BNL--37931
DE86 009919

BNL-37931
CONF-860171-1
RECEIVED BY OSTI MAY 06 1986

HIGH FLUX RESEARCH REACTORS
BASED ON PARTICULATE FUEL

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February 1986

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TABLE 2 VHFR PARTICLE BED FISSION PRODUCT INVENTORY

<u>FISSION PRODUCT</u>	<u>1000 MW(e) PWR</u>	<u>CORE INVENTORY, CURIES</u> <u>[P = 168 MW(th)]</u>	
		<u>0.5 DAY CYCLE (on-line)</u>	<u>2 DAY CYCLE (BATCH)</u>
I ¹³¹	7.3×10^7	8.0×10^4	3.2×10^5
Ce ¹⁴¹	1.3×10^8	6.5×10^4	2.6×10^5
Sr ⁹⁰	3.2×10^6	2.2×10^2	8.8×10^2
Cs ¹³⁷	4.1×10^6	2.2×10^2	8.8×10^2
Kr ⁸⁵	4.8×10^5	2.8×10^1	1.1×10^2
U ²³⁵ FLOW/DAY THROUGH REACTOR	-	2 kg	1 kg

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Abstract

High Flux Particle Bed Reactor (HFPBR) designs based on High Temperature Gas Reactors (HTGR) particulate fuel are described. The coated fuel particles, ~500 microns in diameter, are packed between porous metal frits, and directly cooled by flowing D_2O . The large heat transfer surface area in the packed bed, $\sim 100 \text{ cm}^2/\text{cm}^3$ of volume, allows high power densities, typically 10 MW/liter. Peak thermal fluxes in the HFPBR are 1 to $2 \times 10^{16} \text{ n/cm}^2 \text{ sec.}$, depending on configuration and moderator choice with beryllium and D_2O moderators yielding the best flux performance. Spent fuel particles can be hydraulically unloaded every day or two and fresh fuel reloaded. The short fuel cycle allows HFPBR fuel loading to be very low, ~2 kg of ^{235}U , with a fission product inventory one-tenth of that in present high flux research reactors. The HFPBR can use partially enriched fuel, 20% ^{235}U , without degradation in flux or reactivity.

* Research carried out under the auspices of the U. S. Department of Energy under Contract No. DE-AC02-76CH00016.

Introduction

Coated fuel particles, developed over the past two decades, are used in high temperature gas cooled reactors for electric power and process heat. In these reactors, the particles are imbedded in graphite fuel elements. Both prismatic block (the HTGR) and ball shapes (the Pebble Bed Reactor) are used. The fuel elements are large, typically several inches in diameter or across flats, and have low surface to volume ratios for heat transfer. Power density is very low, and the reactors are large. The corresponding neutron fluxes are low.

If the fuel particles are directly cooled rather than being imbedded in a graphite matrix, their small size (typically ~500 microns in diameter) results in a large surface to volume ratio and very high power density. Reactors with directly cooled particle beds are very compact, with a high neutron flux. The particles are fabricated with a central kernel of uranium oxide or carbide (or a mixture of oxide and carbide) which is coated with several layers of ceramic¹. For water cooled systems, oxide kernels would be used. Fission products are fully retained inside the particles, even with high burnup of the kernel.

In commercial HTGR's, two types of particles are used. In the "burner" particle (Figure 1A), the kernel contains high enrichment uranium (HEU), typically 93.5% ^{235}U . The porous pyrographite layer immediately outside the kernel is of low density. The voids in this layer hold the fission product gases, reducing internal pressure and stress on the external pyrographite and silicon carbide coating. On the "breeder" particle (Figure 1B), the kernel

contains thorium (ThO_2), which captures neutrons to breed ^{233}U . This burns in situ, extending reactor lifetime and reducing fuel cycle cost. Burnup in the thorium kernels is much less than in the HEU kernels, so that a simple, relatively thin, coating is sufficient to retain all fission products.

During the last three years, directly cooled particle bed reactors (PBR) have been undergoing development for space power and propulsion applications^{2 3 4} by the team of Brookhaven National Laboratory, Babcock and Wilcox, Garrett, and Grumman Aerospace Corporation. In these reactors, the particles are packed between two concentric porous frits to form annular bed fuel elements (Figure 2). Pressurized gas coolant--hydrogen for open cycle applications and helium for closed cycle ones--flows radially inwards through the packed bed, where it is heated to high temperature. The hot exit gas then flows out along the central channel to a turbine (for power generation) or to a rocket nozzle (for propulsion). A number of annular elements, typically 19, are arranged in a moderator to form the PBR core. Candidate moderators include metal hydrides, such as zirconium hydride, and beryllium metal.

Based on experiments and design studies, PBR's appear very attractive for space applications. Thermal hydraulic experiments have demonstrated gas cooled bed power densities of 10 MW/liter. Material tests indicate that high operating temperatures can be achieved, i.e., 2000 K for power generation and considerably higher for propulsion. Experiments show that particle beds can ramp to high power density and temperature in a few seconds without damage.

Katscher⁵ has carried out thermal hydraulic experiments on particle beds directly cooled by water. His results indicate that water is also a

viable coolant at high power density. Based on this work, Powell and Takahashi have proposed using directly cooled particle beds for high flux research reactors⁶. This concept, termed the HFPBR, should achieve thermal fluxes of $\geq 10^{16}$ n/cm² sec. It will have the following important operational benefits:

1. Use of highly developed and commercially available particle fuel.
2. Hydraulic unloading of spent particles and loading of fresh ones on a frequent basis (i.e., daily).
3. Low fuel loading in core (typically, 2 kg of ²³⁵U).
4. Low fission product inventory.
5. Use of non-weapons grade fuel (20% ²³⁵U).

HFPBR configuration and performance are described in the remainder of this paper, together with the development and testing necessary for implementation.

HFPBR Configurations and Neutronics

Two HFPBR configurations have been studied. The first configuration, C-1, is a simple annular bed of fuel particles packed between concentric porous metallic zircaloy frits (Figure 3). D₂O coolant flows radially outwards through channels in the central beryllium moderator, then through the inner frit, the packed bed, and exits through the outer frit. A thin outer shell of beryllium (not shown) surrounds the annular bed, followed by a thick D₂O reflector.

Thermal flux profiles for the C-1 configuration, shown in Figure 4, are based on an overall power density of 10 MW/liter in the packed bed region. Parameters for the C-1 configuration are summarized in Table 1. The magnitude of the peak thermal flux depends strongly on ^{235}U loading, since high loadings depress thermal flux in the external moderator (both inner and outer). Fluxes and k_{eff} were calculated with a 1-D, 15 group (9 thermal, 6 fast) ANISN model. ENDFB-V cross sections were used with N-JOY processing.

2-D analyses using the DOT model and the same cross section set have been carried out for PBR's of similar annular geometry but with gas coolant³. In these analyses, reducing the 1-D value for k_{eff} by -0.10 compensated for 2-D end effects. Reducing k_{eff} by an additional -0.10 compensated for fission product poisoning (including Xenon) and a 20% fuel depletion. These analyses suggest that a similar reduction of -0.20 in k_{eff} be made for the 1-D clean HFPBR analyses to account for 2-D effects, fission product poisoning and fuel depletion.

Neutronic studies of the C-1 configuration using Be, D_2O , H_2O , and C moderators (both singly and in combination) indicate that the design shown in Figure 3 achieves the highest thermal flux and flux volume of those analyzed. The design has not been optimized, however, and further improvement could probably be achieved. The C-1 configuration has several operational disadvantages:

1. Pressurizing the coolant requires pressurizing the pressure vessel, making neutron beam extraction more difficult.

2. The annular bed is not as simple to construct and replace as alternative configurations.
3. Hydraulic unloading/loading of fuel particles is harder than with alternative configurations.

Thermal hydraulic experiments indicate that it will be necessary to pressurize the D_2O coolant to avoid local saturation at the coolant-particle interface, which could lead to boiling and steam slug formation. Pressurizing the D_2O tank results in relatively thick walls and potential beam tube problems.

Figures 5 and 6 show the second configuration analyzed, the C-2. Here, the fuel particles are packed into rectangular beds (Figure 5) held between porous zircoloy frits. Individual beds are placed in pressure tubes, which are arranged in an annular ring (Figure 6) inside the D_2O moderator tank. D_2O coolant enters by flowing down through one side of the pressure tube, transversely through the packed particle bed and its frits, and then exits by flowing up the other side of the tube. The bayonet pressure tubes are held by a top grid in the D_2O moderator tank, and can be easily replaced when radiation damage exceeds allowable limits.

The packed particle beds approximate an annular fuel ring. The gaps between them are relatively thin, and will not substantially affect overall neutronic behavior. In 1-D ANISN neutronic analyses of the C-2 configuration, the fuel bed region (region III in Figure 5) was homogenized into a continuous annular ring, as were the inner and outer D_2O coolant zones (regions II and IV). Volumetric averages were taken of the materials in each region.

Figure 7 shows thermal flux profiles for the C-2 configuration for a range of fuel loading and Be/D₂O moderator combinations, with curves b through f based on the core size shown in Figure 5. Results from an analysis of a smaller core are shown in Figure 8. Table 2 summarizes reactor parameters for both core sizes. Fuel enrichment is 20% ²³⁵U in all cases.

Cases with low uranium loading have higher thermal fluxes than those with high uranium loading (Table 1b). Case b differs from case c in that the uranium loading is 2 kg ²³⁵U for the former and 5 kg for the latter. The thermal flux is depressed in the fuel region and the inner and outer reflectors with the higher ²³⁵U loading. The same pattern is shown for cases d and e, with a ²³⁵U loading of 5 kg and 10 kg, respectively. While increasing uranium loading has a large effect on k_{eff} when the ²³⁵U inventory is low, the effect is small when the loading is high. For cases b and c, k_{eff} increases from 1.288 (2 kg ²³⁵U) to 1.425 (5 kg ²³⁵U); in comparison, for cases d and e, k_{eff} increases from 1.249 (5 kg ²³⁵U) to 1.287 (10 kg ²³⁵U). At high uranium loading, the principal effect of additional ²³⁵U is to depress flux.

Therefore, for maximum thermal flux, one should operate at minimum ²³⁵U loading, although, this mode requires that fresh fuel be loaded frequently, i.e., every day or two.

Frequent fuel changing is impractical for fixed fuel reactors, resulting in greatly reduced available operating time, and excessive core fabrication costs. However, with the PBR, spent fuel particles can be hydraulically

unloaded and fresh ones loaded in a few minutes, and fuel fabrication costs are low. Consequently, it appears practical to change fuel every one to two days in a HFPBR.

Although significantly higher thermal fluxes are achieved with beryllium moderator than with D_2O moderator, the effect tends to be confined to the Be moderator zone (curves c and d in Figure 7). Curve c is the same design as curve d, except that the inner 20 cm of the external D_2O reflector is replaced with Be. For case c, the flux in this region is almost double that of d; however, outside the region, fluxes are virtually the same. Moreover, k_{eff} is significantly higher for case c, i.e. 1.425 vs. 1.249 for case d. Substituting an inner D_2O moderator region for Be substantially reduces the thermal flux inside the annular fuel region, but has only a small effect on exterior thermal flux (cases e and f).

Based on these initial studies, the most promising design approach is to place Be moderator inside the fuel ring, and an external Be shell outside it, followed by a relatively thick D_2O moderator region. This approach maximizes both the magnitude and volume of the high thermal flux region. In addition, the Be shell reduces both the gamma and fast flux leakage, compared to a pure D_2O reflector, which is important for cold neutron sources. The optimum thickness of the external Be shell has not been determined, and will depend on the specific requirements of the associated beam tubes and cold sources. The thermal flux in the central beryllium region inside the fuel ring is very high, $\sim 2 \times 10^{16}$ n/cm². With the bayonet pressure tube design, horizontal beam tubes and/or cold sources can be brought immediately below this region to utilize its high flux.

Some materials irradiation and isotope production capability appears practical and will probably be desired. These functions affect reactor design, and may necessitate harder neutron spectrum zones adjacent to the fuel region. Since these requirements have not been determined, they have not been factored into the design.

Maximizing thermal flux for neutron scattering experiments (both room temperature and cold sources) remains the primary function of such a reactor, and design compromises will be necessary to determine the best combination of functions. HFPBR core size and power have not been optimized. However, some compromises have been carried out. Figure 8 shows the thermal flux profile for a smaller core. This design (case A in Table 1) has a 30 cm diameter Be inner moderator region, compared to 40 cm diameter for the other cases. The thermal flux profile for the smaller core is very similar to case B (curve b in Figure 7) both in shape and magnitude. Power level is significantly less (Table 1), but experimental volume is reduced.

Alternatively, reactor power (and proportionately, flux) can be increased for the same size core, either by increasing bed power density or having a thicker bed. The neutronic analyses were made with an average bed power density of 10 MW/liter, which is consistent with thermal-hydraulic (T/H) data for directly cooled particle beds. T/H analyses predict that even higher power density operation should be feasible, but experimental confirmation of such capability is needed.

A more conservative approach is to increase particle bed volume. As shown in Figure 6, the fuel bed region is relatively thin (3.6 cm including frits) and could be doubled by changing the design of the fuel bed pressure

tube. To keep pressure drop through the particle bed reasonable (several atm), bed thickness is limited to ~4 to 5 cm, making a simple increase in bed thickness impractical. One must either use a split bed approach, where two beds are fed in parallel from a central D₂O channel, or make the bed an annular element inside the pressure tube. This latter approach appears the best, and is readily integrated with the pressure tube.

Increasing reactor power to 320 MW doubles thermal flux for the designs in Figure 7. Fluxes of $\sim 4 \times 10^{16}$ n/cm² sec. are achieved in the central Be region, and $\sim 2 \times 10^{16}$ n/cm² in the outer Be shell and D₂O reflector. A power level of 320 MW, while high in terms of present research reactors, appears practical and acceptable. Reactor capital cost will increase with power, though probably less than linearly. Tradeoff studies are necessary to determine optimum power level. The utility of higher flux will have to be evaluated, and balanced against the additional capital and operating cost.

More detailed neutronic studies are planned to examine 2-D and burnup effects. Based on previous neutronic analyses of similar space reactors, an allowance of 0.2 in k_{eff} should account for finite core length, fission product poisoning, and fuel depletion. For the nominal loading of 2 kg ²³⁵U and 20% depletion, fuel would be reloaded every two days if the reactor operated at 160 MW, and daily at 320 MW.

HFPBR Thermal Hydraulics

The large surface area in the packed bed, 120 cm²/cm³ for 500 μ diameter particles, allows high power density operation with a small temperature

difference between the particles and coolant. Figure 9 shows the film temperature drop (ΔT_f) between the particle surface and the bulk D_2O coolant as a function of bed power density and particle size. Film temperature drop is calculated using the Eckert and Drake correlation⁷, derived from heat transfer experiments on gas cooled particle beds. The calculated ΔT_f is small, approximately 10°K, at the design power density (10 MW/liter) and nominal particle size (500 μ). As a result, the D_2O coolant is always strongly subcooled at the particle surface. The bulk coolant exit temperature is 130°C, compared to the saturation temperature of 295°C at the operating pressure of 80 atmospheres.

Katscher's T/H experiments⁵ on water cooled particle beds demonstrated average power densities of ~3 MW/liter before the onset of vapor formation in the bed. However, in Katscher's work, vapor generation occurred at low pressure (1 atm) and relatively high exit temperatures (~80°C). Thus a local film drop of only 20°C would initiate steam slug formation. Such a film drop appears likely to occur under the conditions of the experiment. First, average power density was high, ~3 MW/liter, and water velocity through the bed was relatively low (~10 to 20% of that in the HFPBR). Second, local power densities were probably greater than the average, increasing the film drop. The experimental bed was an annular ring of small diameter stainless steel balls, inductively heated by a high frequency generator. Skin effects (induced current is greater at the exterior of the ring) and increased I^2R heating at the high resistance contacts between balls both would contribute to non-uniform heating.

At the 10 MW/liter power density of the HFPBR, the film temperature drop is small (~10°C) compared to the available subcooling of ~200°C, so that

vapor generation does not appear possible. Analyses predict that considerably higher power densities are practical; nevertheless, experimental demonstration at the higher power densities is needed before they could be used as the basis of a HFPBR design.

Figure 11 shows pressure drop (ΔP) through a 3.0 cm thick particle bed as a function of power density and particle diameter, based on the correlation of Ergun⁸. Pressure drops calculated with this correlation agree closely with experimental pressure drops. ΔP is reasonable (10 atm) at 10 MW/liter and 750 μ , increasing to 14 atm for a particle diameter of 500 μ . Film temperature drop is somewhat less for 500 μ particles but still reasonable with 750 μ particles. The design presented here assumes 750 μ particles, though 500 μ particles would also be acceptable. Determination of optimum particle size depends strongly on fuel element configuration, power level, power density, and other operating conditions.

Changing bed thickness or configuration is the easiest way to accommodate higher power densities and the best approach for higher reactor powers. For a given power density and ΔT across the bed, pressure drop varies as the cube of bed thickness, thus small changes in bed thickness have a major effect on ΔP . At 10 MW/liter, bed thickness is limited to a maximum value of ~4 cm by pressure drop, for a temperature rise of 100°C across the bed. At this limit, ΔP is ~ 10 atm. If one desires higher power densities, either the ΔT across the bed must be larger, or the bed must be thinner. Using the first approach, operating at 20 MW/liter requires a ΔT of 200°C (for the same pressure drop). This ΔT is probably not practical, since particle surface

temperature is then close to the coolant saturation temperature. Using the second approach, reducing bed thickness by 25% allows a power density of 20 MW/liter.

Thermal flux for the nominal size core is doubled if the reactor operates at 320 MW instead of 160 MW. However, if bed power density is held constant (i.e., at 10 MW/liter), the effective bed thickness in the annular fuel ring has to double. But increasing the bed thickness in the C-2 configuration is not practical, since pressure drop is then excessive. One must use either a split bed configuration or an annular packed bed. The latter approach appears preferable. With annular fuel elements inside the pressure tubes, a bed power density of 10 MW/liter and a total reactor power of 320 MW, bed thickness is ~ 2 cm, which compares to 3 cm for the rectangular fuel beds in the 160 MW C-2 design. Pressure drop through the annular bed is reduced to ~ 3 atms.

Power distribution in the beds will not be uniform. There is a radial power density variation in the annular fuel ring; the lowest power density is in the center of the ring, while the highest power densities are at the inner and outer surfaces of the ring. Radial power variation is readily handled by the coolant, since the average film temperature drop ΔT_f is small, on the order of 10 K. Local increases in ΔT_f at the surfaces of the fuel ring are well below those required to induce boiling.

Axial power variations will also be present. These have not been analyzed for the HFPBR, but have been investigated for space power reactors of similar configurations, employing the 2-D DOT transport code. In these space reactors, annular fuel rings were used, of comparable size and shape to the

HFPBR. Beryllium and carbon external/internal moderators were used instead of the Be/D₂O combinations for the HFPBR, and the annular particle bed was cooled by gas (H₂ or He) rather than liquid D₂O. However, their 2-D power distributions should be generally similar to those in the HFPRR.

Power density was found to be essentially constant in the axial direction, except near the ends of the annular fuel ring. The characteristic axial distance for these non-uniform power effects was the radial thickness (ΔR) of the ring. That is, power density in the fuel ring was greater at the ends (due to the extra moderation from the reflectors above and below the ring), approaching a constant value for distances $\geq \Delta R$ from the ends of the ring. Axial peak to average power factors were relatively low, $\sim 1.5/1$, and axial peak to average factors for the HFPBR are expected to be comparably low. In fact, peak to average values for the HFPRR may be even smaller, since it is better moderated and has much lower fuel loadings.

Axial peak to average power ratios of $1.5/1$ can be readily handled by the ΔT_f margin available in the coolant. If higher peak to average ratios are found to be present in the HFPBR coolant flow area in the fuel bed, frits can be locally tailored to compensate for power variations. Flow area would be reduced in regions with low power density relative to the flow area in regions with high power density. This can be easily accomplished by locally sealing small portions of the frit to restrict coolant flow. Such sealing could be done by E-beams, soldering, etc. Alternatively, if the flow holes in the frit were manufactured by automated computer controlled drilling (using either mechanical or laser drills), the local flow area could be readily adjusted to whatever value was desired.

Finally, some azimuthal power variations around the annular fuel ring will probably be encountered, due to the presence of beam tubes. In general, these variations are expected to be substantially smaller than the axial and radial power variations, since the tubes will be located relatively far from the fuel zone and perturbations will tend to smooth out over that distance.

HFPBR Fuel Cycle

A major advantage of the HFPBR is the potential capability to unload spent fuel particles and to load fresh fuel hydraulically. Such unload/load cycles can be carried out remotely and rapidly without opening the reactor vessel, permitting frequent fuel changes, either on a batch basis in which the reactor would be shut down daily for a short time or continuously on-line.

Figure 11 shows a possible batch unload/load cycle in which particles are transported along a small tube at the top of each fuel element. When D_2O is drawn up through the tube, spent particles are carried along to an external fuel storage vessel. Fresh fuel particles are then carried into each element by injecting D_2O through the tube. The D_2O flow is directed downwards, packing the particles into settled beds. The injected D_2O flows out with main exit coolant flow.

During reactor operation, there is no flow of D_2O in the fill tube. The particles are held down by the D_2O flow in the open region above the bed, which is at a slightly higher pressure and flow velocity than the coolant in the bed. Part of this coolant flows down through the top of the bed to join the coolant in the bed. Batch unload/load cycles have been successfully

demonstrated in mockup fuel elements using gas flow to move the particles. Particle transport with liquid coolant is expected to be even easier.

Figure 12 shows a continuous on-line refueling concept for particle bed fuel elements. Fresh particles are injected at the top of the bed, with spent ones withdrawn from the bottom. Fuel particles move in plug flow through each element. Numerous reactors have operated successfully with on-line refueling, including CANDU systems and the Pebble Bed Reactor, and there appears to be no inherent bar to operating the HFPBR in this mode.

To determine which is the better mode, it will be necessary to test mockup and prototype elements to test how well the different methods work, and what their relative advantages and disadvantages are. Table 2 compares the fission product inventory for the HFPBR with that of a 1000 MW(e) PWR, for continuous and batch cycles. The HFPBR inventory is many orders of magnitude below that of a commercial power reactor.

Summary and Conclusions

Neutronic and thermal-hydraulic studies of a high flux version of the particle bed reactor have been carried out. These indicate that thermal fluxes of 10^{16} n/cm² sec. or greater can be achieved using direct cooling of packed particle beds by D₂O. Operating power densities of 10 MW/liter of fuel bed appear possible, based on analyses and experiments. The favored configuration appears to be an annular fuel region comprised of a ring of pressure tubes in which the individual particle beds are located. Commercial HTGR particle fuel can be used for the HFPBR. Total fuel loading is approximately 2 kg, with the fuel being changed every day or two, depending on

reactor power. The low fuel loading results in relatively small flux depression in the fuel region, and substantially higher peak thermal flux, as compared to fixed fuel reactors with high fuel loadings and relatively infrequent fuel changes.

Frequent fuel change can be accomplished by remote hydraulic unloading/loading of fuel particles, either on a batch basis with the reactor shutdown, or continuously on-line. In addition to improving the flux performance of the HFPBR and greatly lowering its ^{235}U loading, frequent fuel changes also greatly reduce fission product inventory, by an order of magnitude or more, compared to fixed fuel research reactors. The HFPBR can use partially enriched fuel (e.g. 20% ^{235}U) without significantly degrading either thermal flux capability or k_{eff} .

Overall, the HFPBR appears to be a very attractive candidate for a high flux research reactor, and further study appears to be desirable.

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FIGURE 1

1B

1A

FIGURE 2

BASELINE FUEL ELEMENT & MODERATOR BLOCK

FIGURE 3

FIGURE 4

FIGURE 5

CROSS SECTION OF FUEL ELEMENT TUBE

FIGURE 6

VHFR

POWER: 163 MW

FIGURE 7

Thermal Neutron Flux Distribution
(based on 10 MW/liter)

FIGURE 8

FIGURE 9

HEAT TRANSFER FILM TEMPERATURE DIFFERENCE

HIGH FLUX RESEARCH REACTOR

COOLANT - WATER; TEMP. RISE - 70°C

AVERAGE TEMPERATURE - 100°C

PACKED PARTICLE BED THICKNESS - 3.0 cm

FIGURE 10

BED PRESSURE DROP
HIGH FLUX RESEARCH REACTOR
COOLANT - WATER; TEMP. RISE -70°C
AVERAGE TEMPERATURE -100°C
PACKED PARTICLE BED THICKNESS -3.0 cm

FIGURE 11

UNLOAD/LOAD CYCLE FOR VHFR PARTICLE BED FUEL ELEMENT

FIGURE 12

ON-LINE FUEL LOADING FOR VHFTR PARTICLE REACTOR BED

TABLE 1 HFPBR PARAMETERS

Table 1A: Configuration Characteristics

<u>Fuel Particles</u>	<u>C-1</u>	<u>C-2</u>
Type	TRISO	TRISO
Diameter, microns	750	750
Kernel	UO ₂	UO ₂
Enrichment, % ²³⁵ U	20	20
<u>Fuel Beds</u>		
Shape	Annular	Rectangular
Width, cm	-	6.06
Thickness, cm	5.0	3.0
Height, cm	50.0	50.0
Number	1	18
Placement	Between Cylindrical Zircoloy Frits	One Per Pressure Tube
<u>Fuel Region</u>		
Shape	Annular	Annular Ring of Pressure Tubes
Equivalent ID, cm	40.0	45.2
Equivalent OD, cm	50.0	52.4
Height, cm	50.0	50.0
<u>Frits</u>		
Material	Zircoloy	Zircoloy
Porosity	50%	50%
Thickness, cm	1.0	0.2
<u>Moderators</u>		
Inner	Be	Be and/or D ₂ O
Outer	Be/D ₂ O	Be and/or D ₂ O

TABLE 1 HFPBR PARAMETERS (Cont'd)

Table 1A: Configuration Characteristics (Cont'd)

	<u>C-1</u>	<u>C-2</u>
<u>Thermal-Hydraulics</u>		
Coolant	D ₂ O	D ₂ O
Bed Power Density, MW/Liter	10	10
Reactor Power, MW(th)	350	163
D ₂ O Inlet Temp., °C	30	30
D ₂ O Outlet Temp., °C	180	130
D ₂ O Pressure, atm	100	80
D ₂ O Flow Rate, Liters/Sec.	580	400
Film ΔT, °C	10	10
Pressure Drop, atm	15	6
<u>Pressure Tubes</u>		
OD, cm	-	8.6
Wall Thickness, cm	-	0.3
Material	-	Zircoloy
Internal Pressure, atm	-	80
Tube Stress, psi	-	16,300

TABLE 1 HFPBR PARAMETERS

Table 1B: K_{eff} Values for Various C-1 Reflector/Moderator Systems

Region Case	I	II	III	IV	V	K_{eff}	Fuel 20% U^{235} Enrichment
a	Be (15)	Zr, D ₂ O (2.6)	Fuel (3.6)	Be (20)	D ₂ O (100)	1.296	2 kg U^{235}
b	Be (20)	Zr, D ₂ O (2.6)	Fuel (3.6)	Be (20)	D ₂ O (100)	1.288	2 kg U^{235}
c	Be (20)	Zr, D ₂ O (2.6)	Fuel (3.6)	Be (20)	D ₂ O (100)	1.425	5 kg U^{235}
d	Be (20)	Zr, D ₂ O (2.6)	Fuel (3.6)	Zr, D ₂ O (2.6)	D ₂ O (100)	1.249	5 kg U^{235}
e	Be (20)	Zr, D ₂ O (2.6)	Fuel (3.6)	Zr, D ₂ O (2.6)	D ₂ O (100)	1.287	10 kg U^{235}
f	D ₂ O (20)	Zr, D ₂ O (2.6)	Fuel (3.6)	Zr, D ₂ O (2.6)	D ₂ O (100)	1.242	10 kg U^{235}

The number inside () is the width in unit of cm.