IAEA CRP Proposal for Benchmark Analysis on Physical Start-Up Experiments of China Experimental Fast Reactor

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Abstract. China Experimental Fast Reactor (abbr. CEFR) is a pool-type sodium-cooled fast reactor in China Institute of Atomic Energy (abbr. CIAE), with a thermal power of 65MW and an electric power of 20MW. The construction started in 2000 and the first criticality was reached in July 2010. On December 15th 2014, CEFR reached full power for the first time and was successfully operated for 72 hours. During the physical start-up of CEFR, a series of tests were carried out in four aspects, i.e., fuel loading and first criticality, control rod worth measurements, reactivity coefficient measurements, and foil activation measurements. A large amount of experiment data was obtained in the process. In order to compile and reserve the experimental data in a standard and refined form, and to benefit the worldwide fast reactor society on the validation of codes and nuclear data, China Institute of Atomic Energy proposed an IAEA Coordinated Research Project, and got approved preliminarily.

Key Words: China Experimental Fast Reactor, sodium-cooled fast reactor, physical start-up, CRP

1. Introduction

China Experimental Fast Reactor (abbr. CEFR) is a pool-type sodium-cooled fast reactor, constructed and operated by China Institute of Atomic Energy (abbr. CIAE). It has a thermal power of 65MW and an electric power of 20MW. The construction started in 2000 and the first criticality was reached in July 2010. On December 15th, 2014, CEFR reached full power for the first time and was successfully operated for 72 hours.

During the physical start-up of CEFR, a series of experiments were carried out in four aspects, i.e., criticality experiments, control rod worth measurements, reactivity coefficient measurements, and foil activation measurements, as is shown in Table 1[1]. As a large amount of experiment data was obtained in the process, a CRP was proposed for a benchmark analysis of the whole experiments.

Table 1. Experiments conducted in CEFR Physical Start-Up

Experiment Category	Objectives of experiment
Criticality experiments	Fuel loading and first criticality
	Criticality at cold state in operation loading

	Criticality at hot state in operation loading
	Measurement of starting point of nuclear heating
Measurement of control rod worth	Coarse calibration during first criticality
	Calibration at cold state in operation loading
	Calibration at hot state in operation loading
Measurement of reactivity coefficients	Pressure coefficient
	Flow-rate coefficient
	Sodium void reactivity
	Rod swap reactivity
	Temperature coefficient
Foil activation measurements	Distribution of reaction rate
	Cross-section ratios
	Neutron spectrum
	Absolute nuclear power

2. A brief description of CEFR core

To give an overview of the CEFR core preliminarily, the radial structure of the fuel subassembly (abbr. SA) is shown in Fig 1, the axial structure in Fig 2, and the core configuration in Fig 3. The basic geometry parameters of the CEFR core are given in Table 2.

Generally, the physical start-up experiments were carried out in three different stages of the core, i.e., the fuel-only loading, the operating loading at cold state, and the operating loading at hot state. In the fuel-only loading, the core reached criticality with the minimum fuel SAs and all the control rods at the top position except for certain control rod to find the exact criticality. Fig 4 shows the three different stages of experiments. [2]

In the fuel-only criticality loading, there are 72 fuel SAs, 8 control rod SAs, and 1 neutron source SA, while in the operation loading 79 fuel SAs should be loaded, as is shown in Fig 3, to compensate for the negative temperature reactivity and the actual operating positions of control rods.

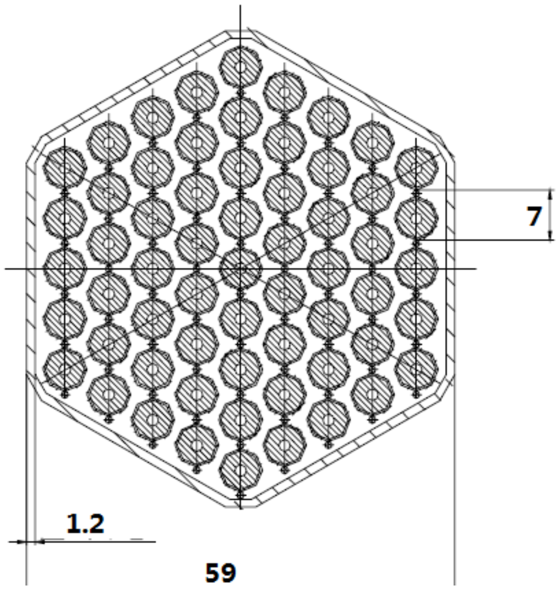

Fig 1. Cross sectional view of CEFR fuel SA

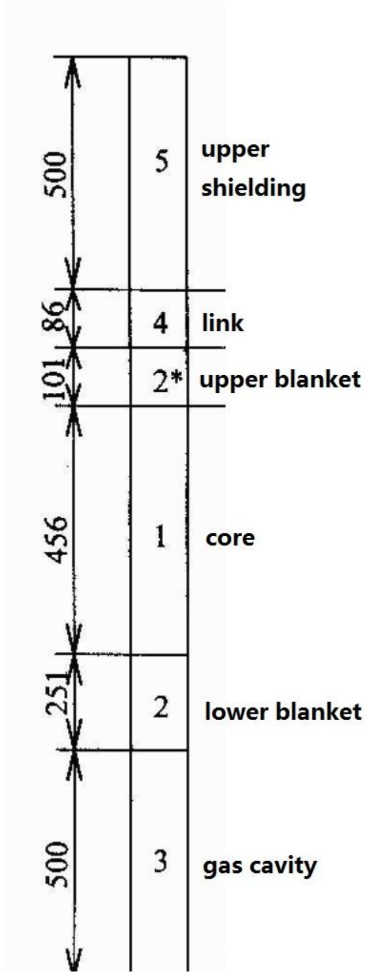

Fig 2. Axial structure of CEFR fuel SA

Table 2 Main geometrical features of CEFR core (cold state, T=250℃)

Parameter	Value
Pitch of fuel SA lattice/mm	61.25
Area of SA lattice/cm^2	32.49
Height of core/cm	45.1
Equivalent diameter of core/cm	60.2
Height of axial blankets/cm	
Lower blanket	25.1
Upper blanket	10.02

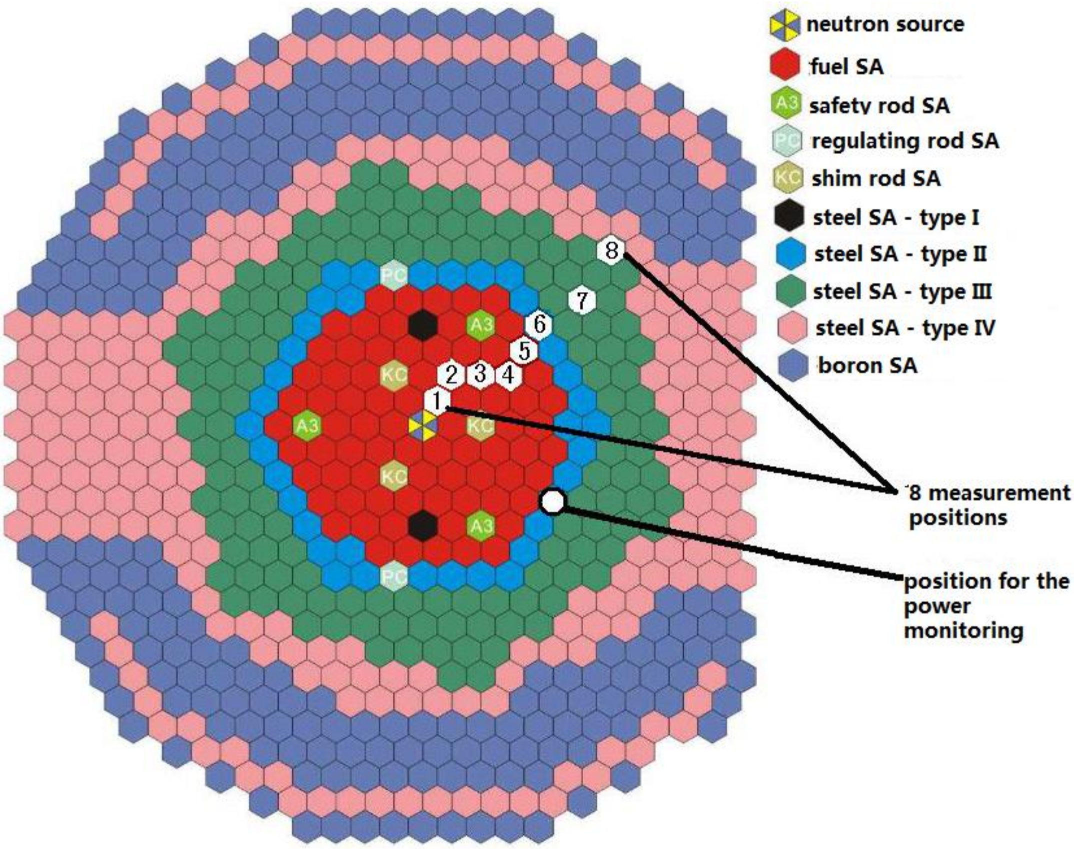

Fig 3. CEFR core for operating loading

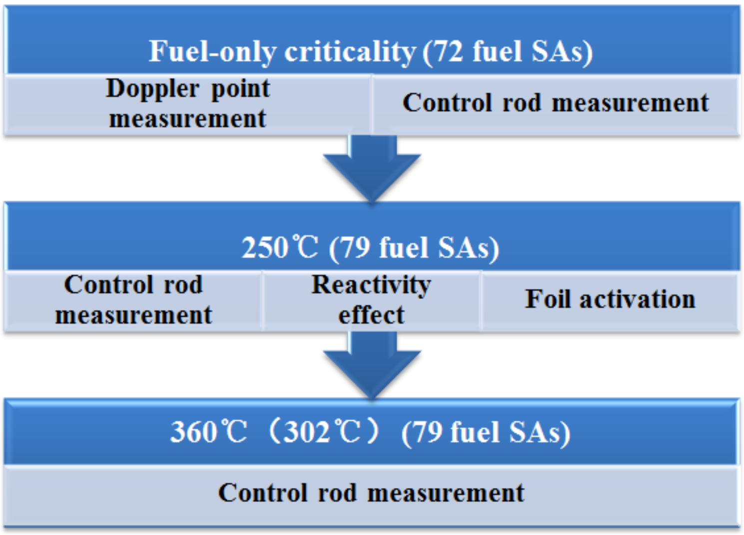

Fig 4. Three stages of CEFR physical start-up experiments

3. Example experiments

To have an overview of the CEFR physical start-up experiments, a brief description is given here for the example experiments. Only some key and representative results are shown in this paper.

3.1. Fuel loading and first criticality

The first criticality of CEFR was reached on July 21, 2010. The experiment was carried out at the sodium temperature of 250±5℃. The criticality was approached by replacing the mock-up SAs with the fuel SAs step by step. In each step, the critical mass was calculated by extrapolation of reciprocal of counting rate, as is shown in Fig 5. The core reached fuel-only criticality with 72 fuel SAs loaded. [1]

A specially designed detector located near the active core was used to get the counting rate for the criticality approaching process. Four neutronics codes were used to get the predicted critical number of SAs, i.e., NAS[3], ERANOS[4], MCNP[5], CITATION[6], and satisfactory agreement was reached between the calculation and experiment results.

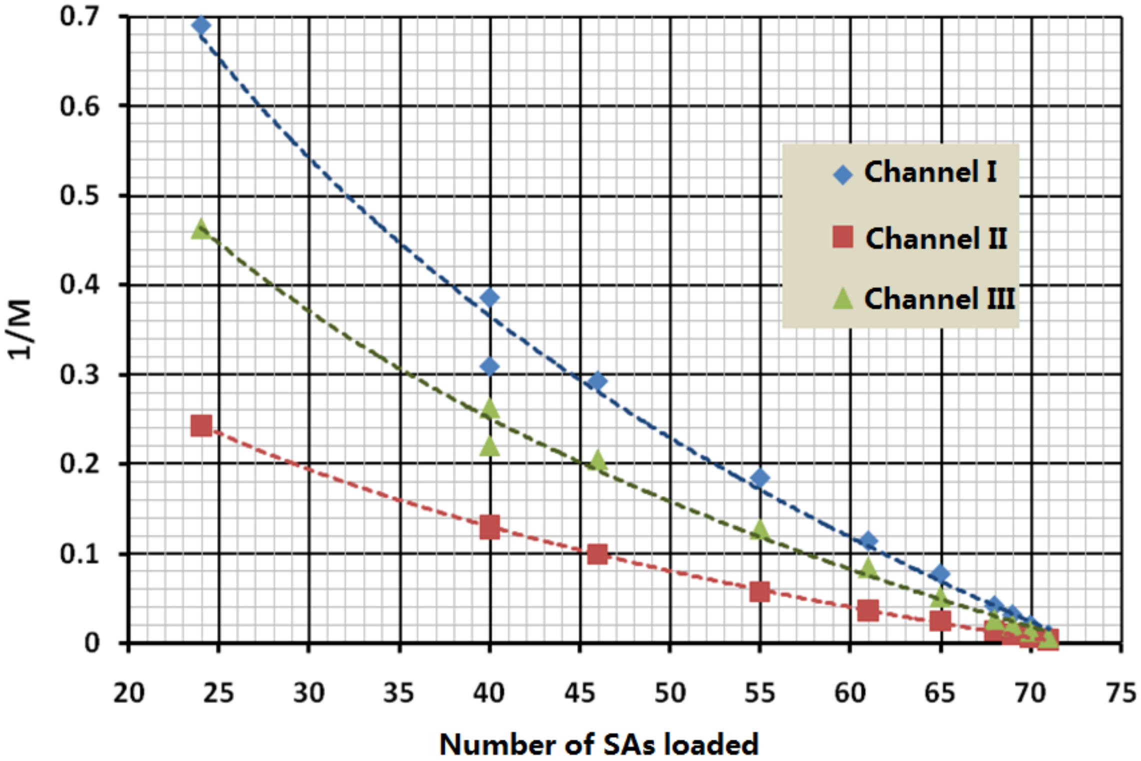

Fig 5. Extrapolation curves of reciprocal of counting rate shown by three detector channels

3.2. Control rod worth measurements

As is shown in Fig 3, the CEFR core has 8 control rods for reactivity control and emergency shut-down, which absorb neutrons by B10. The B10 enrichment of the 3 shim rods (SH) and 3 safety rods (SA) is 92%, while the 2 regulating rods (RE) contains B10 at its natural abundance of 19.8%.

The control rod worth measurements were carried out in all three stages, as is shown in Fig 4. For each stage the worths of each control rod and each rod group were measured mainly by the rod-drop method; the period method was also used for measurement of the worths of each control rod. The discrepancy between the rod-drop method and the period method is below 15%.

In the rod-drop method, the rod to be measured was drawn out to the top position and a +30pcm reactivity was maintained by other control rods; when the counting rate reached 30000cps, the rod-drop process was started. The inverse kinetics calculation was used to get the reactivity, with a dead-time correction and an outer-source correction.

The experimental results obtained by the rod-drop method were also compared with the MCNP calculation results, and the discrepancy is below 10%, as is shown in Table 3. [7]

Table 3. Control rod worths at fuel-only criticality

Rod type	Rod No.	Rod-drop method (E),	MCNP calculation (C), %Δk/k	(C-E)/E, %

		%Δk/k		
Safety rod	SA-1	1.047	1.027	-1.9
	SA-2	1.001	1.024	2.3
	SA-3	0.958	0.973	1.6
Shim rod	SH-1	1.997	1.965	-1.6
	SH-2	1.794	1.825	1.7
	SH-3	1.854	1.895	2.2
Regulating rod	RE-1	0.152	0.137	-9.9
	RE-2	0.149	0.143	-4.0
Shim rod group	All SHs	5.954	5.997	0.7
2nd shut-down system	All SAs	3.057	3.233	5.8
1st shut-down system	All SHs and REs	6.135	6.344	3.4

3.3. Reactivity coefficient measurements

For the measurement of the sodium void reactivity, a special experimental SA was designed, in which a vacuum of $3800cm^3$ was sealed to simulate the sodium void. 5 fuel SAs were replaced by the experimental SA respectively to simulate sodium void in different positions of the core, as is shown in Fig 6. The void reactivity was obtained from the change of the position of control rod, which kept the core at a critical state in the replacement of SAs. [8]

The reactivities were corrected in consideration of the change of coolant temperature during the experiment, the impact from the dead-time and neutron source, and the difference of the contents of fissile nuclides between the fuel SA and the experimental SA.

The CITATION code was used to calculate the sodium reactivity at each position, and the results were compared with the experiment value, as is shown in Table 4.

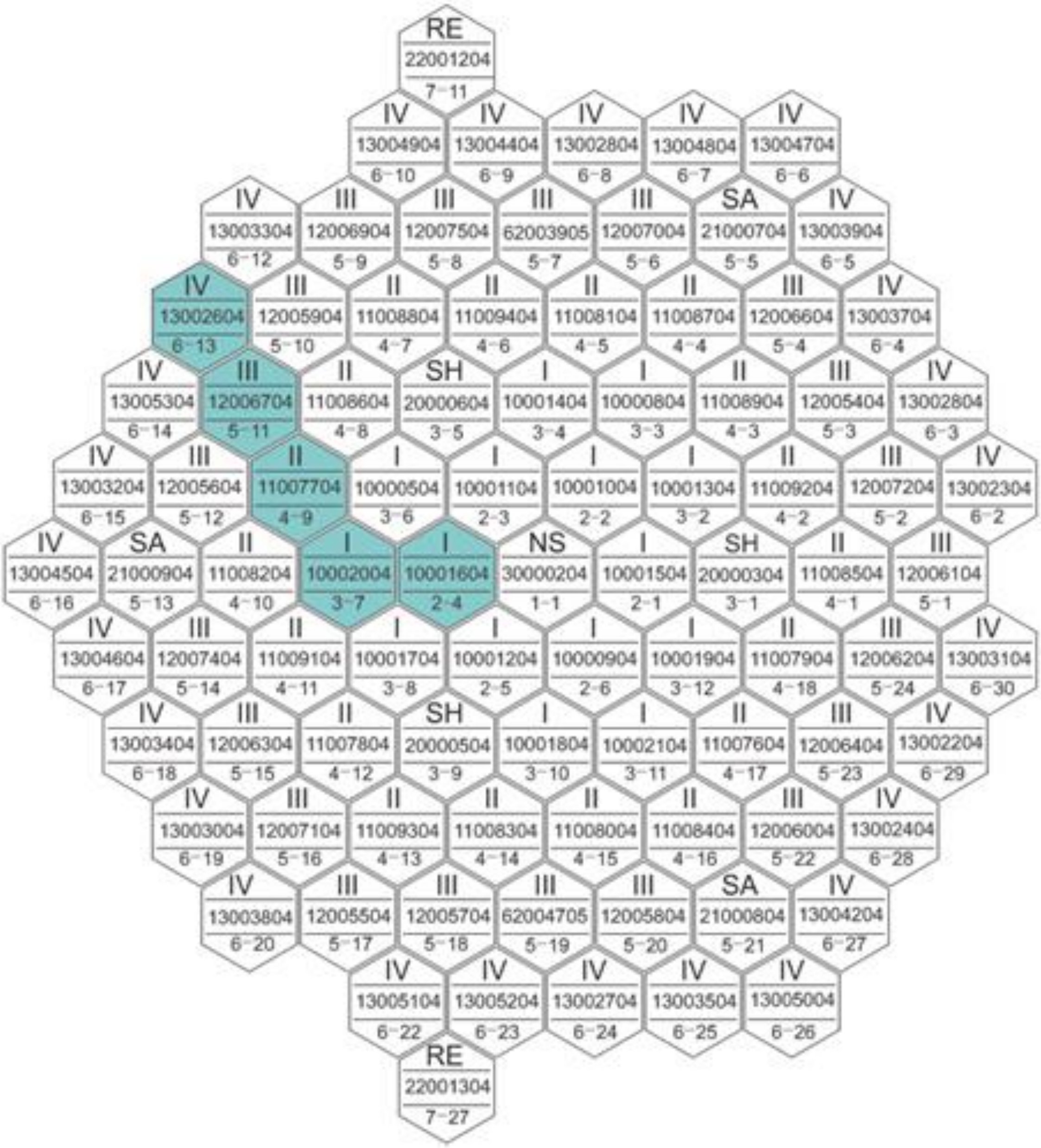

Fig 6. Positions to load the sodium void experimental SA (shown in blue color)

Table 4. Sodium void reactivity of CEFR core

SA Position	**Sodium void reactivity**		**(C-E)/E, %**
	Experiment/pcm	**Calculation/pcm**	
2-4	-38.7	-43.1	11.4
3-7	-39.4	-43.3	9.9
4-9	-39.9	-36.4	-8.8
5-11	-38.2	-40.0	4.7
6-13	-44.5	-36.8	-17.3

3.4. Reaction rate distribution measurement

A specially designed SA was used for the measurement of reaction rate distribution.

Detecting foils containing certain nuclides were loaded in specific positions both radially and axially. The induced radioactivity of the foils was measured and accordingly the relative reaction rate was obtained. 235U(n,f), 238U(n,f), 237Np(n,f) were used for the measurement of radial and axial fission reaction rate, and 238U(n, γ), 197Au(n, γ), 237Np(n, γ) for the capture reaction rate, and the 58Ni(n,p), 27Al(n, α) for corresponding reaction rate. [9]

For the radial reaction rate measurement, 8 SA positions were selected with 5 in the fuel region and 3 in the reflector region, shown in Fig 3. Position 1 is also used for the measurement of axial reaction rate.

As there's only one experimental SA, the SA positions were measured one by one. In such case, the consistency of power between all measurements should be retained with the correction provided by the power monitoring foil located in a reserved position shown in Fig 3.

By a detailed processing of the experimental data, the radial and axial relative reaction rate distributions were obtained, as is shown in Fig 7 and Fig 8.

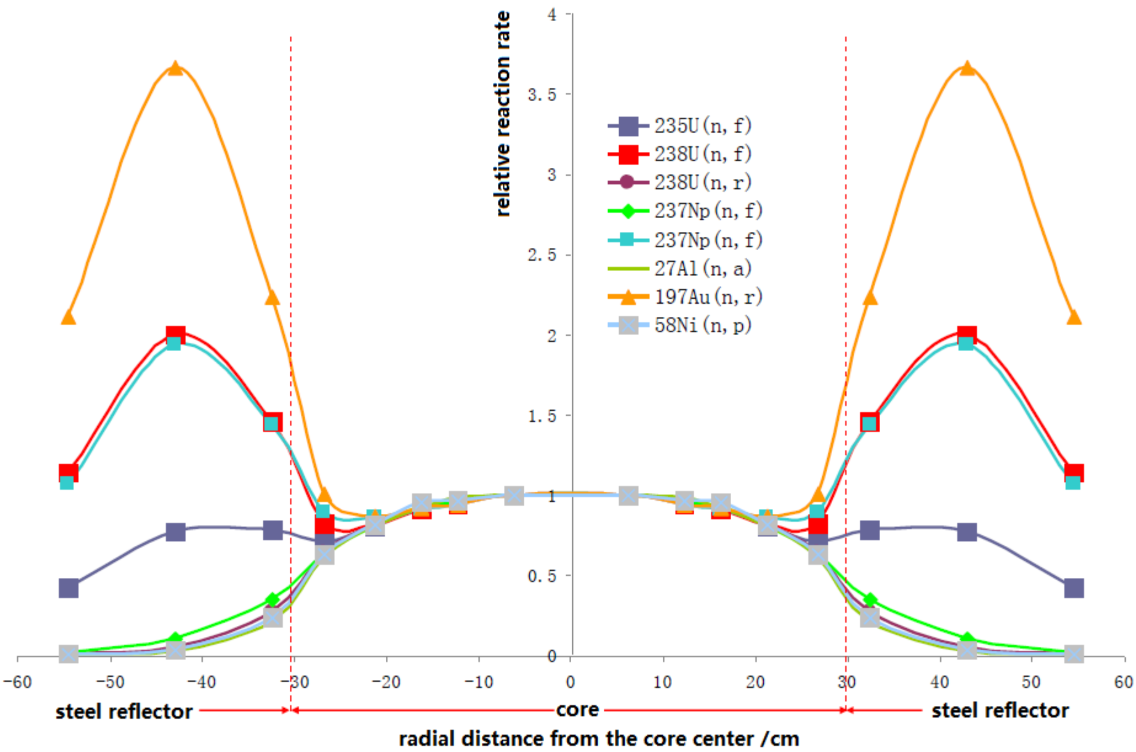

Fig 7. Radial distribution of relative reaction rate

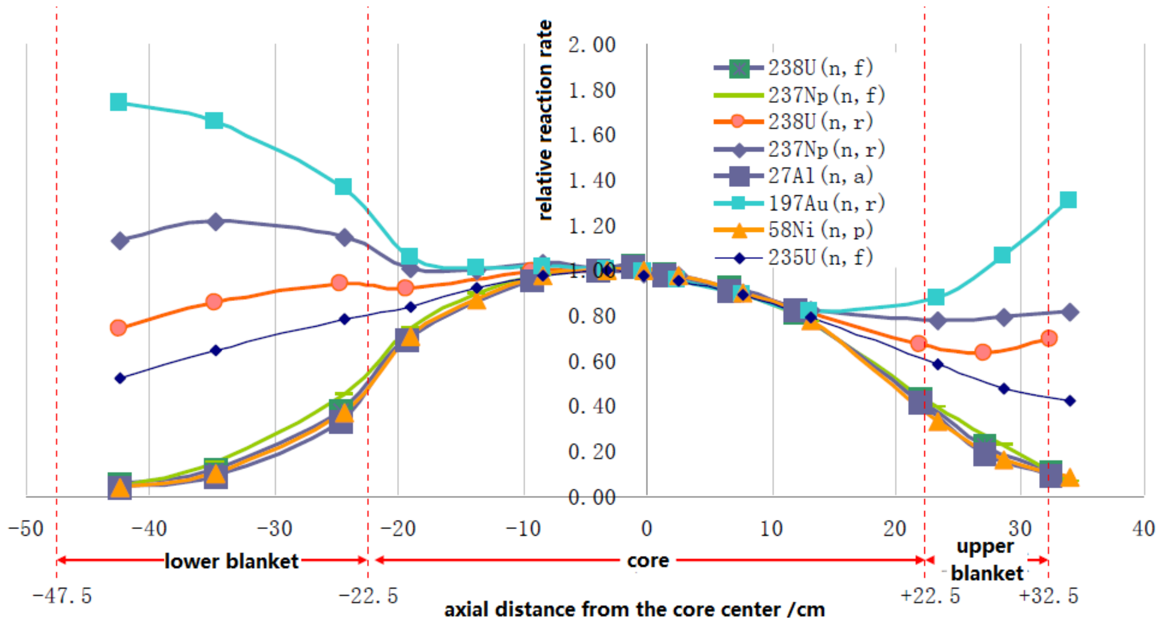

Fig 8. Axial distribution of relative reaction rate

4. Conclusion

The CEFR physical start-up experiments were carried out in 2010 with a lot of valuable data accumulated, which would be beneficial to the nuclear society in code and nuclear data validation. CIAE has done a lot of analysis work ever since, while a joint benchmark analysis participated by fellow organizations would promote the work to a higher level.

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