中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

International Conference on Fast Reactors and Related Fuel Cycles

CEFR Physical Start-up Tests: the Core Specifications and Experiments

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(through WebEx)

China Institute of Atomic Energy

19 April 2022

Contents

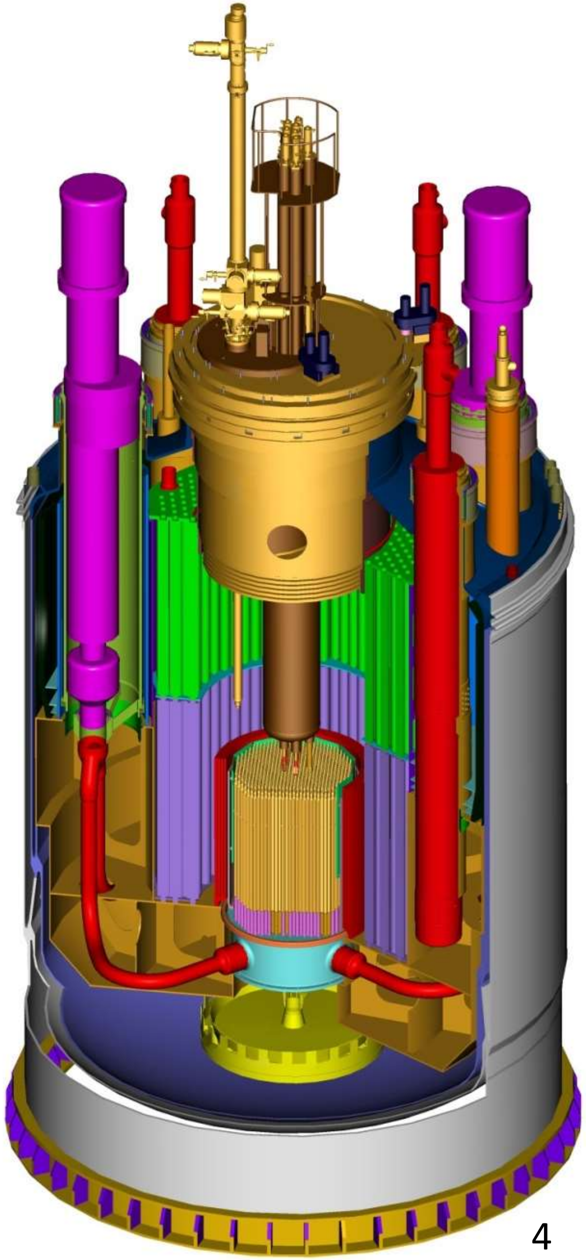
□ CEFR Introduction

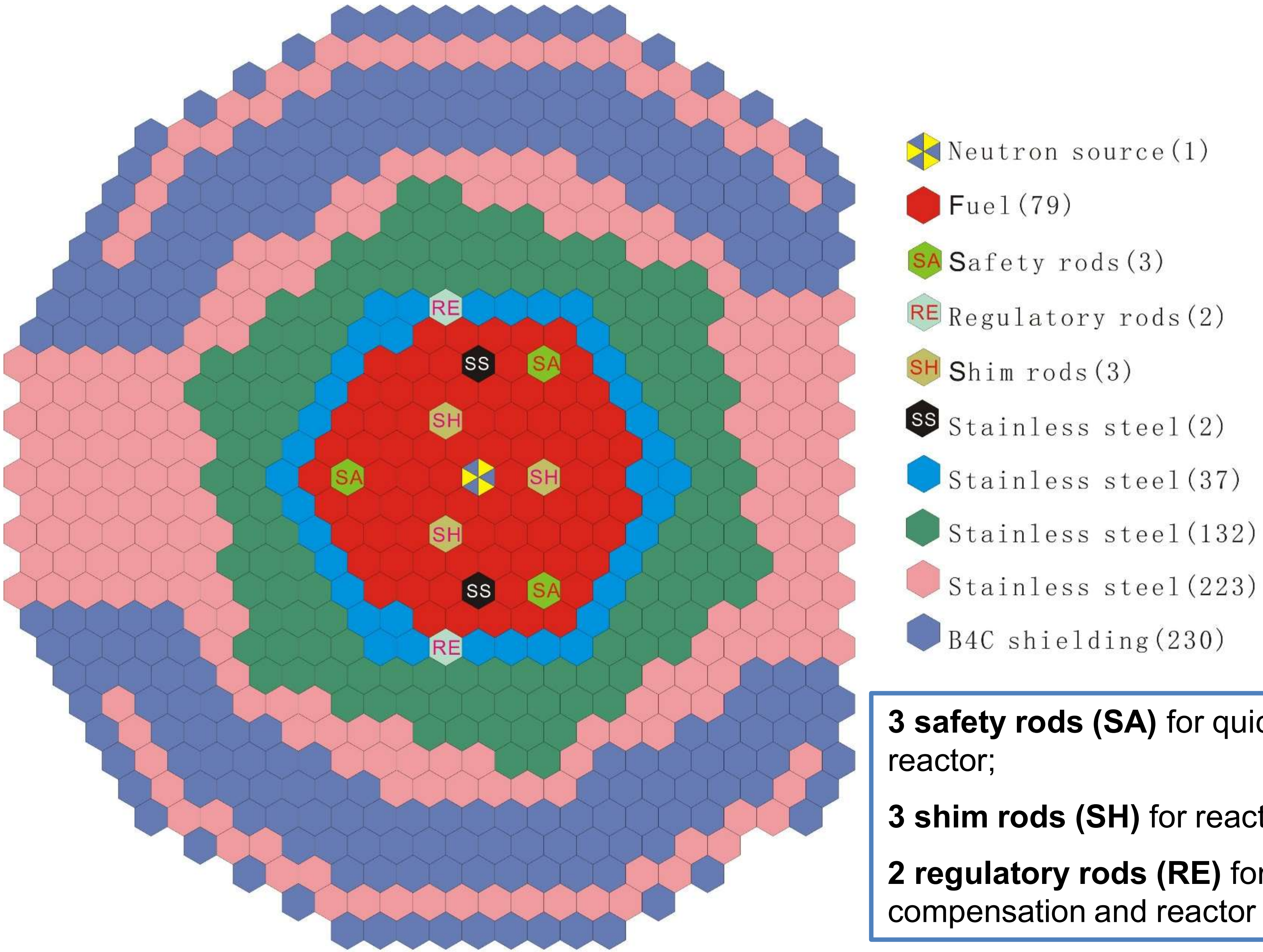
- The first fast reactor in China
- Sodium-cooled fast reactor with nominal power of 65MWt(20MWe)
- Reached the first criticality in July 2010
- Generated electricity at 40% full power and was connected firstly to the grid in July 2011
- Generated electricity at 100% power and operated continuously for 144 hours in Dec. 2015
- Currently, the CEFR is at shutdown state for maintenance and licensing for planed irradiation tasks.

1. Introduction of CEFR

Main parameters

Parameter	Value
Thermal/electric power, MW	65/20
Designed life, year	30
Maximum burn-up, MWd/t	60,000
Maximum neutron flux, $cm^{-2}s^{-1}$	3.2×10^{15}
Refueling period, day	80
Diameter/height of main vessel, m	8.0/12.2
Covering gas pressure, MPa	0.005
Core inlet/outlet temperature (full power), °C	360/530
Fuel	UO2(64.4%)
Max.neutron flux	E (Total), 3.2×1015cm-2s-1 E > 0.1MeV, 2.5×1015cm-2s-1
Max./Ave. burnup	60.0/44.5 MWd/kg
Core height/diameter	450/600mm
UO_2 mass	428kg
Max linear power	43 kW/m





3 safety rods (SA) for quickly shutdown of the reactor;

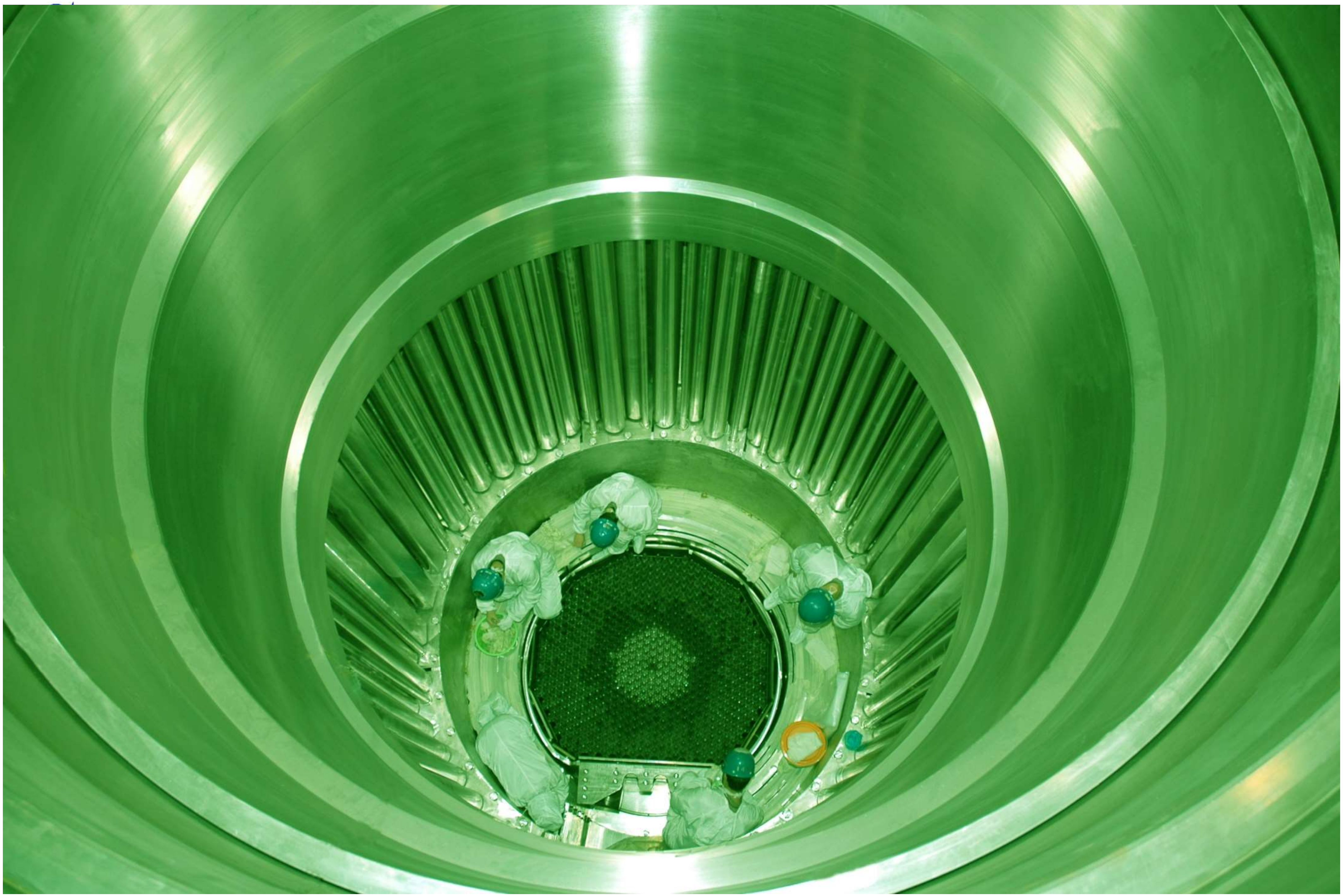
3 shim rods (SH) for reactivity compensation;

2 regulatory rods (RE) for small reactivity compensation and reactor power adjustment.

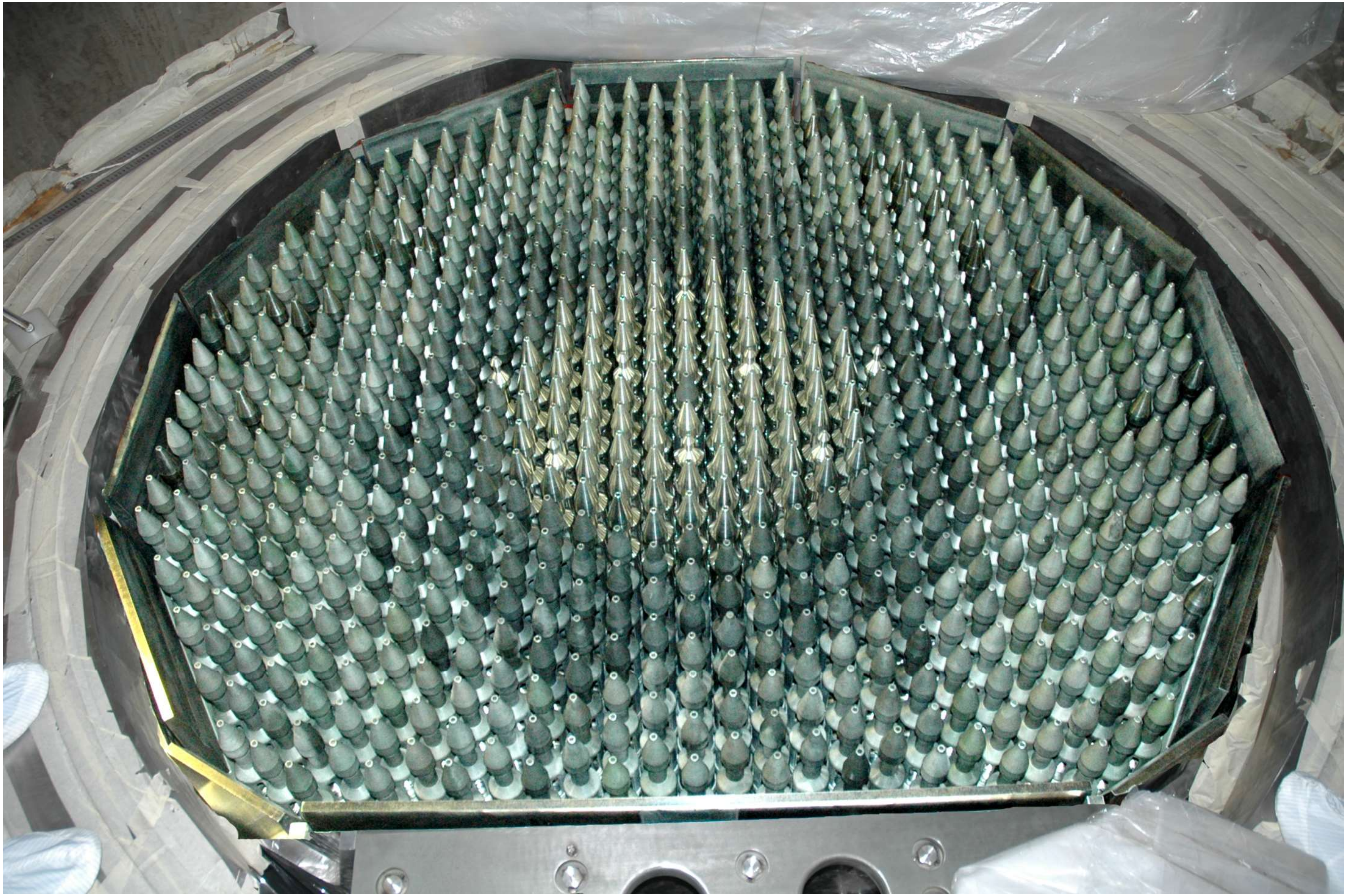
CEFR core layout of 1st loading

CEFR Plant

Main Control Room



Core and Peripheral Shielding



The Core after Installation of Mock-up Subassemblies

CEFR Physical Startup Tests Jun-Nov 2010

A

Jun 2010

Initial criticality

Doppler point	CRD worth measurement

B1+B2

Jul 21, 2010
First Criticality

B3

250°C operation loading criticality

CRD worth	Reactivity effect	Foil irradiation

After initial criticality, continue to load several fuel SAs to achieve the operation loading with excess reactivity.

（Aug.－ Oct.）

360°C operation loading criticality

Increase core temperature to hot state.

Temp. reactivity effect	CRD worth measurement

（Nov.）

Nov 2010

C

List of CEFR Start-up Tests

Starting from 5 June 2010, including 4 categories (totally 18 tests):

Fuel loading and criticality	Measurement of control rod worth	Reactivity effect measurement	Irradiation test of foils
Initial criticality	Initial criticality core	Temperature reactivity coefficient	Reaction rate distribution
250℃(cold state)	Operation loading core (250℃)	Pressure reactivity effect	Cross-section ratio
360℃ (hot standby)	Operation loading core (300℃)	Flowrate reactivity effect	Neutron spectrum
Nuclear heating start point		Sodium void reactivity effect	Absolute nuclear power
		Core SA exchange reactivity effect	

List of CEFR Start-up Tests

Tests Selected for the Benchmark (IAEA CRP)

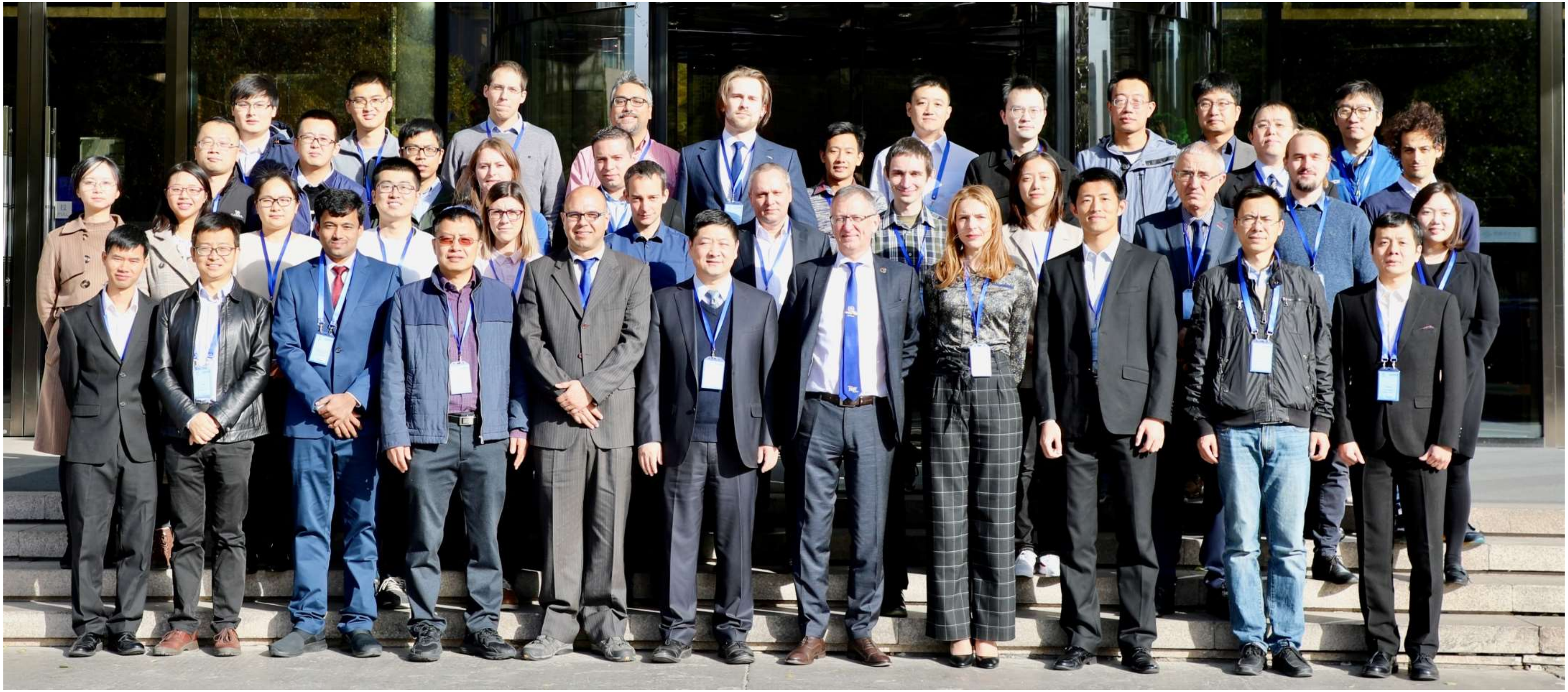
Fuel loading and criticality
- **Initial criticality**
- 250℃(cold state)
- 360℃ (hot standby)
- Nuclear heating start point

Measurement of control rod worth
- Initial criticality core
- **Operation loading core (250℃)**
- Operation loading core (300℃)

Reactivity effect measurement
- **Temperature reactivity coefficient**
- Pressure reactivity effect
- Flowrate reactivity effect
- **Sodium void reactivity effect**
- **Core SA exchange reactivity effect**

Irradiation test of foils
- **Reaction rate distribution**
- Cross-section ratio
- Neutron spectrum
- Absolute nuclear power

IAEA CRP: Neutronics Benchmark of CEFR Start-Up Tests



(CRP Members at 2nd RCM, Beijing, Oct 2019)

The Contents of the Specifications

Core

Geometry:
- Layout
- subassembly
- CR position
- detectors
- foils……

Material:
- fuel
- absorber
- SS
- sodium
- foils……

Experiments

	1	2	3	4	5	6	7
methods	*	*	*	*	*	*	*
environment	*	*	*	*	*	*	*
results	*	*	*	*	*	*	*
simulation	*	*	*	*	*	*	*

Benchmark Specifications

《基准例题详细说明》

Development of the Specifications

Version	Complete Date, y-m-d	Scope of Issuing
1	2018-05-23	CIAE&IAEA
2	2018-05-25	CIAE&IAEA
3	2018-06-01	Distributed
	2018-06-11 to 06-14	**1st RCM**
4	2018-10-5	CIAE internal
5	2018-10-19	Distributed
6	2019-04-29	Distributed
	2019-10-28 to 11-01	**2nd RCM**
7	**2019-11-31**	Distributed
8		updating

Participants' Comments

- Totally 97 comments received by email

No.	Solved	Date	Name	Type	Object	Simplified Question	Original Question	Reply	Final Solution
1	YES	2019/3/26	Jiwon Choe	contradiction	Criticality	70 or 80mm of RE2 position?	I have one more question about criticalit	The Version 5 is right. The RE2 pos	70mm(source: 试验结果报告-淡
2	YES	2019/3/25	Jiwon Choe	contradiction	Geometry	exact diameter of fuel pellet?	What is the exact value of fuel diameter? It i	This is an important issue. The no	Not important. Even the whole
3	YES	2019/3/25	Jiwon Choe	contradiction	Geometry	exact pin pitch?	What is the exact value of pin pitch? It is	The pitch is 6.95mm, which is a ref	Final data to give in specifica
4	YES	2019/3/25	Jiwon Choe	additional requiremer	Geometry	more info of axial SS shielding?	What is exact material composition and g	On CIAE side, we think the geometry of upper & lower structure o	
5	YES	2019/3/25	Jiwon Choe	information absence	Material	S.S. composition?	May I get exact SS composition? According	This is also an issue that is perplexing us. Actually different com	
6	YES	2019/3/25	Jiwon Choe	contradiction	Material	exact fuel density?	What is the exact value of fuel density? T	There is no need to give the actual density now, as the total mas	
7	YES	2019/3/25	Jiwon Choe	contradiction	Geometry	length of fuel SA?	According to Table 2 in version 5, the tota	The difference comes from simplification process. There won't m	
8	YES	2019/3/25	Jiwon Choe	mistake	Geometry	30 degree rotation!	The dimension of pin pitch is not matche	Yes, you are right. We are sorry for the mistake in drawing pictur	
9	YES	2019/3/25	Jiwon Choe	ambiguous	Void	void region scope, upper and lower	What is the exact range of void region? Th	The voided region starts from the nozzle all the way up to the ha	
10	YES	2019/3/25	Jiwon Choe	ambiguous	Void	void region scope, fuel inside?	Is there fuel pellet in the experimental fu	There are fuel pellets in the experimental SA for void reactivity. T	
11	YES	2019/3/25	Jiwon Choe	mistake	Swap	SA layout error in (5-19) position	Is the 'test case (5-19)' in table 21 (versio	Yes, a mistake happened here. Position (5-19) should be loaded	
12	YES	2019/3/25	Jiwon Choe	ambiguous	Swap	difference between 'multi-' and 'single	What is the difference between 'Table 22	"By multiple rods" means the measurement is done by changing	
13	YES	2019/3/25	Jiwon Choe	mistake	Swap	no more than 79 instead of 72	According to Table 20 in version 5, 79 fuel	Yes, you are right. Sorry for the mistake. It should be "the numbe	
14	NO	2019/3/25	Jiwon Choe	additional requirement	Material	info of irridation device?	The composition of irradiation device which d	OK, we will try to find those information and provide it later.	
15	YES	2019/3/25	Jiwon Choe	mistake	Geometry	figure name error	The figure file name should be changed a	Yes, thank you for finding that! It should be "neutron source SA"	
16	YES	2019/3/26	Chirayu Batra	contradiction	Void	void volume don't match	Are there fuel rods in void-SA? The volum	Yes, there are fuel rods in void-SA. I will check the volume later.	
17	YES	2019/3/26	Chirayu Batra	additional requiremer	Geometry	comparision of axial elevations	The elevations of axial sectors of differer	Yes, it is a good idea and has been proposed by more than one.	
18	YES	##########	Devan Kunhiraman	mistake	Geometry	undefined 1.2464mm	1. In Mock-up fuel SA, there is an un-nam	Here is a mistake. The value was already revised in figure 'Mock	
19	YES	##########	Devan Kunhiraman	contradiction	Geometry	mismatch of total length of fuel SA	2. In fuel SA, the sum of total length, as p	Sorry for the mistake, which occurred during the simplification pı	
20	YES	##########	Devan Kunhiraman	development	Geometry	to give a common reference line	3. The geometries of Boron shielding and	Yes, I am considering to do this work.	
21	YES	##########	Devan Kunhiraman	development	Geometry	side by side comparison of other SAs	4. In Figure 5, rod positions of absorber rc	This is a very good suggestion. I will do it.	
22	YES	##########	Devan Kunhiraman	development	Geometry	elevation comparison of all SAs	5. Kindly give an elevation comparison of	Comments No. 3, No. 4, and No. 5 focus on the same problem. I w	
23	YES	##########	Devan Kunhiraman	ambiguous	Void	void region scope	6. In section 3.7, it is mentioned that in e	Actually, the vacuum was obtained by sealing the inlets and out	
24	YES	##########	Devan Kunhiraman	mistake	Detector	detector axial positions	7. Axial height of start-up detectors with r	Sorry, I made a mistake in the figure of detectors (Figure 13). In t	
25	YES	##########	Devan Kunhiraman	additional requiremer	Material	materials till out-of-core detectors	8. The material present between the oute	It's encouraging to know that you would like to simulate the out	
26	YES	##########	Devan Kunhiraman	information absence	Material	unit of enrichment	9. In Table 2, the enrichment of B-10 is giv	Sorry, here is a mistake in Table 2	92atom%, source: Russian Phy
27	YES	##########	Armin Seubert	additional requiremer	Material	helium density of rod?	The helium density is not given - though neutronically not highly relevant, w		Actually, pressure of He is prc
28	YES	##########	Armin Seubert	additional requiremer	Material	sodium density equation	The sodium density is given in terms of a linear dependence in Emil's Excel sheet. Nevertheless, it might t		
29	NO	##########	Armin Seubert	contradiction	Geometry	spring height and expansion issue	From our understanding, there seems to be an issue with the calculation of the spring height. In Emil's excel sheet, th		
30	YES	##########	Devan Kunhiraman	ambiguous	Geometry	drawings of reflector and shielding SA	Revised Drawings of Reflector and Shielding Assemblies showing clearly the axial details are availble no		
31	NO	2018/10/5	UNIST	additional requirement	Geometry	more info of outer core	Dimension of reactor core (baffle/barrel/vessel) to describe reflector region		

Current Contents (V.6, as of Apr 2019)

Chapters:

Current Contents (V.6, as of Apr 2019)

SA Types:

3.1 Fuel SA

3.2 Control SA

3.3 SS SA

3.4 Boron Shielding SA

3.5 Neutron Source SA

3.6 Mock-up Fuel SA

3.7 Experimental Fuel SA for Sodium Void Measurement

3.8 Experimental Fuel SA for Foil Irradiation

3.9 Experimental SS SA for Foil Irradiation

Current Contents (V.6, as of Apr 2019)

Experiments:

Current Contents (V.6, as of Apr 2019)

For each experiment:

6.x.1 State of core

6.x.2 Experiment process

6.x.3 Expected output

中国首座快堆中国实验快堆（CEFR）于2010年7月21日首次临界。

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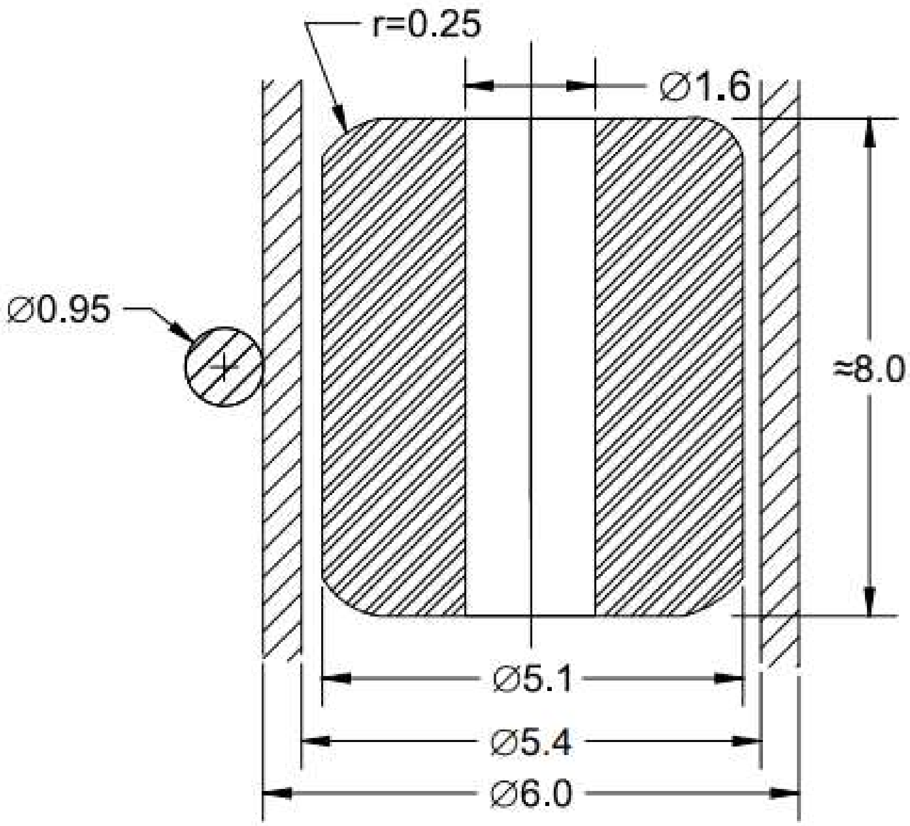
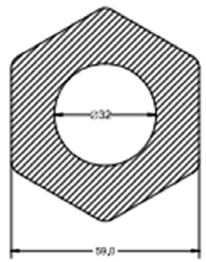
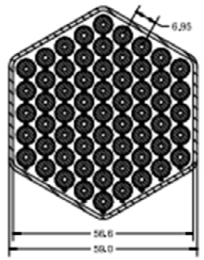


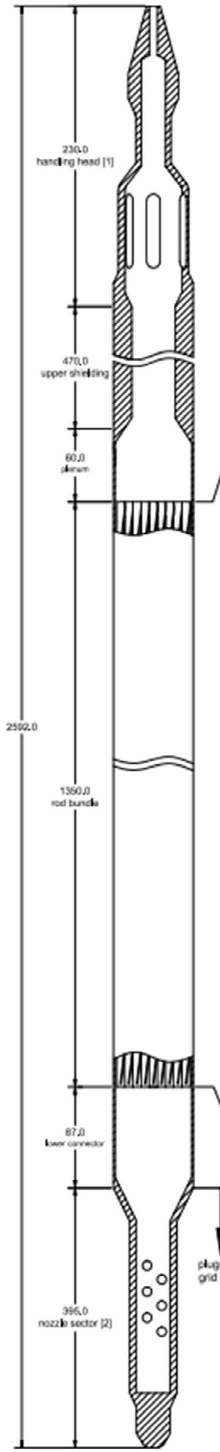
fuel pellet



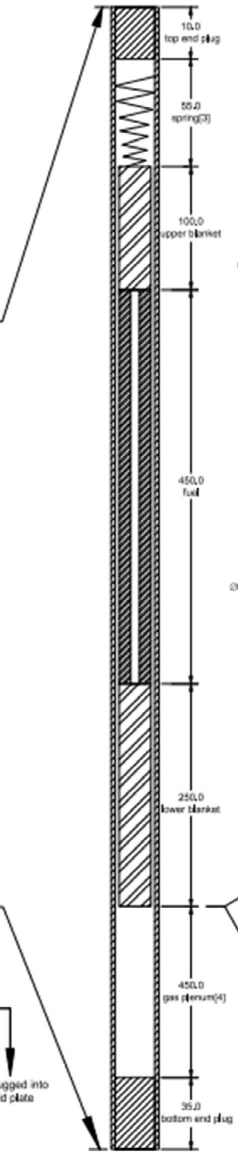
upper shielding



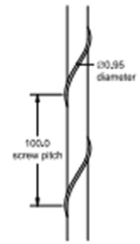
rod bundle



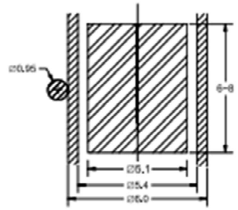
fuel SA



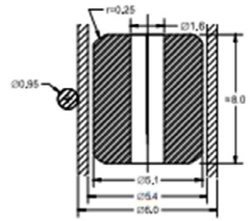
fuel rod



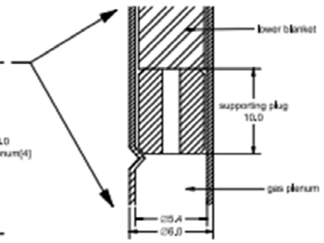
spacer wire



blanket pellet



fuel pellet



supporting plug [5]

Unit: mm
All drawings not to scale;

[1] total SS mass: 2.1kg
[2] negligible for neutronics calculation
[3] mass of spring: 1.4 g
[4] helium gas pressure: 0.28MPa
[5] supporting plug: it is recommended to omit it in neutronics modeling; if it is kept, the length of gas plenum is 440.0mm.

Fuel Subassembly

Main Parameters of Core SAs

	Fuel SA		Control SA		SS SA		Boron Shielding SA	Neutron Source SA
	Fuel	blanket	Regulating	Shim, safety	Type I&II	Type III&IV		
Number of SAs in core (operation loading)	79		2	3+3	39	355	230	1
Length of SA, mm	2592		2580		2592	2592	2592	2580
Mass of SA, kg	29~31		22~23		41~43	42~44	31~33	39~41
Number of rods	61		7		7	1	7	7(1)
Rod lattice pitch, mm	6.95		15.5		20.6	N/A	20.15	20.7
Outer diameter of rod/cladding, mm	6.00		14.9		20.0	54.0	19.2	20
Inner diameter of cladding, mm	5.40		12.9		N/A(2)	N/A(2)	17.2	N/A
Diameter of spacer wire, mm	0.95		1.3×0.6(3)		0.6	N/A	0.95	1.3×0.6(3)
Screw pitch of spacer wire, mm	100		100		100	N/A	100	100
Effective material and enrichment	UO_2		B_4C		SS	SS	B_4C, 19.8a%10B, Natural	Cf-252
	64.4±0.5, wt%	0.3~0.72, wt%	19.6a%^{10}B (Natural)	92.0a%^{10}B				
Total mass of UO2 or B4C in each SA (kg)	5.30±0.13	1.28/ 3.23(4)	0.87		N/A	N/A	2.43	0.43E-6
Length of effective material, mm	450	100/ 250(5)	510		N/A	N/A	800	N/A

Total mass of fuel/blanket in each fuel SA

		Design value	Measured value				
			Average	Standard Deviation	Minimum	Maximum	Total Number *
Fuel	Mass of UO2, kg	5.30±0.13	5.28127	0.01295	5.2570	5.3421	89
	Mass of U, kg	4.66±0.12	4.64602	0.01167	4.6246	4.6979	
	Mass of U-235, kg	N/A	2.98197	0.00852	2.9667	3.0156	
	Enrichment of U-235, wt%	64.4±0.5	64.18315	0.09761	64.08	64.41	
Blanket	Mass of UO2, kg	4.51±0.30	4.56629	0.01548	4.5345	4.6079	
	Mass of U, kg	3.97±0.28	4.01855	0.01418	3.9940	4.0587	
	Mass of U-235, kg	N/A	0.0179	3.1403E-4	0.0172	0.0183	
	Enrichment of U-235, wt%	0.3~0.72	0.44532	0.00719	0.42924	0.45646	

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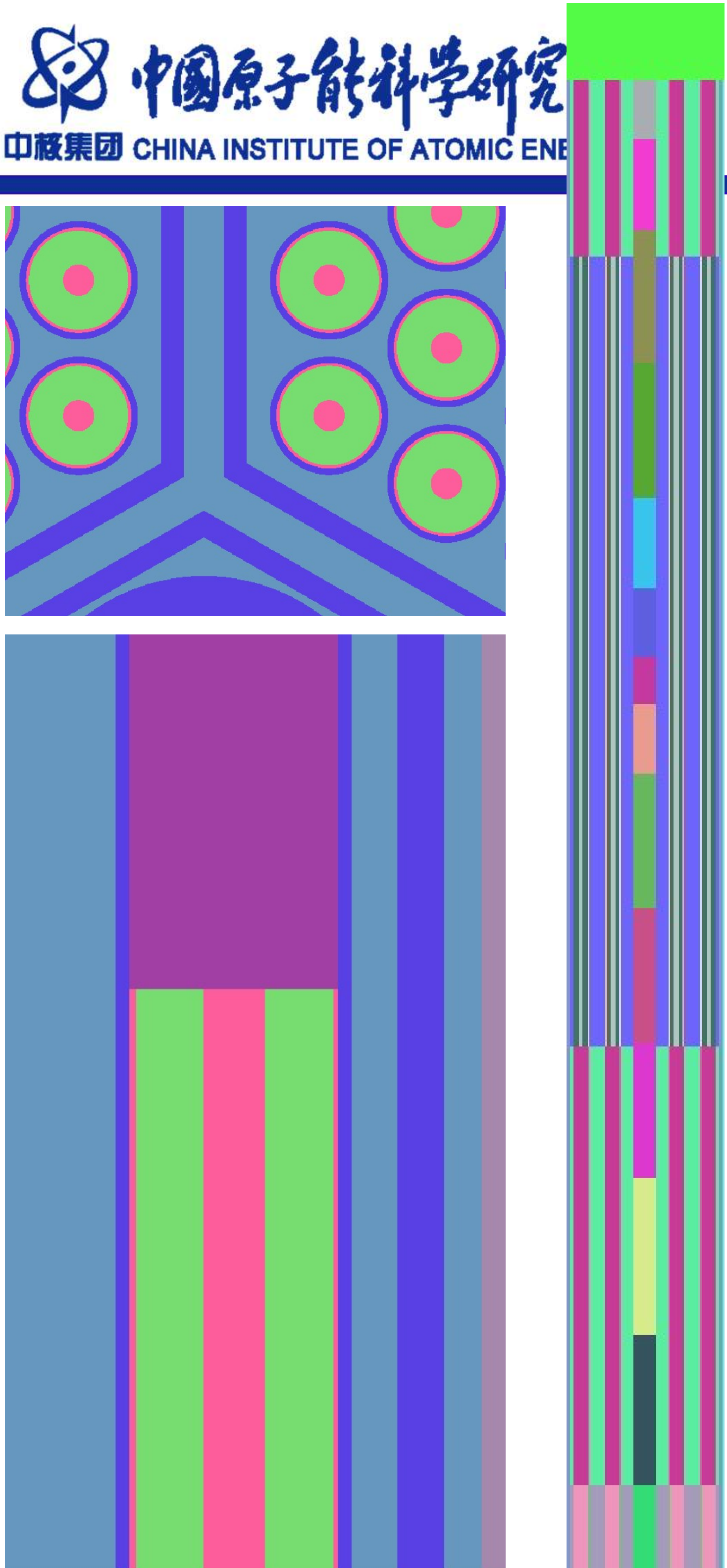
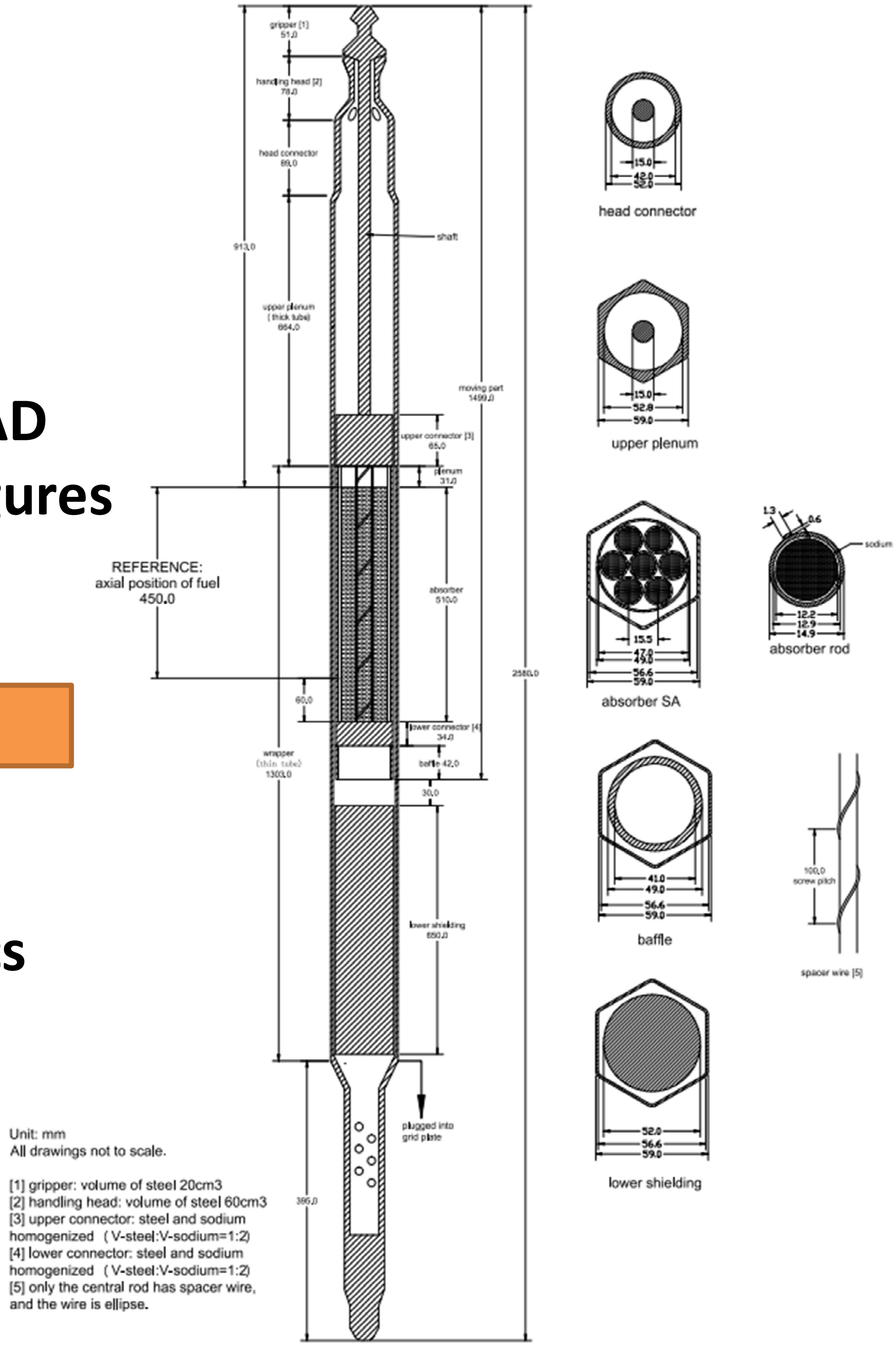


CAD figures

neutroncs models



Control Rod SA （refueling state)

CEFR physics startup progress

2010.6-11

A

20100605

Net criticality（First criticality）

Doppler point	CRD worth measurement

B1+B2

20100721
First criticality

B3

250°C operation loading criticality

CRD worth	Reactivity effect	Foil irradiation

（Aug.－ Oct.）

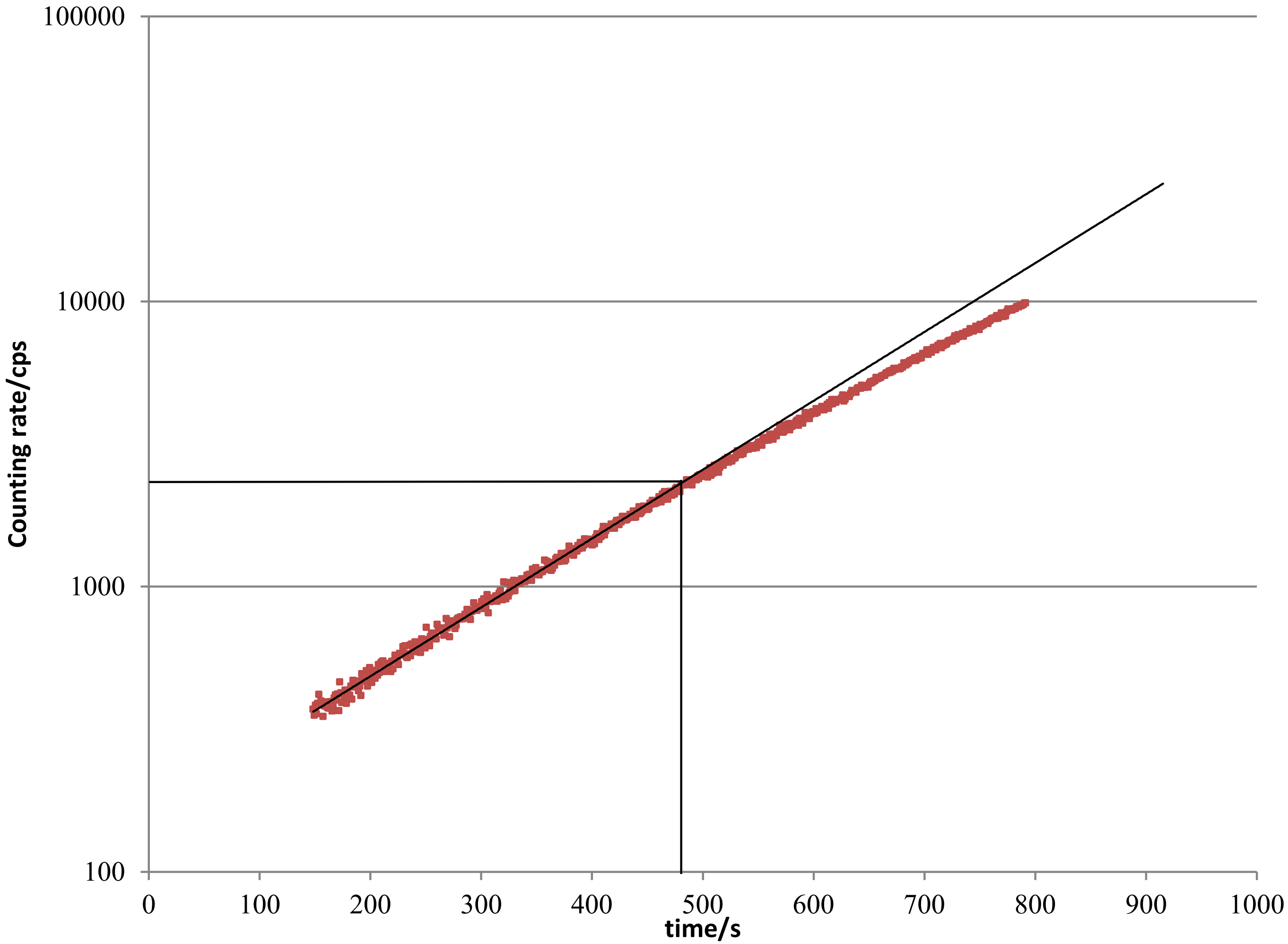
360°C operation loading criticality

Temp. reactivity effect	CRD worth measurement

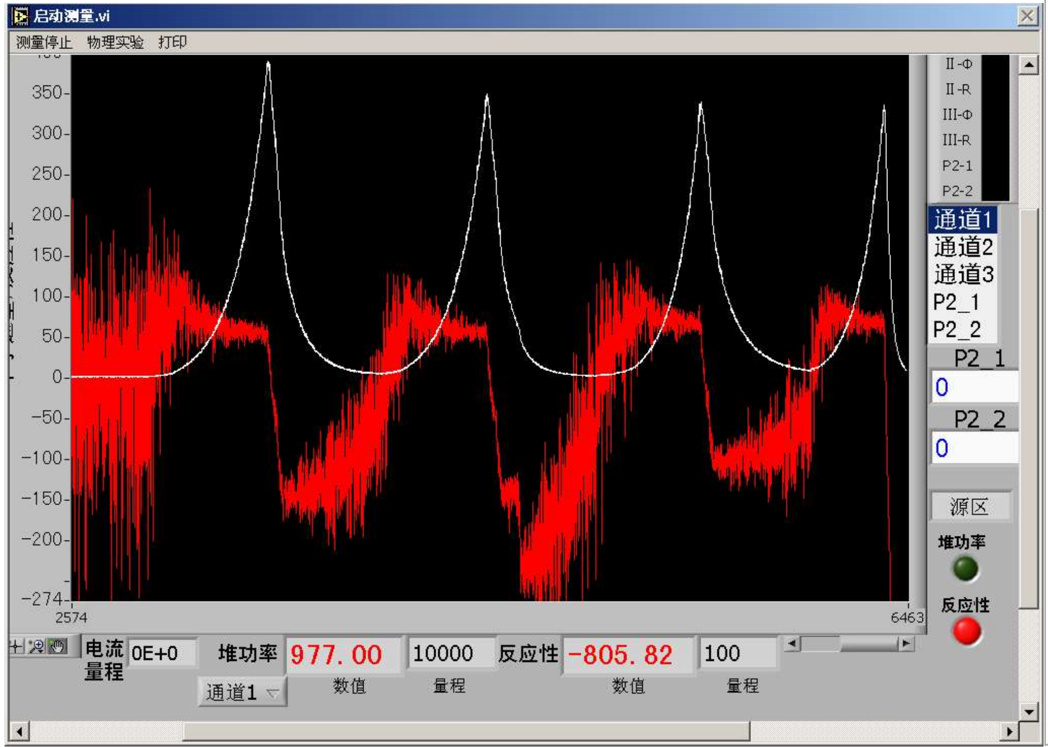
（Nov.）

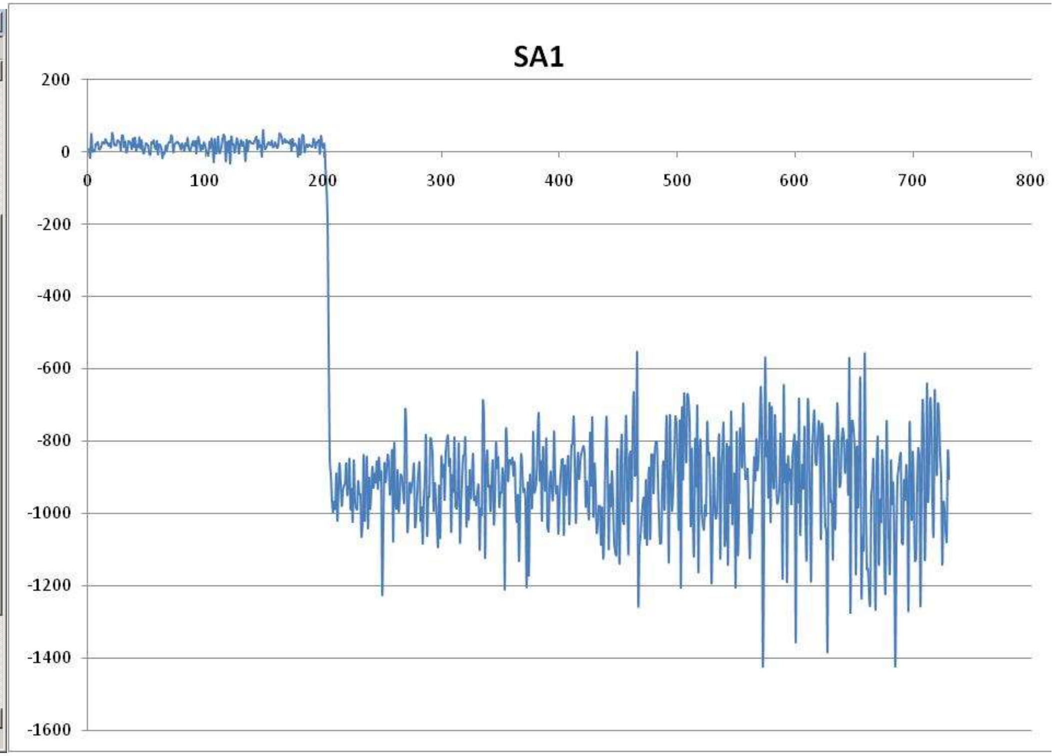
20101130

C



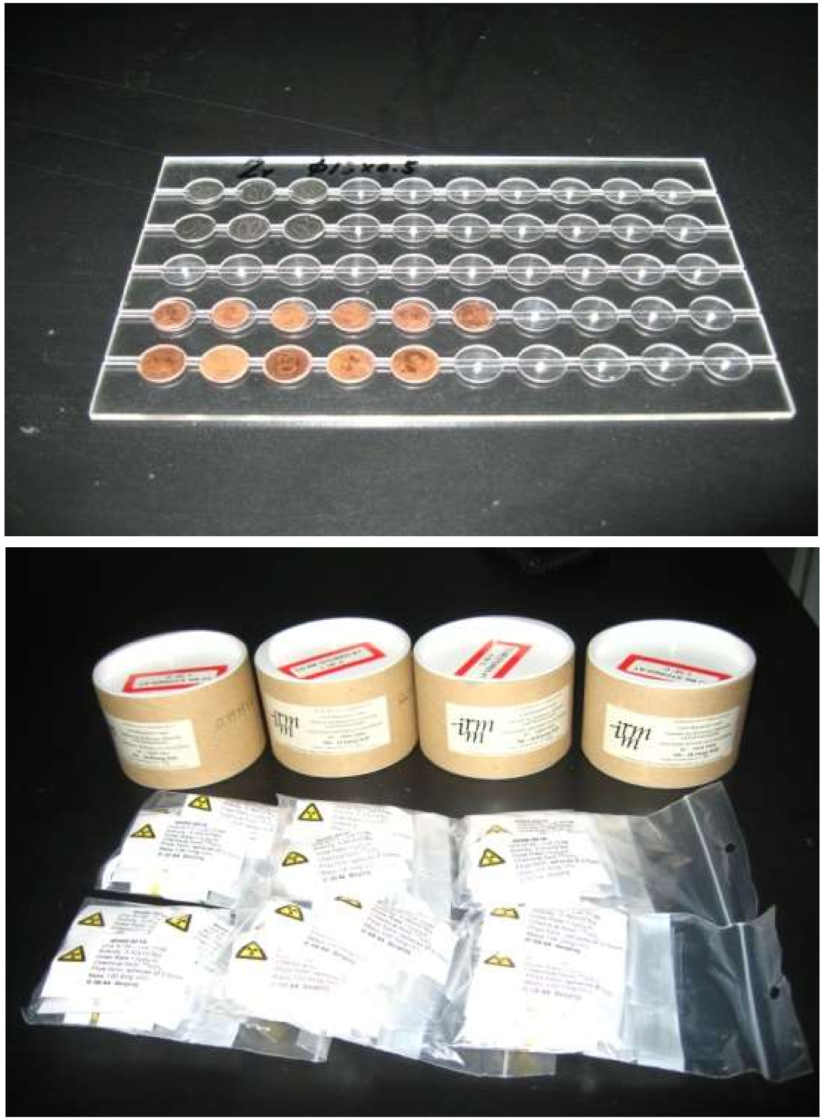
The measurement of starting point of nuclear heating to guarantee that all tests are carried out without temperature effects.





The real-time output of the reactivity meter used in CEFR

The reactivity meter response with SA#1 dropped



Foil Detector

High purity Germanium Gamma-Ray Spectrometer

Fuel Loading and Criticality

Test Method

- Using **neutron count inverse extrapolation method** at subcriticality state to get **fuel SA number** for initial criticality ('clean' criticality)
- Using **reactivity extrapolation method** at supercriticality state to get **RE rod position** for criticality

Neutron count inverse extrapolation method → **Fuel SA number for initial criticality**

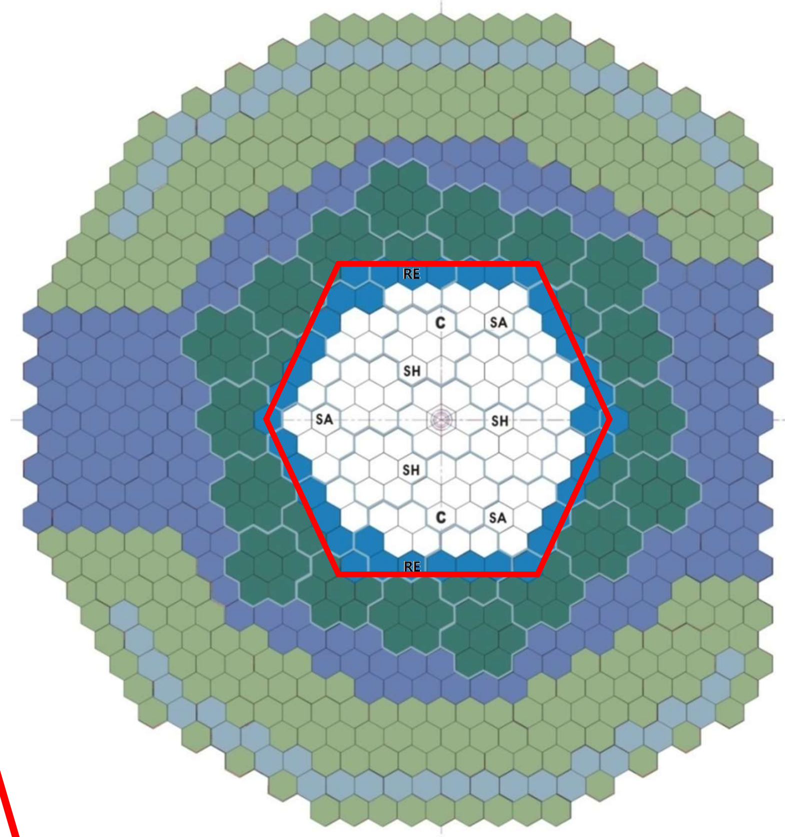
Reactivity extrapolation method → **RE rod position for initial criticality**

Reactor core state before fuel loading

SA type	Number
Dummy fuel SA	81
Neutron sourece SA	1
Control rod	8 SA:3 SH:3 RE:2
S.S. reflector	336 II:37 III:132 IV:167
Boron shielding	230
Spent fuel storage	56
Total	712

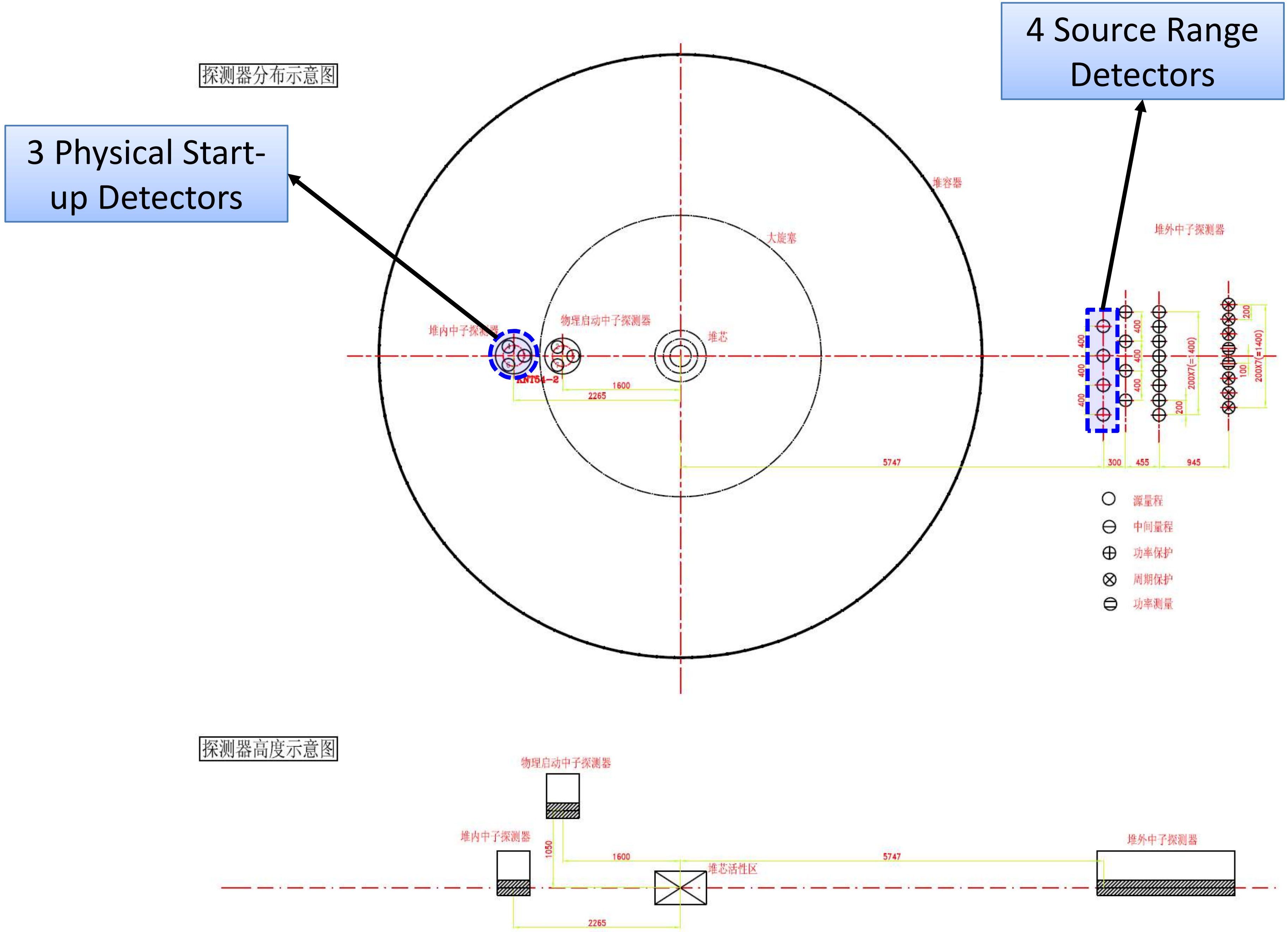
72

575



The predicated(by calculation) number of fuel SAs to be loaded for first criticality is 72

575 real SA have been loaded before fuel loading


4 Source Range Detectors
探测器分布示意图
3 Physical Start-up Detectors
堆容器
大旋塞
堆外中子探测器
物理启动中子探测器
堆内中子探测器
堆芯
1600
2265
5747
300
455
945
源量程
中间量程
功率保护
周期保护
功率测量
探测器高度示意图
物理启动中子探测器
堆内中子探测器
堆外中子探测器
堆芯活性区
1050
1600
5747
2265

Test #1 Fuel Loading and Criticality

Safety principle for fuel loading

- At least two serials of neutron count system on normal working condition
- ½ loading principle and minimal loading principle
- Loading fuel SA near control rod or with large reactivity firstly (such as fuel SA in central position)
- Symmetry principle
- Only one SA can be loaded each batch after keff approaching and larger than 0.99
- Transition to super-criticality state only after keff larger than 0.997

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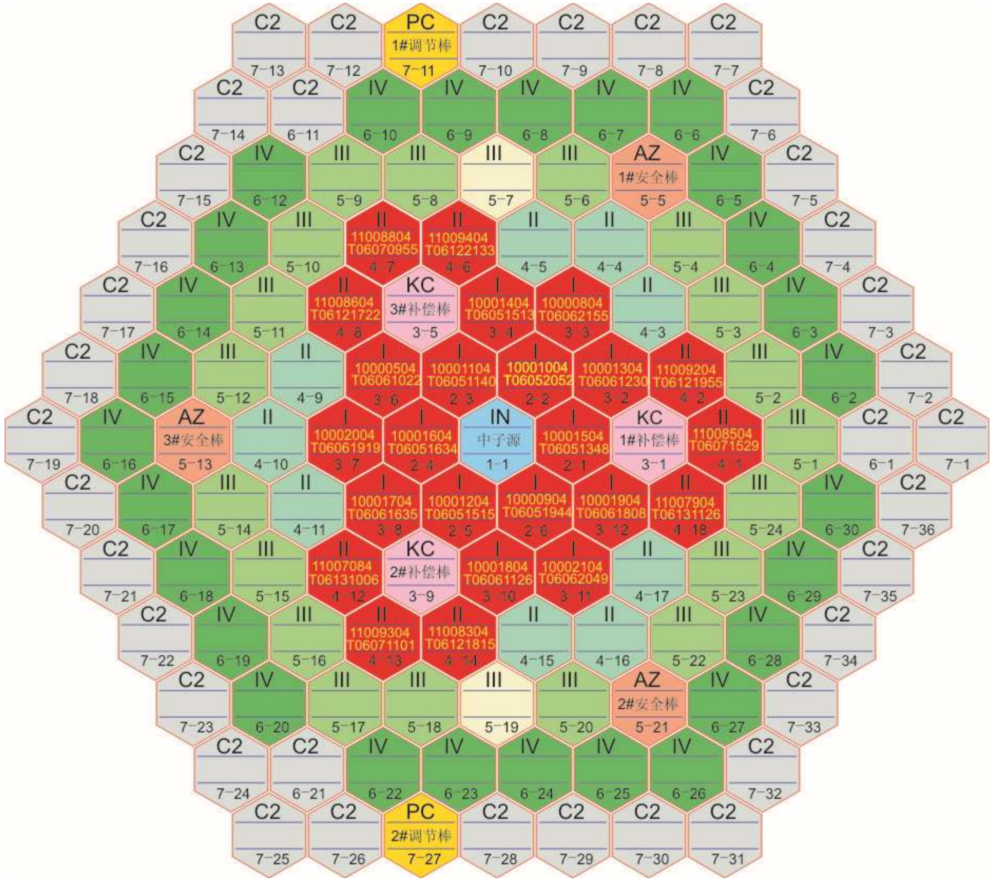
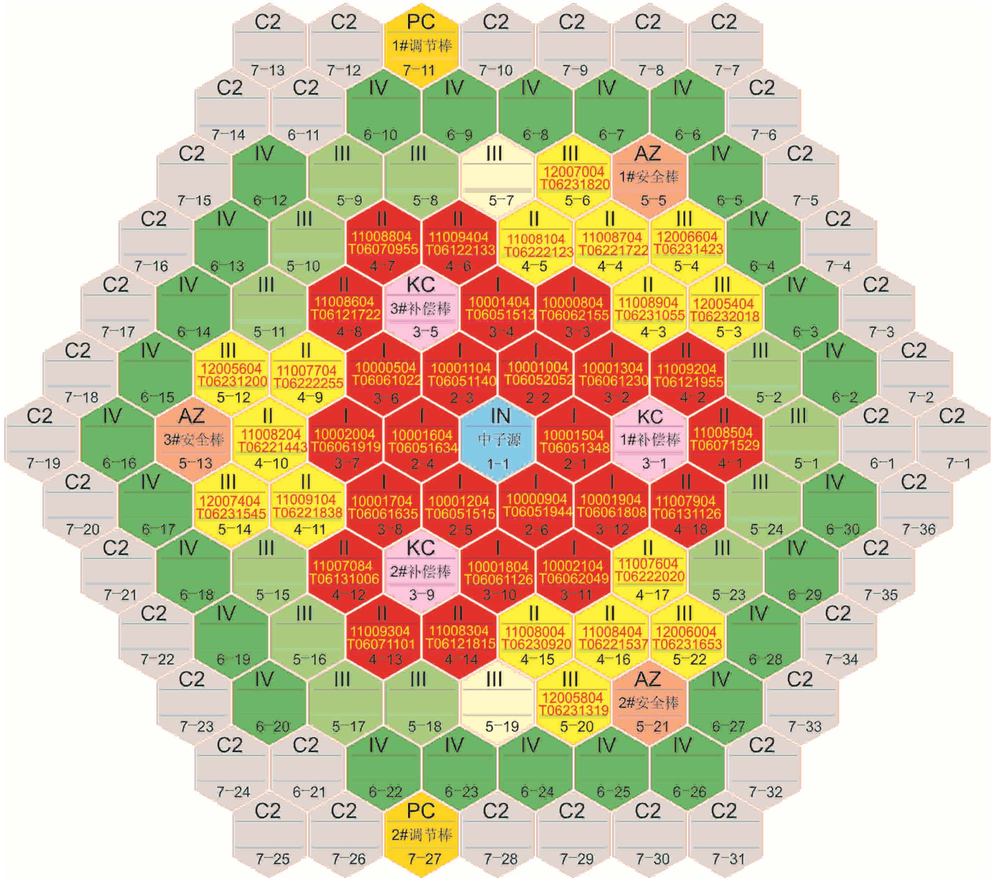
Fuel loading process

Batch 1，+24/24



Batch 2，+16/40


C2 7-13
C2 7-12
PC 1#调节棒 7-11
C2 7-10
C2 7-9
C2 7-8
C2 7-7
C2 7-14
C2 6-11
IV 6-10
IV 6-9
IV 6-8
IV 6-7
IV 6-6
C2 7-6
C2 7-15
IV 6-12
III 5-9
III 5-8
III 5-7
III 12007004 T06231820 5-6
AZ 1#安全棒 5-5
IV 6-5
C2 7-5
C2 7-16
IV 6-13
III 5-10
II 11008804 T06070955 4-7
II 11009404 T06122133 4-6
II 11008104 T06222123 4-5
II 11008704 T06221722 4-4
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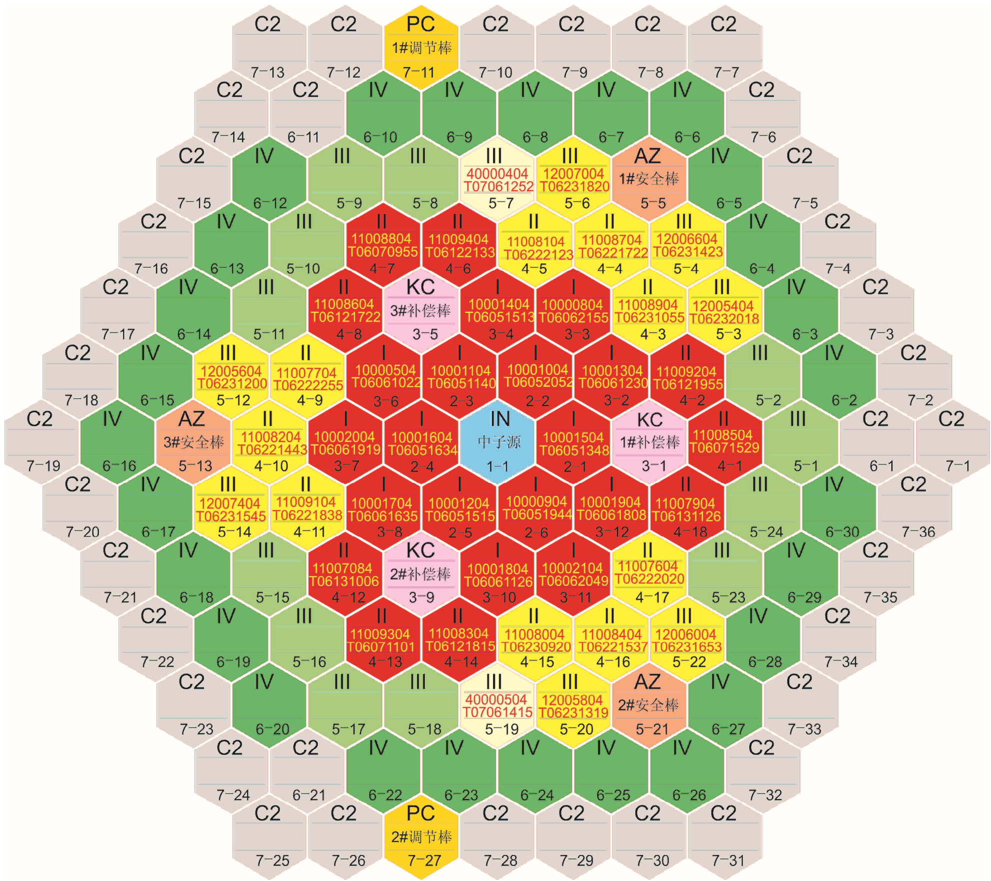

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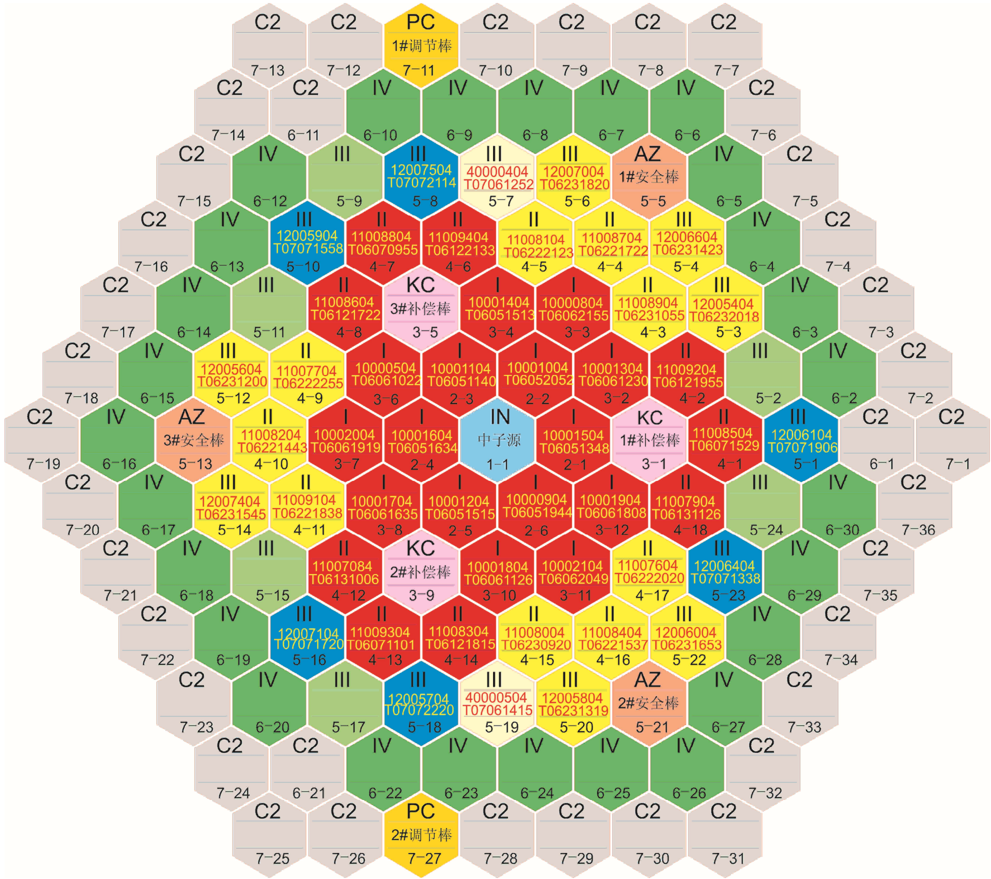
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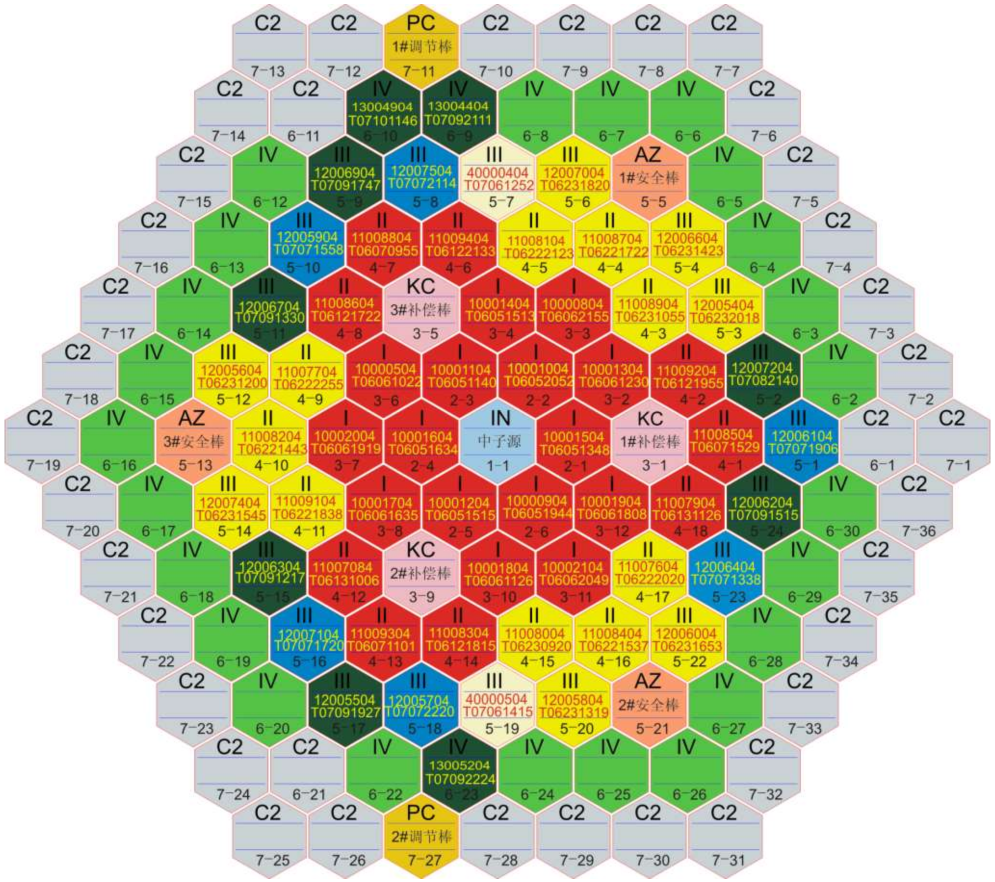

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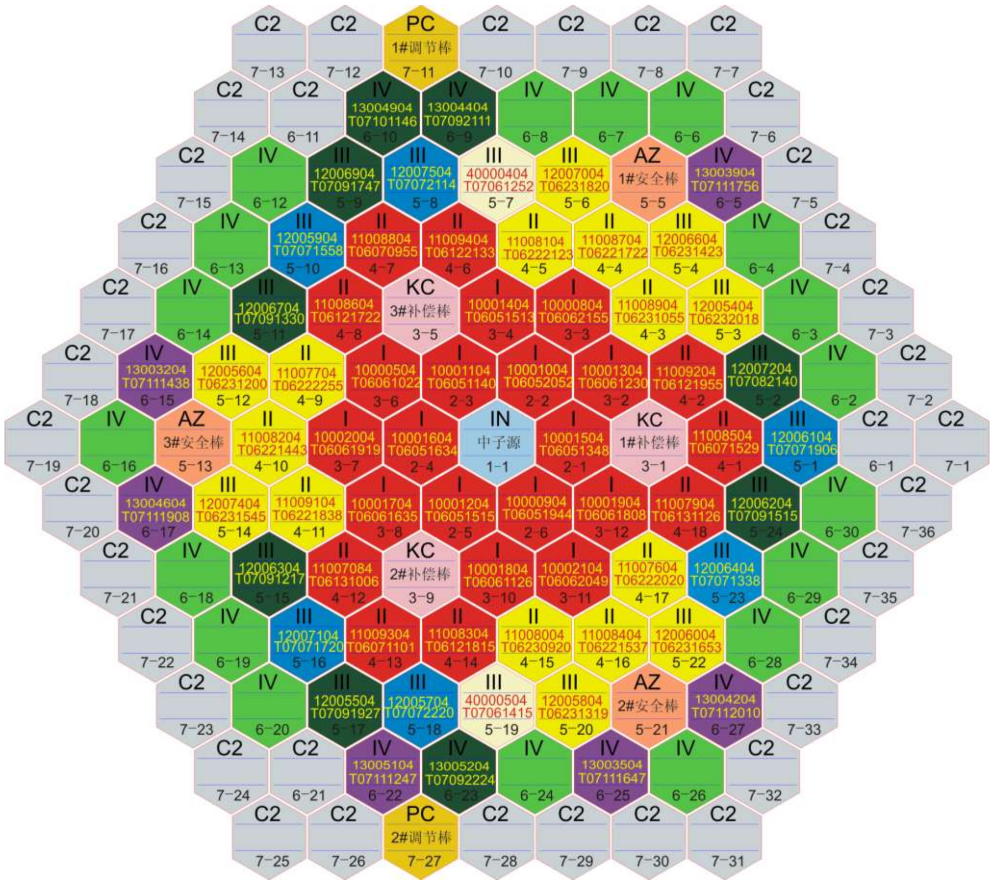

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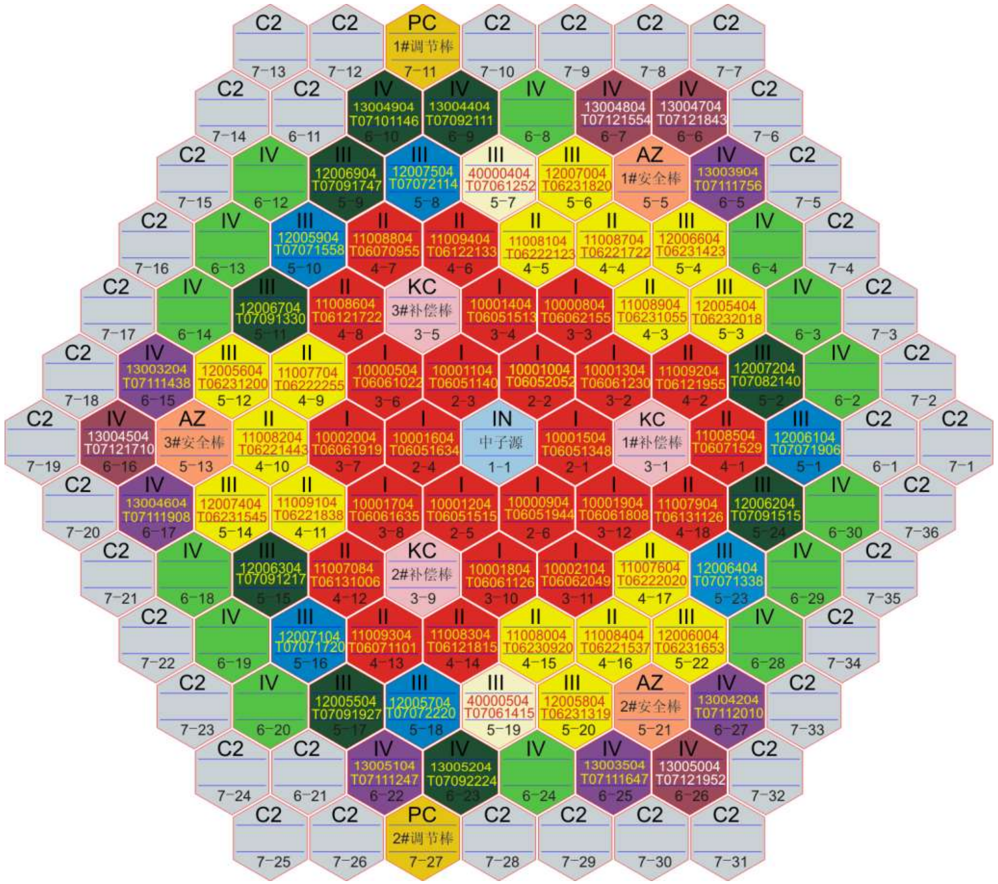
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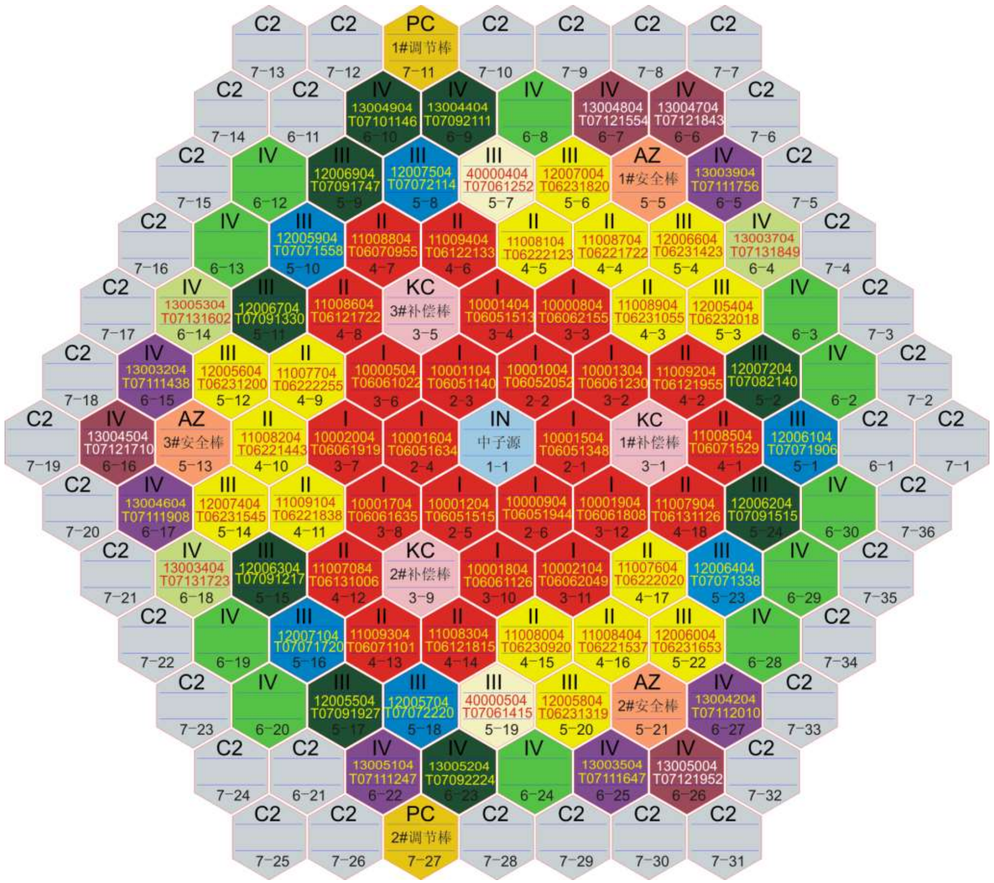
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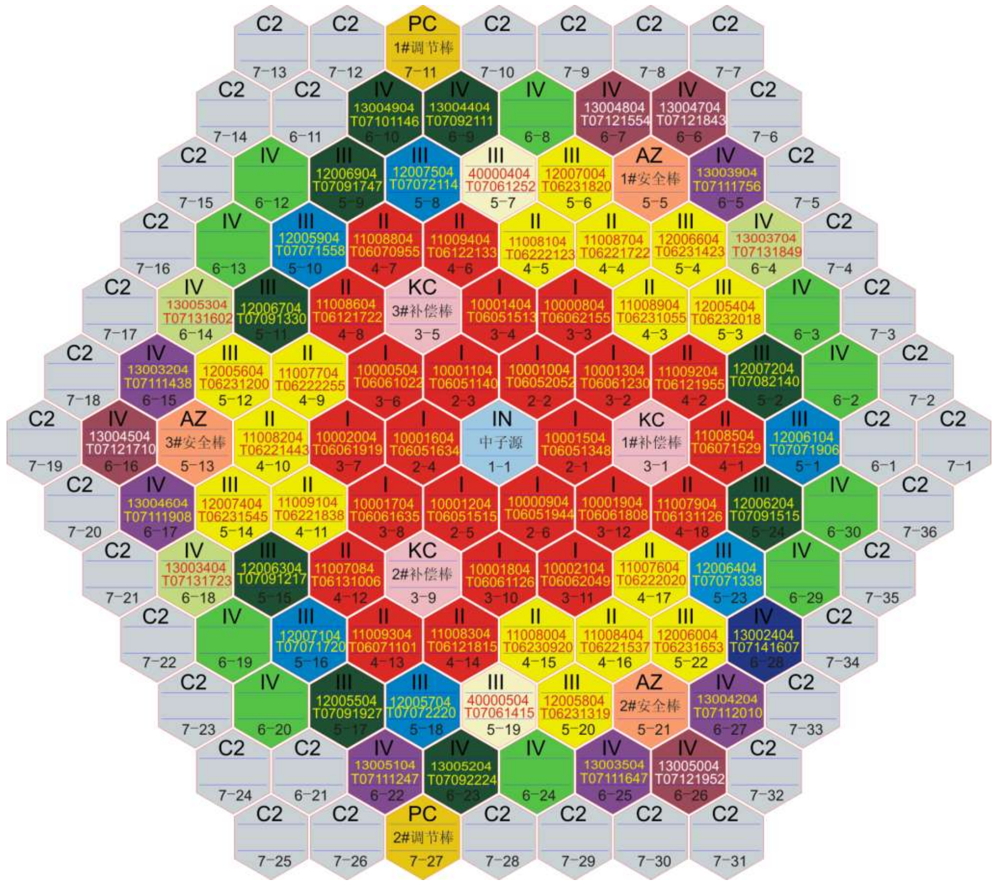
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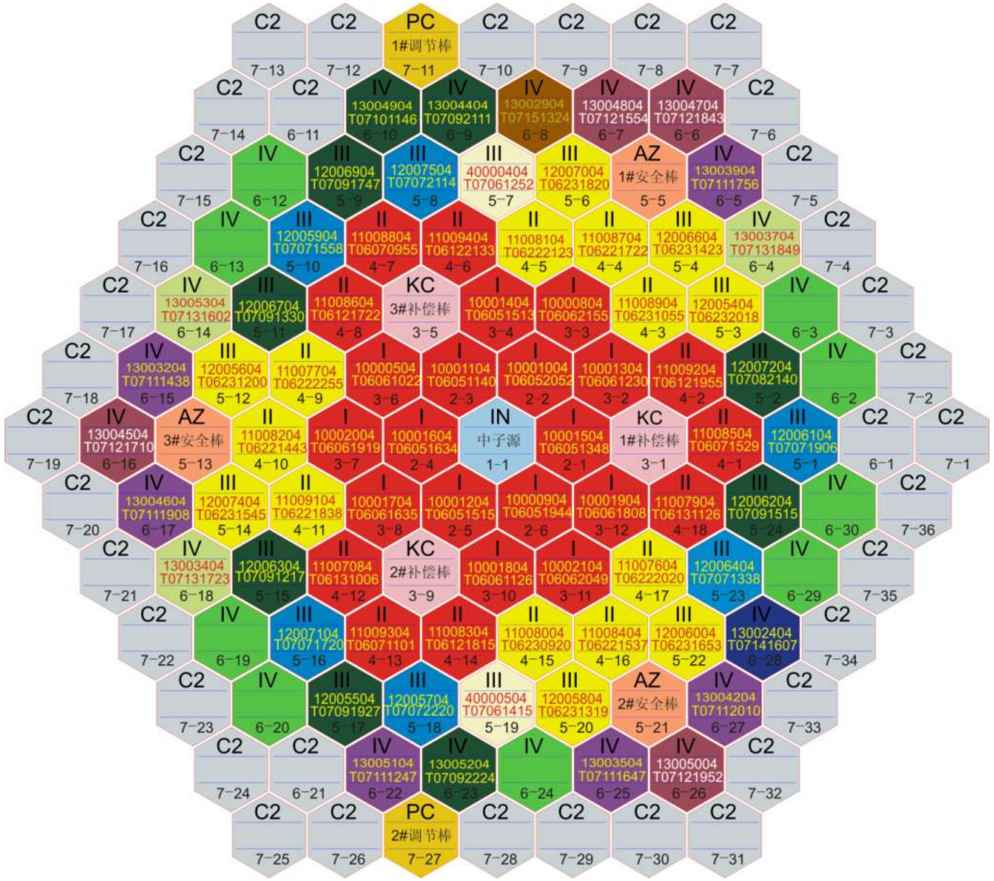
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AZ 2#安全棒 5-21
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C2 7-33
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C2 6-21
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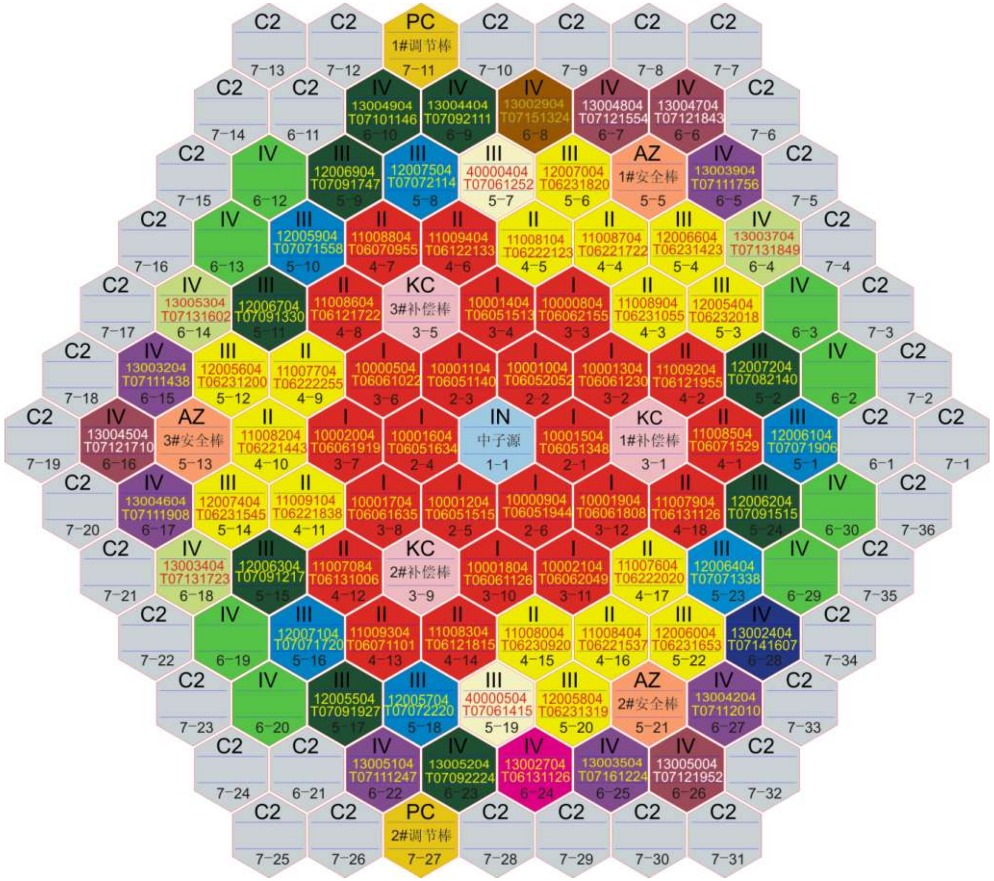
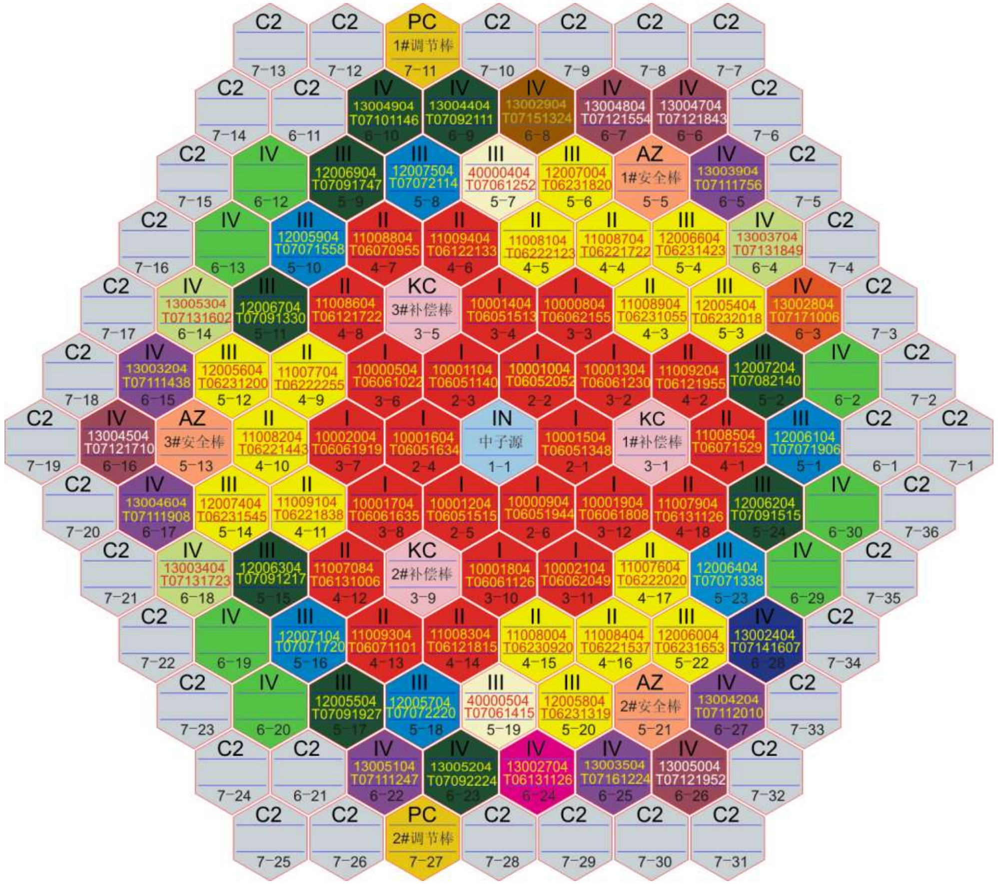
IV 6-24
IV 13003504 T07111647 6-25
IV 13005004 T07121952 6-26
C2 7-32
C2 7-25
C2 7-26
PC 2#调节棒 7-27
C2 7-28
C2 7-29
C2 7-30
C2 7-31

Batch 10，+1/71



Batch 11，+1/72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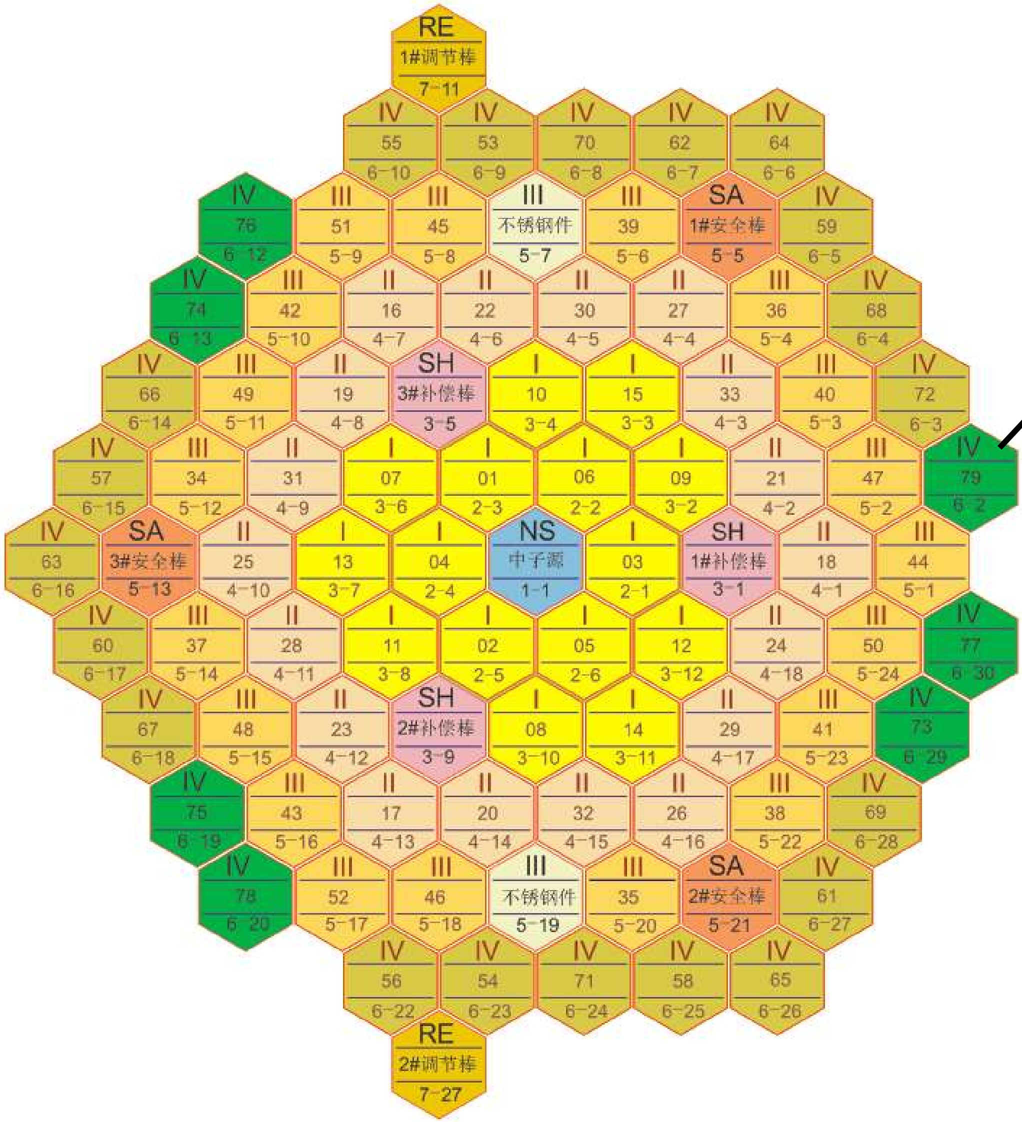
IV 13005004 T07121952 6-26
C2 7-32
C2 7-25
C2 7-26
PC 2#调节棒 7-27
C2 7-28
C2 7-29
C2 7-30
C2 7-31

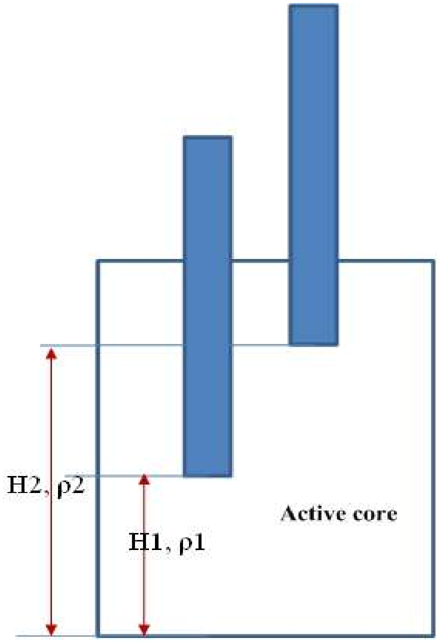
Core state for initial criticality

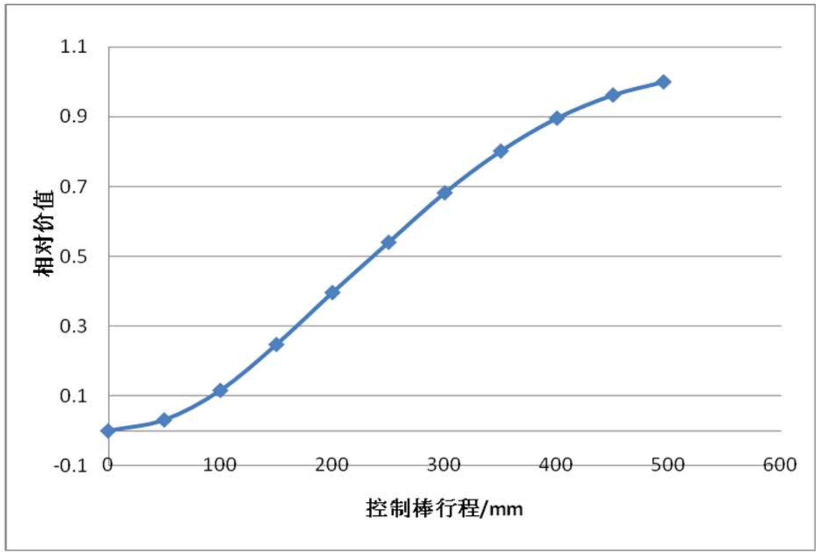


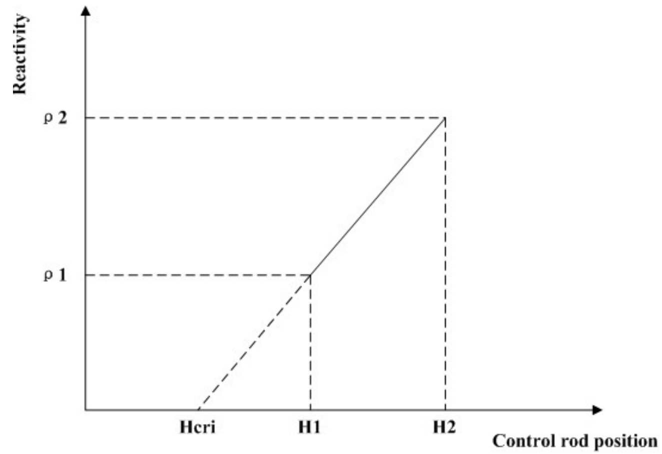
7 dummy fuel SAs to be replaced for operation loading

Using reactivity extrapolation method to get final criticality state

- After loading 72 fuel SAs, there is a little excess reactivity which need to be compensated by control rod; Using RE2 to compensate the excess reactivity with all other control rods out of core
- Move RE2 to make CEFR core to super-criticality and measure reactivity
- Using reactivity extrapolation method to determine final criticality position for RE2







Using reactivity extrapolation method to get final criticality state

Determination of RE2 criticality position by using source range IB

RE position H_i(mm)	Double period T(s)	ρ(Δk/k)	RE2 Relative worth η(H_i)
151	232.0	2.45E-04	0.231
170	162.0	3.35E-04	0.291
190	134.0	3.95E-04	0.332
Extrapolated η(H_0)	0.070	Extrapolated rod position H_0(mm)	70.0

RE2 criticality position determined by different detectors

	Source range detectors			
	IA	IB	IIA	IIB
Hcri/mm	70	70	68	68

Final state for CEFR initial criticality state

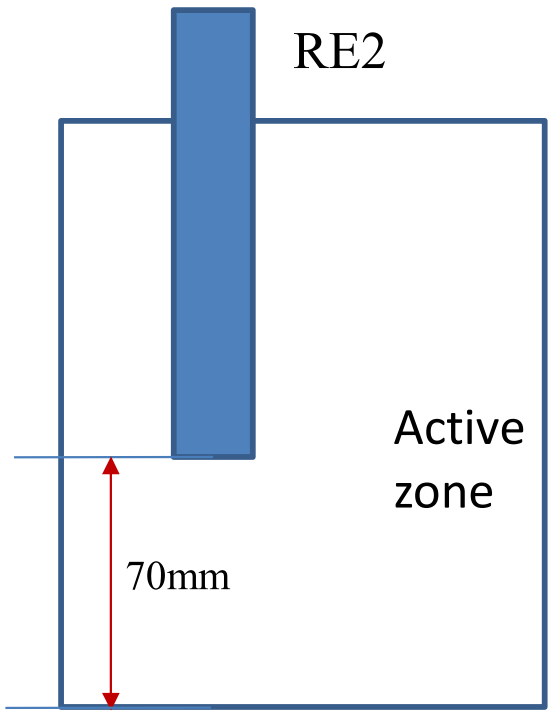
- 72 fuel SAs loading
- Control rod position:

  SA – all out of core

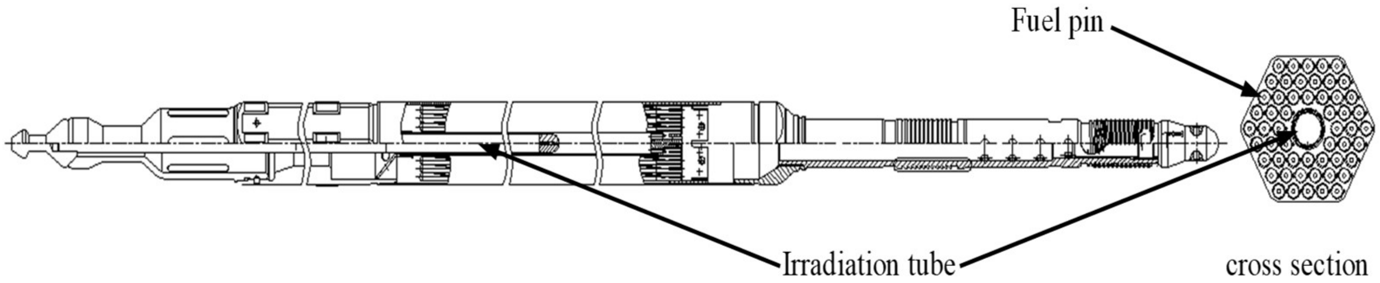
  SH – all out of core

  RE – RE1 out of core, RE2 at the position of 70 mm

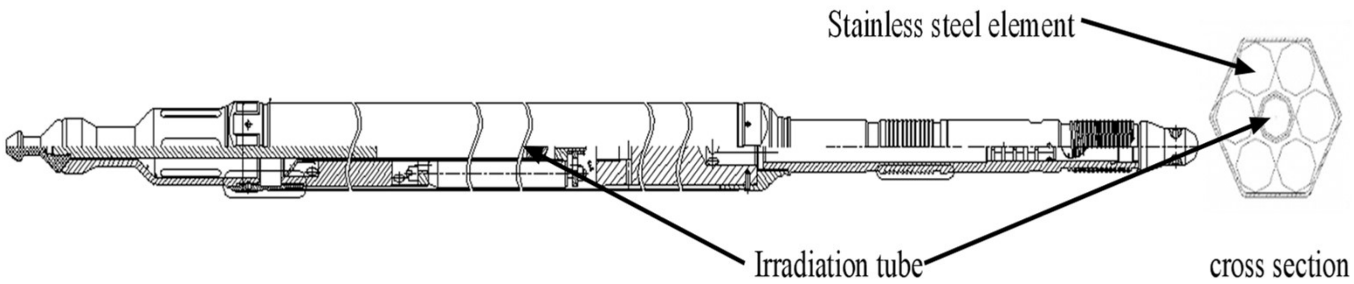
keff=1.00000±0.00005 (reactivity mearsurment error)



3. Experimental method(Irradiation tests of foils)

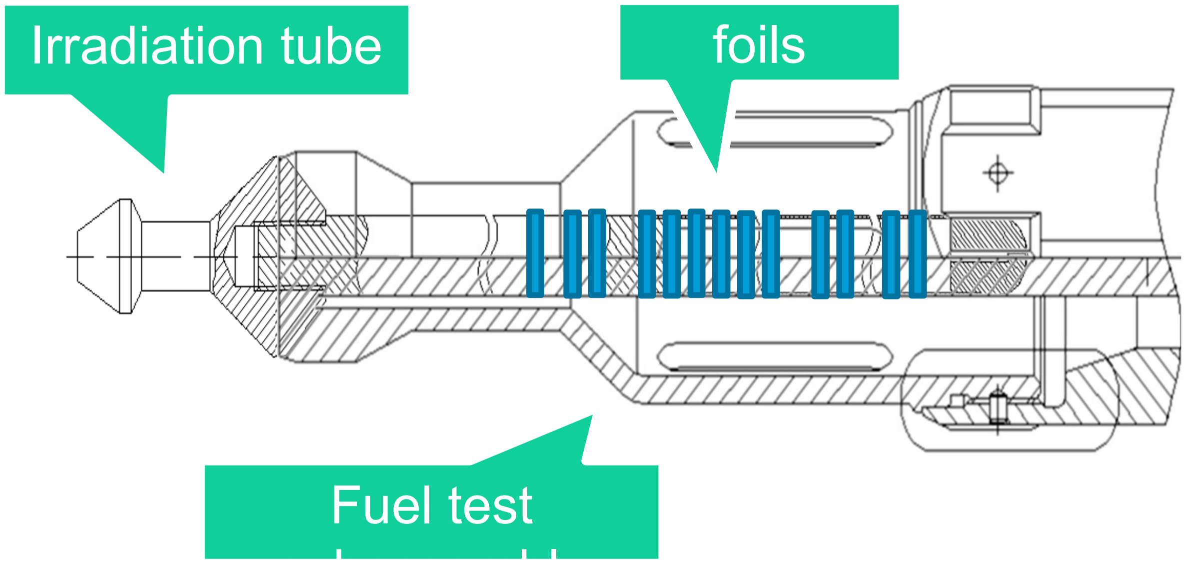


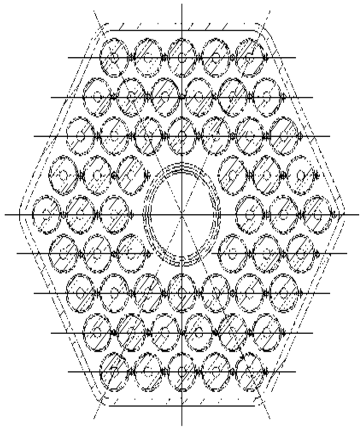
Fuel test subassembly



Reflector test subassembly

3. Experimental method(Irradiation tests of foils)





In order to ensure no high temperature oxidation during the irradiation, the irradiation tube shall be filled with inert gas before entering the reactor, and leakage test shall be carried out. The special test assembly shall be cleaned, dried and

List of possible extension work (1/2)

1. Dynamic simulation
   - rod drop transient (detector signal and measured/calculated reactivity could be provided)
2. Burn-up calculation
   - measured value: number density of MA in spent fuel after one cycle (nominally 82 EFPD);
   - large uncertainty in obtaining experimental data, but can be expected…
   - based on fixed CR positions (difficult to retrieve the actual CR positions due to frequent shutdowns and abnormal operations)
3. Detector response factor (deep penetration problem)
   - out-of-core detector is ~6m away from active core;
   - influence to the detector by temperature/sodium density can be studied;
   - CIAE could provide structures in the neutron path from core to detector, as detailed as we can …

List of possible extension work (2/2)

4. Spectrum of typical positions
   - a comparison of spectrum calculated by different codes;
   - with agreed and fixed group structure;
   - several typical positions could be selected;
5. Comparison of group XS generated
   - with agreed and fixed group structure;
   - targeting several important reaction types;
6. comparison of calculated β_{eff}
   4. In CEFR experiments, the direct measured value is reactivity rather than keff;
   5. keff is obtained by inverse kinetics and in-hour equation, both of which rely on calculated β_{eff}
   6. A joint calculation and comparison of β_{eff} will be a meaningful supplement to the CRP and a good validation of codes and nuclear data of participants
7. Nuclear data adjustment based on experiment

Thank you for your attention!