AN ACCELERATOR-DRIVEN REACTOR FOR MEETING FUTURE ENERGY DEMAND

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Abstract

Fissile fuel can be produced at a high rate using an accelerator-driven Pu-fueled subcritical fast reactor which avoids encountering a shortage of Pu during a high growth rate in the production of nuclear energy. Furthermore, the necessity of the early introduction of the fast reactor can be moderated. Subcritical operation provides flexible nuclear energy options along with high neutron economy for producing the fuel, for transmuting high-level waste such as minor actinides, and for efficiently converting excess and military Pu into proliferation-resistant fuel.

1. Introduction

The necessity has been discussed of introducing the fast reactor as soon as possible to accommodate the increase in energy demand which is expected after the first half of the next century[1]. However, the fast reactor cannot meet this rapid growth in the demand for nuclear energy because it requires a high initial inventory of fissile material due to the poor neutron economy of its large flattened core. Eighteen years is required to produce an initial inventory (initial inventory doubling time) of 3.6 metric tons of fissile material for a 1 GWe fast reactor with a 1.2 breeding gain without taking into account the need to hold fuel for processing; this cannot meet more than a 4% annual increase in energy demand.

To transmute long-lived fission products and to attain a high breeding rate, it is most desirable to use a Pu-fueled fast reactor with a hard neutron energy spectrum, which has a high neutron economy. But the safety of such a fast reactor would be jeopardized in critical operation because of its large positive sodium void coefficient due to the rapid, almost linear, increase of fission.

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neutrons as neutron energy increases; also, the fast reactor has a small doppler coefficient, a small delayed neutron portion, and a short neutron life-time. These safety problems associated with criticality can be avoided by operating the reactor in a slightly subcritical condition, and providing spallation neutrons\(^*2\).

2. Nuclear fuel production by an accelerator-driven reactor

When energy demand surges, a rather deep subcritical reactor is suitable for shortening the initial inventory doubling-time because of the smaller initial inventory of fissile material and the higher breeding gain.

Table 1 shows the initial inventory of fissile material, the initial inventory doubling-time, the cost of fuel production (without selling the electricity generated), and the cost of electricity for a 600 MWe accelerator-driven Pu-fueled fast target assembly. This analysis indicates that a \( k = 0.8 \) subcritical operation results in less than 4.7 years initial inventory doubling-time, and that such an assembly can meet a huge demand for energy at an annual increase of 15 % using natural uranium and accumulating Pu. The cost of fuel produced by a subcritical reactor with a smaller \( k \) value and without selling the electric power generated by this system is less than the one with large \( k \) values. The high fuel cost incurred by this sub-criticality (above \( k = 0.8 \)) can be reduced somewhat by selling the excess electricity produced. When \( k \) is less than 0.6, the electricity to operate a 400 MW beam power accelerator must be bought. In Table 1, we have assumed that the capital costs related to the subcritical assembly targets and the accelerator are, respectively, 2 B$/600 MWe, and 2 B$/300 MW beam power. We also assumed a net discount rate of 5%, 30-year life-time, and a plant factor of 0.75\(^*3\).

Operation at deep subcriticality creates many problems, such as radiation damage to the beam windows and the solid target, and a high power-peaking factor in a large reactor with a localized spallation neutron source. To reduce the peaking factor, it was suggested that many targets should be used, like the control rods in the experimental reactors and proton beams injected into these many targets; alternatively, a scanning-type injection of a proton beam on an annular cylindrical target installed in the core's center might be used. However, these approaches are more complicated than
a slab geometry. We proposed using the accelerator regenerator for light-water fuel; here, high power protons are injected to a liquid Pb jet target and the spallation neutrons generated are captured by the surrounding light-water fuel assembly, which is encased in the pressure tubes. Although the peaking factor is rather high in the case of a small $k$, this geometry is better than the cylindrical geometry in which the target is located in the center. This geometry was adopted in our conceptual design for accelerator tritium production and was followed in the modern design of the LANL APT which uses He-3 instead of Li-6 for tritium production.

3. Use of Liquid or Particle Fuels

The use of a molten-salt fast reactor (not a thermal reactor) has many advantages over a solid fuel reactor; also, the technology of electroprocessing can be utilized.

The very hard neutron spectrum obtained by employing a liquid fuel, such as Pu-Pb, Pu-Pb-Bi or plutonium chloride molten-salt, increases the yield of excess neutrons without heavily depending on the high-powered accelerator. However, an early study at BNL showed that the container wall was severely corroded when operating at high temperatures, so that a large investment in technology development would be needed before these materials were satisfactory for use.

Instead of a liquid Pu fuel, we might use a particle fuel which is directly cooled by liquid metal. This approach would reduce the inventory of Pu-fuel needed because the fuel is not circulated to a heat exchanger; however, the cladding material of the particle fuel reduces neutron energy and results in a lower neutron economy. The cost of manufacturing the particle fuel might be high, and the frequent processing of solid fuel increases the loss of very toxic Pu. These points have be taken into account in producing the fuel, too.

If the development of the accelerator-driven reactor fuel producer proves successful, the demand for the early introduction of the fast reactor can be moderated, even though the expensive accelerator increases the cost of fuel production. However, some of the expense can be saved by not having to install the safety devices which are necessary to operate the reactor in the critical condition.
4. Thorium cycle and cross-progeny fuel cycle

To reduce the number of ponds for spent fuel which is not processed, higher enrichment of the fuel has been suggested so it will burn for a long time. To reduce the high initial reactivity, a poison material like gadolinium is used, and it worsens the neutron economy, such as with a conversion ratio of 0.5-0.6. This practice just consumes the natural nuclear resource, and creates more high-level waste.

The Thorium fuel cycle has been promoted as a means to get an additional natural nuclear energy resource. This system produces far smaller quantities of minor actinides than does the Pu fuel cycle. However, to start this system, we have to create U-233 fuel, and more fissile material is required to start this system because of the larger thermal neutron capture cross section of Th-232 compared to U-238.

The cross-progeny fuel cycle, which produces U-233 fuel from the Pu-fueled fast reactor and is used in the LWR, can save the resources of natural fissile fuel. But also, by using the accelerator-driven Pu-fueled subcritical fast reactor, Pu can be effectively converted to proliferation-resistive U-233 fuel more quickly than by burning it in the critical reactor. Therefore, not only can we save nuclear energy resources but also reduce the anxiety about having excess Pu which cannot be quickly burnt out because of the criticality safety problem. To recover the waste from natural nuclear resource by running the LWR with low conversion and burning out excess Pu, we have to invest a large amount of capital to develop a fast reactor with a much higher breeding gain than the present one.

5. Separation of production of electric energy and fissile fuel

An important point in using an accelerator-driven fuel-producer is the fact that we can separate the energy-production reactors from the fuel production and processing facility; the former then can be located near regions where energy is consumed, while the latter can be located in remote areas far from populated regions. This scheme will be beneficial in advancing popular acceptance of nuclear energy, and in assuring the non-proliferation of fissile material. It also allows more freedom in the choice of the type of reactor such as a liquid-fuel one. This separation cannot be achieved using the fast breeder, which can create fissile fuel only by generating a huge amount of energy.
6. Conclusion

An accelerator-driven reactor can provide a more flexible strategy for nuclear development. Pu, or the more proliferation-resistant U-233 fuel, can be produced at a higher rate than the regular breeder, so avoiding a shortage of fissile material when the nuclear energy growth rate is very high. The necessity of early introduction of the fast reactor and requirement for a high breeding gain can be moderated, and the development of a safer and economically competitive nuclear reactor can be pursued.

The excess neutrons created in this system also can be utilized for reducing the toxicity of the long-lived fission products, or for reducing the long-lived nuclei into shorter-lived ones; also, the volume or heat generation of high-level waste which will be entombed in the geological storage can be lowered.

7. References

8. Acknowledgment

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Table 1 The Initial Inventory of Fissile Material, the Initial Inventory Doubling-Time, the Cost of Fuel Production (without selling the electricity generated), and the Cost of Electricity for a 600 MWe Accelerator-Driven Pu-Fueled Fast Target Assembly

<table>
<thead>
<tr>
<th>Multiplication factor $k$</th>
<th>Production of fuel per year, (ton)</th>
<th>Production of electricity (MW)</th>
<th>Initial inventory of fissile materials (ton)</th>
<th>Initial inventory doubling time (Year)</th>
<th>Cost of fuel without selling electricity (K$/g)**</th>
<th>Cost of electricity without selling fuel (c/kwh)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.119</td>
<td>600.</td>
<td>2.02</td>
<td>16.97</td>
<td>0.997</td>
<td>3.29</td>
</tr>
<tr>
<td>0.9</td>
<td>0.199</td>
<td>466.</td>
<td>1.72</td>
<td>8.62</td>
<td>.733</td>
<td>5.23</td>
</tr>
<tr>
<td>0.8</td>
<td>0.301</td>
<td>300.</td>
<td>1.39</td>
<td>4.61</td>
<td>.60</td>
<td>10.1</td>
</tr>
<tr>
<td>0.6</td>
<td>0.602</td>
<td>-201. *</td>
<td>.81</td>
<td>1.35</td>
<td>.467</td>
<td>---- *</td>
</tr>
</tbody>
</table>

* We have to buy electricity to run the accelerator.

** By selling the electricity, the cost of fuel can be reduced substantially.

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