THE SAFE AND ECONOMICAL OPERATIONS OF A REACTOR DRIVEN BY A SMALL PROTON ACCELERATOR

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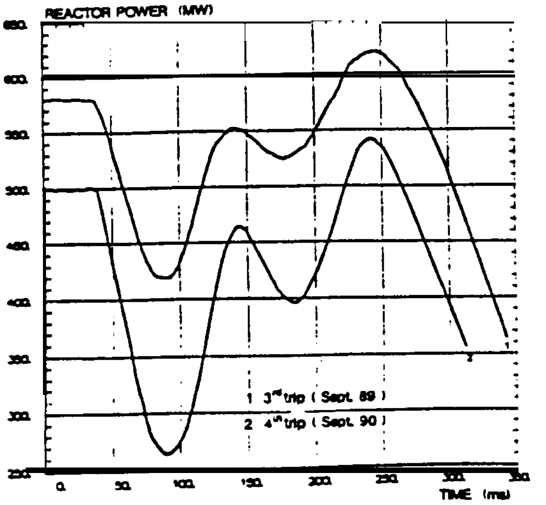
ABSTRACT

An accelerator can be used to increase the safety and neutron economy of a power reactor and **transmutor** of long-lived radioactive wastes, such as minor **actinides** and fission products, by providing neutrons for its subcritical operation. Instead of the rather large **subcriticality** of k= 0.9-0.95 which we originally proposed for such a **transmutor,** we propose to use a slightly subcritical reactor, such as k= 0.99, which will avoid many of the technical difficulties that are associated with large **subcriticality**, such as localized power peaking, radiation **damage** due to the injection of medium-energy protons, the high current accelerator, and the requirement for a long **beam-**expansion section. We analyzed the radiation damage of the target area, and discuss the necessity of high neutron economy to transmute the long lived fission products using the fast reactor system.

I. Introduction

The safety of nuclear power plants is a major public concern, and "the disposal of high-level radioactive waste **(HLRW)** has become a political problem; hence, serious consideration has been given to transmuting the minor **actinides** (MA) and long-lived fission products **(LLFP). After** the dissolution of the Soviet Union, there has been great concern about the proliferation of weapons material, and the suggestion of using weapons-grade Pu in commercial reactors **has** been vigorously pursued. The possibility of nuclear terrorism urges us to consider a nuclear fuel cycle system which is secure and resistant to such acts. In satisfying the mandate to address proliferation problems, the accelerator technology **[1,2],which** hits been extensively developed in the last few decades, will play important an role in nuclear fuel cycles.

Over two years ago, the **Phenix** reactor [3] was shut down because disturbing phenomena were observed: four negative reactivity transients occurred **in** August and September 1989 and in September 1990.



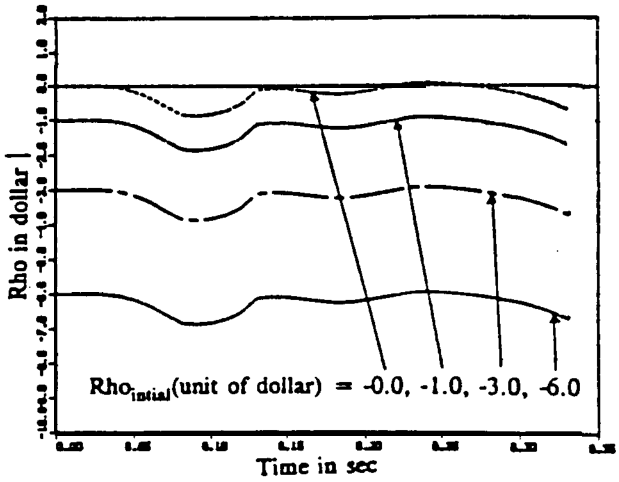


Fig. 1 **Neutronic** chamber **signals recorded during the third and** fourth **trips** at the **phenix** reactor. Ref. 3

Fig.2 Reactivity calculated **from Phenix's** power variation.

Figure 1 shows the remarkably similar signal curves recorded for each transient in the neutronic chamber. The power drops linearly at first, then there is a symmetrical rise up to a level lower than the initial value, a second oscillation with a maximum slightly over the initial value, and finally a decrease corresponding to the control rod dropping about 200 ma after the start of the phenomenon. An extensive study of all possible phenomena was carried out. Currently, the most likely explanations are thought to be either a spurious signal (for example, electrical perturbation of the instrumentation), or a movement of the core's sub-assemblies.

Assuming that this sudden drop in power was due to a change in reactivity, not to a spurious signal, we calculated the variation in reactivity as a function of time from the observed change in reactor power during the 4-th trip that occurred Sept 90. Figure 2 shows the calculated reactivity dropping at 40 msec and falling to about -87 cents at 80 msec. After this, the reactivity shows as oscillation, increasing to -10 cents subcriticality at 130 msec and then dropping again to -25 cents at 180 msec. Between 220 msec and 260 msec, the reactivity becomes positive and then falls into large subcriticality as the control rod drop into place.

Our analysis shows that the change in reactivity has very similar shape to the change in power; the oscillatory behavior suggests that mechanical vibration might have occurred in some component of the reactor core. The movement of core might be caused by the sudden release of some stressed condition, followed by mechanical vibration with period of about 10 msec.

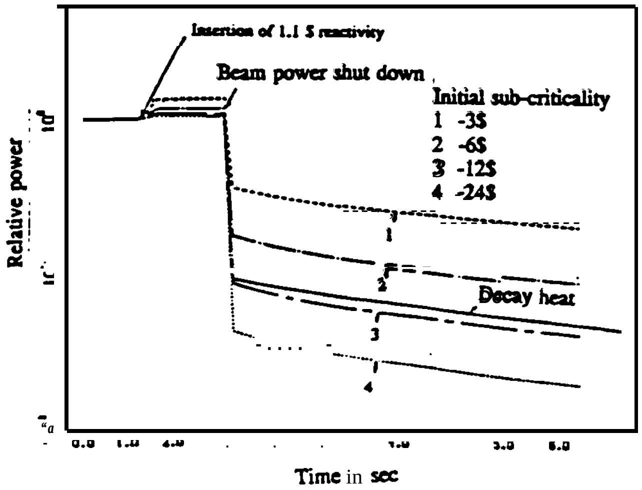
IL The safety advantage of a sub-critical reactor.

When a small reactivity of 0.6 β or 0.8 β is inserted to a fast reactor operated in a critical condition, the power increases by as much as 10 or 10^3 times the normal power within 5 sec after insertion, if feed back such as doppler broardning is very small.

Due to the positive sodium density coefficient, short life time, and the small delayed neutron fraction, the reactivity of the fast reactor, especially one with MA fuel, has to be controlled very carefully in critical operation[4a,and 4b]. In contrast, operating a reactor in a subcritical condition gives an exceptionally gentle change in power and reactor will remain in stable.

Figure 3 shows the power change of a subcritical reactor operated with spallation neutrons in which the initial subcriticalities are -3, -6, -12, and -24$, the reactivity of 1.1$ is inserted step-wise at 1 see, and the proton beam is shut down at 2 sec.

At most, the power increase is less than 44 % in the case of an initial sub-criticality of -3$, and when the proton beam is shut down, the power decreases to 40% of the initial power within milliseconds. Thus, a subcritical reactor can be operated in a more relaxed condition than a critical reactor. The safety of the reactor associated with criticality is greatly enhanced, and also, the subcritical reactor might be more economical because it requires less safety-related equipment to reduce risk. Figure 3 also shows the level of decay heat generated, which we d-id not include in the calculation.



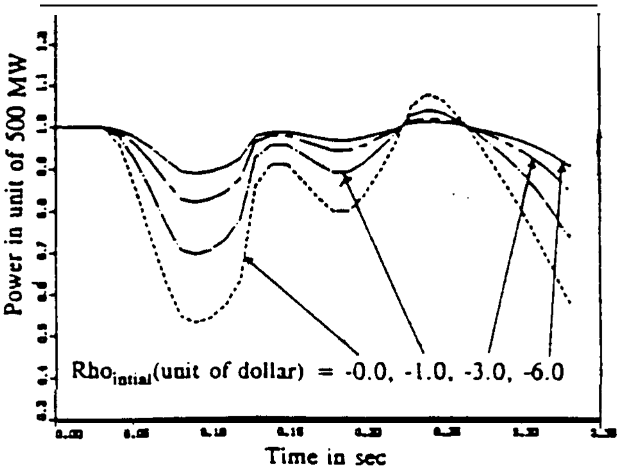


Fig.3. Relative power change in subcritical reactor.

Fig.4 Relative power change of the phenix reactor operated in subcritical condition.

As in the case of the power drop in the Phenix reactor, it is not desirable for safety purposes to operate a reactor in which there might be sudden power change. When a reactor has large power fluctuations, the fuel component and structural materials will be damaged by extra thermal stress; therefore we should avoid power fluctuations.

In critical operation, a reactivity drop of 87 cent (which is equivalent to a reactivity drop of about 0.3 % in the fast reactor) results in a drop of the reactor power about the half of its steady power. When the reactor is operated in a subcritical condition, such a sudden drastic change of power can be minimized.

Figure 4 shows the power changes when the Phoenix reactor is operated in the subcritical conditions of 1, 3, and 6 dollars compared with critical operation. At 1 dollar subcritical operation, the drop in power is 30 % compared with 50 % of the steady state power in the critical reactor, and in the 3 and 6 dollars subcritical operations, the power drops become, respectively, 20%, and 10 % of nominal power.

When we proposed using a subcritical transmutor operated by an accelerator[5], the subcriticality of 0.9-0.95 was chosen rather arbitrarily to prevent re-criticality from occurring, which could happen if there was a loss of coolant. Since the reactor power can be controlled by the beam current, a control rod is not required. This large subcriticality has been adopted in other subcritical transmutors. [6] However, a degree of subcriticality which is chosen for a reactor is very important for the safety. If there was a loss of coolant, it would melt the fuel assembly. Recriticality might occur, due to condensation of the melted core. The choice of a subcriticality of 0.9-0.95 does not guarantee that re-criticality would not occur, and our choice has not been validated further. Melting of the core is a very severe accident that should be prevented from beginning. When a large subcriticality is adopted, many difficulties will be encountered, including large proton accelerator power, local heat generation by local proton injection, and the considerable radiation damage.

The power variations shown in **Fig.4** are calculated with a point kinetics equation; the power distribution was not taken into account. ***When the*** localized neutron source is inserted into a reactor with large subcriticality, power has a peaked and not flattened distribution. The large peaking power factor is undesirable for safety reasons, and the value of subcriticality chosen should reflect this concern. When we use a small subcriticality, these difficulties will disappear.

Under subcritical operation, a kinetic behavior of the reactor's power is gentle and manageable. When a large negative reactivity is required in an accident, a fuse-type of liquid control material can be used to prevent the criticality from occurring, and a few control rods then might be used to maintain this small subcriticality.

To avoid radiation damage to the target, such as the accelerator's tritium production assembly during direct irradiation[7], the current of the 125 mA proton beam is spread widely, using a static magnetic field; this configuration requires a long holraum region to use the spallation neutrons scattered back from the target's surface.

KU. Radiation damage to proton target area.

Because high energy protons produce high-energy spallation neutrons and protons in the target and window areas, the problem of radiation damage is expected to be substantial when the high-power accelerator is used for the large subcritical reactor.

Damage to the structural materials of a proton-accelerator based reactor is being investigated using the Monte Carlo simulation codes LAHET[8], and HMCNP[9]. For comparison, calculations were made with the MCNP code for the critical reactor, which has a softer spectrum than the accelerator-driven subcritical reactor. The atomic displacement (DPA), H and He production rates, and energy deposition were evaluated using the cross-sections calculated by the TRANSX2 code[10] for leas than 20 MeV, and the values given by Kolovin et al [11] for the cross-sections above 20 MeV.

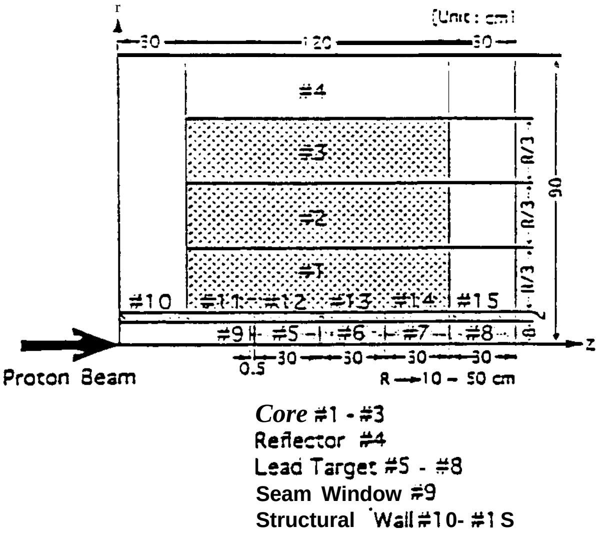
Transmutors with particle fuel (PFT) and MOX fuel (MFT)[12] were studied by varying the thickness of the core; in other words, the K_{eff}. The lead target, the structural walls, and the core were divided into small cells, as shown in Figure 5, to estimate the positional dependence characteristics of radiation damage for PFT and MFT are almost the same. Cell #5 of the lead target has a large DPA, as do the beam window (cell #9), and cell #12, a side structural wall near the window section. The table I shows the results of radiation damage when a proton current of 16.8 mA is injected to the subcritical MOX Fuel transmutor. Figure 6 shows the neutron spectrum in the same region.[13]

These findings indicate that in designing the proton-accelerator based transmutor, the radiation damage to not only the beam window but also the target vessel should be investigated carefully. For the contributions by neutron to DPA neutrons with energies below 20 MeV are dominant compared to those above 20 MEV. Further, the DPA in the accelerator-driven the reactor with a sub-criticality of $K_{eff} = 0.9$, which requires a proton current of 15 mA, is about 1.5 times larger than that of the critical reactor. However, this value for DPA is not unusually large, because this fast reactor has small power and a hard neutron spectrum which produces the DPA effect. When the reactor has a large power and the proton current is high such as 150 mA, then the DPA becomes about five times than the critical reactor.

Our analysis shows that the H and He production rates depend on the proton beam current, as expected, because these rates reflect the high-energy neutron and proton reactions. A higher beam current will give larger values for energy deposition, except in the core, where the fission energy is mainly deposited, and the total fission energy depend mostly on the power density, not on the proton beam current. The beam window (cell #9) and the lead target near the beam window (cell #5) have larger rates of energy deposition and of H and He production. However, the production rate of He is smaller than that of H.

The radiation damage of DPA due to protons were not calculated, but they are not as high as those caused by neutrons, because the cross-sections for protons are about the same order as those of neutrons in the high energy range and the DPAa above 20 MeV neutron are small, as discussed above.

Although this analysis was made for a fast neutron reactor, when the thermal neutron subcritical reactor is used as an accelerator-driven reactor, the DPA due to spallation neutrons will be much higher than that in the critical reactor, because the neutron spectrum in the critical thermal reactor is much softer.



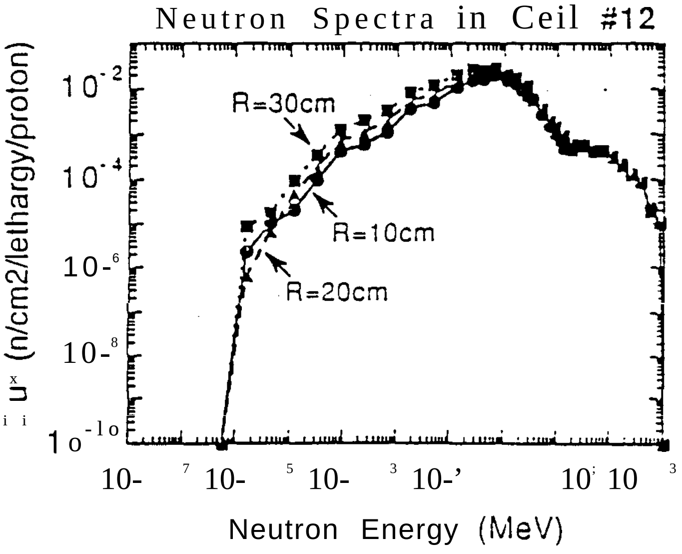


Fig.5 The lead **target, the structural** walls, and the core were divided into small cells.
Fig.6 The neutron **spectrum** in the cell #11.

IV. Accelerator

When a medium-size reactor or **transmutor** less than 600 MW-th is operated with slightly subcritical **transmutor,** such as **k=0.98-0.99,** a small powered cyclotron accelerator of 4-2 MW is sufficient. Presently, the Paul **Sherlling** Institute (PSI) [14] is constructing a high-intensity **spallation** neutron source by upgrading a two-stage accelerator facility: beam currents of 1.5 mA at an energy of 590 MeV are anticipated.

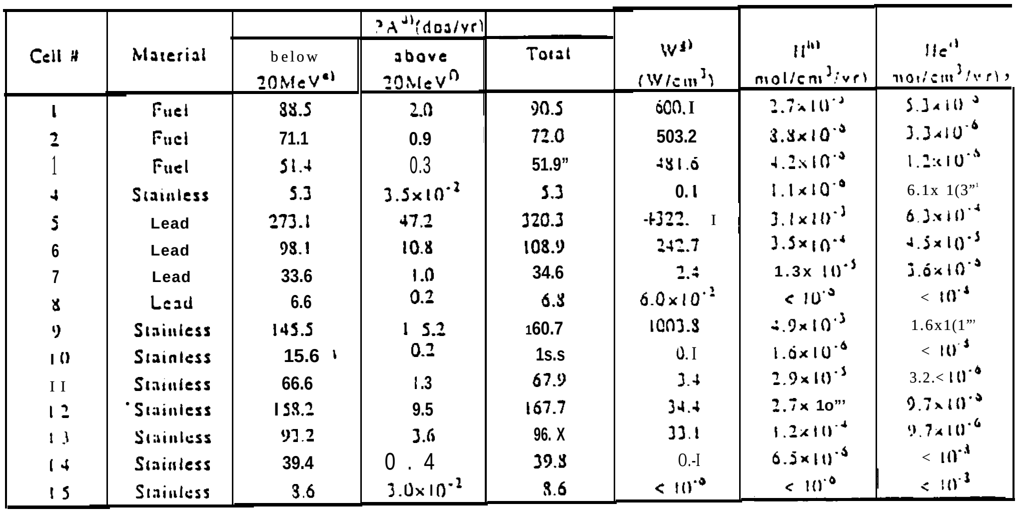
The SNQ program for the spallation-neutron source, studied by Forschungszentrum Julich studied until 1987, was planning to use the 5 MW linac. For the new European pulsed-spallation neutron source (ESS) program[15], the basic design parameters chosen were for a high-power (5 MW), high current (1.7 mA) FFAG synchrotrons as a possible accelerator.

To provide external neutrons for a subcritical reactor, the proton beam should be stable and maintain a constant current, so that there are minimal power fluctuations in the subcritical assembly. Persistent power fluctuations damage the fuel element, especially metal fuel, by causing their elongation. The PSI cyclotron accelerator used as a neutron source currently has a 5 % fluctuation in beam power, due to the instability of high current beam transport.

Table 2

Calculations of Radiation Damage of MOX Fuel Transmuter (MFT)

(c) $R^{a)} = 30$cm, $k_{eff} = 0.858$, $P^{b)} = 300MW_{th}$, $I_p^{c)} = 16.8$mA



Cell #	Material	DPA$^{d)}$(dpa/yr) below 20MeV$^{e)}$	DPA$^{d)}$(dpa/yr) above 20MeV$^{f)}$	Total	W$^{g)}$ (W/cm^3)	H$^{h)}$ mol/cm^3/yr	He$^{i)}$ mol/cm^3/yr
1	Fuel	88.5	2.0	90.5	600.1	2.7×10^{-3}	5.3×10^{-5}
2	Fuel	71.1	0.9	72.0	503.2	3.8×10^{-5}	3.3×10^{-6}
1	Fuel	51.4	0.3	51.9"	481.6	4.2×10^{-5}	1.2×10^{-6}
4	Stainless	5.3	3.5×10^{-2}	5.3	0.1	1.1×10^{-6}	6.1x 1(3"'
5	Lead	273.1	47.2	320.3	4322. I	3.1×10^{-3}	6.3×10^{-4}
6	Lead	98.1	10.8	108.9	242.7	3.5×10^{-4}	4.5×10^{-5}
7	Lead	33.6	1.0	34.6	2.4	1.3x 10^{-5}	3.6×10^{-5}
8	Lead	6.6	0.2	6.8	6.0×10^{-2}	$< 10^{-5}$	$< 10^{-4}$
9	Stainless	145.5	15.2	160.7	1003.8	4.9×10^{-3}	1.6x1(1"'
10	Stainless	15.6	0.2	1s.s	0.1	1.6×10^{-6}	$< 10^{-5}$
11	Stainless	66.6	1.3	67.9	3.4	2.9×10^{-5}	3.2.< 10^{-6}
12	Stainless	158.2	9.5	167.7	34.4	2.7x 1o"'	9.7×10^{-5}
13	Stainless	93.2	3.6	96. X	33.1	1.2×10^{-4}	9.7×10^{-6}
14	Stainless	39.4	0.4	39.8	0.-I	6.5×10^{-5}	$< 10^{-3}$
15	Stainless	8.6	3.0×10^{-2}	8.6	$< 10^{-6}$	$< 10^{-6}$	$< 10^{-3}$

a) Core thickness in the radial direction, b) Total thermal power, c) Proton beam current required to operate the transmuter continuously, d) Atomic displacement, e) DPA by neutron with energy below 20 MeV, f) DPA by neutron with energy above 20 Me V, g) Energy deposition, h) H production rate, i) He production rate.

Table L The radiation damage when a proton current of 16.8 mA is injected to the subcritical MOX Fuel transmutor.

So far, the accelerator developed for nuclear and high energy physics has a small current, of the order of microampere. The particle-beam intensity is so small that the dynamics of the beam can be adequately treated as a that of an independent particle. High current beams create a high EM field which affects the beam's dynamics; the kinetic equation of charged particle transport becomes non-linear, and the stability of the beam has to be analyzed by taking into account the wake field which it creates.

The transport theory for high beam current, such as breakup of the beam is not well developed but should be studied by accounting for the beams as plasma; such a study will not only suppress the beam fluctuations, but also allow manipulation of the beam's expansion, which is currently carried out by a static magnetic field. Beam expansion can be achieved using the plasma in the same way as it is used for plasma focussing in $e^- - e^+$ collider. The use of the static magnetic field for defocusing the beam requires a long expansion section; hence, radiation shielding becomes expensive and the use of neutrons becomes cumbersome. Many plasma theories developed in the nuclear fusion program may be applicable and this will be fruitful field for future accelerator technology, in the same way as the currently popular free-electron laser.

V. Neutron economy and transmutation of minor actinide and long lived fission products.

The **Pu-fueled** fast reactor has the capability to increase neutron economy because of the high η value of high energy neutrons; however, the small core or the flattened core of large- powered fast reactors are designed to reduce the positive Na density coefficient. These reactors, therefore, have a poor neutron economy due to a large leakage of neutrons.

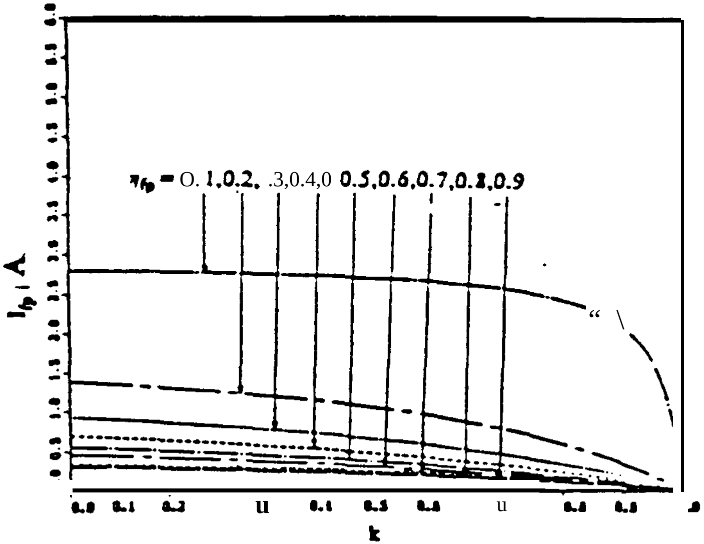


Fig.7 The proton **accelerator current** required to transmute 16.5 % **FP(^{99}Tc, ^{129}I, ^{93}Zr, and, ^{85}Kr) as** function *of k* and η_{fp}, assuming Proton energy 1 **GeV**, n_{sp}(number of **spallation** neutron produced by **1GeV** proton) = 33.3, ν = 2.75.

The use of the fast reactor to transmute minor **actinides** has been discussed. The transmutation of MA by the fission reaction requires a hard neutron spectrum, but then it is more difficult to control the **transmutor.** Concerning softening of the neutron spectrum, our **recent** study indicates that when fission products such as, ·OTC or ^{129}I,are transmuted in the neutron-moderated region located between the core and reflector regions, the overall Na void coefficient becomes negative. However, when minor **actinides** are added to the core region, this trend toward a negative value of the Na void coefficient is reduced [12].

The yield of LLFP is not small, and many neutrons are required to transmute these FPs. Our study [4] of the energy requirements for transmuting LLFP indicates that when **spallation** neutrons are used, whose energy cost is 30 **MeV** of proton beam, then a subcritical **transmutor** with k = 0.7 gives the energy break-even; a 300 MW proton beam power is required to transmute the 16.48% yield of LLFP, such as **(^{99}Tc + ^{129}I + ^{85}Kr + ^{93}Zr)**, created by a 1 GWe LWR in which the **spallation** neutrons are not multiplied. When they are multiplied in the subcritical reactor at k=0.99 and when the ratio η_f of neutron capture by LLFP to the total neutron capture is 20%, the proton power becomes 4 MW. By increasing this capture ratio, the proton beam power required is reduced in inverse proportion to η_f. **Fig.7** shows the proton current required to transmute 16.5 **%** LLFP using 1 Gev Proton accelerator.

Although, we have discussed to the transmutation of the minor actinide as **HLWM,** we can use the MA very usefully to prolong fuel burn up; therefore it would be valuable to use MA in the subcritical reactor instead of simply incinerating them. The metal-fuel fast reactor has a small reactivity swing so that it does not require MA for a long burn-up time. Due to the presence of Na as coolant and covering material of the core, refueling takes longer and is a more complicated procedure than in the LWR. Therefore, infrequent **fuel** exchanges are desirable. Because the addition of MA can change the reactivity swing to a positive one, we **can** lengthen the time for fuel burn-up, provided that the metallurgic properties of the fuel are not greatly changed by the accumulation of fission products.

VI. Conclusion

An accelerator can operate a ***reactor*** running ***in*** subcritical condition with enhanced safety. **In** subcritical operation, high neutron economy can be achieved, which, in turn, can lead to a high rate of breeding of **fissile** fuel or transmutation of MA and LLFP without jeopardizing the reactor's safety.

Accelerator technology has progressed greatly in the last few decades and the cost of the accelerator has become a small percent of the cost of nuclear energy generation when the reactor or transmutor is run in a slightly subcritical state. Due to the substantial increase in safety, and the increase in efficiency of breeding gain or transmutation, the cost of this nuclear system can be reduced below that of the present critical operation. Furthermore, the present reactor does not necessarily need to be changed to adopt a slightly subcritical operation. When a safer operation is required using other types of reactors, such as the Pb coolant or molten-salt reactor, then the experience gained from the accelerator-driven reactor or transmutor will play an indispensable role. By adding MA to Pu-fuel, the burn up reactivity becomes small; thus we should use MAs in the reactor rather than incinerating them.

The first phase of nuclear energy development has been successfully completed by the LWR, tiespite the Three Mile accident. To use this vital nuclear energy source more extensively in the near future, reactor safety must be more improved, and problems of high level waste material and the proliferation of nuclear material must be solved, so that the public can accept nuclear energy more readily as a major source of energy. New technologies are emerging and in the second phase of development, we should actively use these advanced technologies to make nuclear energy systems more friendly to the society. The use of the accelerator cart be one of the options for this purpose, and will be followed by the more inventive technologies in the future.

VII. Acknowlegements

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