

# USE OF ACCELERATOR TO NUCLEAR ENERGY

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## Abstract.

Military Pu and the accumulated Pu from the operation of LWRs provide a great opportunity to start up a proliferation-resistance thorium fuel cycle, which has a high conversion factor in the thermal reactor, coupled with the Pu fuel cycle which has a high neutron economy in the fast reactor. The accelerator can play an important role in the safety of the fast breeder giving high breeding gain, yet separating energy generation and the processing and production of fuel. I will discuss a new approach to disposing of long-lived fission products (LLFPs) type II, such as Tc-99 and I-129, into outer solar space by providing an escape velocity from solar system of 42 Km/ sec from a parking orbit or from moon's surface, using a electro-static or RFQ accelerator and neutralizing the charged ions.

## 1. INTRODUCTION

Reactor safety, the disposal of high-level nuclear waste (HLW), and non-proliferation of nuclear material for military purposes are the problems of the greatest concern for nuclear energy. Technologies for accelerators developed in the field of high-energy physics can contribute to solving these problems [1]. For reactor safety, especially for that of an Na-cooled, Pu-fueled fast reactor, employing an accelerator, even a small one, can enhance the safety of using a slightly sub-critical reactor [2].

There is growing concern about how we can deal with weapons-grade Pu, and about the large amount of Pu accumulating from the operation of commercial reactors. It has been suggested that this Pu could be incinerated, using the reactor and a proton accelerator. However, because Pu is a very valuable material with the future potential of generating energy, we should consider transforming it into a proliferation-resistant material rather than simply eliminating it.

Although transmutation of minor actinides by fission processes produces energy, so that, in this reason, an energy balance easily can be achieved, to transmute the fission products themselves requires a substantial amount of energy[3].

It has been proposed to isolate HLW in outer space using a rocket[4]. However, this approach might disturb astronomical observations because the waste package would be a local source of radiation. Injection of HLW into the sun requires a rocket with more than about 30 km/sec velocity; this is too expensive even if the best chemical rocket-fuel was used, because the mass ratio (MR) of the total mass ( mass of payload + mass of fuel) to the mass of the payload becomes very high, up to 1,235. By using a high-current electro-static or RFQ accelerator, we can disperse the LLFP at a smaller cost than with a rocket.

## 2. $^{233}\text{U}$ PRODUCTION AND TRANSMUTATION OF MINOR ACTINIDES

The volume of the spent fuel can be reduced by burning it for a long time in the reactor, which, in turn, can reduce the area needed for temporal or permanent storage for spent fuel. To do this, a fuel with a higher enrichment of U-235, which is cheap at present due to the small demand for electricity, has been used. The initial reactivity is suppressed with a burnable poison such as Gadolinium isotope, that captures the neutrons. However, this worsens the neutron economy. At present, LWR has a small conversion factor, only about 0.6, so that we are not only wasting the very valuable uranium resource, but also increasing radiation hazard due to mining the uranium source. A recent study carried out at Oak Ridge National Laboratory warned that the disposal of spent fuel containing minor actinides without processing them will create geological hazards.

At the last international fuel-cycle evaluation (INFCE), several options for producing  $^{233}\text{U}$  were proposed[5]; however, this study was carried out before the collapse of Soviet Union, and the use of was not considered. We now have plenty of military Pu accumulated over the last 40 years of Cold War era, and also quantities of Pu operation of LWR. To incinerate completely the military Pu, it was suggested that an accelerator could be used as well as LWR. But Pu fuel is a very valuable fuel for future generations, and we should consider using this surplus Pu to start up  $^{233}\text{U}$  and thorium fuel cycle in addition to a Pu fuel cycle.

It is well known that the  $^{233}\text{U}$  thorium cycle is superior to the Pu fuel cycle for thermal reactors because of its high eta value. The use of Pu fueled fast breeder has been promoted because of high eta value for fast neutron. And this eta value of Pu increases as the neutron energy increases, thus creating a positive coolant-void coefficient even though the resulting hard spectrum can increase the breeding gain. To reduce this positive reactivity, a flat core or a small core has been recommended although they worsen the neutron economy. But using thorium in the blanket region instead of a uranium blanket also can reduce the positive reactivity, and the  $^{233}\text{U}$  produced can be used in the thermal reactor with a high conversion factor.

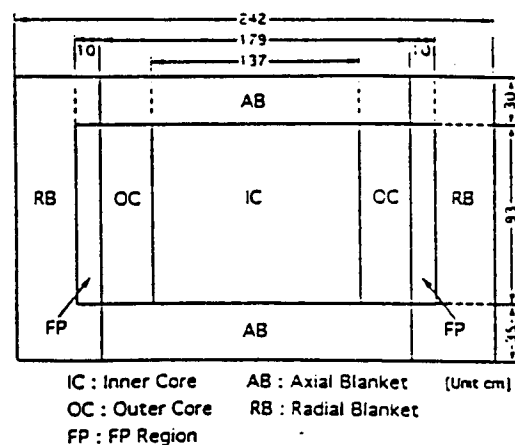


Fig. 1 Geometry of the Fast Neutron  $^{233}\text{U}$  Producer and Transmutor of MA and LLFP when it is operated by subcritical condition, the lead target is installed in the center of the core

Table I. Multiplication Factor, Neutron Life-Time, Production of  $^{239}\text{Pu}$  &  $^{233}\text{U}$ , Transmutation of MA and LLFP, and Initial Breeding Ratio of Various Configuration of Reactor

	<i>Multiplication Factor Neutron Life time*</i>	<i>Production of <math>^{239}\text{Pu}</math> &amp; <math>^{233}\text{U}</math> transmutation MA or LLFP**</i>	<i>Initial Breeding Ratio</i>
a) Uranium Blanket	1.0343+-0.0043 129.4	$^{239}\text{Pu}$ 243.8Kg	0.96026
b) Thorium Blanket	1.0275+-0.0045 134.56	$^{239}\text{Pu}$ 123.8 $^{233}\text{U}$ 122.4	0.9765
c) Thorium Blanket Core	.9503+-0.0046 123.94	$^{233}\text{U}$ 265.5	1.0528
d) Thorium Blanket 5w/0 MA in core	.9808+-0.0042 123.49	$^{239}\text{Pu}$ 122.2 $^{233}\text{U}$ 106.2 Ma(cap) 41. Ma(fis) 10.9	1.02716
e) Thorium Blanket $^{99}\text{Tc}$	.9920+-0.0012 353.77	$^{239}\text{Pu}$ 112.7 $^{233}\text{U}$ 60.1 $^{99}\text{Tc}$ 34.7	0.698
f) Thorim Blanket $^{129}\text{I}$ (30%)	1.002+-0.006 462.18	$^{239}\text{Pu}$ 173.6 $^{129}\text{I}$ 34.4	0.7014

a) Uranium-oxide(UO<sub>2</sub>) in core and blanket(BL), b) Thorium-oxide(ThO<sub>2</sub>) in BL, c) ThO<sub>2</sub> in core and BL, d) ThO<sub>2</sub> in BL & 5w% MA in core, e) ThO<sub>2</sub> in BL &  $^{99}\text{Tc}$  with YH1.7, f) UO<sub>2</sub> in BL & 129I(30%) with YH1.7. \* unit of 10<sup>-4</sup>sec, \*\* in unit of Kg

We propose the use of a thorium blanket in which the neutrons are moderated by a moderator such as graphite, which can enhance neutron capture in the thorium blanket region without sacrificing breeding gain. This neutron modulation can introduce a negative coolant-density coefficient, and also a large doppler coefficient under some conditions, so that the safety-related neutronic behavior is improved together with a gain in the neutron life-time.

Figure 1 shows our geometry for a fast neutron  $^{233}\text{U}$  producer and transmutor of MA which uses conventional mixed-oxide fuel, blended with MAs; thorium oxide is placed in the blanket region in the Prototype 700 MWt fast reactor [6]. Table I shows the initial production rate of  $^{233}\text{U}$  and  $^{239}\text{Pu}$ , the multiplication factors, neutron life time and initial breeding ratios for various blanket materials. When  $^{232}\text{Th}$  is put in the blanket region, the rate of production of the total amount of  $^{233}\text{U}$  created by the  $^{232}\text{Th}$  blanket plus the  $^{239}\text{Pu}$  created in core region is not very different from the total production of  $^{239}\text{Pu}$  in a  $^{238}\text{U}$  system. When  $^{232}\text{Th}$  is put in the core region,  $^{233}\text{U}$  production increases, but the multiplication factor, k, is reduced substantially; thus, a larger core volume is required.

When MA is added into the fuel, the production of  $^{239}\text{Pu}$  increases, but the k value is slightly reduced.

$^{233}\text{U}$  is produced with  $^{232}\text{U}$ , which emits strong gamma radiation making it a more theft-resistant fissile material. However, until a few years ago the use of the thorium and  $^{233}\text{U}$  fuel-cycle

system was opposed because of this high energy gamma-ray radiation generated by  $^{232}\text{U}$ . Now, with the endorsement for mixing minor actinides into fuel cycle, the prospects of using this fuel cycle are far better. The large, heavy-shielded chemical processing facility might then be replaced by a compact facility, such as the facility for pyrolytic fuel developed by Argonne National Laboratory.

Improvements in breeding gain can be made by using a metal fuel in a fast reactor that makes a much harder neutron spectrum, and also in increasing the neutron economy to produce  $^{233}\text{U}$  (or  $^{239}\text{Pu}$ ). Also, by running the reactor in a subcritical condition, the safety problem associated with criticality can be avoided. The produced  $^{233}\text{U}$  fuel can be used in the LWR with  $^{238}\text{U}$ , which produces  $^{239}\text{Pu}$  for the fast reactor.

To prevent the removal of pure  $^{233}\text{U}$ , which is more effective than  $^{239}\text{Pu}$  as bomb material, can be obtained from separated  $^{233}\text{Pa}$ , the  $^{232}\text{Th}$  should be mixed with a small amount of  $^{238}\text{U}$ .

### 3. SEPARATION OF POWER PRODUCTION AND FUEL PROCESSING

From the point of view of non-proliferation, it is desirable to separate the power production and fuel-processing facilities; a small number of fuel-processing facilities which are internationally controlled is beneficial for inspection. The liquid fuel reactor with fuel-processing on site has a disadvantage in this regard, although there are several advantages over a solid fuel reactor.

If and when the world needs a large amount fissile material in a short time due to a rapid growth in energy demand, then the accelerator fuel producer can generate fissile material only from fertile material and electricity, without having a fissile material like breeder. The cost of the producing fissile material in this way is higher than that with a breeder. This high cost can be reduced somewhat by using a subcritical assembly; furthermore, the high cost of the fuel can be recovered by running the reactor with a high conversion factor.

When fuel-processing or fuel production facilities are located in a remote area where there is a fossil-fueled burning power plant or hydraulic power generator, the power can be used for fuel production using the accelerator without any loss during transmission from power generation to the consumer. In this case, a placement of many breeders is not suitable, because the fuel can be bred only by generating electricity which should be consumed; also, it requires a large inventory of fissile fuel.

When a critical reactor is operated, the multiplication factor should be 1, but in operation of a subcritical target, then  $k$  can be less than one, and the neutrons which are needed to maintain the critical condition can be diverted into producing fuel; hence the rate of fuel production can be increased by running the operation at a low  $k$  value. The initial requirement for fissile material will depend on the reactivity; we can adjust the reactivity by the amount of the initial inventory of the fuel material. To run the accelerator, electricity is needed. If we can produce the electricity from the target, the system can be self-sufficient not consume any power. Using a subcritical target which has multiplication factor  $k$ , then the accelerator current can be reduced proportionally to the subcriticality of  $(1-k)$ .

We can deploy one power reactor close to the critical level and produce mostly power, while, the other target can have only a low level of power generation and can concentrate on production of fuel. In this system, the fuel production target has such low power density and the problem of thermo-hydrodynamics can be more easily solved. We might have another option, and instead of running rather many reactors with large subcriticality, use one power reactor and run the accelerator. I proposed using a small segmented cyclotron accelerator to run a slightly subcritical

reactor before, but if we can solve the problem of radiation damage and of non-uniformity of the spallation source by adopting the geometry configuration used for such as our old design of a regenerator for LWR fuel, and successful operation of large power accelerator with large subcritical condition to concentrate the fuel production. Accelerators can provide a lot of flexibility for fuel production than the fast breeder.

To be successful with nuclear power operation, we should have anyhow a reactor with a high conversion ratio or hopefully, a high breeding gain.

#### **4. DISPOSAL OF LLFP INTO OUTER SPACE BY A ELECTRO-STATIC OR RADIO-FREQUENCY QUADRUPOLE (RFQ) ACCELERATOR[7].**

From the point of view of neutron economy, it is not difficult to transmute MA by fission process which create neutrons. However, to transmute LLFP which consumes neutrons in the (n,gamma) reaction, the transmuted reactor has to have a high neutron economy. When the LLFP is transmuted into nuclei which have a large neutron capture cross-section, the neutron economy worsens due to additional neutron capture.[3] Some of the LLFP has a small neutron cross-section; therefore, a high neutron flux is required to transmute it rapidly.

The MOX-typed fast reactor with a thermal power of 700 MWt[6,8], which is described in the above, can transmute a substantial amount of LLFP, but the breeding ratio falls from about 0.96 to 0.7 because of the many neutrons that are consumed in transmutation. The economy of such transmutation should be studied more thoroughly.

It has been suggested that HLW might be disposed of in outer space using a rocket. The National Aeronautical and Space Administration (NASA) studied[4-1] the possibility of using the space shuttle for this. Several possible options for the destination in space have been evaluated, such as Earth orbits, solar orbits, solar-system escape, and solar impact after first launching the HLWs into a parking orbit by space shuttle. Although disposition to Earth orbits and the solar orbit do not require a large propulsion energy even, using a chemical fuel.

However, these methods have several disadvantages; future planetary spacecraft would regularly penetrate this orbit belt; there is no assurance that the waste package would not encounter Earth after a few thousand years; and, the isolation of solid HLW in outer space might disturb astronomical observations because it would be a local source of radiation.

The disposition of the HLW into an orbit escaping the solar system is ideal but requires a large amount of energy; with mass ratios (MRs) of (mass of payload + mass of fuel)/(mass of payload) the MR becomes very high, upto 21,883, when a chemical rocket fuel is used. Such a method of disposal requires a nuclear propulsion rocket which has a large  $I_{sp} = 1000$  sec, or 6000 sec for a solid-core nuclear fuel or gaseous-core nuclear fuel.

Instead of using a rocket to generate such high escape velocity, by ejecting LLFPs using an accelerator, we can reduce substantially the energy needed for their disposal.

To uniformly disperse the LLFPs into outer solar space from a parking orbit, requires an earth escape velocity ( $V_{EE}$ ) = 42.07 Km/sec. Column 2 of Table 2 shows the accelerating energy, which is in the order of 1 KeV, for each LLFP isotope. The third column shows the power required to accelerate the total amount of LLFP isotopes created by one 1 GWe LWR.

Instead of dispersing the LLFPs uniformly in solar outer space, if we disperse them uniformly in the plane of the earth's orbit, then the velocity required to eject them can be reduced from 42.07km/sec to  $\{\sqrt{2-1}\}V_{EC} = 12.32$  km /sec. The fourth column in Table 2 shows the acceleration energy for each LLFP isotopes, and the fifth column shows the power for

accelerating all the isotopes produced by one 1 GWe LWR.

Species	Disposing uniformly in the outer solar system.		Disposing uniformly in the earth orbit plane of outer solar system.	
	Accelerating Energy (eV)	Accelerator Power (W)	Accelerating Energy (eV)	Accelerator Power (W)
<sup>79</sup> Se	722.2	5.523	61.9	0.473
<sup>93</sup> Zr	850.2	669.8	72.9	57.43
<sup>99</sup> Tc	905.0	718.5	77.6	61.6
<sup>107</sup> Pd	978.2	978.2	83.9	17.4
<sup>126</sup> Sn	1151.9	25.374	98.8	2.17
<sup>129</sup> I	1179.3	166.7	101.1	14.3
<sup>135</sup> Cs	1234.2	279.8	105.8	24.0
Total		2843.9		177.4

TABLE 2.

The energy required to accelerate the isotopic species of LLFPs which will be disposed uniformly in the outer solar system and in an Earth orbiting plane. The corresponding accelerator power used for ejecting the LLFPs generated by a 1 GWe light water reactor

Species	Disposing uniformly in the outer solar system.		Disposing uniformly in the earth orbit plane of outer solar system.	
	Accelerating Energy (eV)	Accelerator Power (W)	Accelerating Energy (eV)	Accelerator Power (W)
Se	722.2	525.8	61.9	45.1
Zr	850.2	3374.4	72.9	289.3
Tc	905.0	718.5	77.6	61.6
Pd	978.2	1278.8	83.9	109.7
Sn	1151.9	162.1	98.8	13.9
I	1179.3	218.3	101.1	18.71
Cs	1234.2	2220.3	105.8	190.3
Total		8498.2		728.6

TABLE 3.

The energy required to accelerate the elemental species of LLFPs which will be disposed uniformly in outer solar system and in an Earth orbiting plane. The corresponding accelerator power used for ejecting the LLFPs generated by a 1GWe light water reactor,

The above values were calculated for LLFPs which were separated out isotopically from the other elements. When the isotopes are not separated, the total product has to be ejected into outer solar space; the acceleration energy needed is almost same as the isotopic requirement without taking into account the small mass difference of isotope. Then the power for accelerating all the LLFPs elements produced by one 1 GWe LWR to dispose uniformly in outer space and in the earth's orbit plane, are respectively, 8.5 KW and 0.73 KW, as shown in third and fifth columns in Table 3.

These powers are far smaller than the energy required to transmute the LLFPs by spallation neutrons where the neutrons are multiplied by the subcritical assembly, which is in the order of a few 10s MW.

To prevent these charged ions being trapped by the magnetic field in outer space, the ions should be neutralized in the same way as the neutral beam injection in the magnetic fusion reactor[9].

To reduce the high current, we might to accelerate the singly charged clustered LLFPs, composed of 100-1000 ions.

## 5. CONCLUSION

Accelerators can provide great flexibility for various nuclear options, as well as markedly improving reactor safety. The Thorium-<sup>233</sup>U fuel cycle which has high conversion factor for thermal neutrons, can be started by using military Pu or Pu accumulated from operating LWRs, together with the Pu fuel cycle which has superior neutron economy. To reduce the costs and energy needed for transmuting LLFPs, they can be deposited into outer solar space with high-current, low-energy electro-static or RFQ accelerator.

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