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Power from space

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Abstract

This is a concise review of possibilities and prospects for power generation in space for terrestrial use. Advantages of this approach to power production, the economic and technological obstacles to be overcome, various conceptual approaches, including solar photovoltaic, solar dynamic, nuclear, and the use of chemical energy, and recommendations for progress are summarized. In view of the rising demand for energy, and of the diminishing fuel and available terrestrial area, the use of space for power generation seems to be inevitable: (1) It allows highest energy conversion efficiency, provides the best heat sink, makes best use of solar energy, and relieves the Earth from the penalties of power generation. (2) Both the costs of launching payloads into space and those of energy transmission are declining. The major obstacle is the exorbitantly high cost, which under current conditions requires, for example, the reduction of space transportation costs about a hundredfold for competitiveness. Other issues also need to be resolved, some of general nature, such as environmental effects and security and legal aspects, and some system specific, such as safety of nuclear power plants, and the realization of higher energy conversion and transmission efficiencies. Generation of power in space for terrestrial use will require massive resources, strong international cooperation, and several decades. A staged approach, fortified by developing applications collateral with space power, such as space-to-space power beaming for powering satellites, power relaying by orbital microwave or laser beam reflectors, and orbital mirrors for extended periods of terrestrial illumination, is recommended. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Power generation; Space; Energy conversion; Space transportation; Nuclear power; Solar power; Photovoltaics; Fuel cells

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1. Introduction

1.1. Objective

This is a concise review of possibilities and prospects for power generation in space for terrestrial use. Advantages of this approach to power production, the economic and technological obstacles to be overcome, various conceptual approaches, and recommendations for progress are summarized.

1.2. The need

World energy consumption data and projections [1–3] are summarized in Table 1. Assuming a moderate annual 1.4% population increase, driven primarily by developing countries which have a gradually improving standard of living, the current Earth population of about $(5)10^9$ is going to double, to10^{10} within 50 years, and the associated energy demand is expected to have a 1.5–3-fold increase [3]. With increased introduction of modern technology into the world households, and especially with the likelihood of gradual conversion to electric vehicles, electric power would increasingly dominate the demand.

The expected large rise in power demand during the coming 21st century is accompanied by mounting problems with power plant siting, environmental impact, resource shortages, and increasing shortage of available space for fuel and power generation and distribution. Although industry, often assisted by government, is making gradual progress in addressing these problems, the pace of the progress, when extrapolated into the future, is not likely to meet the needs. Even worse, if not accelerated, it may lead to irreversible harm to the environment and to the ability of future generations to continue their progress toward improved living conditions.

The Earth is also likely to be insufficient even if we are able to use solar energy by collecting it on the terrestrial surface. Roughly, the average solar input to Earth is $(8.6)10^7$ GW. Assuming an overall 10% conversion efficiency for solar electric systems, and a global, highly interconnected system of solar power generation systems, about 7.5% of the Earth surface would be needed to accommodate the projected electric demand in the year 2100, only 100 years from now. Considering the accompanying increased demand for space for the increasing population, and the growing need for power in the years after, this is probably an unacceptably large Earth surface demand even if ocean surfaces are included.

Table 1
World use of energy: past and projected (from Refs. [1,3], [2] for 1950)

Year	World population	World thermal power demand (GWt)	Person thermal power demand (kWt)	World electric power demand (GWe)
1950	$(3)10^9$	$(2.4)10^3$	0.8	$(0.11)10^3$
2000	$(5)10^9$	$(18)10^3$	3.6	$(2)10^3$
2050	$(10)10^9$	$(86)10^3$	8.6	$(32)10^3$
2100	$(20)10^9$	$(210)10^3$	10.5	$(63)10^3$

1.3. Advantages of, and obstacles to, power generation in space for terrestrial use

This rapidly increasing power consumption (which has at least doubled in the last 20 years) and the associated undesirable emissions, as well as mounting opposition to the construction of new power plants reflected in part by an exponential rise in legal and safety costs, on the one hand, and advances in energy conversion and space technology on the other, are making power generation in space for terrestrial use an increasingly attractive goal. Such power generation is often associated with the use of solar energy, but it is noteworthy that it is by no means confined to it. Space offers significant advantages for the use of other energy sources too, as further elaborated below.

The primary advantages, and obstacles which are gradually being overcome, are summarized in the following sections.

1.3.1. Advantages

- Unobstructed by the Earth atmosphere and unlimited by terrestrial surface use considerations, space is ideally suited for power generation from the Sun, which is an essentially unlimited non-polluting energy source.
- Space is a nearly ideal heat sink for power plants. Being at near absolute zero temperature, it is indeed the lowest attainable temperature heat sink, offering a Carnot efficiency of nearly 100%, regardless of the power plant heat source temperature as long as it is higher than that of space.
- Nuclear power generation in space would incur diminished safety and waste disposal difficulties.
- Having immense (and ever expanding . . .?) volume, space would be affected negligibly by any heat addition from the Earth.
- It also appears to be a nearly ideal sink for power-generation associated emissions of species which are harmful to Earth.
- It does not seem that siting of power plants would be faced with the same difficulties and restrictions that are increasingly becoming a dominant obstacle for power plant construction on Earth.
- In the near absence of gravitational forces it allows the construction of much lighter (and hence also cheaper) plants: static, wind, and dynamic (such as earthquake) loads are minimal.
- There is every indication that power plants should last much longer than those on Earth, because of the absence of oxidizing agents, rain, dust, hail, and vandalism.
- There are advantages for the distribution of the generated power to terrestrial locations which need it, replacing oil and gas pipelines, tankers, and electrical power lines which are currently limited by resistance losses and land-use consideration.
- Essentially a vacuum, space is a ‘superconductor’ for electromagnetic-wave/photon energy transmission.
- Accidents, such as fire, explosion or implosion, and spread of toxic, carcinogenic and radioactive materials appear to be orders of magnitude less harmful (if at all) to Earth and its inhabitants.

1.3.2. Obstacles:

- Cost and energy needed to transport the power plant components into space and to construct and maintain the plant there.

- Power transmission from the space station to Earth.
- Environmental issues, primarily related to power transmission and to launch vehicle emissions.
- Space plant security.
- International agreements on space use and power distribution.
- Damage from meteorites, etc.
- Cost, cost, cost ...

2. Location of space power plants

The two primary choices for space power plant location are as satellites in some orbit, or on an existing celestial body such as the Moon. In a relatively recent study [4], NASA claimed that the most appealing locations for solar space power plants are: (1) in geosynchronous Earth orbit (GEO), staying in a constant position over the equator at a maximal distance of 35,785 km, from where they can supply energy to large population centers; (2) in Molniya-type orbits [1] over the Arctic regions (at maximal distances of 1,820 to 40,165 km for 2–24 h Molniya, respectively), for supplying energy to these energy-deficient regions; (3) in Sun-synchronous orbits for providing peaking power in the 6–9 a.m. and 6–9 p.m. periods when utilities have power demand peaks; (4) on the Moon, for base power demand anywhere on Earth, with potential for mining it to provide the material necessary for building the power stations.

Also, space-to-space power beaming is feasible for providing power from a centralized space power generation station to other satellites or to a Moon base. This would simplify the satellites since they would not need independent power generation systems, and would thus extend their life significantly. Typical power use of satellites is 4–6 kW.

The space power plant may be located on the Moon or another planetary object (Fig. 1; cf. Ref. [5]). The advantages of such siting are that the plant does not need to be maintained in orbit, it is on a steadier platform, the same face of the Moon always faces the Earth, and very importantly, that materials existing on such a planetary object can be used for the construction of the plant or/and for providing its fuel. For example, the Moon consists of 30% metals (Fe, Mg, Ti, . . .), 20% Si, 40% oxygen, all directly useful for potential manufacturing the power plants on site (cf. Refs. [6,7]). Human presence in this process can be minimized by using highly robotic techniques. It is estimated that Moon mining for that purpose can save 30% of the plant cost, as compared with Earth-based manufacturing and transportation to the Moon [1] and there is significant interest in this topic by several agencies, including NASA. Also shown in Fig. 1, orbiting reflectors can be used for reflecting the microwave beams to Earth regardless of the Moon's position [5]. The Moon is also a much better launching base for satellites, power or otherwise, especially since the launch energy is about 1/20 of that needed from Earth.

It is claimed [8] that the above-described advantages of the Moon as a base for a solar power transmitting system combine to make it more efficient and power producing than any terrestrial plant (solar PV, solar thermal, coal, nuclear), or a solar power satellite (SPS).

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[1] The Molniya is a Russian satellite communication system using satellites at highly eccentric orbit for relaying communications between two ground stations.

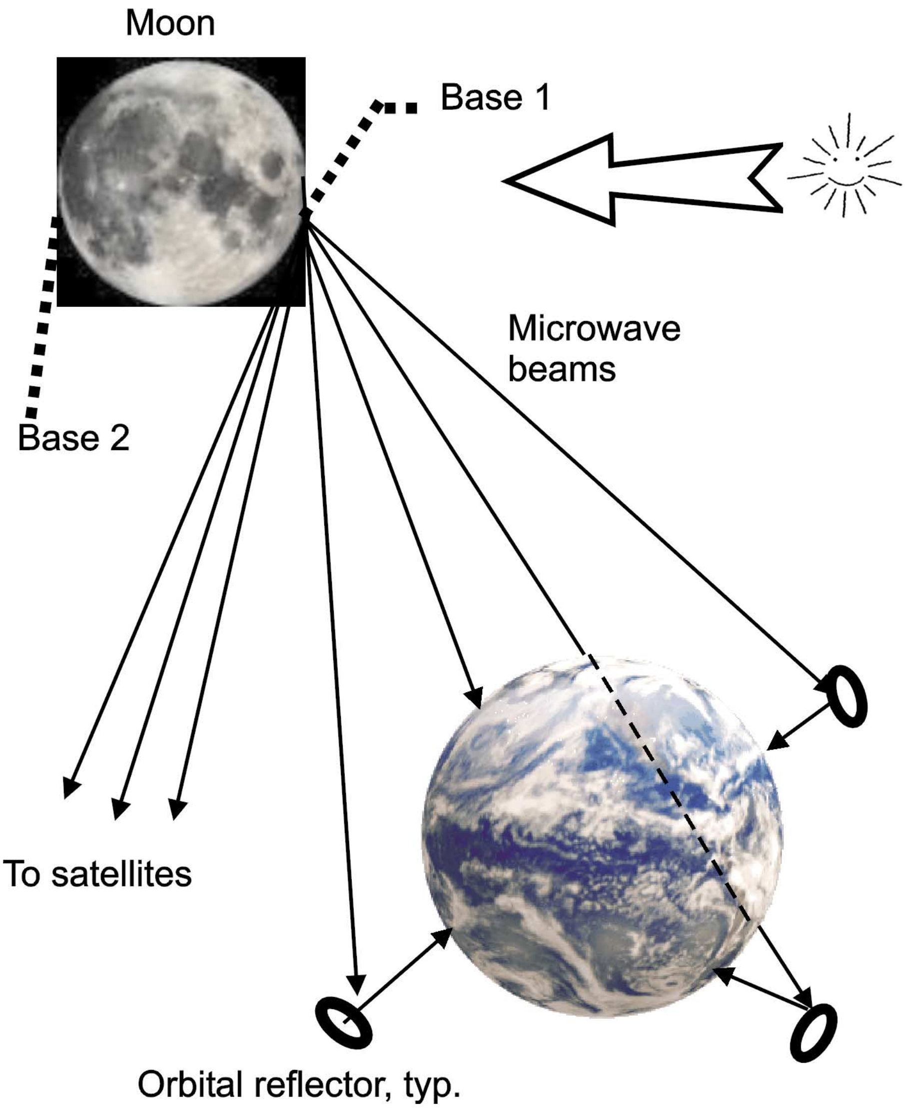

Fig. 1. Conceptual lunar base for generating electricity for terrestrial use (after Ref. [5]).

It is noteworthy that the Moon soil also contains the isotope ^{3}He (cf. Ref. [9]), which, together with deuterium, is a fuel for fusion power production. Operating at a projected efficiency of 70%, fusion power plants on the Moon would, for example, then need only 20 tons of ^{3}He to satisfy the entire annual electric consumption of the US. It is also of significant interest that the mining of 1 ton of ^{3}He produces 500 tons nitrogen, 1600 tons methane, 3100 tons He, 3300 tons water, 3600 tons of carbon–oxygen compounds, and 6100 tons hydrogen, all materials important for manufacturing and for sustaining life there.

3. Methods for power generation in space

3.1. Solar energy

3.1.1. General characteristics and methods for energy conversion

Unobstructed by the Earth atmosphere, the intensity of solar radiation in the near-Earth space is about 1.35 kW/m^2, which is available nearly year-round, 24 h per day. This energy can be used in a number of ways to produce power: by direct conversion to electricity via photovoltaic (PV) cells, by its conversion to heat for operating some type of thermal power cycle (Brayton, Rankine, Stirling, etc.), for operating direct thermal–electric energy conversion systems such as thermoelectric or thermoionic generators, or by using its thermal and/or photon attributes for operating and/or catalyzing chemical processes for the production of fuels or of energy storage materials.

Some of the quantitative advantages of the SPS over solar Earth-based systems are (1) a 4–10-fold increase in available power, due to increased available time and solar flux; (2) structures up to 1000-fold lighter, and having longer life; (3) no need for collector cleaning; (4) no inherent need for energy storage which in an Earth-based system causes a loss that could be larger than 40%; and (5) very easy tracking (cf. Refs. [1,10,11]).

3.1.2. Photovoltaic systems

For PV conversion, it is likely that thin-film cells would be used. The state of the art of overall array efficiency is 6% to 25%, with the higher value attainable so far only in laboratory units. This would yield an overall electric power flux production of up to 150 W/m^2 or 200 W/kg for such thin film systems. In current practice, however, the recently added PV panel by NASA to the Mir space station provides only about 13 W/kg, at 120 W/m^2. Since solar concentrators (Fresnel or other type) can be made at low cost and weight, they would be used to augment the PV cell output. Concentration ratios of up to 100 were proposed to be optimal.

Silicon and GaAs are the current prime candidate materials for PV cells, and expected to have a 2–3%/yr degradation in space. With current technology, silicon arrays are expected to produce 30 W/kg, and GaAs 48 W/kg, but an advanced PV solar array developed on a lab scale by the Jet Propulsion Laboratory already had a specific power output > 130 W/kg. An additional specific mass of 0.02 kg/W is used for electrical power system electronics (power control, conversion). Within the next decade or so it is expected that newer PV cells, such as the thin film multi-bandgap, 'rainbow' (can utilize each component of the solar radiation spectrum), and 'quantum dot' types would become commercially available with overall efficiencies (with concentration) of up to 35%. Arrays of this type are projected to have a specific power of 1000 W/kg, 600 W/m^2 [12]. It is, however, noteworthy that there is some doubt whether there exist sufficient materials to produce the required quantity of GaAs cells. More information can be found in Refs. [4,10–13].

The first comprehensive study conducted on SPSs was in the 1970s [14,15] to determine the primary parameters of a 5 GWe SPS, and they were then determined to be: (1) 50,000 tons weight, (2) 50 km^2 PV array, (3) Klystron converter of the PV-produced electricity to microwaves, (4) 1 km diameter phased-array transmitting antenna, (5) 2.45 MHz microwave beam, (6) 75 km^2 rectifying antenna on Earth, (7) 425 ton single launch capacity to lower Earth orbit (LEO, 200 km from the Earth surface), (8) electric propulsion from LEO to GEO, (9) a 6400 ton construction base at LEO, (10) eight 425 ton launches per week, 400 per year, (11) Earth–GEO personnel transfers 32 times per year, 75–80 passengers per transfer, (12) three month individual stay time. Based on this system (and 1978 prices) the estimated capital investment needed to just get the system started was of the order of 250 billion (in current dollars), with a cost of 1400–7000 per kWe. 25–30% of this cost was for space transportation, 80% of which was for the Earth–LEO portion. To produce a significant fraction of the US power demand, it would have been necessary to manufacture two power satellites per year for 30 years. An examination of this concept by the US National Research Council and the then Congressional Office of Technology Assessment concluded that the concept might be technologically feasible, but programmatically and economically unachievable. A recommendation was made by National Research Council to continue the research and revisit the concept in a decade or so, but in fact support of this effort by the US government ceased till recently.

The rapid increase in energy demand has however not. This, combined with the recently evolving concern about CO_2 generation, and the independent new mission of NASA to reduce the cost of Earth to orbit transportation, has in 1995 prompted NASA, assisted by a number of aerospace companies and other organizations, as well as a large number of individual experts, to commence a broad reexamination (“fresh look”) of all aspects of future space solar power systems (cf. Refs. [12,16,17]). The emphasis was on examination of the feasibility of reducing the cost of terrestrial electricity produced by such systems in comparison with existing ground alternatives, in a variety of markets. A large number of SPS concepts were examined, most of them yet untested, and five markets, focusing on emerging nations where the increase in energy demand would be most rapid, were considered. To keep costs low, a key strategy was to avoid, wherever possible, the design, development, test and evaluation of infrastructures unique to the SPS.

One of the system concepts is the “Sun tower,” depicted in Fig. 2. It is evolvable and modular, consisting of a $\sim$15 km long common tether made of both electrical and mechanical support cables, which is attached to about 30 1-MW PV modules, and at its end to a 200–300 m diameter 250 MW FET device phased RF generator–transmitter aimed at a rectenna (receiving antenna which converts the microwave energy to DC electricity) on Earth. Each PV module is in the center of a 50 m diameter Fresnel thin film concentrator/reflector. With some effort one could envisage the solar tower as an Earth-pointing sunflower in which the face of the flower is the transmitter array, and the leaves on the stalk (tether) are the solar collectors. The tower would initially be deployed in LEO and then moved to its final destination, probably in GEO. A system life > 20 years is sought, and launching at costs lower than $400/kg is expected to be feasible using the ‘highly reusable space transportation’ systems which are currently under development for other needs anyway (Section 5.3 below). This concept was estimated to represent a factor of 30 reduction compared to the investment required for the original 1970s reference system.

3.1.3. Solar thermal (‘dynamic’) systems

A space electric power production approach is via ‘solar dynamic’ systems, which use solar heat to drive a thermal cycle or engine connected to an electric generator (Fig. 3). They have the capability for providing continuous power in LEO without the use of batteries for energy storage. Their efficiency is also significantly higher than current PV array/battery systems planned for space station applications, reaching 20–30% even now. It is also expected that solar dynamic systems will suffer less performance degradation due to aging and environmental interaction

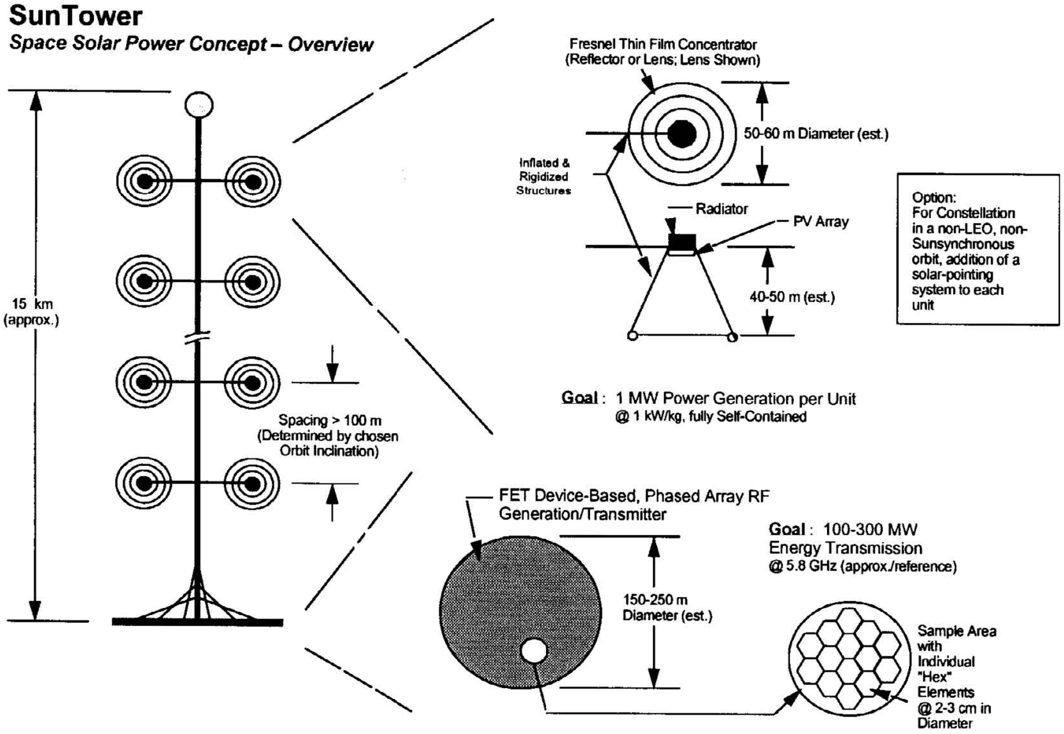

Fig. 2. The Sun tower concept (cf. [17]), NASA.

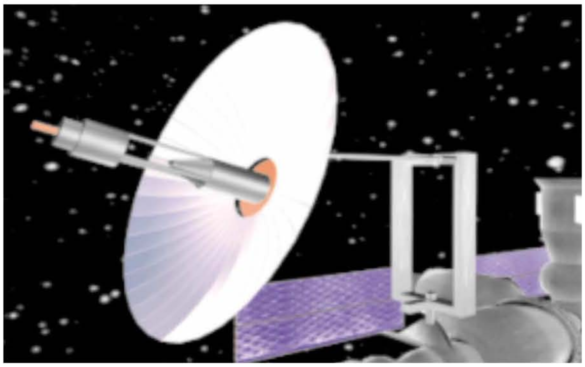

Fig. 3. A solar dynamic concept for space power production: note concentrator and receiver (NASA artist's rendition).

effects. Even for applications which require energy storage, space dynamics systems with thermal energy storage appear to offer lower cost than PV systems [4,18–21].

The International Space Station Project Office, NASA-Lewis, The Russian Space Agency, Allied Signal Co., and RSC-Energia were working cooperatively on a joint US and Russian development of such systems to provide two 10 kWe units to the International Space Station. A

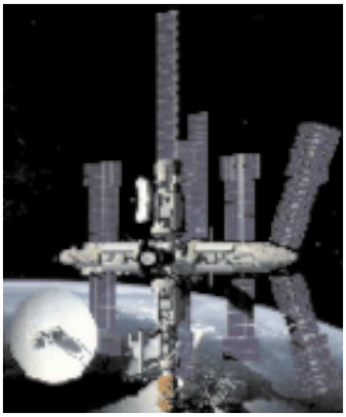

Fig. 4. A solar dynamic system alongside with PV panes for power generation on the international space station Mir (NASA artist's rendition).

concentrator would focus sunlight onto a receiver (Fig. 4) to heat a Brayton cycle using a helium–xenon mixture as the working gas. The generated mechanical energy powers a turbo-alternator–compressor providing electric power. Radiators release the waste heat into space. A phase-change salt storage material contained in the receiver captures the solar energy and provides the stored heat to the system throughout the Sun/shade orbit.

Other advanced energy conversion technologies are also available for possible use with the solar source. One of them is alkali metal thermal energy conversion (AMTEC) [22], boasting at this time an energy conversion efficiency up to 40%, which could use heat from solar concentrators to operate the AMTEC at the recommended 600–800°C, possibly with bottoming cycles using some thermal cycle or fuel cells, and rejecting heat by radiation into space. The AMTEC cell is a thermally regenerative concentration cell using sodium as the working fluid and sodium β''-alumina solid electrolyte as the ion selective membrane, through which expansion of sodium generates high-current low-voltage power. The heat is used to produce the sodium concentration gradient across the membrane (cf. [23]).

3.1.4. Orbital solar reflectors, and other methods

Another interesting approach to using space solar energy is by constructing orbital mirrors of large size, made of reflective thin film plastics, to provide illumination to cities or to extend agricultural production by making longer period availability of sunlight for crops [24], Fig. 5. Experiments on this were conducted by Russian cosmonauts in February 1993. It was also proposed to illuminate terrestrial solar plants by orbital mirrors, to extend their operating time [25]. Although a recent (1999) attempt by the Russian Space Agency to unfurl such a mirror in space has failed, there is no fundamental technical reason why this concept should not work.

Ultimately, recognizing that solar radiation is nearly pure exergy, it is strongly recommended to pursue research paths in which this photon exergy can be used more efficiently for generating electricity.

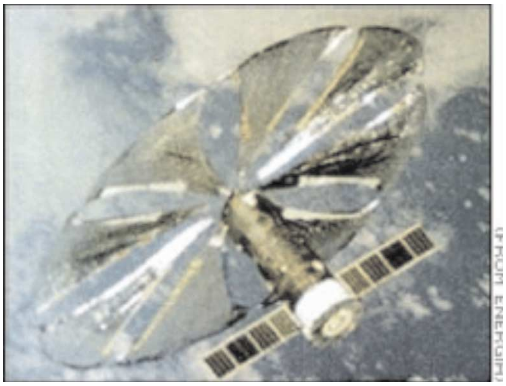

Fig. 5. Space mirror for reflecting solar radiation to Earth (The Russian Energia Co.).

3.2. Nuclear energy

3.2.1. Introductory comments on use and characteristics

Nuclear fuel has important potential for space power applications, as already evidenced by the use of the energy of radioactive isotopes, and of nuclear reactors, for powering existing space vehicles [4,18,21]. Its primary advantage is the very high energy content per unit mass, for fissionable uranium, shown in comparison with some other fuels in Table 2. With current technology, even the entire space reactor system is lighter than a solar PV system producing the same amount of power, noting that reactors for use in space are not designed to be equipped with the same level of protection and containment equipment used in terrestrial nuclear reactors. Space nuclear power systems do not require energy storage. They quite obviously also have a much smaller surface area.

Nuclear energy is in use for space power generation for about 30 years, in at least two ways: by using the decay heat of certain radioisotopes, and by the use of small nuclear reactors. The heat produced by either of these nuclear sources is typically converted to electricity by thermoelectric solid state devices. $Si_{0.78}Ge_{0.22}$ thermoelectric alloys are currently used in the Voyager, Galileo, and Ulysses spacecraft. Tellurides, such as lead telluride, and silver–antimony–germanium telluride (TAGS), have also been used with success, but their top temperature is limited to 825 K. To increase power production, higher temperatures are, however, desired (and obtained) from nuclear power systems which can result in higher power production. Future use of alkali-metal thermal electric conversion (AMTEC) with efficiencies $> 20\%$ and specific power > 18 W/kg is planned to replace thermoelectric solid state devices in these applications, and is claimed (arguably [26]) to have specific power 4–5-fold higher than that of isotope-powered dynamic systems (Brayton, Stirling, which can actually also achieve similar efficiencies). Another interesting proposal is the use of a thermo-PV generator, in which the radioisotope source heat is used to raise

Table 2
Specific energy of some fuels

Fuel	Fissile	Hydrogen	LNG	Coal	Oil
Specific energy (kJ/kg)	$(7.8)10^{10}$	$(12.08)10^{4}$	$(5.11)10^{4}$	$(3.25)10^{4}$	$(4.57)10^{4}$

the temperature of a black body, which in turn radiates its thermal energy to a PV converter, with appropriate wavelength matching. The efficiencies are predicted to range between 13% and 18%, with major reductions in cost and weight, essentially tripling the power production capability when compared with conventional thermoelectric converters [27].

3.2.2. Radioisotope-based systems

The radioisotope sources should have a high energy to weight ratio, a long life, and low γ emissions. A commonly used radioisotope in US systems is Pu-238 (an α emitter), with a half-life of 87.7 yr. It is enclosed typically in a high-temperature (such as iridium alloy) containment which serves both as a structural and radiation shield. Due to the formation of gas (mostly He) the enclosures must be vented. Additional impact protection is provided. Another radioisotope used is polonium-210, which has very high energy to weight ratio and low γ emissions, but a half-life of only 138.4 days.

A recently developed radioisotope space power system was found to be about 10 times lighter than a PV system using batteries for energy storage and producing the same amount of power. Isotope source power systems have been built successfully for electric power yields of up to a few kW. To provide some current criteria, current NASA plans for solar system exploration, using small low-cost spacecraft, recommend the employment of 100 W electric class radioisotope source power generation systems, with an end of mission specific power output > 11 W/kg and a 15 yr lifetime from launch [28].

3.2.3. Fission-reactor-based systems

For large power requirements, nuclear reactors are clearly superior to radioisotope systems, and indeed, beginning from 1965, several of them were used by the US and the former Soviet Union. Those built so far use enriched U-235 as fuel (originally in the form of a uranium–zirconium-hydride), and experiments were also conducted on liquid metal cooled fast neutron reactors, advanced high-temperature gas, fluidized bed, and gaseous cores (uranium metal plasma surrounded by a high-velocity propellant gas, usually hydrogen, primarily for propulsion), reactors. Cermet fuel, in the form of uranium oxide or uranium nitride, gas cooled through small holes bored through the cermet were also proposed because of their high power-density capability, of the order of several GW thermal per m^3, and high-temperature operation of about 2700 K [29]. In the original U-235 fueled reactors the heat was converted to power via thermoelectric systems. Since the latter have an energy conversion efficiency of only about 4%, it is inevitable that they would be supplanted by more efficient systems, such as ‘dynamic’ (Brayton (cf. Ref. [30]), Stirling, Rankine (cf. starting with early work at NASA [31])) or other ‘static’ ones, such as AMTEC, which have efficiencies $> 20\%$.

An active US effort to develop nuclear reactors for space use, started in 1983, is the SP-100 reactor [19,21,32,33] (Fig. 6) capable of producing 100 kW (but scalable to larger capacities), with an operating life goal of 10 yr. It is a fast reactor, using enriched uranium in the form of a nitride. To obtain and sustain criticality it has beryllium oxide reflectors, and also employs control rods. It can sustain the chain reaction only when the neutron reflectors are in place and the control rods withdrawn. The heat is transferred to liquid lithium, pumped by sealed electromagnetic pumps with no moving parts. The operating temperature of the reactor is 1350 K, and the pressure 1.5 bar. The heat is supplied to the high-temperature side of a thermoelectric converter made of

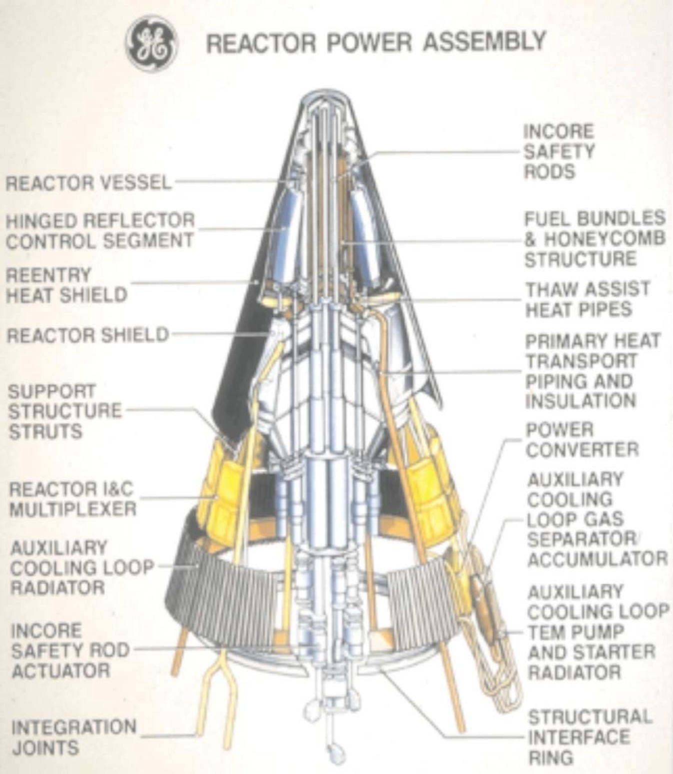

Fig. 6. The SP-100 space nuclear reactor design (General Electric Co., also Refs. [32,33]).

silicon/germanium–gallium phosphide semiconductors. The low-temperature side of the converter is maintained 500 K lower by using a lithium loop which rejects heat by radiation to space via heat pipes. Potassium or NaK are recommended as the heat pipe fluid. An auxiliary core cooling system is employed to be used if the reactor is accidentally incapacitated. The reactor is surrounded by a lithium hydride/tungsten radiation shield to protect the remainder of the space vehicle and its cargo.

The SP-100 is planned to have a weight of 4000 kg, a life of 10 yr and dimensions of 4.5 m diameter and 8.3 m length. The specific power is expected to exceed 20 W(e)/kg. The expected cost is \$100 million, reducible to \$75 million in larger quantities.

The reactor is to be turned off during launching until it reaches the desired orbit. After mission completion it is planned to be shut down and kept in orbit long enough for the fission products to decay to acceptable levels. If an accidental re-entry occurs, the reactor is designed to re-enter intact and turn off.

A Russian counterpart space reactor is the Topaz II, a heterogeneous small epithermal core loaded with 96% enriched ^{235}U, with zirconium hydride moderator and beryllium and beryllium oxide end reflectors [34]. It can be used for power generation, at present at a level of 6–45 kW, and for thermal jet propulsion, the latter discussed in Section 3.2.4 below. The total weight is somewhat more than 2 tons. The heat generated by the nuclear fuel in nuclear reactors can be converted to electricity also by other ‘static’ methods, such as thermionic, where a heated electrode emits electrons in a conductive vapor environment and the electrons are collected by a cooler electrode, the anode [35]. Yet another promising 'static' system is the above-mentioned AMTEC [22,23].

The heat from reactors can also be used in a 'dynamic' system, to power moving machinery, such as turbines or other engines. For example, a Brayton cycle was also proposed, for both satellite- and lunar-based power plants (cf. Ref. [19]). The operating fluid is a helium–xenon mixture, and initial studies proposed a pressure ratio of about 1.9. The proposed turbine inlet temperature was 1300 K, and the compressor inlet temperature about 400 K. The net efficiency was about 0.26, still rather low but higher than competing direct energy conversion schemes. The system specific mass was about 90 kg/kWe for net power output of 100 kWe, reduced to about 67 kg/kWe ($\sim$13 W/kg) for higher power outputs. R&D is under way to attain a ratio of 50 We/kg. A Sandia Laboratories study [33] found that for power generation levels beyond 40–60 kWe, the most promising SP-100-based power systems would be those employing Brayton or Rankine cycles.

In a program to design multi-MW space nuclear power reactors, several companies proposed reactors in the 10–100 s of MW range [36]. Boeing, General Electric, Westinghouse and Grumman have proposed different concepts of reactors employing an open Brayton cycle, using hydrogen as the reactor coolant and power cycle fluid. General Atomics developed a closed cycle system consisting of an in-core thermionic reactor and a bank of alkaline fuel cells. The fuel cells are used to supply a burst of power and the reactor power is used to regenerate the fuel cells. The water generated by the fuel cells is recycled by electrolysis to hydrogen and oxygen as the fuel cell fuel. Rockwell International developed a liquid metal cooled, Rankine cycle fast nuclear reactor system using sodium sulfur batteries for burst power supply. A secondary loop is a potassium Rankine cycle. The most important conclusions from these designs are that a very large amount of long-life power can be packaged into a relatively small and light package, and that, as expected, closed cycle systems are heavier than open cycle ones.

3.2.4. Multi-modal use of nuclear energy

Bimodal systems use the power source to provide both power and propulsion. In the Topaz II, for example, hydrogen is the coolant in the rector radiator heat rejection system and is preheated there up to about 650 K, is then passed through the reactor for further heating to about 2200 K, and is brought to its final temperature of up to about 3000 K with current technology, by an electric heater powered by the thermionic converter and possibly a Stirling engine, of the reactor. The hot hydrogen flows then through the exhaust nozzle to provide thrust. Low thrust can additionally be obtained by a xenon electric propulsion system, which is also powered by the reactor's electric output [37]. Multi-modal application of energy sources, here nuclear power, in space, has several attractive features [38]. The same power source providing electric power as well as propulsion results in cost advantages, not only in simplification or reduction of needed components, but also in the fact that propulsion is not constrained by the chemical reaction of the fuel and oxidizer; the heat is provided by the power source and the only significant consumable is the propulsion gas. Furthermore, the specific impulse that can be obtained by such engines is about twice that of oxygen–hydrogen chemical rockets, reducing flight time by the same proportion. A positive assessment of the bimodal use of the US SP-100 space reactor is described in Ref. [39].

3.2.5. Safety

Safety in operation of nuclear sources in space is of critical importance. Several techniques have been employed so far (cf. Refs. [40,41]). If the satellites are placed in a sufficiently high orbit, it is predicted that the isotope would stay in space, before descending into the atmosphere, for a time long enough to allow the radioactivity to decay to harmless levels. In low-orbit satellites the fuel source is to be boosted into a high orbit before the rest of the satellite descends into the atmosphere. Two opposite design philosophies are used for protection during mission aborts and Earth re-entry: one is to build a sufficiently strong containment which would retain the fuel upon re-entry, and the other is to allow fuel dispersal, by evaporation in the atmosphere. Both techniques were deployed and it is reported that no substantial radioactive particulates were found in the atmosphere after re-entry. Fallout from Soviet Union's Cosmos 954 accidental entry to northwest Canada in 1978 was carefully investigated and found not to have posed a consequential hazard, mostly due to the wide dispersal. Tethered stations were also proposed to separate the nuclear power generators from the operators.

At the same time, it appears obvious that neither of these techniques is totally, nor even acceptably, safe, and further development in this area is required.

3.3. Fuel-oxidation-based systems

3.3.1. The concept

The advantages of power generation in space remain valid even if fuel needs to be brought from Earth, as long as the fuel transportation costs to space are not prohibitive. This would be so if the fuels have a large specific energy, and/or the transportation costs are low enough. Table 2 indicates that the specific energy of combustible fuels is low, by six orders of magnitude, relative to that of fissile fuel, and thus proportionately that much more weight must be brought to orbit to produce similar amounts of power. Nevertheless, the potential for their use remains.

3.3.2. Conventional power cycles

While all power cycles used on Earth can also be used in space, system weight becomes a significant criterion in the latter. The Brayton cycle, as used in jet propulsion, has a weight advantage over other types of power cycles.

A system composed of a steam Rankine cycle and hydrogen Brayton cycle, both heated by a common hydrogen fuel combustor, and incorporating an electrolyzer in the Rankine cycle to generate the combustion hydrogen and oxygen from the water, was proposed and underwent a preliminary study [42]. While the electrolyzer energy consumption penalizes the efficiency somewhat, the fuel is recycled continuously and the presence of the electrolyzer provides some amount of cycle power output control. Condensation of the steam and cooling of the helium is accomplished by radiation to space.

3.3.3. Fuel cells (cf. Ref. [43] for general reference)

Fuel cells can be used either as an electricity source, or as a regenerative electric power storage system. In the former role, fuel and oxidant must be provided, as has indeed been done using hydrogen-oxide fuel cells in many space vehicles, including the US Gemini and Apollo missions. The reaction byproduct is water, which could either be used directly or electrolyzed in a regenerative storage system to hydrogen and oxygen for reuse in the fuel cell. The need for fuel and oxidant transportation to space may be obviated on a Moon base, where, e.g., hydrogen and oxygen could be made from lunar soil, even as a byproduct of producing other minerals such as metals, silicon, or of ^{3}He. Other fuels can also be used with varying degrees of preconditioning. The estimated specific power output for current systems is 20 We/kg. As fuel cell technology advances, higher efficiencies and specific energies will become available.

4. Power transmission to Earth

Power transmission by microwaves or laser beams [1,44–49], or on-site manufacturing of easily transportable fuels for electrochemical or combustive energy conversion (cf. Ref. [50]), are some of the technologies to be explored and advanced for bringing the energy from space to Earth.

The most commonly proposed method is the conversion of the produced electricity to microwave beams, the beaming of this energy to terrestrial receiving antennas (rectennas), and conversion at that site of the collected microwave energy to electrical power compatible with the grid. While this technique has been proven in principle, very little progress and research took place during the past two decades, and much work is needed.

Microwave energy transmission can be conducted at all frequencies above 1 GHz, into the optical band. Lower frequencies offer more efficient transmission through the atmosphere, especially in the presence of rain. An increasingly important constraint on frequency is to choose it in bands where it would not interfere with the ever increasing use of wireless communications. For example, the preferred [46] 2.45 GHz band which was originally proposed for such power transmission has recently been taken over by communications uses.

The microwave beam emitted by the transmitting antenna must be aimed accurately at the rectenna and have maximal convergence. Since the transmitting antenna is very large and may move, the proposed design of the transmitter is as a “retroactive” array, where a beacon at the center of the rectenna is pointed toward the SPS and illuminates its surface. Each subarray detects the phase of the incoming reference beacon and emits its power in the conjugate phase. But, each subarray must also have a reference phase signal sent out from the central control in the transmitter that will be identical in all subarrays, whose distance from the central control will vary with time. A free-space laser modulated with the microwave frequency was suggested for distributing this reference signal.

The rectennas are very large, pose some land use problems, and are about 10% of the overall cost. With the satellite in geostationary orbit, the rectenna can remain stationary. The size can be reduced by increasing the microwave frequency, but this also increases the transmission losses. They are expected to be made of a wire mesh, which is thus light, stops most of the microwave energy but allows transmission of sunlight and water to the ground under it for sustenance of the existing flora and fauna, has low wind loads, thus needing much lighter support structure and requires much reduced cleaning. It is estimated [11] that in comparison with a terrestrial PV power generation system, the rectenna of a space power satellite would require only 1/10 to 1/15 of the

PV solar collector area, that including a 5 km wide buffer zone around the rectenna, where the microwave beam power drops to 1 W/m^2, about the same as that at a 2 m distance from a closed domestic microwave oven. The efficiency of conversion of microwave energy to DC electrical power is about 82%, and that of the DC to AC conversion is about 98%. The overall transmission efficiency, from the DC power source at GEO to the customer's grid on Earth is estimated to be about 36–40%, for the currently regarded compromise of operation at about 5.8 GHz (or 70–80% at 2.3 GHz according some earlier predictions). There is, however, very little experience with microwave energy transmission in this frequency range.

Another possible approach, but currently of very low efficiency, is converting electric energy generated in space to laser beams, which would be collected on Earth by PV cells [44,47–49], or alternatively by concentrators/receivers providing heat to thermal energy conversion systems, either of which would convert it back to electricity for use on Earth. Current efficiencies of conversion of electric power to laser beams are however very low, below 5% typically, but suggestions have been made that quantum box driven semiconductor lasers which are pumped directly by solar energy [47,49] could be developed with an efficiency $> 40\%$.

Using similar technologies, it was proposed by Ehricke (cited in Ref. [51]) that power relay satellites could be used for transmitting electricity from regions where it is available to others which need it. Converting the produced electricity at the space supply site to microwaves, and beaming them to a satellite which would reflect it to the consumer site for conversion to electricity and use, would avoid the difficulties and losses associated with the conventional ground (or underwater) cables which are presently limited to distances of about 1500 km. This could, for example, open excellent opportunities for using renewable energy from favorable sites at energy needy regions very far away. For example, the overall efficiency of such transmission from new hydro-power sources in South America to Europe was estimated to be about 50%.

There is public concern about the effects of the microwave and laser radiation proposed for energy transmission. This concern has been somewhat increased by the ongoing debate about the effects of electrical fields on human health, particularly as related to the fear that it causes cancer [52], and of the effect of radio-frequency emitting appliances such as the cellular phone. Many strong arguments have been made that these effects, in the range and methods of proposed use for the power transmission are unfounded [53]. No mutagenic or chromosome effects were found from high-frequency radio energy unless it heats the tissue [54]. Briefly, the average power of the beam is planned to be 75 W/m^2, which is just about 8% of the solar radiation. At the beam center the energy would thus be 230 W/m^2 ($<1/4$ of the solar flux), dropping at the edges to about 1% of that at the center, well below the 10 W/m^2 limit for microwave power in the US, with maximal allowed human exposure of 6 min at that level, or can even be adjusted to below the 0.1 W/m^2 most conservative limit set in the world. It is actually thought that microwave radiation at the planned levels may be safer than the existing high-voltage long-distance transmission lines with their electric fields. At the same time, transmission at such low fluxes penalizes the overall economics significantly, and it was suggested that perhaps a fourfold increase in the power density would be necessary for acceptable cost, which would require restriction of passage through the beam column [17].

Standards of allowed exposure have been established by several countries (cf. NCRP [55], ANSI/ IEEE [56], NRPB [57], VDE [58]), and the United Nations (IRPA [59]) setting the most strict limit as 10 W/m^2 for frequencies above 1 GHz, and 0.1 W/m^2 somewhat below it.

5. Space transportation

5.1. The challenge

The development of space-based commercial energy producing systems depends in a major way on the feasibility of launching into orbit the required large amounts of materials, and on the associated costs and environmental impact. It is noteworthy that 4299 space launches have been made in the period 1957–1998, by 12 countries, with an average success rate of 91.1% [60].

The establishment of space power stations will require an enormous amount of traffic into space [1]; the expected transportation system must accommodate a mass of 25,000 kg or more per single launch and high launch rates, with potential for more than 750 launches per year with 45,500 kg payload launch vehicles. The total transport time to geostationary orbit is about 100 days. Since the power systems must be placed in specific constellations and planes, the time windows will be limited for launch. This would require, in turn, the establishment of a highly increased number of launch facilities. Larger payloads can be considered to reduce the required launch rate.

At the present cost of placing a 1 kg payload in LEO hovering around $20,000, launching large payloads for planned orbital power stations is much too expensive to be considered commercially feasible. Even at that cost, about 150 payloads were launched into orbit in 1997. Half of these payloads were commercial craft, as the ratio of commercial and civil to government payloads tripled over the last few years, and this growth in commercial space launches is estimated to continue. Some market estimates predict that about 1200 civilian use satellites will be completed and launched between 1998 and 2007. Even this may be an underestimate in view of the booming increase in the use of mobile phones and other wireless communications, including wireless internet.

Present satellites weigh up to 2300 kg, with future ones about 10,000 kg. The planned International Space Station will need dozens of deliveries of crew, fuel and other cargo, over its 15 yr life. These launches are in addition to the 43 planned assembly flights needed for the station. These predictions clearly suggest an existing need for development of more efficient launch technologies for placing increasing number of payloads into orbit. Such less-costly launch technology, when developed, will also accelerate the economic development of space-based power stations.

5.2. Existing technology and technology developments (cf. NASA [61], Boeing [62], Lockheed Martin [63], US Air force [64] web sites)

Existing conventional rockets, mostly originally developed by governments for military purposes include the Delta, Atlas-Centaur, Saturn, Titan, Zenit, Proton (Fig. 7), Energia, Ariane, H1, H2, and the Shuttle Inertial Upper Stage. The payloads reach about 20 tons, and the delivery cost to LEO is, as mentioned above, around $20,000/kg. The high cost is associated with several factors: the need to carry the fuel and oxidizer and the guidance system, the total loss of the rocket after each launch, the low energy efficiency of rocket propulsion, the low production volume, and the costing philosophy based on military rather than commercial applications.

Fig. 7. The Russian Proton rocket (The Russian Energia Co.).

Many large aerospace companies are testing the limits of this existing technology. Examples of these developments are the Delta 3 from Boeing (Fig. 8), the Titan 4A (Fig. 9) from a joint venture between Lockheed Martin and the US Air Force, and the Ariane boosters (Fig. 10) from the European consortium of Ariane Space [65]. Additionally a private company, Beal Aerospace Technologies in Texas [66], was till October 2000 developing a three-stage launcher that was scheduled to fly in the third quarter of 2000 (the company then ceased operations). Although these boosters are a viable launch option today, they are too expensive for the future development of space power.

The only operational semi-reusable launch system, the NASA Space Shuttle (Fig. 11), having a payload of about 30 tons, was intended to be an inexpensive way to space, but its cost turned out to be no lower than those of typical expendable rockets. Additionally, the shuttle has been unavailable for commercial launches since the Challenger disaster in 1986. Other shuttles are being developed by the Russians (Buran) and the Ariane consortium (Hermes).

To cut much of the existing launch cost, a primary ongoing development is a reusable craft that would need only refueling and some basic checks between flights. This holds true for technologies using conventional as well as unconventional launch energy sources, such as magnetism.

Fig. 8. The Delta 3 rocket (Boeing [62]).

5.3. Reusable launch vehicles

Several ongoing developments will be described here briefly. Kistler Aerospace [67] is developing launchers that will employ available LOX/kerosene Russian-built engines. The first stage of the vehicle, called K-1, will be designed to fly back to the launch site while the second would orbit Earth before returning. Both stages are being designed to descend by parachute and land on inflatable air bags. The two-stage-to-orbit system is intended to have a payload capacity of 4500 kg to a standard LEO at an estimate initial cost of $3750/kg to orbit. Commercial interest has already been expressed for using this technology.

Pioneer Rocket Plane [68] is developing a system which uses atmospheric oxygen instead of the oxygen carried by the launch vehicle. It is developing a lightweight, two-seater vehicle powered by a rocket engine as well as conventional turbofan engines. Named Pathfinder (Fig. 12) and originating in some earlier USAF research, the vehicle design calls for it to take off and land horizontally just as a conventional aircraft. The craft, with a payload and attached second stage in its small cargo bay, will take off from a runway under turbofan engine power and then will climb to 6100 m. There it will meet a fuel tanker and take on 64,000 kg of liquid oxygen. After separation from the tanker, the liquid oxygen is used to fire up the orbiter's RD-120 rocket engine that takes it to Mach 15 and 113 km altitude. At this point the craft can release its payload and second stage. The planned payload for the Pathfinder is about 2000 kg. Similarly to the Kistler K-1, the Pathfinder uses primarily existing technology and components. The propulsion system uses

Fig. 9. The Titan 4A rocket (Lockheed Martin [63] and US Air Force [64]).

proven GE F404 turbofan engines and one kerosene/oxygen-burning RD-120 rocket engine. The avionics systems are derived from existing military aircraft.

Kelly Space and Technology [69] is developing another horizontal takeoff launcher. The Astroliner, which looks like a smaller version of the space shuttle (Fig. 13), has to be towed to an altitude of 6.1 km by a modified Boeing 747 aircraft, but it can handle payloads up to 4550 kg. The Astroliner is 38 m long and will be powered by a reusable rocket engine or a multiple engine configuration. Once released from its tow aircraft the Astroliner's rocket engines are fired and the craft ascends to 122 km altitude. At that altitude the nose of the vehicle will open and release the payload and the upper stages that will lift the payload to orbit. These upper stages are expendable solid or liquid rocket designs depending upon mission requirements. The Astroliner then re-enters the atmosphere and returns to land at a conventional airfield under the guidance of its two-pilot crew and with the help of wing-mounted jet engines for powered descent and landing. The company claims that the costs would be about \$4400/kg payload to LEO, and reduced launch insurance rates for Astroliner payloads. Current plans call for the first launch of the Astroliner in 2002.

Weight of the oxidizer is not the only excess weight that new technologies hope to eliminate in order to reduce the cost of launch vehicles. An example in this area is the elimination of some

Fig. 10. The Ariane 5 rocket (Ariane Aerospace [65]).

Fig. 11. The space shuttle (NASA [59]).

Fig. 12. Pathfinder, a reusable space transport vehicle under development by Pioneer Rocket Plane Co. [68].

Fig. 13. Astroliner, a reusable space transport vehicle under development by Kelly Space and Technology Co. [69].

propulsion components by redesigning the vehicle's configuration. One company that is attempting such approach is Rotary Rocket Co. [70]. The company is building a rocket design that would take off and land vertically powered by an innovative engine design. In the Roton C-9 (Fig. 14), Rotary Rocket's vehicle, the oxidizer and kerosene fuel are fed into 96 combustors inside a horizontal disk 7 m in diameter that is spun at 720 RPM before launch. Centrifugal force created within this disk provides the pressure for combustion, thereby eliminating the need for massive, expensive turbo pumps present in the present engine designs. The saved weight allows the 19.5 m high Roton C-9 to fly single stage to orbit. On the way back the Roton descends with the aid of foldaway helicopter-like blades that are spun by small hydrogen peroxide/methanol rockets on their tips. The rotor blades are folded flat against the exterior during launch. Rotary Rocket Co. is targeting ultimate turnaround times between flights of 24 h or less to create additional efficiency through frequent launch capability.

Fig. 14. The Roton-C9, a reusable space transport rocket under development by Rotary Rocket Co. [70].

Rotary Rocket conducted successful flight tests in 1999, with orbital flights and commercial operations targeted for later in 2000.

5.4. New propulsion technologies and the highly reusable launch vehicle

Since improvements in present rocket engine technology are already being approached asymptotically, other propulsion methods are being developed for propelling craft into orbit. These new technologies include the ejector ramjet, aerospike, scramjet, and combined cycle engine technologies. One common characteristic among these engines is the ability to fly at hypersonic velocities through the atmosphere at altitudes not achievable by present jet engine technology.

The ejector ramjet engine is currently under development by the Space Access LLC, of Palmdale, CA. The resulting craft, SA-1, is planned to take off and land horizontally under the power of the ejector ramjet and will handle payloads of around 14,000 kg, similar to those carried by the shuttle. As designed, the vehicle is approximately the size of a Boeing 747. At high altitude the design uses a conventional liquid rocket to exit the atmosphere and release an upper payload carrying stage. The SA-1 can carry either a single upper stage for low-orbit missions, or two upper stages for higher-orbit deployment. Each of the stages features a lifting-body design and autonomously de-orbits and lands horizontally following satellite deployment. Full-size vehicle testing is planned for 2001 with launch operations commencing in 2002.

Linear aerospike engine technology is considered by many as the most prominent launch vehicle technology in development. This technology, under development by Boeing's [62] Rocketdyne Division, is the core of the X-33 space plane design (Fig. 15) under construction by Lockheed Martin. The X-33 and its planned commercial derivative called the VentureStar (Fig. 16) [63], are a part of a joint industry – NASA effort to reduce launch costs 10-fold. The design of the X-33 calls for a vertical takeoff vehicle capable of reaching near orbit altitudes with a single stage. The X-33 will fly to a maximum altitude of about 91 km at a maximum speed of about Mach 13.8. The aerospike engines provide the advantage of adapting automatically to changing atmospheric pressure at higher altitudes. Combined with the aerospike engine is the vehicle's wedge-shaped lifting-body design known as an aeroballistic rocket. The VentureStar vehicle will

Fig. 15. The X-33 technology demonstrator for full-scale commercially developed reusable launch vehicles. 23 m long, 26 m wide, LH_2/LO_2 fueled, it is unpiloted, to take off vertically like a rocket and land horizontally; maximum speed Mach 13+ [61–63].

Fig. 16. VentureStar, one of the most promising reusable space transport vehicles, under development by Lockheed Martin Co. [63].

be twice the size and about eight times the launch mass of the initial X-33 craft. While the X-33 employs two linear aerospike engines, VentureStar will be powered by seven of these powerplants. Lockheed Martin plans a flight rate of 40 launches per year, leading to launch costs of approximately $450/kg.

An additional development to the X-33, the X-34 is designed for carrying payloads of about 1100 kg and for serving as suborbital technology test bed. New technology demonstrations will include composite primary and secondary airframe structures; cryogenic insulation and propulsion system elements; advanced thermal protection systems and materials; and low-cost avionics, including differential global positioning and inertial navigation systems. The X-34 and the X-33 are the initial steps in development of fully operational large payload craft like the VentureStar. Once such a vehicle is operational, it is expected that lifting large payloads, such as those required for construction of space-based power stations, would be possible and economically feasible. Lockheed Martin officials estimate the new system would decrease the cost of putting a payload in space from $4,500/kg to $450/kg, and that the VentureStar would be operational by 2004.

The main difficulty faced by the developers of all these jet derivative technologies is the ability of the designs to effectively use the surrounding air for the combustion process. The combined cycle engine that would be both a rocket and an atmospheric jet engine in one is addressing this particular difficulty. Boeing [62] is currently involved in a cost-shared program investigating the combined cycle engine for the Future-X Advanced Technology Vehicle.

5.5. Fundamental examination of energy and weight

A simple calculation shows that under ideal conditions the minimal energy needed for transporting 1 kg to geostationary orbit should not cost more than $2. One reason for the much higher actual costs is the inefficiency of current rockets, which is only 5%, but even 100% efficient rockets should not bring the minimal energy costs above $50/kg. The remainder of the very high transportation cost is the hardware and management. For example, even just weightwise, currently the (launcher hardware mass)/(payload mass) ~ 2. Hardware and management should therefore be the primary targets for improvement. In some comparison, commercial airline capital costs are a few hundred $/kg payload, two orders of magnitude lower.

It is also noteworthy that it is much more efficient to first transport the vehicle and payload just to LEO, and then transport the payload with a lighter vehicle to final orbit. The latter stage of transportation requires a much lighter vehicle and much less energy. To illustrate this point, transport from Earth to LEO requires a thrust of about 10 m/s^2, while the transport from there to geostationary orbit requires a thrust of only 10^{-4} m/s^2. Typically 5/6th of the transportation cost is delivery to LEO.

5.6. The long-term future prospect

The continued development of these new launch technologies has the ultimate goal of reducing launch costs from the present figure of $20,000/kg to as low as $20/kg over the next 40 years. Many industry insiders predict that fully reusable single-stage-to-orbit launchers should achieve the first factor of 10 within a decade and the DCX Delta Clipper prototype is predicted to reduce launch costs 100-fold, to below $100/kg [71]. Another factor of 10 may be achieved through the use of engines that combine hypersonic technology and rocket propulsion with new high-energy propellants.

There are several other ideas, beyond those under development today, that could find eventual use as launch technologies. A most primitive but efficient one is a projectile gun which at this time was proposed to lift a payload of a few hundred kg into orbit. A more realistic idea for high payloads is the magnetically levitated catapult. Here, a craft magnetically suspended above a track, similar to maglev trains, is catapulted into space. Placed on a mountain slope, the track would allow the craft to leave at a 45°C angle at close to sonic speed. It is expected to have much higher efficiencies than rockets.

Electric propulsion, such as Hall thrusters using krypton or xenon, is becoming a most viable option for the future because it offers much higher specific thrust and lower specific mass than chemical propulsion. Further is the related possibility of powering the space vehicles by microwave energy transmitted from Earth or space. Because they are powered by beamed energy, the vehicles would require neither fuel nor oxidizer thus reducing the weight dramatically. Specifically, it was proposed [44] that microwave energy can be beamed from the Earth to LEO for powering electric thrusters which would complete the transport from there to geostationary orbit, reducing by a factor of 20 the amount of propulsion fuel that should have otherwise been brought from Earth. A further possible version is the microwave thermal–electric thruster. It would use vortex-stabilized, electrodeless microwave discharge to heat water vapor fuel in a thrust chamber. Efficiencies of nearly 80% have been achieved in the laboratory, with significantly lower specific mass than that in chemical propulsion.

The maglev and microwave powered vehicles are in such early stages of development that cost analysis for their application is impossible. Analysis of the development costs of the other technologies however, is very feasible, as many of the components of these technologies are already in use today. With the ultimate goal of reducing the $20,000/kg-to-orbit cost to the level needed for space power generation system applications, the merits of all launch technologies mentioned above can be evaluated using existing cost models for space vehicles.

There are more futuristic propulsion technologies even beyond the above described ones. For example, anti-matter propulsion (cf. Refs. [72,73]) proposes to exploit the energy released from the annihilation of subatomic particles with their anti-matter counterparts. The outstanding advantage of this concept is that the energy released in such reactions is expected to be at least 100 times higher than this of fission or fusion, and could be used for propulsion in a number of ways.

6. Summary of environmental effects

A number of important negative effects on the environment accompany large-scale space power generation, and they have largely been described in the paper. A brief summary and some further issues are given below.

The primary effects include (1) pollutant emissions and ozone effects of launch vehicles, (2) microwave or laser power transmission, (3) health consequences of ionizing galactic radiation on space workers, (4) pollution collateral with the energy conversion system, such as the production and ultimate disposal of PV cells or nuclear fuel. These environmental effects are controllable, but they require further study, innovation, and possibly larger investments.

To elaborate, the large number of launches required will require development of methods for reducing the environmental impact, still not completely understood, that they have on the atmosphere. Rocket fuel would at least produce water vapor and NO_x (in the shuttle the fuel is hydrogen and the oxidant is oxygen) but if hydrocarbon fuels are used, as usual (say the Saturn rocket), there would also be emissions of CO_2, and some CO, unburned hydrocarbons, SO_x and other species. If ion thrusters are used, as planned, they may inject argon ions into the plasmasphere and magnetosphere. The interactions between the electric components and the plasmasphere are unknown.

Other likely environmental effects are interference with communications, and possibly with astronomy.

7. Security and safety

7.1. Security

Governments and power utility owners make a significant effort to keep the power plants secure from vandalism, terrorism, and war. While vandalism and terrorism may not be as likely a threat to space power plants, at least in the near future, war is. It is clear that space power plant owners would wish to develop and implement measures for securing their plants and for preventing unacceptable disruptions in power generation.

7.2. Launch vehicle safety

Launches are not completely safe, and even manned one may suffer from occasional failures as evidenced by the tragic explosion of the Challenger space shuttle (Fig. 17). Safety requirements for space power are especially severe due to the need for frequent launches which generate time

Fig. 17. The Challenger accident, 28 January 1986 (NASA).

pressures, a factor that increases risk. With the reusable launch vehicle designs, including ones from private firms, on the horizon, and the competitive nature of the development business where numerous private companies are tempted to cut corners for selling the first technology used, the safety of their operation has been addressed by the US Federal Aviation Administration (FAA) [74], which developed a draft system safety program plan (SSPP) for use by both government and private ventures in developing reusable launch vehicles. The plan covers the design and fabrication of the vehicle, its ground operations, launch facilities, support equipment, flight tests, and subsequent operations. The purpose of the FAA plan is to describe the tasks and activities of system safety management and engineering required during the vehicle development and operations and to identify, evaluate, and reduce or eliminate hazards. While it is impossible to study the individual safety plans of the existing and the developing launch technologies, an overview of the SSPP allows for an understanding of the issue of safety.

As drafted, the SSPP consists of a minimum of four elements identified in an effective system safety program: a planned approach for task accomplishment, qualified people to accomplish tasks, authority to implement tasks through all levels of management, and appropriate commitment of resources to assure tasks are completed. When applied to a development project the SSPP creates a safety matrix that is in turn used for safety control of the vehicle development and operations. The matrix identifies the specific series of tests throughout the life of the program with the object of verification of vehicle performance, validation of the design, identification of system deficiencies, and demonstration of safe operations. It is only following the successful completion of this test program that the vehicle will become operational and begin to carry cargo into space. The effect of the SSPP starts at the very beginning of the design phase with the parent company of the vehicle as well as its subcontractors being fully involved in the safety plan. The main elements of the SSPP are:

Quality assurance (QA): The design and operating company must establish a QA program suitable to the launch vehicle safety objectives, QA program management, vehicle/hardware acceptance, QA engineering, supplier selection, supplier quality surveillance and audits, production quality performance and evaluation, verification, configuration assurance, calibration/metrology, test assurance, material reviews, non-conformance reviews, process review and corrective action identification, and quality data collection and reporting.

Reliability: The company must perform reliability analysis, determine failure mode, effect, and criticality analysis, reliability predictions, reliability critical item identification, reliability testing and demonstration, develop parts selection and rating criteria, and identify and resolve reliability issues on safety-critical systems.

Maintainability: The company must provide a maintainability program that addresses safety critical system and subsystem maintenance and refurbishment considerations. Identify and track limited life items.

Design: The company must provide design hazard mitigation. Define verification/test requirements for design features.

Flight test: The company must provide test procedures and hazard mitigation.

Subcontractors/vendors: The company must provide reliability, quality, and safety data on components designed or supplied.

Albeit small, there also exists a risk of damage from meteorites and space debris to spacecraft during orbit, or on stationary bases such as the Moon. This requires adequate protective struc-

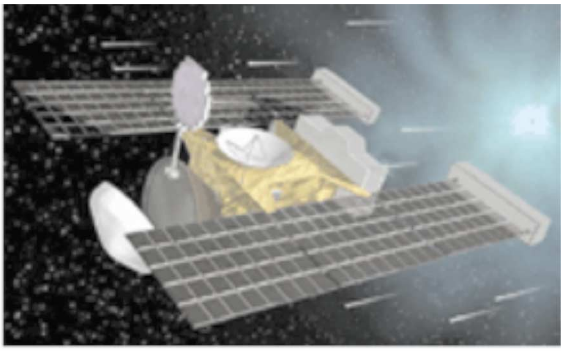

Fig. 18. Artist's concept of a spacecraft flying through the recent Leonid meteorite shower (NASA).

tures and redundant systems. An artist's concept of a spacecraft flying through the recent Leonid meteor shower is shown in Fig. 18.

8. Some basic space power economics

8.1. Current space power generation costs, electricity costs on Earth, and their costing

Faced with current costs of launching by *Atlas*, *Energia*, or *Saturn* rocket ($120 million, payload of about 10 tons), or by the Shuttle ($20,000/kg cargo), and the costs of the specialized power generation, transmission and collection equipment (say $1.2 million/kWe), the cheapest electricity from space, using current technology, would be about $35/kWe. Current costs of conventionally generated electricity against which space power must compete, are about 0.03–0.08 $/kWh. NASA's objective is space power generation at a cost of 0.05$/kWh for terrestrial consumers, a need for a monumental 700-fold cost reduction. Major reductions need thus to be achieved in the leading cost items, by reducing system weight, hardware and launch costs, and increasing energy conversion, transmission, and collection efficiency. In attempting to identify markets which are more economically amenable to the use of solar space power, a recent study [4] concluded that the only promising combination at this time is (1) space transportation costs lower than about 220/kg, (2) the satellite power system in Molniya orbit, (3) service to remote high-latitude sites (where the cost of conventional electricity is high). The same study concluded that the Sun-synchronous power satellite concept for peak power provisions does not appear to be a viable market opportunity, regardless of price. The reasons are the low price for power provided and the fact that these satellites do not have a high duty cycle per orbit.

A continuous concern about evaluating any new energy resources and conversion systems, and especially those using renewable energy, is that the comparisons with competing systems be made on an equitable basis. At this time the price of electricity from conventional energy systems, such as those based on fossil or nuclear fuel, does not include many upstream and downstream costs, such as those of the environmental and health effects related to the beneficiation of the fuels, and of those associated with various emissions and wastes. Furthermore, the depletion of the limited natural resources and of their exergy is not fully accounted for either. If these costs were included, space power would have a much easier competition with conventional power generation schemes.

8.2. Transportation costs

These are the costs of (1) launching components, fuel, and other materials, as well as the labor needed for the construction and operation of space power plants, and (2) returning products and people to Earth. Some of the current cost examples are $20,000/kg cargo for the existing shuttles, all the way down to $400/kg for future highly reusable unmanned space transport systems considered by NASA.

Cost analysis for future launch technology is very difficult to perform, since it depends on the progress and success of all the successive phases of the development program. If the program is successful, the development cost must be amortized over the life span of the vehicle program, and is dependent on the launch rate achieved by the vehicle. A number of cost models have been created by national institutions, such as NASA, for analysis of a launch vehicle design and development cost, but their marketplace validity still needs to be examined. With the obvious efficiencies stemming from the involvement of the private sector in the development of launch vehicles, the cost of placing payloads into orbit will drop. The need for launching satellites of any type, communications, power, or otherwise will generate competition among the industry players for launch customers (as it already does), which in turn will bring the launch price down (cf. [75]). The extent of this reduction is highly dependent on the market dynamics.

Table 3 presents cost comparisons of the presented technologies, showing that the VentureStar program has the best ultimate prospective performance with the highest payload capability. This high payload capability is the important factor in consideration of a launch technology for space-based power generation, and it is noteworthy that among the lower cost vehicles, only the VentureStar and the SA-1 have above 10 ton payloads.

Even the VentureStar promised costs of near $500/kg to LEO are still too high to make the space-based power generation economical, and a 4–5-fold reduction may be needed unless terrestrial power production costs increase in similar proportion due to steep increases in fuel and environmental costs, which is also a likely future scenario. For example, the increased cost of electricity due to CO_2 mitigation is estimated in the US alone to be about $85 billion/yr [76], probably enough to pay for the SPS development.

8.3. Some comments on transmission economics

Another approach to commercialization of space power was to regard the SPS microwave (or other beam) power as fuel, and sell it to any rectenna on Earth with whom the SPS owner has an agreement. This idea was developed further [45], where rectennas could be designed to be manufactured by low skilled labor, and used in small communities in the developing world. The latter appears to be far fetched, as it would be probably impractical to transmit microwave energy to many small locations. Nevertheless, the flexibility, at least conceptually, of transmitting the electricity to the most appropriate market at any period of time is economically very appealing. It is consistent with current schemes used by utilities to dynamically ‘wheel’ electricity through the

Table 3
Characteristics and costs of some existing and evolving space transportation vehicles [61,64]

Vehicle name	Type	Payload to LEO (kg)	Total launch vehicle mass (kg)	Development cost (M$)	Approximate cost per kg to LEO ($)
Delta III	Expandable booster	(GEO) 3800	N/A	N/A	20,000
Titan IV	Expandable booster	17,600	865,000	N/A	20,000
Ariane V	Expandable booster	17,900	710,000	N/A	20,000
Space shuttle	Reusable launch vehicle	24,200	2,036,000	N/A	20,000
Beal BA-2	Partially reusable booster	7700	950,000		15,000
Kistler K-1	Reusable launch vehicle	4500	380,000	150 each, for first five vehicles	3750
Pathfinder	Reusable launch vehicle	2000	N/A	275	
Astroliner	Reusable launch vehicle	4550	N/A	N/A	4400, ultimate 1000
Roton C-9	Reusable launch vehicle	3200	181,000	N/A	2200
SA-1	Reusable launch vehicle	14,000	N/A	N/A	N/A
VentureStar	Reusable launch vehicle	22,600	1,885,520	N/A	Ultimate 450

wire transmission grid according to market conditions. Transmission through space, especially when aided by satellite beam reflectors, adds the significant advantage of a constant power output electric supply from space economically meeting loads which vary strongly either by the time of day or time of year, on the entire surface of the Earth.

8.4. Overall costs

Many cost models are continuously being developed as the technology is changing and as new and improved designs are being proposed. It is interesting to note that in recent designs, such as the solar tower [12,16] the costs are approximately equally divided between the solar array, the launching system, and the transmission system. A NASA study indicated that high-latitude (Molniya orbit) space solar power plants, which may be the most economical prospect at this time, can only become competitive if the transportation costs drop below $31–101/kg, a rather unlikely expectation in the near future. The situation for space nuclear power plants is predicted to be somewhat better, $132–271/kg, but still not realistic in the near term.

Another promising possibility for improving space power economics is to use the same satellites also for satisfying the exponentially increasing needs for satellite communications, and thus share the costs.

8.5. Embodied energy and environmental impact economics

Some recent projections intimate that, conservatively, SPSs would produce 0.1 kW electricity on the ground per kg mass in orbit. Under these circumstances the energy expenditure of 10 kWh/kg to bring the satellite into orbit would be repaid in electrical energy in only 100 h, less than five days. While conventional economic analyses of space power as performed by NASA and some affiliated industries consider just actual costs of hardware, propulsion power, labor and capital, a project of this large magnitude requires a more profound evaluation. After optimal system definition based on the conventional economic analysis, and prior to any programmatic and budgetary commitment, the embodied energy in the entire system, the return on energy investment, and the economic costs of the system's impact on the environment and on competing electric supply development approaches, as well as of the use of depletable fuels and materials must be conducted. Final system optimization must be based on all of these parameters. This approach would reduce the risk of constructing a system which may have an immediate-term economic viability but an untenable longer-term overall cost.

9. Political issues

Superpower animosities have been the major political obstacle in all areas of commercial development in space. Although they have now abated, the use of space for power production still faces important political problems. One is that at most a handful of countries are capable of developing and implementing this technology at this time. The other countries, which would in fact be the most needy power customers, must be reassured that this power supply would not be governed by monopolistic economics and would not subject them to undue political pressure by the vendors. An increasingly peaceful world and healthy free market economics governed by international law are the obvious remedies for solutions equitable to all participants. Both, but especially the former, are difficult to establish.

Ownership of space (including lunar) locations, as well as of paths through which power is transmitted to Earth, are also complicated but resolvable issues. Future generation of power in space for terrestrial use will require massive resources and a long time.

Glaser et al. [77] have proposed 'terracing', a staged approach which, instead of engaging all at once in the development and construction of a large-scale space power generation station, would gradually develop components and smaller-scale systems, which would generate not only technological experience, but also wider confidence and acceptance of such a revolutionary approach to power generation.

10. Conclusions and recommendations

Power can be produced in space for terrestrial use by a using a number of energy sources, including solar, nuclear, and chemical. On the one hand, in view of the rising demand for energy, the diminishing fuel and available terrestrial area for power plant siting, and the alarmingly increasing environmental effects of power generation, the use of space for power generation seems to be inevitable: (1) it allows highest energy conversion efficiency, provides the best heat sink, allows maximal source use if solar energy is the source, and relieves the Earth from the penalties of power generation, and (2) it is technologically feasible, and both the costs of launching payloads into space and those of energy transmission are declining because of other uses for space transportation, dominantly communications.

On the other hand, the major obstacle is the exorbitantly high cost, which under current conditions requires the reduction of all costs by orders of magnitude; for example, space transportation costs by at least a 100-fold: to less than 200/kg into orbit, for competitiveness. It is noteworthy that any comparative economical analysis must be conducted on an equitable basis: here specifically including all of the costs of power generation including those of the environmental effects, resource depletion, and embodied energy. Other issues also need to be resolved, some of general nature, such as environmental effects and security and legal aspects, and some system specific, such as safety of nuclear power plants, and the realization of higher energy conversion and transmission efficiencies.

Compared with nuclear space power, most studies have concluded that SPSs appear to have poorer prospects for economic viability with current technology. The major needed improvements are in (1) efficiency, (2) weight, and (3) cost.

Much R&D would be needed to overcome these obstacles. Some of the primary subjects are (1) alternate propulsion processes, which requires less energy, produces less undesirable emissions, and have higher specific power, (2) reusable unmanned light space vehicles, (3) robotic plant manufacturing and operation, (4) new static energy conversion systems which have efficiencies much higher than the 6–10% in current systems, (5) advanced dynamic energy conversion systems which take better advantage of the near-0 K space heat sink, (6) efficient conversion of the solar photon exergy to electricity, (7) higher efficiency power transmission, (8) effects of space transportation and power transmission on the atmosphere, (9) launch safety, (10) space nuclear power safety. It is very noteworthy that many of these objectives are of primary importance even just for terrestrial considerations.

Due to the major obstacle of high cost of space transportation, "breeder" concepts are being proposed and should be carefully studied and developed. In these, a small amount of matter is lifted into space to construct the final, larger facility using resources, such as materials and energy, available in space. The Moon is often being considered as a source for materials for the construction of such power plants.

Future generation of power in space for terrestrial use will require massive resources, a long time, and strong and fair international cooperation. Glaser and others have proposed ‘terracing’, a staged approach which, instead of engaging all at once in the development and construction of a large-scale space power generation station, would gradually develop components and smaller-scale systems, which would generate not only technological experience but also wider confidence and acceptance by the people. This staged approach would be strongly fortified if applications collateral with space power, such as space-to-space power beaming for powering satellites, power relaying by orbital microwave or laser beam reflectors, and orbital mirrors for extended periods of terrestrial illumination, are developed. National and international work on this subject should be invigorated so that humankind will continue having the energy it needs for its happiness and, indeed, survival.

11. Some of the organizations active in space power development

Boeing Defense and Space Group/McDonnell Douglas Aerospace; Central Research Institute of the Electric Power Industry (CRIEPI), Japan; Edison Electric Institute; Electric Power Research Institute (EPRI); Electricité de France; The European Space Agency; The French National Space Agency (CNES); General Dynamics Space Systems Division; Institute of Space and Astronautical Science, Japan; International Academy of Astronautics; International Astronautical Federation, Jet Propulsion Laboratory; Lockheed Missiles and Space Company/Martin-Marietta Astronautics; Lunar Power Coalition; Mission Energy Company; Moscow Aviation Institute, Russia; National Aeronautics and Space Administration (NASA); National Space Development Agency (NASDA), Japan; National Renewable Energy Laboratory (NREL); New Energy and Industrial Technology Development Organization (NEDO), Japan; Rockwell Space Systems Division; The Russian Space Agency (RSA), SUNSAT Energy Council; United Nations; US Department of Energy (DOE).

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