A ROLE OF ACCELERATOR-DRIVEN REACTOR TO MEET FUTURE ENERGY DEMANDS

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ABSTRACT

Fissile fuel can be produced at a high rate using an accelerator-driven Pu-fueled fast reactor operated at deep subcriticality. This approach avoids encountering a shortage of Pu during a high rate of growth in the production of nuclear energy. Slightly reducing the acceleration field minimizes the tripping of the beam and the radiation dose from the accelerator. Hence, the accelerator can be operated as a highly reliable industrial machine. The usefulness of a windowless liquid jet target, which eliminates the spreading of the beam and problems of radiation damage is emphasized, in association with the small size of the target. The requirements for a proton beam accelerator for this system are discussed.

INTRODUCTION

The necessity has often 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 (Suzuki, 1995). However, the fast reactor cannot meet this rapid growth in the demand for nuclear energy because of the high initial inventory of fissile material that is needed, and also because the neutron economy is not high enough due to a large flattened core which is required to get a negative coolant void coefficient. The time required to produce an initial inventory of 3.6 metric tons of fissile material (initial inventory doubling-time) for a 1 GWe fast reactor with a 1.2 breeding gain is 18 years, without taking into account the need to hold fuel for processing. This cannot meet an annual increase in energy demand greater than 4 %.

A high breeding gain can be obtained by running the fast reactor in a slightly subcriticality condition without jeopardizing the reactor's safety (Takahashi, 1991). But, in this paper we discuss the case when we will need a much higher rate of production of fissile energy for the surge in energy demand that might occur in the next century. Fissile material can be produced at a higher rate using the excess of neutrons generated by adopting a deep subcritical condition, although the cost of fuel production will be more than if a regular fast reactor was used due to the extra expense for the accelerator and for using some of the electricity produced to run it.

For the industrial use of an accelerator, such as for generating electric power, a reliable machine is essential. The possibility of tripping the accelerator and shutting off must be eliminated; even a once-a-year stoppage is very destructive when supplying electricity energy. Reliability can be greatly improved by applying engineering safety factors and not using the accelerator up to its maximum limit. A study on coupling the spallation neutrons and the subcritical assembly is extremely important, especially for a deep subcritical reactor using a high current accelerator.

PRODUCTION OF NUCLEAR FUEL BY AN ACCELERATOR REACTOR

When energy demand surges, a rather deep subcritical reactor is particularly 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 k=0.8 subcritical operation reduces the initial inventory doubling-time to less than 4.7 years, and that such an assembly can meet a huge demand for energy at an annual increase in rate 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 is less than one with large k values. The high cost of fuel 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 the 400 MW beam power accelerator must be bought. In the table, we assumed that the capital costs related to the subcritical assembly targets and the accelerator are, respectively, $2B/600 MWe, and $2B/300 MW beam power. We also assumed a net discount rate of 5%, a 30-year life-time, and a plant factor of 0.75 (Fernandez, Mandarillon, et al., 1996)

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.

Multi-plication Factor k	Production of Fuel Per Year, (ton)	Production of Electricity (MW)	Initial Inventory of Fissile Materials (ton)	Initial Inventory Doubling Time (Year)	Cost of Fuel without Selling Electricity (k$/g)**	Cost of Electricity without Selling Fuel (c/kWh)***
1.0	0.119	600	2.02	16.97	0.997	3.29
0.9	0.199	466	1.72	8.62	.733	5.23
0.8	0.301	300	1.39	4.61	.60	10.1
0.6	0.602	-201*	.81	1.35	.467	-*

* 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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USE OF THORIUM

The use of thorium has been proposed to save nuclear resources, and to reduce the production of minor actinides. The U-233 fuel, which is produced from the thorium, does not exhibit a sharp increase in η values as neutron energy increases as does Pu-239; thus, the harder neutron spectrum in the U-233-fueled fast reactor is not as effective as is the Pu-239-fueled fast reactor. We suggested employing the cross-progeny (Takahashi and Chen, 1995) cycle which generates U-233 fuel from thorium fertile material using a Pu-fueled fast reactor, and consumes the produced U-233 fuel in a LWR which has U-238 fertile materials.

USE OF A LIQUID TARGET

In our old design for an LWR fuel generator, we proposed having a liquid-lead jet-flow target. When a solid material, such as tungsten, is used as the target, it is necessary to widen the proton beam to reduce radiation damage and the high deposition of energy in the target.

To avoid a lot of trouble, such as that from radiation damage, it is extremely desirable to have a windowless target, achieved by installing long expansion regions and a complex of magnetic fields for widening the beam. Windowless beam injection (Orlov, Sotov, et al., 1996) was proposed using a liquid jet; for this, Pb liquid-jet is very suitable because of its small vapor pressure, and also, because it can be quickly solidified at a low temperature.

To get a high multiplicity of neutrons from a high-energy nuclear-cascade reaction, a multiplication zone is needed surrounding the target regions. Widening the beam requires much more space for the target and multiplication regions in the core, and it worsens the neutron economy.

The small-sized beam hole of a liquid-jet nozzle window is beneficial in obtaining low pressure in a vacuum chamber; the proton beam passes through this small nozzle hole, and the radial size of target can be minimized rather than having to widen the beam to reduce radiation damage as in a solid window. Orlov et al.'s experiment demonstrated that a high speed liquid nozzle at 8-10 m/sec can keep the vacuum pressure below 10^{-4} Torr. By providing another high-performance vacuum pump in this chamber, and using the liquid-lead jet, the pressure in the vacuum chamber can be further reduced, maintaining its surface at a low temperature due to solidification of the lead particles at the surface wall. Thus, the high vacuum which is needed for high-energy proton acceleration can be maintained.

USE OF LIQUID OR PARTICLE FUELS

We earlier discussed a deep subcritical reactor that uses solid fuel and for which technology is well developed. But using a molten-salt fast reactor (Sasa, Katsuta, et al., 1994), (Haron, et al., 1997) (not a thermal reactor) has many advantages over a solid fuel reactor; also, the technology of electro-processing can make the separation facility small, making radiation shielding less expensive.

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 depending heavily 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 developing the technology would be needed before these materials were satisfactory for use.

Instead of a liquid Pu-fuel, we might use a particle fuel (Takahashi, 1990) 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 its need for frequent processing increases the loss of very toxic Pu.

TRIPPING THE ACCELERATOR

When we first proposed an accelerator-driven reactor, the concept was opposed by physicists who had earlier used an accelerator for their physics experiments. This opposition arose because they had nuisance experiences because the accelerator was not reliable, and very often disrupted their work as it shut down due to electric tripping. It still is not infrequent to have the accelerator trip during physics experiments. While this might be tolerable in experimental work if it does not occur too frequently, for industrial use, such as for power generation, the possibility of shutting off the accelerator by tripping must be eliminated. Even a once-a-year stoppage is very destructive especially when supplying electricity energy.

Very short trips of the beam do not affect power production due to the large heat capacity of the subcritical reactor; nevertheless, the lack of the beam for a short interval creates a loss of heat generation, and causes thermal shock to the reactor’s elements.

One cause of an accelerator trip is the sparking of a cavity due to the application of a high electric field which generates flakes from the impurities, defects, or dust on the cavity’s surface, resulting in electric avalanches.

Figure 1 shows the radiation dose-rates from X-rays as a function of electric field for two cavity temperatures of 80° and 5°C.

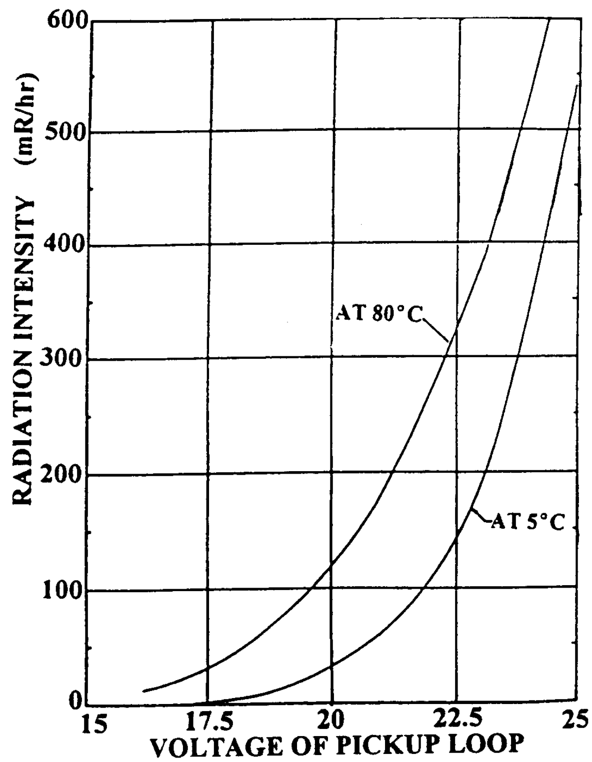

Figure 1 The Radiation Dose Rates from X-rays

Near the Kilpatric electric field, the radiation dose-rate and electrical breakdown increase with the electric field strength (E) according to $E^{11\pm3.9}$ and $E^{19.5\pm1.2}$ respectively (Zhao, 1996). A small reduction in the electric field drastically reduces these X-ray dose rates and sparking probabilities, while the length of an accelerating particle's track is inversely proportional to E. Thus, by slightly lowering the accelerating field and lengthening the accelerator beam's track, electrical breakdown in the cavity can be reduced without incurring a big economical penalty. To prevent electron avalanches, cleaning the cavity's surface by injecting clear water, eliminating impurity materials that produce flakes, and conditioning are essential.

Another cause of tripping is the breakdown of the coupler between the wave-guide to the cavity, and the RF windows for its transmission. This cause also can be eliminated by reducing the high gradient in electric field caused by sharp edges.

SPREAD OF THE PROTON BEAM AND ITS SHAPE

When the beam window is installed in the beam's entrance or when solid material is used as the target, the proton beam has to be spread to reduce radiation damage and high heat-deposition. A uniform transverse distribution can be achieved by using quadrupole and octupole magnets (Tsoupas, Zucker, et al., 1996). The analysis shows that a long expansion length of 17 meters is required before injecting the 1.5 GeV proton beam with a spread of 15 cm x 20 cm into the target assembly. Injecting the proton beam vertically requires a lengthy beam-expansion, so that the reactor has to be located deep down to accommodate this length. When the beam power is much higher, then it requires a wider window, and lengthy beam expansion; horizontal injection is preferable to vertical injection for a deep subcritical reactor.

Figure 2 a and b show the horizontal and vertical beam envelopes and X-profile with octupoles. It shows that the beam spread has some peaking at its edge, but the uniformity of the beam spread is important to reduce the radiation damage of solid beam windows or solid target due to high peaking of beam. Additional expansion length may be required to achieve uniformity. The old design of beam spreading using the rastering method, which is used for TV beams, is not suitable for our heat-generation system because a pulsed beam with a large time-interval generates repeating shock waves which is harmful to the integrity of the fuel and other component elements in a reactor due to the material fatigue.

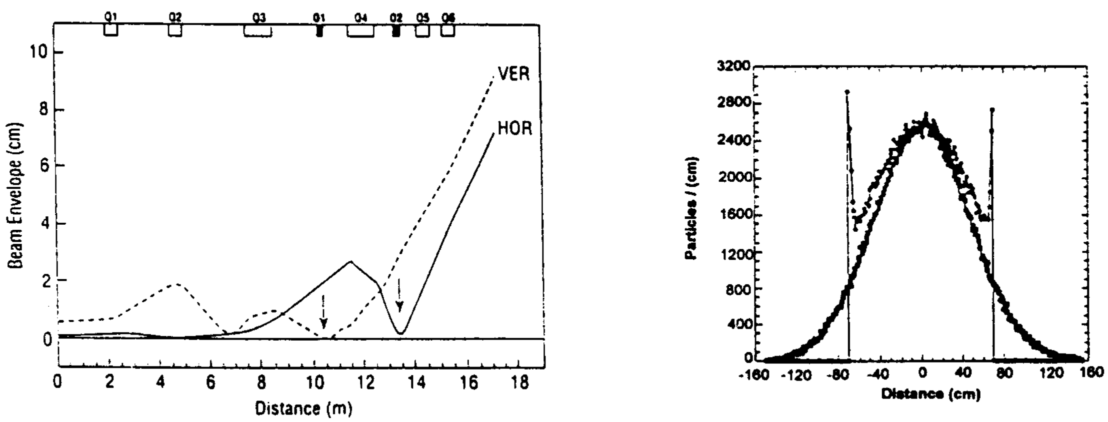

Figure 2 (a) and **(b)** Horizontal and Vertical Beam Envelopes and X-Profile with Octupoles (on/off)

Another caution in using an electric magnet to spread the beam is that a cut off might occur in the electricity for the magnet. If this happens, the spread of the beam shrinks, and then a high intensity beam could instantaneously melt the window's material, making a hole. To prevent such an accident, some part of the expanding magnet should be a permanent magnet. The magnetic field created by a permanent magnet is of the order of 0.2 Tesla; thus, its configuration can be designed such that the beam is still spread, even in this accidental situation. Also, the sharp edges created in tailoring the beam should not contribute to radiation hazards in the target's design.

VARIABLE BEAM POWER

In some designs for the accelerator-driven reactor, a change of proton-beam power has been suggested as a means to control the reactor's power. But a large change in beam current to compensate for the large reduction of k by the burn up of fuel is uneconomical. An expensive accelerator facility then is not fully utilized unless the beam is split to run another subcritical reactor, although neutron economy can be increased without using a neutron absorber, such as control rods. Although a reactor without control rods becomes a simple mechanical system and confers an economical benefit, this benefit is not large enough to compensate for the economical penalty of the high cost of an accelerator facility. The use of control rods is much more economical.

When subcriticality is changed by a large amount, the spatial distribution of heat generation for the localized spallation-neutron source will be changed (Tucek, Gudowski, et al., 1997); then, a simple change in the accelerator's power cannot accommodate it unless the subcritical reactor is a liquid-fueled one. The slow response time of the control rods can be sufficient to adjust to the slow change in power due to subcritical operation, and a fast change in power, which may be needed in an emergency, can be achieved with the accelerator.

A high-powered accelerator with a high current creates a high wake field besides an accelerating RF, and the temperature of the accelerating cavity will be affected by the power change. A large change in beam current is not desirable in terms of the beam’s stability, and also the beam’s halo created by phase mismatch increases the radiation level; these effects should be avoided. Due to the large Q value in the superconductive cavity, the effect of the wake field on the beam's stability is especially large. The jittering of an unstable beam creates fluctuations of fission power in the reactor. This occurrence also should be avoided as much as possible so that the plant can have a long life, which is very important for its overall economy.

CONCLUSION

An accelerator-driven reactor can provide a flexible strategy for nuclear development. Pu, or the more proliferation-resistive U-233 fuel, can be produced at a higher rate by using deep subcritical operation of k=0.8-0.9 than can the regular breeder, so avoiding a shortage of fissile material when the growth rate in nuclear energy production is very high. Although the cost of the fuel produced in this manner is higher than when a breeder is used, the necessity of the early introduction of the fast reactor and the requirement for a high breeding gain can be moderated; hence, the development of a safer, economically competitive nuclear reactor can be pursued.

A liquid-fuel reactor such as the molten-salt one is not presently recommended as a regular power plant because of the risk of proliferation of fissile material since it is easy to take out U-233 fissile material. But processing is limited only to the area controlled by the international organization, so the use of liquid fuel has advantages over solid fuel.

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