Proceedings HTR2006:
3rd International Topical Meeting on High Temperature Reactor Technology
October 1-4, 2006, Johannesburg, South Africa

D00000052

COMMISSIONING AND OPERATION EXPERIENCE AND SAFETY EXPERIMENTS ON HTR-10

Shouyin HU **Xihua LIANG** **Liqiang WEI**

Institute of Nuclear Energy Technology, Tsinghua University
P.O. Box 1021,Beijing 102201, China
E-mail:hyyhtr@tsinghua.edu.cn

ABSTRACT

The 10MW High Temperature Gas-cooled reactor-test Module (HTR-10) is a graphite-moderated helium gas-cooled reactor. It is the first gas-cooled reactor in China. The first criticality of HTR-10 was attained on December 26, 2000 and it was confirmed that the thermal power and the reactor outlet helium temperature reached 10MW and 700˚C respectively on January 26, 2003. Following completion of all the commissioning tests; the HTR-10 began power operation for generating electricity and electricity-heat co-generating on December 2003.

The experimental results indicate that the basic performance and main technology specifications such as reactor physics, heat exchanger, radiation shielding, full digital instrumentation, control system and others meet the design requirements. The measured values are in good agreement with design values. The codes employed in design and analyses are available. After more than 480 days power operation experience, it is shown that HTR-10 has good self-stabilizing and self-adjusting transient performances.

Six safety demonstration tests were done on HTR-10. The Experimental result of the helium circulator trip without cram at 100% rated power is briefly described.

1.INTRODUCTION

The 10MW High Temperature Gas-cooled reactor-test Module (HTR-10) is a graphite-moderated helium gas-cooled reactor. The HTR-10 design represents the features of modular HTGR design. The reactor core and the steam generator are housed in two steel pressure vessels that are arranged side-by-side. A connecting vessel in which the hot duct is designed connects these two vessels to each other. These entire steel pressure vessels are in touch with the helium coolant of about 250˚C coming out from the circulator which is located on the steam generator. The HTR-10 main design parameters are listed in Table 1.[1]

The objective of the HTR-10 is to verify and demonstrate the technical and safety features of the modular HTGR and to establish an experimental base for developing nuclear process heat applications. The specific aims of the HTR-10 have been defined as follows:

-To acquire the experience of HTGR design, construction and operation.

-To carry out the irradiation tests for fuel elements.

-To verify the inherently safe features of the modular HTGR.

-To demonstrate the electricity/heat co-generation and steam/gas turbine combined cycle.

The first criticality of HTR-10 was attained at December 26, 2000. The first time feeding the electricity to public grid was on January 7, 2003, and reaching rated power of 10MW was at January 26, 2003. Up to now, the HTR-10 has operated for district heating or heat-electricity co-generated for more than 480 days. The actual values of the main parameters detected by a variety of sensors during HTR-10 power operation are in good agreement with design parameters. The key components, such as control rod driving machine, helium blower, and steam generator are operation well. During power operation, a series of experiments were conducted.

In HTR-10, spherical fuel elements are circulated through the reactor core in a “multi-pass" pattern. Thus all fuel elements attain a relatively uniform burn-up distribution in the core. Fuel pebbles are continuously discharged via a pneumatic pulse single-exit gate that is situated inside the reactor pressure vessel. The burn-up of the discharged fuel elements is measured individually and those elements which have not reached the limit are sent back pneumatically to the top of the reactor core. For the initial core loading, dummy spheres (graphite spheres without nuclear fuel) were firstly placed into the discharge tube and the bottom conical region of the reactor core. Then, a mixture of fuel spheres and dummy spheres were loaded gradually to approach first criticality. The percentages of fuel spheres and dummy spheres are envisaged to be 57% and 43% respectively. After the first criticality was reached, mixed spheres of the same ratio were further loaded to full core in order to make the reactor capable of being operated at full power. The full core, which is estimated to have a volume of 5m^3, was reached on December 21, 2004. At that time charging and discharging the fuel spheres (including dummy spheres) continually by means of the fuel handling system commenced. The burn-up of the first fuel sphere discharged from core was about 8000MWD/TU. Up until April 2006, there were 5745 graphite spheres and 882 fuel spheres discharged .The burn-up of the discharged fuel elements was measured individually did not exceed 13000MWD/TU, so those spheres which had not reached the limit were sent back pneumatically to the top of the reactor core.[2]

2. STEADY STATE TEMPERATURE DISTRIBUTION IN THE REACTOR

In order to determine the temperature distribution in the reactor, many temperature detectors were located in the graphite reflector and carbon bricks. Fig. 1 shows the distribution of temperature detectors in the reactor core. The experiment started after HTR-10 had been operated 72 hours with a thermal power of 10MW.The main operation parameters are listed below: the thermal power is 10MW,the hot helium temperature is 700.5°C, the cool helium temperature is 235.8°C, the helium pressure is 3000kPa. Figures 2 to 4 show the temperature distribution in the top reflector, side reflector and bottom reflector. It is satisfying that the measurement values correspond well with the design values in the stable operation, and the tolerance is acceptable. During power operation, the hot helium temperature was maintained at 700°C. Because the steam generator has 15% margin of heat transporting capacity, the cool helium temperature was 14.2°C lower than the design value. Therefore the temperatures of the top reflector, side reflector, bottom reflector, internal metal support parts and pressure vessel, etc, that are affected by the cool helium, are slightly lower than the design values.

3. THE DYNAMIC TEMPERATURE AFTER THE HTR-10 SCRAM

One of the main safety features of HTR-10 is the passive residual heat removal capability. In the normal shutdown operation, with the helium circulator in the primary loop and the steam generator still working, the residual heat in the reactor core is transported to the startup and shutdown loop through the steam generator and finally transported to the final heat sink through the heat exchanger.

In the scram operation, with the helium circulator stopped, the residual heat is passively transported only through conduction and heat radiation between the graphite and the fuel spheres in the reactor core, and then conducted through the graphite reflector to the reactor pressure vessel and finally transported to the water wall of the residual heat removal system that has been arranged outside the pressure vessel, through heat radiation and natural convection .The water wall which consists of cooling water tubes that have been installed in the concrete wall of the primary cavity connects with the air-cooler that have been installed outside the cavity. These components form a natural convection loop system. The system has no circulation drive and transports the residual heat through natural circulation. The residual heat removal system consists of two respective tube sets; each one has a 100% capacity to remove all the residual heat. If one set is out of service and the other one is still working, the maximum temperature value of the fuel spheres in the reactor core is predicted to be lower than 1230°C.

3.1 THE TEMPERATURE CHANGE OF THE TOP REFLECTOR

At the top of the reactor core, 3 layers graphite form the top reflector. The cool helium flow channel, cool helium connected plenum, the control rods channel, the absorption sphere channel and fuel sphere channel are housed in the top reflector, and a layer of insulation carbon bricks has been installed above the top reflector. Take the reactor top as the elevation 0 (up is negative, down is positive), a series of temperature detectors have been installed along the axial direction of a column which radius is 40cm,T-JKA01a (Z=-40cm), T-JKA01b (Z=-130cm), T-JKA01C (Z=-170cm). Fig.5 shows the temperature trend change on the top of the core. The sensor T-JKA01a, which is near the core, rises quickly through heat radiation, reaches the maximum value after about 2 hours. The temperature value rises from 242.2°C to 454.6°C□with an increment of 212.3°C□and then reduce. The sensor T-JKA01b, the temperature at the top edge of the top reflector, rises through the graphite conduction, because the graphite thermal capacity is large, the temperature rises slowly in the first hour, with an increment of only 15°C□and reaches the maximum value of 317°C after 4 hours. The sensor T-JKA01c, which is installed at the back of the insulation bricks, has only a little increment, and rises from 220°C to 255°C after 4 hours.

3.2 THE TEMPERATURE CHANGE OF THE SIDE REFLECTOR

The side reflector of the reactor core consists of 10 layers of graphite inside and 10 layers of insulation carbon bricks outside. In the graphite reflector, 10 control rod channels, 7 absorption sphere channels and 3 irradiation channels are arranged near the reactor core and 20 cool helium flow channels are arranged near the pressure vessel. There are two sets of temperature detectors positioned at 80cm and 170cm respectively along axial direction in the reflector. Figure 6 shows the change of the temperature at Z=170cm.Because the reactor power reduces quickly after the reactor scram, the sensor T-JKA02l, which is near the core this temperature descends from 510°C to 407°C in an hour, and then falls slowly. The sensor T-JKA02k, which is between the control rod channels and the cool helium flow channels, almost has no change. Because lose of helium circuit, the temperature between the cool helium flow channels and the insulation layer rises a little by conduction and radiation. The sensor T-JKA02g, which is installed outside the insulation layer, almost has no change in the first hour and then slowly falls down at a rate of 3°C in 3 hours. Figure 7 shows the temperature change trend at the position of Z=80cm after reactor scram. The sensor T-JKA02f, which is near the core, descends from 364°C to 330°C in the first half an hour due to the falling of reactor power, and then begins to rise due to conduction and radiation, and then reaches a maximum value of 362°C after about 2 hours. There after, the temperature drops again. Sensor T-JKA02e, situated between the control rod channels and the cool helium flow channel, have the similar trend with a 30 minutes delay. The change range is small, firstly the temperature drops from 316°C to 309°C, and then rises, finally reaches a maximum value of 330°C. The temperature between the cool helium flow channel and the insulation layer rises slowly. The sensor T-JKA02a, which is outside the insulation layer, temperature rises 3°C in the first 5 minutes, and then slowly reduces.

3.3 THE TEMPERATURE CHANGE OF HOT HELIUM MIXING ROOM

There is a hot helium mixing room in the graphite layer under the bottom of the reactor core. Four thermocouples, which can approximately indicate the outlet temperature of the reactor core, have been installed. Among these detectors, T-JKA03a is positioned near the center of the reactor. Figure 8 shows the temperature trend after the reactor scram. Because the convection is shut off after the reactor scram, T-JKA03a falls rapidly. T-JKA03b falls rapidly too after increasing 38°C in a short time, and the two temperature values gradually approach, and reach 400°C after 4 hours.

3.4 TEMPERATURE TREND ON SURFACE OF THE PRESSURE VESSEL

Figure 9 shows the temperature trend on different parts of the reactor pressure vessel after the reactor scram. T-JAA01a is the top cover temperature, T-JAA02a is the bottom cover temperature, T-JAA03a is the temperature on the terminal of the hot-gas duct, and T-JAA04a is the temperature on the side of the pressure vessel. Because there is no water wall on the top of the pressure vessel, T-JAA01a rises a little, the increment of 1.5°C. because there is a large space in the bottom of the pressure vessel, which is full of helium, and the helium thermal capacity is small, T-JAA02a remains unaltered for 15 minutes and then reduces rapidly for 42°C in 4 hours. T-JAA03a and T-JAA04a continuously decline from commencement of the test.

4.TRANSIENT FEATURES OF HTR-10

4.1 HTR-10 REGULATION METHODS

In power operation, four kinds of regulation method of HTR-10 are listed below:

(1) Move control rods to change reactivity

There are 10 control rods in HTR-10, 2 rods are safety rods, they are used in emergency shutdown which is activated by the protection system; 6 rods are compensating rods, they can compensate for the slow reactivity change caused by temperature, xenon poisoning and experiment samples in the reactor startup and power operation, while the remaining 2 rods are regulating rods. The operator can move the control rods through the distribution control system (DCS).

(2) Change of the helium circulator rotational speed to regulate the helium flow rate

The helium circulator circulates the helium forced in the primary circuit. A transducer supplies electricity to the helium circulator, the helium circulator rotational speed is proportional to the output frequency of the transducer, and the helium flow rate is proportional to the helium circulator rotational speed. The output sensitivity of the transducer is 0.1 Hz; the circulator rotational speed can be precisely controlled from 10% to 100% rated speed, and therefore the helium flow rate can be regulated between the ranges.

(3) Change of the feed-water pump rotational speed to regulate the feed-water flow rate

Two feed-water pumps (one operational, the other on standby) are supplied power by a transducer. Two regulating valves are installed in the feed-water pipe. The two measures of controlling the feed-water pump rotational speed and valve position combined to regulate the feed water flow rate and pressure in the secondary circuit. [3]

4.2 THE RESULT AND ANALYSIS OF THE TRANSIENT FEATURES EXPERIMENT

4.2.1 Withdrawing the control rod induces positive reactivity

With the reactor kept in a stable power operation of 3MW, withdrawing a control rod by 10mm, the induced positive reactivity is $6\times10^{-5}\Delta k/k$. the main parameters transient response curve are shown in the Fig.10 and 11.

In the figures, due to the inducement of exterior positive reactivity, the reactor power rises by 86kW in 40 seconds (a relative increase of about 2.8%). The increasing power causes the temperatures in the reactor to rise. Because of the large negative reactivity temperature coefficient of HTR-10, negative reactivity feedback is produced to compensate the inducement of exterior positive reactivity; the nuclear power rises to the maximum value and then falls slowly, and finally settling at a level near the initial value after about 200 seconds.

The increase in nuclear power also induces the helium temperature increase, the temperature in the small cavity at the outlet of the reactor core rises by 1.8°C, the hot helium temperature rises by 1.1°C and the cool helium temperature has almost no change. Furthermore, the helium temperature does not increase continuously; it corresponds to the little range attenuation fluctuation on the end of the nuclear power curve.

It is obvious that the reactivity affects the nuclear power quickly, but due to the large negative temperature reactivity coefficient, the reactor has a strong self-adjusting power property, so the net change in nuclear power is small in the end.

4.2.2 The effect of helium flow rate change

During stable operation, changing the helium circulator rotational speed suddenly changes the helium flow rate in the primary circuit. The dynamic response curves of related parameter are shown in Fig. 12 to 14.

Increasing the helium flow rate from 1.42kg/s to 1.5kg/s (relative increasing 5.6%), more heat remove from the primary circuit, thereby reducing the fuel temperature in the reactor. Due to the negative temperature reactivity coefficient, positive reactivity is induced; causing the nuclear power to rise. The power increase and the helium flow rate change are approximately synchronization. The power reaches a peak value after 60 seconds, increasing by 230 kW (or relative increasing by 7.6%), and then again to stabilize at a level that is 5.3% higher than the initial .The hot helium temperature changes slowly, increases by about 0.2°C only and the cool helium temperature rises by 3.1°C after 500 seconds. At the same time, because the helium flow rate in the primary circuit increased and the feed water flow rate in the secondary circuit remained unchanged, the outlet steam temperature increased by 24 ° C, while the feed water temperature remained unchanged at 101°C.

Once the parameters were stabilized, reducing the helium flow rate from 1.5kg/s to 1.42kg/s, a conversant dynamic process occurs. In the end of the cycle, the power reduces by 4.9%, the hot helium temperature falls by 0.6°C, and the steam temperature falls by 21°C after 500 seconds.

From the analysis of the experiment, the change of the helium flow rate affects the nuclear power sharply, but the hot helium temperature changes a little. The direct-through flow steam generator with combined structure of small helical tube units has a small thermal capacity, so the helium flow rate change quickly affect the steam parameters, and the cool helium temperature also changes markedly. The dynamic processes caused by the increasing and reducing the helium flow rate are symmetric.

4.2.3 The affect of feed water flow rate change

With the parameters stabilized initially, the dynamic response curves of the parameters following adjustment of the feed water pump rotational speed to change the feed water flow rate are shown in Fig.15 to 17.

From the figures, when the feed water flow rate is increased from 1.09kg/s to 1.18kg/s (a relative increase of 8.2%), the secondary circuit's heat transfer increases. Because of the small thermal capacity of the secondary circuit, the outlet steam temperature is reduced by 42°C in 700 seconds. The change of the secondary circuit parameters affects the helium parameters of the primary circuit, causing the cool helium temperature to drop by 2.8°C. the nuclear power rises 33Kw (a relative increases of 3.3%), and the hot helium temperature increases by only 0.8°C.When the feed water flow rate is reduced from 1.18kg/s to 1.09kg/s, the outlet steam temperature drops by 39°C in 700 seconds, the cool helium temperature drops by 2.8°C. In turn, the nuclear power rises 36kW (a relative increases of 1.2%) and the hot helium temperature changes by only 0.7°C.

It is obvious that changing the feed water flow rate has a little effect on the nuclear power and the hot helium temperature, but affects the steam temperature markedly. The dynamic processes caused by increasing and reducing of the feed water flow rate are therefore symmetric as well.

5. SAFETY EXPERIMENTS

The aim of safety demonstration tests is to demonstrate the inherent safety features of modular HTRs, in particular, the goal was to obtain the core and plant transient data for the validation of computer codes for safety and transient analysis to assure that the maximum fuel temperature would not exceed 1600˚C and that the temperature of components, including pressure vessels and their supports, the reactor internal as well as the concrete of cavity, would not exceed the temperature limits of the respective materials. In addition, safety demonstration tests done on a real reactor will persuade peoples to believe the high temperature gas cooled reactor is an inherent safety reactor and also persuade safety authority to use new design criteria for the HTGR instead of the original ones, which are mainly based on the light water cooled reactor experience.

Six safety demonstration experiments has been carried out at HTR-10 since 2003.The experiments completed are included as follows:

-Loss of helium flow

-Loss of off-site power supply

-Turbine trip

-Primary loop cut-off valve does not close when scram

-Helium circulator trip without reactor scram at 3MW

-Reactivity insertion without reactor scram at 3MW

-Helium circulator trip without reactor scram at 10MW

To assure that no components or systems would be failure or be seriously damaged, the temperature of the surface of the reactor vessel, the steam generator pressure vessel and the hot gas duct pressure vessel, the temperature of the reactor internal as well as the temperature of the shielding concrete and supports of the reactor vessel were monitored during the safety demonstration tests. The temperature limits for these were set to 350˚C, 400˚C and 70˚C respectively. As soon as any one of the monitored temperatures was reached the temperature limit, the safety demonstration test would be stopped by the operator.

In addition to maintain the integrity of the primary circuit and to avoid the release of helium to the surrounding, the primary pressure was also monitored at all times. The pressure limit was set to 3.3MPa. As with the monitored temperatures, the safety demonstration test would be sopped by the operator and the helium would be release to the helium storage tank, if the primary pressure should exceed the pressure limit.

The experiment of Helium circulator trip without reactor scram at 10MW was conducted in July 2005. The initial conditions of the experiment have been list in Table 2; the reactor power level is 10MW, the core inlet helium temperature is 230.8°C, the core outlet temperature is 700.7°C, the core are constituted of 17086 fuel elements and 13865 dummy spheres.

When the helium circulator was tripped, although there was no control rod insertion, the reactor power decreased rapidly from 10MW to zero automatically and maintained reactor in sub-criticality for a long time, as shown in Fig.18. This is due to the negative reactivity feedback caused by the rising of temperature in the core due to the decrease of heat removal capability of primary circuit. During the test, the temperature of in core structure was redistributed, and the upper part of the reflector was increased significantly. However, the temperatures of other parts of core structure decreased slowly. [4]

6.CONCLUSION

The operating parameters of HTR-10 compare well with design values**.** Meanwhile, HTR-10 has demonstrated good performance of self-adjusting and self-stabilizing during commissioning and power operation phase. The results of a series of safety demonstration tests illustrated the passive safety features of HTR-10 practically. Even in accidents such as loss of helium flow or withdrawing the control rod without reactor scram and operator intervention, the large negative temperature coefficient of the reactivity and temperature margin can shut the reactor down automatically. The large heat capacity of the pebble bed core prevents excessive increases in fuel temperature, and maintains the maximum fuel temperature below limit. The decay heat is dissipated through the surface cooling system without causing unacceptable high temperature of the in-core components.

REFERENCE:

[1] The final safety report of 10MW high temperature gas-cooled module reactor, Institute of nuclear energy technology (INET), Tsinghua University, 2000.8

[2] Shouyin HU, annual report on HTR-10 operation, Institute of nuclear energy technology (INET), Tsinghua University, 2006.4

[3] Shouyin HU, the experiments of dynamic character of HTR-10, nuclear power engineering, 2003.10

[4] Shouyin HU, summary of the safety feature test of HTR-10, Institute of nuclear energy technology (INET), Tsinghua University, 2005.10

Table 1 the HTR -10 main design parameters

Reactor thermal power	MW	10
Active core volume	m^3	5
Average power density	MW/m^3	2
Primary helium pressure	MPa	3
Helium inlet temperature	˚C	250
Helium outlet temperature	˚C	700
Helium mass flow rate	kg/s	4.3
Fuel		UO_2
U-235 enrichment of fresh fuel elements	%	17
Diameter of spherical fuel elements	cm	6
Number of spherical fuel elements		27000
Average discharge burn-up	MWD/T	80000

Table 2 Initial status of helium blower trip ATWS at 10MW

Reactor thermal power	MW	10
Primary helium pressure	MPa	3
Helium inlet temperature	˚C	230.8
Helium outlet temperature	˚C	700.7
Helium mass flow rate	kg/s	4.2
Helium pressure	MPa	2.5
Feeding water flow rate	kg/s	3.5
Feeding water temperature	˚C	100
Steam temperature	˚C	435
Steam pressure	MPa	3.5
Number of fuel elements in core		17086
Number of graphite ball in core		13865

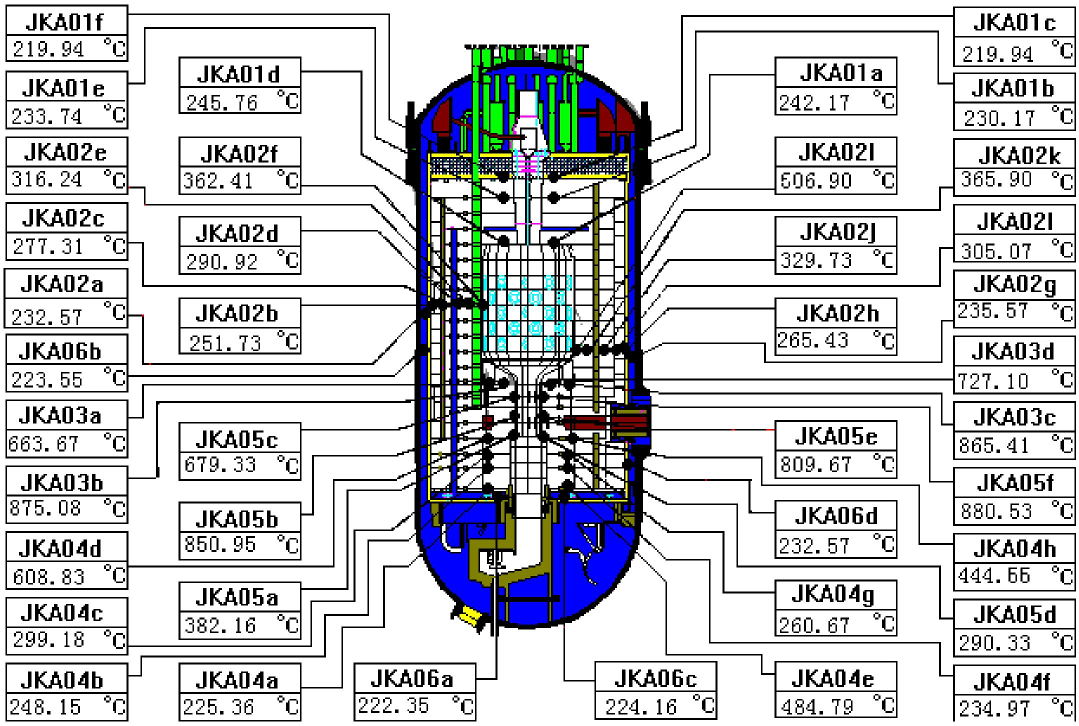

Fig. 1 The distribution of temperature detectors in the reactor core

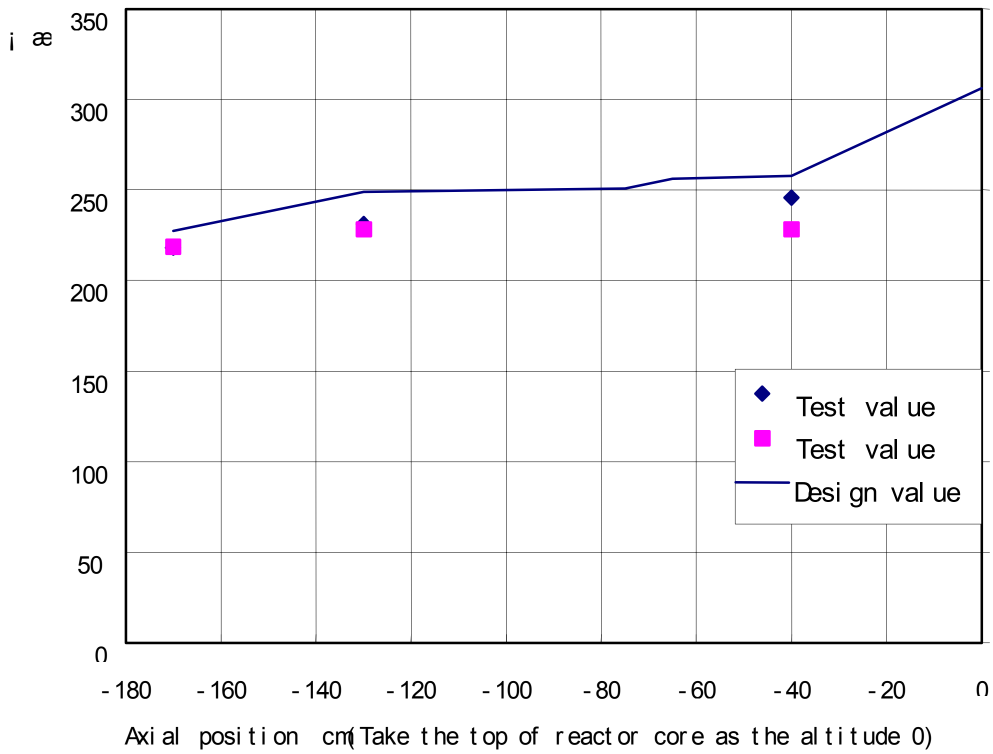

Fig. 2 Comparison of the top reflector temperatures at R=40cm

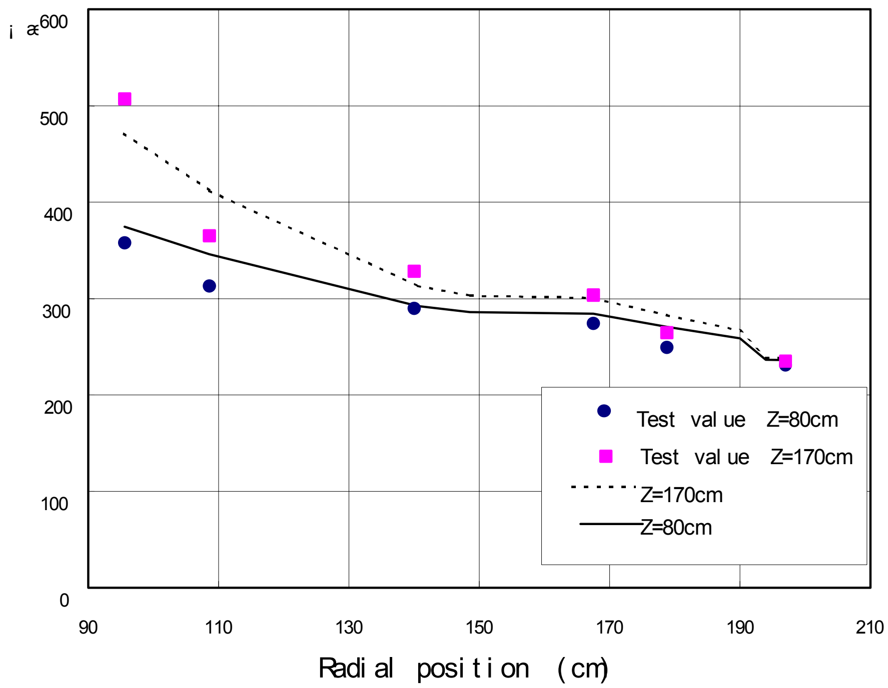

Fig. 3 Comparison of side reflector temperatures

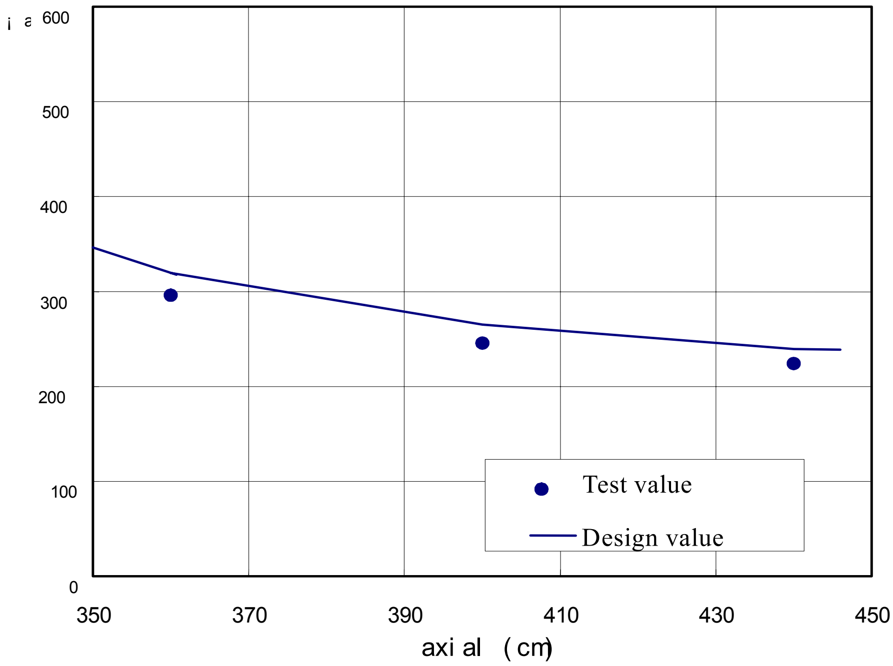

Fig.4 Comparison of the bottom reflector temperatures at R=90cm

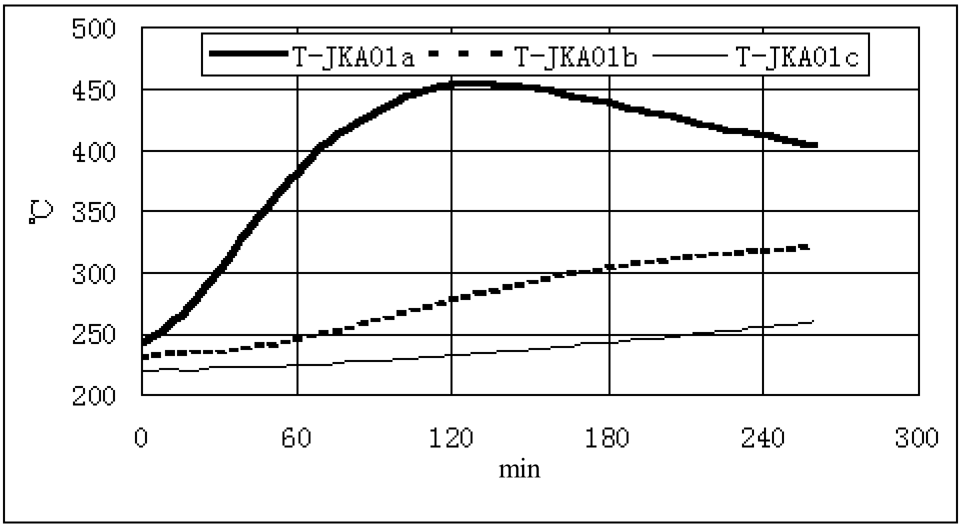

Fig.5 The temperature trends of top reflector

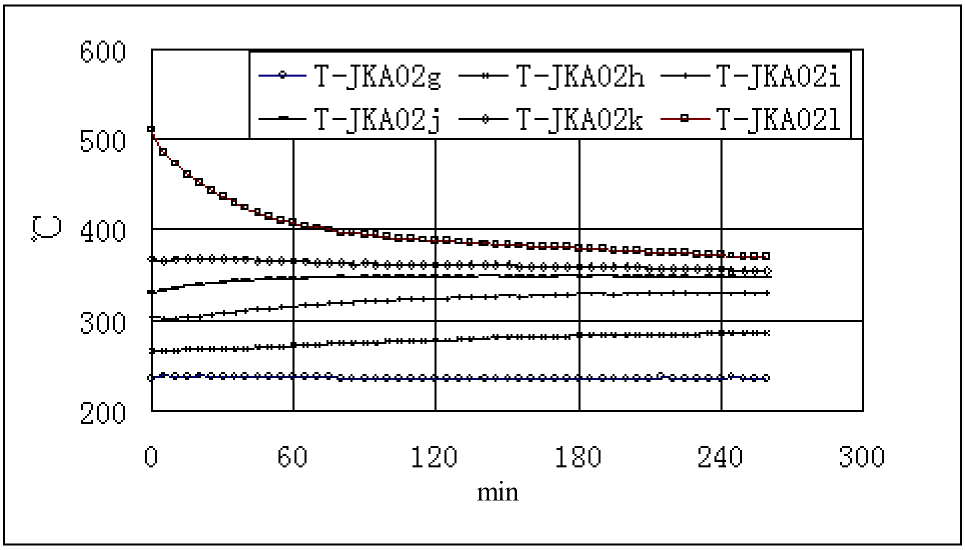

Fig.6 The temperature trends in the side reflector (Z=170cm)

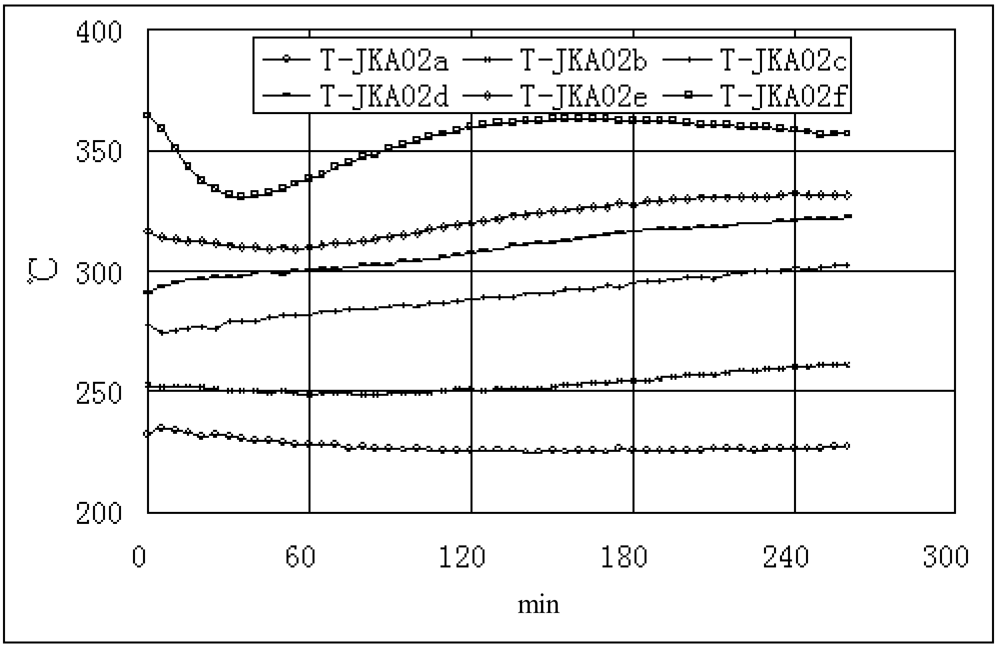

Fig.7 The temperature trends in the side reflector (Z=80cm)

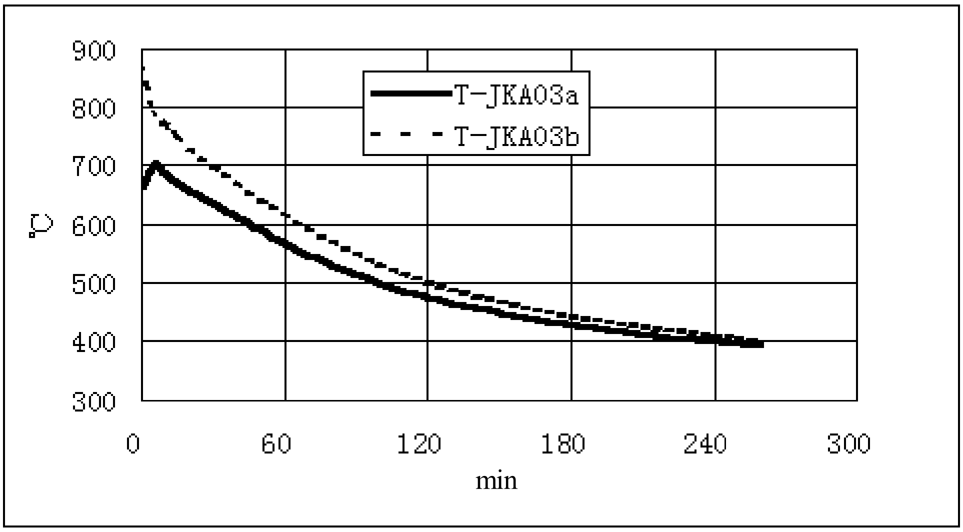

Fig.8 The temperature trends in the hot helium mixing room

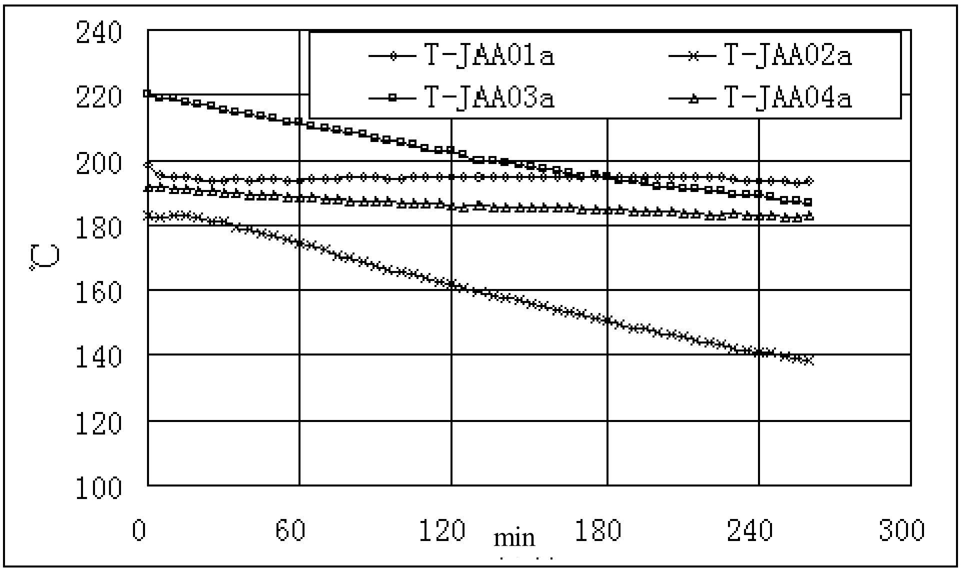

Fig.9 The temperature trends on the surface of pressure vessel

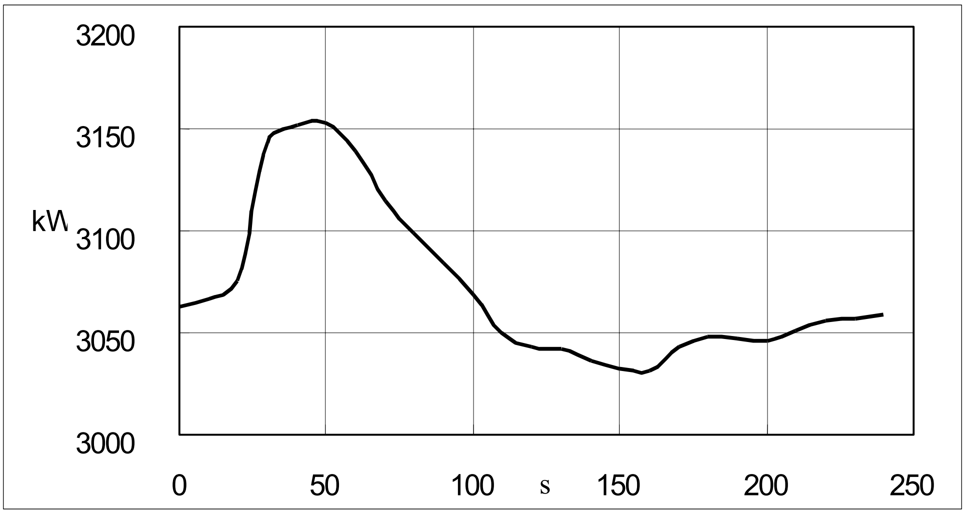

Fig.10 The nuclear power trend when withdrawing control rod

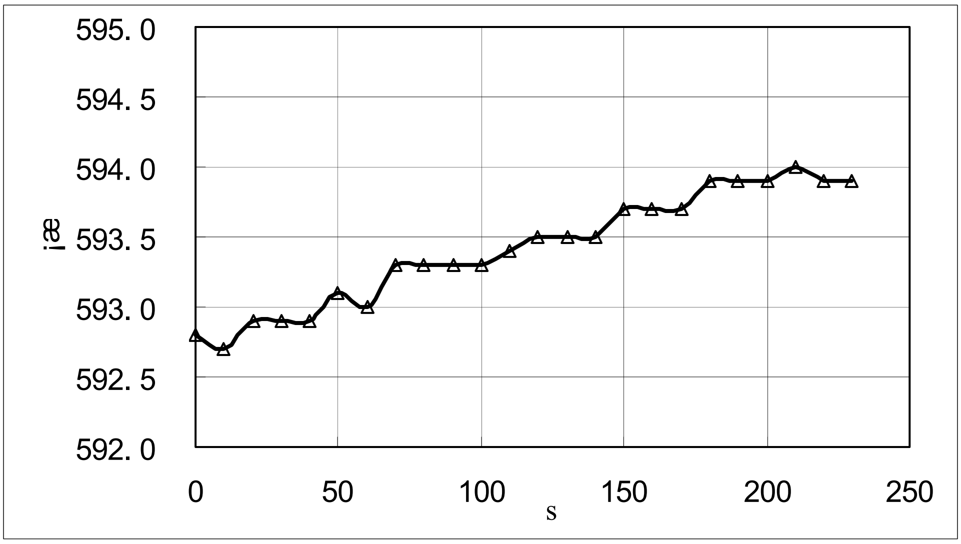

Fig.11 The hot helium temperature trend when withdrawing control rod

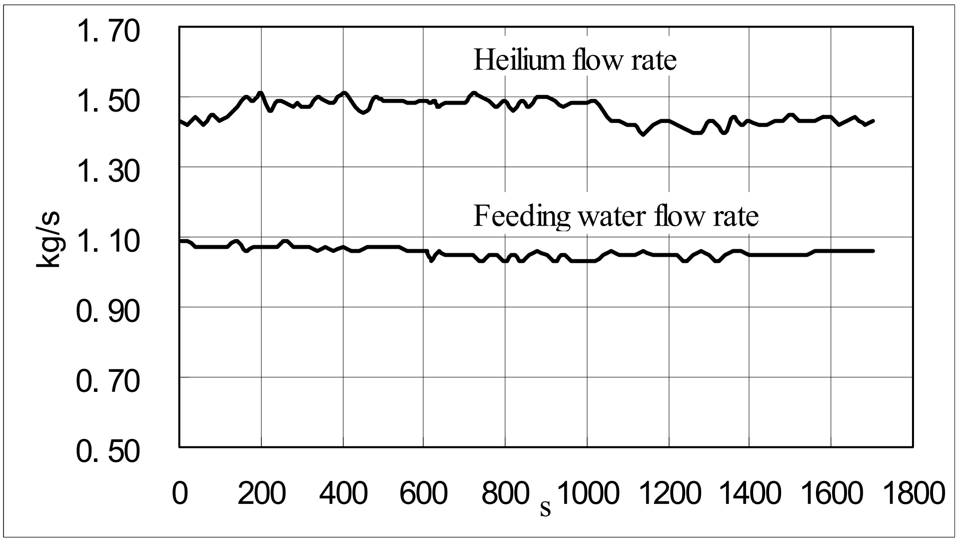

Fig.12 The helium flow rate alteration (increased then decreased) And feed water flow rate kept stable

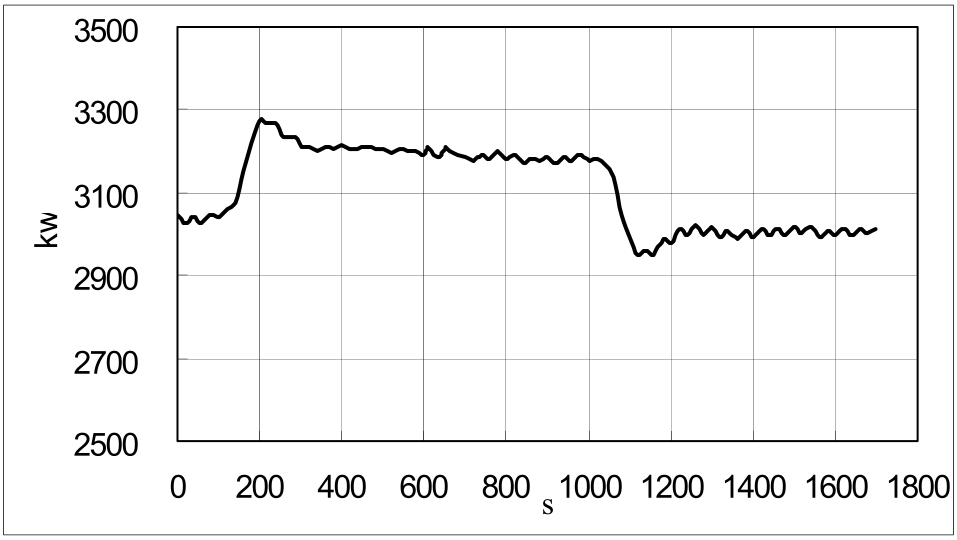

Fig.13 The dynamic power changes as a result of the helium flow rate alterations

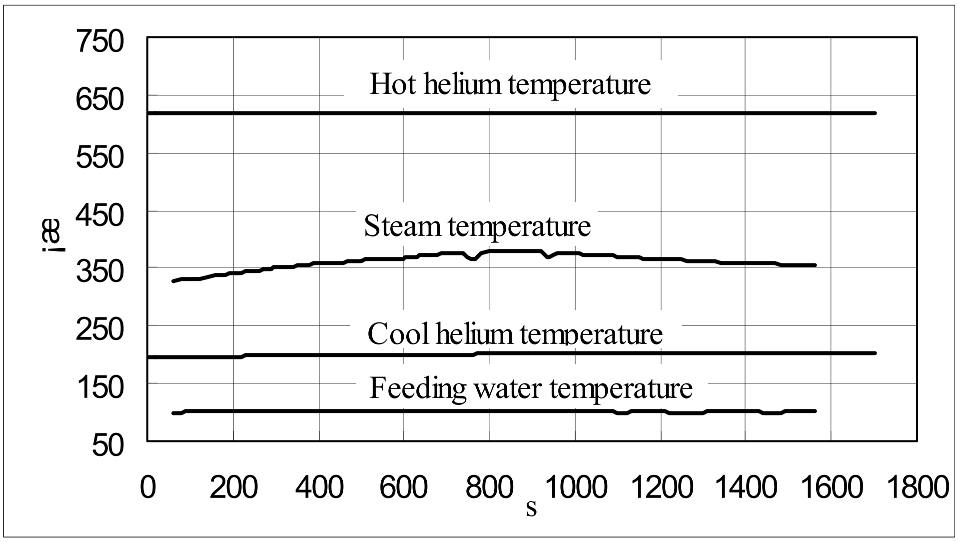

Fig.14 The dynamic temperatures changes as a result of the helium flow rate alterations

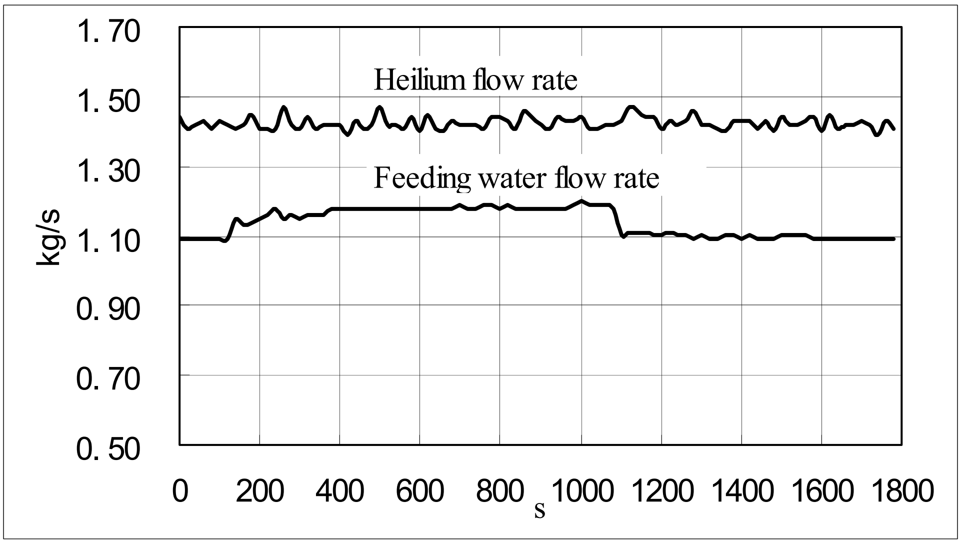

Fig.15 The feeding water flow rate alterations (increased-then decreased) And helium flow rate kept stable

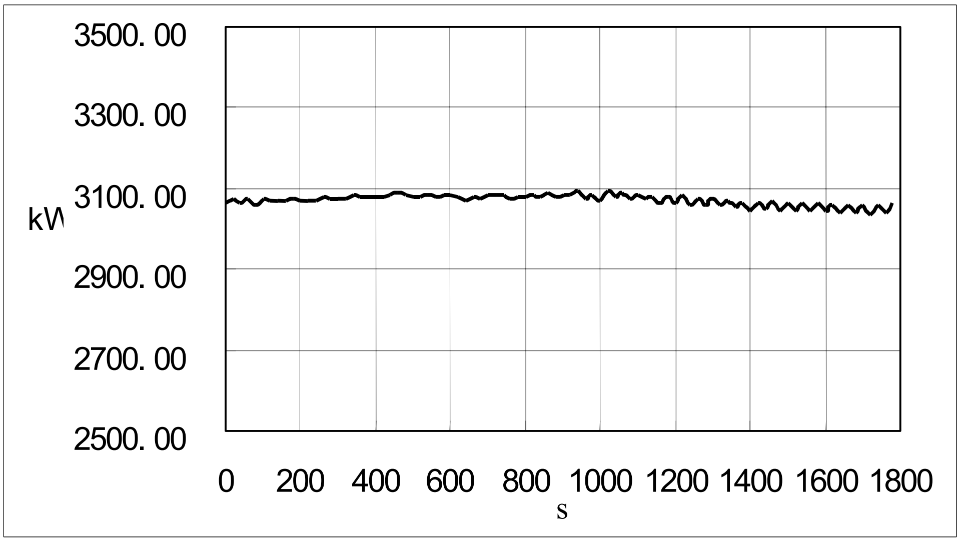

Fig.16 The nuclear power changes as a result of the feed water flow rate alterations

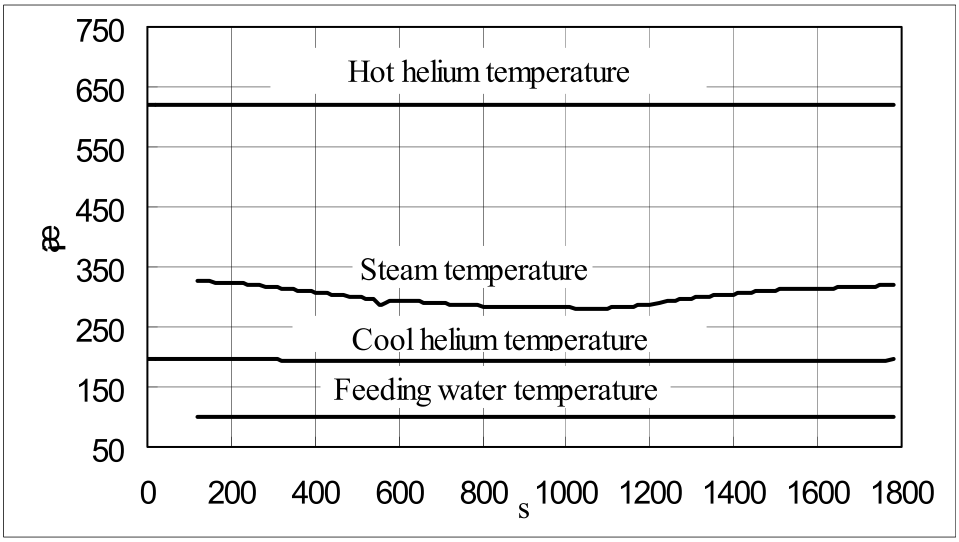

Fig.17 The dynamic temperatures change when the feed water flow rate is altered

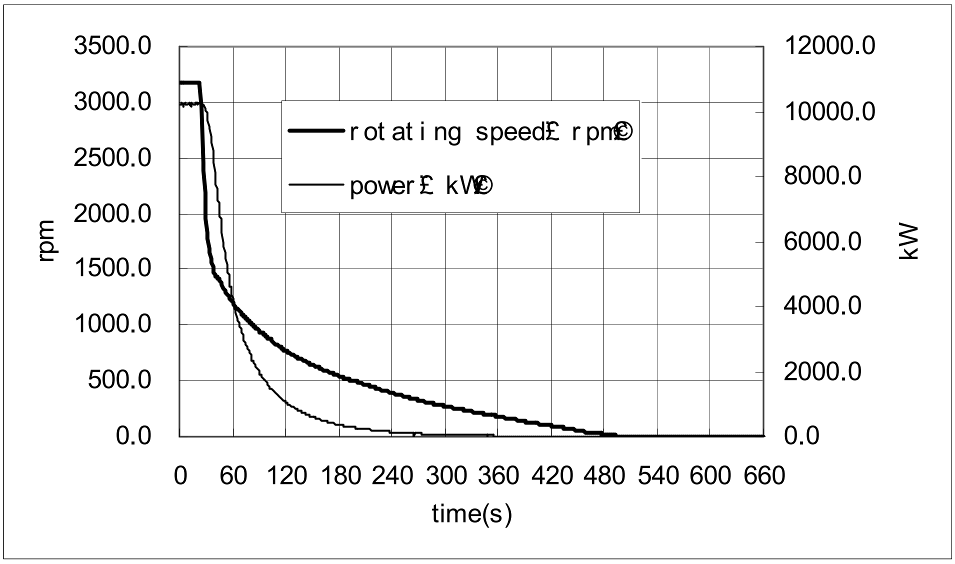

Fig.18 Transient of helium circulator trip without scram at 10MW