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Neutronic Design of Experimental Zero-power ADS Facility

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1. Introduction

Accelerator Driven subcritical System (ADS) is one of the most promising systems to transmute high level nuclear wastes utilizing high energy neutron. The system consists of three main parts, namely proton linear accelerator, high power spallation neutron target and subcritical reactor core. [1]The difference between ADS system and the traditional reactor is that it contains an external neutron source. In order to adjust the calculation results, experimental ADS zero-power facility should be established. [2] Two different types of zero-power facilities has been planned to be built in China in nowadays since Chinese national government has been decided to build the first ADS prototype ADS facility on the year of 2020s from China ADS roadmap.[3] One is water-coolant zero-power facility, and the other is lead. The water cooled facility has been used as the neutronics measurement benchmark facility since much more experience of experimental zero-power facility have been acquired in China. In this paper, the neutronics and safety characteristics have been studied for the water-cooled ADS zero-power facility.

2. Reactor Core Arrangement

The central region of the Zero-power ADS facility is for the spallation target zone which is shown as shadow area in Fig.1. The reactor core adopts light water as the moderator. 300mm thickness light water is arranged as reflective layer both in the bottom of the support plate and outward the fuel rods. Part of the space upper the fuel rods is used for conducting control and experiments. The thickness of the light water is reduced to 150mm at the top of fuel rods. In order to reduce the leakage of neutrons from the top of the core, the reflective layer is added for fuel rod. Detail parameters of the core arrangement are shown in Table I.

Two sets of safety and adjust rods mechanisms are arranged inside the core, choosing cadmium as absorbing material. The safety rods are designed as multi-rod plate-like structure arranging in rectangles in left and right sides in Figure 2. The adjust rods is rod-like structure arranging in upper and lower circle in Figure 2.

Only one kind of fuel rods is assembled in the water cooled reactor. The fuel rods are surrounded by target in the concentric cycles. Total number of fuel rod rings is 14 with full loading .The distance from the first ring to the center axis of the core is 101mm. Pitch between each ring is 14mm.The fuel rods pitch in the same ring is about 14.5mm, which is the best arrangement according to H/U ratio. The rod is composed of 20% enriched uranium oxide powder with zirconium clad. Each rod is loaded with 22.5 ± 0.1g U_3O_8 powder. The length of fission material is 400mm. In order to reduce the neutron leakage from the top of fuel rods, polyethylene is added as the reflective layer .The encapsulated fuel rod cross-section is shown in Figure 3.

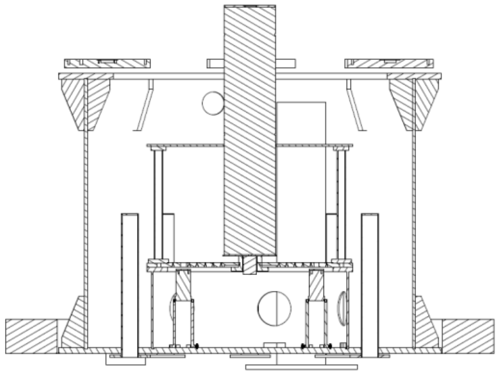

Fig.1. Cross-section of the core

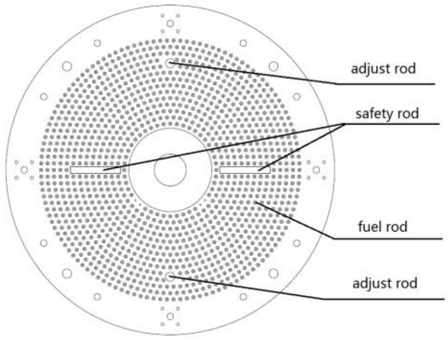

Fig.2. Grid plate front view

Table I. Main Parameters of the Core

Name	Unit	Value
Maximum power	W	10
Maximum power density	W/L	0.2
Highest neutron flux density	$n/cm^2 \cdot s$	1×10^8
Pitch	mm	14.0~14.6
Active core height	mm	400.0
Target inner diameter	mm	170.0
Core diameter	mm	566.0

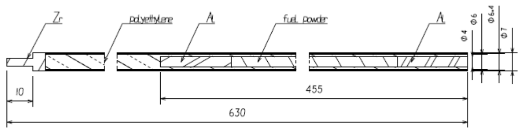

Fig.3. Cross-section of fuel rod

3. Calculation Method

The whole calculation is done by Monte-Carlo code MCNPX based on the nuclear data library ENDF-7 which is modified with six different temperatures (300, 600, 900, 1200, 1500 and 1800K). [4]Since the maximum power of the facility is only 10 W, it is assumed that the temperature of fuel rods, the moderator, the reflective layer, the shield and structural materials is 300K.

4. Neutronics Design and discussion

In order to acquire precise neutronics measurement characteristics, this zero-power facility has been set to be critical in the first step in our experimental process. Secondly, the subcritical experiment will be studied since the critical experimental measurement database can be used as measurement benchmark. According to reactor physics theory, the critical point is a turning point representing the chain fission reaction in reactor core. [5] Zero-power ADS core will reach to the critical by increasing the number of fuel rods in the last rings.

Table II. Different K_{eff} with Multiple Loading

Number of fuel rods	k-effective
1016	0.99085
1020	0.99267
1024	0.99296
1028	0.99373
1032	0.99381
1036	0.9958
1040	0.99579
1044	0.99663
1048	0.99735
1052	0.99911
1056	0.99921
1060	0.99974
1064	1.00035
1068	1.0016
1072	1.00214
1076	1.00349

With the zero loading the k-effective will be 0.9946±0.0001. With the full loading the k-effective will be 1.0185±0.0001. In order to evenly change fuel loading in the fourteenth ring, k-effective calculation is done by changing every four fuel rods each step. The result is shown in Table III. Worth of one fuel rod is 80PCM. The critical loading number is 1040.

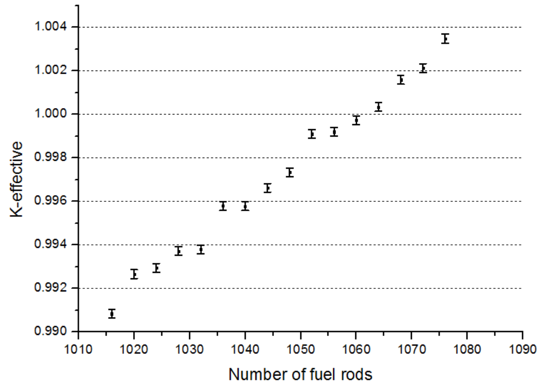

Fig.5. Loading Curve of k-effective

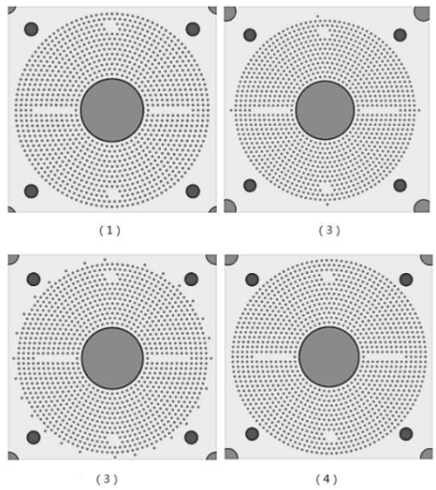

Fig.6. Cross-section of core with multiple loading

According to nuclear critical theory in uniform bare reactor, the value of neutron flux reaches the maximum in the central region. According to reactor physics theory, the critical point is a turning point representing the chain fission reaction in reactor core.

In ADS case, the central target region would be a significant neutron leakage area. The more neutrons leak from the target region, harder the reactor tends to critical. The cylinder has smaller area than polyhedral with the same height, when they both have same volume. Concentric pattern arranging fuel rods leads to less leakage than hexagonal assembly. Since water is an excellent moderator and reflector, the core relies solely on almost 1000 fuel rods to be critical. Although the facility power is quite small, the safety rules are still needed to be satisfied.

Temperature coefficient is -4.30PCM/K. The core gets the negative temperature feedback. When the temperature rises, reactivity decreases due to negative temperature coefficient of moderator and Doppler effect. The delayed neutron fraction is 670pcm, only a bit smaller than 731pcm in China Experimental Fast Reactor. It is reasonable to believe it meets the reactor safety control requirements. [6] The radial neutron flux distribution is shown in Fig.4. Radial power peak factor is 1.833. The average flux is 2.5×10^4 n/cm^2·s based on design power. The neutron flux reaches high level from second to ninth ring.

Table III. Temperature Effects and Reactivity Control

Name	Unit	Value
delayed neutron fraction	pcm	670
control rod worth	pcm	2.4×10^3
highest neutron flux	n/cm^2·s	1×10^8
built-in reactivity	pcm	1.85×10^3
reactor shutdown margin	pcm	-2.4×10^3
temperature coefficient	pcm/K	-4.30

Arranging multi-rod like plate-structure safety rods from the second to the ninth ring, safety rod worth achieves at 2400 PCM. The adjust rod worth is more than 200 PCM. The adjust rod bundle is consists of four cadmium rods with stainless steel clad arranging in tenth and eleventh rings.

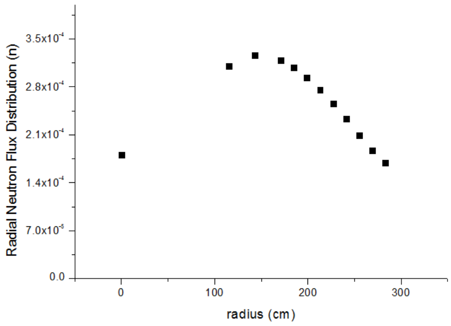

Fig.5. Relative value of radial neutron flux distribution

5. Conclusions

The experimental Zero-power ADS facility gets negative feedback when the temperature rises. The delayed neutron fraction would be enough to make the reactor core controllable. In ADS system, the reactor core needs external neutron source to be sustainable. In DF-1 zero-power facility, the way from subcritical to critical is installed the fuel rods at first, then increase the water height level to reach critical. In DF-2 zero-power facility, the way to be critical is the water height is 15cm higher than the top of fuel rod, then increase fuel rod symmetrically to reach critical. [7] Critical extrapolation experiment will be a research method. In the next step, the sustainable scheme of the subcritical core will be studied.

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