THE ROTATING-BED REACTOR AS A POWER SOURCE FOR EM GUN APPLICATIONS*

J. Powell, T. Berts, C.M. Stickley, and S. Math

Abstract - Electromagnetic gun applications of the Rotating Bed Reactor (RBR) are examined. The RBR is a compact ($\sim 1 \text{ m}^3$), (up to several thousand MW(th)), high-power reactor concept, capable of producing a high-temperature (up to $\sim 3000^\circ\text{K}$) gas stream with a MHD generator coupled to it, the RBR can generate electric power (up to $\sim 1000 \text{ MW(e)}$) in the pulsed or cw modes. Three EM gun applications are investigated: a rail gun thruster for orbit transfer, a rapid-fire EM gun for point defense, and a direct ground-to-space launch. The RBR appears suitable for all applications.

INTRODUCTION

The Rotating Bed Reactor (RBR) is a very compact, high-power nuclear reactor concept originally under development for the space nuclear propulsion program. As designed, the RBR could generate up to several thousand MW of thermal power in the form of a high-temperature ($T_{\text{max}} \sim 3000^\circ\text{K}$) gas stream, using a reactor volume of $\sim 1 \text{ m}^3$ and a weight of $\sim 3 \text{ MT}$. It would have rapid start/stop capability ($\sim 1 \text{ sec}$) and could operate cw or in a pulsed mode.

The RBR appears attractive for those EM gun applications that require high average power and/or remote basing, e.g., space or airborne. Three illustrative applications are examined:

1. Electromagnetic thruster for space propulsion (LEO to GEO and planetary missions),
2. Rapid-fire EM gun, and
3. Direct ground-to-space launch.

Rail gun thrusters for space electric propulsion appear very attractive; they promise high specific impulse (e.g., in the range of 1000 to 3000 sec (10 to 30 km/sec projectile velocity)) at high thrust levels. This would allow efficient transport of large masses of material to geosynchronous orbit, as well as manned planetary missions.

For LEO and GEO transfer, systems are examined with payloads in the range of 100 to 1000 MT. The latter is appropriate to the construction of geosynchronous solar power satellite systems for power beaming to earth. Thrust levels in the range of 100 to 1000 N would allow reasonable orbit transfer times (~ 3 months), with mass ejection rates in the range of 4 to 40 g/sec at rail gun exit velocities of 25 km/sec. Required power levels are in the range of 5 to 30 MW(e) for a 50% efficient rail gun.

A RBR/recuperated Brayton cycle is examined. Turbine inlet temperatures of $\sim 2000^\circ\text{K}$ appear achievable with refractory metal blading, and heat rejection

* Work performed under the auspices of the U.S. Department of Energy, Washington, DC 20585.

† By acceptance of this article, the publisher and/or recipient acknowledge the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper.

Manuscript received January 23, 1981.

The authors are with Brookhaven National Laboratory, Upton, NY 11973 and BDM Corporation, McLean VA 22102, respectively.

temperatures of $\sim 700^\circ\text{K}$ can be accommodated with a light weight liquid tin drop radiator of the type proposed by Hartsberg. Power cycle efficiencies of $\sim 40\%$ and specific weights of ~ 0.5 to 2 kg/kW(e) (depending on power level) appear achievable for the RBR power source. The RBR/rail gun thruster system appears quite attractive in terms of weight, efficiency, and payload capability.

Electromagnetic guns with very high fire rates could destroy high value targets, at long range (10 km or more). Such systems could be deployed on airborne, high altitude weapons platforms or mobile ground units. The compact, high power, rapid start/stop capabilities of the RBR appear quite attractive for these guns.

An inert gas, closed-cycle RBR with intermediate heat exchange to air appears to be the most promising approach for airborne systems. The RBR would provide electric power to the EM guns through a light turbo-alternator (probably with superconducting windings) as well as direct propulsion for the airframe. Cruising time would be virtually unlimited since fuel would not be required.

The RBR could also power mobile ground or sea-based rapid-fire EM guns. At the required power levels, i.e., several hundred MW(e), MHD appears to be the only practical power conversion option, probably using a cryogenically stored working fluid (e.g., air, nitrogen, hydrogen, helium, or argon) which would be heated to high temperatures (2500° to 3000°K) by the RBR. A RBR-mobile EM gun unit would be able to operate for several hundred seconds of integrated firing time using stored oxygen.

Direct ground-to-space launch applications pose difficult problems of very large peak powers and very large integrated energy requirements. For example, launch of 1000 kg to 10 km/sec by a 4-km long accelerator requires peak input powers of 150,000 MW(e) and total input energy of 55 GJ (90% efficient accelerator). The energy could be drawn from a grid and stored prior to launch; however, grid limitations will dictate relatively long storage times ($\sim 1000 \text{ sec}$), which would require expensive and technically difficult large, fast discharge superconducting magnets. An alternate option is the use of the RBR to provide a relatively short pulse of power (e.g., 30 sec at 2000 MW(e)) which would be stored in low cost cryo-cooled normal metal windings, e.g., Al at 80°K . Dissipation is relatively small on these time scales with stored cryogen cooling, and the integrated input requirements of energy for refrigeration is comparable to those for launch.

DESCRIPTION OF THE RBR

Figure 1 shows an overall view of the RBR as developed for the original rocket propulsion application. Rotating Bed Reactors for electric power generation would be very similar, with the chief difference being that the hot outlet coolant would exhaust into a duct leading to a power conversion system using either MHD or turbine-generator.

The RBR was being developed as a second generation nuclear propulsion device to follow NERVA [1-3]. Development on the RBR was stopped in 1973 when the U.S. Space Nuclear Propulsion program was cancelled because there was no intention, at that time, for lifting large payloads into high orbit.

DISCLAIMER

The RBR has a number of important advantages over the first generation nuclear engines. The nuclear fuel is in the form of fine particulates (typically several hundred microns in diameter) contained inside a rotating porous cylinder or "frit" (Fig. 1). Gas is admitted through the frit at low temperature and then passes through the nuclear fuel and exits at high temperature through a small nozzle at one end of the reactor.

Fig. 1. Rotating fluidized bed rocket engine.

In NERVA-type reactors, the fuel is contained in relatively large fuel rods (typically on the order of centimeters in thickness) which are cooled by the flowing gas stream. The enormous heat transfer area associated with the RBR fine particulate fuel results in a much higher power density capability than reactors with relatively large fuel rods, such as NERVA. As a result, for any given power, the RBR is the most compact reactor possible and considerably smaller and lighter than the NERVA reactor. Size is set by neutron leakage and moderating conditions. The RBR is an externally-moderated reactor; neutrons are generated in the fissile fuel and travel outwardly into the external moderator/reflector and then diffuse back into the fuel region where they are captured. The minimum dimensions for a RBR are on the order of a meter in diameter and height. In this size, it can supply virtually any desired power level up to several thousand megawatts, using appropriate operating parameters, i.e., coolant pressure and effective β force on the rotating fuel bed.

The RBR has other important advantages besides very high power density, including:

1. Very high coolant outlet temperature,
2. excellent thermal shock resistance,
3. rapid start/stop capability,
4. all structural components at low temperature,
5. simple, precise power control, and
6. ability to operate with a wide variety of coolants.

Measurements of heat transfer coefficients in packed and fluidized beds have been carried out [6]. These indicate that even with high power RBR systems, on the order of 1000 MW(th), the local temperature difference between fuel particles and gas will be very small, on the order of 30°K. The gas coolant outlet temperature can thus approach the melting point of the fuel particles without concern about fuel slumping or agglomeration. With refractory carbide fuel, e.g., mixed UC-ZrC, it appears possible to operate at temperatures of at least 3000°K. (Higher temperatures may be possible since the melting point of ZrC is 2400°K. The projected outlet temperature for NERVA was 2400°K. For MHD power conversion systems and/or open power generation, the substantially higher outlet temperature achievable with the RBR is a great advantage. It results in much higher cycle efficiency, particularly with MHD power conversion, and considerably lighter radiators for space power systems, since higher temperatures can be used for waste heat rejection. (Radiator mass varies as T_r^{-4} , so that a few hundred °K higher rejection temperature can greatly reduce radiator weight.)

The small particle size, typically 200 to 300 μ in diameter, and the small temperature differences between gas and particles results in excellent thermal shock resistance. Temperature differentials — the particles are only a few °K, and rapid changes in reactor power or gas flow will not cause particle cracking or fragmentation.

As a result of this excellent thermal shock resistance and short thermal diffusion time for the small particles (~ 1 msec), it is possible to start and stop the reactor in very short times. In fact, the start/stop response will probably tend to be controlled by control rods and valve travel time. Reactors with relatively massive fuel elements, such as NERVA, must ramp up and down over relatively long times, e.g., a minute or more. The RBR, in contrast, will be able to start and stop in ~ 1 sec.

The design of the RBR is also unique in that all structural components are at low temperature (essentially inlet gas temperature). This includes the frit, reflector, control rods, bearings, etc. The only part of the reactor at high temperature is the rotating particulate fuel bed, which does not perform any structural function. As a result, materials demands are minimal and state-of-the-art materials appear very satisfactory.

Control of the RBR appears simple and precise. The external moderation feature of the RBR results in relatively long neutron lifetimes (e.g., an order of magnitude greater than current light water reactors) and high effectiveness for neutron absorbers in the moderator adjacent to the fuel region. This permits one to control large amounts of reactivity using simple rotatable drums. These would have a moderator on one side and a neutron absorber on the other. Reactivity would be precisely controlled by small angular adjustments of the control drum. For rapid starts, the control drum could insert a large reactivity increase in a few milliseconds and quickly cut back to steady power operation as the desired power level was reached. Rapid shutdown would be achieved by rotation of the poison sections to points adjacent to the fuel, again in a few milliseconds.

The RBR propulsion device was originally intended to operate using hydrogen coolant so as to achieve a high specific impulse, i.e., ~ 1000 sec. For electrical power generation applications, a wide range of coolants could be used, depending on mission requirements. For high pulse power, open-cycle applications in space,

hydrogen is probably still the best coolant choice because of weight considerations. For closed-cycle generation, either cv or pulsed, inert gas coolants like helium, neon, or argon are probably superior, since they would cause minimal long-term material problems with the nuclear fuel. Helium would probably be the best choice for MHD power cycles because its high sound speed would lead to relatively small MHD channels. Neon or argon would probably be preferable for turbine power cycles since it would minimize the size of the rotating equipment, i.e., the turbine and compressor.

For terrestrial applications, one could either directly use air as a coolant or use a closed-cycle system with inert gas coolant and heat rejection to the atmosphere. The choice will depend on the type of application. For long integrated power generation times where small amounts of fission product release is of concern, a closed-cycle approach would probably be optimum. For short integrated power generation times, e.g., a few hours, fission product release would be very small with open-cycle cooling. In these applications, air coolant would be used with suitable oxide refractory fuel particles, e.g., UO_2 coated with ZrO_2 .

An extensive series of experiments was carried out on a half-scale RBR (height = diameter = 25 cm) to test hydraulic behavior of the rotating fluidized bed. In these experiments, spherical beads (either glass or copper) simulated the nuclear fuel particles, with pressurized nitrogen gas ($p \sim 10$ atm) at room temperature used as the coolant.

Figure 2 shows the experimental facility. The rotating frit was inserted in a ribbed support (Fig. 3) which was driven by a V-belt-pulley arrangement. Nitrogen gas was delivered to the vessel holding the rotating frit through four supply lines (Fig. 3) at rates up to 300 cubic meters per minute. The nitrogen mass flow/unit area of the frit at peak gas flow rate was equal to the hydrogen mass flow rate ($p \sim 100$ atm) in the nuclear rocket application. Although this experiment did not fully duplicate the behavior of an actual RBR, particularly with respect to the action of a bed with a large temperature gradient, results should be generally applicable to the actual system.

Fig. 2. Rotating fluidized bed experimental facility. (7-315-71)

10-778-70

Fig. 3. Frit for rotating fluidized bed in support.

Pressure drop measurements across the settled and fluidized bed were taken as a function of gas flow rate, rotational speed, and particle size, for glass and copper beads. Figure 4 shows typical results for pressure drop as a function of gas flow rate. The solid line represents the analytical prediction of pressure drop through a settled bed. As shown in Fig. 4, the experimental and analytical predictions agree closely. As

Fig. 4. Pressure drop in rotating fluidized bed experiments (frit dimensions - height = diam = 25 cm).

gas flow rates increases, pressure drop through the settled bed increases until the bed fluidizes. After fluidization starts, pressure drop remains constant as gas flow increases. In effect, in a fluidized bed the gas pressure drop equals the effective weight (mass $\times$ g force) of the suspended particles. Fluidization is initiated at different gas flow rates, depending on the effective g force in the rotating bed, the density of the bed particles, and the thickness of the bed.

Strobe pictures and high-speed movies of the rotating bed were also taken using the arrangement shown in Fig. 5. A rotating mirror is used to focus on a

Fig. 5. Arrangement for high-speed still and movie pictures of rotating fluidized beds.

small arc of the bed. The bed sits on a transparent plexiglass bottom plate, with grid lines one-eighth inch apart.

Figure 6 shows the rotating fluidized bed with no gas flow. The bed is fully settled against the rotating frit. The curved inner surface of the settled bed is seen at the top of the picture. The surface is a smooth arc, as would be expected considering the high centripetal acceleration on the bed.

Figure 7 shows the same bed with a nitrogen flow rate of $170 \text{ m}^3/\text{sec}$. The bed is fluidized, with all particles separated by thin gas films. Motions of colored individual beads can be followed through the fluidized bed by means of high-speed movies. The particles appear to move throughout all parts of the fluidization zone, but the movements are gentle and do not appear to result in collisions that would damage or fragment the particles. In fact, the rotating bed was operated for relatively long periods, i.e., minutes, with no particle damage. The inner surface of the rotating bed remains smooth as if it were a single fluid.

Fig. 6. View of bed taken through bottom plate, series 4-1 500 μ glass, 2,000 rpm, 0 m^3/min .

Fig. 7. View of bed taken through bottom plate, series 4-3 500 μ glass, 2,000 rpm, 170 m^3/min .

Fig. 8. View of bed taken through bottom plate, series 3-4 500 μ glass, 1,000 rpm, 213 m^3/min .

If gas flow increases beyond some limiting rate, bubbling flow (Fig. 8) begins. Particle density in the bed becomes spatially and temporally nonuniform, and low density "bubbles" rise through the bed. As the bubbles burst through the inner surface of the bed, particles are thrown into looping orbits free of the bed. All particles eventually return to the bed, with none carried away by the flowing gas. However, the relatively high particle velocities in this flow regime imply that fragmentation or damage may occur when particles collide.

This flow regime can be readily avoided, however, by ensuring that g forces on the bed are sufficient for any desired flow rate. In practice, this corresponds to selecting a rotational speed for the frit that will give a stable, smooth fluidization at the given gas flow rate.

Extensive neutronic analyses were carried out on the RBR using one- and two-dimensional neutron diffusion codes. Figure 9 shows the geometry used for the two-dimensional neutron analyses. Effects of the nozzle and nonuniform moderator distribution are included.

Fig. 9. Two-dimensional reactor neutronics model.

Table I lists illustrative neutronic parameters for three RBR designs, two with ^{233}U fuel. A number of conclusions can be drawn with respect to RBR neutronic behavior:

1. Uranium-233 fuel is substantially superior to ^{235}U fuel because of its higher η value,
2. Uranium-235 reactors tend to be substantially larger and have higher critical masses,
3. Very small RBR beds tend to be undermoderated, resulting in considerably higher critical masses than larger beds,
4. Reflector thicknesses of ≥ 30 cm are desirable to minimize critical mass, and
5. An attractive design point is reached with ^{233}U fuel and 50 cm beds (height = diameter). Critical mass of this unit is only 48 kg, and uranium concentration in the ZrC particles is only 7.5 at.-%.

TABLE I
ILLUSTRATIVE RBR DESIGNS

	^{233}U Fuel		^{235}U Fuel
	A	B	
Bed internal diam, cm	24	50	63.5
Bed height, cm	44	56	63.5
Fuel bed thickness, cm	10	7.5	10.2
Reflector thickness, cm			
Radial	16	30	30
Axial	23	30	30
Throat diam, cm	11	18	18
Overall height, cm	94	116	123.5
Overall diam, cm	76	125	143.9
Critical mass, kg	140	48	156
Bed voidage, %	50	70	60
U concentration, at.-%	100	7.5	9.5
Chamber pressure, psia	750	1125	1125
H ₂ flow rate, kg/sec	7	20	20
Power, MW ($T=3000^\circ\text{K}$)	350	1000	1000
Reactor weight, kg	2500	3300	4750
(including pumps and pressure vessel)

Fig. 10. Spatial variation of the neutron flux in the Rotating Bed Reactor.

Figure 10 shows the spatial variation of neutron flux from the reflector, through the frit, and into the fuel bed, for a ^{233}U -fueled reactor. The variation is indicated for two neutron energies, 0.053 eV (near thermal), and 0.765 eV. Flux depression is less at higher neutron energies because of the smaller effective cross section. The steep flux gradient corresponds

to a steep radial power gradient through the fluidized bed, as shown in Fig. 11.

Fig. 11. Power distribution as a function of radial position within the bed of a ^{233}U -fueled RBR.

The peak-to-average radial power ratio is on the order of 5/1 for the case shown. High peak-to-average radial power ratios are accommodated in the RBR, since heat transfer is not limiting. The very large surface area in the fuel bed results in very small temperature differences between the particles and the gas, so that local heat rates much higher than the average value can be readily handled. This is particularly helped by the inherent feature that the high peak powers are on the outside of the bed where the gas is at the low inlet temperature conditions.

Axial peak-to-average ratios are of more concern than radial peak-to-average, since axial variations will correspond to locally differing exit temperatures as the gas leaves the inner surface of the rotating bed. This results from the condition that gas velocity is essentially uniform over the inner surface of the bed. As shown in Fig. 11, axial peak-to-average ratios of $\sim 1.5/1$ are calculated for the RBR design examined, with the lowest powers being in the center where the external reflector/moderator is less effective. The throat end has significantly lower power than the opposite end, because of neutron leakage through the nozzle. The axial peak-to-average ratio can be easily flattened by axially controlling the reflectivity and/or moderating power of the external moderator.

A range of RBR designs corresponding to different power levels have been examined and summarized in Table II. For the same size reactor, the power level can be measured by using higher coolant pressures and/or coolant temperatures. The highest power level shown is 6000 MW(th), which should be sufficient for virtually all applications. However, higher power levels are possible with a physically larger reactor if desired. Reactor weight is essentially independent of power level at ~ 3 MT until power levels where very high coolant pressures and flow rates are required. The pressure vessel and turbopumps tend to dominate in these cases. Cases 1 to 6 have total weights (reactor, nozzle, pressure vessel, and turbopumps) of ~ 3 MT, Cases 7 and 8, ~ 6 MT, and Cases 9 and 10, ~ 12 MT, even though reactor weight remains fixed at 2.3 MT.

RBR POWER GENERATION SYSTEMS

For EM gun applications, it is necessary to generate electric power using the hot gas coolant from the RBR. Various power generation modes are possible, as outlined in Table III, depending on application. For cw or long pulses, either turbines or MHD could be used with the edge going to MHD at high power levels, i.e., > 50 MW(e). For short applications, e.g., ~ 1 sec or less, pulsed flow MHD appears to be the only viable system.

Very short high power pulses, on the order of 1 msec, could be generated by periodically modulating the electrical conductivity of the flowing gas in the MHD generator. The gas would repetitively speed up, acquiring kinetic energy, and slow down as the high conductivity (i.e., high speed concentration) zone entered the MHD channel. Peak power levels of 10^{10} to 10^{11} W could be generated depending on design. Such a power generation system could be attractive for repetitive

TABLE II

SYSTEM PERFORMANCE FOR ^{233}U - AND ^{235}U -FUELED ENGINES

Case	Cavity pressure		Cavity temperature		Power MW	N (propellant flow rate)		Thrust lb x 10 ³	γ _{SP}		233U-fueled Thrust/weight		235U-fueled Thrust/weight		
	psia	MMH ²	°F	°C		lb/sec	kg/sec		sec	m/sec	lb/lb	N/kg	lb/lb	N/kg	
1	750	5.2	4,250	2,367	439	62.3	28.3	52	231	034.6	8,185	5.5	54	7.9	77
2	750	5.2	6,120	3,400	527	51.9	23.5	52	231	1,001.5	9,921	5.6	55	8.0	78
3	1,125	7.8	4,250	2,367	559	93.4	42.3	70	347	034.6	8,185	7.4	73	10.7	105
4	1,125	7.8	6,120	3,400	790	77.5	35.3	70	347	1,001.5	9,921	7.5	74	10.9	107
5	1,500	10.3	4,250	2,367	878	124.6	56.5	104	463	034.6	8,185	10.7	85	12.7	126
6	1,500	10.3	6,120	3,400	1053	103.0	47.1	104	463	1,001.5	9,921	0.9	07	11.1	120
7	3,000	20.7	4,250	2,367	1757	249.2	112.9	200	925	034.6	8,185	11.6	114	15.6	153
8	3,000	20.7	6,120	3,400	2106	207.5	94.7	208	925	1,001.5	9,921	12.1	119	16.5	162
9	6,000	41.4	4,250	2,367	3513	488.3	226.0	416	1,850	034.6	8,185	12.5	123	15.6	153
10	6,000	41.4	6,120	3,400	4211	415.3	186.4	416	1,850	1,001.5	9,921	12.4	121	17.0	167

TABLE III

RBR POWER GENERATION MODES

Continuous wave or long pulse electrical generation

Turbine (~ 1 to 50 MW(e))
MHD (~ 10 to 1000 MW(e))Short Pulse (≤ 1 sec)

Pulsed gas flow MHD (several thousand MW(e))

Very short pulse (≤ 1 msec)Modulated conductivity MHD (~ 100 GW(e))

fire EM guns since a great deal of the power conditioning equipment could be eliminated.

Table IV compares overall features of various RBR/MHD power systems for space power generation. High

TABLE IV

RBR/MHD SPACE POWER SOURCES

Pulsed power (~ 100 to 1000 MW(e))

Open cycle

 H_2 cooled
Pulse duration > 0.5 sec
Specific power ~ 30 kW(e)/kg
Fuel consumption $\sim 10^{-4}$ kW(e)/kg/sec

Closed cycle

He cooled
Pulse duration $0.5 < t < 10$ sec
Duty cycle $\sim 10\%$
Specific power ~ 10 to 20 kW(e)/kg
Fuel consumption zero for radiative heat rejection
 $\sim 10^5$ kW(e)/kg/sec for Li boil offContinuous wave Power (~ 10 to 30 MW(e))Closed Brayton cycle (MHD generator/turbo-compressor)
He cooled
Radiative heat rejection at $\sim 1000^\circ K$
Specific power ~ 1 kW(e)/kg

power levels could be handled either by open-cycle or a pulsed closed-cycle system with the choice being determined by the total integrated power demand. Typically, for integrated generation times of a thousand seconds or more at full power, closed-cycle, appears preferable. Relatively short pulses of power, i.e., a few seconds, could be generated without excessive radiator weights, since a thermal ballast could smooth out the heat rejection over a much longer period. Duty cycles of up to $\sim 10\%$ appear feasible at peak power levels of several hundred MW(e). Heat can be rejected either by a radiator (true closed-cycle) or lithium evaporation. The latter approach is akin to the open-cycle, but the mass regulation requirements are much smaller than a pure open-cycle, even with hydrogen coolant.

Continuous wave operation at power levels up to ~ 30 MW(e) appears practical using a closed Brayton cycle with a MHD generator. Specific powers of ~ 1 kW(e)/kg total system mass and heat rejection at $\sim 1000^\circ K$ can be achieved.

Table V lists the principle characteristics of a 1000 MW(th) baseline RBR reactor that could power a MHD generator. Table VI compares the electric power output capability from this baseline reactor with that from a high power version (basically the same reactor operating at higher pressure). In the cv long pulse system, gas flow rate through the MHD generator equals that through the reactor while in the enhanced pulse systems, but gas from the reactor is stored in a small chamber between the reactor and the MHD generator. The stored gas is then released in a short burst to produce the

TABLE V

MHD GENERATOR/RBR SYSTEM PARAMETERS
(BASELINE DESIGN)

Parameters	MHD Generator
Reactor power, MW(th)	1000
Coolant	H_2
Exit gas temperature, $^\circ K$	3000
Gas flow rate, kg/sec	20
Fuel composition	UC-2rC
Uranium concentration, %	7.5
Critical mass, kg ^{235}U	48
Inner diameter of bed, cm	50
Height of bed, cm	56
Rotational speed, rpm (100 μ)	3200
(400 μ)	780
Frit thickness (inc. support ribs), cm	3
Reflector material	Be
Reflector thickness, cm	30.5
Overall diam (inc. pressure vessel), cm	135
Overall height (inc. pressure vessel), cm	165
Reactor weight (inc. pumps, pressure vessel, etc.), kg	3300
Cavity pressure, mpa	7.8 (1100)

TABLE VI

MHD GENERATOR/RBR SYSTEM PARAMETERS
(OPEN-CYCLE)

PARAMETER	BASELINE REACTOR		HIGH POWER REACTOR	
	CV OR LONG PULSE	ENHANCED PULSE	CV OR LONG PULSE	ENHANCED PULSE
REACTOR POWER, MW(th)	1000	1000	4000	4000
ELECTRIC OUTPUT POWER, MW(e)	300	1500	1200	4000
PULSE LENGTH, sec	CV OR LONG PULSE	0.5	CV OR LONG PULSE	0.5
COOLANT	H_2			
REACTOR COOLANT FLOW RATE, kg/sec	20	10	80	80
CHANNEL MEAN DIAM., m	0.62	1.4	1.25	2.6
CHANNEL LENGTH, m	3			
CHANNEL AREA, m ²	0.31	1.36	1.24	6.16
VELOCITY OF FLUID & CHANNEL, kg/sec	3000	10000	6000	> 10000
REACTOR WEIGHT, kg	3300	1300	6000	4000
NET GAS STORAGE VOLUME, m ³ (BETWEEN RBR AND MHD CHANNELS)	—	75	—	100
MAGNETIC FIELD IN CHANNEL, Tesla	6			

* ONE-HALF OF TOTAL CHANNEL LENGTH (FLOW ENTERS AT CENTER)

** WEIGHT INCLUDES TWO CHANNELS, MAGNET WEEDERS AND SUPPORT STRUCTURE

enhanced pulse. This can be accomplished with a valve, or more likely, by modulating the conductivity of the MHD channel flow. High seed concentrations would brake MHD flow, permitting a buildup of gas pressure ahead of the generator. A sudden decrease in seed injection rate would then allow gas to flow at a much more rapid rate through the MHD generator to generate the enhanced pulse.

Though these RBR/MHD power systems were examined for space power applications, similar systems could be used for terrestrial-based power generation. Since heat sinks are readily available, either atmospheric or water, the RBR/MHD system is substantially simpler.

Terrestrial RBR/MHD systems could be deployed on high altitude weapons platforms, mobile ground-based units, or ships. The ground- or ship-based systems could use stored coolant (probably cryogenic air) for open-cycle pulse power generation. Air-based systems would have to dump heat to the atmosphere at high altitudes, which probably would require a closed-cycle RBR with an intermediate heat exchanger.

For ground- or ship-based RBR/MHD systems, peak powers up to ~1000 MW(e) appear feasible using either enhanced pulse or high power RBR's. Even higher levels could be achieved by combining the two approaches. Air-based RBR/MHD systems would have to operate at substantially lower power levels because of the heat rejection requirements, i.e., down to 100 to 200 MW(e) peak power.

As discussed later, these power levels appear appropriate for rapid fire EM guns or direct ground-to-space launch applications. In terms of EM thrusters for space propulsion, smaller closed-cycle cw power systems appear appropriate, on the order of 10 MW(e).

Figure 12 illustrates a 15-MW(e) closed cycle RBR/MHD system suitable for space electric propulsion.

Fig. 12. 15 MW(e) RBR/MHD space power system.

with system weights given in Table VII. Table VIII lists the operating parameters and system weights for a 15-MW(e) closed-cycle RBR/turbogenerator system. Comparison shows that the turbine system is substantially lighter (11.3 MT vs 17.8 tons), higher thermal efficiency (29 vs 20.52), and lower outlet reactor temperature (2000° vs 3000°K). Turbine inlet temperatures of 2000°K appear feasible using refractory metal blading, e.g., TZM or tungsten rhenium. The RBR/turbine system

TABLE VII

COMPONENT WEIGHTS FOR A 15 MW(e) SPACE-BASED CW RBR/MHD POWER SYSTEM

Power Components*	Weight, MT
RBR (reactor, nozzle, preformed vessel, controls)	3.3
partial shield	2.0
MHD channel	1.0
MHD magnet (Al-stabilized and reinforcing structure)	2.0
Piping	1.0
Compressor	1.0
Miscellaneous (refrigerator, system controls, etc.)	1.0
Subtotal	11.3
Heat Rejection Components**	
A section radiator (900°K)	4.6
B section radiator (2300° to 900°K)	0.9
Total	17.8

* Power component weights almost constant with power output.

** Weight of heat rejection components linearly proportional to power output. Numerical values derived from R. Swift (~0.2 kg/nW(th) (T/1000)⁴)

TABLE VIII

CHARACTERISTICS OF AN RBR/TURBINE POWER SOURCE FOR OUTER SPACE

Cycle.....	Brayton-closed, with 3-stage comp. and intercooling
Output power.....	15 MW(e)-cw
Electrical conversion efficiency.....	29%
Reactor outlet temperature.....	2000°K
Turbine inlet temperature.....	2000°K
Compressor inlet temperature.....	1000°K
Working fluid.....	Argon
Pressure ratio.....	2.5
Turbine, compressor efficiency.....	0.9
Intercooler effectiveness.....	0.8
Minimum radiator temperature.....	1000°K

COMPONENT WEIGHTS FOR A 15-MW(e) BRAYTON CYCLE RBR WITH INTERCOOLING

Reactor.....	3000 kg
Turbine and compressor.....	1500
Radiators.....	5280
Piping.....	500
Structure.....	1000

thus appears to be a better system for space EM thrust- or applications.

EM GUN AND LAUNCHER APPLICATIONS OF THE RBR

A variety of EM gun and launcher applications based on RBR power sources appear possible. Some of the general applications are given in Table IX, with space propulsion applications listed in more detail in Table X.

If space power beaming by sub-millimeter waves or lasers is developed, a small number of RBR generating

TABLE IX

EM GUN AND LAUNCHER MISSIONS USING RBR POWER SOURCES

EM rail gun thruster for space propulsion

LEO to GEO transfer
Deep space missions

Rapid fire EM guns for point and area defense

Ground-to-space direct launch

TABLE X

RBR/EM THRUSTER SPACE APPLICATIONS

Power beaming from RBR source to multiple EM thrusters

Interorbital tug

Integral RBR/EM thruster

Interorbital tug

Payload to high earth orbit (1 way)
Crew shuttle (2 ways)

Payload and RBR source to high earth orbit

Manned platforms
Space weapons systems

Deep space propulsion

Unmanned large payloads (Jupiter explorer, Mars
lander-returner)
Manned missions

platforms could power a large number of interorbital EM tugs. The power receiving and conditioning equipment appears quite small and light for the wavelengths and distances that would be used. Such a system would permit large volume traffic between low- and high-earth orbits.

Without power beaming, RBR/EM thruster units would be required. For some applications, the RBR could be used at destination as the prime power source (e.g., manned orbiting platforms or space weapons systems), so that it would serve double duty as a propulsion and end-use power source.

Illustrative performance of an integral RBR/EM thruster system for LEO to GEO transfer missions is shown in Table XI, as a function of power generation level and payload (the RBR and EM thruster are included in the payload, with their fraction of the total payload as indicated). The specific impulse of the rail gun thruster is taken at 1500 sec (15 km/sec projectile velocity). The RBR power supply, shield, and radiator specific weight values (listed in Table XII) were estimated as a function of power level from several point designs in the range covered. The EM thruster weight was based on a rough estimate of rail gun performance (50% efficient). A 20-MW(e) plant, for example would have a total weight for the rail gun, power conditioning, and radiator (rail gun only) of 10 MT.

For payloads on the order of 100 tons, the RBR output should be about 5 MW(e), with orbit transfer times on the order of a couple of weeks. The RBR/EM thruster weight makes up ~13% of the total payload. Higher power levels result in shorter trip times, but

TABLE XI

RBR/EM THRUSTER PERFORMANCE FOR LEO TO GEO
TRANSFER MISSION

RBR Generation, MW(e)	Payload, metric tons		
	100	1,000	10,000
5 MW(e)			
Trip time, days	11	106	1060
RBR + EM weight (fraction of payload)	0.3	0.01	0.001
20 MW(e)			
Trip time, days	2.6	27	270
RBR + EM weight (fraction of payload)	0.30	0.03	0.001
80 MW(e)			
Trip time, days	--	6.7	67
RBR + EM weight (fraction of payload)	--	0.08	0.008

TABLE XII

RBR/EM THRUSTER PERFORMANCE FOR LEO TO GEO
TRANSFER MISSIONS

Basis:

EM thruster + power conditioning = 50% efficient

EM thruster + power conditioning
+ radiator for reject heat = 0.5 kg/kW(e) (independent of total power)RBR power supply + shield
+ radiator = 2.0 kg/kW(e),
5 MW(e)= 1.0 kg/kW(e),
20 MW(e)
= 0.5 kg/kW(e),
80 MW(e)

EM thruster specific impulse = 1500 sec

the power system becomes too large a fraction of payload weight.

For higher payloads, larger and proportionately lighter RBR/thrusters can be used. For 1000-ton payloads, a 20-MW(e) RBR appears near optimum, with a transfer time of ~1 month and a fractional weight of 0.03.

Higher payloads are probably unlikely unless space power satellites are under construction. A power level of ~80 MW(e) would appear appropriate for payloads in this range, with transfer times of ~2 months and a fractional weight of ~0.01.

Even at relatively high power levels, the mass flow of pellets is relatively small, e.g., 140 g/sec at 20 MW(e), and this could be readily handled by a small number of rail guns or mass drivers.

At the desired pellet velocity, ~15 km/sec, pellets will not remain in stable orbits and do not appear to pose any hazard for other spacecraft. Principle concerns in developing the EM thruster appear to be the need for high velocity if the system is to offer a significant advantage over competing propulsion methods.

and the need to have an efficient EM accelerator to minimize waste heat rejection problems.

For rapid fire EM guns, the RBR can provide the high power that would be required. As an example of the power requirement, a ground-based EM gun firing 100-g projectiles at a rate of 300/sec and a velocity of 3 km/sec would require a power input to the gun of 300 MW(e) (30% efficient EM gun), with likely firing times of several seconds for point defense. The RBR/MHD system could turn on in approximately a second, provide the needed power for whatever firing period was necessary, and then shutdown in less than a second.

For direct ground-to-space launch, the RBR could provide the energy for short-term storage prior to launch. Payloads of 1 MT at 10 km/sec would require 50 GJ of kinetic energy or 60 GJ of stored energy for the launcher (~80% efficient).

This energy could be supplied from the grid over a long period, e.g., 10 min at 60 MW(e) (very high pulse power from the grid would probably not be possible). However, storage for long periods would require either superconducting magnet energy storage or many rotating mechanical devices.

Storage in cryogenic coils (e.g., aluminum at 80°K) is an attractive, considerably cheaper storage option since cheap aluminum coils could be used with reinforcement by natural or rock structures. Air could be liquified for short-term cooling during the storage period. For short period storage, e.g., tens of seconds, the energy for cryogenic cooling is comparable to the delivered energy. A pulsed RBR delivering ~2000 MW(e) for 30 sec could energize a cryogenic storage coil, which would then discharge to a launcher in ~0.5 sec. The RBR would use the evaporating cryogen as the coolant, heating it to ~2500°K before entering a MHD channel.

SUMMARY

The RBR power system appears to be an attractive power source for a variety of applications, including those involving high power inputs to EM guns. The RBR can deliver high pulsed or cw powers up to levels on the order of 1000 MW(e). It can be turned on and off very rapidly, in a second or less. The RBR can be coupled to MHD or turbine power conversion systems with the choice being determined by the required power level and operating time. The RBR is very compact, on the order of 1 m³ in volume and lightweight, on the order of 3 MT. It appears uniquely suited for missions in space requiring very high or long-life power delivery, as well as ground-based missions where mobility and/or very high power levels are required.

REFERENCES

- [1] H. Ludwig, A.J. Manning, and C. Raseman, Feasibility of Rotating Bed Reactor for Rocket Propulsion, J. of Spacecraft and Rockets, 11, 65-71, 1974.
 - [2] K.C. Hoffman, et al., Rotating Bed Reactor for Space Nuclear Propulsion: Annual Report, July 1972-January 1973, 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, Informal Report, BNL 27460, 1980.
 - [4] G. C. Lindauer, Heat Transfer in Packed and Fluidized Beds by the Method of Cyclic Temperature Variations, American Institute of Chemical Engineers Journal, v. 13, p. 1181, 1967.
- 10 2. 11