Submitted to: 16th IECEC Meeting, Atlanta, Georgia, August 9-14, 1981

BNL 29582
CONF-810812 --37

APPLICATIONS OF POWER BEAMING FROM SPACE-BASED NUCLEAR POWER STATIONS*+

J.R. Powell and T.E. Botts
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, NY 11973

and

Abraham Hertzberg
Aerospace Laboratory
University of Washington
Seattle, WA 98195

ABSTRACT

Power beaming from space-based reactor systems is examined using an advanced compact, lightweight Rotating Bed Reactor (RBR). Closed Brayton power conversion efficiencies in the range of 30 to 40% can be achieved with turbines, with reactor exit temperatures on the order of 2000 K and a liquid drop radiator to reject heat at temperatures of ~500 K. Higher RBR coolant temperatures (up to ~3000 K) are possible, but gains in power conversion efficiency are minimal, due to lower expander efficiency (e.g., a MHD generator). Two power beaming applications are examined—laser beaming to airplanes and microwave beaming to fixed ground receivers. Use of the RBR greatly reduces system weight and cost, as compared to solar power sources. Payback times are a few years at present prices for power and airplane fuel.

INTRODUCTION

Power beam from satellites has been investigated during the past few years. While such systems are technically feasible, they require development of the capability to lift very large amounts of material into high earth orbits, the construction of large structures in space, and long-lived solar cells. In addition, component costs must be greatly reduced along with launch and interorbit transfer costs.

Nuclear power satellite systems will be much lighter and smaller than solar systems, can operate reliably for many years, and would require minimal construction in space.

Space-based reactors could beam power to fix central station ground receivers, mobile receivers (airplanes and ships), or users in space (orbiting platforms and interorbit tugs).

Power beaming by microwave, millimeter waves, and lasers have been investigated. Microwaves require large arrays and are best suited for fixed ground receivers. Atmospheric absorption limits millimeter waves to space-only transmission. Lasers require relatively small arrays and can beam to a variety of users, but the conversion of electrical energy to laser energy imposes an efficiency penalty.

Two applications appear promising—laser power beaming to airplanes and microwave transmission to central station receivers. Typically, beam powers of ~40 MW are required for the first application and ~1000 to 2000 MW for the second.

For such applications, nuclear reactors should have high temperatures (to maximize cycle efficiency), high-power density (to minimize reactor size and weight), minimum maintenance and refueling requirements, high reliability, and long-component life. High-temperature, gas-cooled reactors—similar to those developed for space propulsion—appear best suited for power beaming.

The NERVA reactor system was successfully tested during the early 1960's. Although NERVA is a possible source, its fixed fuel design necessitates an extensive refueling operation with personnel. Depending on power level and reactor design, fuel would be replaced at intervals of a few months to a year. The original NERVA used hydrogen coolant, which limited reactor lifetime to a few hours because of chemical reaction. With inert gas coolant (He or A), such reactors could operate until burnup required fuel replacement.

An advanced reactor system is described which appears very desirable for space power generation. In the RBR, which was under development as an eventual successor to NERVA, the nuclear fuel is an annular bed of small particulates with diameters of several hundred microns. (The particulates are similar to those in HTGR fuel elements.) The fuel bed is held inside a thin porous rotating cylindrical basket (or "frit"). Inlet coolant (He or A) passes through the frit and is heated in the partially- or fully-fluidized bed. There is an external moderator (beryllium or graphite) outside of the fuel bed, and control rods in the moderator.

The RBR can be remotely refueled by discharging the fuel into a shielded case and adding fresh fuel. Fuel would be discharged by reducing the rotational speed of the frit; full speed would then be reestablished and fresh fuel added.

The power density (~1000 MW(th)/m^3) and specific power (~300 kW/kg) of the RBR are extremely high. Outlet temperature capability is very high, up to ~3000 K. Structural requirements are simple since all components operate at low temperature (i.e., inlet gas conditions) except the particulate fuel.

Power conversion systems include both Brayton and Rankine cycles. The Brayton cycle is probably more desirable for space power systems with inlet gas coolant. Compression would involve conventional rotating compressors, while the high temperature expander would be either a high-temperature turbine, MHD generator, or energy exchanger.

The most promising radiator option is the droplet radiator, where heat is directly radiated to space from a sheet of small diameter drops (e.g., tin or oil). Droplets are sprayed from an injector into space and subsequently collected. Typically, specific powers range from 50 to 100 kW(th)/kg.

DESCRIPTION OF THE ROTATING BED REACTOR

Figure 1 shows the RBR for rocket propulsion. In RBR's for electric power generation, the hot outlet coolant exhausts into a duct to the power conversion system.

*Work performed under the auspices of the U.S. Department of Energy, Washington, DC 20545.

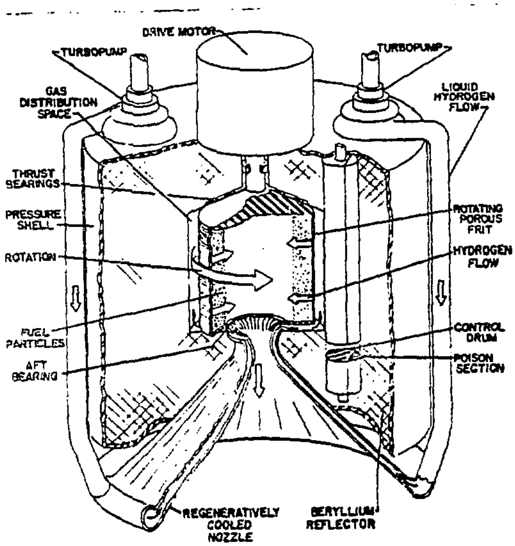

Fig. 1. Rotating fluidized bed rocket engine.

The RBR (1-3) was intended to follow NERVA. Rotating Bed Reactor development stopped in 1973 when the US Space Nuclear Propulsion program was canceled because, at that time, there was no intention of raising large payloads into higher orbits.

The RBR has a number of important advantages over NERVA. In the RBR, fine particules (typically several hundred microns in diameter) of nuclear fuel are contained inside a rotating porous cylinder or "frit" (Figure 1). Low-temperature gas passes through the frit into the fuel and exits at high temperature through a small nozzle at one end of the reactor.

In NERVA-type reactors, the fuel rods are relatively large (centimeters in thickness) and are cooled by the flowing gas stream. The enormous heat transfer area of the RBR fine particulate fuel allows much higher power density than NERVA. The RBR is the most compact reactor possible. Minimum size is set by neutronics. The RBR is externally moderated; fast neutrons generated in the fuel are slowed down in the external moderator/reflector, diffuse back into the fuel, and are captured. The minimum RBR dimensions are ~1 m in diameter and height. At this size power levels up to several thousand megawatts are possible, using appropriate coolant pressures and g forces on the rotating fuel bed.

Other important advantages of the RBR are:

- very high coolant outlet temperature,
- excellent thermal shock resistance,
- rapid start/stop capability,
- all structural components at low temperature,
- simple, precise power control, and
- ability to operate with a wide variety of coolants.

Measurements of heat transfer coefficients in packed and fluidized beds (4) show that in high-power RBR systems [~1000 MW(th)], local temperature differences between the fuel particles and gas are very small ~30 K. Gas coolant outlet temperatures can approach the fuel melting point without fuel slumping or agglomeration. With refractor carbide fuel, e.g., mixed UC-ZrC, one could operate at temperatures of ~2500 K for many months. For space power generation, the high outlet temperature of the RBR allows high-cycle efficiency and light radiators. (Radiator mass varies as T^4, and an increase of a few hundred degrees K in rejection temperature greatly reduces radiator weight.)

The excellent thermal shock resistance and short thermal diffusion time for the small fuel particles (~1 ms), allows very rapid start and stop times. Start/stop response will be controlled by control rods and valve travel to times of ~1 s. Reactor with massive fuel elements, such as NERVA, must ramp up and down over relatively long times, i.e., minutes.

The RBR is unique in that all structural components are at inlet gas temperature including the frit, reflector, control rods, and bearings. Only the rotating particulate fuel bed is at high temperature, and it has no structural function. Materials demands are minimal and existing materials are satisfactory.

Control of the RBR is simple. Because of its external moderation, the RBR has longer neutron lifetimes than current light-water reactors and high effectiveness for neutron absorbers in the moderator. Control drums would have moderator and neutron absorbers on opposite sides, with reactivity controlled by small angular adjustments of the drum. Rapid shutdown (milliseconds) would be achieved by rotating absorber sections next to the fuel.

An extensive series of experiments on a half-scale RBR (height = diameter = 25 cm) tested hydraulic behavior of the rotating fluidized bed. Spherical beads (either glass or copper) simulated the nuclear fuel particles, and ambient temperature nitrogen gas (p ~10 atm) simulated the coolant. The nitrogen mass flow rate/unit area of the frit matched projected flow rates for full-scale, full power RBR's. Although exact behavior of actual RBR's was not duplicated, the results should be representative.

Pressure drops for glass and copper beads were measured across settled and fluidized beds, as a function of gas flow rate, rotational speed, and particle size. Figure 2 shows pressure drop as a function of gas flow rate. The solid line is the analytical prediction of pressure drop through a settled bed, and it agrees closely with the experimental results. With increasing gas flow rate, pressure drop through the settled bed increases until it fluidizes. After fluidization, pressure drop remains constant as gas flow

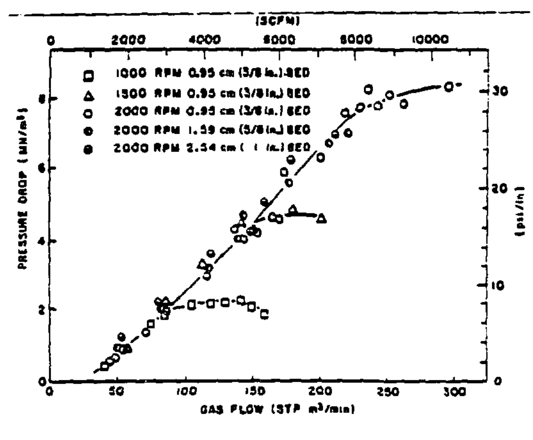

Fig. 2. Correlation of fluidization data for 500 μ glass beads (specific gravity = 2.5).

increases, although the bed voidage becomes greater. (In fluidized beds, pressure drop equals the effective weight (mass x g force) of the suspended particles.) Initiation of fluidization depends on effective g force, density of bed particles, and bed thickness.

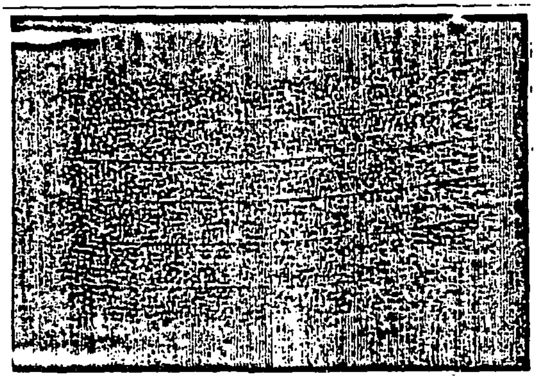

Fig. 3. View of bed taken through bottom plate, Series 4-3 500 μ glass, 2,000 rpm, 3 m^3/sec.

Figure 3 shows the rotating fluidized bed with a nitrogen flow rate of 3 m^3/sec. In the fluidized bed, particles are separated by thin gas films. Motions of colored individual beads can be followed through the bed by high-speed movies. The particles move through the fluidization zone, but movements are gentle and collisions that would damage or fragment the particles do not appear likely. The rotating bed has operated for many minutes with no particle damage. The inner surface of the rotating bed remains smooth.

At gas flow beyond some limiting rate, bubbling flow begins. Local voidage becomes spatially and temporally nonuniform, and low density "bubbles" rise through the bed. As the bubbles burst through the bed surface, particles are thrown into looping orbits. All particles return to the bed; however, the high particle velocities may cause fragmentation or damage.

This flow regime is readily avoided by ensuring sufficient g forces on the bed. This corresponds to selecting a rotational speed that gives stable, smooth fluidization at the given gas flow rate.

Extensive neutronic analyses were carried out using one- and two-dimensional diffusion codes. Figure 4 shows the geometry for two-dimensional neutron analyses. Nozzle effects and nonuniform moderator distribution are included. Table 1 shows typical RBR designs. A number of conclusions can be drawn with respect to RBR neutronics:

- Uranium-233 fuel is substantially superior to U-235 because of its higher η-value; U-235 reactors tend to be substantially larger and have higher critical masses,
- very small RBR beds tend to be undermoderated, resulting in considerably higher critical masses than larger beds,
- reflector thicknesses of ≥30 cm are desirable to minimize critical mass, and
- an attractive design point is reached with U-233 fuel and a 50-cm bed (height = diameter).

TABLE 1

Illustrative RBR Designs

	^{233}U fuel A	^{233}U fuel B	^{235}U fuel
Bed internal diam, cm	24	50	63.5
Bed height, cm	44	56	63.5
Fuel bed thickness, cm	10	7.6	10.2
Reflector thickness, cm			
Radial	16	30	30.0
Axial	25	30	30.0
Throat diameter, cm	11	18	18.0
Overall height, cm	94	116	123.5
Overall diameter, cm	76	125	143.9
Critical mass, kg	140	48	156.0
Bed voidage, %	50	70	60.0
U-concentration, at.%	100	7.5	9.5
Chamber pressure, psia	750	1125	1125.0
H_2 flow rate, kg/s	7	20	20.0
Power, MW (T = 3000 K)	350	1000	1000.0
Reactor weight, kg (including pumps and pressure vessel)	2500	3300	4750.0

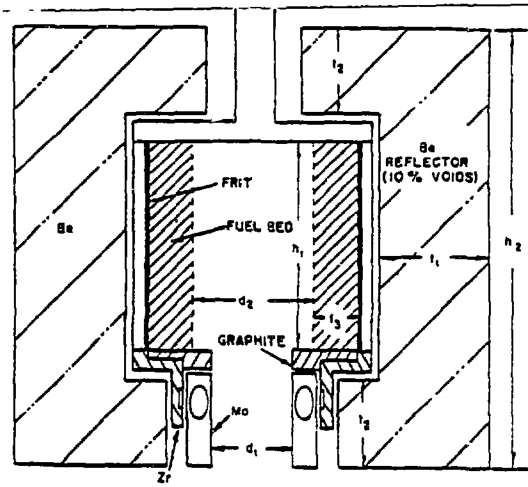

Fig. 4. Two-dimensional reactor neutronics model.

Critical mass is 48 kg, and U-concentration in ZrC particles is only 7.5 atom-percent.

Peak-to-average radial power ratio tends to be large, e.g., ~5/1, because of flux depression in the fuel bed. High peak-to-average radial power ratios are readily accommodated in the RBR, however. The very large fuel surface area makes temperature differences between particles and gas very small, so that high peak heat rates are readily handled. Also, the high peak powers are experienced in the outer part of the bed where gas temperature is low. Axial peak-to average ratios are close to one and can be easily shaped by axial control of the external reflector/moderator.

A range of RBR designs corresponding to different power levels is summarized in Table 2. For the same size reactor, power level can be increased by going to higher coolant pressures and/or high coolant temperatures. The highest power level shown is 3000 MW(th). However, higher power levels are possible with

TABLE 2

Parametric RBR designs

Case	pressure (psia)	Exit coolant temperature (K)	Power[(a)] (MW)	Coolant[(b)] flow rate, (kg/s)	^{233}U system[(e)] Reactor[(c)] weight (t)	^{233}U system[(e)] Total[(d)] weight (t)	^{235}U system[(f)] Reactor[(c)] weight (t)	^{235}U system[(f)] Total[(d)] weight (t)
1	750	2370	440	28	2.3	2.8	3.4	4.2
2	750	3400	530	24	2.3	2.7	3.4	4.1
3	1125	2370	660	42	2.3	3.1	3.4	4.5
4	1125	3400	790	35	2.3	3.2	3.4	4.5
5	1500	2300	880	56	2.3	3.3	3.4	5.1
6	1500	3400	1050	47	2.3	3.3	3.4	5.1
7	3000	2300	1760	113	2.3	4.2	3.4	6.4
8	3000	3400	2110	94	2.3	4.2	3.4	6.4
9	6000	2300	3510	226	2.3	6.1	3.4	9.0
10	6000	3400	4210	188	2.3	6.1	3.4	9.0

(a) Power corresponds to temperature rise from inlet temperature of 20 K.

(b) Hydrogen coolant.

(c) Fixed reactor weight-reflector, fuel, frit, rotating drive.

(d) Total includes fixed reactor weight, nozzle, controls, and pressure vessel, but not pump.

(e) Critical mass of 48 kg.

(f) Critical mass of 156 kg.

physically larger reactors. Reactor weight tends to be independent of power level and fixed at ~3 metric tons until very high power levels are reached which require very high coolant pressures. Pressure vessel and turbo-pump weights tend to dominate in these cases. Cases 1-6 have total weights (reactor, nozzle, pressure vessel, and turbo-pumps) of ~3 t, Cases 7-8, ~6 t; Cases 9-10, ~12 t, even though reactor weight remains fixed at 2.3 t.

ROTATING BED REACTOR POWER GENERATION SYSTEMS

Figure 5 shows two generic space power systems based on the RBR. In the first, the hot gas from the RBR expands directly through an expansion device, e.g., a turbine or MHD generator. In the second, the hot gas expands through an energy exchanger which expands the hot gas and compresses a lower temperature gas stream. The low temperature gas stream then expands through a turbine, generating external work.

The energy exchanger is not as limited by temperature as turbines. The exchanger is a rotating cylinder with many longitudinal tubes which cylically expand and compress the hot and cold gas streams. The cylinder temperature averages the hot and cold gas streams, and is much lower than the inlet hot gas temperature.

Thus, while turbines are limited to RBR outlet temperatures of ~2000 K (using either uncooled refractory metal blades or cooled blade technology), the energy exchanger could handle outlet temperatures up to ~3000 K. However, while the energy exchanger transforms the work potential of a hot gas stream with high efficiency (~80%), it does introduce some loss.

Also shown in Figure 5 are optional recuperators. Recuperators increase cycle efficiency, but recuperator temperatures above 2000 K appear difficult. Switch flow ceramic bed devices (either stationary or rotating) probably would be required.

Table 3 shows cycle efficiency for a RBR/closed-Brayton cycle power system as a function of expansion inlet temperature for simple and regenerative Brayton cycles. Compressor inlet temperature is 500 K, which is readily achievable with liquid drop radiator systems. Cycle efficiency is the maximum achievable for the given conditions, together with the corresponding pressure ratio (in parentheses). Compressor mechanical efficiency is assumed constant at $\eta_C = 0.9$, with expander efficiency at $\eta_T = 0.9$ for $T \leq 2000$ K, and $\eta_T = 0.7$ for $T \geq 2000$ K. Expander efficiencies above 2000 K correspond to either use of a less efficient expander (e.g., a MHD generator) or the extra inefficiency associated with using an energy exchanger to transform work to a lower temperature turbine circuit.

For the regenerated Brayton cycle, a regenerator effectiveness of 0.8 is assumed, which should be readily achievable.

While definitive conclusions in choice of power cycle conditions must await detailed trade studies including effects on total system weight and cost, some preliminary conclusions can be made.

First, high expander temperatures are not desirable if they necessitate using an expander with a lower equivalent mechanical efficiency. Only by going to 3000 K inlet temperatures can one begin to approach the overall cycle efficiency achievable at 2000 K, when expander efficiency drops from 0.9 to 0.7 in the high-temperature range.

Second, the regenerative Brayton cycle does not offer a major advantage in cycle efficiency, especially —as will be shown later— when the power system comprises a small part of the total orbiting beam power system. Accordingly, a simple Brayton cycle with a turbine probably is the most desirable choice.

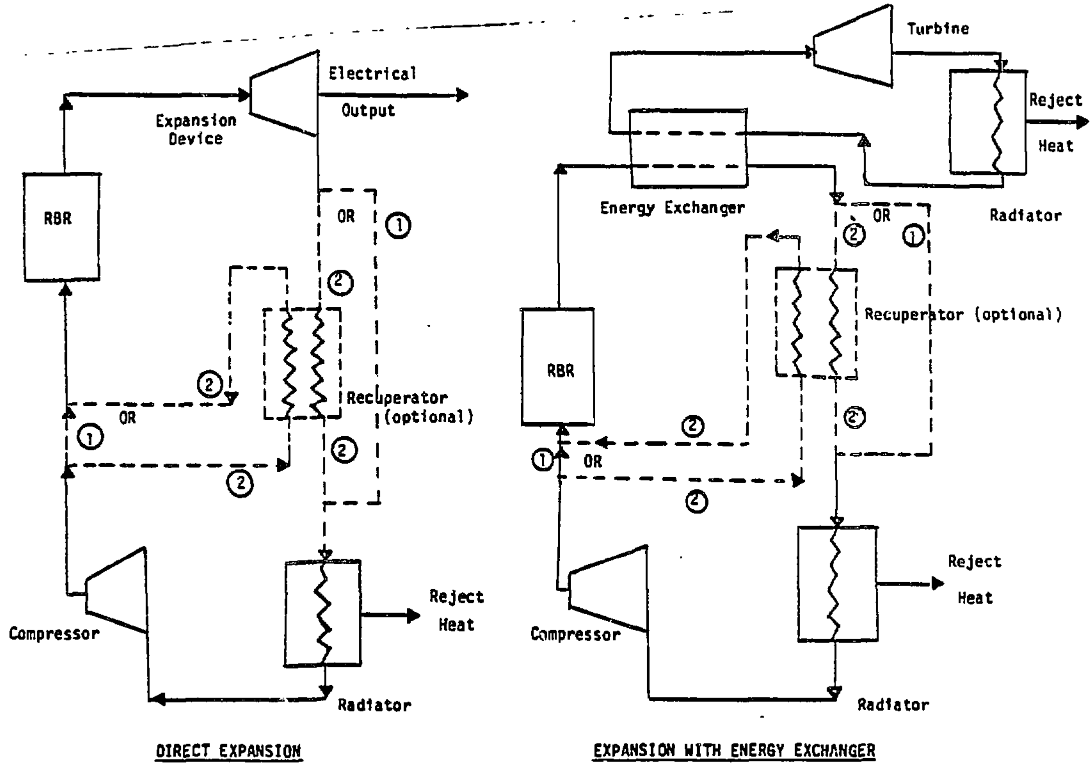

Fig. 5. Generic RBR space power systems.

TABLE 3

RBR/Brayton cycle system efficiency

Compressor inlet temperature = 500 K

Expansion inlet temperature (K)	Carnot	Maximum cycle efficiency, % (pressure ratio): Simple Brayton $\eta_T=\eta_c=0.9$	Simple Brayton $\eta_T=0.7$ $\eta_c=0.9$	Regenerated Brayton $\eta_T=\eta_c=0.9$ $\varepsilon=0.8$	Regenerated Brayton $\eta_T=0.7$ $\eta_c=0.9$ $\varepsilon=0.8$
1500	67	28 (4.5)	10 (2.5)	35 (2.1)	21 (1.9)
1750		34 (6.2)	14 (3.1)	40 (2.5)	26 (2.1)
2000	75	38 (7.9)	17 (4.0)	44 (2.8)	31 (2.3)
2250		42 (9.4)	20 (4.7)	48 (3.1)	34 (2.5)
2500	80	45 (12.0)	22 (5.7)	51 (3.4)	38 (3.0)
2750		47 (14.0)	24 (6.4)	53 (3.8)	40 (3.3)
3000	83	50 (16.0)	26 (7.2)	55 (3.8)	43 (3.3)

An overall cycle efficiency of 30% appears readily achievable after including pressure drops and housekeeping power, with a turbine inlet temperature of ~2000 K.

Third, the use of relatively low temperatures from the RBR simplifies ducting materials and insulation problems and ensures that evaporation of fuel particles will be negligible and fission product release minor, except for gaseous fission products.

The power system can be grouped into four major subsystems: the RBR heat source (with associated shielding), the radiator, the power conversion machinery (turbine, generator, and controls), and piping. Approximate specific masses [kg/kW(e)] for each component are shown in Table 4 as a function of power level at a cycle efficiency of 30%.

TABLE 4

Specific mass for RBR power systems
kg/kW(e)

Subsystem	Power level, MW(e) 20	1000
RBR with shield	1.00	0.02
Droplet radiator	0.04	0.04
Turbomachinery	0.30	0.30
Heat exchangers and ducting	0.30	0.30
TOTAL	1.64	0.66

The RBR specific mass tends to decrease with power; its total mass is relatively constant. Radiator specific mass tends to remain constant, since the amount of reject heat is linearly proportional to power level.

The liquid drop radiator proposed by Mattick and Hertzberg (5) appears very desirable for space power applications since it has an order of magnitude lower mass per kW than any fixed system and is immune to meteoroid damage. A spray of small diameter liquid droplets (~50 μ diameter) is produced by techniques similar to those developed for ink jet printing.

A liquid tin droplet radiator of 50 μ diameter would have a mass of 0.02 kg/kW(e) (30% cycle efficiency, 500 K compressor inlet temperature, and 950 K peak radiator temperature). The liquid droplets would lose, by evaporation, only about 10% of their mass over a 30-year operation period. The specific radiator mass, shown in Table 4, has been doubled to allow for spray ejection and collection equipment. Even lower radiator weights and lower rejection temperatures could be achieved using silicone oil for the droplets. This would increase cycle efficiency.

Detailed design studies of ground-based closed-cycle helium turbomachines and heat exchangers have been carried out for the direct cycle HTGR (6,7), for output power levels of 400, 500, and 600 MW(e) per loop. (The complete HTGR plant would use either two or three loops.) The 400-MW(e) turbomachines (turbine, compressor, generator, case, containment, etc.) has a specific mass of 0.75 kg/kW(e), and the 600 MW(e) machine has 0.6 kg/kW(e).

Large reductions in turbomachine mass appear feasible for space-based RBR power systems. Over two-thirds of the ground-based machine weight is associated with the case and containment rings. Light-weight composite material can be used in these components; optimization should easily reduce specific mass to 0.3 kg/kW(e) (the value used in this study), and probably to considerably lower values. Light-weight turbines for helicopters at relativel low powers (~1 MW), for example, achieve specific masses of ~0.1 kg/kW. Specific masses should be still lower as power increases.

Recuperators and precoolers in the direct cycle HTGR have specific masses on the order of 1 kg/kW(th). Large reductions in specific mass for these components appear possible by using larger pressure drops, extended heat transfer surfaces (especially roughening) and larger ΔT's to increase heat flux above the ~2 W/cm^2 characteristic of the HTGR. [The HTGR precooler, for example, has a low mean ΔT (30 K) across the tubes, and a low pressure drop (0.75% of base pressure).] Specific masses of ~0.3 kg/kW(e) for the heat exchangers and ducting in the RBR/Brayton cycle should be achievable.

Total specific mass for the RBR power system is thus conservatively estimated at ~1.6 kg/kW(e) for lower power levels and ~0.7 kg/kW(e) for high power levels (Table 4). Substantially lower values appear likely when detailed design studies are undertaken.

POWER BEAMING SYSTEMS

Space-based systems that have been studied include:

- Beaming microwave power from solar power satellites in geosynchronous orbit to fixed-ground-based receivers, and
- beaming laser power from solar power satellites to aircraft at cruising altitudes (i.e., 40,000 ft).

Other interesting systems are possible, such as:

- Space-to-space beaming with submillimeter waves, and
- laser beaming to ships.

Space-to-space beaming would allow many users, e.g., (various types of satellites (communication, surveying, scientific, etc.), ion propulsion orbital transfer vehicles, manned space platforms, etc.) to be powered from a few large power satellites. With submillimeter waves (e.g., λ ≤0.1 cm), transmitting and receiving antennas can be smaller than those for microwave antennas (λ ~10 cm). Atmospheric absorption is too high to be for submillimeter waves to transmit power to earth, but space-to-space beaming appears quite promising.

Laser beaming to ships is intriguing, since ships account for about 7% of total world oil consumption. With an efficient, optimum wavelength laser (e.g., a free electron laser at ~2 μ), lasers could power ships from space with minimal losses. However, it will be hard to compete economically with coal for ship power.

A number of detailed studies of the first two systems have been made. Table 5 illustrates system performance when RBR's are substituted for the solar power source.

Laser beaming to aircraft using solar power satellites has been extensively studied by Hertzberg and Sun. Two systems were investigated—a CO_2 laser in geosynchronous orbit (8), with direct beaming to aircraft, and a CO laser in low sun synchronous orbit (9), with beaming to relay satellites in high elliptical orbits, which then beam to aircraft.

In both systems, placement of the satellites is dictated by the need to have the power source in view of the sun for almost all of its orbit. With RBR power sources, this condition is no longer necessary, and more attractive systems can be devised.

An illustrative system, though not optimized, is given in Table 5, using a near-term CO_2 laser (30% efficiency) in a high-elliptical ("Molnya") orbit of

TABLE 5

Power Beaming Systems

Parameter	Application: CO_2 Laser Beam to Airplanes	Microwave Beam to Ground
Delivered power, MW	42	10,000
Transmitter power output, MW	50	13,690
Number of transmitters/satellite	1	2
Satellite electric power, MW(e)	167	16,860
Total RBR thermal power, MW(t)	500	56,200
Number of RBR's/satellite	1	20
Radiator reject heat, MW(t)		
—Power cycle	333	39,340
—Transmitter	117	3,170
System mass, metric tons		
--Power cycle	100	10,000
--Laser system	10	----
—Transmitter, optical	66	----
—Transmitter, microwave (including converters)	---	25,000
TOTAL	176	35,000
Cost, M$ (1981)		
--RBR power system (including radiator)	50	5,050
—Laser	5	----
—Transmitter, optical	18	----
—Microwave transmitter and ground rectenna		7,000
—Space transportation ($80/kg)	14	4,900
—Space assembly	8	700 ($20/kg)
—Capitalized O&M (10% of initial cost, less transport)	7	1,300
TOTAL	97	18,250
Payback time, years	3 at $1.50/gal	6.5 (@ 50 mils/kWh & 90% plant factor)
Cost range for equivalent product	$1.20-$2.00 per gal for jet fuel	30-60 mil/kWh

500-km apogee, 12,000-km apogee. Each satellite comprises a complete RBR/CO_2 laser system, which directly beams to one aircraft. The satellite is over the Northern hemisphere for 75% of its orbital period. This matches air traffic conditions fairly well, since most traffic is in the Northern hemisphere.

A 60-m diameter is required to focus on an 8-meter diameter receiver on the aircraft. As in Hertzberg's original concept, the aircraft follow a flight path which uses kerosene fuel for the engines during takeoff, climb to cruising altitude (40,000 ft) and descent from cruising altitude. Laser power is used only during the cruising portion of the flight. The laser power is deposited as heat in a heat exchanger ahead of the turbine section, with transmission of the beam through a transparent (e.g., sapphire) window. Turbine inlet temperature using laser heat is 1100 K, as compared with 1400 K with combustion (i.e., kerosene heat)

The substitution of laser power for kerosene power in a dual mode, laser-kerosene, aircraft will save 5000 kg/h of fuel (8,9). The modified aircraft proposed by Hertzberg and Sun represents a relatively slight change from present aircraft--a more optimized version flying at higher altitudes, e.g., ~70,000 ft, would have lower drag and require less laser power. Further design studies are thus likely to show even greater economic advantages for the laser-powered aircraft.

The cost figures, summarized in Table 5, are based on an estimated cost of $330/kW(e) for the RBR, which requires much less mass and equipment than present reactors. A detailed point design is necessary to arrive at a firmer cost for the laser optical system. The range shown corresponds to an estimate derived from the more detailed studies for the CO_2 geosynchronous system (8) and the CO low-orbit sun synchronous system (9).

The total cost range for the laser beam application is then $80 M to $150 M, which corresponds to an equivalent cost of $1.09/gal to $2.04/gal for the delivered power at the aircraft. These costs are in inflation-free dollars. If a 3% fossil energy escalation factor is assumed, the average cost of jet fuel with an assumed present cost of $1.20/gal over the next 20 years is $1.64. For a 5% fossil energy escalation factor, the average cost is $2.04. Both of these escalation factors are probably conservative due to the eventual need to switch to an alternative fossil-based energy source, e.g., coal derived synfuels. Fixed charges are 15% per year, operating fraction for the laser power satellite is 90% (Southern hemisphere flights are also powered), and the fuel savings is 5000 kg/h.

The cost of kerosene jet fuel is indicated as in the range of $1.20/gal to $2.00/gal. The former represents approximate present cost (in constant dollars). The laser system thus appears to be cost effective. Even greater savings appear likely when aircraft have to go to synthetic fuels derived from coal, which appear considerably more expensive than $2.00/gal in constant dollars.

A similar analysis has been carried out for the microwave beam power system, based on an adaptation of Piland's (10) study of the solar power satellite. Costs have been increased by a factor of 1.3 for inflation to 1981 dollars. The total cost of $1820/kW(e) delivered is somewhat greater than present average nuclear power capital costs (though less than some sites), but the higher plant factor, i.e., 90% vs. 70% makes up the difference. The RBR system is substantially cheaper than a solar power system, and delivers power at a cost comparable to present power costs of ~30 mils/kWh, reflects the increases likely to occur with more stringent environmental and safety requirements for ground-based systems. A RBR power beaming system would then exhibit a substantial cost benefit.

SUMMARY AND CONCLUSIONS

Beaming of power generated by high-performance nuclear reactors in space appears to offer substantial benefits. This concept shows sufficient promise to justify further development. On the basis of scoping examination, systems involving laser beaming to aircraft and microwave beaming to fixed ground receivers appear to be cost effective. More detailed studies, particularly of the laser aircraft application appear warranted. The laser system is very interesting since it offers an alternate option to synthetic fuels for aircraft, which will be very expensive. Also, laser beaming to airplanes offers the promise of substantial improvements in aircraft performance by cruising at higher altitudes.

REFERENCES

1. H. Ludewig, A.J. Manning, and C. Raseman, Feasibility of rotating bed reactor for rocket propulsion, J. Spacecraft & Rockets, 11, 65 (1974).
2. K.C. Hoffman et al., Rotating bed reactor for space nuclear propulsion: Annual Report, July 1972-January 1973, Brookhaven National Laboratory Informal Report, BNL-50405, 1973.
3. T. Botts, J. Powell, P. Grand, and H. Makowitz, A compact, high-performance electrical power source based upon the rotating bed nuclear reactor, Brookhaven National Laboratory Informal Report, BNL-27460, 1980.
4. G.C. Lindauer, Heat transfer in packed and fluidized beds by the method of cyclic temperature variations, A.I.Ch.E. J., 13, 1181 (1967)
5. A.T. Mattick and A. Hertzberg, Liquid drop radiators for space, in Proc. 15th IECEC, 1980, Seattle, WA, Vol. 1, pp. 143-50, AIAA, New York, New York 10104, 1980.
6. C.F. McDonald and M.J. Smith, Turbomachinery design considerations for the nuclear HTGR-GT power plant, ASME Paper 80-GT-80 (1980).
7. T.H. van Hagen, C.F. McDonald, and R.B. Creek, Heat exchanger designs for gas turbine HGTR power plant, ASME Paper 79-WA/GT-2 (1979).
8. A. Hertzberg and K.C. Sun, New energy conversion techniques in space, applicable to propulsion, 15th Joint AIAA/SAE/ASME Propulsion Conference, Paper 79-1338 (1979).
9. A. Herzberg and K. Sun, Laser aircraft propulsion, in Radiation Energy Conversion in Space, K.W. Billman, Ed., pp. 243-64, Progress in Astronautics & Aeronautics, Vol. 61.
10. R.O. Piland, The solar power satellite concept evaluation program, in Radiation Energy Conversion in Space, K.W. Bilman, Ed., pp. 3-25, Progress in Astronautics & Aeronautics, Vol. 61