THE FEATURE OF HIGH FLUX ENGINEERING TEST REACTOR AND ITS ROLE IN NUCLEAR POWER DEVELOPMENT

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ABSTRACT

The High Flux Engineering Test Reactor (HFETR) designed and built by China own efforts reached to its initial criticality on Dec. 27, 1979,and then achieved high power operation on Dec. 16 , 1980. Until Nov. 11, 1986, the reactor had been operated for thirteen cycles.

The paper presents briefly main feature of HFETR and its utilization during past years. The paper also deals with its role in nuclear power development. Finally, author gives his opinion on comprehensive utilization of HFETR.

I. THE FEATURE OF HFETR

The High Flux Engineering Test Reactor is a pressure vessel type reactor, using multi-tubular fuel element of highly enriched uranium, water as moderator and coolant and beryllium as reflector. The principal parameters of the reactor are listed in Table 1.

Table 1.
The Principal Parameters of the Reactor

Thermal power	125 MW
Core loading at the rated power	13 kg ^{235}U
Maximum thermal neutron flux in the fuel	6.2×10^{14} n/(cm²·s)
Maximum fast neutron flux in the fuel (E>0.625 eV)	1.7×10^{15} n/(cm²·s)
Mean specific power of the fuel(^{235}U)	9.6 MW/kg
Mean power density of the core	610 kW/L
Indefinite multiplication factor k_∞	1.78
Effective multiplication factor k_{eff}	1.226
Operation cycle	30 d
Average burnup of ^{235}U	34 %
Maximum surface heat flux	3.56×10^{6} W/m²
Maximum surface temperature of fuel cladding	195 °C
Internal coolant flow velocity of fuel assembly	10 m/s
Reactor inlet pressure	1.6 MPa

The reactor structure is shown in Fig. 1. The height of the pressure vessel is 11.83m. The upper inside diameter of the vessel is 3.2m and lower inside diameter is 2.15 m. There are four elliptic operating openings of 450x600 mm on the closure head of the vessel. There is an oblique discharge canal of 350 mm in diameter, connecting a storage pool, on the middle side wall of the vessel. The core components are surrounded by a 1.4 m flow baffle in diameter. They are placed at the bottom plate of the reactor vessel through the grid plate and supporters. A distributing water tank is installed at the inlet of primary water to prevent water flow from directly impacting the irradiation tubes. The control rod drive mechanisms lie in lower part of the vessel to provide a large space for the upper part of the vessel so as to advantage arranging irradiation tubes and easily refuelling operation.

The arrangement of the reactor core is more flexible. The grid plate contains 313 grid holes. Among them, 18 lattic cells are occupied by control rods. The fuel assembly, beryllium assembly, aluminium assembly and non-duct type irradiation capsules may be flexibly placed at the reactor core. The core configuration at the rated power is shown in Fig. 2. The flux levels at different irradiation channels at the rated power are listed in Table 2. The irradiation channels which are

Table 2. The Flux Levels at Different Irradiation Channels

Channel number	Size (mm)	Thermal neutron flux (n/(cm²·s))	Fast neutron flux (E>0.625eV) (n/(cm²·s))
I	Φ150	4.2×10^{14}	1.6×10^{15}
II III IV V	Φ150	2.9×10^{14}	1.0×10^{15}
VI VIII	Φ230	1.2×10^{14}	0.34×10^{15}
VII IX	Φ122	1.2×10^{14}	0.25×10^{15}
X XI	Φ 63	3.1×10^{14}	1.2×10^{15}

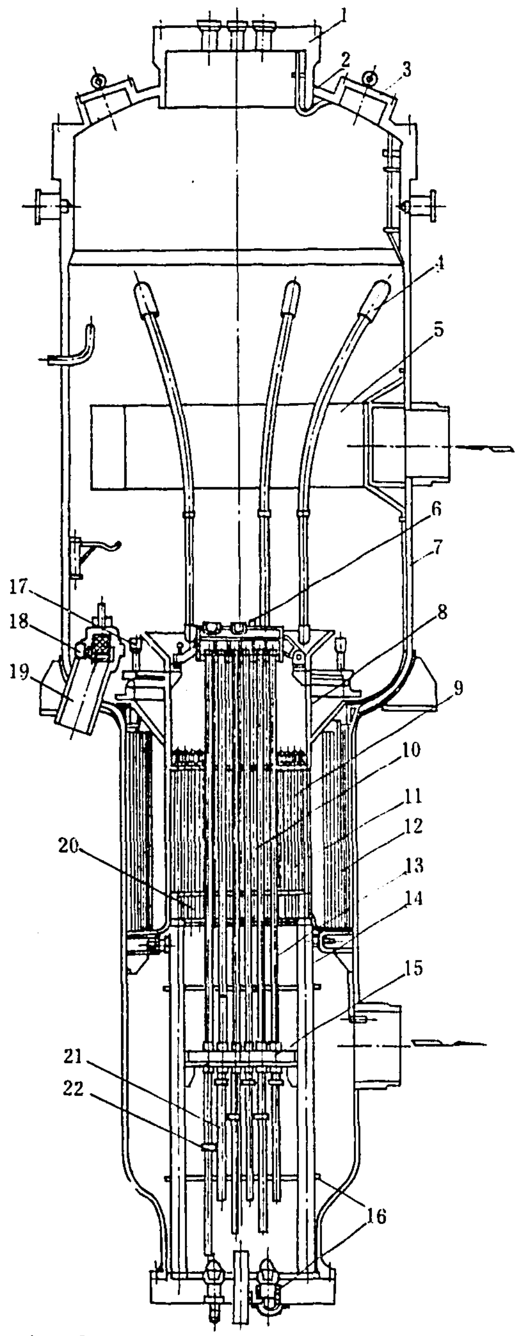

Fig. 1. Reactor Structure

1. Top head, 2. Closure head of pressure vessel, 3. Handling holes, 4. Guide tube for neutron detector, 5. Distributing water tank, 6. Supporters of guide tube for control rod, 7. Pressure vessel, 8. Flow baffle, 9. Beryllium assembly, 10. Fuel assembly, 11. Aluminium assembly, 12. Inner thermal shield, 13. Guide tube for control rod, 14. Supporter, 15. Support plate, 16. Movable seal plug, 17. Rotating shelf, 18. Seal plug, 19. Discharge canal, 20. Grid plate, 21. Rock of control rod, 22. Shelf of pinion.

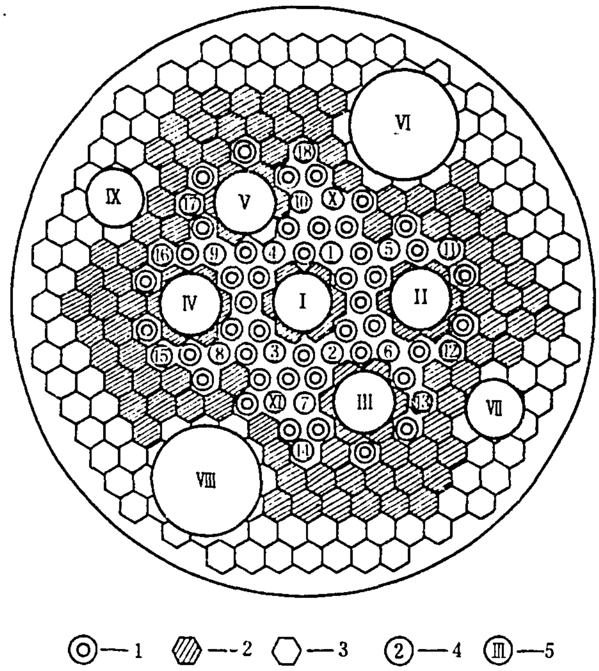

Fig. 2. 125 MW Core Configuration

1. Fuel assembly, 2. Beryllium assimbly, 3. Aluminium assembly, 4. Control rod (Number in figure is rod No.), 5. Irradiation channel (Number in figure is channel No.)

used practically may be more of less. And thus, placing special filler block in those unused irradiation channels, they could be restored to normal grid holes. Some small samples can be irradiated in the central holes of fuel assemblies, beryllium assemblies and aluminium assemblies. We can obtain different neutron energy spectrum by means of different arrangement of fuel assemblies and beryllium assemblies so as to meet various irradiation requirements.

II. MAIN UTILIZATION OF HFETR IN THE FIRST THIRTEEN CYCLES

According to the needs for irradiation tasks, HFETR was operated in the conditions of small and medium loading from the first cycle to the 13th cycle. The number of fuel assemblies loaded is 20 to 40. Each fuel assembly is allowed to stay in the core for 2 cycles or 3 cycles. Until Nov. 11, 1986, the integrated power of the reactor is as high as 17,300 MWd.

Operating tests for the first cycle were to examine the reactor behaviour. We performed full-load tests at the early, middle and late operation stages. The maximum surface heat flux achieved 3.56×10^6 W/m². We also performed the simulated blackout test of whole reactor building at the late stage of the first cycle. During the second cycle operating, we performed the test of deepened depletion for the fuel assembly. The average burnup of the tested fuel assembly achieved 44.8% which is much higher than the design value of 34%.

From the first cycle beginning, we performed about 65 items of irradiation research tasks, including the tests of fuel rods and materials for power reactor and the production of radioisotopes. The total of irradiation targets and devices are about 650 items.

Because the first high temperature pressurized water test loop is now under construction, the irradiation research on fuel elements is only at the stage of single rod and fuel samples to be irradiated in-core. Irradiation of most materials is carried out by in-core or in the dry irradiation channels which are filled with gas. For the irradiation in-core, temperature and hydraulic parameters of the irradiation devices need not be outside controlled and regulated. The operating parameter range of the irradiation devices was determined in advance by thermo-hydraulic design. For the irradiation in the dry irradiation channels, the stricter irradiation conditions and control of temperature are realized by means of changing content of gas, pressure and power of electric-heating elements. Generally speaking, the irradiation of pressure vessel steel and structure steel for power reactor is conducted by dry irradiation channels.

In the first thirteen cycles, the production of radioisotopes occupied considerable percentage. The main products are as follows:

^{60}Co source. We had produced about 100 ^{60}Co sources with the activity of each being 1.11×10^8 MBq for medical use and about 1.48×10^{10} MBq for industry and agriculture. ^{60}Co source for in-cavity-loading-late medical treatment was put on market.

^{113}Sn-^{113m}In isotope generator. We had produced about 500 generators with the range of source activity being from 1110 to 5550 MBq.

^{99}Mo-^{99m}Tc isotope generator. We had succeeded in studies on reactor-produced ^{99}Mo-^{99m}Tc isotope generator. The range of the source activity is from 1.85×10^4 to 7.4×10^4 MBq.

High specific radioisotope ^{14}C. The range of the specific activity of ^{14}C being from 7.4×10^5 to 1.7×10^6 MBq per mole $Ba^{14}CO_3$ was formed.

^{192}Ir flaw detection source. The products with the source activity of 1.48×10^3MBq have been produced and have been made standardized and seriated.

All of the isotope targets were irradiated in-core.

III. ITS ROLE IN NUCLEAR POWER DEVELOPMENT

According to the government requirements, the purposes of the reactor should be mainly focused on the irradiation research on fuels and materials for nuclear power station, while consideration should be given to the isotope production and other irradiation tasks.

A. Irradiation Research on Fuel for Nuclear Power Station

The safety and economy of power station are mainly depended on the advanced characteristic and reliability of fuel assembly. Besides the tests of thermohydraulic, materials and mechanics etc., any new type fuel has to be comprehensively irradiated to examine the fuel behaviour of irradiation-resistant. Generally, there are two kinds of way of comprehensive irradiation for testing fuel. One is that a fuel assembly of 1 : 1 is irradiated in-core when power station is operating. The other is that a small fuel assembly which is a typical unit taking out from a fuel assembly is put in a special test facility to be irradiated in the engineering test reactor. For the countries having adequate experience in design, fabrication and operation of fuel and having nuclear power station in operation , new fuel assembly may be irradiated in-core , provided finished some basic test during research, fabrication and modification of fuel assembly for power station. However, for the countries having no experience in design, fabrication and operation of fuel and especially having no nuclear power station in operation, the simulated test of small assembly is carried out in test reactor before fuel assembly of 1 : 1 to be irradiated in-core, provided the countries have also finished the basic test during research, fabrication and modification of fuel.

Apparently, China belongs to the latter. In the past, we did extensive work in research, design and fabrication of fuel assembly for PWR and made some progress. In comparison with advanced country, we still have many works to do and in particular, we are just beginning in the field of research, design and fabrication of fuel assembly for large power station. So far, our country has no power station which is in operation except Taiwan. The irradiation of fuel assembly for large power station is not conducted. In order to ensure that fuel assembly of large power station is safely irradiated in-core, small fuel assembly must be arranged for the irradiation in engineering test reactor to examine the techniques of home-made fuel assembly.

Recently, reducing failure and deepening depletion have become a trend in research and development of fuel assembly of nuclear power station in the world so as to prolong refuelling period and to raise economy and safety of power station. At present, average burnup of fuel assembly of nuclear power station in the world is generally about 30,000 MWd/tU and advanced level is about 50,000 MWd/tU. As burnup of fuel was deepened, some unfavourable to fuel behaviour occured, such as pellet swelling, fission gas release and PCI increasing, cladding growing, fuel surface corrosion, and relaxation of spring of spacer grid etc. Facing this, advanced countries had made huge investment to quicken implementing the program on research and development of high burnup fuel assembly. Our country is determined to catch up with world-class of nuclear power station technology development in short period. We must make a plan on research of high burnup fuel assembly. With development of high burnup fuel element, we should also develop dismantling technology of fuel assembly, and some equipments and technology for middle inspection and maintenance.

There are more irradiation channels in HFETR which are characterized by large size and high thermal neutron flux level. The reactor can better meet the needs for irradiation of fuel assembly of nuclear power station. Particularly, it is of advantage to over-power test of fuel assembly irradiated, power cycle test and other transient tests of fuel assembly . In the main building of HFETR, special rooms with an area of 5,000 m^2 are prepared for installing various experimental facilities. A high temperature pressurized water test loop with power of 500 kW is nearly completed. In addition, around the reactor, radiation technology laboratories, hot cells, reactor physics and radiochemical laboratories have been set up. Research of the behaviour of fuel assembly and reactor material during irradiation, post-irradiation non-destructive inspection, physical and mechanical inspection, metallographic research, fuel burn-up measurement etc. can be carried out in these laboratories.

Irradiation of UO_2 fuel rod in-core was conducted. Now, the conceptual design of comprehensive irradiation of large nuclear power station fuel assembly is carrying out. Finishing this work is of extreme significance to domestic fuel assembly of large nuclear power station, and research and development of high property fuel assembly.

B. Irradiation Research on Materials for Nuclear Power Station

The safety and economy of nuclear power station are also directly effected by the irradiation behaviour of the core structural materials. Although a great quantity and systematic research works in irradiation behaviour of reactor materials have been done in the world, they could not replace our research work in the same field. Moreover, new core structure materials need all the more to be develop. As we know, irradiation of materials needs fast neutron. HFETR has high fast neutron flux level which is an order higher than that of other reactors in China. Therefore, it is not only of advantage to raising irradiation quality of materials but also to shorten greatly irradiation time of materials.

Since the first cycle began, we have done radiation research on a series of materials for nuclear power station, such as pressure vessel steel of type A508-3, core structure steel, spacer grid materials, cladding Zr-4 and series combustible poisonous materials including B_4C-Al_2O_3 , B_4C-Zr-2, borated stainless steel and boron glass etc.

As mentioned above, HFETR has become a powerful medium for irradiation research on fuel and materials for nuclear power station and predicts that China has technology for constructing nuclear power station.

IV. OPINION ON COMPREHENSIVE UTILIZATION OF HFETR

A. Develop the Comprehensive Utilization of the Reactor, Improve Utilization Factor of the Core Space as High as Possible

No matter which region, fuel region with high neutron flux, beryllium reflectors region with middle neutron flux, or aluminium reflectors region with low neutron flux, may be, it should be sufficiently utilized. The emphases should be placed on irradiation of fuel and materials for nuclear power station. We should make an overall arrangement for isotope production and other irradiation research tasks. We must not only pay attention to the domestic irradiation tasks, but also win over the foreign irradiation tasks. In this way, the teactor core space can be fully used for each operation cycle.

B. Increase the Operation Cycle Number Per Year, Improve Time Utilization Rate of the Reactor

In the past years, the reactor was only operated two cycles per year and this is the lowest limit. It is not difficult to understand that this case is unfavourable to the radioisotope production: such as for ^{60}Co production, the decay loss is large and it is not easy to get higher specific, for production of ^{99}Mo-^{99m}Tc generator, the continuous supply will not be guaranteed, for irradiation of materials which need high integral neutron flux and of fuel assemblies which require the deep depletion, the long working period is needed. Therefore, I suggest increasing the operation cycles per year, preferably to operate 4 cycles per year from next year.

C. Strengthen the Research on the Irradiation Techniques

To strengthen the research work of irradiation techniques has profound significance for giving play to the action of the reactor. The emphases of the research are different kinds of irradiation facilities which need high technology and measuring techniques in-core. In this respect, developing cooperation with specialists at home and abroad is necessary and significant. From the point of some universities research ability of nuclear technology, we should set up and strengthen the relation and cooperation with them in nuclear field. The relation and cooperation will be of benefit to both parties.

D. Perfect Auxiliary Research Facilities

As a test reactor, how to make the most of its function is not only depended on whether it is advanced or not, but also depended on whether its auxiliary facilities is perfect or not.

As mentioned above, in the main building of the reactor there are special rooms for installing various experimental equipments. According to the program the rooms are used for setting up nine loops including test loops of water-cooled, of gas-cooled and of sodium-cooled and so on. Because of various reasons, now only a high temperature pressurized water test loop is under construction, which can not meet irradiation research requirments. As our government has decided to develop greatly nuclear power station, we should build another high temperature pressurized water test loop and two simple gas-cooled test loops which are used to irradiate fuel assembly and core structure materials respectively for PWR.

Taking long views, we should set about designing a sodium-cooled test loop and a high temperature gas-cooled loop so as to suit research and development of sodium-cooled fast reactor and high temperature gas-cooled reactor.

In addition, we must perfect post-irradiated fuel examination facilities. Especially hot cells and semi-hot cells should be equipped with advanced experiment devices and instrumentation.

E. Develop Utilization of Spent Fuel

Spent fuel from HFETR have γ source with high radiation activity. Investigation indicates that energy of γ radiation source of spent fuel is the same as that of a ^{60}Co source with 2.1×10^{10} MBq after the reactor is shut down for half a year. We have already set up the irradiation apparatus by using spent fuel which are used for irradiation research on polyethylene interlinkage. Now, the products in small amount are formed. The result of irradiation satisfied us.

Another usage of the spent fuel is that they can be loaded in the core of the low power reactor to continue using. Because heat flux of fuel element of low power reactor is an order lower than that of HFETR's fuel element, the spent fuel loaded in low power reactor can be operated in deepening depletion to serve scientific research and industries. This is feasible in both technology and economy.