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Neutronics Conceptual Research on a Hybrid Blanket of CFETR

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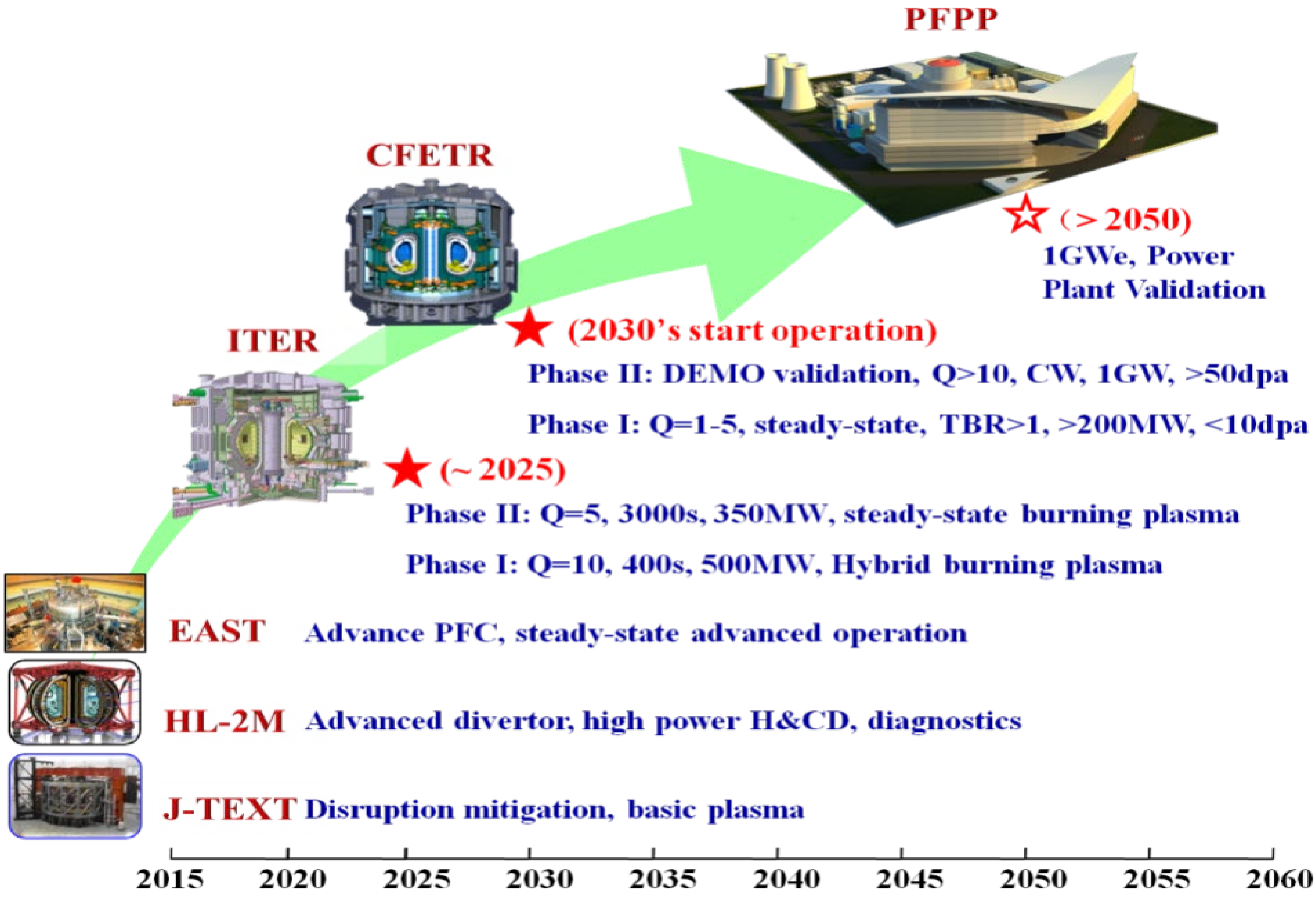
Outline

1. Background
2. Blanket neutronics and Numerical tools
3. Numerical results
4. Summary

1. Background

CFETR is under engineering design…



PFPP

☆ (>2050)
1GWe, Power
Plant Validation

CFETR

★ (2030's start operation)
Phase II: DEMO validation, Q>10, CW, 1GW, >50dpa
Phase I: Q=1-5, steady-state, TBR>1, >200MW, <10dpa

ITER

★ (~2025)
Phase II: Q=5, 3000s, 350MW, steady-state burning plasma
Phase I: Q=10, 400s, 500MW, Hybrid burning plasma

EAST Advance PFC, steady-state advanced operation

HL-2M Advanced divertor, high power H&CD, diagnostics

J-TEXT Disruption mitigation, basic plasma

Fig.1 Roadmap of China magnetic confinement fusion development

Tritium self-sufficiency challenge: $\mathrm{TBR}_{ach} \geq \mathrm{TBR}_{req}$

- TBR_{ach} mainly depends on blanket design, it can be evaluated by calculated TBR_{3D}.
- According to Professor Abdou,

  $\max(\mathrm{TBR}_{ach}) < 1.15$
- Considering the 10-20% uncertainties （in nuclear data, detailed 3D modeling, fusion design elements）, there must be a range of breeding margins in TBR_{3D}, so as to keep the Net TBR greater than TBR_{req}..

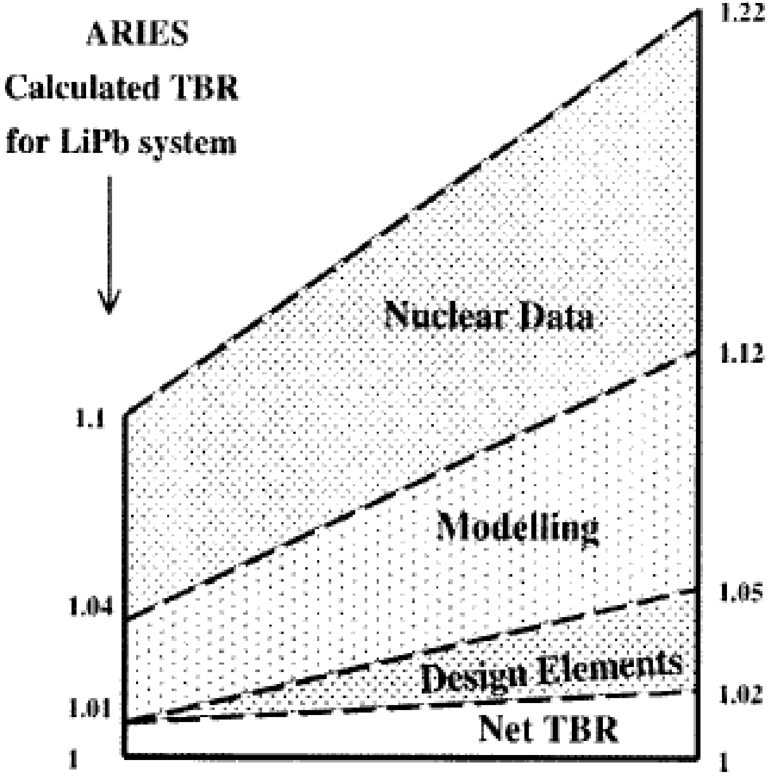
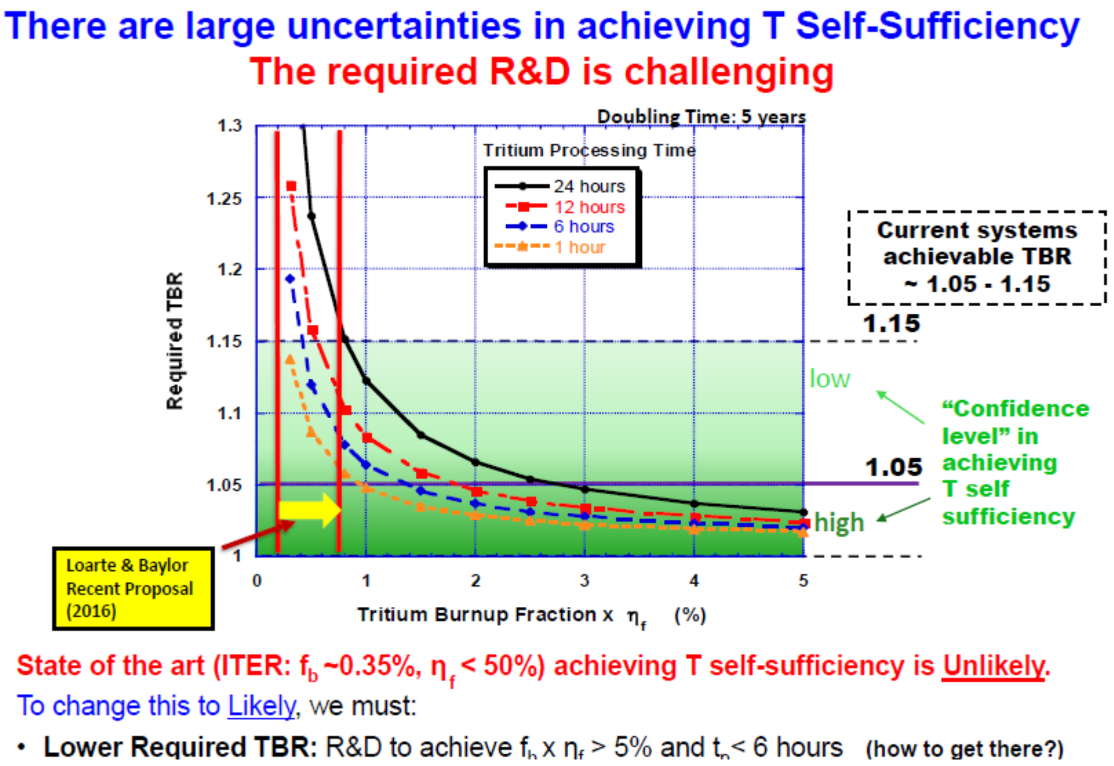


Fig. 2. Calculated TBR for a range of breeding margins.

L.A. El-Guebaly, S. Malang / Fusion Engineering and Design 84 (2009) 2072–2083

Tritium self-sufficiency challenge: $\mathrm{TBR}_{ach} \geq \mathrm{TBR}_{req}$

- TBR_{req} mainly depends on Tritium burnup fraction(η_f) and Tritium processing Time(t_p)
- According to current technique status, $\mathrm{TBR}_{req} > 1.2$
- As the progress in fusion technology, TBR_{req} may be lowered dramatically but uncertainty still exits.



There are large uncertainties in achieving T Self-Sufficiency

The required R&D is challenging

State of the art (ITER: f_b ~0.35%, η_f < 50%) achieving T self-sufficiency is Unlikely.

To change this to Likely, we must:

- **Lower Required TBR:** R&D to achieve $f_b \times \eta_f > 5\%$ and $t_p < 6$ hours (how to get there?)

Fig.3 TBR_{req} Vs η_f and t_p

Tritium self-sufficiency challenge: $\mathrm{TBR}_{ach} \geq \mathrm{TBR}_{req}$

- If TBR_{req} cann’t be lowered into a reasonable level in the future, **Tritium self-sufficiency** is impossible for pure fusion.

Table 1 European Demo blanket design results in 2014

DEMO Concept	Tritium Breeder	Coolant	TBR_{3D} (2014)
HCPC	Li_4SiO_4/Be	He	1.04
HCLL	PbLi	He	1.07
WCLL	PbLi	Water	1.04
DCLL	PbLi	He/PbLi	1.13

- Fusion fission hybrid blanket is an backup for the traditional fusion blankets concept.

Fusion Fission Hybrid Reactor

- **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
- **Breeding and burning.** Fusion power 300~500MW, Q~5.

  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

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

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

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

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

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

$$M = \frac{\mathit{energy}\ \text{deposited in the blanket by one fusion source}}{\text{energy released by one fusion reaction(17.6Mev)}}$$

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

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

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

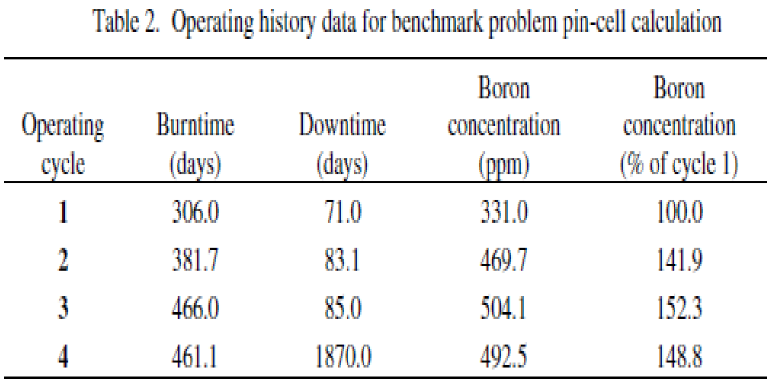


Table 2. Operating history data for benchmark problem pin-cell calculation

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

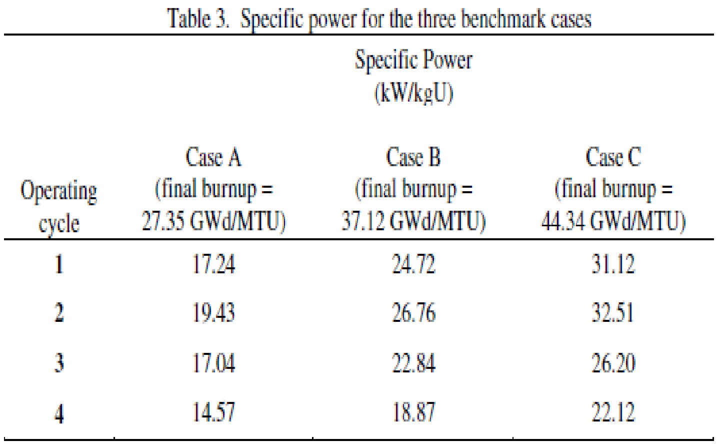
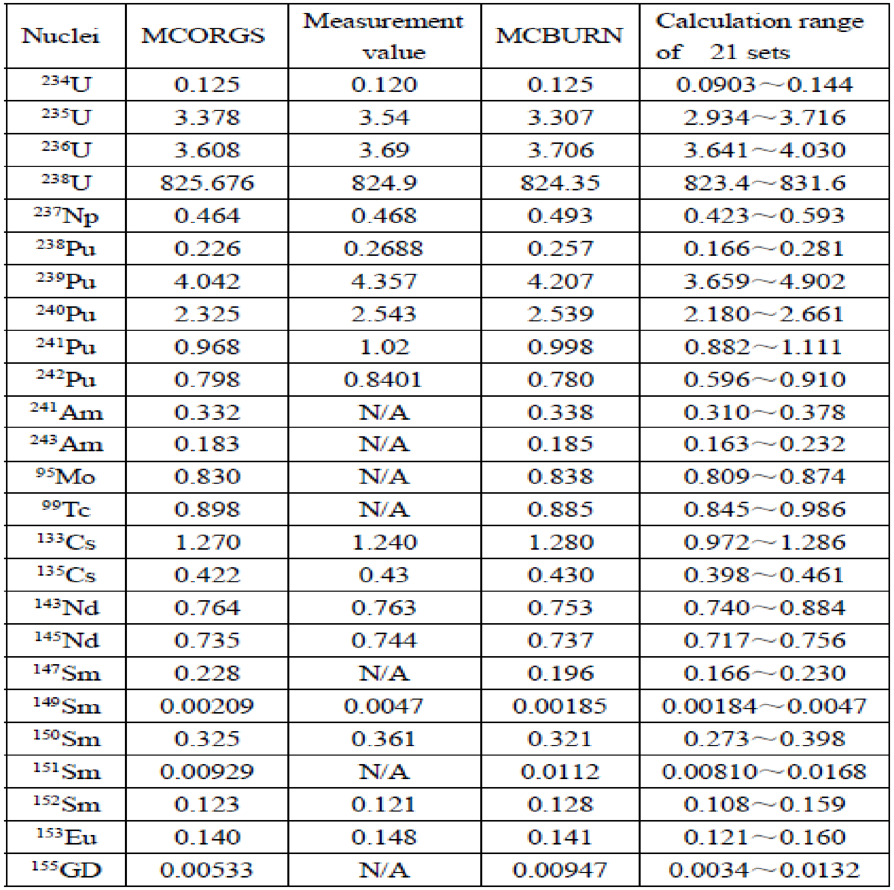


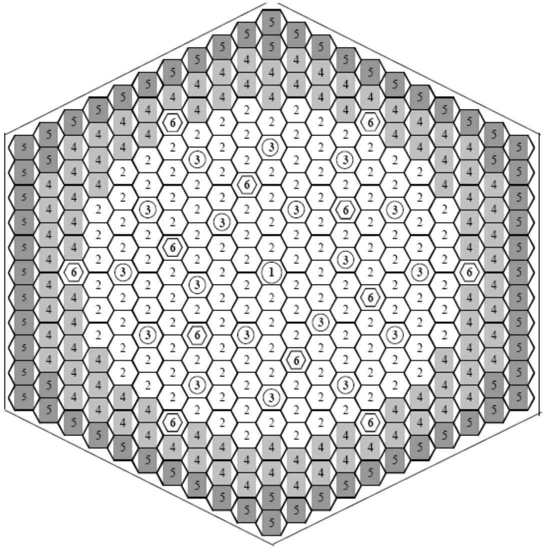
Table 3. Specific power for the three benchmark cases

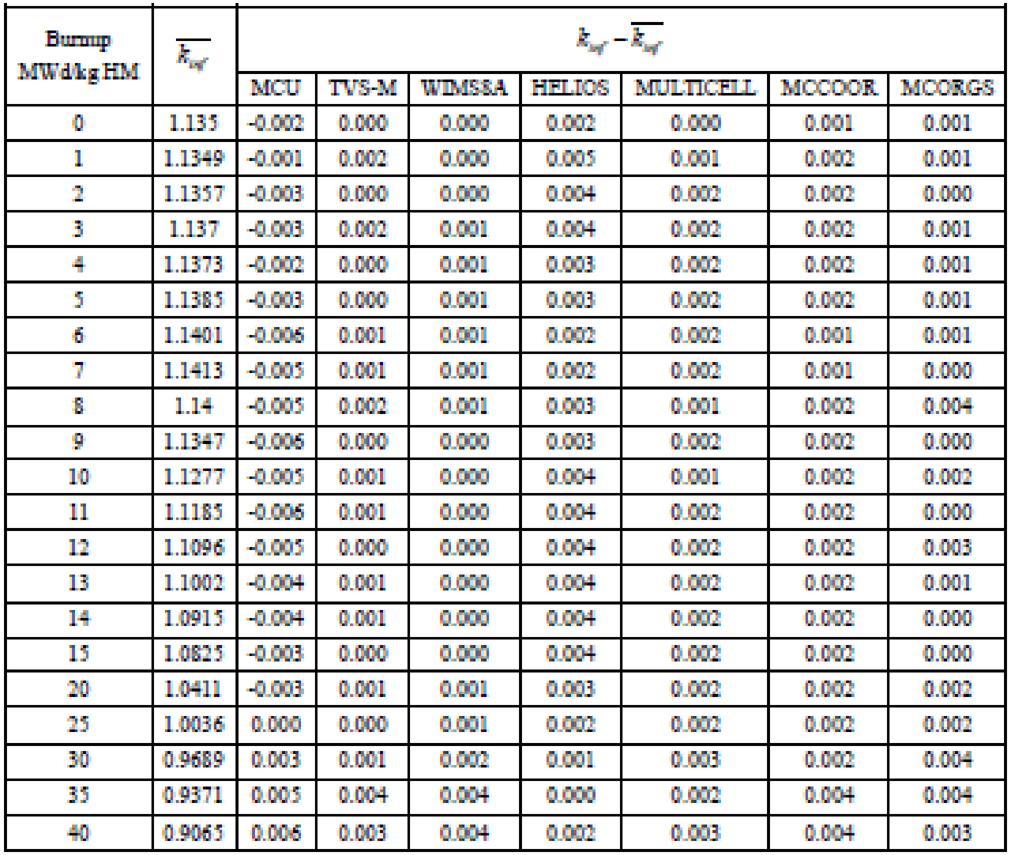
	Specific Power (kW/kgU)		
Operating cycle	Case A (final burnup = 27.35 GWd/MTU)	Case B (final burnup = 37.12 GWd/MTU)	Case C (final burnup = 44.34 GWd/MTU)
1	17.24	24.72	31.12
2	19.43	26.76	32.51
3	17.04	22.84	26.20
4	14.57	18.87	22.12



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

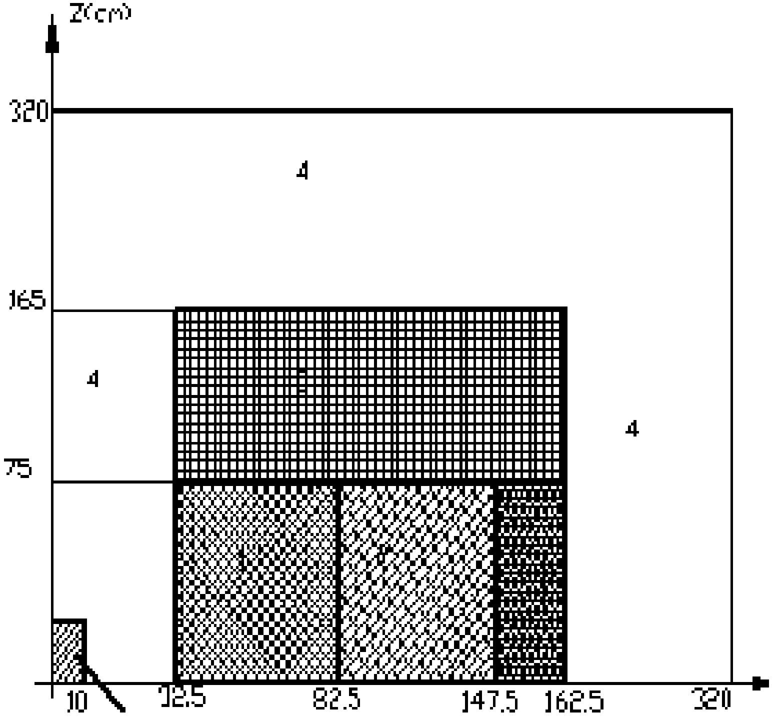
VVER MOX-Gd Benchmark

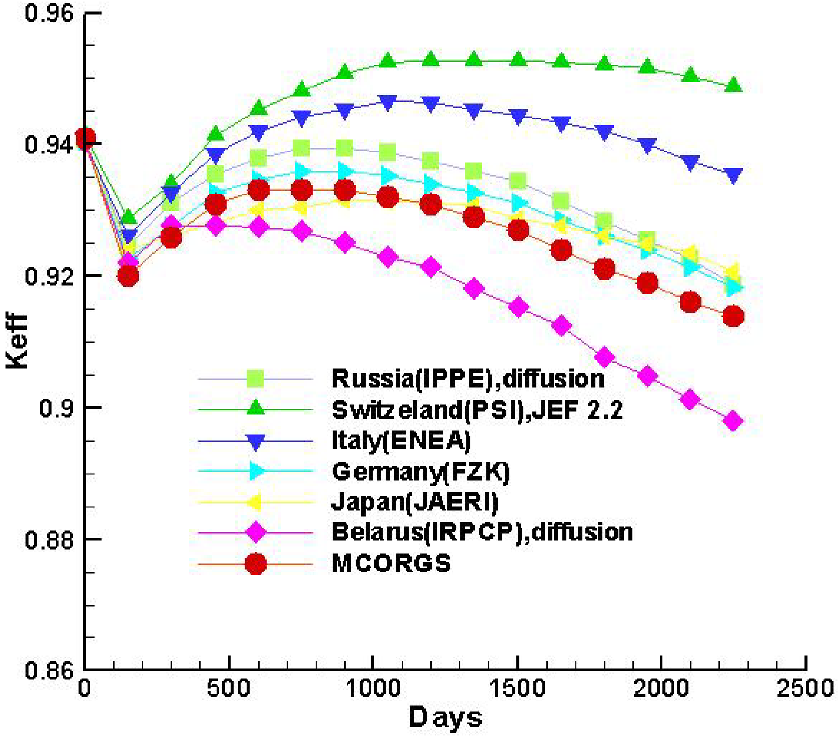




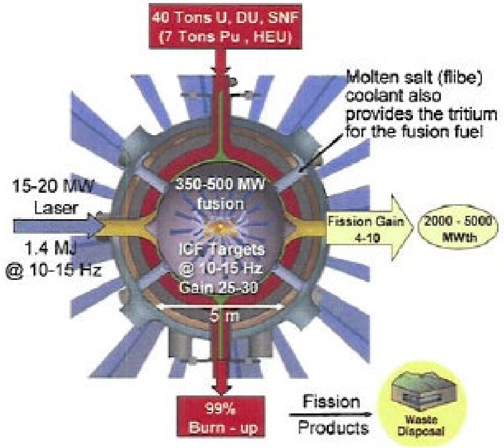
Burnup MWd/kg HM	$\overline{k_{inf}}$	$k_{inf} - \overline{k_{inf}}$						
		MCU	TVS-M	WIMS8A	HELIOS	MULTICELL	MCCOOR	MCORGS
0	1.135	-0.002	0.000	0.000	0.002	0.000	0.001	0.001
1	1.1349	-0.001	0.002	0.000	0.005	0.001	0.002	0.001
2	1.1357	-0.003	0.000	0.000	0.004	0.002	0.002	0.000
3	1.137	-0.003	0.002	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

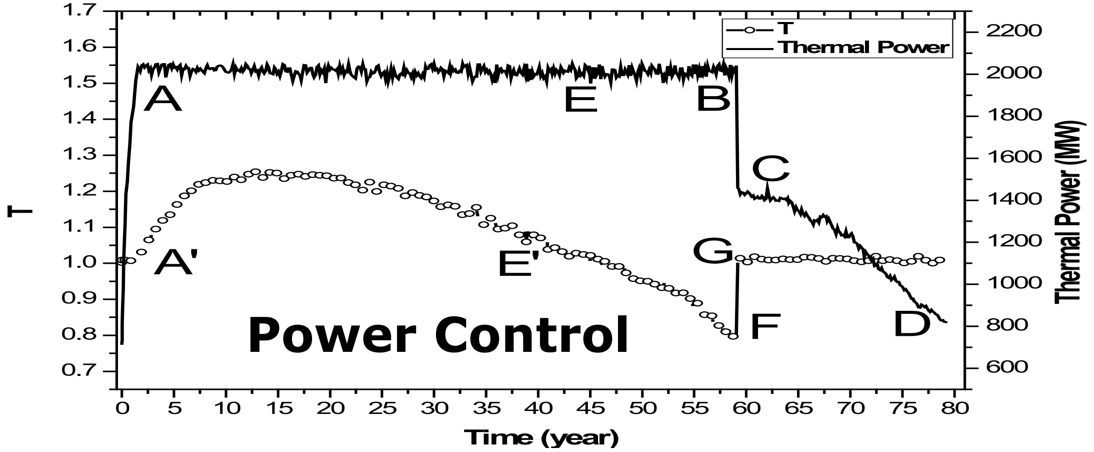
IAEA ADS Benchmark

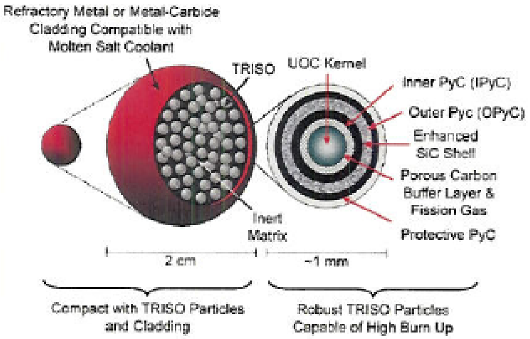


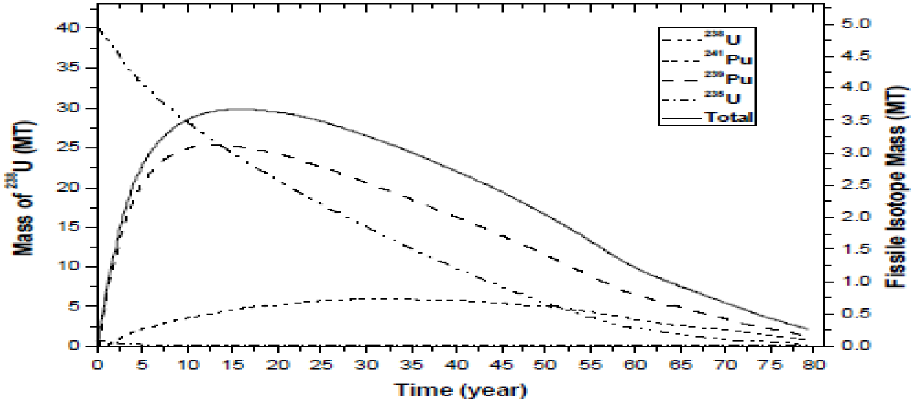


Numerical results of LIFE

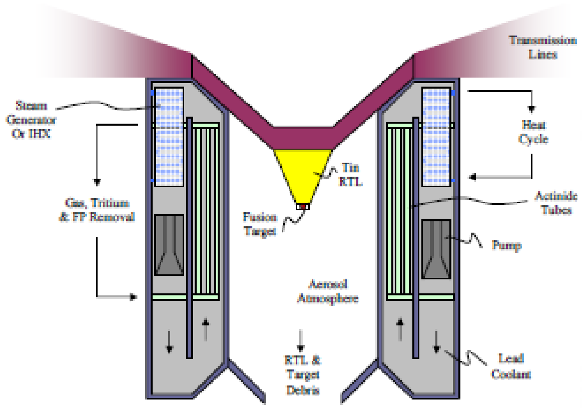


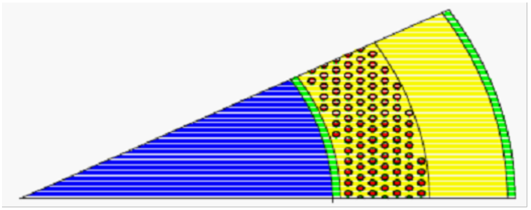


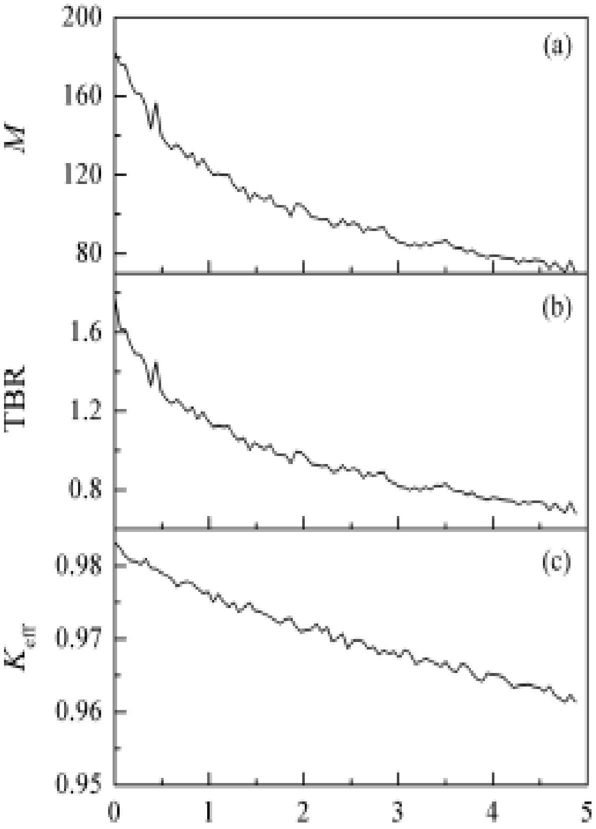




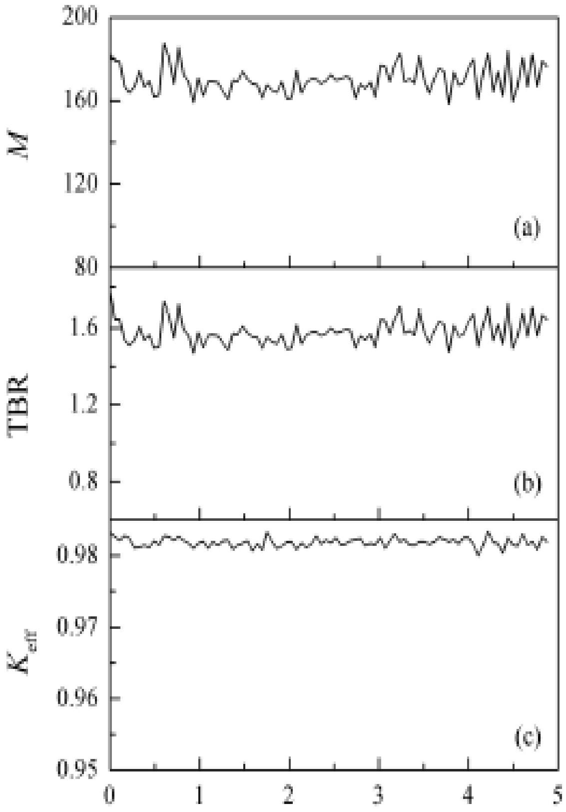
Numerical results of In-Zinerater







a. No reactivity control



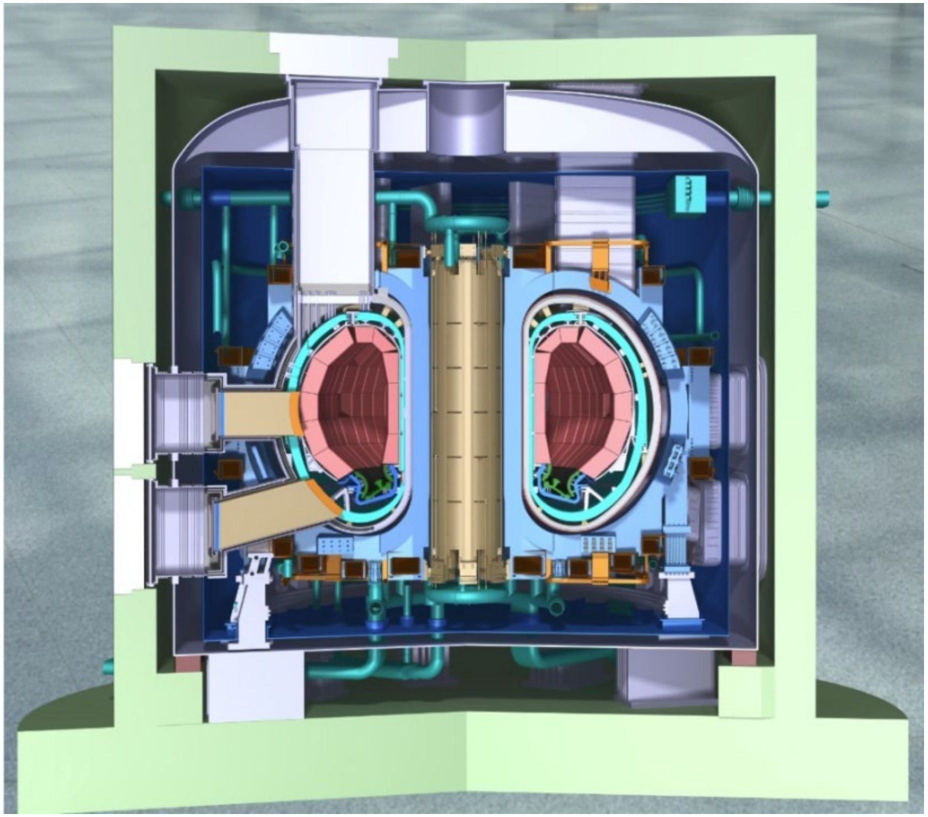
b. reactivity control

3 Numerical results

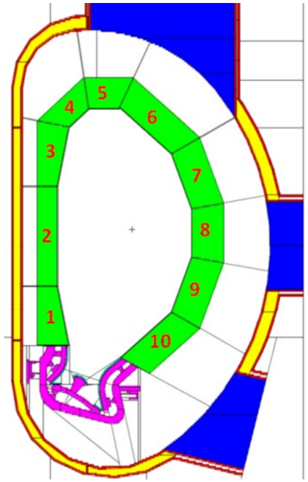
1D design and optimization

- One dimensional design and optimization is firstly made to obtain maximum Tritium Breeding Ratio (TBR) and a moderate energy Multiplication (M).
- Two kinds of blanket configuration are compared.
  1. The tritium breeding zone is behind the fission zone
  2. The fission zone and tritium zone are arranged alternatively.
- It is found the second scheme is better to obtain bigger TBR while in the first scheme more plutonium are produced.
- A 3D neutronics model of CFETR based on detailed CAD design is then used in the blanket conceptual research.

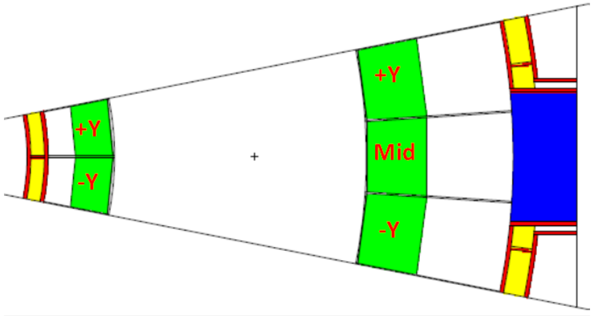
3D neutronics model (22.5°）



CFETR



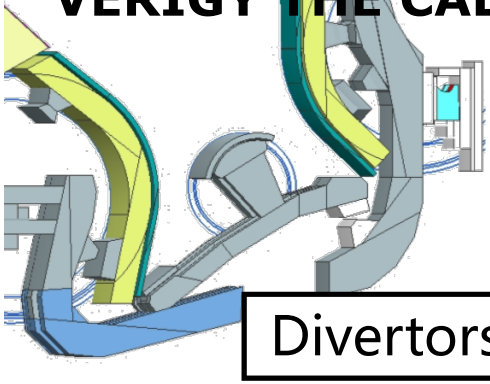
Blanket cross section in X-Z direction （MCNP）



Blanket cross section in X-Y direction （MCNP）

CFETR Benchmark modeling (JMCT)

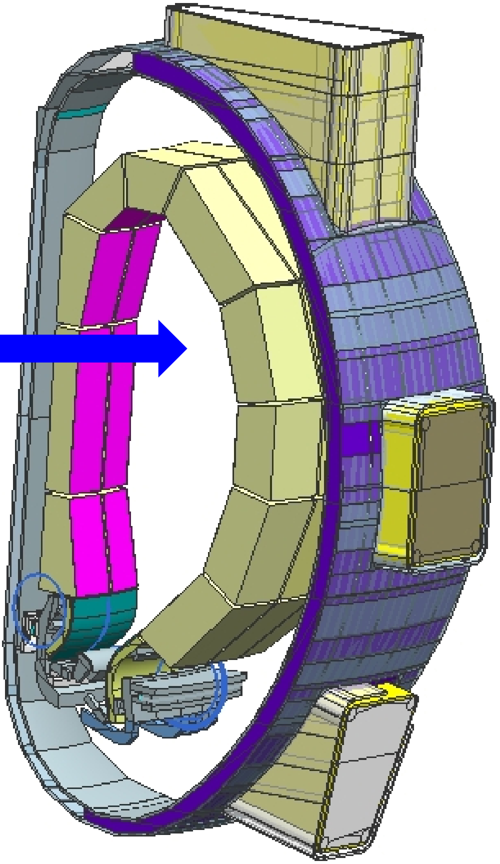
Under support of **NATIONAL MAGNETIC CONFINEMENT FUSION ENERGY RESEARCH PROJECT，JMCT IS ALSO USED TO VERIGY THE CALCULATION**

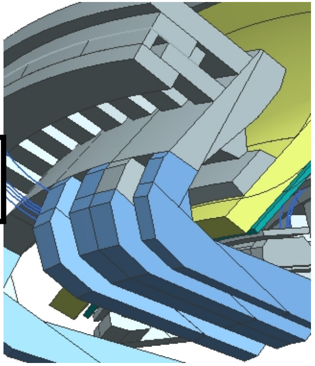


Divertors

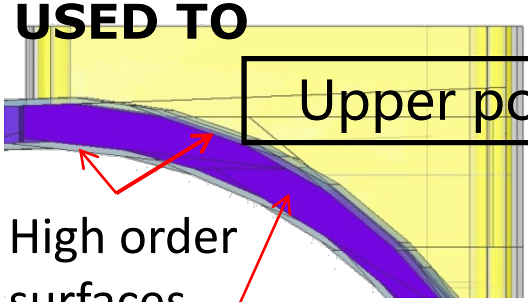
~20,000 bodies are used to defing the CFETR framework

Blankets are modeled separately so as to compare different design cocepts





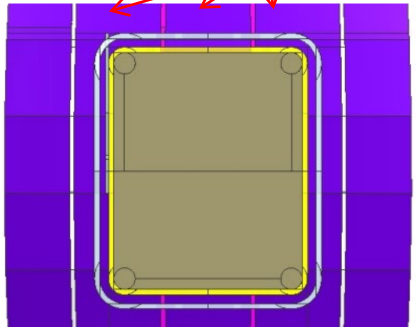
Cassette

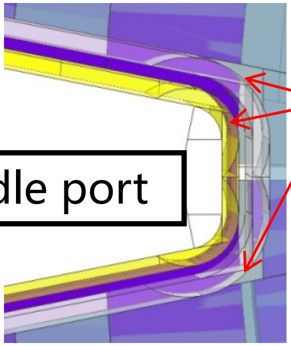


Upper port

High order surfaces

Water layers

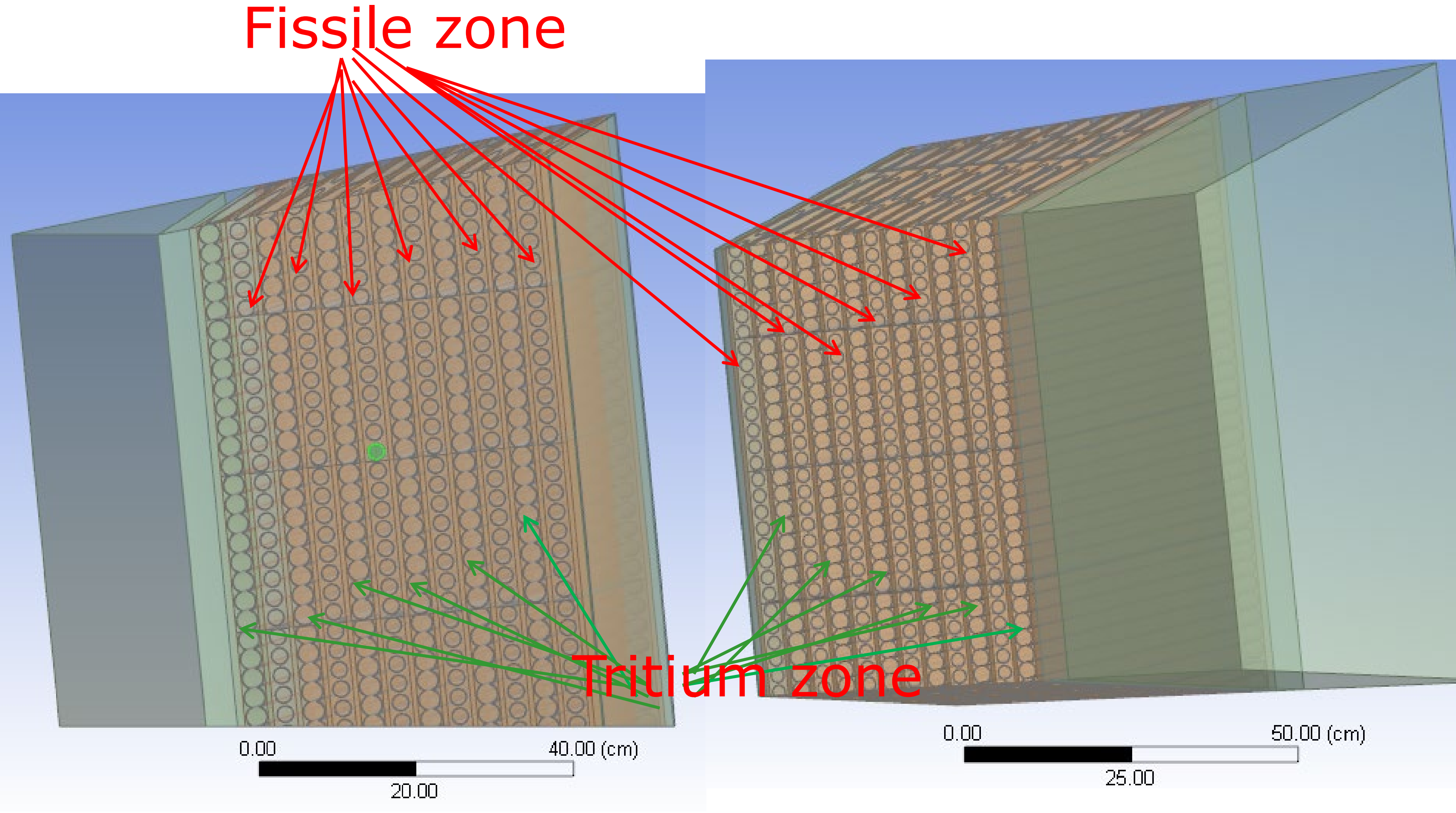




Middle port

Conner details

Blanket module details



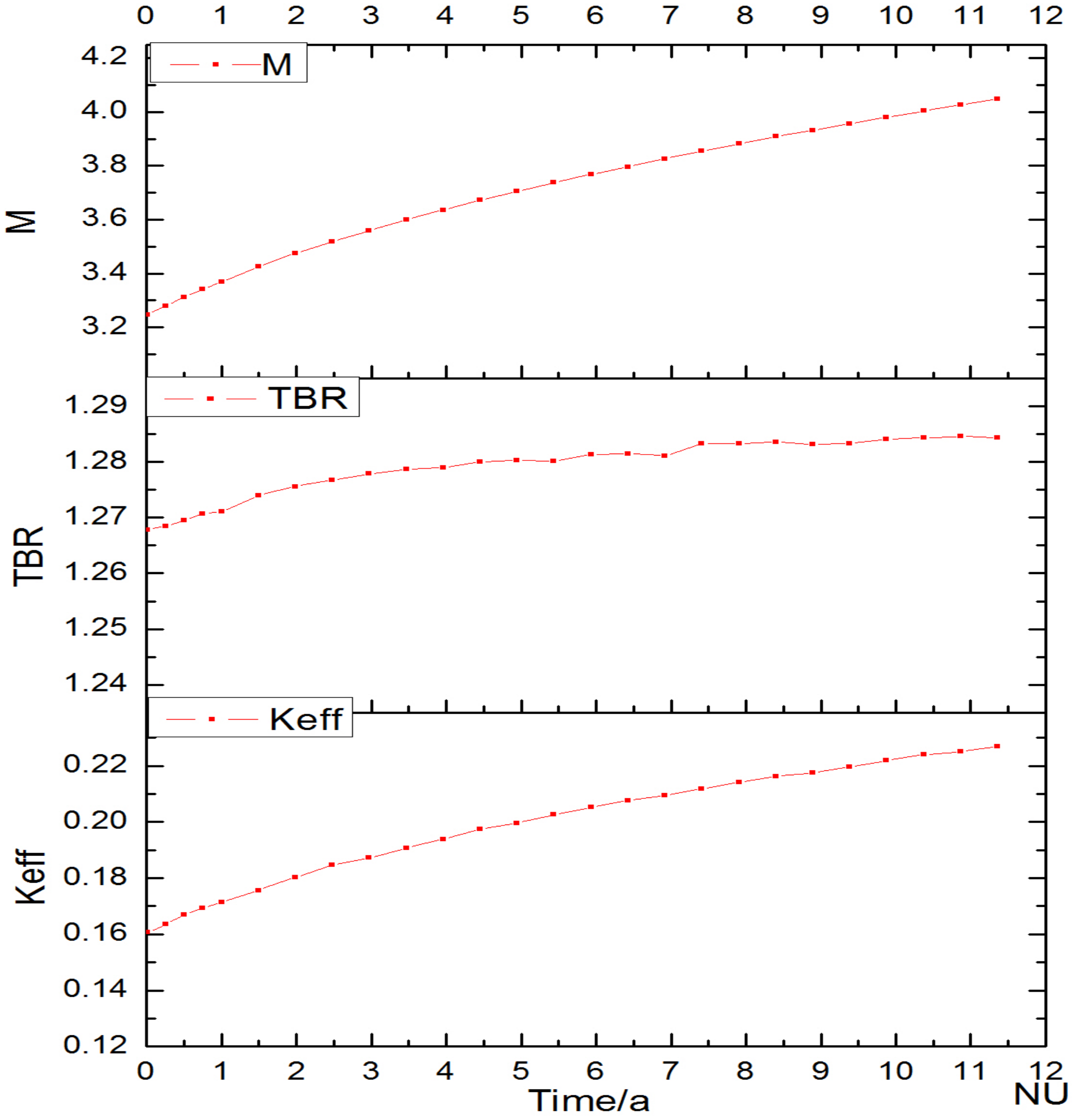
Module 1

Module 11

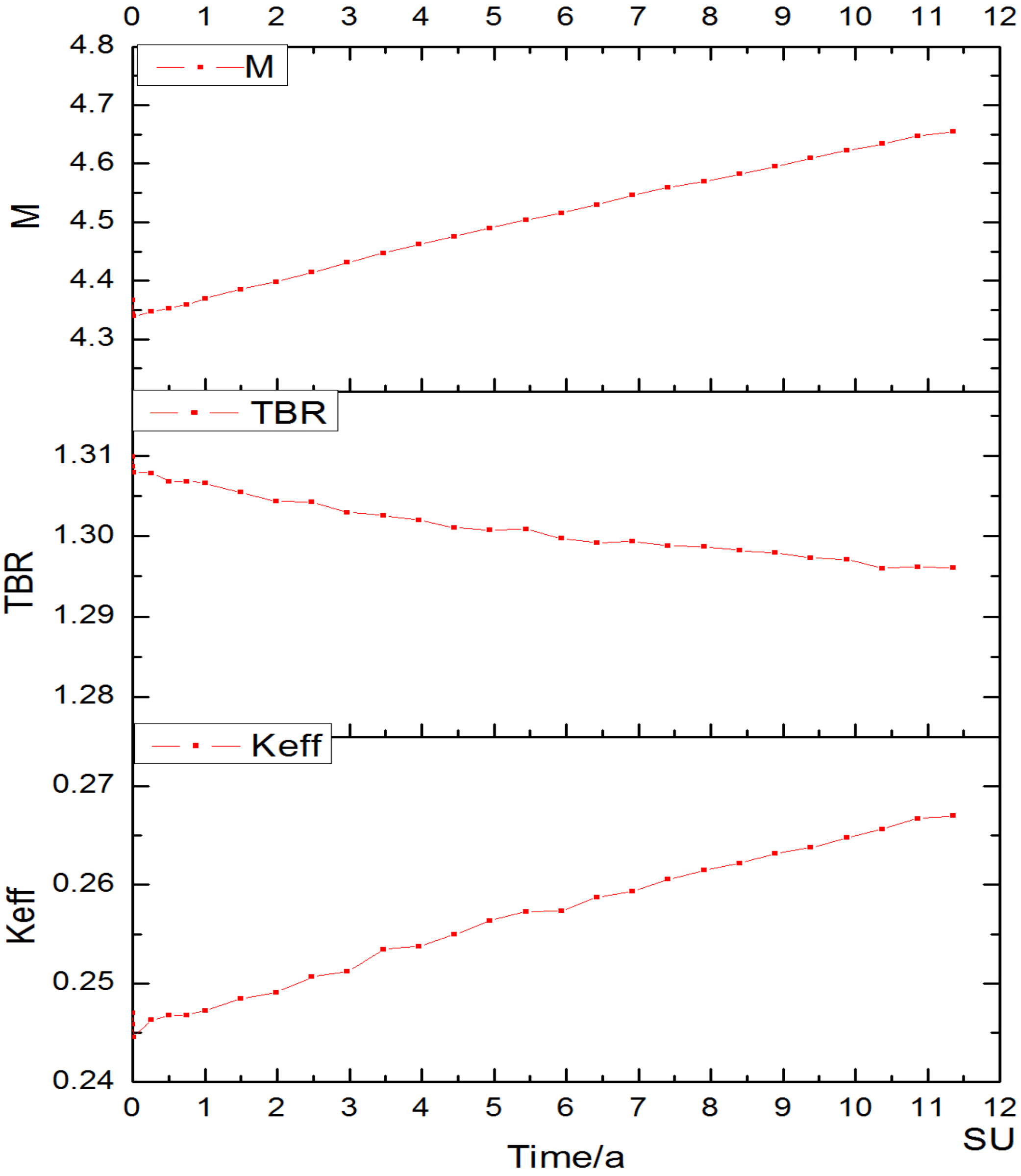
JMCT-MCNP Verification at BOC

Cells in Blanket	19991(5992)	
Cells in T-zone	861(861)	
TBR	JMCT 1.268	MCNP 1.267
TBR error(%)	0.079	
err in T-zones	cells	Tritiu contribution
<1%	682（79.3%）	1.108(87.35)
1%-2%	106（12.32%）	0.084(6.62%)
2%-3%	27(3%)	0.01(0.72%)
3%-5%	18(2.09%)	0.023(1.82%)
>5%	28(3.25%)	0.043（3.4%）

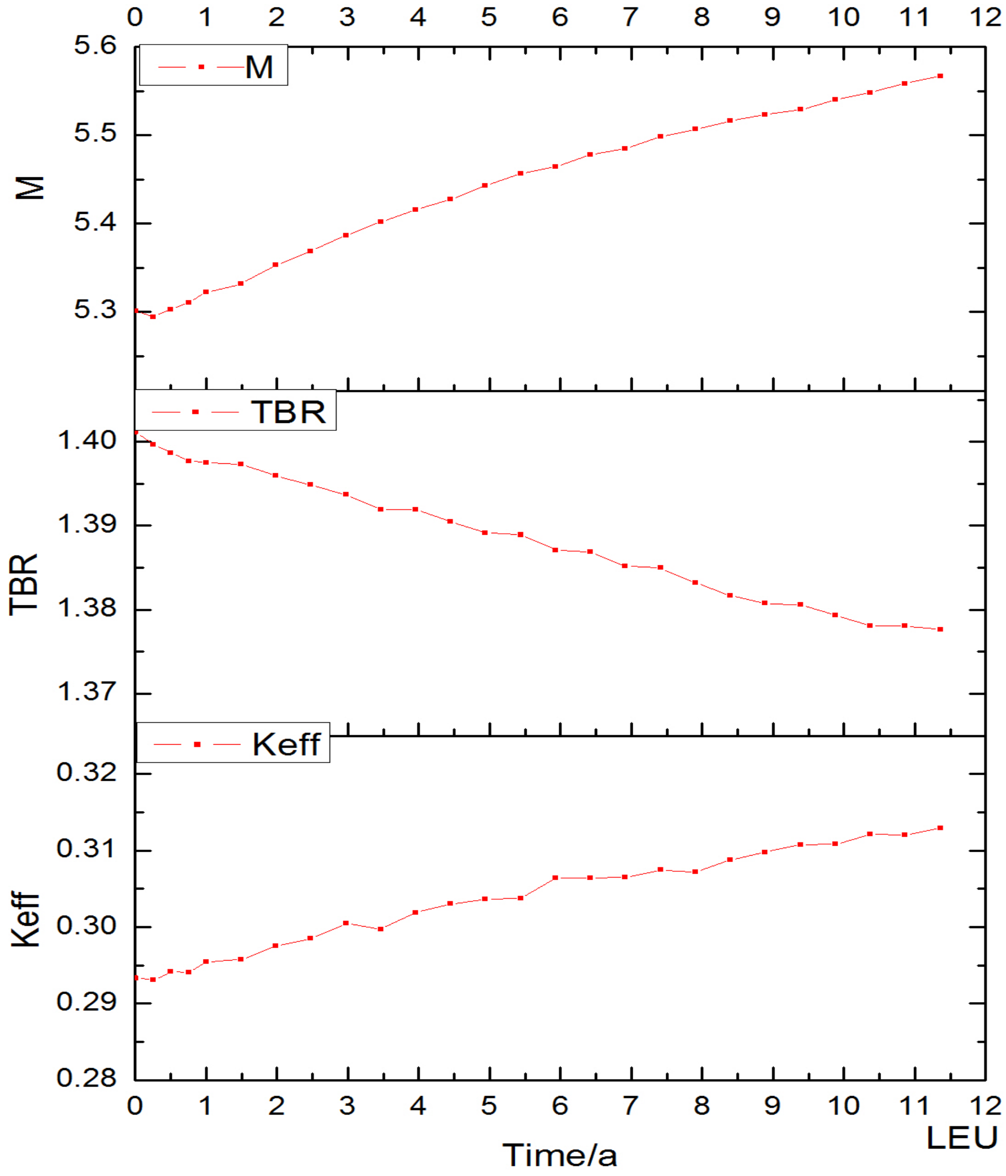
Natural uranium in blanket:TBR>1.26



Spent fuel in blanket: TBR>1.29



LEU in blanket: TBR>1.37



4 Summary

- **A hybird blanket concept which use natural uranium as fissile material and water as coolant is given is this work.**
  - MCORGS is used to simulate the burnup Process in the hybrid blanket.
  - JMCT is used to verify the TBR Calculation
- **BOC: TBR= 1.26, M= 3.18, Keff=0.16**

  12y later: TBR= 1.28, M= 4.05, Keff=0.23
- **If spent fuel or LEU is used instead of natural uranium, better neutronics performance will be obtained.**

Acknowledgement

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Thanks