PreliminaryDesign of Zero Power Reactor Core for CEFR MOX core

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Abstract. Research on MOX fuel has lasted for a long period in China Institute of Atomic Energy(CIAE). Right now, the focused topics are the manufacture and irradiation of test China Experimental Fast Reactor(CEFR) MOX assembly, large batch production for CEFR MOX fuel assembly and the CEFR core transition from UO_2 fuel to MOX fuel. To determine the uncertainty of the CEFR MOX core design and improve the design codes and nuclear data, a zero-power reactor(ZPR) using MOX fuel will be built based on an existed fast zero power reactor, DF-VI in CIAE. The preliminary design is carried out UK Monte Carlo code MONK, using MOX fuel rods replacing part of its 90% uranium fuel rods. New DF-VI will be the first MOX fuel ZPR and experimental research platform in China used to study the measurement technology, obtain important neutronic parameters and validate the design methods for the CEFR MOX core.

Key Words: ZPR, CEFR MOX, DF-VI

1. Introduction

Nuclear power is playing animportant role in China as irreplaceable energy supply for fast growing economic and essential reduction of greenhouse gas emission. The government choseclosed nuclear fuel cycle as national strategy to secure the long-term supply of nuclear fuel. Fast breeder reactors with MOX fuel are the best choice for the effective uranium resource utilization. The research on MOX fuel and fast reactor have lasted for a long time in CIAE supported by the government. The China Experimental Fast Reactor with 25MWe reached critical in 2010 and the experimental MOXfabrication line with 0.5t/a capacitywas built in 2008.The commercial demonstration reactor CFR-600 and the MOX fabrication plant with 40t/a capacity will be the target in the next stage.

Right now, CEFR is still using high enrichment UO_2 fuel. The urgent work is the transition from UO_2 to MOX fuel. Soon, the irradiation test of CEFR MOX fuel will be carried out and the design for CEFR MOX core will be done. But there is no ZPR with MOX loading in China, design method, codes and data libraries for the CEFR MOX core couldn’t be validated fully, the bias and uncertainties couldn’t be determined without experimental results.

To solve this problem, building a ZPR using MOX fuel based on an existed fast zero power reactor DF-VI is planned in CIAE.The preliminary design is carried out by UK Monte Carlo code MONK, using MOX fuel rods replacing part of its uranium fuel rods. The design and experiments performed at the BFS facilities are fully considered for reference [1]. New DF-VI will be the first MOX fuel ZPR and experimental research platform in China to study the measurement technology, obtain important neutronic parameters and validation the design methods for CEFR MOX core.

2. DF-VI configuration

DF-VI (see Fig.1.) is the first zero power fast reactor in China.It is in the IAEA research reactor database registered as ZPR FAST with IAEA code CN0003. It is designed and constructed by reactor physics laboratory from 1967 and reached first critical in June 29th 1970. As the cradle of fast reactor in China, DF-VI provides plenty of experiments for code validations, experimental technology developments and personnel trainings, gradually stopped its activities since the last critical experiment in 2007.

FIG. 1. DF-VI zero power fast reactor

DF-VI uses 90% enrichment metal uranium as nuclear fuel. The fuel rod has stainless steel clad tube and 16 pellets（9mm diameter, 10mm height) with nickel coat. The core has regular triangle arrangement with maximum loading of 313rods, the pitch is 10.5mm see Fig.2.

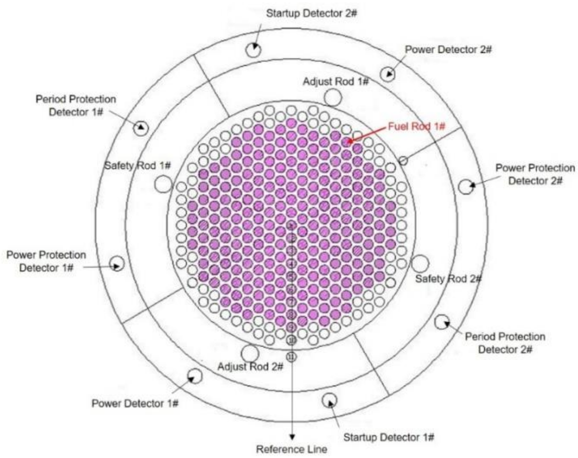

FIG. 2. DF-VI core

DF-VI has 400mm height stainless steel top reflector and 300mm height stainless steel bottom reflector with one moveable part as shutdown safety block. DF-VI has two safety rods and two adjust rods in the 300mm thickness cast iron side reflector, controlling the reactivity by neutron leakage. In the first critical, the core has a 38 seconds’ double period with 237 rods loading.

3. Design of New DF-VI

As mentioned before, DF-VI couldn't satisfy the raising demand in fast reactor experimental research. New fuel and new core arrangement must be considered for CEFR MOX core. The uranium fuels, startup neutron source and the control-instrument system may stay, but other parts of the old DF-VI will be replaced.

3.1.Design requirements

New DF-VI core is designed by UK code MONK10a with ENDF/B-VII.0 data library. The main design requirements are listed below.

- Similar neutroniccharacteristics with CEFR MOX core
- Enough nuclear material for critical loading
- Effective control of reactivity
- Radiation safety
- Economics

Following these requirements, the new DF-VI is designed as a fast reactor consist of uranium and MOX fuel in hexagonal arrangement with stainless steel reflectors.

3.2.Fuel Rod and Assembly

New DF-VI will have two kinds of fuel rods and assemblies. Onetypeof fuel rod is uranium fuel rod with the original fuel pellets（9mm diameter and10mm height with nickel coat). Each uranium fuel rod has 19 pellets (190mm) and 310mm length stainless steel 316L as top reflector inside the rod.Outside pellets are 0.1mmthickness gap and 0.4mm thickness 316L clad, thus the fuel rod has 10mm out diameter and 500mm length.

Seven uranium fuel rods constitute oneuranium fuel assembly(UFA) in hexagonal arrangement with the pitch 10.5mm. UFAhexagonal prismhas 17.5mm side and 520mm length, and seven holes inside with 10.2mm diameter and 515mm length for loading fuel rod. The top of UFA will be welded to avoid water or steam penetration. See Fig.3 below.

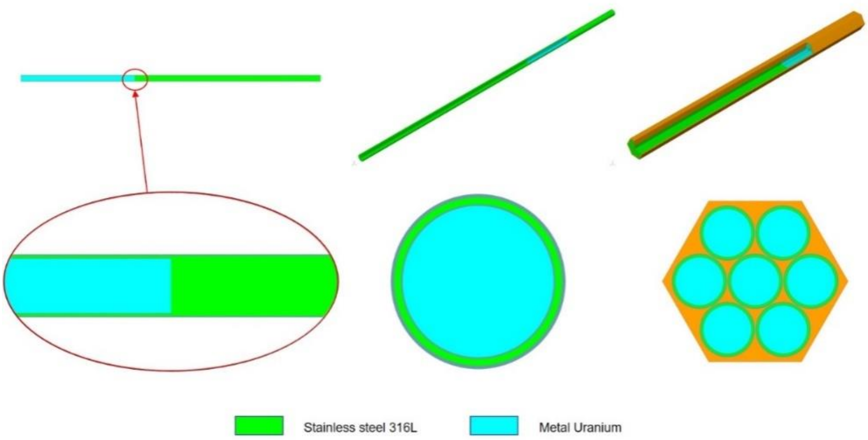

FIG. 3. Uranium fuel rod and UFA structure

The other type of fuel rod is MOX fuel rod, which has the same 190mm length of MOX pellets and 310mm length stainless steel 316L as top reflector inside the rod, is very similar with unranium fuel rod.MOX fuel pellet has 5.1mm out diameter and 1.6mm inner diameter with the actual density 10.4g/cm^3. These parameters are designed according to the development progress of the CEFR-MOX fuel [2]. MOX pellet has 29.4wt% industrial PuO_2 and70.4wt% UO_2. The ^{235}U enrichment of UO_2 is 36wt% and the plutonium isotope compositions are listed in Table I below. Each pellet has 0.1mm thickness gap and 0.4mm thickness 316L clad [3], thus the fuel rod has 6.1mm out diameter and 500mm length. There are no wrapping wire and duct materials outside the rod.

TABLE I: Plutonium isotope compositions

	Pu-238	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
Weight percentage, %	3.84	52.74	24.38	11.11	7.93

Seven MOX fuel rods constitute oneMOX fuel assembly (MFA) in hexagonal arrangement with the same pitch of rods and same size of hexagonal prism as UFA. MFA also has 17.5mm side and 500mm length, and seven holes inside with 6.9mm diameter and 515mm length for loading fuel rod. The top of MFA will be welded to avoid Pu leakage and water or steam penetration. Stainless steel around and above the MOX fuel rods will act asno only the reflector but also shielding of spontaneous fission neutrons and gamma ray from plutonia. See Fig.4 below.

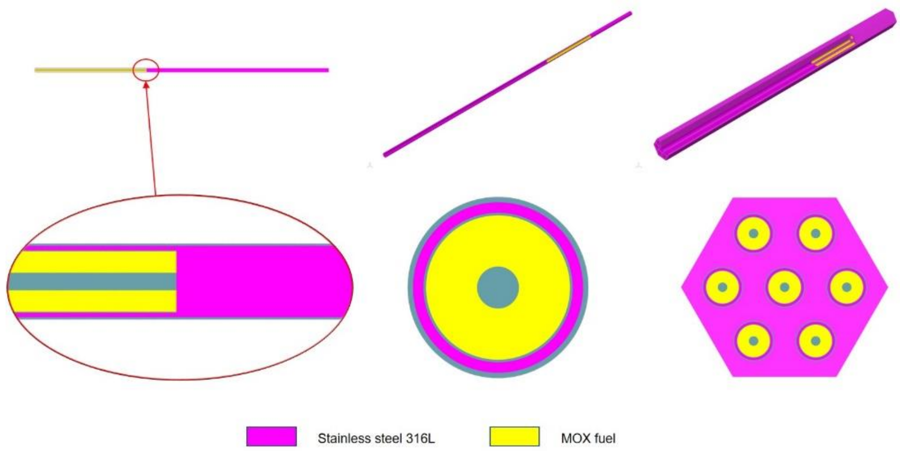

FIG. 4. MOX fuel rod and MFA structure

3.3.Core Arrangement

New DF-VI has similar core arrangement as CEFR, there are three types of assemblies, uranium fuel assembly(UFA), MOX fuel assembly(MFA) and stainless steel assembly(SSA). They have the same out shape and size, 17.5mm side length and 520mm height hexagonal prism. The pitch of assemblies in the core is 30.7mm, the air gap thickness between assemblies is 0.4mm. The weightof fissile material and structure material of three assemblies are listed in Table II below.

TABLE II: Contents of each assembly

	UFA-Metal U	MFA-MOX	SSA
U weight, g	1586.81	186.12	0
UO_2 weight, g	0	211.47	0
Pu weight, g	0	78.00	0
PuO_2weight, g	0	88.44	0
Stainless steel weight, g	1550.83	2425.31	3182.64
Total weight, g	3137.64	2725.22	3182.64

Obviously, UFA has the largestmassof fissile materials. It's best to place UFA in the middle of the core because it has the largest contribution for reactivity. MFA and SSA could be placed around the UFA. Because of 310mm stainless steel inside UFA and MFA, the radioactivity of MFA will be shielded as much as possible. The core has five rings of hexagonal prisms with total assembly number 61, see Fig.5 below.

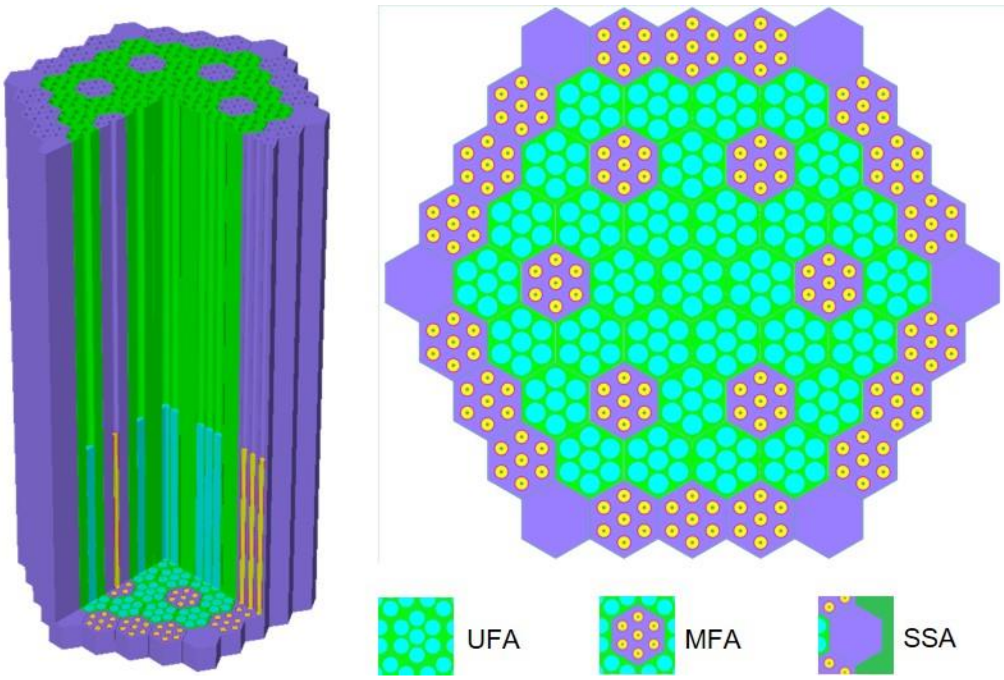

FIG. 5. MOX rod and assembly structure

Consider the limited number of UFA and the participation of MFA in the core, different loading pattern will have different k-eff. Several cases by loading different numbers of MFA in the fifth ring of the core are calculated with 350mm thickness side stainless steel reflector, see Fig.6. below.

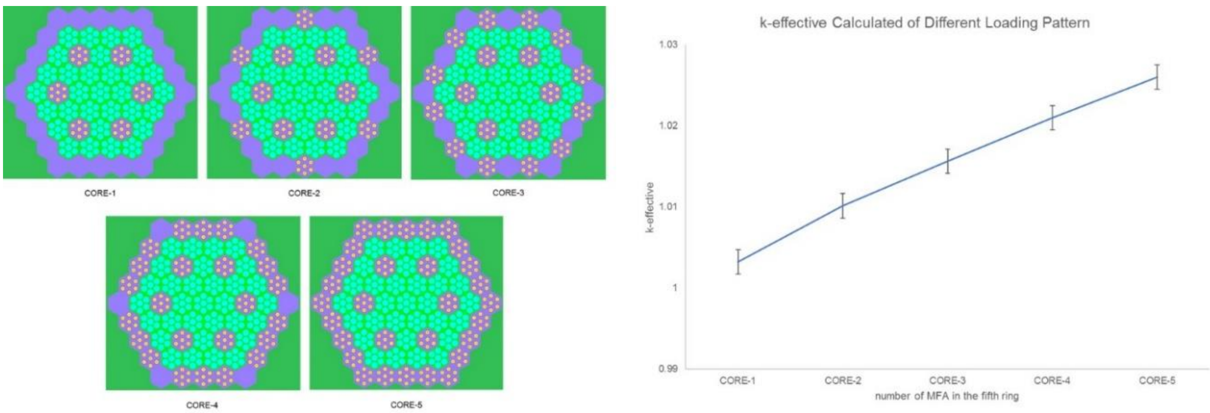

FIG. 6.k-eff calculated for different loading patterns

The fifth ring of the core bring total 2.23%Δk/k reactivity adjustment in this loading pattern series, that may cover the bias of design code and data library, uncertainties of composition and dimensional tolerance. The flexible arrangement of MFA and UFA in the core will bring more positive or negativevaluesfor reactivity adjustment.

3.4.Reflector and Control Rods

The reflector is very important for fast reactor because of large leakage of fast neutrons. Stainless steel 316L will be the reflector for new DF-VI. The whole reflector is a cylinder with 1000mm out diameter and 950mm height. The thickness of side reflector is over 350mm. The top reflector consists of reflector inside the fuel rods and around the core with 310mm thickness, and the bottom reflector is 450mm thickness.

Using neutron absorber as reactivity control inside the core isnot a best choice for small fast reactor. The guide tubes will be big gaps for neutron leakage when control rods are out of core. Holding the fuel assembly position while helping the leakage neutron will seriously increase the critical mass of the core and the fuel cost.

The reactivity control for fast reactor can rely on neutron leakage by creating cavity[4] in the reflector. It's also a most economical way without introducing additional structures and materials, just use parts of side reflectors to play the control role. The reactivity control system consists of three parts, two (for redundancy) safety rods, two adjust rods and safety block. Safety rods and one safety block are the shutdown means with reactivity worth should be more than 1%Δk/k/each one. Adjust rod worth should be 0.2%Δk/k/each one to have fine control of power and reactivity. In the loading pattern calculated in section 3.3 above, many cases for different sizes and positions of stainless steel cylinders near the core were calculated. The safety rod is a cylinder with 127mm diameter and 590mm height, 2.0mm away from the edge of fifth ring assembly. The adjust rod is a cylinder with 59mm diameter and 590mm height, 7.5mm away from the edge of fifth ring assembly. Safety rods and adjust rods are placed in each direction with 90º degree angle. The safety block is a cylinder underneath the core with 222mm diameter and 175mm height, 50mm away from the bottom of core. See Fig.7. below.

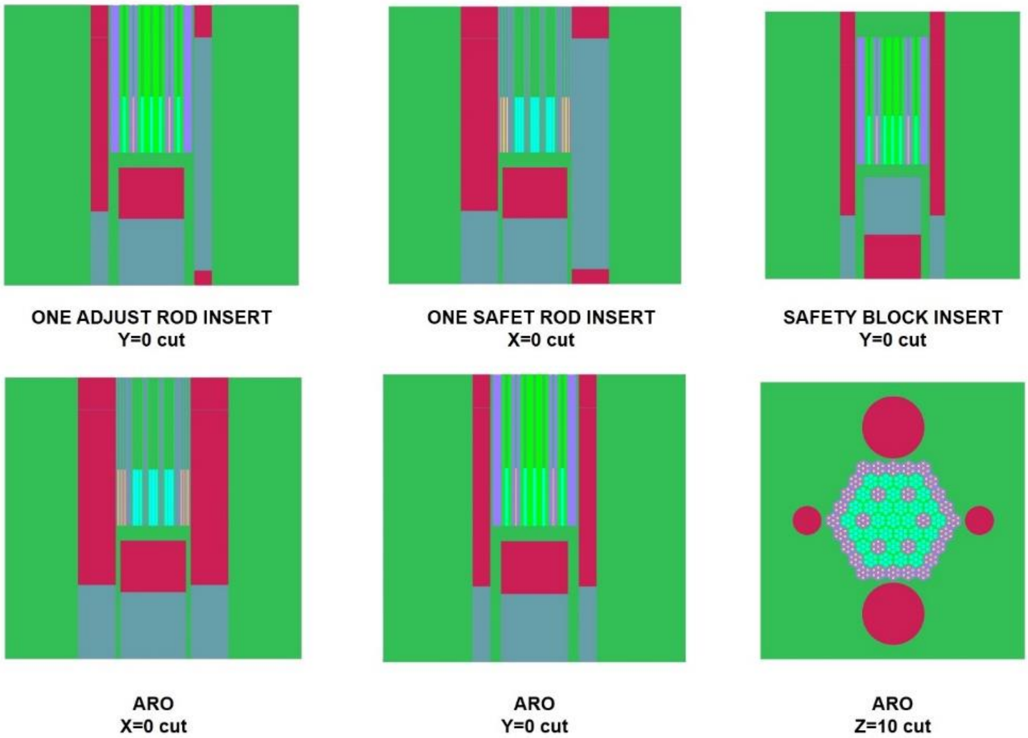

FIG. 7. Control rods layout of new DF-VI

The reactivity worth of control rods is calculated in all five loading patterns with less than 0.00015 k-effective standard deviation.The calculation results of reactivity worth meet the design requirement according to the Table III below.

TABLE III: Reactivity worth of control rods

	Average reactivity worth
One safety rod	1.315%Δk/k
Two safety rods(insert together)	2.748%Δk/k
One adjust rod	0.311%Δk/k
Two adjust rods(insert together)	0.565%Δk/k
Safety block	1.305%Δk/k
Total (all rods and block insert together)	4.635%Δk/k

When the fifth ring of the core is filled with MFA, the maximumexcess reactivity is 2.23%Δk/k. The total worth of control rods is 4.635%Δk/k. The minimum shutdown margin is -2.405%Δk/k, which is enough for criticality safety.

3.5.Uncertainty and Sensitivity Analysis

The first order sensitivities of the k-estimators to several nuclides including U-235, U-238, Pu-239 and Pu-241 cross-section (the ENDF/B-VII BINGO dataset) have been calculated by MONK code in uncertainty and sensitivity analysis. Sensitivity results of capture, elastic scatter, inelastic scatter, fission and total reactions are considered in MONK's standard 33 energy group scheme. The nuclear data k-effective sensitivity calculation results in all energies are listed in Table IV. The results in each energy bin can be found in Fig. 8.

TABLE IV: Nuclear data k-effective sensitivity

	U-235	**U-238**	**Pu-239**	**Pu-240**	**Pu-241**	**Fe-56**
Total	5.80E-01	1.09E-02	2.31E-03	4.24E-04	4.73E-04	1.56E-01
Capture	-6.36E-02	-4.39E-03	-1.15E-04	-5.46E-05	-2.45E-05	-1.07E-02
Elastic	2.39E-02	3.22E-03	1.41E-04	5.86E-05	7.08E-05	1.40E-01
Inelastic	3.11E-02	3.22E-03	-7.78E-06	-3.21E-05	-4.58E-05	2.67E-02
Fission	5.88E-01	8.70E-03	2.29E-03	4.52E-04	4.62E-04	0.00E+00

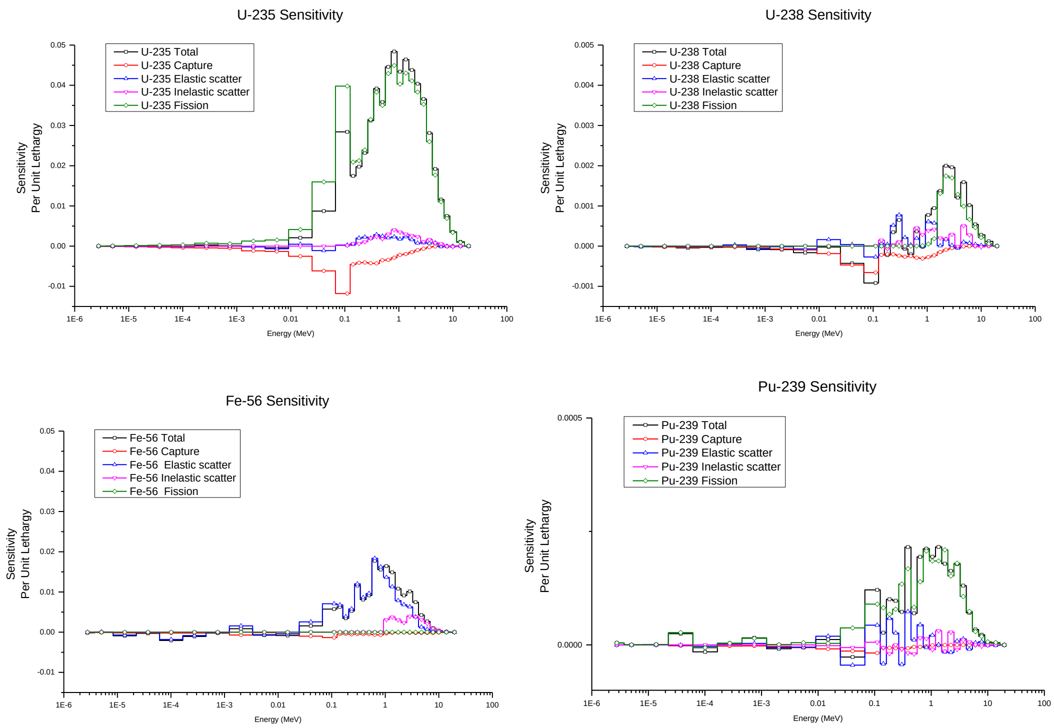

FIG. 8.Nuclear data k-effective sensitivity

There are many other uncertainty and sensitivity analysisfor new DF-VI, such as MOX fuel compositions, size of pellets and amounts will be determined in later work.Sensitivity analysis of CEFR MOX core will also be performed. The research on similarities of two nuclear systems will be very important to improve the design of new DF-VI to achieve the best effect of code validation, uncertainties determination and other purposes.

The full view of new DF-VI can be find in Fig. 9 below.

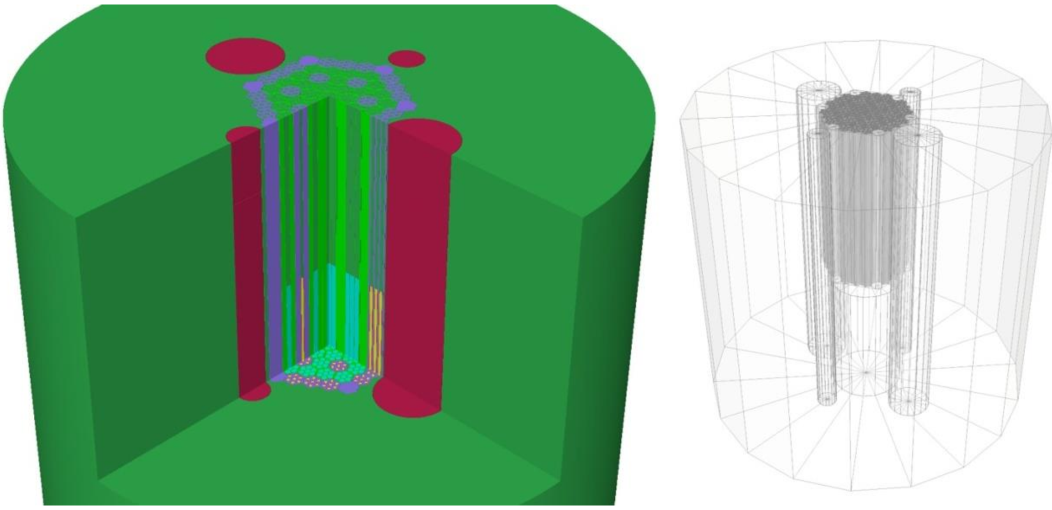

FIG. 9. Full view of new DF-VI

4. Conclusion

The preliminary design of new DF-VI was carried out by MONK10A code in CIAE for the transition of CEFR MOX core. The new DF-VI will utilize MOX and uranium fuel assemblies in hexagonal arrangement with stainless steel as reflector. The reactivity of DF-VI is controlled by neutron leakage in the reflectors. New DF-VI will be the first fast neutron ZPR loading MOX fuel assembly and experimental research platform in China to study the measurement technology, obtain important neutronic parameters and validate the design methods for CEFR MOX core.In the next stage, uncertainty and sensitivity analysis will help to improve the physics design, along with structural and mechanical design.

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