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SAFETY ASPECTS OF PARTICLE BED REACTOR PLUTONIUM BURNER SYSTEM

J.R. Powell, H. Ludewig, M. Todosow
Reactor Systems Division
Brookhaven National Laboratory, Upton, NY 11973
(516) 282-2624

ABSTRACT

An assessment is made of the safety aspects peculiar to using the Particle Bed Reactor (PBR) as the burner in a plutonium disposal system.

It is found that a combination of the graphitic fuel, high power density possible with the PBR and engineered design features results in an attractive concept. The high power density potentially makes it possible to complete the plutonium burning without requiring reprocessing and remanufacturing fuel. This possibility removes two hazardous steps from a plutonium burning complex. Finally, two backup cooling systems depending on thermo-electric converters and heat pipes act as ultimate heat removal sinks in the event of accident scenarios which result in loss of fuel cooling.

INTRODUCTION

The disposal of weapons grade plutonium by "burning" it in high flux reactors has been proposed by DOE. A Particle Bed Reactor (PBR) has been proposed as a candidate reactor for this purpose, PBR's can be characterized by having separate fuel elements embedded in a moderator, which are composed of directly cooled particulate fuel. The direct cooling of the particulate fuel results in extremely good heat transfer from the fuel to the coolant, making it possible to operate at extremely high power densities. This ability to operate at high power densities makes it an attractive candidate to efficiently "burn" unwanted fissile material. PBR's also have several safety features which set it apart from other high flux reactors. These features include the ceramic nature of the fuel particles, low fissile inventory, and choice of structural materials to ameliorate accident consequences.

DESCRIPTION OF THE PARTICLE BED REACTOR PLUTONIUM BURNER

The Particle Bed Reactor (PBR) has fuel elements arranged in a hexagonal pattern and surrounded by a suitable moderator (e.g., graphite, beryllium carbide, heavy water, etc.). Each fuel element consists of small diameter fuel particles packed into an annular fixed bed, which is held between two coaxial porous tubes (frits). In the baseline configuration of the PBR/Pu Burner, inlet gas coolant flows radially through the inner frit, is heated in the fuel bed and exits through the outer frit. It then flows axially out between the elements. The inner (inlet) frit is termed the cold frit and the outer (outlet) frit, the hot frit. In other design configurations, it may be desirable to have the coolant flow in the reverse direction; that is, the coolant would enter through an outer cold frit, flow radially inwards through the packed particle bed and exit through the inner hot frit.

Direct cooling of the fuel particles results in very efficient heat transfer, allowing very high power densities (on the order of 5 MW/liter for the Pu Burner). Operating at these high power densities results in very rapid burn up of fissile material in the fuel particles.

The PBR Pu Burner concept is based on the PBR nuclear rocket system currently under development by the Air Force Space Nuclear Thermal Propulsion (SNTP) Program. It draws on much of the technology that has been developed by the SNTP Program including fuel particles, frits, thermal hydraulics, neutronics, etc. In general, the operating parameters for the PBR Pu Burner (power density, temperature, coolant corrosion, etc.), are much less stressing than those required for the SNTP Program, and it is expected that the Burner components will be substantially simpler and easier to develop and qualify.

The basic building blocks of the PBR are the fuel particles. These particles are similar to those used in the High Temperature Gas Cooled Reactor (HTGR), with a diameter of approximately 500 microns (0.5 mm). Each particle consists of a central graphite kernel that contains an admixture of fissile plutonium. There is an outer coating of pyrolytic graphite that contains the fissile Pu loading, as well as all the fission products that are generated (including noble gases).

The integrity of HTGR fuel particles is excellent. Typically, only about one particle in 10^5 releases fission products to the coolant stream under irradiation. The very small amount of released fission products can readily be trapped out. The fuel particles in the PBR-Pu burner are expected to exhibit even greater integrity, since their internal gas pressure due to fission

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products is approximately a factor of 10 lower than the pressure inside present HTGR particles.

Figure 1 shows the baseline fuel element design for the PBR-Pu burner. The fuel element structure (frits, etc.) remains in place inside the reactor core. The fuel particles are hydraulically loaded and unloaded into each fuel element, when appropriate, by a side coolant stream. The reactor would be shut down during load/unload operations. Normally, fuel particles remain in the core on the order of 2 to 4 weeks, with the residence time being a function of the reactor design parameters.

When loaded as fresh particles, the average Pu content is ≤ 0.2 g/cm^3 of particles, with the Pu being almost pure Pu^{239}. When unloaded as spent particles, the average Pu^{239} content is a factor of 20 smaller. Virtually all of the original Pu^{239} has either fissioned or been converted to higher isotopes of Pu (e.g., Pu^{240}) or other elements (e.g., Am and Cm). This waste material, even if some group were to recover and reprocess it, would not be suitable for weapons purposes. The PBR-Pu Burner is thus very proliferation resistant, since the discharged fuel need not be reprocessed or safeguarded.

Because of its small size and capability for simple, quick unloading and refueling, the fuel inventory in the PBR-Pu Burner is very low and the neutron flux level very high. This results in very rapid burnup of the fissile material in the reactor. The fissile and fission product inventory in the PBR-Pu burner are less than one tenth of that in a commercial LWR power reactor, which is very attractive from the standpoint of safety.

The baseline reactor core design based on the fuel element described above takes the shape of a series of hexagonal rings shaped patterns contained in a moderator volume. This arrangement is shown schematically on Figure 2. In the design considered here the moderator is beryllium carbide (Be_2C). However, any moderator with low neutron capture properties could be used. The pitch of the hexagonal rings can be varied, changing the neutron energy spectrum. Depending on design, the spectrum can range from thermal to epithermal, and would be chosen to yield optimum performance.

Core configuration A corresponds to a loading strategy in which elements containing fresh fuel particles (black circles) alternate with elements containing high burnup particles (light circles). Once loaded, fuel particles remain in place until they are unloaded. The positions of black and light circles thus swap places during the fuel cycle, returning to their original position after a full cycle has been completed. Configuration B is a "seed-blanket" type of arrangements, in which fresh fuel particles are always placed at the dark circle locations shown, being shuffled to the high burnup light circle locations at an appropriate point during the fuel cycle.

Two burner reactor design approaches are being investigated. The baseline approach used helium coolant, with the outlet temperature in the order of 1000K and the inlet temperature approximately 300K. The hot frit would be made of Incollay, and the cold frit of Zircalloy. Helium is neutronically benign and chemically inert. Operating pressure is assumed to be 7 MPa. The alternate design approach uses light water as a coolant. Operating conditions in this design are similar to a light water reactor with the outlet temperature approximately 575K and the inlet temperature close to room temperature. The hot frit and cold frit are both made of Zircalloy. Operating pressure for this design is approximately 15 Mpa.

SAFETY ASPECTS OF THE PARTICLE BED PLUTONIUM BURNER

The PBR "burner" concept possesses safety aspects which are centered around unique features of the reactor concepts. These features are related to the particulate fuel, ability to remove large amounts of heat, and design features associated the particular reactor design.

FEATURES ASSOCIATED WITH THE PARTICULATE FUEL

Particulate fuel to be used in the proposed plutonium "burner" reactor consists of a graphitic kernel containing the fissile material, and coated by appropriate graphitic and metal carbide layers. It is estimated that this particle will be able to survive temperatures of up to 2500K, thus allowing for a large thermal margin above operating temperature levels. The mixed mean coolant outlet temperature of the proposed reactor is approximately 1000K, thus allowing a margin of 1500K at the outlet end.

The critical fissile loading at beginning of life is composed entirely of Pu-239, and is 53 Kg. This mass of fuel is spread out over 240 l of particulate fuel bed, resulting in an extremely low plutonium loading per particle. Since the fuel particle size is fixed by fluid dynamic and heat transfer constraints, the low loading results in a large volume, within the kernel for fission products. This large open volume is made possible by the use of graphite as the basic kernel material. Thus, it should be possible to completely transmute the initial fissile inventory without building up an inordinate inventory of fission products in the particles, resulting in low internal pressure despite high burn-up. Thus, even in an accident situation which results in particle heat-up the increase in pressure within the particle will be modest, resulting in few if any particle failures due mechanical failure.

Finally, the total fission product inventory within the core will be extremely low compared to commercial light water reactors. Thus, if an accidental release should occur the implied consequences will be correspondingly lower.

FEATURES PECULIAR TO THE PBR

The PBR is characterized by direct cooling of the particulate fuel, and this property has safety implications as well as operational implications. The extremely large heat transfer area per unit volume possible with particulate fuel (approximately 100 cms.^{2}/ cms.^{3}) makes it possible to operate at extremely high power densities within the bed (5 MW/l-10 MW/l). In the case of accidents which involve either an interruption in cooling or a depressurization following scram this efficient heat removal ability makes it possible to remove the decay heat with easily engineerable features described below.

The extremely high heat transfer area makes it possible for the fuel particle surface to operate at close to the mixed mean gas temperature. Furthermore, the small conduction path together with the good convective heat transfer ensures that the maximum centerline temperature is close to the gas temperature. This results in the maximum temperature margin possible which is desirable in under cooling accidents. This margin is as large as it can be for any combination of fuel type, and outlet temperature in the case of the PBR. The almost complete and rapid destruction of the plutonium has safety and safeguards implications. It is desirable to minimize the number of times the fuel needs to be removed to be reprocessed and or reconstituted. In the PBR burner system it is not necessary to remove the fuel from the reactor to be reprocessed. This eliminates all the safety issues associated with reprocessing. Once the fuel is removed from the reactor the particles can be disposed of in a suitable waste disposal area.

FEATURES ASSOCIATED WITH THE PROPOSED PBR DESIGN

The proposed PBR design includes two passive safety systems to guard against a fission product leak to the environment from any accident scenario.

An auxiliary residual heat removal system will be included in the cooling loop (schematically shown on Figure 3), and is designed to maintain adequate cooling flow for a scrammed reactor even if the primary system is depressurized. It uses multiply redundant gas circulators powered by thermo-electric converters. These converters will generate sufficient electricity to operate the cooling circulators to remove all the decay heat at atmospheric pressure. Thus a depressurization accident following scram can be tolerated and will not result in the release of fission products.

In the event that there is a failure in the above mentioned cooling system, and there is not cooling flow to the particle bed, the resulting fuel heat-up will melt the safety plugs. A schematic of these plugs is shown in Figure 1. The particles, which would not be damaged by this over-heating event, would drop into a core catcher. The core catcher volume would be cooled by passive heat pipes, which would discharge their heat to the atmosphere. Furthermore, the core catcher would be designed and constructed in such a manner to guarantee the occurrence of a secondary criticality.

The two systems outlined above are based on known technology, and only needs to be demonstrated in an integrated test. The development program for the proposed PBR would include these tests as part of the system feasibility validation.

CONCLUSIONS

The following conclusions can be drawn from this study:

1) The use of particulate ceramic fuel makes it possible to have a fuel which will survive to extremely high temperatures. This ability coupled with the high heat transfer, allows fuel temperatures to be very close to gas the temperature during operation.

2) The high power densities possible, allows this reactor to essentially burn all the fissile material, and the low operating inventory greatly reduces the fission product inventory for release during accidents.

3) The almost complete destruction of the plutonium, reduces safeguards concerns.

4) The proposed PBR design has two redundant safety systems. These are thermoelectric driven circulation and a core catcher to contain any molten fuel. The thermoelectric circulators are sized to remove all the decay heat even in the event of a depressurization accident.

5) The ability of the PBR system to essentially burn all the plutonium makes it possible to dispose of the burner fuel without reprocessing. This is an additional safety advantage, since during reprocessing fission product release is also possible.

The two safety systems outlined above are based on known technology, and only needs to be demonstrated in an integrated test. The development program for the proposed PBR would include these tests as part of the system feasibility validation.

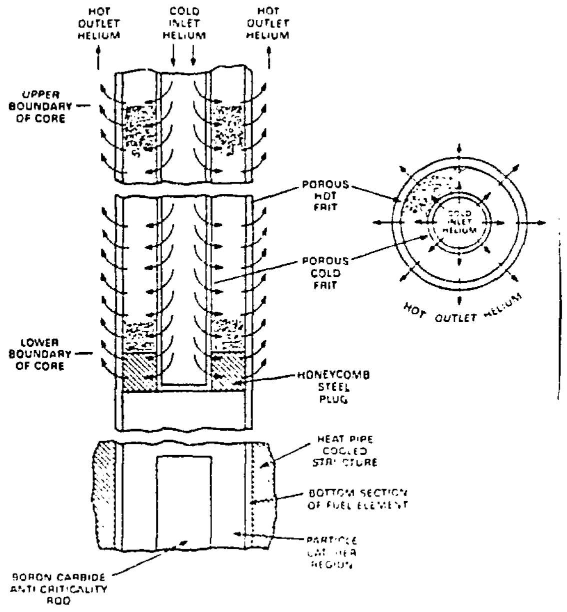

Figure 1

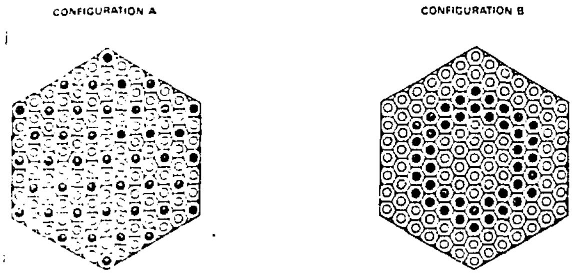

Figure 2

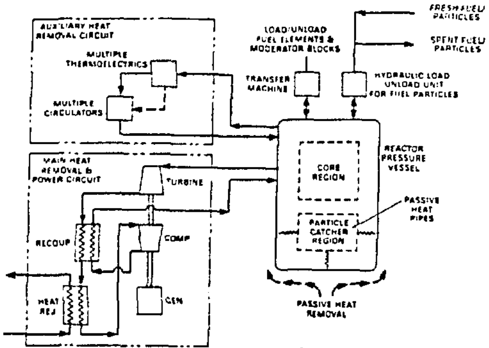

Figure 3