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Pellet Bed Reactor Concepts for Nuclear Propulsion Applications

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Pellet bed reactor (PeBR) concepts have been developed for nuclear thermal and nuclear electric propulsion, and bimodal applications. This annular core, fast spectrum reactor offers many desirable design and safety features. These features include high-power density, small reactor size, full retention of fission products, passive decay heat removal, redundancy in reactor control, negative temperature reactivity feedback, ground testing of the fully assembled reactor using electric heating and non-nuclear fuel elements, and the option of fueling on the launch pad, or fueling and refueling in orbit. In addition to these features, the concepts for nuclear electric propulsion and for bimodal power and thermal propulsion have no single point failure. The average power density in the reactor for nuclear thermal propulsion ranges from 2.2 to 3.3 MW/l and for a 15-MWe nuclear electric propulsion system the total power system specific mass is about 3.3 kg/kWe. The bimodal-PeBR system concepts offer specific impulse in excess of 650s, tens of Newtons of thrust, and total system specific power ranging from 11 to 21.9 We/kg at the 10- and 40-kWe levels, respectively.

I. Introduction

THE nuclear propulsion technology development program has addressed multiple approaches for future space exploration and for enabling manned missions to Mars[1]: 1) solid-core and gaseous nuclear thermal propulsion (NTP) reactors capable of long life and multiple starts; and 2) nuclear electric propulsion (NEP) systems, including nuclear reactor, low mass radiators, power management technologies, and high-powered long life electric thrusters. Potential transfer of NTP reactor technology to NEP minimizes development cost of NEP missions. One of the solid-core reactors concepts that satisfies this criterion is the pellet bed reactor (PeBR), which offers unique design and safety features.[2–7] It is an annular-core, fast-spectrum reactor that draws on established pebble-bed, high-temperature gas cooled terrestrial reactors, and NERVA nuclear fuel and materials technology bases.[8,9] The PeBR is designed for multiple starts to meet projected mission requirements. The technologies that it employs and the conditions it operates at are all within the state-of-the-art limits, which translates into low development risk and cost. This basic reactor concept represents the first-generation design in the evolutionary development of future high-performance packed bed space nuclear reactor power and propulsion concepts.

The major design features and operational characteristics of the PeBR concepts for NTP, NEP, and bimodal applications are described in this article. The results of reactor design, neutronics, and thermal hydraulics analyses and mass optimization of the PeBR for these applications are presented. While the basic reactor concept is the same for all three applications, there are some differences in design and structural materials.

II. PeBR Design for NTP Applications

Figures 1a and 1b show an axial cross section and a radial cross section of the PeBR core for NTP applications, respectively. It is a hydrogen cooled, fast spectrum reactor consisting of a single annular region filled with randomly packed spherical fuel pellets. Because the pellets, stacked between hot and cold frits, are self-supported, the core has no internal structure. The frits are made of a perforated structure with openings 4–8 mm in diam. The average porosity of the frits ranges from 10 to 30%, depending on the axial flow distribution desired in the reactor core during operation, as will be shown later. The PeBR may be launched unfueled, fueled at the launch facility or in orbit, and refueled in orbit for unique safety and longer operation lifetime advantages. Since the rocket nozzle would likely need to be replaced after each round-trip to Mars, refueling the reactor in orbit could be accomplished remotely or in conjunction with replacing the rocket nozzle, if multiple reuse of the propulsion system is required.

The projected operational lifetime of PeBR for NTP applications is 5 yr, which supports at least three round-trips to Mars. The radial and axial Be_2C reflectors help flatten the axial and radial fission power profiles in the reactor core. The high melting temperature Be_2C is selected because of the high temperature associated with passive decay heat removal from the reflector outer surface by thermal radiation to outer space.[6] In order to meet the operational and power requirements, the excess reactivity in the PeBR at the beginning-of-mission (BOM) is approximately \$1.25 and \$4.0 for NTP and NEP applications, respectively.[5,6]

Because the PeBR is a fast spectrum reactor, the effect of carbon losses, due to hydrogen corrosion, on the reactor neutronics (excess reactivity) is significantly lower than in other solid core, thermal neutron spectrum reactors. At low fission power requirements ($\lesssim$500 kWt), thermal solid-core reactors are not neutronically limited, unlike fast spectrum reactors, and are usually smaller and lighter. Conversely, for higher power requirements, fast spectrum reactors are no longer neutronically limited and could be smaller in size and lower in mass than thermal solid-core reactors, which translate into better performance and high-power density. At high-power density it is important to design the reactor core with large

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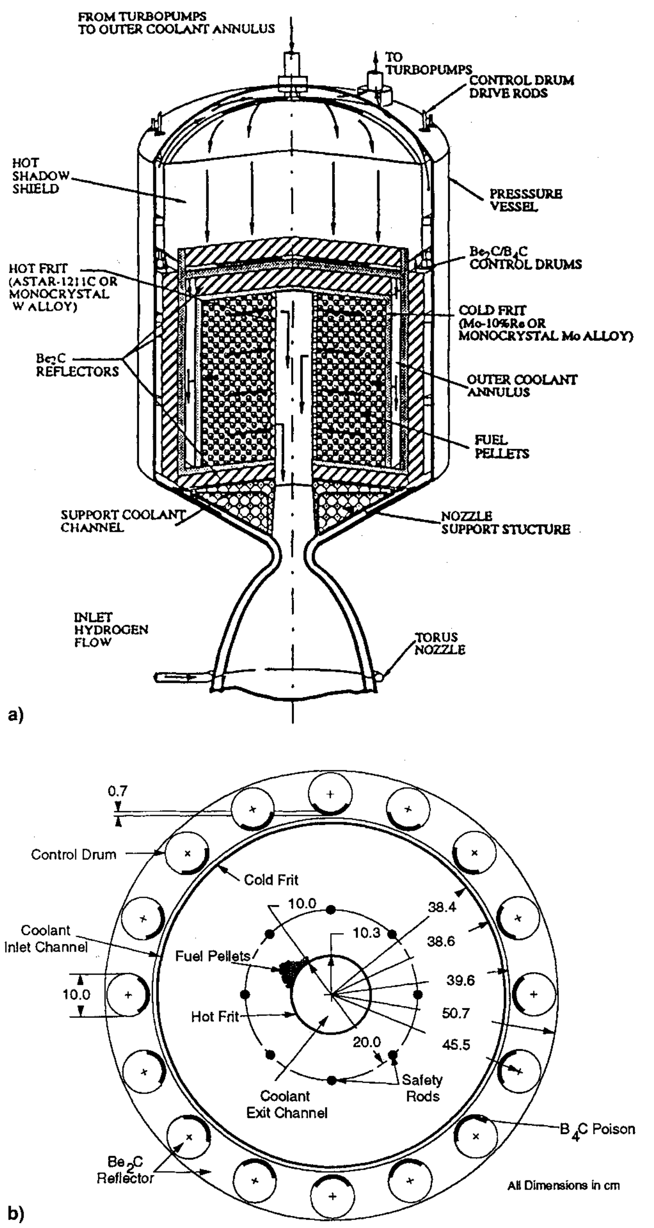


Fig. 1 Cross-sectional view of the PeBR for NTP applications: a) axial and b) radial views.

heat transfer area in order to maintain the maximum fuel temperature safely below its melting point. This requirement is satisfied in the PeBR through the use of spherical fuel pellets whose diameter can be changed, depending on the reactor thermal power. The ability of scaling the reactor performance by only varying the pellet size is a unique design feature of PeBR for NTP, NEP, and bimodal applications. Varying the pellet size commensurate with reactor thermal power also minimizes hydrogen corrosion, which is proportional to the surface area of the pellets.

Reactor control is accomplished by using two independent control systems: 1) 16-Be_2C/B_4C segmented control drums, which are embedded in the radial reflector (Fig. 1b); and 2) eight, 20-mm-diam B_4C safety rods, which are used primarily to ensure that the reactor remains subcritical when fully submerged in water following a launch abort accident. These two systems provide redundancy in reactor control, since each system is independently capable of starting up and shutting down the reactor in orbit.

Non-nuclear, ground testing of the fully assembled PeBR reactor can be accomplished using electric heaters and non-nuclear fuel pellets. A total of eight, 1.0-m-long tungsten electric heaters can be inserted in place of the safety rods. Additional electric heaters can also be inserted in the central flow channel (Figs. 1a and 1b). During testing, the pellets will be identical to those used during reactor operation, except that the microspheres are loaded with depleted uranium kernels. Although actual power and temperature profiles during ground testing with electric heaters will be different than those expected with nuclear heating, the test results can be used to benchmark reactor thermal hydraulics models.[11] Test results can also be used to characterize the pressure and flowfields in the reactor core, the thermal stresses in the structure due to thermal cycling, and the passive decay heat removal capability of the reactor design.

Because of the small diameter of the PeBR core (0.77 m), it is possible to fit more than one PeBR engine within the optimum cone half-angle of 15 deg of the radiation shield, which allows sufficient separation distance between the propellant tank and the reactor core to avoid boiling of liquid hydrogen, but without a significant increase in the mass of the shadow shield.[12] The reactor shield consists of two lithium hydride (LiH)-tungsten (W) layered portions. The hot portion of the shield is contained within the reactor vessel and actively cooled by hydrogen (Fig. 1a). The cold portion of the shield is located outside the reactor core, between the reactor vessel and the propellant tank and passively cooled by radiation to outer space.

The NTP engine design employs a high-performance expander cycle. Liquid hydrogen, at about 13–20 K, is pumped from the hydrogen tank by a turbopump feed system. It is first pumped through the regenitively cooled nozzle and the lower axial reflector, then flows axially through the radial reflector where it boils off, transforming into gas, as it exits the reflector structure. The hydrogen gas flow then operates the two hydrogen turbopumps before returning to the reactor vessel dome where it is directed downward to cool the hot shield (Fig. 1a). The hydrogen gas from the shield cools the upper axial reflector then flows downward through the annular space between the core cold frit structure and the radial reflector. It enters the core radially through the outer frit at about 120–200 K and exits at the hot frit at approximately 3000 K where it is collected in the 0.20 m diameter central channel. The hot hydrogen in the central channel then flows through a supersonic rocket expansion nozzle creating thrust. Because the average radial temperature gradient within the PeBR core for NTP applications is less than 7 K/mm, thermal stresses within the fuel pellets, due to the non-uniform axial and radial fission power profiles are insignificant.

Each spherical pellet is composed of hundreds of coated DISO-type fuel microspheres embedded in a zirconium carbide (ZrC) matrix. This matrix protects against carbon loss to the hot hydrogen during firing operation. The diameter of and fuel microspheres loaded in the pellet can be varied to meet different mission operation and power requirements, such as excess reactivity at BOM and heat transfer surface area to keep the maximum fuel temperature in the core sufficiently below its melting point. The material of the matrix in the pellets can also be selected to enhance the compatibility with the coolant; it is graphite for He cooled NEP and bimodal PeBR concepts, discussed next, while ZrC matrix, although heavier, is a better choice for NTP applications to combat hydrogen corrosion. Each microsphere consists of a (80 wt.% U-20 wt.% Nb)C fuel kernel (400–500 mm in diam), a 15–20-mm-thick NbC inner coating, and a 15–20-mm-thick ZrC outer coating for full retention of fission products[13] (Fig. 2). The differences between the NTP and NEP fuel microsphere and pellet designs can be attributed to the differences in coolant type, the maximum, full power fuel temperature, and fuel burnup requirement for each application. The (0.8 U-0.2 Nb)C fuel is selected because of its high melting temperature (~3400 K) and compatibility with the NbC coating, hence avoiding formation of lower melting temperature eutectics.[13] The NbC coating accommodates the fission products recoil and partially accommodates the fission gases, while the ZrC coating acts

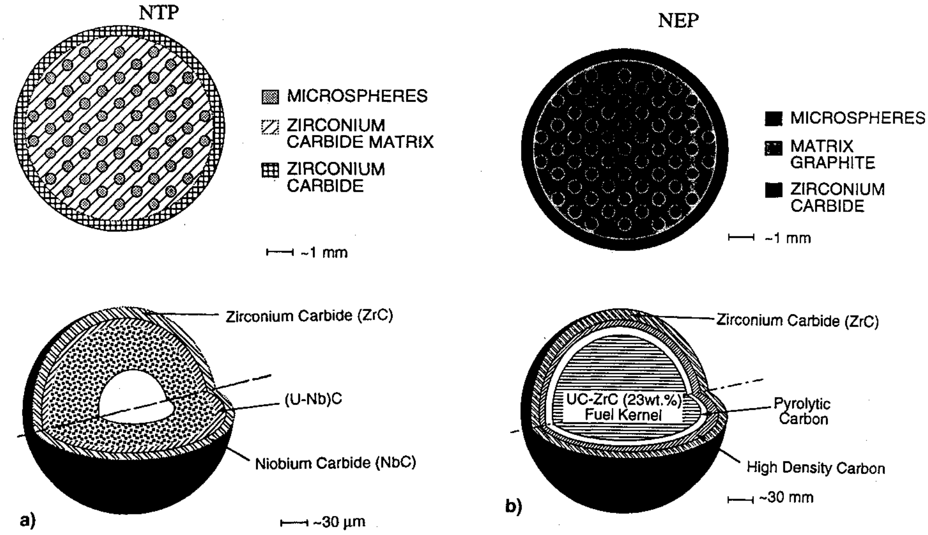


Fig. 2 Radial cross-sectional views of pellet and fuel microspheres in the PeBR for a) NTP and b) NEP applications.

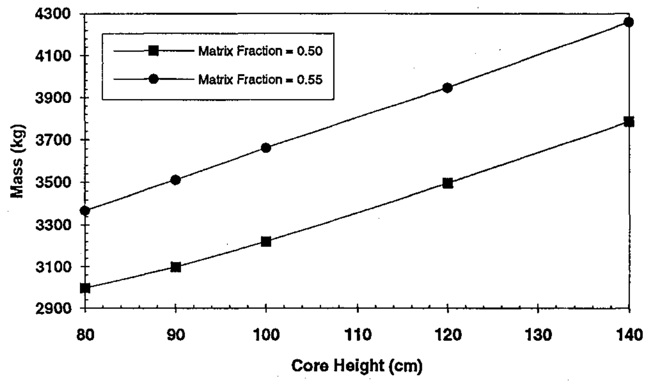


Fig. 3 Effect of pellet matrix fraction and core height on total mass of the PeBR for NTP.[10]

as a pressure vessel for a full retention of fission gases. The ZrC matrix in the pellet provides an additional barrier for the release of fission products from the fuel into the propellant flow.

A key for sizing the reactor core is the required excess reactivity (or the effective multiplication factor, k_{eff}) at BOM. The excess reactivity requirement at BOM depends on several considerations, including fuel depletion, Doppler broadening, and production of fission product poisons. Due to the fast neutron spectrum in the PeBR core, the effect of Doppler broadening is small compared to thermal reactors.[10] However, carbon loss by erosion of the ZrC matrix in the fuel pellets by hot hydrogen gas might affect the fuel requirements in the core at the BOM. The calculated reactivity requirement due to buildup of fission products during the total operation time of the reactor (9–15 h) at a thermal power of 1000–1500 MW, is negligible, $\sim 10^{-7}$ $\Delta k/k$.[14] Nonetheless, a k_{eff} of 1.01 (or excess reactivity of \$1.25) is used in the neutronics design to account for the above considerations, effect of geometry change due to thermal expansion, and error induced in transport calculations using the discrete structure of the neutron cross sections.[10]

Neutronics analysis for sizing the PeBR core for NTP is performed using the TWODANT neutral particle transport code.[15,16] The calculations used a two-dimensional, cylindrical representation (r, z) of the reactor core. As shown in Fig. 3, for a ZrC matrix fraction in the pellets of 0.5 and a reactor thermal power of 1000 MW (engine thrust of ~230,000 N), the total reactor mass increases from 2990 to 3785 kg as the core height increases from 0.8 to 1.4 m. These masses exclude those of the radiation shield, propulsion nozzle, external engines structure for the propellant flow into the core, and drive mechanisms of the control drums. For a pellet matrix fraction of 0.50 in a 1500 MW (approximately 310,000 N thrust) engine, the core power density decreases from about 3.3 to 2.7 MW/l as the core height increases from 0.8 to 1.4 m. When the reactor thermal power decreases by 33% to 1000 MW, the power density decreases by 35% to 2.2 and 1.8 MW/l for a core height of 0.8 and 1.4 m, respectively.

For these dimensions, the total peak-to-average power density ratio in the core ranges from 1.386 to 1.5.[10] This relatively low peak-to-average power density is due to the effects of the radial and axial reflectors (Figs. 1a and 1b). The radial reflector raises the fission power density at the core periphery, which increases the radial average-to-peak power density in the core. The axial reflector also decreases the axial peak-to-average power density in the core. Neutronics analysis of the PeBR for NTP applications also showed that the reactor has a total negative temperature reactivity feedback, an attractive safety and operation feature.[17] The total temperature reactivity feedback in the reactor core changes with increasing temperature due to the reduction in the moderating effect of the hydrogen coolant and in the macroscopic fission cross section. At an inlet propellant pressure of 9.0 MPa, the calculated temperature reactivity feedback in PeBR for NTP applications, changes from $-\$6.03 \times 10^{-3}$/K and $-\$1.29 \times 10^{-2}$/K at 300 K to $-\$6.21 \times 10^{-5}$/K and $-\$6.96 \times 10^{-4}$/K at 3000 K for the hydrogen and the fuel, respectively.[17] Figure 4a shows the normalized neutron energy spectrum in PeBR for NTP.[10,17]

An important design and safety requirement is to ensure that during water submersion, following a launch abort accident, the reactor remains subcritical with all the voids inside the reactor filled with water. Results of neutronics analysis indicate that the 16 control drums are insufficient to maintain the reactor subcritical when submerged in water. However, when an additional 8, B_4C safety rods are introduced into the reactor core at a radial position of 0.20 m (Fig. 1b), it is possible to maintain the submerged reactor subcritical in water by as much as 7.5 dollars (k_{eff} = 0.94). Another safety and operational concern is the coolability of the PeBR core after each firing operation. Active cooling had been proposed for the NERVA reactor using discrete pulses of hydrogen through the core over a period of 24 h.[18] The penalty of using active cooling for such a long time is the increase in the propellant mass. The additional propellant mass could effectively reduce the average specific impulse (I_{sp}) of the rocket engine by as much as 4–6%, depending upon the full power run time of the engine.[3,12] Therefore, a partial or a total passive decay heat removal is preferable, since it enhances both rocket per-

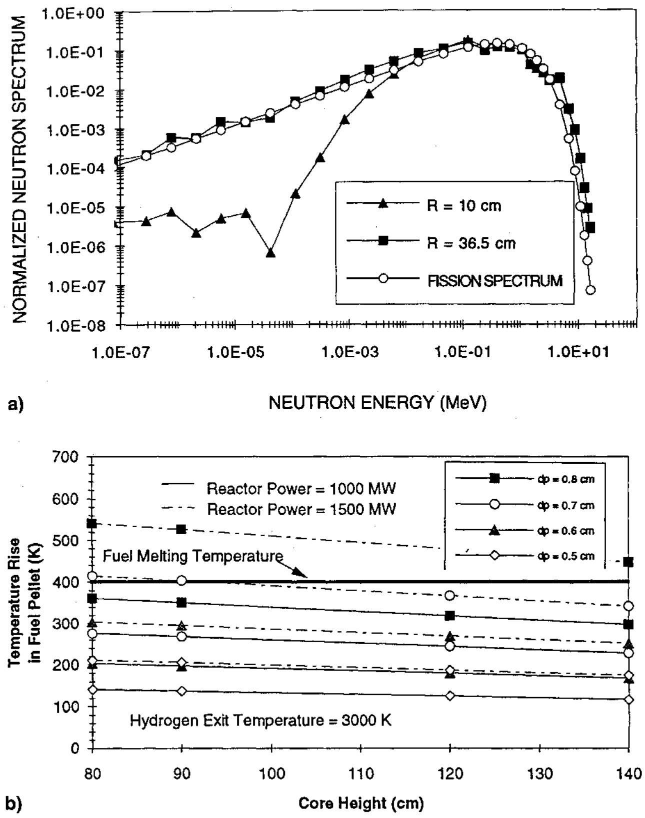


Fig. 4 a) Calculated neutron energy spectrum in the PeBR for NTP applications[10] and b) effect of pellet diameter and core height on maximum fuel temperature in the PeBR for NTP.[10]

formance and reactor safety. For example, when active cooling is used after a full power run time of 30 min, the average I_{sp} could be as low as 96% of its full power value.[3,12] However, with little active cooling required, as is the case in the PeBR,[4,6] the average I_{sp} could be as high as 99.6% of its full power value, for a net gain of approximately 40 s. This increase in the average I_{sp} in PeBR is equivalent to increasing the maximum full temperature in other solid-core concepts, requiring active cooling for hours after each firing operation, by an additional 140 K or more. Results of decay heat removal from a PeBR thermal rocket, after it has been operating at 1000 MW, showed that an active cooling period of 45 min to 1 h, followed by a passive decay heat removal will maintain the PeBR safely coolable.

To identify an optimum core point design, neutronics results are used as input to a thermal analysis of the fuel pellets using a one-dimensional thermal-hydraulics model of the PeBR core.[4] In this analysis, the hydrogen temperature at the exit of the core is kept at 3000 K ($I_{sp} \sim 1000$ s). Based on the results of the thermal analysis (Fig. 4b), a pellet diameter of 7 and 6 mm is suitable for reactor thermal power of 1000 and 1500 MW, respectively. For 1.20-m-height core, the maximum temperature in the fuel pellet at the peak fission power location in core is 220 and 150 K below the fuel melting point, at 1000 and 1500 MW, respectively. Results show that higher reactor thermal power favors smaller pellet size (larger heat transfer surface area); a pellet diameter of 6 mm is selected for operating at any thermal power of or below 1500 MW, while keeping the maximum fuel temperature in the core more than 200 K below its melting temperature. In summary, the selected PeBR point design parameters for NTP applications are as follows: 1) core diameter and height of 0.77 and 1.20 m, respectively; 2) pellet matrix fraction of 0.5; 3) total reactor mass of 3500 kg, excluding those of radiation shield, propulsion nozzle, external engines structure for the propellant flow into the core, and drive mechanisms of the control drums; 4) reactor core power density of 2.2 and 3.3 MW/l for a reactor thermal power of 1000 and 1500 MW, respectively, these power levels correspond to an engine total thrust of approximately 230,000 and 310,000 N, respectively; 5) total peak-to-average power density ratio in the core of 1.386; and 6) fuel pellet diameter of 6 mm.

Because of the nonuniform fission power profiles and the complexity of the flow and temperature fields in the PeBR,[10,17] a one-dimensional thermal-hydraulics analysis has been shown to be inadequate for characterizing the flow, pressure, and temperature fields.[4] Thus, a two-dimensional, steady-state nuclear propulsion thermal-hydraulics analysis model (NUTHAM) has been developed.[11,17] The design parameters and the calculated axial and radial fission power profiles are used in the two-dimensional thermal-hydraulics analysis of the PeBR for NTP. In an annular, fission heated, packed particle bed having a large aspect ratio (height-to-diameter ratio) much greater than unity, the radial flow in the bed is highly one-dimensional.[19] This type of flow can effectively be controlled by optimizing the axial porosity distribution in the cold frit commensurate with the nonuniform axial fission power profile, hence avoiding the development of hot spots.[19] However, as the aspect ratio decreases, the flow in the particle bed becomes more two-dimensional, and less dependent on the porosity in the cold frit. In this case, the flow and the pressure fields in the bed become more dependent on the porosity distribution in the hot frit. Therefore, in the case of the PeBR (aspect ratio ~1.56), changing the porosity of the hot frit, where the gas temperature and flow velocity are the highest, strongly affect the pressure field in the reactor core.

Therefore, in order to avoid developing a hot-spot in the PeBR core, it was necessary to optimize the flow porosity in the hot frit so that the regions of low-power generation experience lower hydrogen gas flow while the central region of the core is provided with a higher flow. The optimized axial porosity profile of the hot frit, determined by NUTHAM, is shown in Fig. 5. As shown in Figs. 6a and 6b, with an optimized hot frit, it is possible to avoid developing hot-spots, but at the expense of increasing the pressure losses in the core to about 1.0 MPa. These pressure losses are only about 11% of the inlet pressure of 9.0 MPa. With the optimized hot frit porosity distribution indicated, the axial maximum fuel temperature in the PeBR is almost uniform and equal to 3150 K (Fig. 6b); this temperature is 250 K below the fuel melting temperature. It is worth noting that the effectiveness of the porosity distribution in the hot frit depends not only on the reactor thermal power, but also on the coolant flow rate (e.g., during engine startup).[19] Future analysis of PeBR will address this important operation and safety question.

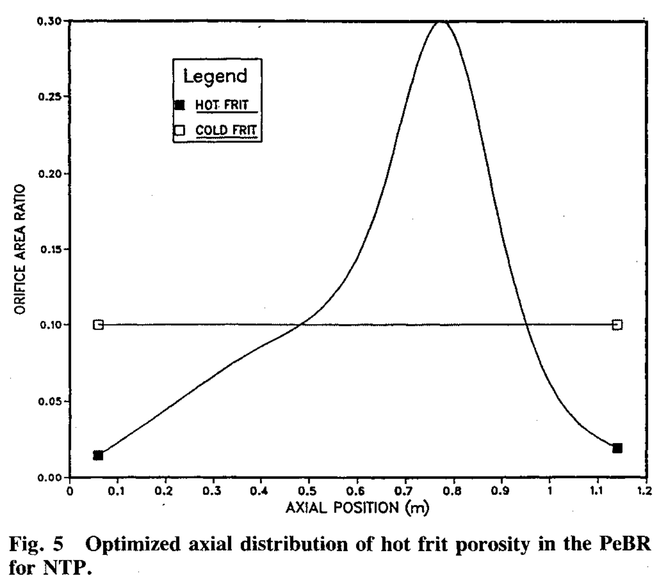
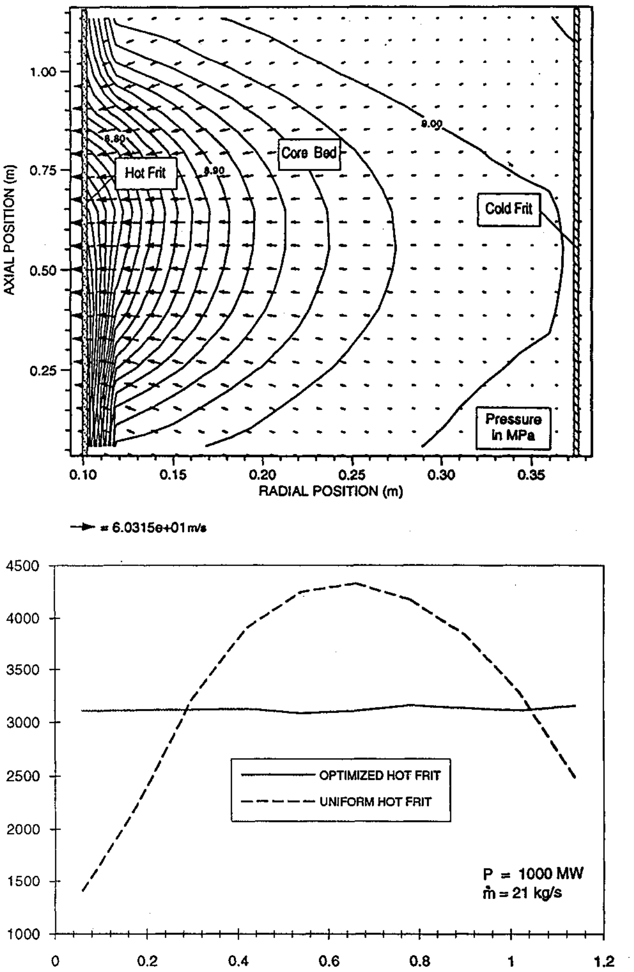


Fig. 5 Optimized axial distribution of hot frit porosity in the PeBR for NTP.



a) b)

Fig. 6 a) Velocity fields and pressure isobars for an optimized hot frit porosity profile in the PeBR core for NTP and b) axial fuel temperature profiles in the PeBR for uniform and optimized hot frits.

III. PeBR Design for NEP Applications

The PeBR for NEP applications has the same basic design as that for NTP, except it is cooled with helium (He) gas and employs larger size pellets (10 mm in diam). The composition of the pellets and the fuel microspheres are also different from those for NTP (Fig. 2). To eliminate the likelihood of a single-point failure in the core and enhance power system redundancy, the annular core of the PeBR is divided into three, 120 deg sectors (Fig. 7b). Each sector is self-contained, separate and distinct from the other sectors, capable of operating and being cooled on its own, and in cooperation with either one or two other sectors. Likewise, each sector has its own closed Brayton cycle (CBC) energy conversion engine. To enhance the overall system reliability, the three CBC engines are coupled to the main heat rejection radiator, but each engine has a separate flow duct through the radiator. Therefore, a loss of flow in one of the core sectors allows the use of the total radiator area to reject the heat for the other two core sectors. The heat rejection radiator for the CBC engines comprises of heat pipes of different lengths and different working fluids to cover the wide range of the He gas temperature drops expected in the radiator ducts (from 1100 to 430 K). Water heat pipes could be used in the lower temperature range, and potassium or sodium heat pipes at the higher temperature range. In the intermediate temperature range, sulfur-iodine heat pipes are attractive.[7]

Each fuel pellet in PeBR for NEP is composed of hundreds of TRISO-type fuel microspheres dispersed in a graphite matrix (Fig. 2). The TRISO microspheres consist of a UC-ZrC fuel kernel (~400–500 mm in diam) with a triple coating: inner coating of low-density, pyrolytic graphite (PyC), 15 μm thick; intermediate coating of high-density graphite, 5–10 μm thick; and a 10-μm-thick ZrC outer coating. Similar to the NTP fuel microspheres, the ZrC coating serves as a pressure vessel for the retention of fission products within the fuel kernel. The UC-ZrC fuel material has a melting temperature of 3693 ± 20 K, which at high carbon contents drops to 3123 ± 50 K at the $ZrC_{0.96}$ + C eutectic composition.[13] This temperature is still significantly higher than the peak fuel temperature expected at full power operation (2200–2300 K) for a He exit temperature of 2000 K. From the thermal-hydraulics point of view, the fuel pellets in the PeBR for NEP have a high heat transfer area-to-volume ratio (0.6–0.8 m^2/l), resulting in a specific mass of less than 4 kg/kWe for the entire power system, including the reactor, radiation shadow shield, structure, radiators, and energy conversion engines.[7] The radiation shield, located outside the reactor core, consists of two lithium hydride (LiH)-tungsten (W) layered portions that are actively cooled with the helium gas flow from the radiator at 430 K. The He gas exits the radiation shield structure to the compressor at 450 K. Because of the large height-to-diameter ratio of the PeBR core for NEP (1.2–1.5), the outer surface area of the reactor is large enough to enable the passive removal of the decay heat.[6] The decay heat generated in the reactor core is transported radially by both conduction and radiation in the core to the cold frit structure, then by radiation through the coolant feed annulus to the radial reflector (Fig. 7a). The heat in the radial reflector is then conducted to the reactor vessel walls and then to an auxiliary heat pipe radiator for rejection into space. This radiator, which is separate from that of the energy conversion engines, consists of potassium heat pipes that are formed around the radiation shield of the reactor core.

The PeBR employs two independent control systems with redundancy in each system: 1) 15 segmented Be_2C/B_4C control drums spaced equally within the radial Be_2C reflector, five in each sector (Fig. 7a), these drums maintain the reactor subcritical during launch; and 2) 6-B_4C safety rods, two in each sector, which are placed at about 0.20 m radial distance from the center of the core. The safety rods provide additional redundancy in the reactor control, while the control drums-safety rods combination ensures subcriticality of the reactor core in case of a water submersion accident. Should the option of fueling the reactor in orbit be selected, the launch procedures will be significantly simplified. Consequently, the radius of the core will be smaller, lowering the masses of the reactor, shadow shield, and the auxiliary radiator.

During power system operation, He gas exits the radiation shield at 450 K to the compressor and then returns to the PeBR reactor at 800 K (Figs. 7a and 7b). In the reactor, the gas first flows radially between the stainless steel reactor vessel wall and the top Be_2C axial reflector for cooling of the latter. It then flows axially downward through the annulus between the cold frit and the radial reflector to cool the reflector structure and the control drums. Then, the He gas flows radially through the cold frit structure into one of the PeBR core sectors to remove the fission heat generated in the fuel pellets (Figs. 7a and 7b). The hot He gas exits the core sectors through the hot frit to the center channel where it returns to the turbine. A small fraction of the He gas flowing through the outer annulus of the core sector is used to cool the Be_2C axial reflector at the bottom of the core, then mixed with the hot helium in the exit channel. The radial reflector and the reactor vessel wall are cooled by the auxiliary potassium heat pipe radiator, which is also used to remove the decay heat from the core after reactor shutdown or following a loss-of-coolant accident (LOCA) in one of the reactor sectors. The radial flow in the PeBR significantly reduces the pressure losses in the core, hence enabling the operation at low system pressure (1–5 MPa), which translates into thinner wall thickness for the connecting pipes and lower overall system mass. Since the radial temperature gradient within the PeBR core is less than

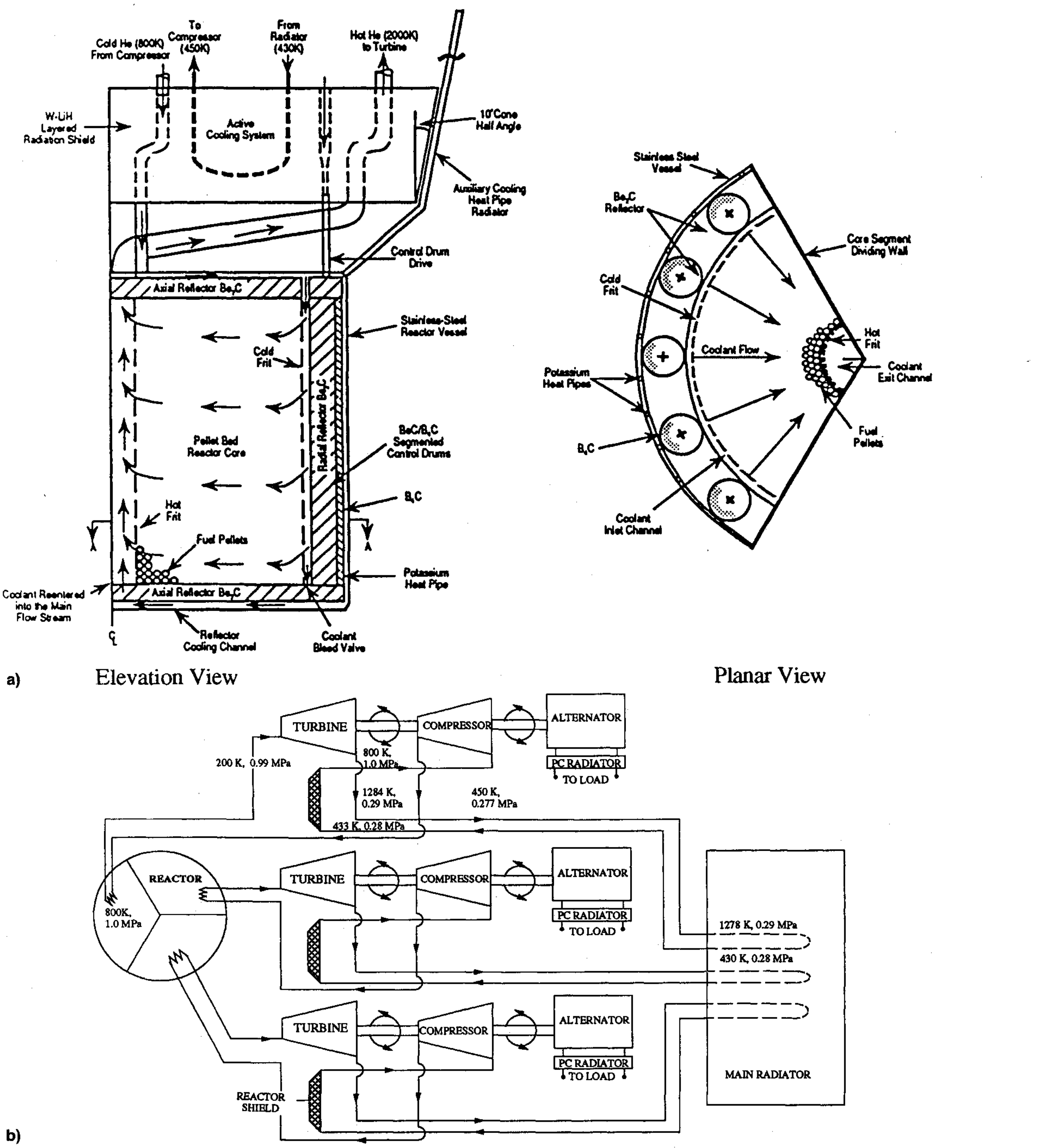


Fig. 7 a) Elevation and planar views of one 120-deg sector in the PeBR core and b) a schematic layout of the 15-MWe PeBR/CBC power system for NEP applications.[7]

5 K/mm, local hot spots and thermal stresses in the fuel pellets, due to flow inhomogeneity and nonuniform fission power profiles, are minimal.

Recently, Juhasz et al.[7] performed a conceptual design study of a 15-MWe power system for NEP based on PeBR that source to meet future Mars planetary transportation requirements (2–5 yr operation with high reliability, and up to 10 yr lifetime). A schematic of this power system, with the state points, temperatures, and pressures, is shown in Fig. 7b. The power system consists of three independent, He-CBC units each generating 5 MWe. The nominal thermal power of the nuclear reactor is 50 MW for an overall power system efficiency of 29.1%. The NEP power system's main radiator is a flat plate, heat pipe radiator that is shared by the three CBC loops (Fig. 8). The radiator is divided into five temperature regions, each of which is bounded by the temperatures corresponding to the operating limits associated with the selected heat pipe working fluids. The heat pipe working fluids, in a descending order from higher to lower temperature, are: sodium, potassium, cesium, sulfur-iodine, and water.[7] The major design features and operating conditions for the PeBR point designs for both NTP and NEP application are summarized in Table 1.

In NTP systems the mass of the reactor subsystem, which includes its internal hot shield, is typically a high percentage (greater than 70%) of the total engine system mass.[12] Hence, the reactor's specific mass is a good indicator of the NTP engine system mass, and can be used for relative mass comparison with other solid-core reactor concepts, when designed to meet the same basic requirements. At a low reactor thermal power, the core dimensions and thus the reactor mass, are driven by criticality considerations. At high powers, the core dimensions are driven by the operational power density in the reactor core, which depends on design parameters such as fuel elements surface-to-volume ratio, maximum fuel temperature allowed by the material selected, and fuel loading

Table 1 Point design features and operation parameters of the PeBR for NTP and NEP applications

Parameter	NTP	NEP	Parameter	NTP	NEP
Thermal power, MWt	1,000–1,500	50	Coolant flow rate, kg/s	24–32	2.75
Total electric power, MWe	NA[a]	15	Power density, MWt/l	2.2–3.3	0.1–0.3
System total efficiency, %	NA[a]	29.1	Thrust, kN	205–310	[c]
Coolant/propellant type	Hydrogen	Helium	Total operation time, h	5	25,000–40,000
Coolant inlet temperature	200 K	800 K	Total system mass, kg	[c]	49,300[b]
Coolant exit temperature	3,000 K	2,000 K	System specific mass, kg/kWe	NA[a]	3.29[b]
Specific impulse, s	1,000	3,000–5,000	Main radiator area, m^2	NA[a]	5,300
Maximum fuel temperature	3,250 K	2,200 K	Effective radiator temperature	NA[a]	645 K
			Excess reactivity at BOM, $	1.25	5–7.5

[a]Not applicable. [b]Excludes electric propulsion subsystem. [c]Not available at this time and are mission-dependent.

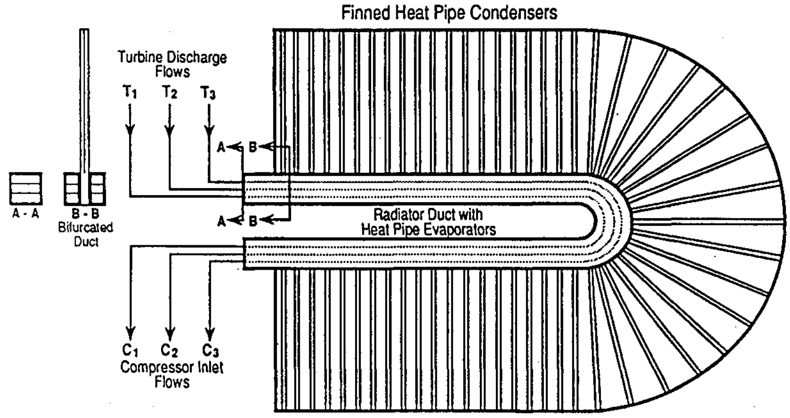


Fig. 8 Conceptual design of a flat plate heat pipe radiator for the PeBR/CBC power system for NEP.[7]

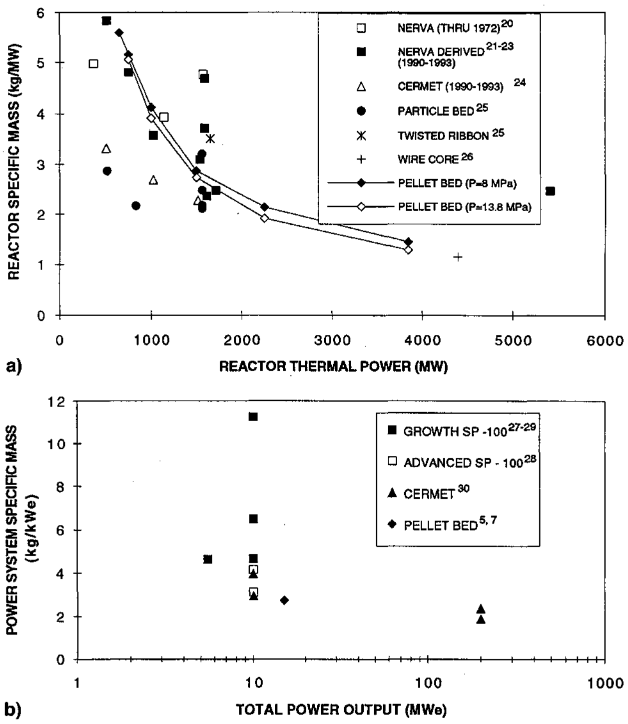


Fig. 9 Comparison of PeBR specific mass with those of other solid core reactor concepts for a) NTP and b) NEP applications.

and thermal conductivity. In addition, the masses of the moderator (if used), reflector, and radiation shield contribute to the total specific mass of the reactor. In Fig. 9a, the calculated specific masses in kg/MWt (which includes the internal hot shield) of the PeBR point design for NTP are plotted vs the reactor thermal power for a chamber pressure and temperature of 8–13.8 MPa and 3000 K, respectively. These specific mass values are compared with those of other comparable solid-core reactor concepts.[20–26] These concepts were designed to meet the long operating life and the high reliability requirements of planetary space exploration. The PeBR is slightly heavier than other thermal spectrum concepts (NERVA and NERVA derived) at low reactor thermal power, below 500 MWt. However, as the reactor thermal power and, hence the rocket engine thrust increases, PeBR specific mass compares more favorably with other advanced concepts such as the wire core, cermet, particle bed, and the Russian twisted ribbon fuel concepts. Because of the moderate surface-to-volume ratio (S-V) of the pellets, the PeBR offers a lower reactor specific mass than the NERVA/NERVA derivative concepts, but a higher specific mass than the particle bed reactor (PBR) concept (Fig. 9a). On the other hand, such moderate S-V ratio in the PeBR would significantly lower the hydrogen corrosion of the ZrC matrix in the pellets relative to that expected of the fuel microspheres in the particle bed reactor (PBR).[13] Figure 9b compares the total NEP system specific mass (including reactor, radiation shield, structure, energy conversion engines, radiator, and power conversion subsystem) with those of other comparable systems.[27–30] The values in Fig. 9b do not include the mass of the power conditioning subsystem. As this figure indicates the specific mass of the PeBR for NEP (~2.74 kg/kWe) compares very favorably with that of other advanced concepts. This specific mass for the PeBR system is lower than that listed in Table 1, because it excludes the mass of the power conditioning subsystem. In addition to the favorable comparison with other concepts based on the specific mass of the reactor and of the total power system for NTP and NEP, respectively, the PeBR possesses unique safety and operational features not offered by other solid core concepts. These features include the following:

1) A passive decay heat removal after firing operations enhances reactor safety and engine performance, resulting in a high average I_{sp} (about 40 s higher) due to the reduction in the mass of the hydrogen required for active cooling of the reactor core after firing operations.[12]

2) PeBR can be launched unfueled, and fueled after it reaches its operation orbit, or fueled on the launch pad. Also, if multiple reuse of the propulsion system is required, refueling the reactor can be accomplished remotely. This feature

not only enhances safety, increases operation lifetime, and reduces mission cost, but also simplifies ground handling and launch operations of the PeBR. However, the technology of remote refueling in orbit would have to be developed and demonstrated.[2]

3) Low neutron self-shielding in the PeBR causes a small differential in the fission power density within the fuel pellets, resulting in higher power density in the core, higher chamber temperature, and lower reactor mass.

4) With the successful optimization of the porosity distribution in the hot frit (Figs. 6a and 6b), no hot-spots are expected to develop in the core and hydrogen exit temperature from the hot frit would almost be uniform, despite the nonuniform fission power profiles in the reactor core. However, additional sensitivity analysis need to be done to investigate the effect of hot frit porosity optimization on the temperature and flowfields in the reactor core during transient operation, such as during startup or shutdown of the reactor.

5) Basic NTP reactor design and technology, except for some differences in material choices can be transferred to NEP and low-power bimodal applications (details in the next section). This is an attractive feature for enhancing reliability and minimizing development cost of future space exploration missions.

6) Average radial temperature gradient within the PeBR core for NTP and NEP applications is less than 7 and 5 K/mm, respectively, hence, thermal stresses would be insignificant.[19]

7) Non-nuclear, ground testing of the fully assembled PeBR reactor can be accomplished using electric heaters and non-nuclear fuel pellets. Although actual power and temperature profiles during ground testing with electric heaters will be different than those expected with fission heating, the test results can be used to benchmark reactor thermal hydraulics models, characterize pressure and flowfields in the reactor core, and measure induced stresses in the structure due to thermal cycling.

It is worth noting that based on the large sizes of the fuel pellets and the orifices in frits for the PeBR concepts, plugging the frits is highly unlikely. Also, no problem is foreseen regarding the design and reliability of the frits; the frit design and manufacturing technology is well in hand from the PBR technology development program.[31]

IV. PeBR Design Concepts for Bimodal Applications

Besides the high power NTP and NEP engine systems, bimodal nuclear reactor power and thermal propulsion systems could enable a variety of potential space missions.[32] Examples of these missions are planetary exploration, transport of payloads to geosynchronous (GEO) orbit at an overall saving in launch cost, and rapid change of flight orbit (within tens of hours instead of months with electric propulsion).[32,33] For these missions, the electric power could vary from a few to tens of kilowatts, for up to 10 yr, and the propulsion requirements include a thrust of tens to thousands of Newtons I_{sp} of 600–850 s, for hundreds of hours. These electric power and propulsion requirements exceed those currently achievable with solar and chemical propulsion options and are better met using nuclear reactor bimodal systems. Such systems also offer an electric propulsion option for orbit adjustment and limited maneuverability of satellites. Bimodal nuclear reactor systems can generally be classified into two categories, depending on mission requirements:

1) *Power driven (PoD) design*, in which the system is optimized based on considerations of electric power level. This system dictates the nuclear thermal propulsion capabilities attainable, for which the system is not optimized, that could include a thrust of a few to hundreds of Newtons and I_{sp} from 650 s to 850 s.

2) *Propulsion driven (PrD) design*, in which the system is optimized primarily based on thermal propulsion considerations. This system can provide hundreds to thousands of Newtons at an I_{sp} of 850 s or higher and power in the hundreds of kWe; likely for operation time less than that for the PoD design.

A PoD system design concept of a bimodal-pellet bed reactor (BM-PeBR) has been developed.[33,34] This system utilizes only state-of-the-art, low risk technologies and as much off-the-shelf hardware as possible in order to meet a near-term flight demonstration date, with little development required. The two point designs developed are for 10 and 40 kWe system can can easily be scaled to higher performance parameters at more favorable specific power. The reactor core for the BM-PeBR system consists of a single annular region filled with randomly packed, TRISO-type, 6-mm-diam mini-spheres, similar to the fuel microspheres in the pellets for the NEP reactor design (Fig. 2). The Inconel cold frit and the tungsten hot frit are made of a perforated structure with round openings that are 3–5 mm in diam. The axial porosity of the frits can be optimized to ensure a uniform maximum fuel temperature at the exit of the core of below 1600 K.[10] The BM-PeBR core has both radial and axial beryllium (Be) reflectors to help flatten the axial and radial fission power profiles. The radial reflector is thermally insulated from the reactor vessel using multifoil insulation to prevent overheating the reflector by the hot He-Xe working fluid entering the core (inlet temperature ~900 K) and/or after reactor shutdown (Fig. 10). An auxiliary, sodium heat pipe radiator is conductively coupled to reactor vessel for passive cooling and decay heat removal from the reactor core. This radiator is separate from the main radiator for the energy conversion engines. The heat generated in the radial reflector by fast neutrons and gamma radiation is rejected by radiation into space.

The excess reactivity in the BM-PeBR at BOM is approximately \$1.5 at a 1600 K core temperature (k_{eff} = 1.012), for which the optimized dimensions of the core, 0.32 m diam and 0.45 m height, are determined using three-dimensional MCNP neutronics calculations.[34] The BM-PeBR also has a total negative temperature reactivity feedback of as much as \$3.0 at 1600 K, an excellent safety and operation feature. The reactor thermal power for the PoD point designs of the BM-PeBR, determined using CBC engines efficiency of 22.7% with a recuperated cycle, is 44 and 176 kWt for the 10- and 40- kWe systems, respectively (Table 2). The temperature of the He-Xe gas to a CBC engine is kept at or below their design values of 1144 K, respectively.[35] The 10-kWe CBC engines have been tested successfully at the above efficiency and at an inlet turbine temperature of 1144 K for 39,000 h. At this temperature, the specific mass of the CBC engines increases from approximately 34 We/kg for the 3.3-kWe units to 43 We/kg for the 13.3-kWe units.[35] Since the reactor thermal power is quite low, the thickness and mass of the radiation shadow shield would also be low. The shield is located outside the reactor core and consists of lithium hydride (LiH) cast in a stainless-steel or aluminum honeycomb structure and enclosed in a

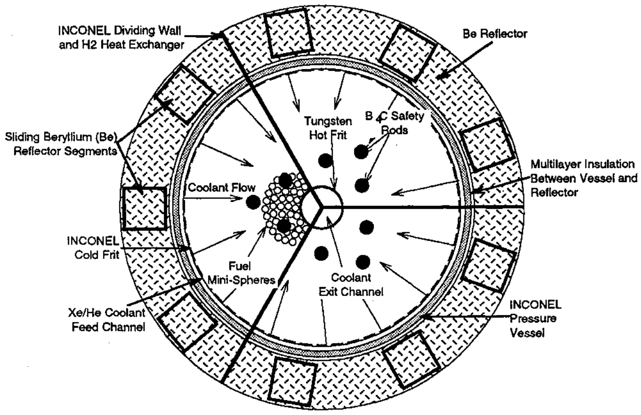


Fig. 10 Radial cross-sectional view of the BM-PeBR design concept.[34]

Table 2 Design parameters and mass estimates of the PoD point designs of the BM-PeBR system

Parameter	Value	
Core dimensions		
Height/radius, m	0.45/0.16	
Hot/cold frit thickness, mm	2.0/2.0	
Minispheres packing in core, %	62	
Axial/radial reflector thickness, mm	45/80	
Materials/operation		
Fuel enrichment (wt.%)	9.5	
Fuel material	UC	
Hot/cold frits	W/Inconel	
Core sector dividers	Inconel/W	
Hydrogen heat exchanger	W/Re	
Reactor vessel	Inconel	
Reflector	Be	
Propellant	H_2	
Coolant type	He/Xe	
Turbine inlet temperature	1144 K	
Maximum fuel temperature	1600 K	
Parameter	**10-kWe system**	**40-kWe system**
Mass		
Reactor, kg	327	347
Radiation shield,[a] kg	180	320
CBC engines subsystem,[b] kg	295	920
Propulsion subsystem,[c] kg	50	125
Additional structure, kg	50	100
Total system, kg	902	1812
Reactor thermal power, kW	44	176
Operation lifetime, yr	10	10
BOM excess reactivity at 1600 K, $	1.1	1.5
Temperature reactivity feedback, $	−1.1	−3.0
Propulsion time, h	>250	>250
Auxiliary radiator area, m^2	2.0	1.0
Main radiator area, m^2	24.9	75.6
Radiator specific mass, kg/m^2	5	5
CBC specific mass, kg/kWe	29.5	23
Total system specific power, We/kg	11.0	21.9
Thrust, N	7–14	25–55
Specific impulse, s	650–750	650–750

[a]Includes radiator, turbo-alternator, cooler, ducting, control/power conditioning, parasitic load radiator, structure, and miscellaneous.
[b]Excludes separation boom structure.
[c]Excludes propellant tank assembly.

stainless steel canister. The large height-to-diameter ratio of the BM-PeBR also lowers the radiation shield mass (Table 2).

Basically, there are two types of fuel elements that can be used in BM-PeBR concepts. For PoD reactor designs operating at low thermal power (<500 kWt) for up to 10 yr, a TRISO-type minisphere design (4–6 mm in diam) is preferred.[33] This fuel element design provides high fuel loading in the core to satisfy the excess reactivity requirement at BOM as well as results in smaller reactor size and mass. The basic design and coating materials of the fuel minispheres are identical to those for the TRISO-type microspheres with silicon carbide (SiC) coating. However, the technology to apply a multilayer coating to a 4–6-mm-diam fuel minispheres needs to be demonstrated. The maximum fuel burnup expected in the 40-kWe point design of the BM-PeBR system is less than 1.0 atom %, and about four times less in the 10-kWe system. However, for conservative design considerations, the minispheres are designed for a fuel burnup of 2 atom % and maximum temperature of 1600 K.[33] The maximum stress in the SiC coating of the minispheres when loaded with UC and UO_2 fuel is about 73% and 20% of the design stress of the coating, respectively.[33] The fuel material considered for the PoD point designs of the BM-PeBR is either uranium dioxide (UO_2) or uranium monocarbide (UC), since their fabrication techniques are known and they have an extensive irradiation data base. Despite their good irradiation stability, thermal cycling during bimodal operation would cause UC and UO_2 to crack, increasing fission gas release. The fuel swelling and fission gas release also increase rapidly with fuel temperature, presenting a strong incentive to lower the fuel temperature in the core. For these reasons, the maximum fuel temperature in the BM-PeBR point designs is limited to 1600 K, which is maintained almost constant during the power and propulsion modes to minimize thermal stresses in the fuel elements and core structure. Among the two fuel materials considered, UC offers significant improvement in properties, operation, and performance over UO_2. The higher atom density and the significantly higher thermal conductivity of UC reduces the critical size and mass of the fast spectrum PeBR. Because of the superior neutronics and thermal properties of UC, it was selected as the fuel of choice for the PoD point designs of the BM-PeBR at the low electric power levels of 10–40 kW (Table 2).[33,34]

The relatively large height-to-diameter ratio of the PoD design of the BM-PeBR core (Table 2), the small radial heat transfer path in the core, and the large outer surface area of the reactor enable full passive cooling and decay heat removal from the reactor core. A thermal-hydraulic analysis of the BM-PeBR is performed using a three-dimensional, conduction/radiation representation of the BM-PeBR core.[6,33] Results showed that for the reactor dimensions specified by the neutronics analysis, the passive heat removal capability of the core is more than 29 kWt. This power level, which is about 65 and 16% of the operating reactor for the 10- and the 40-kWe BM-PeBR system, respectively, is much higher than the decay heat levels expected in PeBR (≤8% of the steady-state reactor power before shutdown). The BM-PeBR employs two independent control systems with redundancy in each system: 1) nine sliding reflector segments that are spaced equally within the radial Be reflector, three in each sector,[34] these segments are kept open in the shutdown mode of the reactor; and 2) nine 35.0-mm-diam, B_4C safety rods, three in each sector (Fig. 10). The safety rods provide additional redundancy in the reactor control, while the control segments-safety rods in combination ensure subcriticality in case of a water submersion following a launch abort accident.[34]

In the power mode, the BM-PeBR is cooled with a He (70 mole %)-Xe (30 mole %) gas mixture which also serves as the working fluid for the CBC engines. The hot gas flows radially through the core sectors and the hot frit to the central channel, and exits the core at about 1350 K. It mixes with a cooler gas (900 K) that is bled from the main gas flow before entering the reactor core. The mixing ratio of the two gas streams is adjusted to keep the gas temperature at the inlet of the turbine at the CBC units design value of 1140 K.

To eliminate the likelihood of a single-point failure in the reactor cooling system and enhance system redundancy, the annular core of the PeBR is divided into three, 120-deg sectors as previously mentioned for NEP reactor design. Each sector in the core has its own CBC energy conversion engine. The He-Xe gas from the compressor enters the feed annulus and cools the reactor vessel, then is bled through the cold frit to flow radially through the core. The radial temperature gradient in the core at full power is <1.5 K/mm; thus thermal stresses are negligible. In the propulsion mode, He-Xe continues to flow through the core, while H_2 propellant flows axially through heat exchangers built into the core sector dividers.[33] In addition, the electric power generated when operating in the power mode can partially be used for electric propulsion to provide low-cost on orbit maneuverability.

V. Concluding Remarks

The pellet bed reactor concepts for nuclear thermal and nuclear electric propulsion, and bimodal applications are described and their point design and safety features and operational parameters are presented and discussed. This annular core, fast spectrum reactor offers many desirable performance and safety features. These features include: high-power density, small reactor size, full retention of fission products, passive decay heat removal, negative temperature reactivity feedback, redundancy in reactor control, ground testing of the fully assembled reactor using electric heating and non-nuclear fuel elements, and the option of fueling on the launch pad, or fueling and refueling in orbit. In addition to these features, the PeBR concepts for nuclear electric propulsion and bimodal applications have no single point failure. The specific masses of the PeBR reactor for NTP applications, including its internal hot shield, compares favorably with those of other comparable solid-core reactor concepts, which were designed to meet the same basic NTP requirements. The specific mass of the PeBR-NEP total system engine, excluding the propulsion and power conditioning subsystems, also compares favorably with those of other solid-core reactor, advanced NEP systems. The PeBR concept offers the design flexibility to meet a wide spectrum of NTP, NEP, and bimodal mission requirements. The technologies that it employs and the conditions that it operates at are all within the state-of-the-art limits, which translates into low development risk and cost.

In addition to being modular and scalable, the BM-PeBR system operates at low maximum fuel temperature (<1600 K) that is maintained almost constant during the power and propulsion modes. The performance parameters of the 10 and 40 kWe point design system concepts include a specific impulse >650 s, thrust from 7–55 N or higher, and a specific power of 11.0 and 21.9 We/kg at 10 and 40 kWe, respectively. Future emphases on the development of the PeBR concepts should focus on 1) studying the dynamic behavior and stability of the reactor; 2) benchmark experiments to verify the thermal-hydraulics characteristics of the reactor core, fuel pellet design, reactor criticality and safety; 3) feasibility of non-nuclear testing of the fully assembled reactor; and 4) additional engineering analyses of the reactor and its application(s).

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