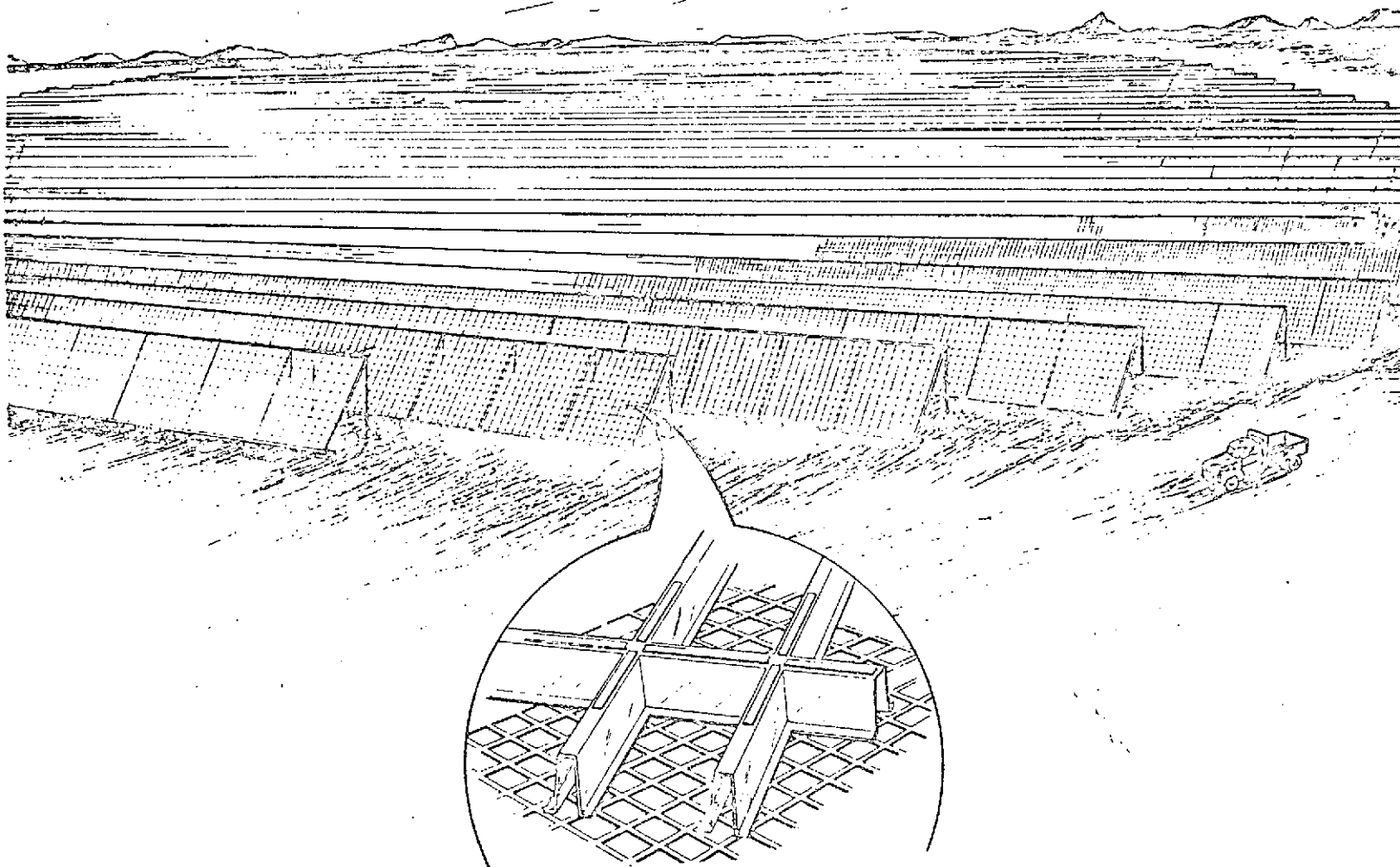
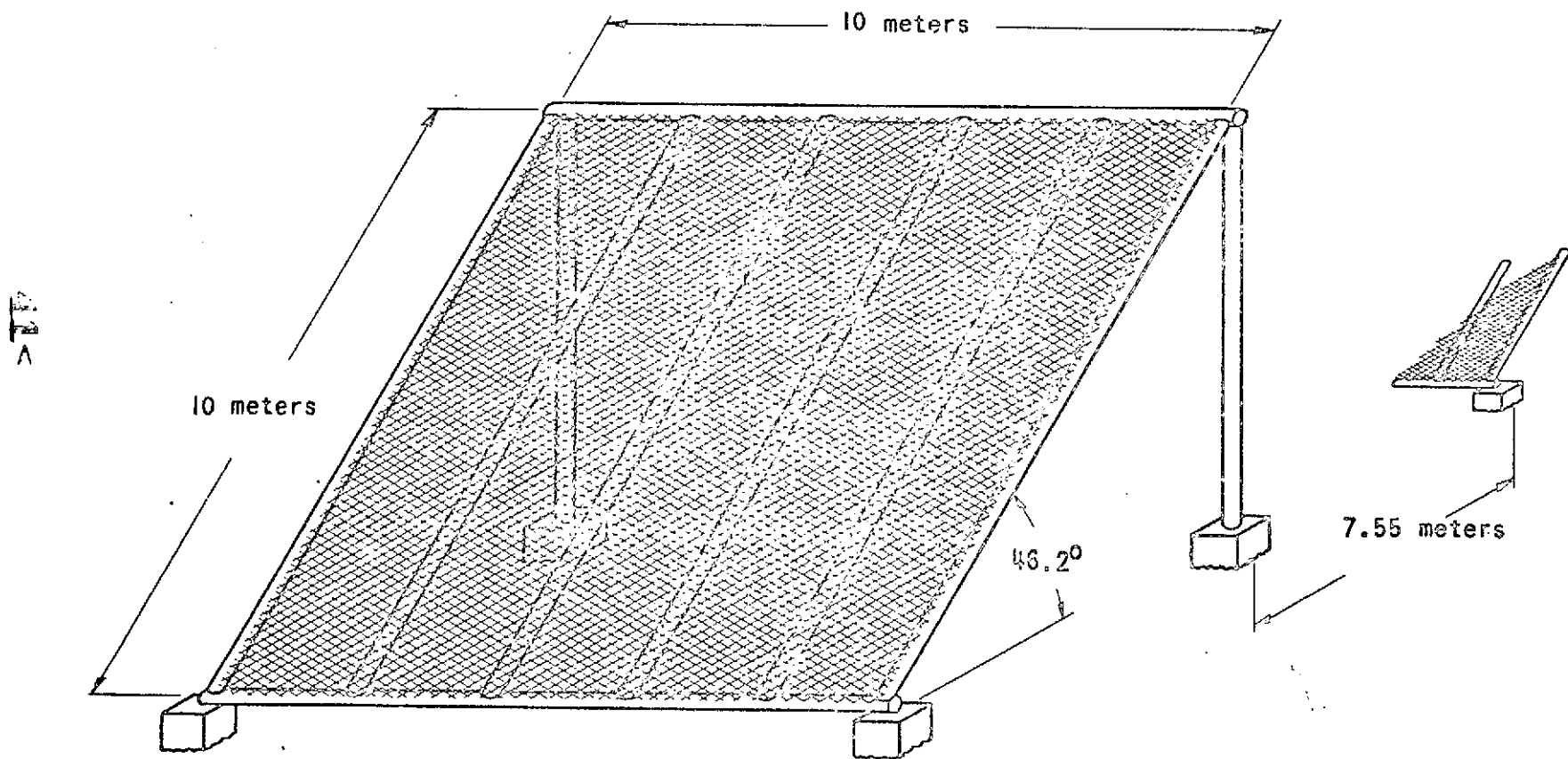Figure 19. Rectifying Antenna for Receiving Microwave Beam and Converting
It to Electric Power.[40]

10 meters

10 meters

46.2°

7.55 meters

Figure 20. Supporting Structure for Rectenna Array.[40]
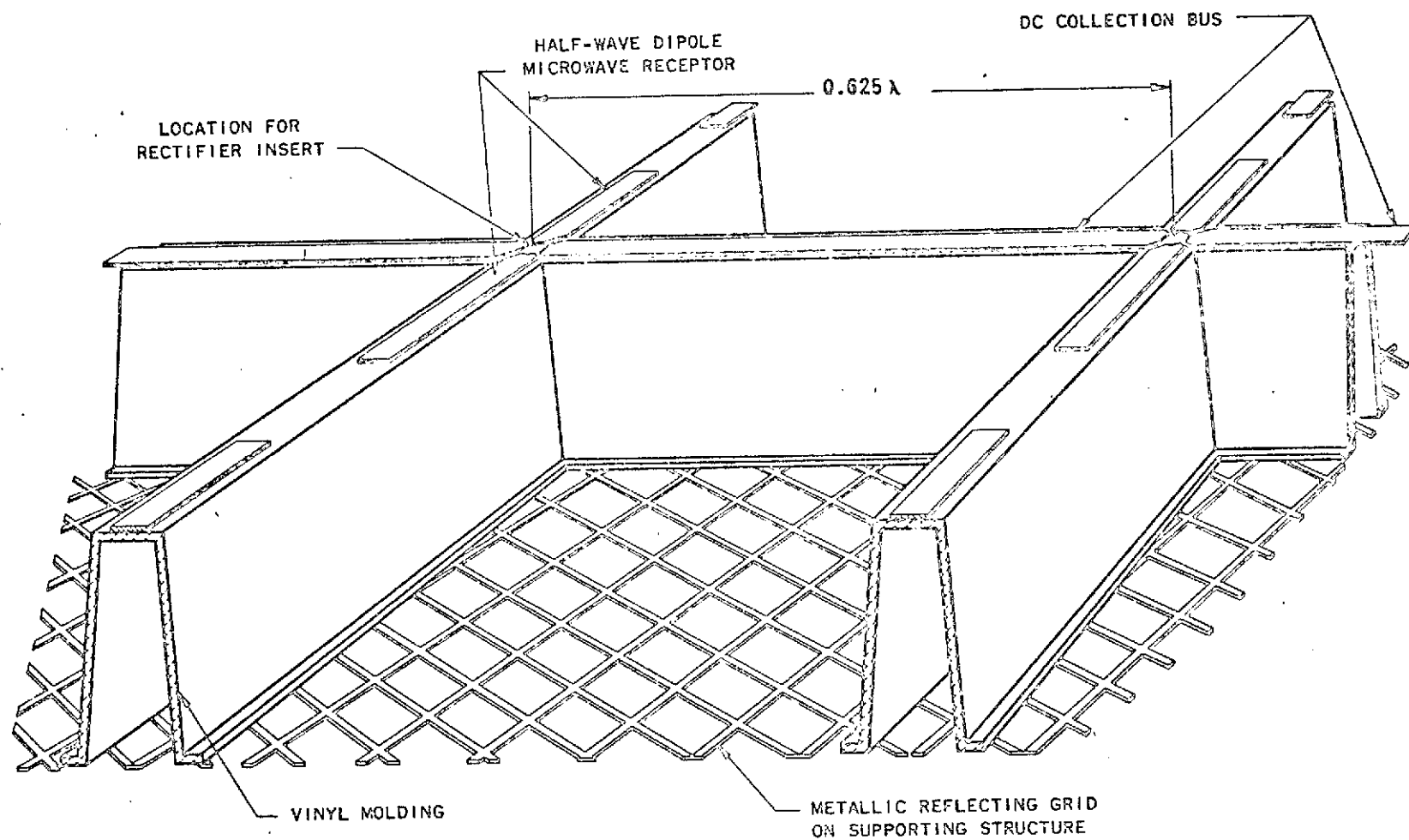
Figure 21. Close-up of Rectenna Structure.[40]

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