Progress in Conceptual Research on Fusion Fission Hybrid Reactor for Energy (FFHR-E)

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Outline

1. Background
2. Blanket neutronics and Numerical tools
3. Design guide line and the blanket model of FFHR-E
4. Numerical results of FFHR-E
5. Summary

1. Background

Fusion science and technology is making progress, but…

- International Thermal Experimental Reactor (ITER) is under construction,

  preliminary feasibility of controlled fusion will be demonstrated in ITER,
  Fusion Gain Q~5, Fusion Power:300-500MW

- There are still a long way to go for pure fusion reactors:

  High Q: ~30
  Material Irradiation: ~200 dpa for structural material

- FFHR can accelerate the early application of fusion energy

…

Traditional Fusion Fission Hybrid Reactor (FFHR)

- FFHR can be classified as Breeders and Transmuters

Breeders were popular before 1980s, to produce plutonium for fission reactors, and form the so called fusion fission symbiotic system

Breeders will need frequent separation of plutonium from uranium , which limits its development

Transmuters become more popular after 1990s， as the inventory of accumulated spent fuel increased.

Transmuters need tens of tons of plutonium in the blanket, which is nearly ten times the plutonium in a fast reactor

FUSION FISSION HYBRID REACTOR FOR ENERGY (FFHR-E)

- fusion power 300~500MW, Q~5.

  The average energy multiplication (M) is about 10, and Tritium Breed Ratio (TBR) is greater than 1.15, blanket power ~3000 MWth

  Nearly 600 tons **nature uranium**, which can be reused in multiple cycles, **Breed and burn of plutonium in blanket**

  simplified reprocessing without separation of TRUs

2. Blanket neutronics and Numerical tools

Couple of Neutron transportation and burnup

$$\vec{\Omega}\bullet\nabla\Phi(\vec{r},E,\vec{\Omega})+\Sigma(\vec{r},E)\Phi(\vec{r},E,\vec{\Omega})=q(\vec{r},E,\vec{\Omega})$$
$$+\int\Sigma(\vec{r},E')f(\vec{r},\vec{\Omega}',E'\rightarrow\vec{\Omega},E)\Phi(\vec{r},E',\vec{\Omega}')d\vec{\Omega}'dE'$$

$$\Phi(r)=\int\Phi(r,E)dE$$

$$\sigma^{i}_{a,eff}=\frac{\int\sigma^{i}_{a}(E)\Phi(r,E)dE}{\Phi(r)}$$

$$dN_i(r,t)/dt=\sum_{k\neq i}N_k(r,t)\sigma^{k\rightarrow i}_{eff}(r,t)\Phi(r)-N_i(r,t)\sigma^{i}_{a,\,eff}(r,t)\Phi(r)$$
$$+\sum_{j\neq i}f_{j\rightarrow i}\lambda_j N_j(r,t)-\lambda_i N_i(r,t)\qquad(i=1,N)$$

Nearly 340 nuclei and 9 different types transition cross sections are considered in the transport calculation(MCNP)

Nearly 1700 nuclei are considered in burnup calculation(ORIGENS)

MCORGS＝MCNP+ORIGENS

$$M = \frac{\mathit{energy}\ \text{deposited in the blanket by one fusion source}}{\text{energy released by one fusion reaction(1 7.6Mev)}}$$

$$TBR = \int (\Sigma_{(n,T)}^{Li^6} + \Sigma_{(n,n')}^{Li^7})\Phi(r,E)drdE$$

$$\frac{F}{B} = \frac{\mathit{fissile}\ \text{material generate rate}}{\text{fissile material consume rate}}$$

MCORGS VERIFICATION

MCORGS HAS BEEN TESTED BY THE FOLLOWING PROBLEMS

1. OECD/NEA burnup credit calculation criticality benchmark phase I-B, 1996, ORNL-6901
2. VVER-1000 LEU and MOX assembly computational benchmarks”.NEA/NSC/DOC(2002), ISBN 92-64-18491-0
3. IAEA ADS benchmark results and analysis”. IAEA ADS Benchmark , Madrid: TCM.1999:451-482.
4. It is also used to calculate and analysis the following hybrid system the ultra deep burnup hybrid model of Laser Inertial Confinement Fusion Fission Energy(LIFE)
5. Analysis the fluid Transmuter model of In-Zineraters.

OECD/NEA Burnup Credit Calculation Criticality Benchmark Phase I-B

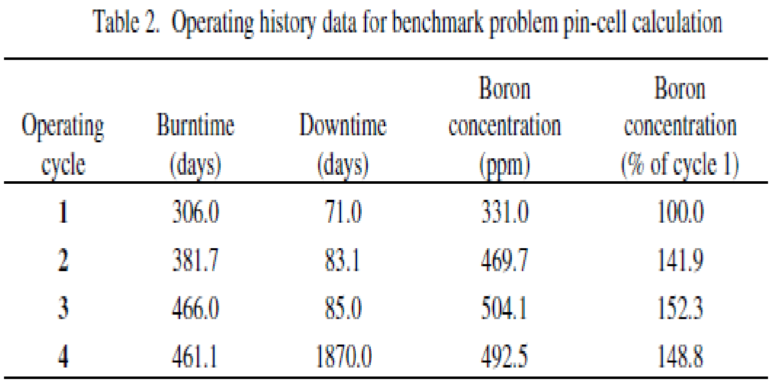


Table 2. Operating history data for benchmark problem pin-cell calculation

Operating cycle	Burntime (days)	Downtime (days)	Boron concentration (ppm)	Boron concentration (% of cycle 1)
1	306.0	71.0	331.0	100.0
2	381.7	83.1	469.7	141.9
3	466.0	85.0	504.1	152.3
4	461.1	1870.0	492.5	148.8

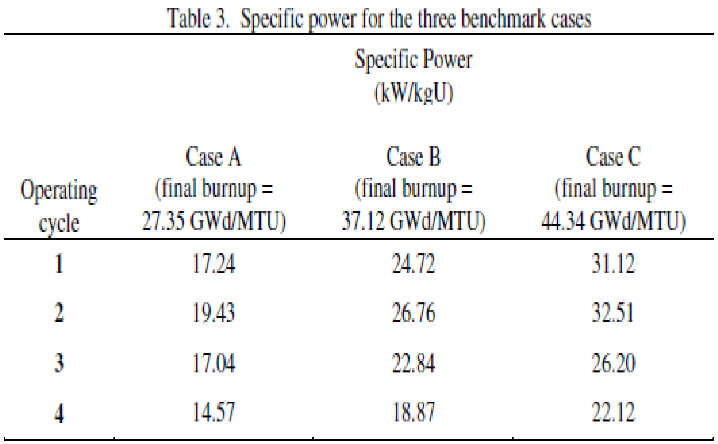
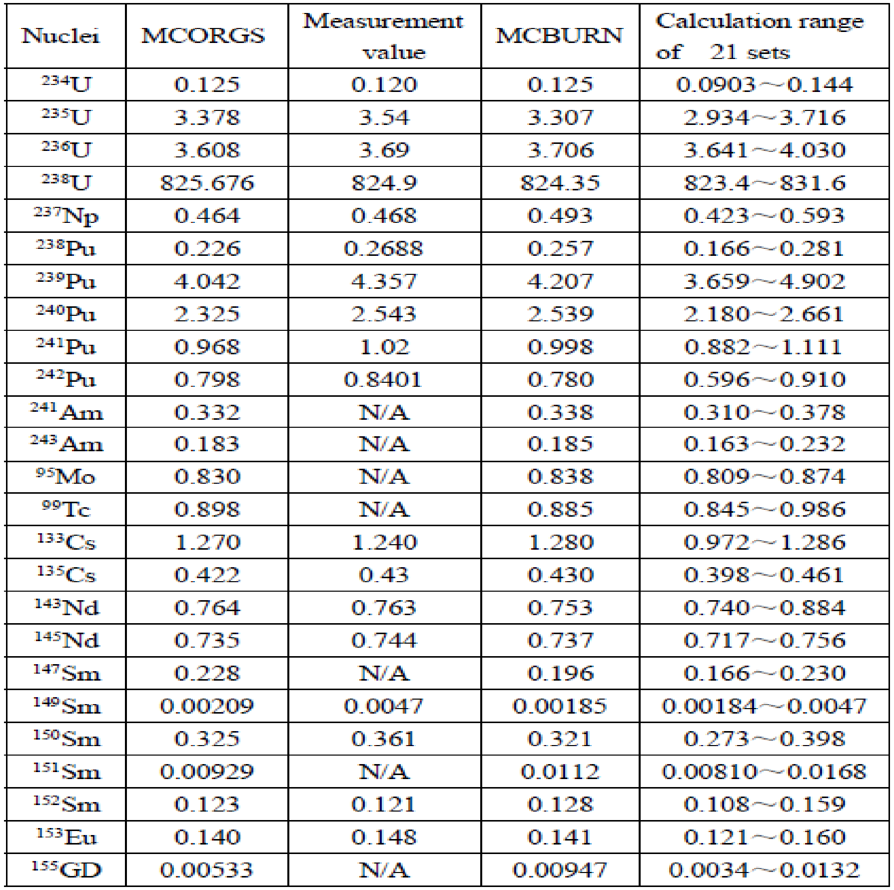


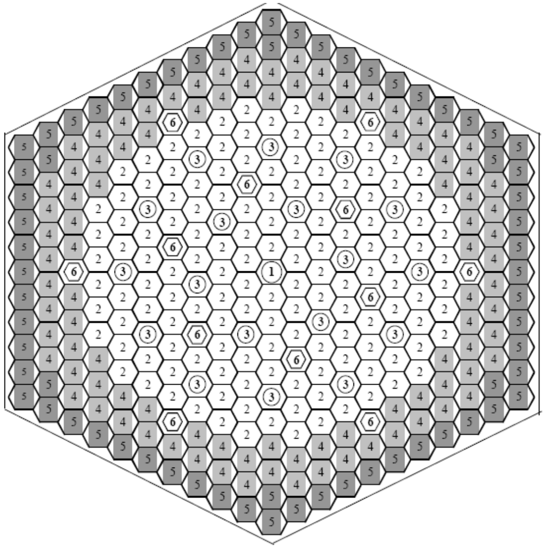
Table 3. Specific power for the three benchmark cases

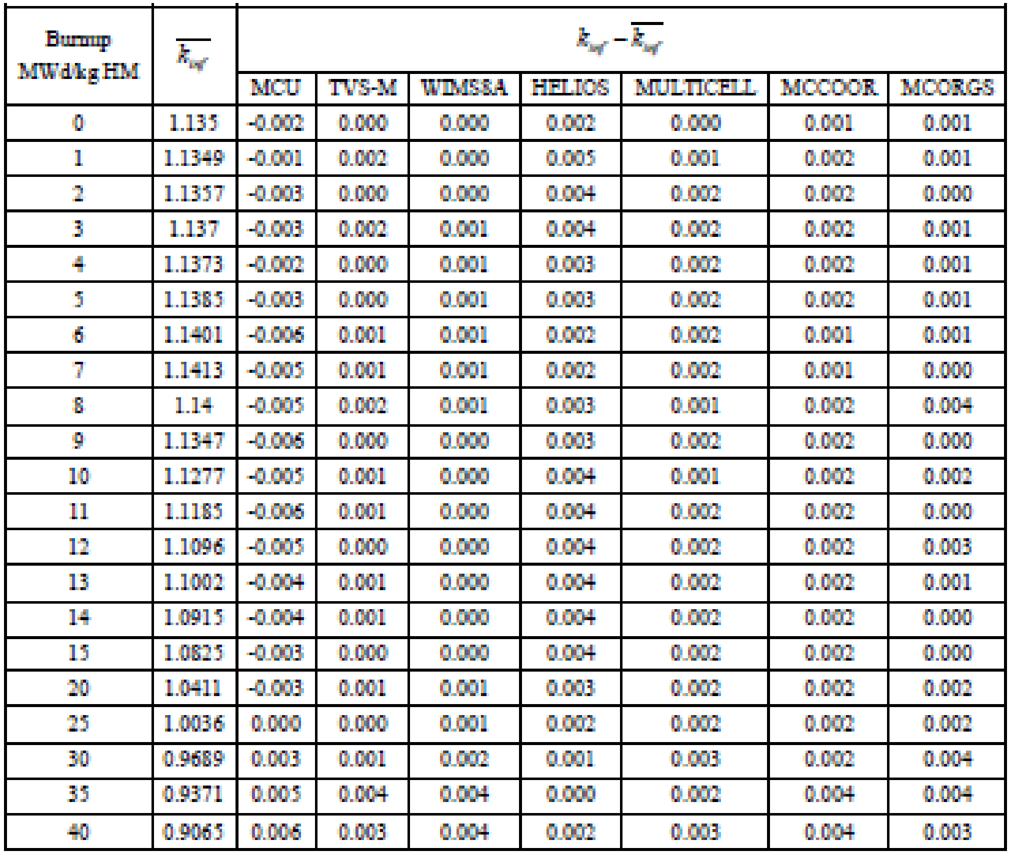
Operating cycle	Specific Power (kW/kgU) Case A (final burnup = 27.35 GWd/MTU)	Case B (final burnup = 37.12 GWd/MTU)	Case C (final burnup = 44.34 GWd/MTU)
1	17.24	24.72	31.12
2	19.43	26.76	32.51
3	17.04	22.84	26.20
4	14.57	18.87	22.12



Nuclei	MCORGS	Measurement value	MCBURN	Calculation range of 21 sets
^{234}U	0.125	0.120	0.125	0.0903～0.144
^{235}U	3.378	3.54	3.307	2.934～3.716
^{236}U	3.608	3.69	3.706	3.641～4.030
^{238}U	825.676	824.9	824.35	823.4～831.6
^{237}Np	0.464	0.468	0.493	0.423～0.593
^{238}Pu	0.226	0.2688	0.257	0.166～0.281
^{239}Pu	4.042	4.357	4.207	3.659～4.902
^{240}Pu	2.325	2.543	2.539	2.180～2.661
^{241}Pu	0.968	1.02	0.998	0.882～1.111
^{242}Pu	0.798	0.8401	0.780	0.596～0.910
^{241}Am	0.332	N/A	0.338	0.310～0.378
^{243}Am	0.183	N/A	0.185	0.163～0.232
^{95}Mo	0.830	N/A	0.838	0.809～0.874
^{99}Tc	0.898	N/A	0.885	0.845～0.986
^{133}Cs	1.270	1.240	1.280	0.972～1.286
^{135}Cs	0.422	0.43	0.430	0.398～0.461
^{143}Nd	0.764	0.763	0.753	0.740～0.884
^{145}Nd	0.735	0.744	0.737	0.717～0.756
^{147}Sm	0.228	N/A	0.196	0.166～0.230
^{149}Sm	0.00209	0.0047	0.00185	0.00184～0.0047
^{150}Sm	0.325	0.361	0.321	0.273～0.398
^{151}Sm	0.00929	N/A	0.0112	0.00810～0.0168
^{152}Sm	0.123	0.121	0.128	0.108～0.159
^{153}Eu	0.140	0.148	0.141	0.121～0.160
^{155}GD	0.00533	N/A	0.00947	0.0034～0.0132

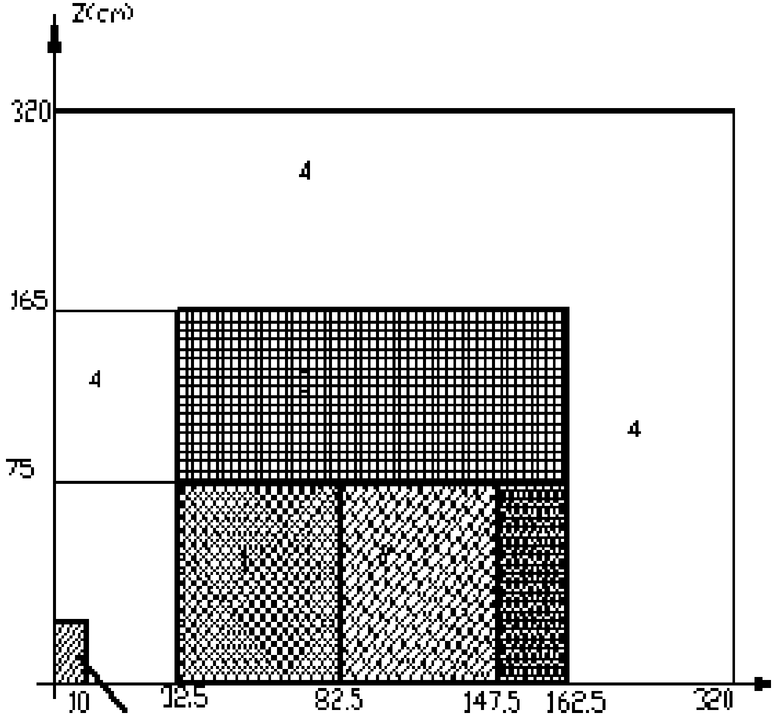
VVER MOX-Gd Benchmark

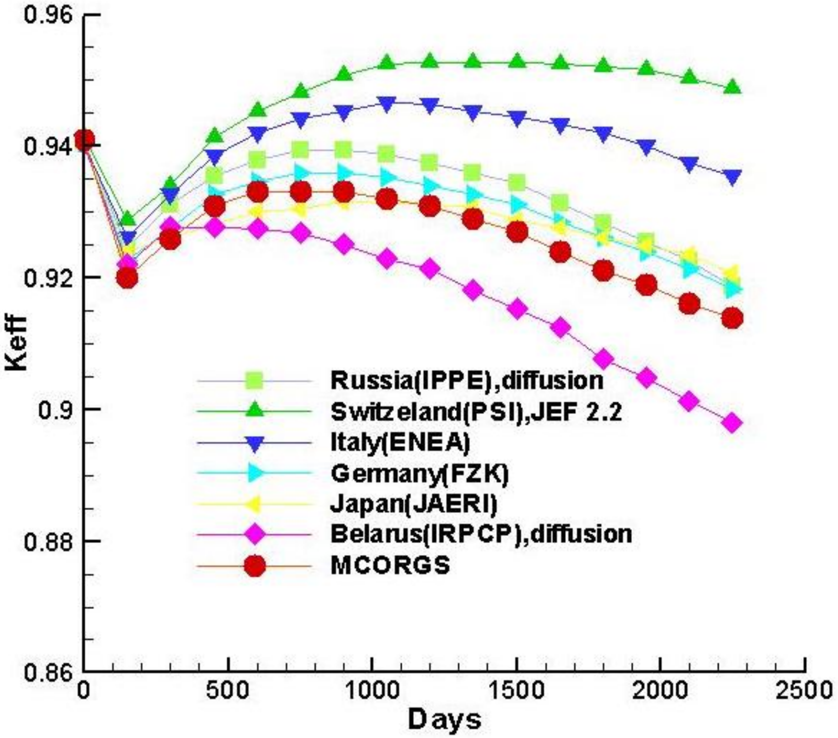




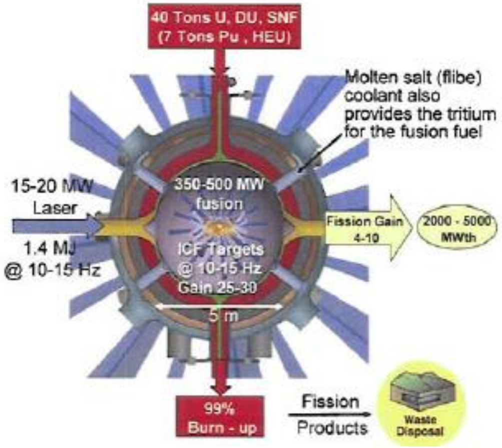
Burnup MWd/kg HM	$\overline{k_{inf}}$	$k_{inf} - \overline{k_{inf}}$						
		MCU	TVS-M	WIMS8A	HELIOS	MULTICELL	MCCOOR	MCORGS
0	1.135	-0.002	0.000	0.000	0.002	0.000	0.001	0.001
1	1.1349	-0.001	0.002	0.000	0.005	0.001	0.002	0.001
2	1.1357	-0.003	0.000	0.000	0.004	0.002	0.002	0.000
3	1.137	-0.003	0.002	0.001	0.004	0.002	0.002	0.001
4	1.1373	-0.002	0.000	0.001	0.003	0.002	0.002	0.001
5	1.1385	-0.003	0.000	0.001	0.003	0.002	0.002	0.001
6	1.1401	-0.006	0.001	0.001	0.002	0.002	0.001	0.001
7	1.1413	-0.005	0.001	0.001	0.002	0.002	0.001	0.000
8	1.14	-0.005	0.002	0.001	0.003	0.001	0.002	0.004
9	1.1347	-0.006	0.000	0.000	0.003	0.002	0.002	0.000
10	1.1277	-0.005	0.001	0.000	0.004	0.001	0.002	0.002
11	1.1185	-0.006	0.001	0.000	0.004	0.002	0.002	0.000
12	1.1096	-0.005	0.000	0.000	0.004	0.002	0.002	0.003
13	1.1002	-0.004	0.001	0.000	0.004	0.002	0.002	0.001
14	1.0915	-0.004	0.001	0.000	0.004	0.002	0.002	0.000
15	1.0825	-0.003	0.000	0.000	0.004	0.002	0.002	0.000
20	1.0411	-0.003	0.001	0.001	0.003	0.002	0.002	0.002
25	1.0036	0.000	0.000	0.001	0.002	0.002	0.002	0.002
30	0.9689	0.003	0.001	0.002	0.001	0.003	0.002	0.004
35	0.9371	0.005	0.004	0.004	0.000	0.002	0.004	0.004
40	0.9065	0.006	0.003	0.004	0.002	0.003	0.004	0.003

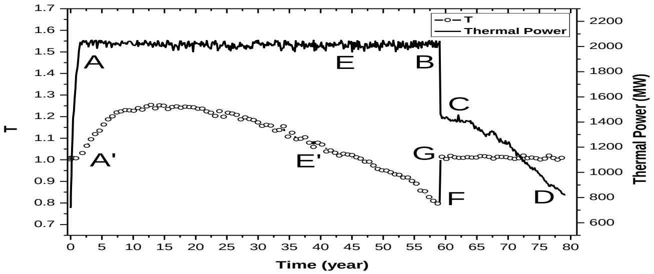
IAEA ADS Benchmark



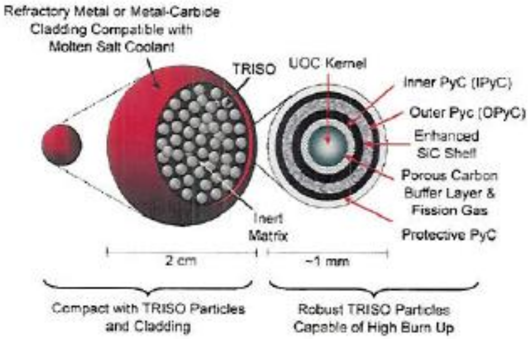


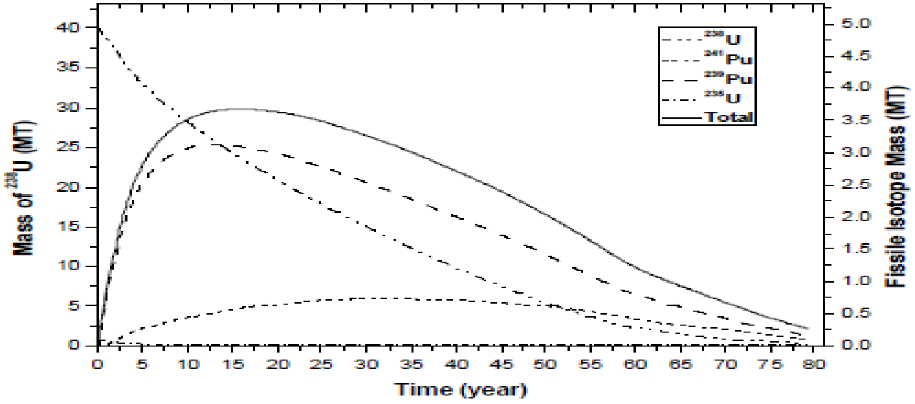
Numerical results of LIFE



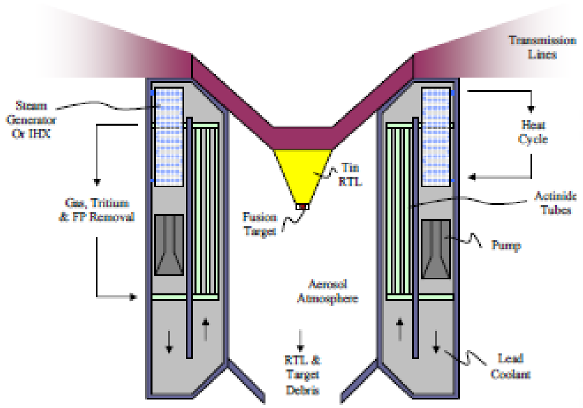


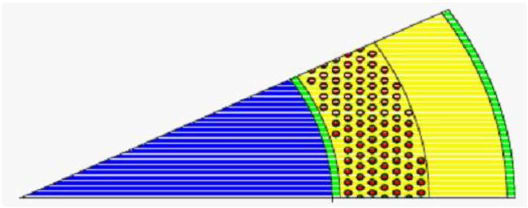
Power Control

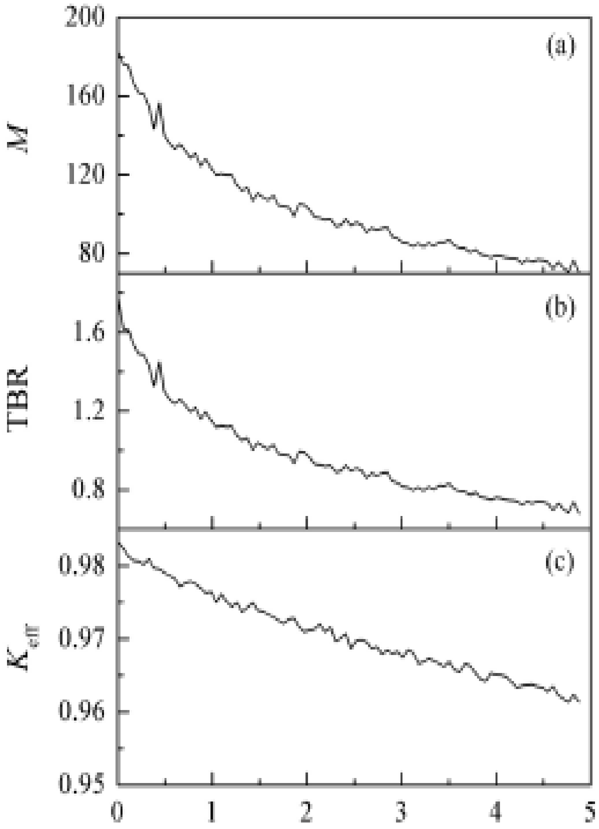




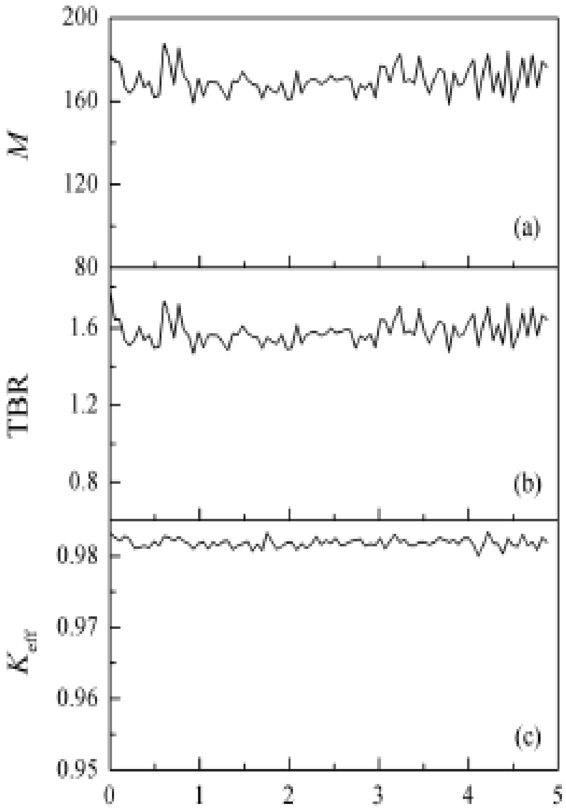
Numerical results of In-Zinerater







a. No reactivity control



b. reactivity control

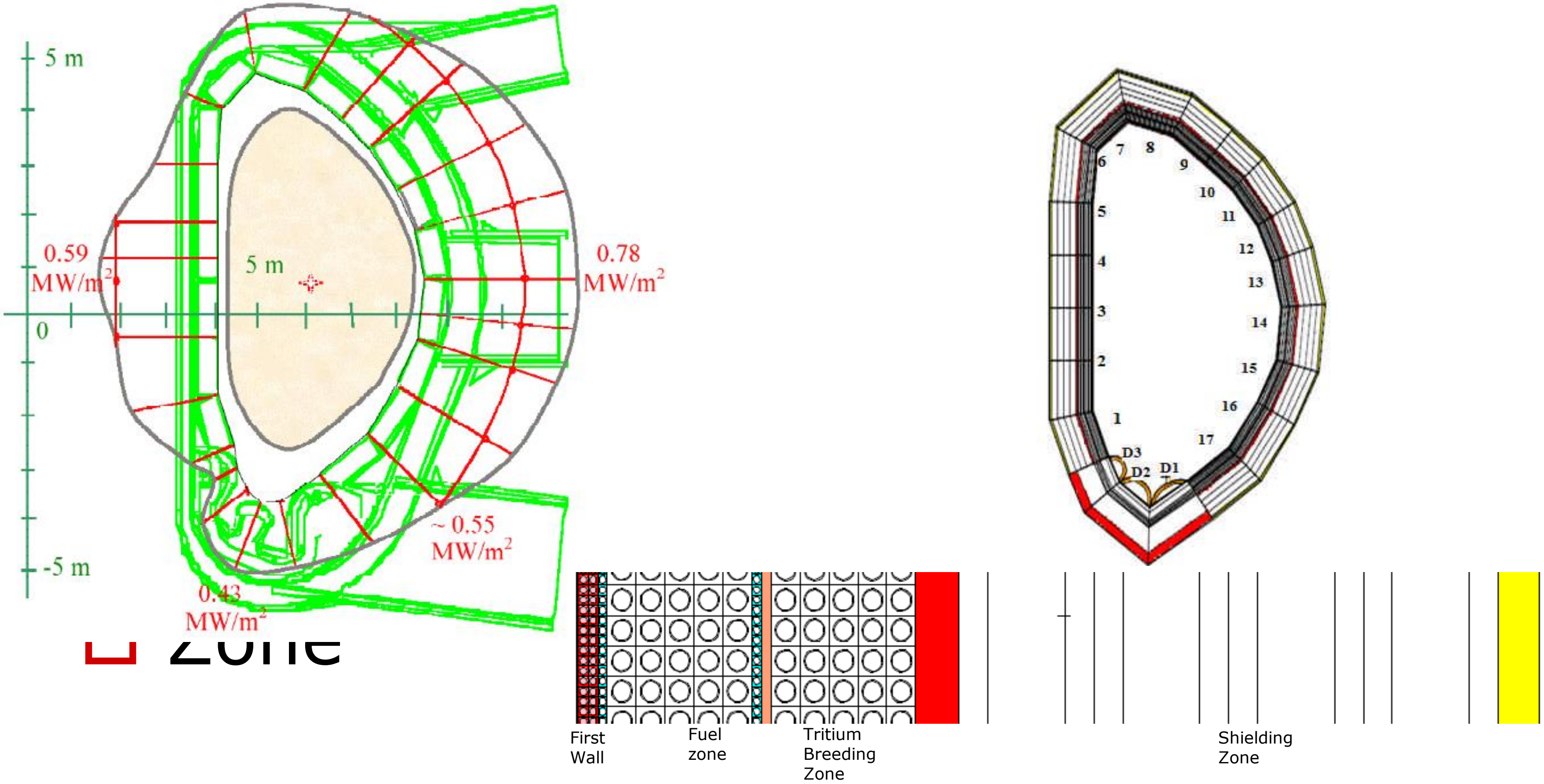
3.Design guide line and the blanket model of FFHR-E

Design guide line of FFHR-E

1. Tritium self-sufficiency. Average TBR in the long run should be greater than 1.15
2. M is about 6~10 to maintain 3000MWth in the blanket.
3. More fissile material generated than consumed.

The blanket model of FFHR-E

- Zone



The blanket model

The fusion source

14.1Mev isotropic homogeneous volume neutron source

Blanket thermal power is kept at 3,000 MWth

The fission fuel zone

0.3 cm Be/ 2 cm first wall(FW) /1cm separator/12cm fuel zone/1cm separator

hollow pipes in FW and separators, to remove heat by pumping water in case of an emergency.

The VR of solid part to water is 2:1

Average burnup over 5 years is less than 1%.

The tritium breeding zone

- 15 cm thick
- Li_4SiO_4 is the tritium breeder, the packing ratio is 0.6.
- The enrichment of ^6Li is 90%.
- light water is used to moderate the neutron so as to improve the tritium generation efficiency and reduce the amount of Li_4SiO_4 in the blanket.
- The VR of lithium to water is 1:1.

The shield zone

- 68cm thick.
- Fe and light water are arranged alternately.
- neutrons are moderated dramatically by the Light water, so are absorbed in Fe.
- The leakage rate of neutron from the blanket is less than 10^{-4}.

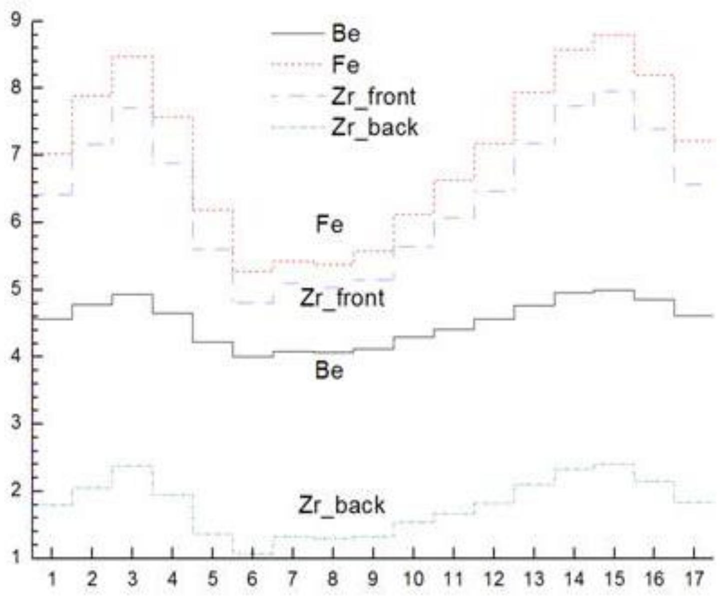
4 Numerical results of FFHR-E

BOC

- TBR=1.06, M=9.14, F/B=2.27, F-B=0.78.
- fusion power~ 280MW, and 1100Kg fissile material will be bred the first year in FFHR-E.
- both TBR and M will improve in a long time for the better fissile material breeding capability of the blanket.

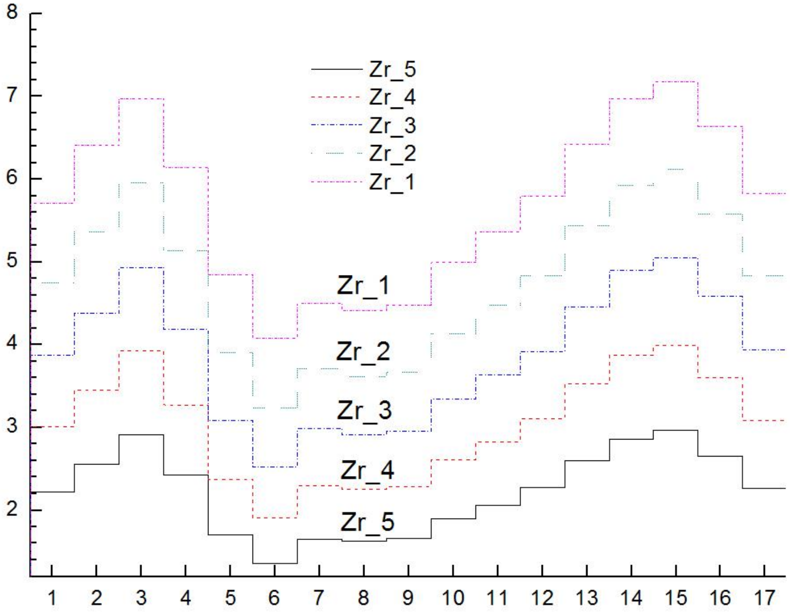
DPAs from neutron irradiation

Max dpa less than 50 in five years



DPAs in FW， poloidal direction

Be：plasma facing material
Fe：FW structure material
Zr_front/back：front/back row emergency pipe



DPAs in coolant pipes, poloidal direction

Zr_1~Zr_5: Coolant pipes from row 1 to row 5

The reprocessing strategy

- Decreasing the reprocessing frequency

  the spent fuel is reused **every 5 years** and 5 tons of depleted uranium is added

- Simplifying the reprocessing procedure

  heating the spent fuel by the decay heat since the melting point of the alloy is lower than traditional UO_2 fuel.

  no separation of TRUs

  remove only part of the fission products

Two kinds of reprocessing Scenarios

1. **Only part of fission products are removed**.

   Simplified pyro-reprocessing every 5 years

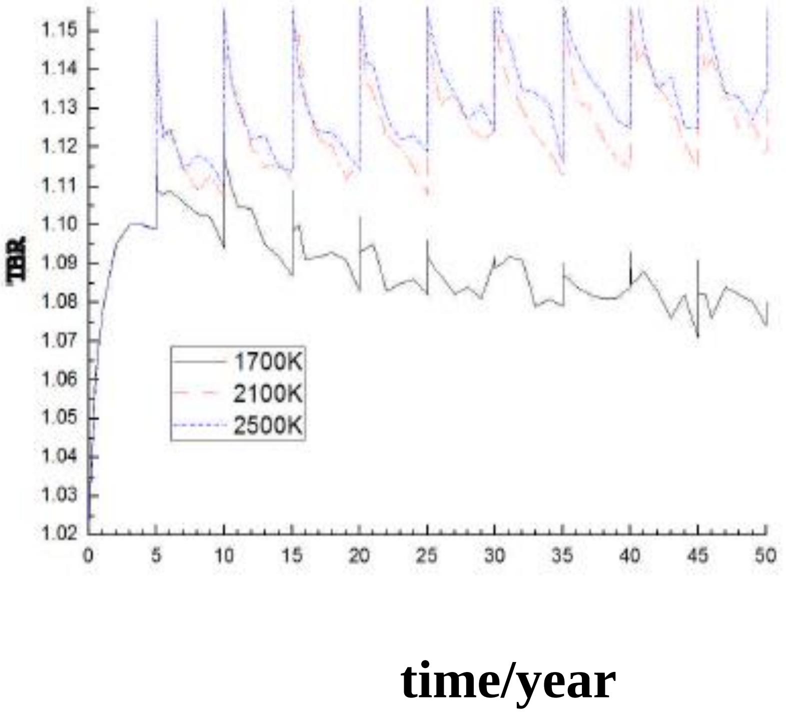
   Heat up the spent fuel to a high reprocessing temperature by decay heat, fission product elements whose boiling points are below the temperature will evaporate.

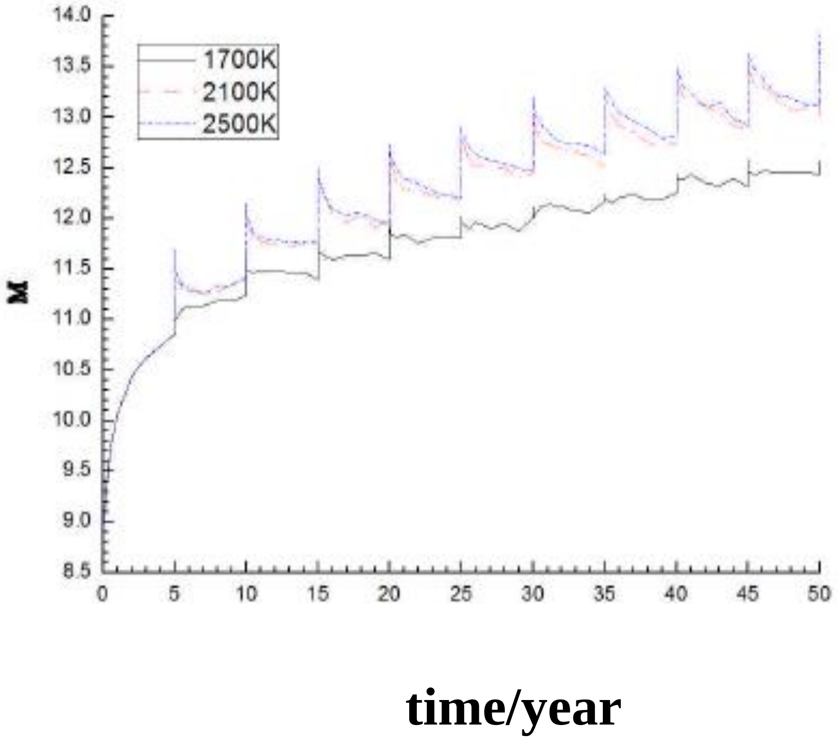
2. **All the fission products and no transuranics are removed**.

   Simplified aqueous-reprocessing or advanced pyro-reprocessing every 60 years

The selection of pyro-reprocessing temperature

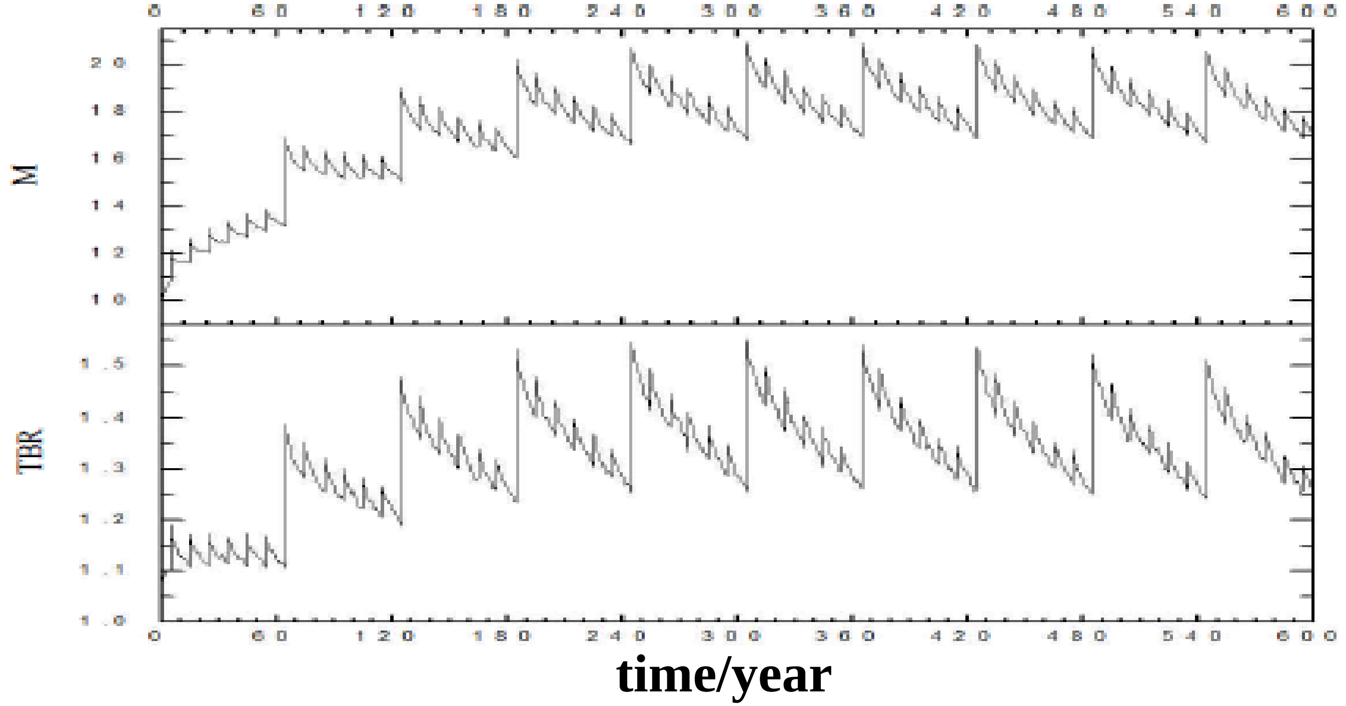
- **2100K is highly suggested**



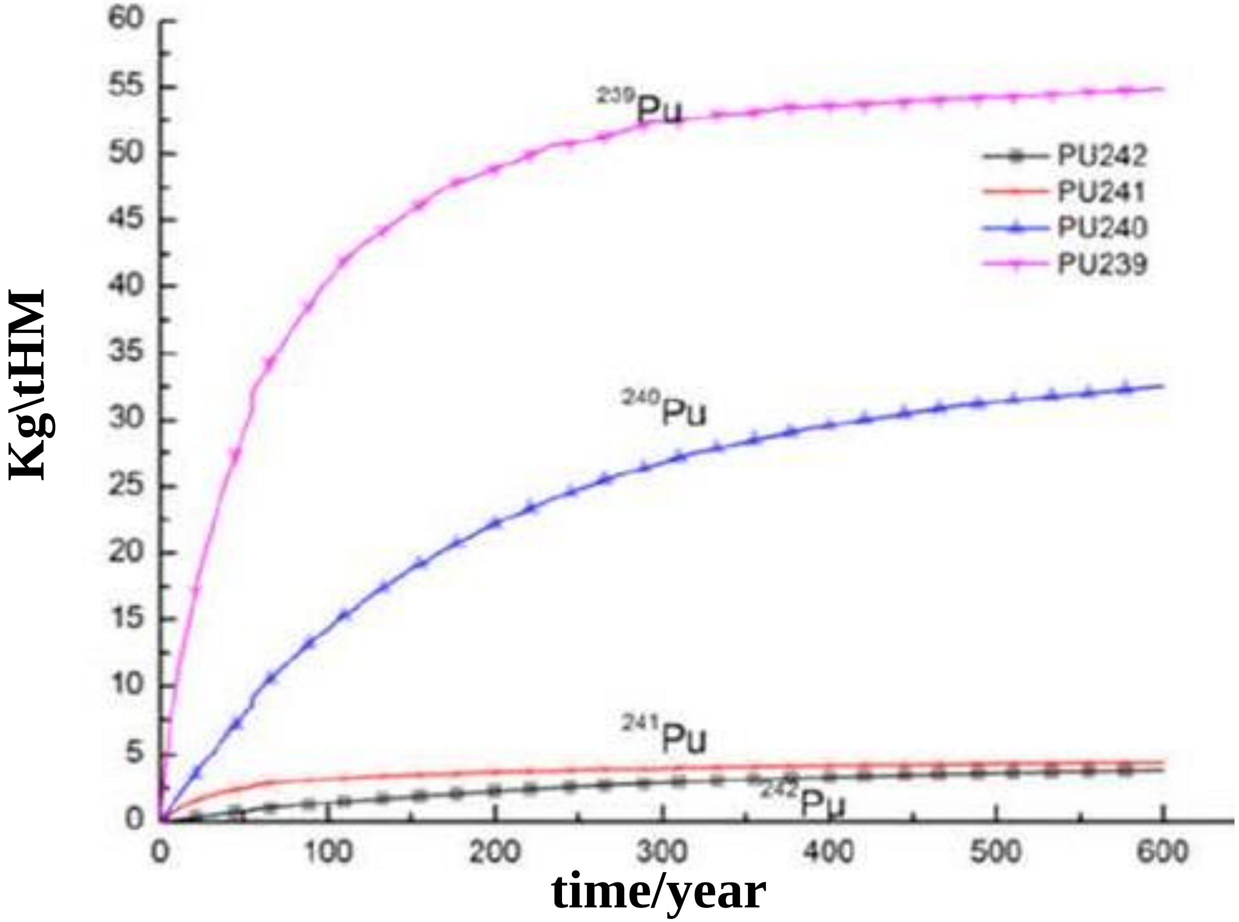


The combination of scenarios 1 and 2

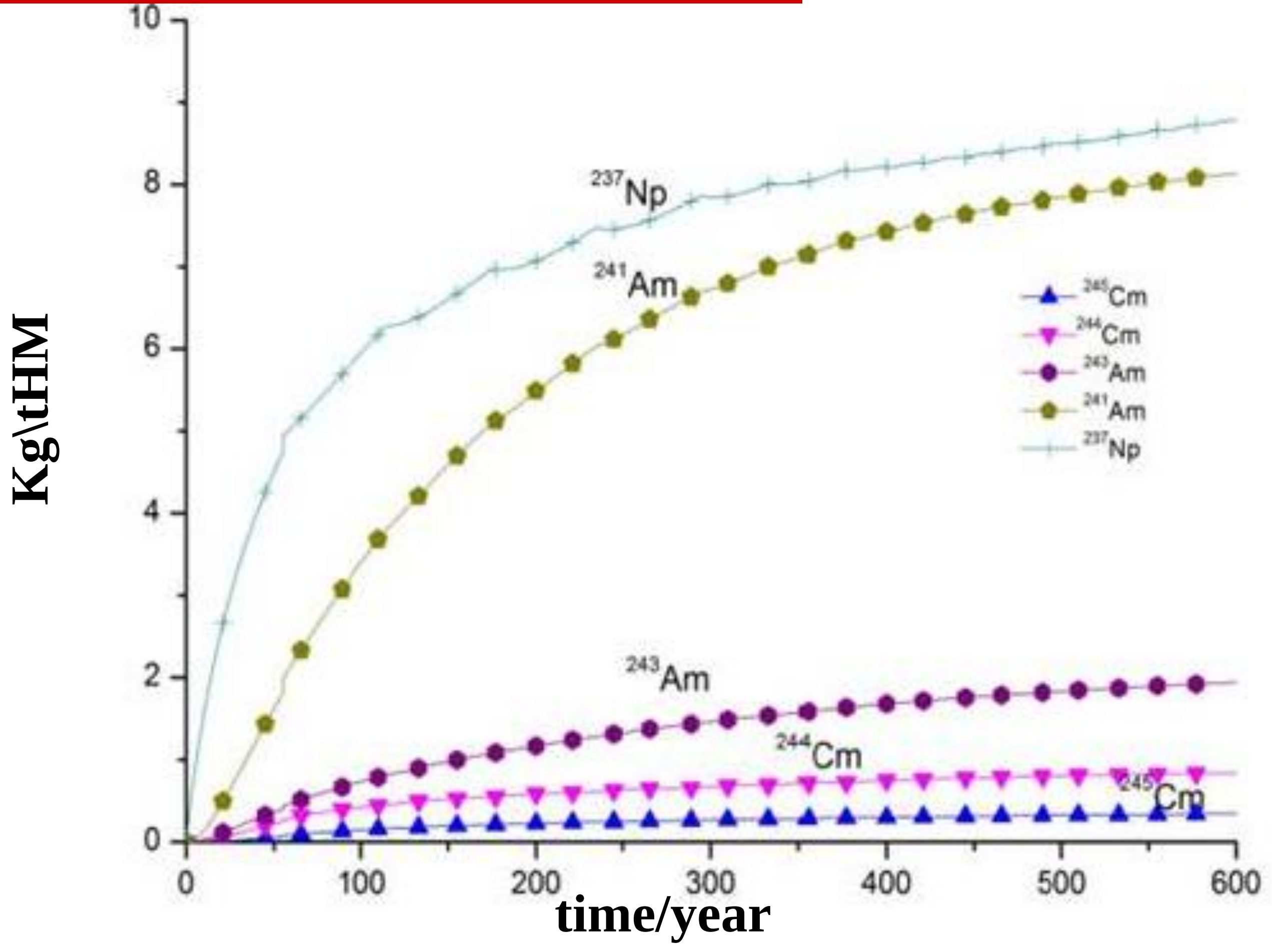
- **In the first 60 years, the average TBR and M are 1.15 and 12. From the second to tenth 60 years, the average TBR and M are above 1.35 and 18.**



Plutonium inventory



MA inventory



5 Summary

- MCORGS is used to simulate the Breeding and Burning Process of Plutonium in FFHR-E
- **FFHR-E** can accelerate the early application of fusion energy
  - **The temperature for simplified pyro-reprocessing is suggested to be 2100K**
  - **The refuelling period is around 10 years; the spent fuel can be reused multiple times so as to make fuller use of natural uranium.**

Acknowledgement

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Thanks