

INES-1 International Symposium

# THE FEASIBILITY STUDY ON PERFECT BURNING REACTOR SYSTEM

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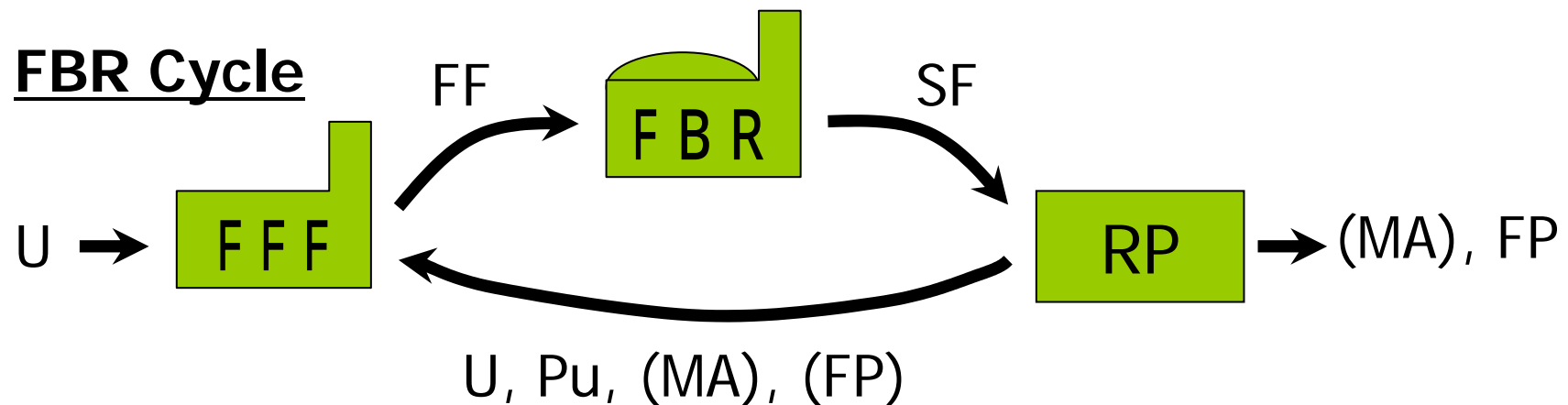
Innovative Research Promotion Office,  
Japan Nuclear Cycle Development Institute

November 1, 2004

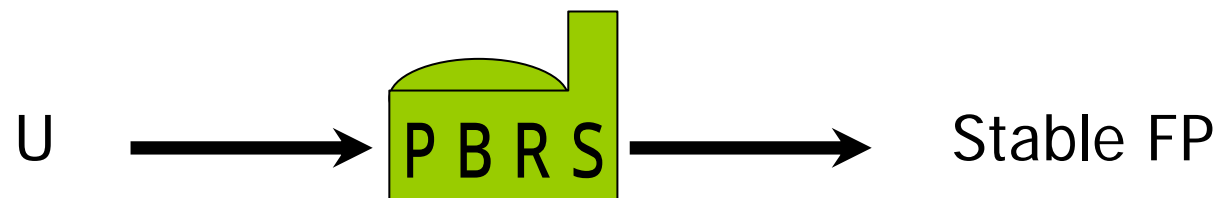
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## Definition of Perfect Burning Reactor System (PBRs)

- The system that can realize the 100% fuel burning with once-through is defined as “Perfect Burning Reactor System (PBRs)”.
- If natural uranium can be perfectly burned including the annihilation of generated minor actinides and some fission products with once-through, such a system might be considered to be a very simple nuclear system aiming the resource efficiency and radiotoxicity reduction goals together.



### **PBRs**



# Objective

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- The objectives of this study are:
  - To qualitatively examine the feasibility of the system that natural uranium is perfectly burned with once-through and to point out some problems accompanied with the system.
  - In addition, to suggest some of the newly developed nuclear systems based on the results obtained here.

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- Introduction
  - Analytical Method
  - Results
  - Discussion
  - Conclusion
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# Introduction (1): Uranium is a very valuable material

- It is well known that the energy of about 200 MeV is generated per fission based on “Special Theory of Relativity” proposed by Albert Einstein.
- The fact means that the energy of about 1 MWD is gained when only 1 gram of uranium is perfectly burned.
- If 10 tones of uranium are perfectly burned, the energy of  $1 \times 10^7$  MWD is produced. The energy generates about  $1 \times 10^{11}$  KWh of electric power and it has a value of 10 billion dollars when a parameter of 10cents/KWh is used.

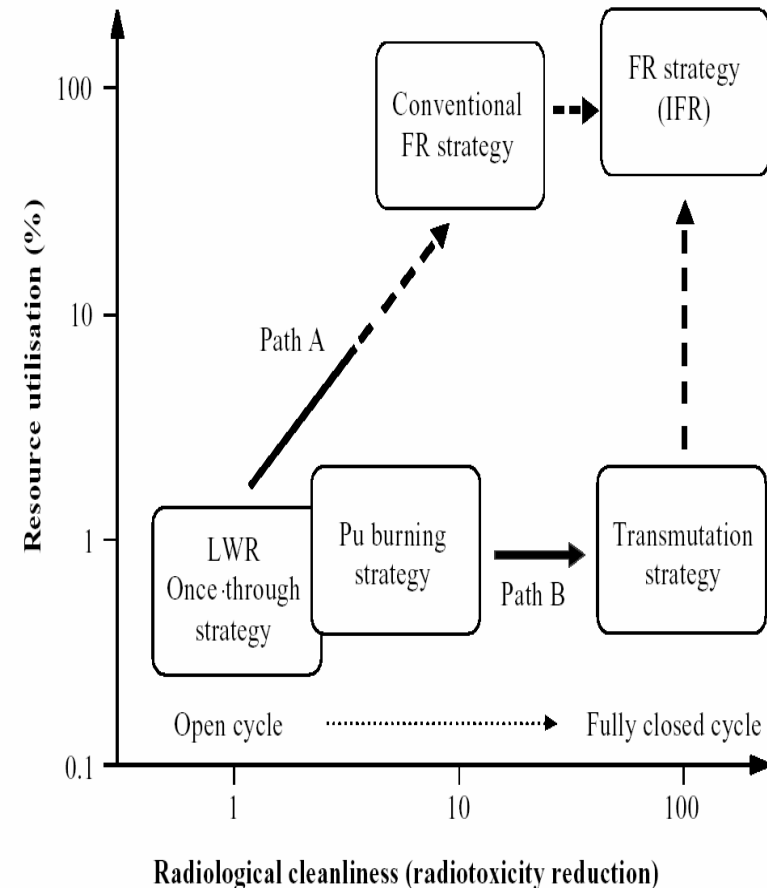


“Special Theory of Relativity”  
written by A. Einstein

## Introduction (2) : History of nuclear reactor system development

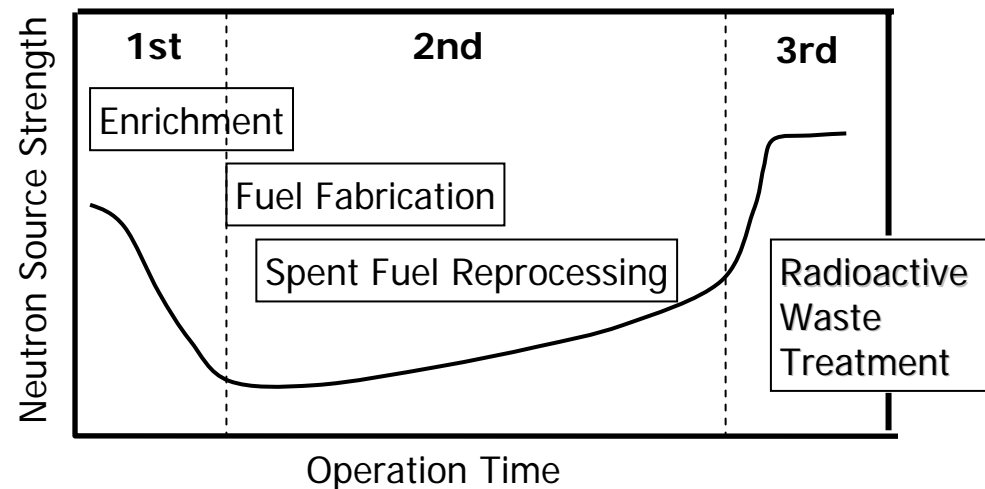
- Most of the development has been focused on LWR and its fuel cycle.
- The plutonium generation in LWR fuels was considered to be utilized in FBR.
- In the early days, less attention was given on the back-end of fuel cycle.
- However, some forty years of nuclear energy deployment caused a growing stock of spent fuel, or separated plutonium and HLW, and environmental friendliness became major concern of the public.
- The newly developed nuclear system should, therefore, involve some good characteristics such as resource efficiency and radiotoxicity reduction together with proliferation, nuclear safety and cost effectiveness.

OECD/NEA suggested nuclear energy strategies and paths to the future.



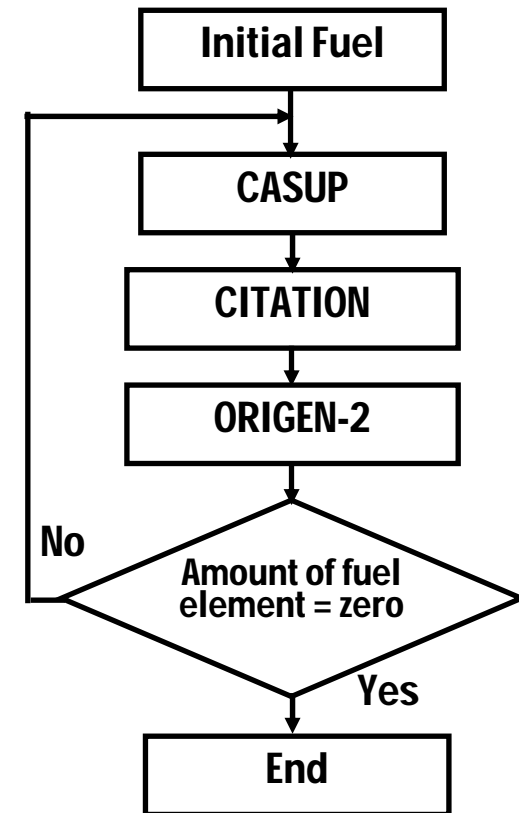
## Introduction (3) : PBRS needs external neutrons

- A strong neutron source might be needed in the first stage, because a rapid conversion to plutonium is demanded.
- A gradual increase might be followed in the second stage, because the amount of plutonium decreases with operation.
- A very large amount of external neutrons might be again needed in the third stage, because uranium and plutonium do not remain in the core any more.
- It might be speculated that some of fission products inconvenient to radioactive waste disposal for a long period are transmuted in the third stage, if external neutron supply is continued even after the thermal output is zero.
- It is clearly found that the neutron plays an important role on the PBRS and it substitutes for fuel cycle activities such as uranium enrichment, fuel fabrication, spent fuel reprocessing and radioactive waste treatment.



## Analytical Method (1): Flow chart of the analysis

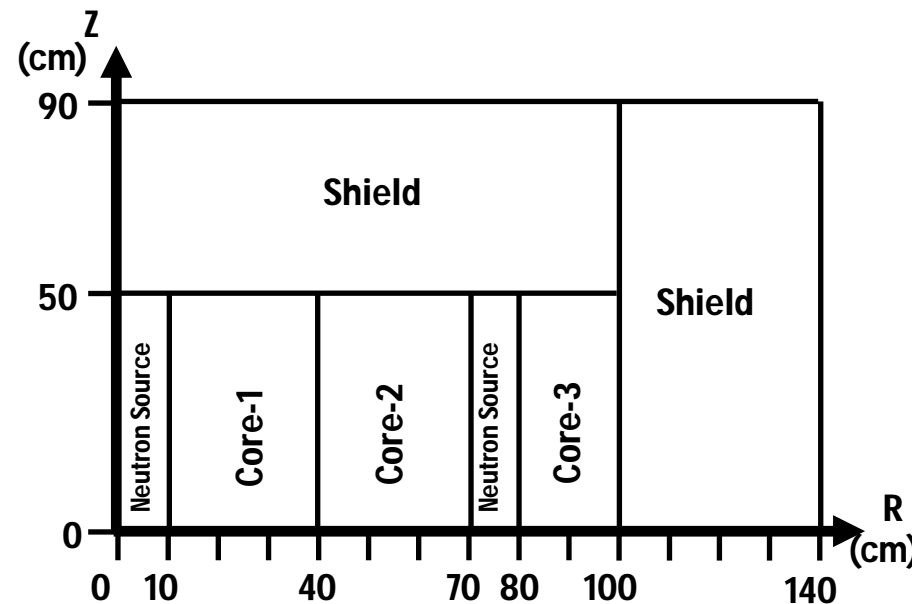
- As shown in the figure, the initial fuel composition is at first set.
- The cell calculation follows and the 70 groups of effective microscopic cross sections are prepared based on the JFS-3-J3 by use of the CASUP that is developed by Osaka University.
- The two-dimensional diffusion code CITATION is used for the whole core calculation. The code is slightly modified in order to take into account the external neutron source. The whole core calculation gives the neutron spectrum at each region in the RZ-geometry.
- The burn-up calculation is then done by using the ORIGEN-2 and the amount of each nuclide after one year is calculated and the fuel composition is revised.
- The time step interval is set to be one year in the series of calculations. The spectrum of the external neutrons is considered to be equal to that of the neutrons in FBR core.





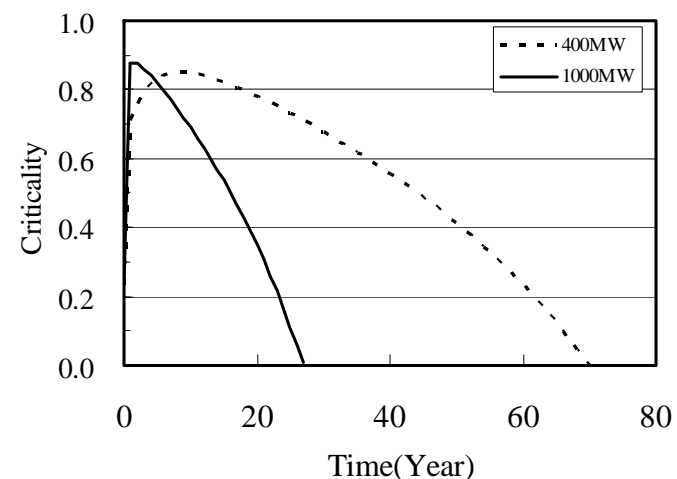
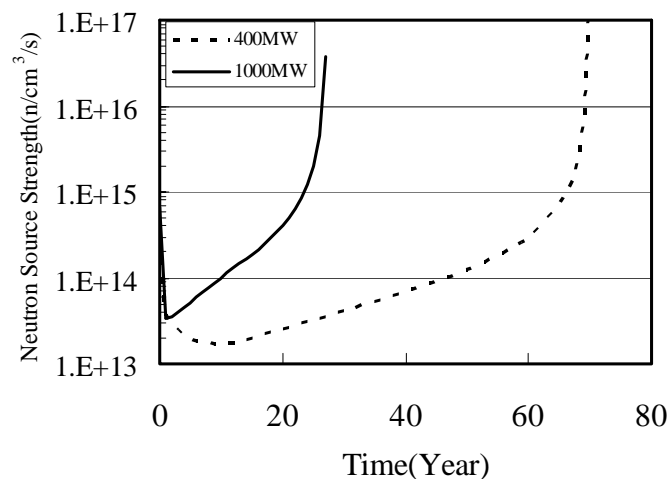
## Analytical Method (2): Geometry of the analysis

- The core configuration is similar to that of the prototype FBR “Monju”, and both radial and axial blanket regions are removed from the original “Monju”.
- The neutron source regions are installed in order to minimize the distortion of the distribution of neutron flux, and the regions are situated at the center and intermediate radial positions of the core. The fuel region is divided into three.
- The amount of natural uranium is 10 tones and the thermal outputs are fixed to be 400 and 1000 MW throughout the operation period.



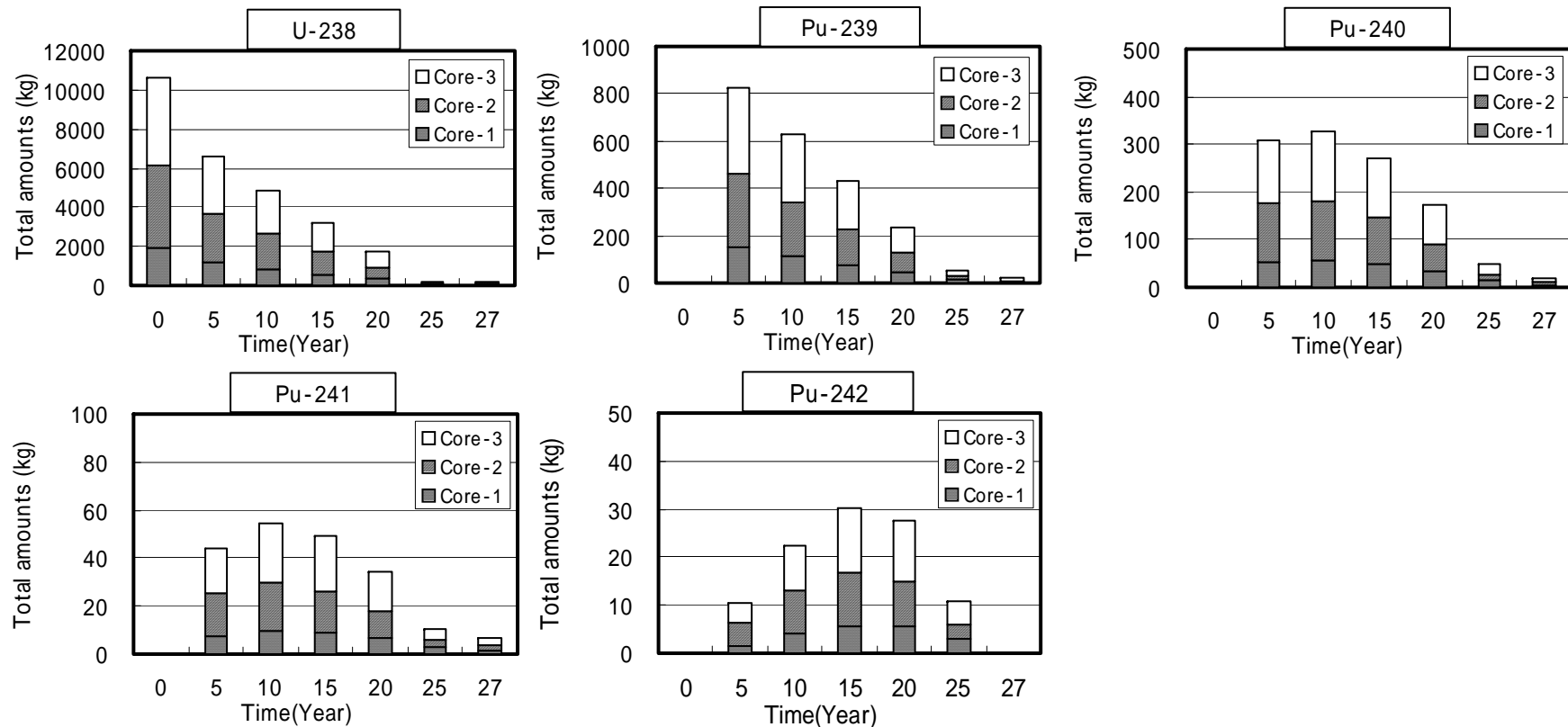
## Results (1) : Neutron source strength and criticality

- The neutron source strength per unit volume is assumed to be uniform in the target of the neutron source region.
- The strength rapidly decreases due to rapid conversion from U-238 to Pu-239 and gradually increases and then the rapid increment follows at EOL.
- The parameter indicating the criticality (k-effective value) at every burning stage is evaluated by supposing that the neutron source strength is zero.
- The k-effective value at BOL is 0.23 and it rapidly increases and gradually decreases and then becomes zero where no fuel elements exist. The sub-criticality maintains during the operation period, but the level is very low.



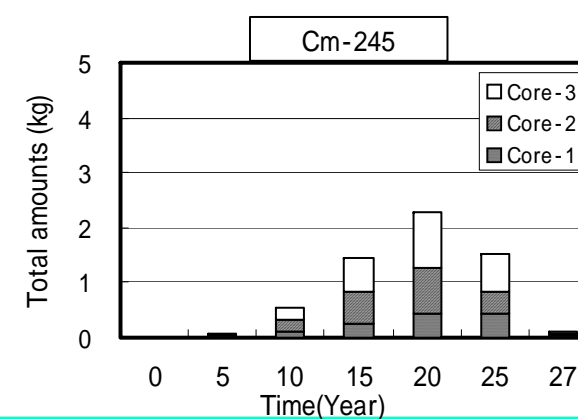
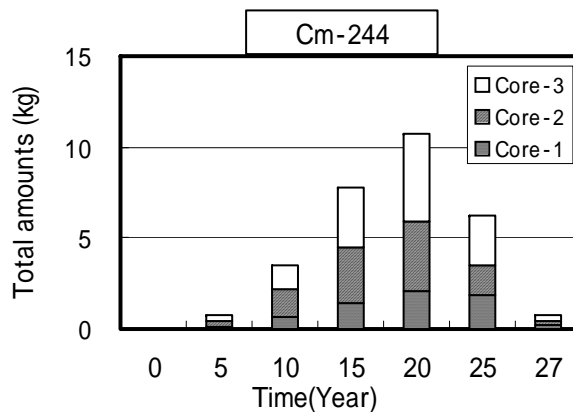
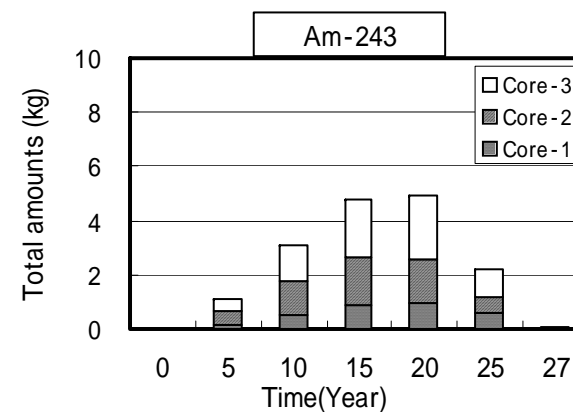
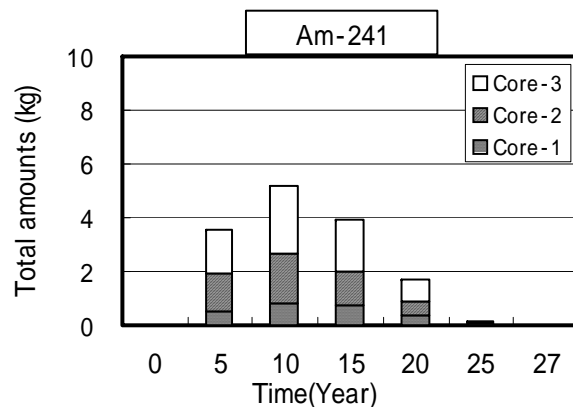
## Results (2): Amount of uranium and plutonium

- The U-238 gradually decreases with operation time and the Pu-239 rapidly increases at BOL and then gradually decreases with operation time.
- The residual plutonium isotopes gradually increase and have a maximum value and then decrease. All kinds of plutonium isotopes eliminate at EOL.



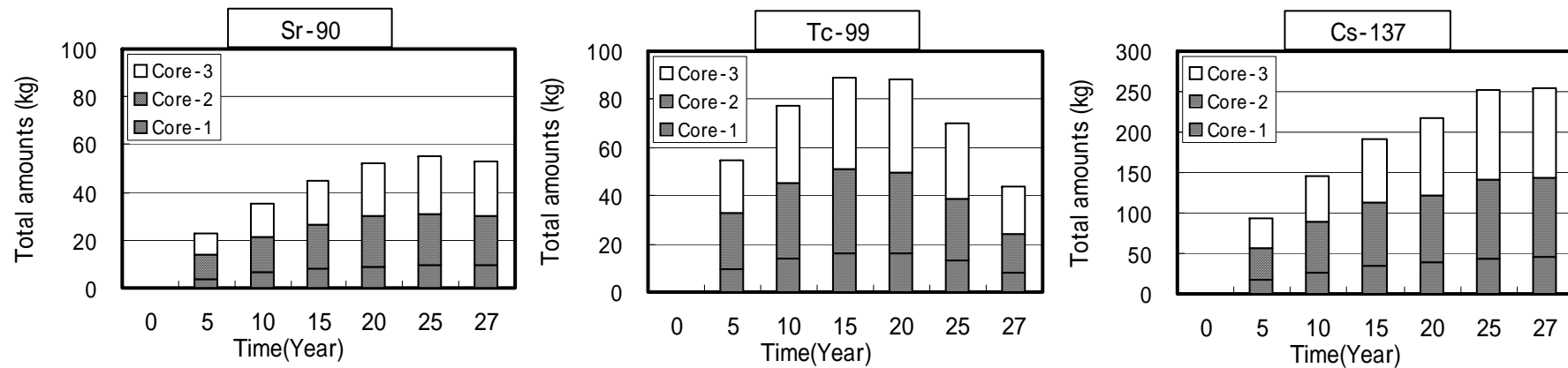
## Results (3) : Amount of minor actinides

- The minor actinides such as americium and curium isotopes gradually increases and reaches maximum and then decreases at EOL.
- It is found that the heavy elements such as uranium and plutonium are perfectly burning but a very few of minor actinides remains at EOL.



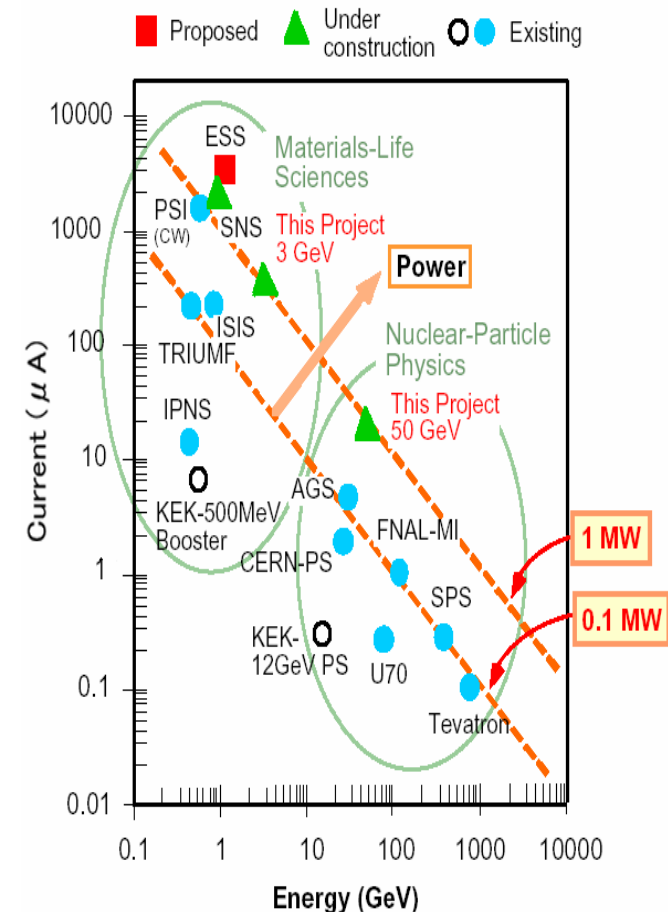
## Results (4) : Amount of fission products

- The fission products such as Sr-90, Tc-99 and Cs-137, which are inconvenient to radioactive waste disposal, gradually increase and the sign of the decrement of these elements is observed at EOL.
- It is speculated that these fission products and minor actinides might decrease if external neutrons are supplied even after the thermal output reaches to zero.



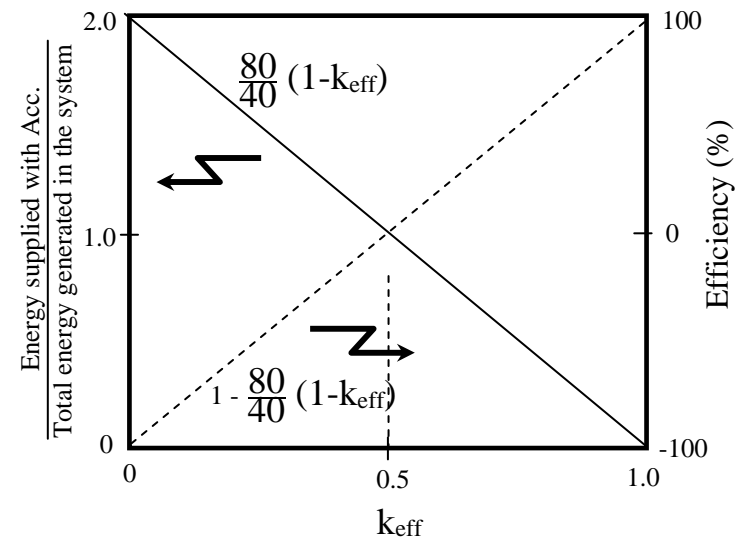
## Discussion (1) : Performance of accelerator

- The amount of external neutrons needed in the PBRs is estimated to be  $1.5 \times 10^{20}$  n/s .
- The 50 neutrons are produced by the spallation of one proton having 2 GeV of beam energy.
- The necessary proton current is calculated to be 480 mA by using the value (50 neutrons/proton) and the proton charge of  $1.6 \times 10^{-19}$  Coulomb.
- The maximum proton current is reported to be in the order of 10 mA. A number of accelerators is thus needed for the supplement of the neutrons.
- If the 20 accelerators are equipped, the necessary proton current should be decreased and the proton current is 24 mA and the value goes into the possible range of the current technology.
- It might be possible for us to realize the concept of the PBRs by use of the current accelerator technology.



## Discussion (2) : Energy balance

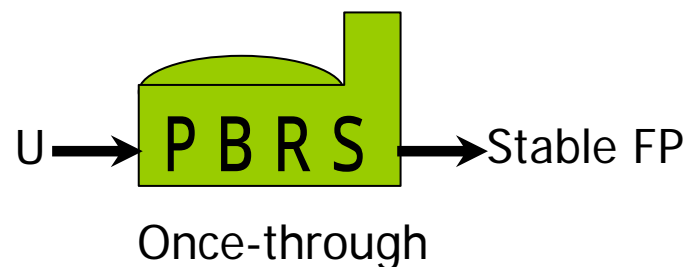
- The 80 MeV of electric energy is needed for getting one spallation neutron. One spallation neutron yields 40 MeV of electric energy.
- The electric energy can be multiplied by introducing sub-critical core. The amplification factor depends on k-effective. If the k-effective value of the system equals to be 0.5, the electric energy generated in the system is used only to supply the energy with the accelerator.
- The optimistic estimations mean that the 60-70 percent burning of natural uranium might be possible with maintaining the energy balance. The time averaged utilization efficiency of thermal energy becomes about 16 % in the system including the energy supplement with the accelerator.
- It is concluded that the PBRS can be possible, but cannot be consistent with the economic rationality, and that the nuclear fuel recycling shall be required to achieve the rational utilization of nuclear energy aiming the resource efficiency and radiotoxicity reduction goals together.



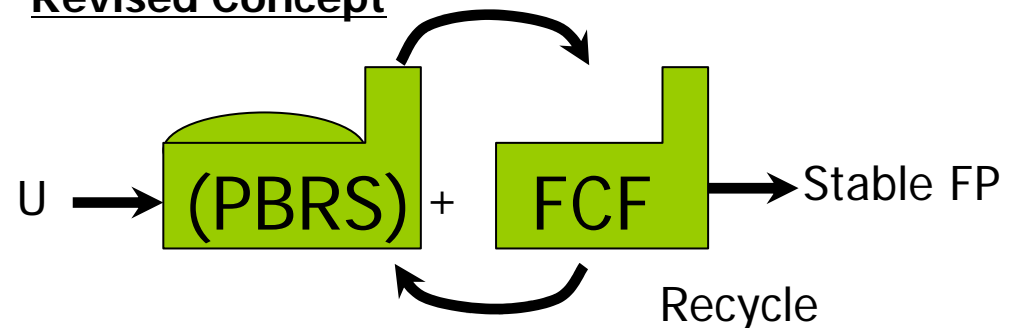
## Discussion (3) : Revised concept of PBRS

- The original concept shall be revised and the revised PBRS is as follows;
  - The initial loaded fuel is burned until the energy balance is maintained and the residual materials in the system are removed and are roughly separated into two groups of stable fission products and others that contain uranium, plutonium, minor actinides and fission products inconvenient to radioactive waste disposal. The residuals except for stable fission products are recycled in the system together with the additional natural uranium and this cycle is repeated.
  - The revised one has many good characteristics such as very high resource efficiency, ultra high fuel burn-up capability, radiotoxicity reduction, infrequent reprocessing and fuel fabrication, proliferation and nuclear safety.
- The revised one is very similar to Integrated Fast Reactor (IFR) except for introducing ADS, however, the introduction of ADS is accompanied with much cost and it causes the loss of economic rationality.

### Original Concept



### Revised Concept

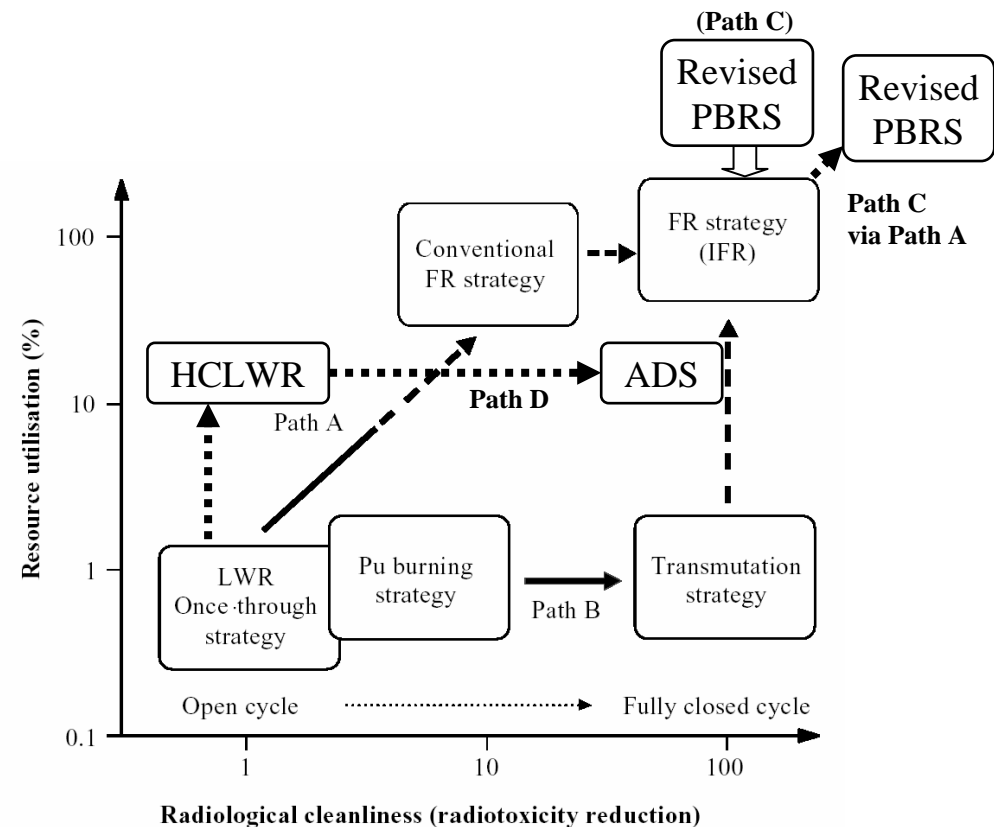




## Discussion (4): Nuclear energy strategy and paths to the future

- The fast reactor system with a fully closed cycle (IFR) is considered to be the most probable one. The transition from the conventional fast reactor to the IFR was envisaged already in the 1980s, but not given much attention. (Path A)
- Another path was favored and it was attempting to reach the IFR via the transmutation strategy, with and without a preceding plutonium burning phase. (Path B)
- The selection of the revised PBRS is one of the strategies, and it might aim to reach the revised PBRS via Path A. The revised PBRS shall be replaced by the IFR, or located at the extension of the IFR. (Path C)
- The combination of LWR improving its conversion ratio and ADS burning actinides is also the strategy and it leads to another new path. (Path D)

OECD/NEA suggested nuclear energy strategies and paths to the future.



## Conclusion

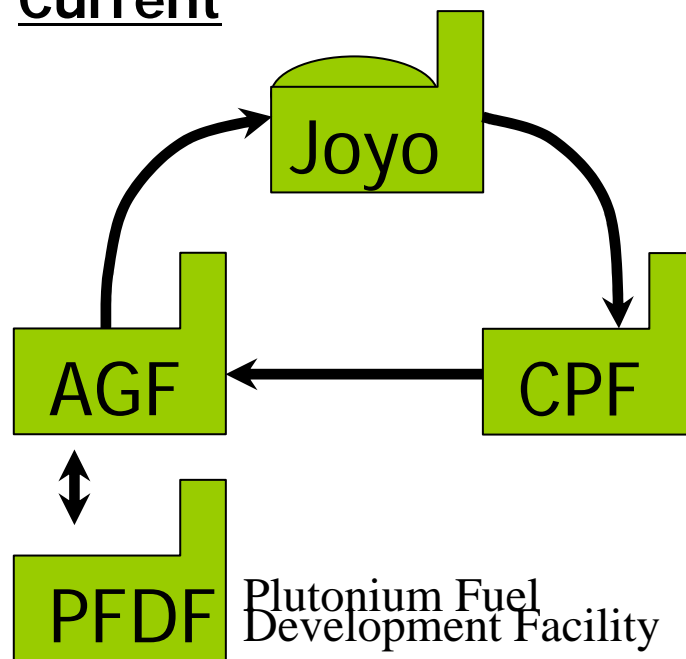
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- The PBRS corresponding the system of 100% fuel burning with once-through is feasible but cannot be consistent with the economic rationality.
  - Nuclear fuel recycling shall be required to achieve the rational utilization of nuclear energy aiming the resource efficiency and radiotoxicity reduction goals together.
  - Even though the original concept of the PBRS shall be revised, the revised PBRS has a lot of good characteristics.
  - The scope of the newly developed nuclear system is discussed and several possible nuclear energy strategies and paths to the future are introduced.
  - The base technologies are quite common to all of the strategies.
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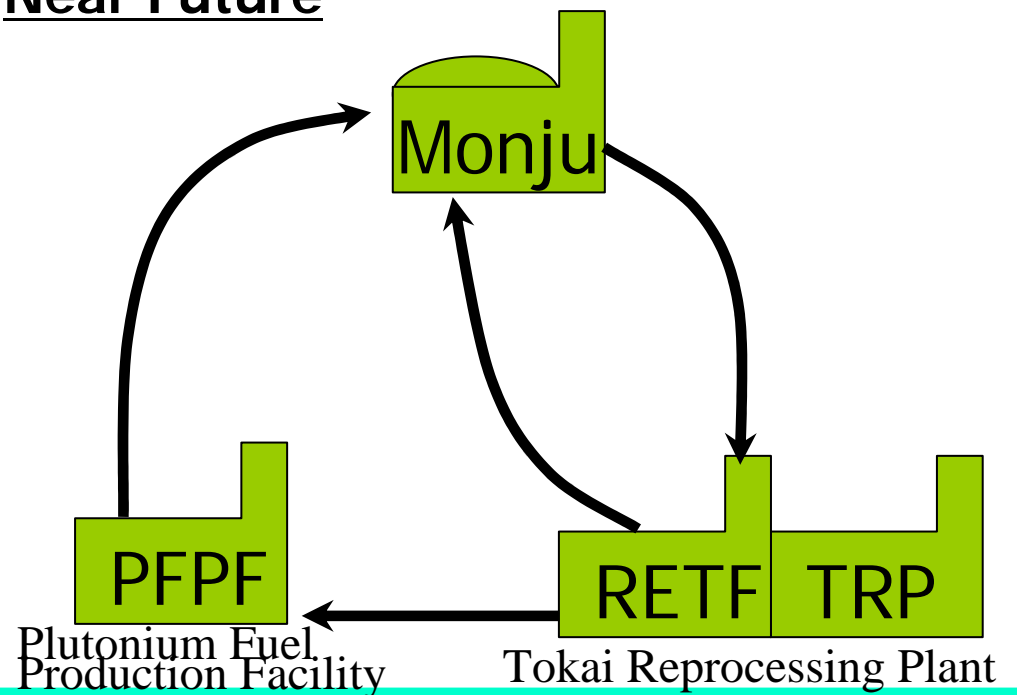
## What shall we do now ?

- We shall continue to make research and development on FBR cycle using the existing facilities such as “Joyo”, CPF (Chemical Processing Facility) and AGF (Alfa Gamma Facility).
- We shall re-start “Monju” project as soon as possible together with the related nuclear fuel cycle facilities such as RETF (Recycle Equipment Test Facility).

### Current



### Near Future



# The Feasibility study on Perfect Burning Reactor System

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Thank you very much for your attention!

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Head of Innovative Research Promotion Office  
Japan Nuclear Cycle Development Institute

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## How do we think about Molten Salt Reactor ?

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- It might be requested to discuss whether the molten salt is probable or not as nuclear fuel of the PBRS.
- It might be considered that the molten salt reactor system seems to be consistent with the concept of the PBRS because the fresh fuel supply and fission products removal can be continuously done without reactor shut down and the k-effective of the core is kept to be constant.
- However, it is considered that the corrosion of the structure material due to the molten salt shall be death to the system and that very few amount of the knowledge on the characteristic and irradiation behavior of the molten salt fuel are available at present.
- Therefore, the conventional type of fuel is considered in this paper.

## What kinds of R&D on the revised PBRs are necessary ?

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- It is well accepted that the base technologies are common to all of the strategies and they are the technologies of the advanced reprocessing and fuel fabrication, the investigation of fuel and material behavior at ultra high burn-up condition, accelerator technique, sub-criticality measurement technique, and system engineering.
- The fuel and material development is a key issue to obtain ultra high burn-up of fuels.
- The oxide fuel is considered to be most probable type of high burn-up fuel because it is still stable even at very high burn-up, if the oxygen getter should be developed in order to consume the excess oxygen at very high burn-up.
- The ventilation type fuel shall be requested because of the reduction of the internal pressure increment at very high burn-up.
- The HT-9 stainless steel developed in USA and the ODS ferrite steel in Japan are considered as the promising candidates for fuel cladding materials because of their very high resistance with void swelling.
- It shall be needed to make sure the fuel behavior at ultra high burn-up condition by both theoretical and experimental approaches.

## How do we understand the Energy Balance ?

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- Electric energy which is needed for getting one spallation neutron is 80 MeV.
  - The proton accelerator, the beam energy of which is 1 GeV, generates 25 neutrons.
  - The proton beam energy of 40 MeV is needed for getting one spallation neutron.
  - The conversion efficiency from electric energy to proton beam energy is estimated to be 0.5.
  - Thus the electric energy of 80 MeV is needed for getting one spallation neutron.
- One spallation neutron yields 40 MeV of electric energy.
  - The thermal energy of 200 MeV is generated by a fission.
  - The conversion efficiency from thermal to electric energy is estimated to be 0.4.
  - The ratio of fission to capture cross section is estimated to be 0.5.
  - Thus the electric energy of 40 MeV is generated by one spallation neutron.
- Electric energy generated by spallation neutron is multiplied by introducing sub-critical core.
  - The amplification factor depends on k-effective of the core.
  - The factor is proportional to the reciprocal of  $(1 - k\text{-effective})$ .

## Why the amplification factor is proportional to the reciprocal of (1 -k-effective) ?

- The sub-critical core of P GW is now considered.

- *The number of neutrons generated in every one second is defined by  $n_g$ .*
- *The number of neutrons supplied by proton accelerator is defined by  $n_s$ .*
- *The relationship between  $n_g$  and  $n_s$  is obtained as follows;*

$$n_s = n_g - k_{eff} \times n_g = n_g \times (1 - k_{eff}), \quad n_s / n_g = (1 - k_{eff}), \quad 40 \times n_g = P$$

- Consideration 1 : Effective electric energy for generating one spallation neutron

- *80 Mev corresponds to the case that all neutrons in the core are supplied by spallation.*
- *The effective electric energy for generating is considered to be expressed as follows;*

$$80 \times n_s / n_g = 80 \times (1 - k_{eff})$$

- *The ratio of electric energy supplied with accelerator to total energy generated in the core is*

$$80 \times (1 - k_{eff}) \times n_g / 40 \times n_g = (80 / 40) \times (1 - k_{eff})$$

- Consideration 2 : Effective electric energy generating by one spallation neutron

- *The total energy of P GW is considered to be generated by spallation neutron of  $n_s$ .*
- *The effective electric energy generated by spallation neutron is considered to be expressed as follows;*

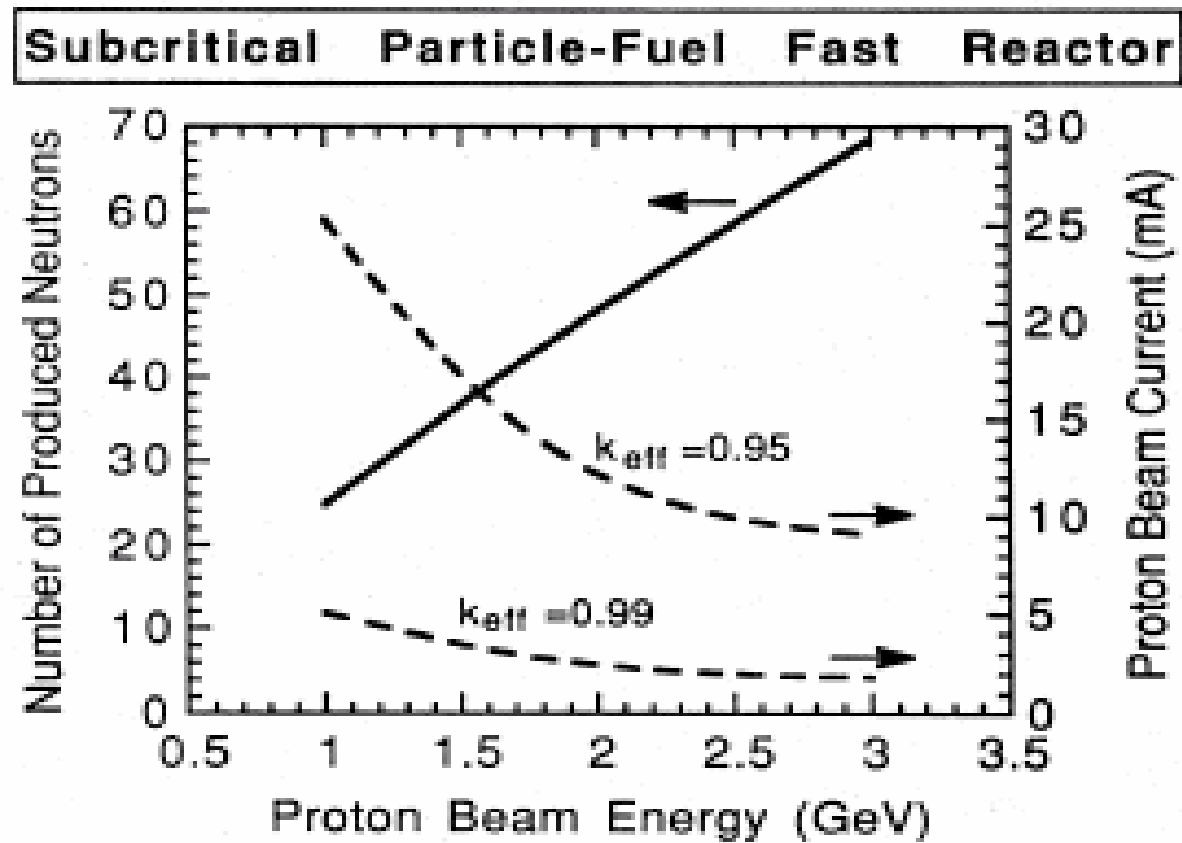
$$(40 \times n_g) / n_s = 40 / (n_g / n_s) = 40 / (1 - k_{eff})$$

- *The ratio of electric energy supplied with accelerator to total energy generated in the core is*

$$80 \times n_s / 40 \times n_g = (80 / 40) / (n_g / n_s) = (80 / 40) \times (1 - k_{eff})$$



## Sub-critical Particle-Fuel Fast Reactor



# What kinds of fission products are considered ?

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- Radiation level is high, but the half life time is not long:  
(First Group)  
 $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{151}\text{Sm}$
- Radiation level is not high, but the half life time is long:  
(Second Group)  
 $^{79}\text{Se}$ ,  $^{126}\text{Sn}$ ,  $^{93}\text{Zr}$ ,  $^{99}\text{Tc}$ ,  $^{135}\text{Cs}$ ,  $^{107}\text{Pd}$ ,  $^{129}\text{I}$
- First Group is decayed or transmuted in the nuclear reactor system.
- Second group is transmuted in the nuclear reactor system.
- The isotope separation is needed when the transmutation is done.

## Transmutability of long-lived fission products

Table 2.6. Transmutability of long-lived fission products

Fission product	$T_{1/2}^{\text{Decay}}$ (y)	$T_{1/2}^{\text{Trans}}$ (y) <sup>1</sup>	Isotopic separation	Transmutable (yes/no)
<sup>129</sup> I	$1.6 \cdot 10^7$	51	no	yes <sup>2</sup>
<sup>135</sup> Cs	$2.3 \cdot 10^6$	170	yes	no
<sup>99</sup> Tc	$2.1 \cdot 10^5$	51	no	yes
<sup>126</sup> Sn	$1.0 \cdot 10^5$	$4.4 \cdot 10^3$	yes	no
<sup>79</sup> Se <sup>3</sup>	$6.5 \cdot 10^4$	$2.2 \cdot 10^3$	yes	no

1. Thermal flux:  $10^{14}$  n/cm<sup>2</sup>-s.
2. R&D necessary to improve the iodine separation yield and the stability of the target material.
3. Half-lives for <sup>79</sup>Se around  $6.5 \cdot 10^4$  years have been used widely in waste inventory and repository performance assessments. Recent nuclear data studies, however, indicate a much longer half-live for this nuclide (see <http://nucleardata.nuclear.lu.se/nucleardata/>).

## How do we think about ADS in nuclear reactor system strategy ?

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- ADS needs a lot of electric energy, so it is difficult to get economical rationality.
- It shall be well discussed the policy in view point of economy that ADS is especially used in order to eliminate minor actinides and fission products inconvenient to radioactive waste disposal.
- If the sub-critical reactor with k-effective of very close to 1.0 is introduced, the load to the accelerator is reduced and the economical rationality might be expected.
- Although several studies in this fields have been done all over the world, many problems to be solved might be remained.
- It is better for us to develop IFR at first and to proceed R&D on the revised PBRS if additional requirements are needed with IFR. (Path C)