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THE FBR AND RBR PARTICLE BED SPACE REACTORS

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ABSTRACT

Compact, high-performance nuclear reactor designs based on High-Temperature Gas Reactors (HTGRs) particulate fuel are investigated. The large surface area available with the small diameter (~500 microns) particulate fuel allows very high power densities (MW's/liter), small temperature differences between fuel and coolant (~10 K), high coolant outlet temperatures (1500 to 3000 K, depending on design), and fast reactor startup (~2 to 3 seconds). Two reactor concepts are developed - the Fixed Bed Reactor (FBR), where the fuel particles are packed into a thin annular bed between two porous cylindrical drums, and the Rotating Bed Reactor (RBR), where the fuel particles are held inside a cold rotating (typically ~500 rpm) porous cylindrical drum. The FBR can operate steady-state in the closed-cycle He-cooled mode or in the open-cycle H_2-cooled mode. The RBR will operate only in the open-cycle H_2-cooled mode.

INTRODUCTION

Future activity in space will require major advances in power and propulsion. High-performance space reactor systems are being investigated at Brookhaven National Laboratory (BNL) based on the small diameter particulate fuel developed for HTGRs.

At higher power levels, outputs of tens to hundreds of MW would power pulsed energy devices or provide direct thrust for orbit raising. These will probably be open-cycle reactors with high-temperature H_2 coolant and short operating lifetimes (minutes to hours). Heat will be rejected by exhausting coolant to space. Open-cycle chemical systems (H_2/O_2 with turbines or MHD) are another option. In comparing these two competing technologies one must be mindful that chemical systems store most of their cryogens at higher temperatures and apparently offer less complexity while requiring up to three to four times the mass of stored cryogens required for a similar nuclear program.

Reactors can generate intermediate powers for electric thrusters or advanced energy systems in a relatively long-term, closed-cycle mode. At the required power levels, light-weight radiators will be necessary. An attractive light-weight Liquid Droplet Radiator (LDR) has been proposed.(1) In this concept, reject heat radiates from a sheet of small diameter liquid drops (e.g., 100 micron lithium drops). The sheet is sprayed from a set of nozzles toward a collector. Collected liquid is reheated and recycled to the spray generator. The LDR has the potential to be lighter and more stowable than conventional fin and tube or heat pipe radiators. If it can be developed, heat rejection up to tens of MW may be practical.

The compact reactor concepts under development at BNL may be used from the low power (hundreds of kW) to high power (hundreds of MW) ends of the spectrum, in either open- or closed-cycle mode. The high-power density and high-temperature capability of particulate fuel results in high-performance systems.

PARTICULATE FUELED REACTOR CONCEPTS

BNL compact reactor concepts are based on small diameter (~500 μ) particulate fuel that has been developed and used in high-temperature, gas-cooled reactors in the US and abroad (e.g., the US-HTGR, German-HTR, etc.).

Particulate fuel has been chosen as it appears to be especially well suited to the requirements of space reactors: the fuel technology is well characterized; operation at fuel temperatures up to 1500 K has been demonstrated; operation in helium, closed cycle, to over 2000 K and in hydrogen, open cycle, to nearly 3000 K is projected; very high power densities (up to 10 MWth/l) are considered to be feasible for particle beds; fuel to coolant temperature differences on the order of 10 K are predicted; small particles are highly resistant to thermal shock, allowing fast starts and stops; and excellent fission product retention and very high burnup have been demonstrated in a reactor environment at 1500 K.

Figure 1 shows the BISO and TRISO fuel particles developed by General Atomics for the HTGR.(2) BISO particles have a coating of pyrographite over a kernel of fissile or fertile material and are suitable for low burnups, where the internal pressure of gaseous fission products is small. (Gaseous fission products are held in the inner porous, low-density layer.) BISO ThO_2 particles are used in the HTGR for in situ breeding of fissile ^{233}U.

TRISO particles have a multi-layered structure and achieve high burnups (>50%) at high internal pressures of gaseous fission products. They have a fissile kernel of $^{235}UO_2$ or $^{235}UC_2$ (or mixed oxycarbides), with a porous low-density pyrocarbon layer. The SiC layer mechanically contains high internal fission gas pressures.

Commercially available HTGR fuel, or particulate fuel with a greater heavy metal loading, is suitable for the closed-cycle reactors considered in this study. Open-cycle reactors will require a modified coating (eg., ZrC instead of pyrographite) in order to prevent attack by H_2 coolant.

The small diameter of the fuel particulates makes the internal heat transfer area per unit volume in a particle bed of fuel very large. A packed bed of 500 μ particles, i.e., has an internal surface area of 100 cm^2/cm^3 of bed. This allows very high power densities and small ΔT's between coolant and fuel. The small particle diameter also minimizes thermal stress and thermal shock.

Two types of particle bed reactors are being investigated at BNL. In the first, the FBR, particles are packed between two porous screens or "frits," as shown in Fig. 2. The "frits" can be metallic or ceramic. Pressure drop through the frits is generally designed to be comparable to that through the particle bed. Frits can be fabricated by sintering wires or particles into appropriate shapes. Gaseous coolant (i.e., He or H_2) enters through the cool inlet frit, passes through the bed, and exits through the hot outlet frit. The packed fuel bed is typically several centimeters in thickness. Bed thickness is determined by fuel loading, pressure drop, and heat transfer requirement. Particles in the FBR are held in place and cannot move.

In the second type of particle bed reactor, the RBR, fuel particles are held by centrifugal force inside a rotating cylindrical metal frit (Fig. 3). Cold gas enters through the cool frit and is heated as it passes through the fuel bed. There is no hot outlet frit; the hot gas enters the internal cylindrical cavity and exhausts through a nozzle at its end.

The rotating bed can operate in either of three modes: 1) fully settled (all particles held against the rotating frit), 2) fully fluidized (all particles suspended by gas flow), and 3) partly-fluidized. In the latter mode, gas velocity in the cool outer bed is insufficient for fluidization. At some point, coolant velocity increases sufficiently due to increasing specific volume to fluidize the hot inner bed.

Fuel particles are to be fully contained in all three modes. The fluidized region acts like a dense fluid, with gas passing between the suspended particles. Calculations indicate that particles cannot escape unless the bed expands to more than ~80% voidage. Operating parameters can be chosen to prevent such "flooding." For any given design (flow rate, reactor size, etc.), rotation speed controls the degree of fluidization. As rotation is decreased, the bed changes from the fully-settled to the partly-fluidized mode and then to the fully-fluidized mode. These operating modes have been experimentally demonstrated in a half-scale unheated demonstration experiment.

Because RBRs have no high-temperature frit and lower pressure drops than FBRs, their outlet temperature and power can considerably exceed those of FBRs. Figure 4 compares pressure drop in FBR and RBR beds as a function of average bed power density (in megawatts per liter) for a set of typical operating conditions [pressure = 100 atm, particle diameter = 500 μ, bed thickness = 4 cm].

Closed-cycle, long-duration FBRs would use inert coolant (e.g., He or He-Xe) at relatively low temperatures (1300 to 1500 K), because of limitations on inlet temperatures for long-life turbines. Open-cycle FBRs would use H_2 to minimize the coolant mass dumped to space. Short operating life (minutes to hours) associated with open cycle operation allows higher outlet temperatures in the range of 1500 to 2500 K. Outlet temperature is determined by the materials used in the inner frit as well as turbine blades. Open-cycle RBRs have higher outlet temperatures (up to ~3000 K) because they do not require a high-temperature frit. They could provide direct propulsion or electric power using MHD generators or high-temperature turbines.

The large heat transfer area in the bed allows the coolant temperature to nearly approach local fuel temperatures. Film ΔT is only a few degrees Kelvin, even at very high power densities. The ΔT inside the fuel particles (center to the surface) is even smaller, about 1 K. Thermal stress in the particles is very low, less than one MPa. Thermal diffusion time is across the particle is ~5 ms for 500 μ particles. This is much shorter than the ramp time for power or coolant flow changes. Thermal shock or fatigue damage to the particles appears unlikely.

Particle beds may be expected to survive a ramp from zero to full power in a few seconds. Experiments have demonstrated that electrically heated beds can reach full power in times on the order of 2 sec. The bed was cycled repeatedly with no apparent damage to the particles. In contrast, power ramp rate with rod or plate fuel elements is limited because of thermal shock problems.

Two possible FBR fuel bed configurations have been considered. In the first type (Fig. 2), the particles are packed between two annular cylindrical frits to form a single bed. Coolant flows radially through the annular bed from an adjacent inlet plenum to an outlet plenum. In the second type (not shown), the particles are packed into a number of small annular fuel elements between two frits. These elements are spaced in a moderator matrix and held by a grid plate. Coolant flows radially through each element.

The first type of FBR is simpler, while the second type can achieve higher power densities and use hydrogenous moderators such as ZrH_2. (The first type will not go critical with hydrogenous moderators.) The first type of FBR (Fig. 5) has been designed to operate up to ~1000 MW(th) with H_2 coolant and ~300 MW(th) with He coolant. Reactor size depends on power level and operating lifetime. Minimum fuel bed diameter is about 30 cm, from neutronic considerations.

FBR's with fuel bed diameter up to 80 cm, have been designed. At this size, energy outputs of 50 to 100 MW(th) years appear achievable, depending on fuel burnup capability. Larger diameters are possible, but a more efficient packing configurations would probably be used if higher powers and/or longer lifetimes are desired. Thickness of the annular fuel bed depends on reactor diameter and ranges from ~3 to ~8 cm

The moderator/reflector zones in the first type of FBR (Fig. 2) slow down fission neutrons and reflects them back into the fuel to be absorbed. Beryllium appears to be the best outer moderator/reflector. The reflector thickness should be ~25 to 30 cm. Thicker reflectors may perform slightly better neutronically, while thinner reflectors leak too many neutrons. Graphite is an acceptable internal moderator/reflector and is compatible with the high temperature helium or helium/xenon.

The FBR is designed to be controlled by movable absorbing drums in the external moderator/reflector. Control drums (Fig. 2) have a neutron absorber (e.g., B_4C) on one side and a moderator on the other. Rotation of the drum moves the poison towards the fuel decreasing k_{eff}, while movement away increases it.

Reactivity control by absorption in externally moderated reactors is very effective, due to the high neutron importance. Also, externally moderated reactors have long neutron lifetimes. This makes them neutronically "sluggish," so that even very large reactivity insertions cause only a relatively slow rate of power rise. Both factors tend to make them appear easy to operate remotely or via computer, especially during rapid start up.

Scoping studies of FBR neutronics have been carried out with the 1-D ANISN transport code. A 15-group structure was used (7 thermal groups), with collapsed cross sections derived from the ENDF-B-V file and a P_1S_8 scattering kernel. End effects could not be calculated with analyses, but were calibrated by carrying out some 2-D transport analyses using DOT (with the same cross section set). End effects reduced k_{eff} by 0.09 to 0.10.

Over 100 FBR cases were examined, evaluating the effects of the following variables: 1) uranium loading, 2) reflector thickness, 3) fuel bed diameter, 4) frit composition and thickness, 5) control drum composition and design, and 6) reflector temperature. Detailed discussion of the neutronics analyses are given elsewhere.(3) In summary, enriched ^{235}U appears to be a very satisfactory fuel, with critical masses in the range of 10 to 80 kg depending on design, power, and lifetime. Beryllium appears to be the best outer reflector/moderator, with optimum thickness in the range of 20 to 30 cm. Graphite and ZrD_2 also appear to be workable outer reflector/moderator materials, though the reactor will be substantially larger and heavier. Frit absorption was found to be an important design factor, limiting the composition of the frit and its thickness. Zirconium frits appear desirable for the cool outer frit, and Inconel (or Hastelloy) for the hot inner frit. Preliminary studies indicate that reflector control will provide more than adequate control rod worth.

Thermal-hydraulics performance of the FBR can be predicted using correlations for pressure drop and heat transfer coefficient in packed beds. For pressure drop in packed beds, the correlation of Ergun (3) is used. Pressure drop across the frits is typically taken to be 40% of the total pressure drop across the bed and frits. This pressure drop is chosen in order to keep gas flow uniform even if local bed voidage varies. Frit thickness and porosity can be adjusted to compensate for axial power variations.

The thermal-hydraulic behavior of FBR's have been examined for a large number of cases as a function of: 1) fuel bed diameter and thickness, 2) inlet and outlet temperature, 3) power level, 4) fuel particle diameter, and 5) inlet pressure.

Table 1 compares thermal hydraulic parameters for three representative point designs. Case 3 has the same fuel bed diameter as Case 2, (75 cm), but a higher power (250 vs. 100 MW) and lower pressure drop (25 vs. 36 psi). The higher power and lower pressure drop in Case 3 is achieved with split flow. The fuel bed is radially split into two parts, with the inlet plenum between the outer and inner halves. Coolant flows radially through each half to adjacent outlet plenums. Coolant flows in from and out of both ends of the reactor. The shorter flow path and reduced mass flow through each half greatly increases power output for the split flow design. Coolant ducting is more complex.

Maximum power for He-cooled FBRs is about 300 MW(th). A single reactor could be designed to generate up to ~100 MW(e) in a closed-cycle cw power system. At this power level, operating lifetime would be relatively short, i.e., about six months. It appears possible, in principle, to remotely refuel the FBR with the particulate fuel in order that operating life could be extended to much longer times. However, it appears likely that continuous power outputs at this level may not be required for decades. Near-term needs are more likely to be in the range up to 10 MW(e) for the next twenty to thirty years.

Scaling of FBRs has been examined from two perspectives: firstly, the relationships between size and mass with power; and secondly, the possibility of providing power over a wide range of powers with a minimum number of reactor designs.

Assuming the first perspective, Fig. 6 shows reactor weight scaling as a function of power. Conditions were taken to be an FBR with the following characteristics - gas pressure of 100 atm, fuel particle diameter of 500 μ, fuel bed thickness 6 cm, a ΔT across the core of 800°C (He) and 2000°C (H_2), and a pressure drop (bed plus frits) of 3 atm. While these conditions are not truly optimum, they are reasonably representative.

Based on the second perspective, the entire power range could be handled by two FBR sizes without departing too far from the base case size and weight represented by Fig. 5: 1) a 50-cm-diameter fuel bed for lower powers, and 2) a 80-cm-diameter fuel bed for the higher powers.

The boundary between low and high power modes of operation appears to be about 50 to 100 MW(th) for He-cooled reactors, and about 200 to 400 MW(th) for H_2-cooled reactors. The reactor will be somewhat larger than optimum at the low end of its power range, and somewhat smaller than optimum at the high end. There appear to be no major penalties to using two FBR designs to cover the expected power range.

Detailed neutronic, thermal-hydraulic, and mechanical analyses of the RBR, shown in Fig. 3, have been carried out at a level comparable to that for the FBR. Space limitations prevent detailed discussion of the results, which are described elsewhere.(4)

In summary, the RBR is neutronically similar to the FBR, except that its uranium loading is a factor of about two greater at equivalent k_{eff}. This is a result of not having an internal reflector. The mobile fuel bed does not appear to cause any safety problems since fuel motions have only minor (<1% Δk) effects on reactivity. Thermal-hydraulics of the RBR are much more complex than the FBR. Power outputs for the RBR are much higher than the FBR for the same reactor size and pressure drop. Power levels of several gigawatts can be achieved with RBRs about 1 m in diameter. RBRs are more complex mechanically than FBRs due to the need for bearings and labyinth seals. However, the RBR appears to be constructable withr undue difficulty.

POWER SYSTEM PERFORMANCE

The characteristics and performance of space electric systems using FBRs and RBRs have been investigated. For the RBR, open-cycle, turbine expanders and MHD cycles were considered; for the FBR, both closed- and open-cycle turbine cycles were examined. The size, weight, and layout of the various components making up a complete power system were estimated as a function of power, operating time (for open cycle), coolant temperature, (both inlet and outlet), generator efficiency, etc. These components were then integrated into self-consistent designs.

Initially, MHD was viewed as the most promising route for high-power, open-cycle operation. This assessment is now seriously questioned. Outlet temperatures of at least 2750 K are needed to operate a H_2 MHD generator. At this temperature, although MHD generators are feasible, performance is poor. Higher temperatures, e.g., 3000 K, result in more practical generators, but efficiency is still only about 20% (H_2 coolant enthalpy converted to electricity). This efficiency makes H_2 mass throughput very high and greatly increases H_2 storage requirements.

Turbines with H_2-cooled blading were operated successfully by General Electric Co. (GE) in the early 1960's at turbine inlet gas temperatures of ~2500 K. Metal blade temperatures were only about 700 K. Under these conditions, it might be anticipated that the turbine could extract 45 to 50% of the H_2 enthalpy. Thus, although turbines would operate at lower reactor outlet temperatures, turbines can generate twice as much electrical energy per kg of H_2 coolant as MHD generators. Advanced turbines using high-temperature ceramic or carbon-carbon blading are also potential options for high-power, high-efficiency open-cycle systems. The relatively short operating lifetime requirement for these systems will permit the use of blade materials not practical for commercial turbines.

Light-weight turbines and generators are being developed for airborne applications. A preliminary version of a 20-MW(e) superconducting generator has been tested by GE and the Aero-Propulsion Laboratory (APL). This device weighs about one metric ton. Single units can be scaled to higher powers, possibly about 50 MW(e). Multiple generators could be used for powers above 50 MW(e). Small generators, i.e., up to a few MW(e) in output, would use Sm-Co permanent magnets for field excitation. A 5-MW(e) permanent magnet generator is under construction for APL. Scaling relations for turbines, compressors, and generators for this study were based on work by APL, Rocketdyne, and Garrett.

Closed-cycle, Brayton-cycle designs using He-cooled FBRs were developed for a range of cw powers from 100 kW(e) to 100 MW(e). Both regenerative and non-regenerative cycles were investigated.

Figure 6 shows the main component weights for He-cooled, closed-cycle FBRs as a function of output power. Lithium LDRs would be used for heat rejection. LDRs are projected to be nearly an order of magnitude lighter than conventional fin-tube or heat pipe radiators. Even with LDRs, however, the radiator is still the heaviest part of the unshielded system. With LDRs, it appears feasible to construct closed-cycle power systems rated up to several tens of MW(e). If conventional radiators have to be used, weight limitations will restrict power levels to a few MW(e).

Figure 7 illustrates the trade-offs between closed- and open-cycle power systems using FBR reactors. The breakeven point is the operating time for which open- and closed-cycle systems have equal mass (including the stored H_2 and tankage in open-cycle systems). The breakeven point appears to be about 6000 sec and is relatively independent of system power output. For times less than 6000 sec, open-cycle systems are lighter; for times greater than 6000 sec, closed-cycle systems are lighter. High power applications being considered probably would not require operating times exceeding ~6000 sec. Open-cycle systems are thus likely to be preferred over closed-cycle for high powers.

At the low power end of the spectrum, hundreds of kW(e) to ~10 MW(e), total weight is low enough that practical closed-cycle systems can be carried in a single shuttle load.

RBR/FBR EXPERIMENTS

Scoping experiments on simulated RBR and FBR particle beds have demonstrated capabilities comparable to those expected for operational reactors. However, these preliminary experiments have not fully explored all conditions appropriate to FBRs and RBRs.

Electrically heated FBR particle beds have operated at power densities of ~1 kW/cm^3. Direct resistance heating and induction heating have both been used with helium cooling. The beds have been composed of 500-μ BISO particles (used in the HTGR) as well as 1000-μ stainless steel spheres.

The experimental power density, ~1 kW/cm^3, is comparable to the design power in full scale cw FBRs. Results are very impressive, considering that the average He-coolant pressure in the bed was approximately 1.5 atm. Higher coolant pressures allow much higher power densities. Experiments are being carried out at higher pressures (~15 atm). The measured pressure drops matched predicted values within acceptable limits. Helium outlet temperatures of ~1200°C were achieved with electrically heated BISO-type particle beds. This matches desired FBR outlet temperature in the closed-cycle mode. Stainless steel frits showed no reaction at 1200°C during the experiments (~5 hr). Zirconium frits did react with fuel particles at this temperature, however. Particle beds have been rapidly ramped up to full power (typically, in 2 to 3 sec) without damage to the particles. Bed power has also been rapidly cycled without observable damage to the particles. All experiments have so far been on He-cooled particle beds. Experiments are planned on H_2-cooled beds.

An extensive series of hydraulic tests were carried out at BNL in the early 1970's modelling flow in rotating fluidized bed. In these experiments, the hydraulic behavior of half-scale rotating fluidized beds was studied using nitrogen coolant and glass or copper particle beds. The beds were not heated. Hydraulic behavior of the simulated RBR beds appeared to correlate with analytical models and confirmed that stable operation and complete particle confinement could be achieved. Although heated beds could not be examined with the apparatus, experiments with rotating combustion fluidized beds have been carried out by other researchers. These studies indicate that stable operation is practical in volume-heated beds with much lower temperatures and power densities. They also indicate that there is considerable radial mixing that tends to make bed temperature profiles uniform except near the inlet frit. In this region, a sudden temperature jump is observed. It is expected that such behavior will be encountered in the RBR. It is not expected to adversely affect performance, but may aid stability.

SUMMARY AND CONCLUSIONS

Compact high-performance nuclear reactors (the FBR and RBR) can be based on direct cooling of HTGR-like nuclear fuel particles. The very large surface area of the particles allows very high-power densities, high-coolant outlet temperatures, small temperature differences between fuel and coolant, and very fast startup and shutdown of the reactor. These reactors can operate in the open-cycle mode (H_2-cooled) at power levels up to thousands of MW and temperatures up to ~3000 K. In the closed-cycle (He-cooled) mode, they can operate for years at temperatures up to ~1500 to 2000 K with burnup and reactivity swings limiting lifetime. Typically, size is on the order of 1 m overall, and weight is on the order of 2 to 3 MT.

TABLE 1: FIXED BED REACTOR POINT DESIGNS

	Case 1	Case 2	Case 3 (Split-Flow)
Thermal Power	15 MW	100 MW	250 MW
Inlet Temperature	200°C	200°C	200°C
Outlet Temperature	1000°C	1000°C	1000°C
Inlet Gas Pressure	100 atm	100 atm	140 atm
Fuel Bed Diameter	30 cm	75 cm	75 cm
Fuel Bed Thickness	3 cm	6 cm	6 cm (+3 cm plenum)
Fuel Particle Diameter	400 μ	500 μ	500 μ
Pressure Drop (Frits and Bed)	21.5 psi	35.9 psi	24.7 psi
Temperature Difference (Fuel Surface-Gas)	10°C	7°C	16°C
Fuel Surface Heat Flux	10 W/cm^2	13 W/cm^2	34 W/cm^2

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REFERENCES

1. 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.

2. T.E. Gulden and H. Nickel, Editors, Coated particle fuels, J. Nucl. Tech. Vol. 35, No. 2, (1977).

3. E.R.G. Eckert and R. M. Drake, Heat and Mass Transfer, McGraw-Hill Book Co., NY, 1972, p. 415.

4. J.R. Powell and T.E. Botts, Particle bed reactors and related concepts, Presented at Symposium on Advanced Compact Reactor Systems, National Research Council, Washington, DC, Nov. 15-17, 1982.

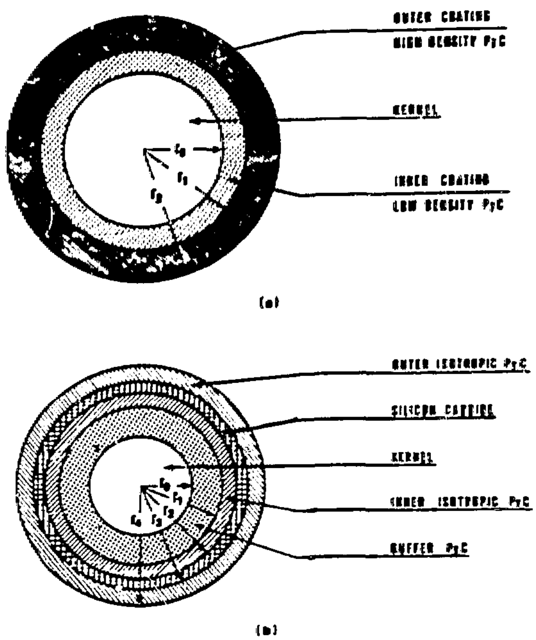
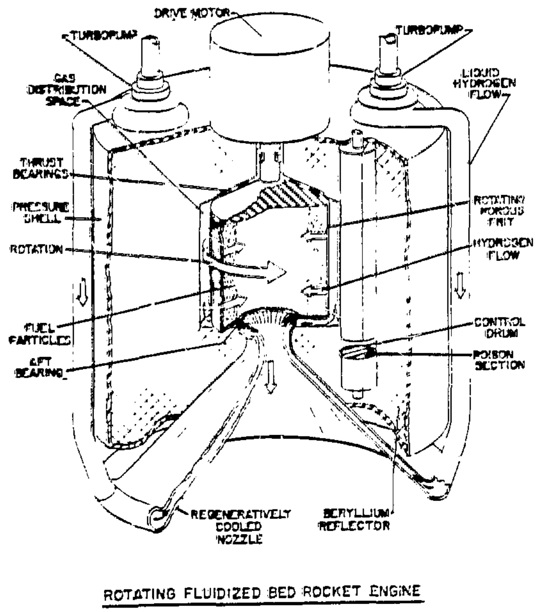


Figure 1



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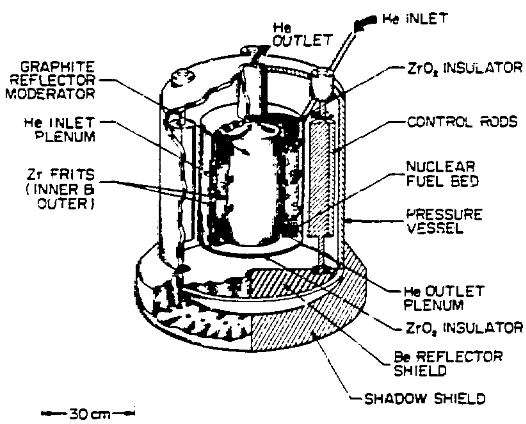

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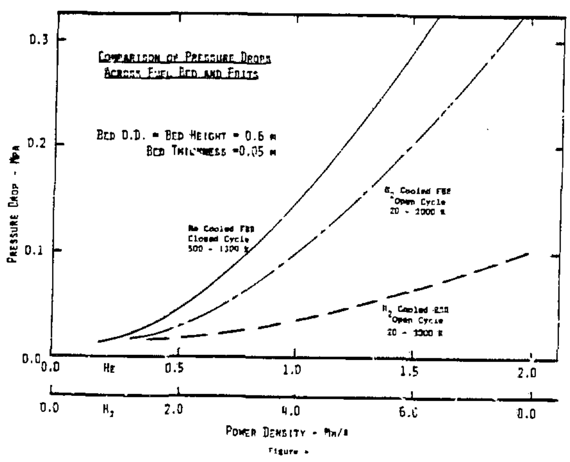

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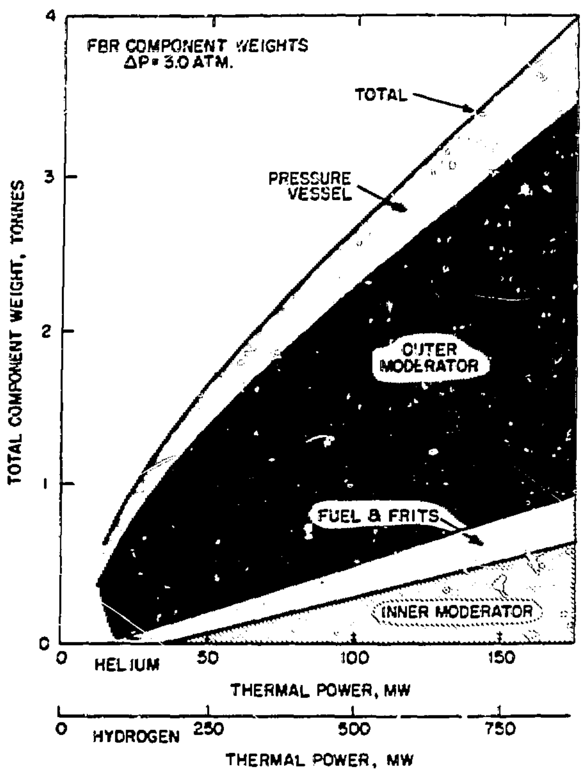

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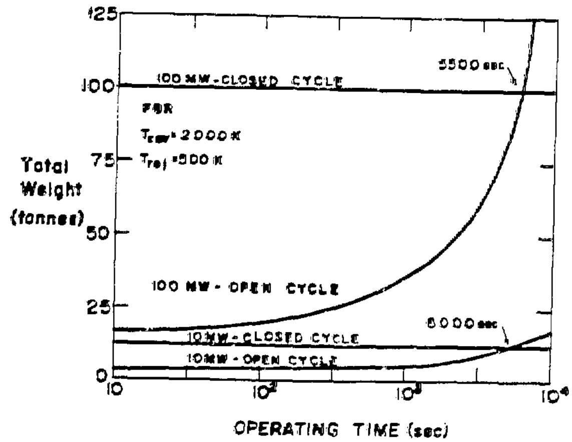

Figure 7

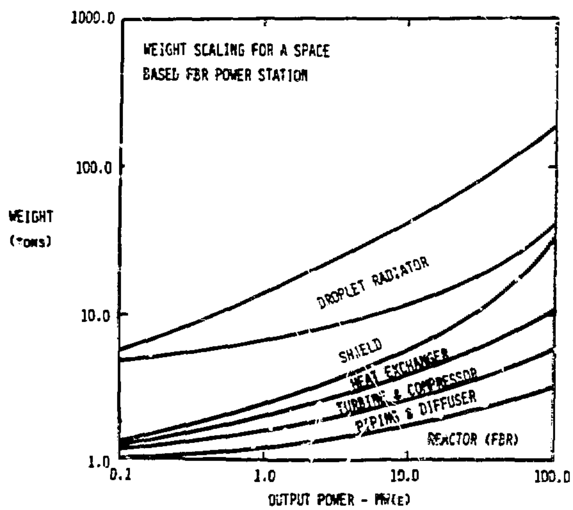

Figure 6