COMPACT NUCLEAR POWER SYSTEMS BASED ON
PARTICLE BED REACTORS*

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ABSTRACT

Compact, low cost nuclear power systems with an extremely low radioactive
inventory are described. These systems use the Particle Bed Reactor (PBR), in which
HTGR particle fuel is contained in packed beds that are changed daily. The small
diameter particle fuel (500 μm) is directly cooled utilizing the large heat transfer
area available (7.8 m²/liter), thus allowing high bed power densities
(MW/liter).

NUCLEAR REACTORS based on the Particle Bed concept have the advantage of being compact
as well as highly efficient in their heat transfer properties. The proposed class of
reactors covers the range from 600 to 3000 megawatts, with either deuterium oxide or
helium as a coolant. The size of the reactor core is only 1.2 to 2.0 meters in
diameter and length; therefore, with the 0.3 meter thick D₂O reflector, the outer
pressure vessel is 2.0 to 2.8 meters in diameter.

The particle bed reactor is fueled with spheres about a half-millimeter in
diameter, which are immersed directly in the coolant. The spheres are not dispersed
in some other solid material as in previous applications. The outer pyrocarbon layer
is coated with silicon carbide or zirconium carbide to make the particle even more
impervious to the coolant and to the release of fission products (Ref. 1). The
small particle size produces a large heat transfer surface, for example, there are
studied as to life and fission product retention; however, in this proposed
design, the fuel is used for only one or two days and then discharged. The build-up
in the reactor of the longer-lived fission products is prevented. The new fuel, which
is added every day or two, will have a high burnup because the fuel inventory is in the
order of ten kilograms of ²³⁵U. The mechanism for charge and discharge is
simply the pneumatic transfer of the particles from one container to another
(Fig. 2). To prevent the necessity of shutting down the reactor for refueling,
"on-line" fuel loading may be accomplished as is illustrated in Figure 3.

The safety of the reactor is greatly enhanced because its maximum fission
product content is extremely low compared to conventional reactors that burn their
fuel for many months or years. Any discharge of radioactivity must, of
consequence, be many orders of magnitude less than a conventional reactor. The
discharged fuel will be stored in nuclear safe containers while awaiting periodic
shipment to a reprocessing plant. The total amount of fuel discharged over a year
will be approximately the same as a conventional plant of the same power.

The table of proposed reactor designs (Table 1) indicates ²³⁵U fuel loadings from
7 kg at 600 MW to 20 kg at 3000 MW. The burn-up after two days is 17% and 30%
respectively, and the fuel enrichment needed is 5.8 and 4.2% respectively to give
K_eff=1.15 (Fig. 4). The reactors cooled with D₂O include the 600 MW and the
1000 MW, which have a discharge temperature of 327°C. The D₂O is fed to a conventional
light water saturated-steam generator for electric power generation. The helium
cooled reactors have a discharge
megawatts, with either deuterium oxide or helium as a coolant. The size of the reactor core is only 1.2 to 2.0 meters in diameter and length; therefore, with the 0.3 meter thick D₂O reflector, the outer pressure vessel is 2.0 to 2.8 meters in diameter.

The particle bed reactor is fueled with spheres about a half-millimeter in diameter, which are immersed directly in the coolant. The spheres are not dispersed in some other solid material as in previous applications. The outer pyrocarbon layer is coated with silicon carbide or zirconium carbide to make the particle even more impervious to the coolant and to the release of fission products (Ref. 1). The small particle size produces a large heat transfer surface, for example, there are 7.8 square meters of area in every liter of fuel. Experiments of Reference 2 show that 1 MW/liter can be removed by coolant.

The result of this large area is that at a power generation rate of five megawatts per liter of bed, the temperature difference between the particle and a gas coolant is only about one hundred degrees Celsius (Ref. 3). The small particles also have about a ten degree temperature difference from the center to their surface at this power density. The coolant temperature will vary by hundreds of degrees in passing through the bed, but the fuel operates near the coolant temperature and is not highly heated (Ref. 4).

The reactor fuel is the high-temperature gas-cooled reactor pellets, which has been in use for many years (Fig. 1). Its characteristics in various configurations have been well

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The 1000 MW reactors cooled with D₂O and helium are similar in design with 69 pressure tubes and a 1.5 m core diameter and length. The only difference is the higher pressure drop of the helium in the reactor compared to D₂O (about four times), although both pressure drops are acceptable.

The zircaloy-2 pressure tube design is illustrated in Figure 5. The materials proposed are shown as well as some nominal thicknesses. The frit materials holding the fuel were assumed to be zircaloy-2 with 50% porosity, 1.5 mm thick on the inlet and 3.0 mm thick on the outlet frit. The beryllium moderator surrounding each pressure tube element varies in thickness.
with each design from 18 mm to 46 mm, while maintaining a 3 to 1, Be to D₂O ratio. The power density in the fuel varies from 0.8 to 2.4 MW/liter as shown in Table 1. The pressure tubes vary in diameter from 99 mm to 155 mm and are also shown.

In conclusion, the particle bed reactor offers advantages over conventional power reactors in size and inherent safety when continually refueled because of the small inventory of fission products. The fuel is of a proven type with some development needed in fuel element design and fuel transfer capability. The possibility of on-line refueling of one fuel element at a time, should be investigated.

References


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TABLE 1
Design Parameters For Six Particle Bed Power Reactors
With $K_{\text{eff}}=1.15$

<table>
<thead>
<tr>
<th>Reactor No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>Reactor Thermal Power (MW)</td>
<td>600</td>
<td>800</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>3000</td>
</tr>
<tr>
<td>Type of Coolant</td>
<td>$D_2O$</td>
<td>He</td>
<td>$D_2O$</td>
<td>He</td>
<td>He</td>
<td>He</td>
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<tr>
<td>Core Diameter &amp; Length (m)</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>Reactor Outlet Temp. (°C)</td>
<td>327</td>
<td>800</td>
<td>327</td>
<td>800</td>
<td>800</td>
<td>800</td>
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<tr>
<td>System Operating Pressure (atm)</td>
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<td>51</td>
<td>136</td>
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<tr>
<td>Bed Fuel Loading (kg $^{235}U$)</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>20</td>
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<tr>
<td>Enrichment of Fuel (%)</td>
<td>5.8</td>
<td>6.4</td>
<td>6.4</td>
<td>6.4</td>
<td>4.2</td>
<td>4.2</td>
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<tr>
<td>Number of Pressure Tube-Fuel Elements</td>
<td>69</td>
<td>37</td>
<td>69</td>
<td>69</td>
<td>69</td>
<td>69</td>
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<td>Pressure Tube O.D. (mm)</td>
<td>99</td>
<td>149</td>
<td>120</td>
<td>120</td>
<td>125</td>
<td>155</td>
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<td>Outlet Tube I.D. (mm)</td>
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<td>60</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>55</td>
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<td>Outlet Channel $\Delta P$ (atm)</td>
<td>0.27</td>
<td>0.95</td>
<td>0.30</td>
<td>1.21</td>
<td>1.21</td>
<td>2.46</td>
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<td>Ratio $\text{Be}/D_2O$ Moderator</td>
<td>3</td>
<td>1.6</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Power Density of Fuel (MW/Liter)</td>
<td>2.2</td>
<td>1.5</td>
<td>1.9</td>
<td>1.9</td>
<td>0.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>
FIGURE 1
BISO & TRISO FUEL PARTICLE CONSTRUCTION

(a) OUTER COATING
HIGH DENSITY PyC

KERNEL $UO_2$ & $Z_R$

INNER COATING
LOW DENSITY PyC

(b) OUTER ISOTROPIC PyC

SILICON CARBIDE

KERNEL $UO_2$ & $Z_R$

INNER ISOTROPIC PyC

BUFFER PyC
FIGURE 2
UNLOAD/LOAD CYCLE FOR PARTICLE BED FUEL ELEMENT

External Unload/Load Valve (Closed)

External Unload/Load Valve (Open)

External Load/Unload Valve

Unload/Load Tube
Open D₂O Region
Outlet D₂O Coolant
Particle Bed
Outlet Frit
Pressure Tube
Inlet Frit
Inlet D₂O Coolant
Support

Operating Fuel Element
Unloading Spent Fuel
Loading Fresh Fuel
FIGURE 3

ON-LINE FUEL LOADING FOR PARTICLE REACTOR

BED
FIGURE 4
PARTICLE BED POWER REACTOR

(PBPR) • 20 kg$^{235}$U, 2.0 m DIA., He COOLED

• 7 kg$^{235}$U, 1.2 m DIA., D$_2$O COOLED

• 10 kg$^{235}$U, 1.5 m DIA., He COOLED

NEUTRONIC CALCULATIONAL RESULTS

MULTIPLICATION CONSTANT - $K_{EFF}$

% ENRICHMENT
FIGURE 5
PARTICLE BED POWER REACTOR (PBPR)

REACTOR CROSS SECTION:

- $D_2O$ REFLECTOR -30 cm THICK-
- $D_2O$ MODERATOR
- PRESSURE TUBE AND FUEL ELEMENT (SEE BELOW)
- 1 cm ALUMINUM WALL AT CORE DIAMETER
- 10 cm STAINLESS STEEL PRESSURE VESSEL

PRESSURE TUBE-ELEMENT:

- $D_2O$
- Be MODERATOR
- Zr-2 PRESSURE TUBE
- COOLANT INLET PLENUM
- INLET POROUS FRIT, 1.5 mm (Zr-2)
- PARTICLE BED FUEL
- OUTLET POROUS FRIT, 3.0 mm (Zr-2)
- COOLANT OUTLET PLENUM