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FIVE MW NUCLEAR HEATING REACTOR

ZHANG DAFANG, DONG DUO, SU QINGSHAN
Institute of Nuclear Energy and Technology,
Tsingua Uiversity,
Beijing, China

Abstract

The 5 MW Nuclear Heating Reactor (NHR-5) developed and designed by the Institute of Nuclear Energy Technology (INET) has been operated for four winter seasons since 1989. During the time of commissioning and operation a number of experiments including self-stability, self-regulation, and simulation of ATWS etc. were carried out. Some operating experiences such as water chemistry, radiation protection and environmental impacts and so on were also obtained at the same time. All of these results demonstrate the design of the NHR-5 is successful.

1. INTRODUCTION

The 5MW Nuclear Heating Reactor (NHR-5) developed and designed by the Institute of Nuclear Energy Technology (INET) has been in operation for four winter seasons. The construction of NHR-5 began in March 1986, the civil engineering was completed in September 1987, and the erection of the NHR-5 was finished in April 1989. The initial criticality of the NHR-5 was reached in Nov. 1989 and full power operation began in Dec. of the same year.

In order to expand the utilization of the NHR and to improve its economic competitiveness, the operational experiments of cogeneration- heat and electricity- and refrigeration for air condition using nuclear steam from NHR-5 were carried out in 1992. The milestones of NHR-5 are listed in table 1.

TABLE 1: THE MILESTONES OF NHR-5

Beginning of construction	Mar. 1986
Completion of civil engineering	Sept. 1987
Completion of erection of reactor	Apr. 1989
Beginning of commissioning	May 7, 1989
Initial fuel loading	Oct. 9, 1989
Initial criticality	Nov. 3, 1989
Full power operation	Dec. 16, 1989

The operational practice shows that the NHR - 5 has excellent operating and safety features, and a high availability of 99%. The practice also shows that the NHR-5 is easy to start up and to be operated. The operating results demonstrated that the NHR-5 has fully reached the design requirements and meets the main design parameters. Table 2 gives the main operating parameters in comparison with the design values. In the table the operation temperature of the reactor inlet is higher than the design value, which shows that the reactor has a larger than estimated natural-circulation capability.

2. DESCRIPTION OF NHR-5

The NHR-5 is the first heating reactor in operation in the world. It is an integrated vessel type light water reactor cooled by natural circulation with self-pressurized performance.

TABLE 2: MAIN OPERATING PARAMETERS OF THE NHR-5

	Design value	Operation value
Reactor thermal power	5MW	5MW
Reactor		
Outlet temperature	186°C	186°C
Inlet temperature	146.6°C	151°C
Pressure	1.37MPa	1.37MPa
Intermediate circuit		
Primary heat exchanger		
Outlet temperature	142°C	144°C
Inlet temperature	102°C	100°C
Flow rate	107t/hr	97 t/hr
Intermediate heat exchanger		
Outlet temperature	75.2°C	80°C
Inlet temperature	142°C	144°C
Flow rate	64 t/hr	67 t/hr
Pressure	1.7MPa	1.7MPa
Heating grid		
Outlet temperature	90°C	84°C
Inlet temperature	60°C	56°C
Flow rate	143t/hr	152t/hr

2.1. Structures of NHR-5

Integral design and natural circulation

The core and main components of the primary circuit are housed within a reactor pressure vessel (RPV). The reactor core is located at the bottom of a hanging barrel; underneath the hanging barrel a secondary support is placed in the bottom of the vessel. There is a long riser above the core outlet to enhance the natural circulation capability. There are four primary heat exchangers in the downcomer between the riser and the vessel wall. The reactor core is cooled by natural circulation and the carried heat is transferred to the intermediate circuit via primary heat exchangers.

Dual pressure vessel

A dual pressure vessel is adopted in the design of the NHR-5. The reactor pressure vessel is designed for an operating pressure of 1.5MPa. Outside the RPV, a second metallic vessel containment is mounted. The design pressure is 1.5MPa at a temperature of 177°C. The gap between the RPV and the containment is very small. The location of all RPV penetrations are at a height of 2m above the core outlet and there are no large-bore piping.

All of these measures can avoid and mitigate serious consequences which result from loss of coolant accidents. If the RPV would develop a leak at its bottom the core can also be kept covered with water. Fig. 1 shows the reactor structure with dual vessel. The main technical parameters of the dual pressure vessel arrangement are listed in table 3.

TABLE 3: THE MAIN PARAMETERS OF DUAL PRESSURE VESSEL

Pressure vessel		
ID	m	1.8
Total height	m	6.5
Working pressure	MPa	1.5
Working temperature	°C	198
Lining thickness (Braze welding)	mm	~6
Thickness of wall	mm	90
Total weight	t	35
Containment		
ID	m	2.8
Total height	m	9.5
Thickness of wall	mm	20
Design temperature	°C	177
Design pressure	MPa	1.5
Material		16MnR
Weight	t	29

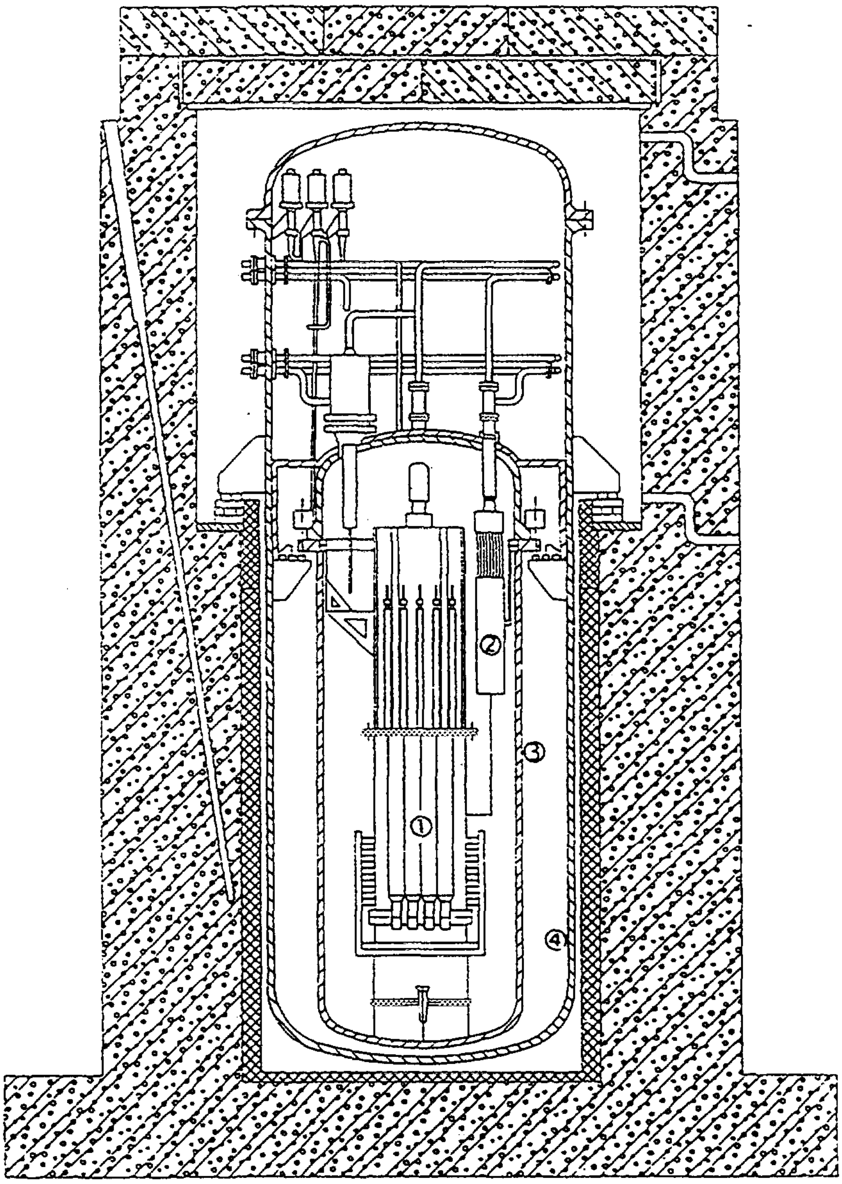
Self-pressurized system

A space above the coolant level inside the RPV acts as self-pressurizer. The pressure inside the RPV is depends on initial partial pressure of nitrogen and saturate vapor pressure corresponds to the core outlet temperature in the pressurized water operation mode. Due to the nitrogen partial pressure existing, the coolant can be kept subcooling in the core outlet. This is called pressurized water operation mode.

2.2. Overall arrangement of reactor core

Reactor core

The core cross section of NHR-5 is shown in Fig.2. In the core there are 12 fuel assemblies with 96 fuel rods, and 4 with 35 fuel rods. The fuel rod with a cladding of Zircaloy-4 has an active length of 690mm and a diameter of 10mm. The nuclear fuel is uranium dioxide with an enrichment of 3%. The total amount of UO_2 loaded in the core is 0.508 tons.

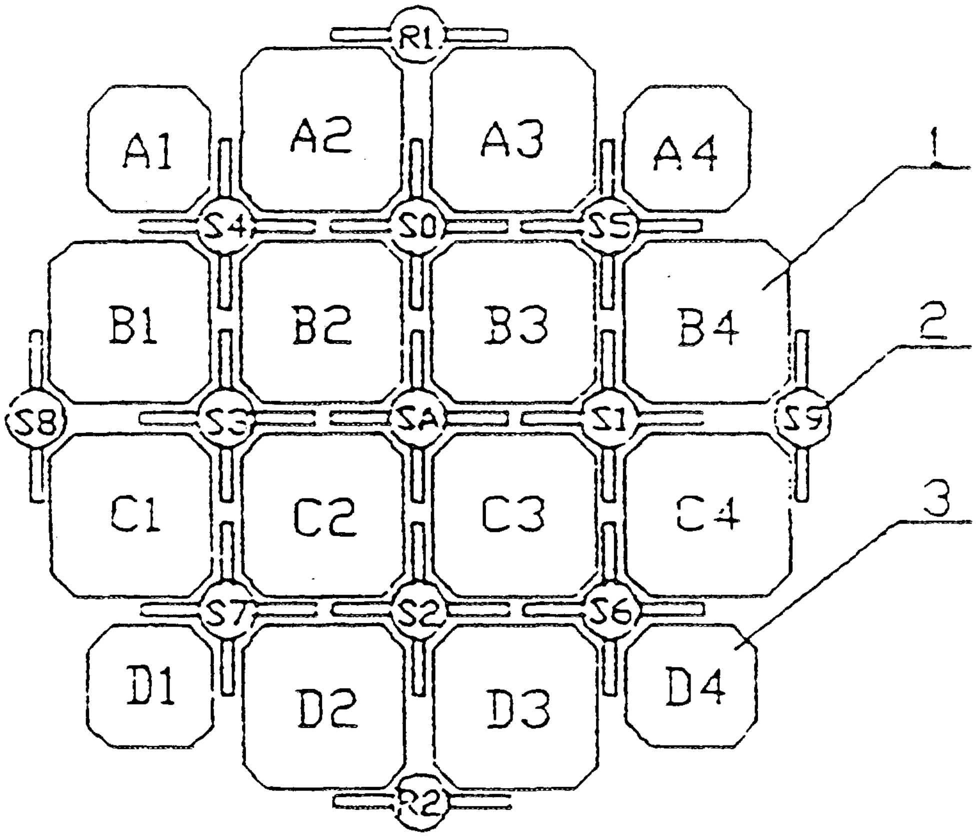


1. core
2. primary heat exchanger
3. reactor pressure vessel
4. containment

Fig.1 The NHR-5 structure with dual vessel

Control of reactivity

The reactivity is controlled by a combination of fuel rods containing fixed burnable poison of 1.5% Gd_2O_3, movable absorption rods (boron carbide) and the negative reactivity coefficient of the coolant. In the core there are 13 control rods which are all driven by a hydraulic driving system. The control rod drive system consists of three parts: an actuating loop outside the containment, 13 hydraulic step cylinders in the core and two control units (combined valves). The control rods can be dropped into the core by gravity when reactor shutdown is needed. Boron injection as a standby shutdown system is initiated by pumps or pressurized nitrogen during ATWS events.



1. assembly with 96 fuel rods 2. control rod
3. assembly with 35 fuel rods

Fig.2 The core cross section of NHR-5

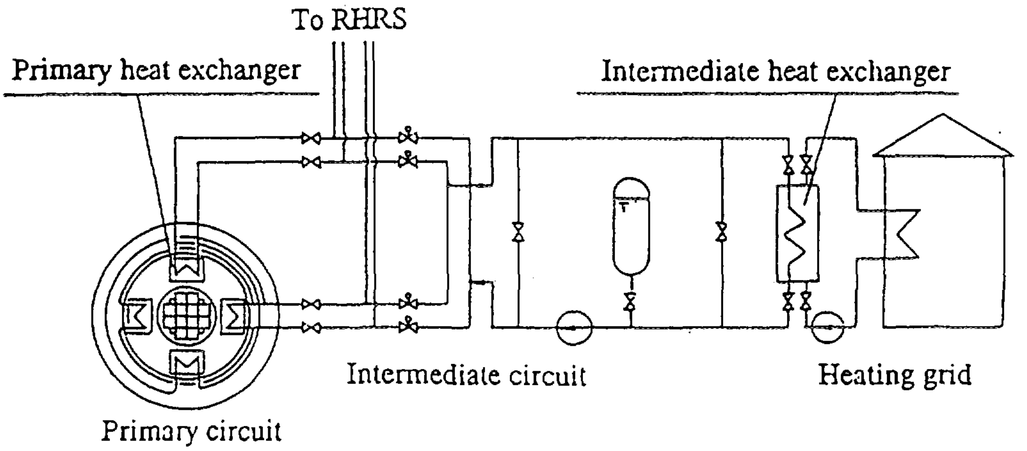


Fig.3 The main heat transfer system of NHR-5

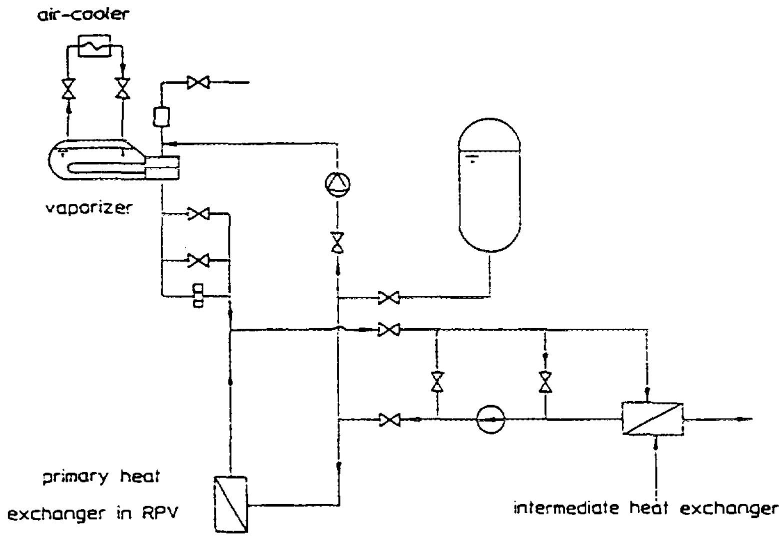


Fig.4 The schematic system diagram of RHRS

2.3. Main heat transfer system

The main heat transfer system is composed of three circuits, i.e. the primary circuit, the intermediate circuit and the heat grid. The intermediate circuit is a single loop which connects with the primary circuit and the heat grid via the four primary heat exchangers and two intermediate heat exchangers. The four primary heat exchangers are divided into two groups in parallel operation, which are merged into a single loop through isolating valves. The operating pressure in the intermediate circuit is higher than in the primary circuit. This choice can keep the heat grid free of radioactivity. Heat generated in the core is transferred to the heat grid via the intermediate circuit. The main heat transfer system is shown in Fig.3.

2.4. Residual heat removal system

The residual heat removal system (RHRS) of the NHR-5 consists of two independent trains which are assigned to two groups of primary heat exchangers. In each train there are three natural circulation paths. Figure 4 shows the schematic system diagram of the RHRS. After reactor shut-down the decay heat will be transferred to the intermediate circuit via the primary heat exchangers. Then the heat carried is going to a vaporizer located at a high local position in the reactor hall. This is the first natural circulation path. The second natural circulation path consists of the vaporizer, air cooler and related piping and valves. Finally, the decay heat can be discharged to the atmosphere via the air cooler on the floor of the building by natural convection of air.

3. OPERATIONAL EXPERIENCE OF NHR-5

3.1. Reactor operating conditions

Start up

Start up of the NHR-5 is the process from cold condition to the expected operation state by means of nuclear heating. During the start up process three things have to be done,

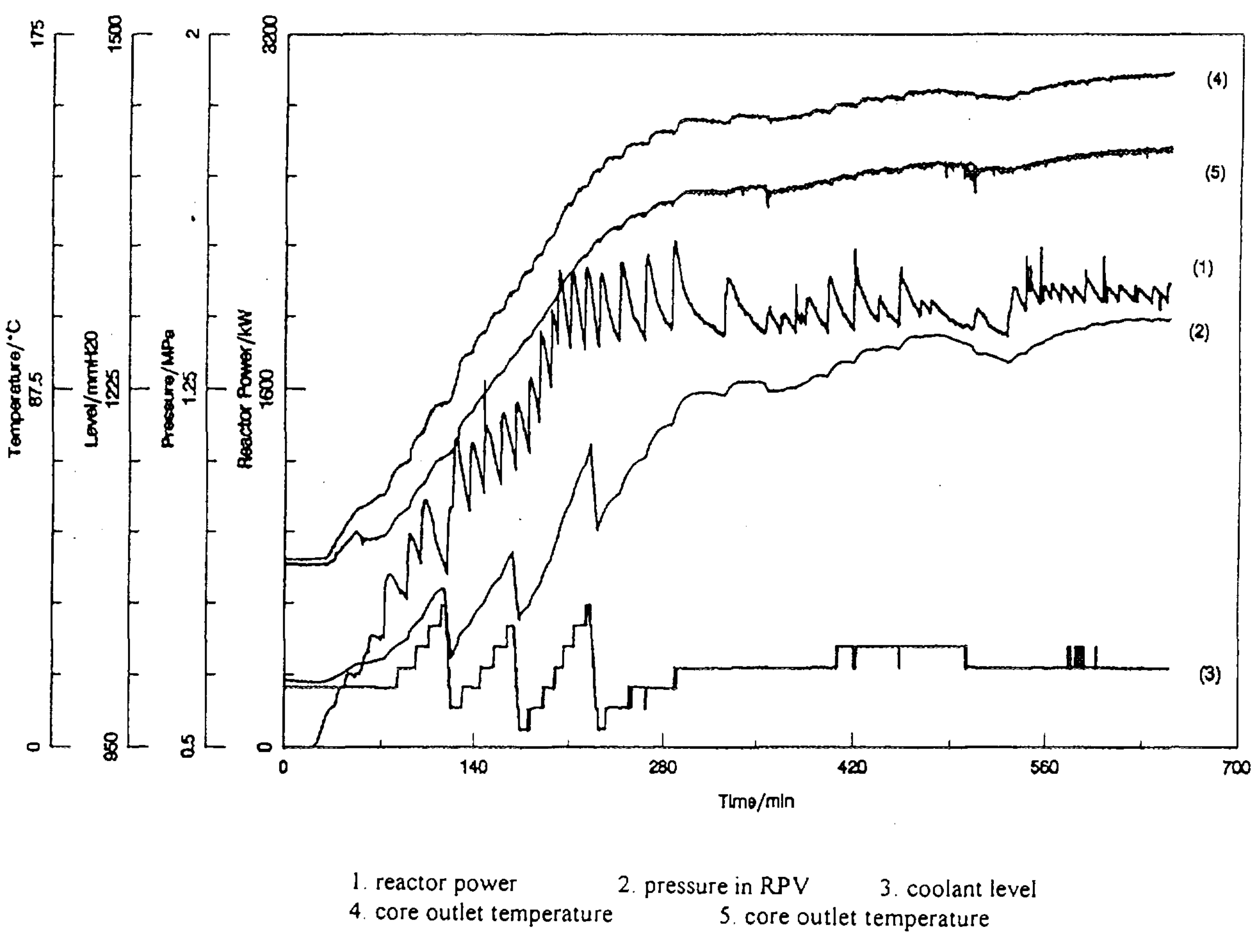


Fig.5 The start up process of NHR-5

i.e. to set up the initial partial pressure of nitrogen in the RPV, to limit the rising temperature rate to less than 50°C/hr in primary circuit and to keep the coolant level in the RPV in a certain range. Fig.5 shows the start up process to full external load.

Feeding nitrogen and water into RPV

Feeding nitrogen and water into the RPV to compensate their loss caused by various reasons (mainly sampling) is needed for maintaining the normal operating conditions of the NHR-5.

As a result of feeding gas into the RPV, the reactor power increases with the pressure increases and comes to a peak. After that it begins to decrease and finally reaches a new steady state. The result is given in Fig. 6. In the process of this experiment, the reactor power increased by 5.7%, the core inlet and outlet temperature rose 1.1°C and 1.4°C, respectively. The variation of reactor power indicates that there is a certain void content in the core at operation condition.

The reactor has a similar behavior when the water enters the downcomer and then into the core. Due to the coolant level rising, and the feed water temperature being less than the coolant temperature, the core inlet temperature slightly decreases and the pressure increases. For both reasons of pressure rising and temperature decreasing the reactor power increases. The experimental results are given in Fig. 7.

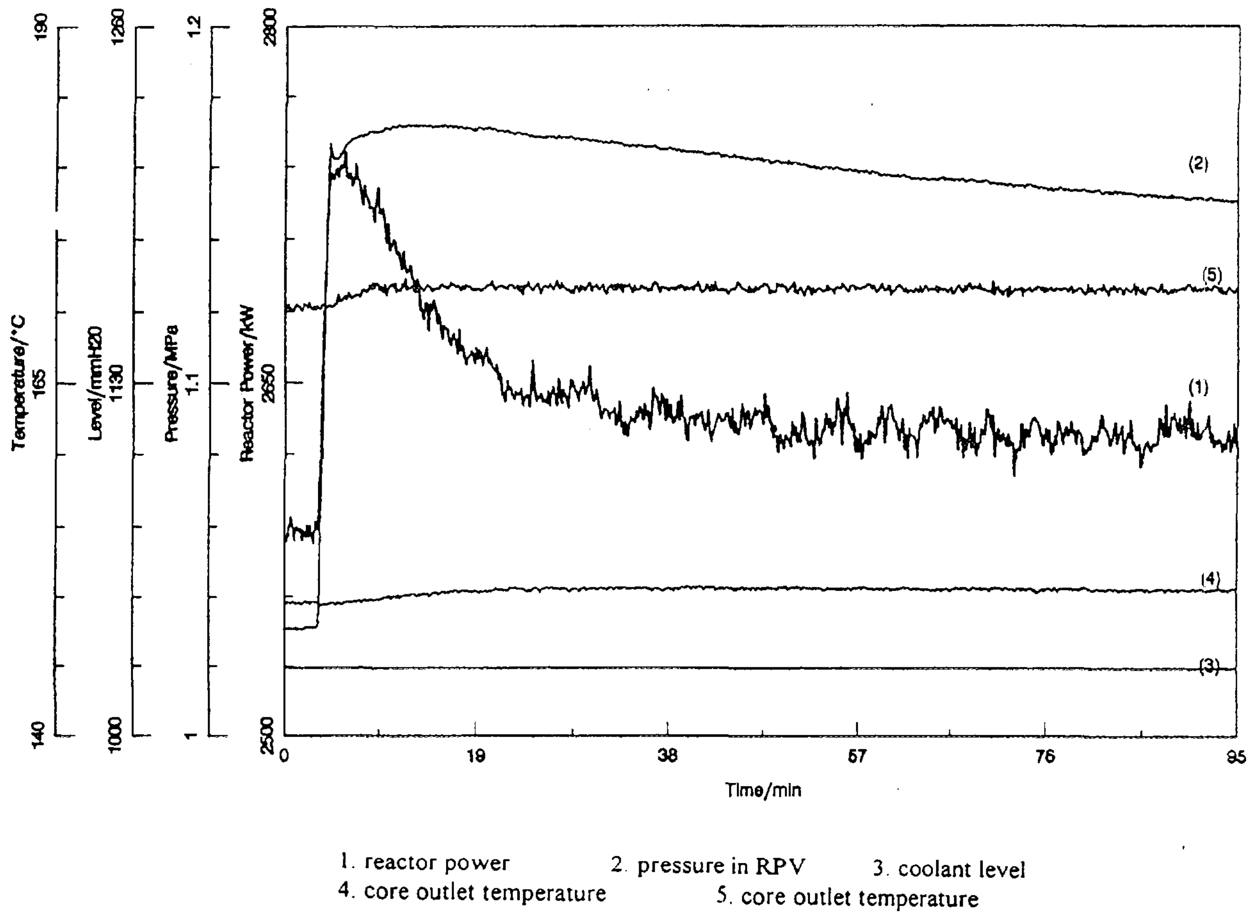


Fig.6 Feeding nitrogen into the RPV

Self-pressurized performance

A space in the upper part of the vessel is used for self-pressurizing. The total pressure in the RPV is formed by both a nitrogen partial pressure of 0.3MPa and a saturated steam partial pressure of 1.17MPa which corresponds to the core outlet temperature of 186°C.

The change of the total pressure in the RPV caused by various transient conditions is smooth and small, which results from the large coolant inventory and the large self-pressurized space. For example, when the external load changed to 60% the total pressure in RPV only changes 5%.

The changes in total pressure is by reason of both the changes of core outlet temperature and coolant level.

High operational availability

As a heating reactor, the NHR-5 is only operated in winter. The operational availability of the NHR-5 is evaluated by comparing the actually operated days with the planned operation days. From December 1989 to March 1993, the NHR-5 has been operated for more than 9330 hours. The average availability of the heating operation was about 99%.

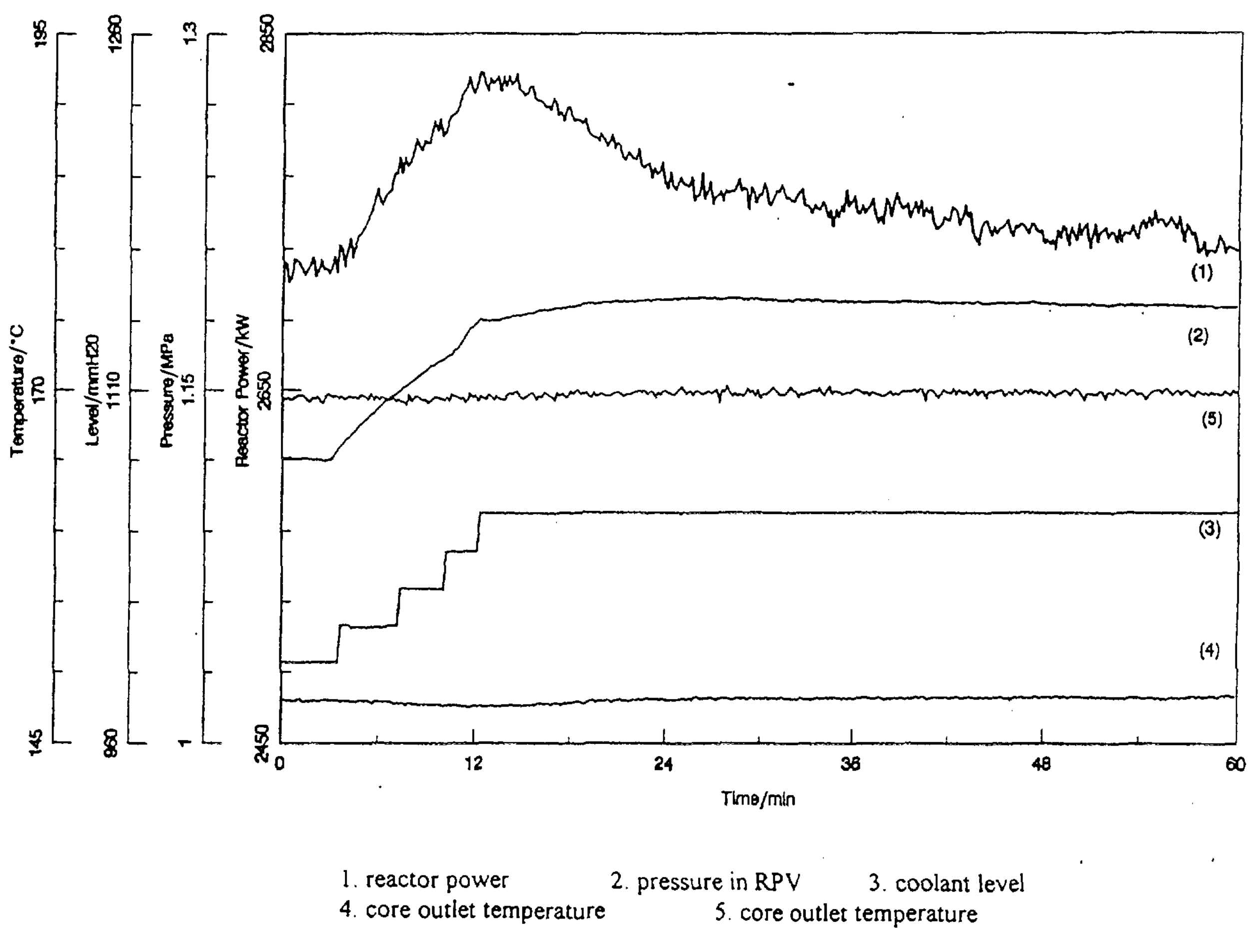


Fig.7 Feeding coolant water into the RPV

During the four winters operation, there were four unexpected reactor shutdowns caused mainly by failures of electric power supply and faults in the auxiliary systems. Each duration of reactor shutdown was less than 4 hours, so space heating was not affected very much due to the great heat capacity of the heat grid. In spite of the fact that the NHR-5 is the first kind of vessel type heating reactor, it has reached a high availability of heating operation.

3.2. Radiation protection and environmental impacts

Specific radioactivity of water in three loops

During operation the water radioactivity level in the primary circuit, the intermediate circuit and the heating grid have been regularly monitored. The radioactive back-ground of potable water of the site area is about 0.10 Bq/l. The radioactivity level in the water of the intermediate circuit and the heating grid are as low as that of potable water. In the primary circuit the specific radioactivity of coolant is at the level of 2.5E2 to 2.7E3 Bq/l. The nuclide analysis showed that there were no fission products in the coolant.

From the point of view of radioactivity, the isolating the intermediate circuit performs a perfect function in keeping the heating grid free of radioactivity.

Radiation exposure rate

The distribution of radiation exposure in the NHR-5 building is reasonable. A large part of the building have a very low exposure rate near the background level. A higher exposure rate is found outside the biological shielding where the reheater of the primary purification system is placed. A local shielding with lead had to be added to reduce the radiation exposure rate.

Effluents

During normal operation, the gaseous effluent radioactivity level is at the same level as that of the background. The nuclides analysis indicated that there was no artificial nuclide in the effluent. The nuclides in the effluent are natural ^{40}K and Radon daughters. The amount of waste water produced from operation and maintenance is about 10.2 m^3 in four years.

Collective dose

The collective doses for all operators in each heating period are also very low, and are indicated in Table 4. The data demonstrate that the radiation protection design of the NHR-5 was successful.

TABLE 4: COLLECTIVE DOSE FOR ALL OPERATORS IN EACH HEATING PERIOD

Period	Collective dose (mSv-man)
11.1989 - 3.1990	2.4
11.1990 - 2.1991	3.2
11.1991 - 3.1992	11.4

In addition, there are many items to regularly monitor onsite and offsite, such as gamma exposure, gross beta-radioactivity level of aerosol and service drains, offsite samples of water, soil, air and plants, etc.

All measured data indicate that the NHR-5 operation does not cause any changes in radioactivity levels in this area.

3.3. Water chemistry of NHR-5

In consideration of the features of NHR-5: low temperature, low power density, and refueling period being longer than for a PWR, and by reference to the operating experience of nuclear powered ship "Otto Hahn", a water chemistry differing from PWR and BWR is adopted in the operation of the NHR-5. This water chemistry is based on neutral water, not to contain boron and not to add hydrogen to the primary coolant; oxygen is removed by chemical additive (C_2H_4).

The results of monitoring and analyses show that the dissolved oxygen can maintain the level of 40 ppb and a pH value of 6-7. Table 5 lists the analysis results and the specification of primary coolant.

TABLE 5: SPECIFICATION AND MONITORED RESULTS FOR PRIMARY COOLANT

Item	Specification	Analysis results
Dissolved oxygen	<50 ppb	30-40 ppb
pH (25°C)	6-10	6-7
F	< 100 ppb	< 50 ppb
Cl	< 100 ppb	< 50 ppb
Cr	< 10 ppb	< 0.1 ppb
Fe	< 10 ppb	< 0.05 ppb
Na	< 5 ppb	< 5 ppb
Cu	----	< 0.2 ppb
NO_3-	----	< 5 ppb
NO_2-	----	< 5 ppb
Total solids	< 100 ppb	< 0.5-1ppm

The nitrate and nitrite contents are less than 5 ppb in the coolant at any operating condition. This concentration is too low to cause metal structures to corrode. So, nitrogen used as cover gas is feasible for the NHR-5.

In order to effectively decrease the dissolved oxygen level in the primary coolant, three things have to be done in the future. The first is to remove the oxygen from the makeup water, the second is to add an additive to the primary circuit continuously, and the third is to exhaust the air from the nitrogen supply lines, especially the nitrogen cylinder.

3.4. Operation of intermediate circuit

Function of intermediate circuit

Besides the function of isolating radioactivity, the intermediate circuit also has other important functions. The heat generated in the core has to pass through it on its transfer to the heat grid. That means a change in operation mode (for example to change the flow rate) will affect the heat transfer to the heat grid. The operation practice demonstrated that the present operation mode of intermediate circuit to be changed is favorable over increasing its average temperature, especially when the reactor is operated at partial load.

To maintain isolating function

To keep the pressure in the intermediate circuit higher than in the primary circuit is the important condition to keep the isolating function. The RHRS is a part of the intermediate circuit during normal reactor operation. In the normal operation condition the pressure in the intermediate circuit depends on the pressure of the pressurizer tank (A) in this circuit. When the intermediate circuit is isolated the isolating condition depends on the pressure of the pressurized tanks (B and C) installed in the RHRS. The two pressurized tanks are connected to the RHRS by small bore valves and piping. Its advantage is that the isolating function can be kept beyond a large loss of water from the intermediate circuit.

Detection of leakage rate for the intermediate circuit

The changes in water level in the three pressurized tanks (A, B and C) is used for detecting the leakage rate. This method is applicable for steady state operation. The operation practice indicates that the leakage rate is more than 2 l/hr (normal leakage rate). This abnormal leakage must occur somewhere else in this circuit.

3.5. Operation of RHRS

The reactor residual heat is removed by a passive residual heat removal system which connects to the intermediate circuit. There are two independent trains of the RHRS which is composed of three natural circulation loops (see Fig. 4).

Hot standby condition

When the reactor is operated in normal condition, the RHRS is working in a hot standby condition. In this case the vaporizer of RHRS and primary heat exchangers work in parallel, and a very small part of the flow rate in the intermediate circuit passes through the vaporizer to prevent freezing in the air-cooler. In order to set up the second circulation-vaporization- and condensation loop, the air on the shell side of the vaporizer has to be discharged at high temperature.

The outlet and inlet temperature of the air-cooler have the approach value, which is the main feature of hot standby condition.

Direction of natural circulation

When the RHRS is put into operation the primary heat exchanger and vaporizer will change from parallel mode to series mode. So the direction of water flow must change in either the vaporizer or the primary heat exchangers, depending on the temperature distribution in this system. In general, if the reactor is operated at a high power level the direction of natural circulation will be the same as in the primary heat exchanger. If the reactor is at a low power level, the direction will be the same as in vaporizer. The experimental results indicated that both circulation directions have the same capacity to remove the decay heat from the core.

From the experimental results it is indicated that the natural circulation of the RHRS can be reliably established, and that the direction of natural convection in the intermediate circuit did not affect the decay heat removal.

Capability test of RHRS

According to the principle of thermal energy balance, the heat removal capability of RHRS is measured at a steady operation state of NHR-5. The heat generated in the reactor core should be balanced by the heat loss, the heat drawn by the purification system and the heat removed by the RHRS. A heat removal capability of 116 KW was measured at the average temperature of 166°C in the primary circuit. This value is more than the design value of 75 KW for each train.

In addition, the RHRS can be operated at a lower temperature than 100°C, and still has a certain capability to remove the residual heat from the core. This shows that the reactor can be cooled down to the cold shutdown by the RHRS only.

3.6. Operational status of control rod driving system

The control rod driving system was satisfactory for starting up, regulating reactor power, and reactor shutdown during the past operation. The full travel time for dropping into the core was still less than 2 seconds.

Owing to the use of a temperature compensation device in the hydraulic drive system, it is not necessary to adjust the flow rate at high temperature.

The ultrasonic position indicators were also satisfactory for indicating the position of the control rods under the pressurized water operation mode. The ultrasonic indicator system can not work under two phase flow or the condition with an interface of gas and liquid. Therefore, the correct position of control rod would not be indicated in this system at the loss of pressure or fast pressure reduction inside RPV.

At the beginning of commissioning a special method has been used for eliminating the interference with ultrasonic sensors to the fission-chamber detecting system.

4. SAFETY FEATURES EXPERIMENT OF NHR-5

In the course of commissioning and operation, a number of experiments have been carried out to demonstrate the feasibility and safety of the vessel type heating reactor concept. In these experiments there were no any external interferences by the operators.

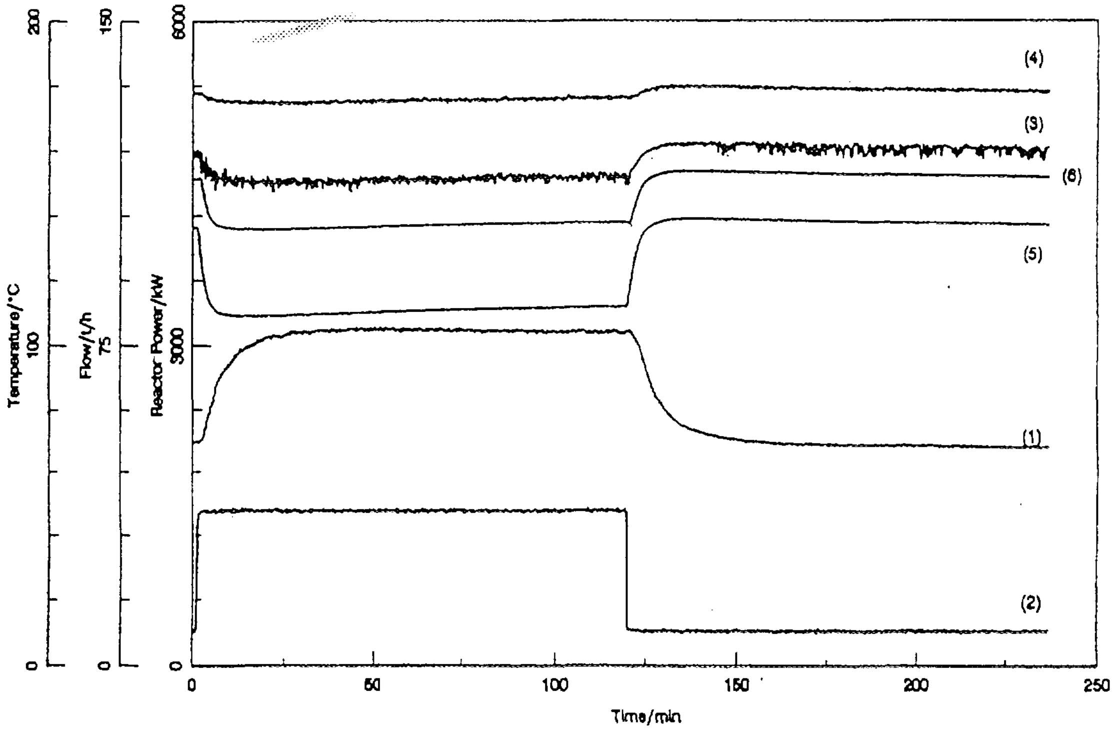
4.1. Self-regulation feature

The self-regulation experiment has been performed to investigate the reactor self-regulation ability to follow a change of the heating load. The heating load can be varied by means of changing the flow rate through the intermediate heat exchangers.

The flow rate through the intermediate heat exchangers was changed from 8 t/hr to 35 t/hr, then back to 8 t/hr. This value corresponds to a heating load change from 1.5 MW to 2.5 MW, a variation of about 66%. Figure 8 shows the behavior of the NHR-5 following the heating load change. The reactor power, caused by the self-regulating mechanism automatically to vary within 90 seconds, reached a new power level to match the heating load within 30 minutes. The moderator temperature coefficient plays a main role in this process. The experimental results show that the NHR-5 has a very good self-regulation ability to follow a load change without any operator action.

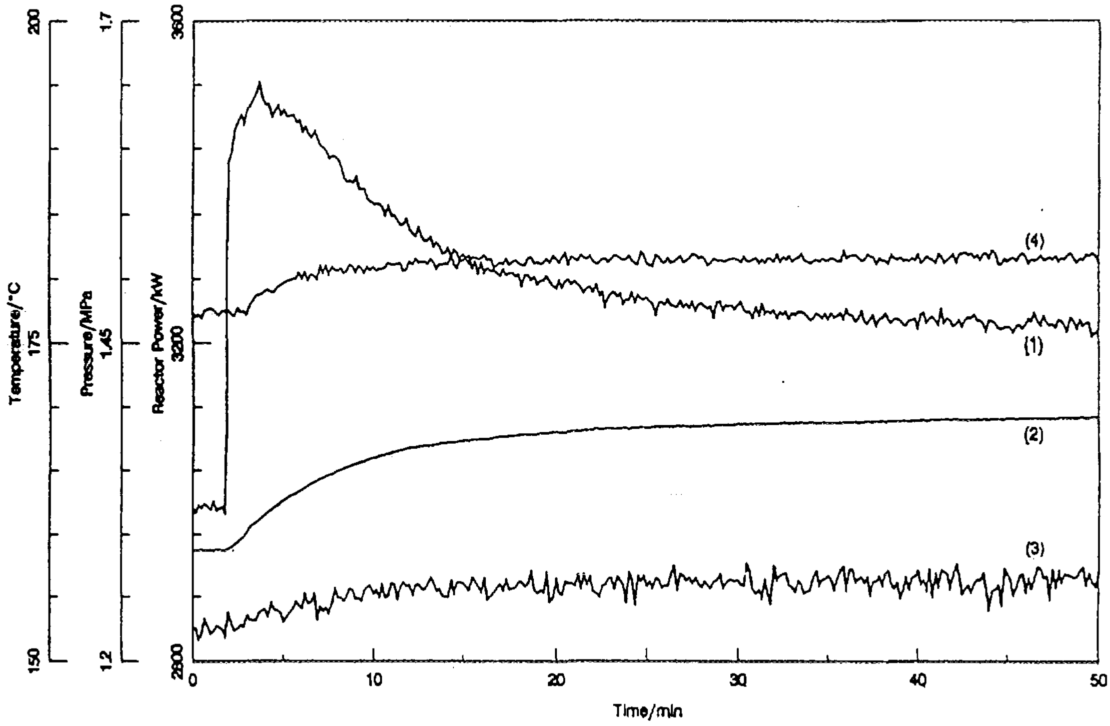
4.2. Self-stability feature

The self-stability experiment was performed in order to investigate the response to a reactivity insertion. In this experiment the reactor was operated at a power of 3.0 MW, then a step insertion of 2 mk reactivity was introduced. Figure 9 indicates the variation of the reactor parameters. At the beginning of the transient, the reactor power increased rapidly due to the extra reactivity and reached a maximum relative value of 1.18 in 100 seconds.



1. reactor power
2. flow rate through intermediate heat exchanger
3. core inlet temperature
4. core outlet temperature
5. inlet temperature in the 2nd of primary heat exchanger
6. outlet temperature in the 2nd of primary heat exchanger

Fig.8 The NHR-5 self-regulation feature



1. reactor power
2. pressure in RPV
3. core inlet temperature
4. core outlet temperature

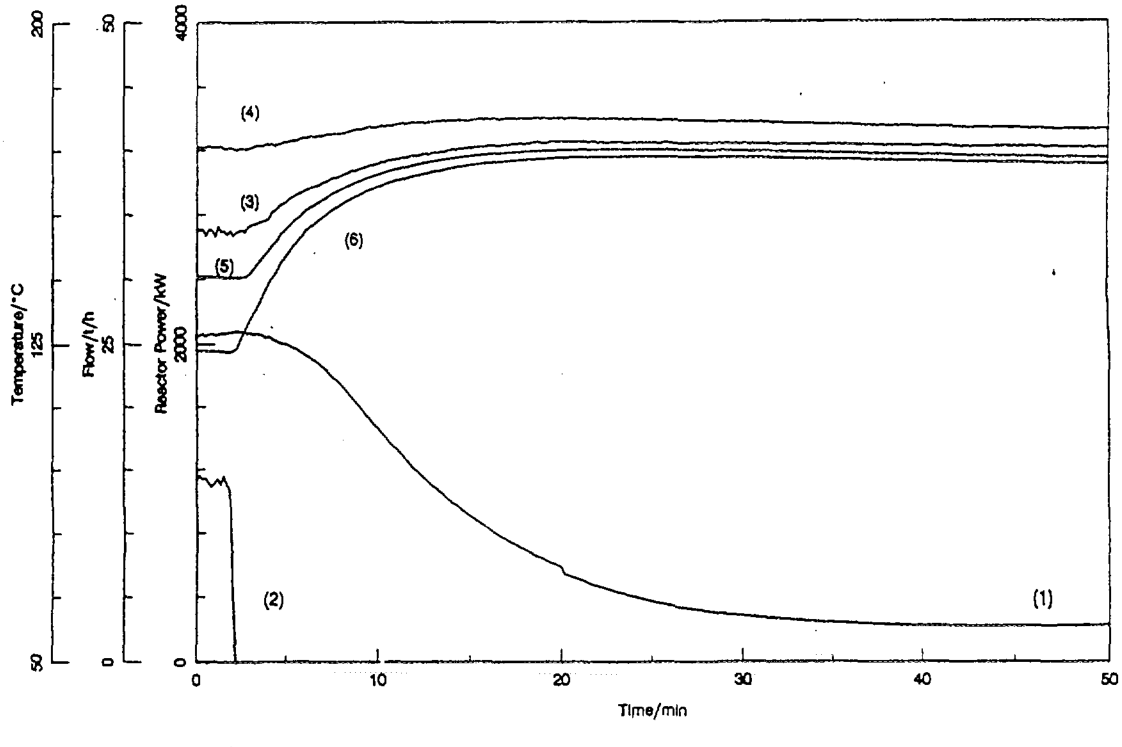
Fig.9 The NHR-5 self stability feature

Then the reactor power began to decrease due to the feedback of the negative reactivity coefficient, and came to a new relative power level of 1.08 in 30 minutes. The core inlet and outlet temperatures added an increment of 3.8°C and 4.2°C, respectively. The reactor pressure increased with a Δp of 0.102 MPa.

4.3. Experiment for ATWS

In order to study the safety behavior of the NHR-5, in 1990 an experiment has been carried out which simulated an ATWS, i.e. a loss of the main heat sink followed by the failure of all 13 shutdown rods.

In this experiment, the intermediate heat exchangers were isolated at a reactor power of 2 MW, and none of the shutdown rods was inserted. Figure 10 shows the power variation observed, together with the changes in temperature and pressure of the reactor. The power decreased as a consequence of the feedback due to the negative temperature coefficient to a stable value of about 0.2 MW in about 30 minutes. The inlet and outlet temperature of the reactor core rose by 20.4°C and 4.7°C respectively. The temperature variation is not serious at all. The primary system pressure rose by 0.23 MPa. The result of the experiment demonstrated that the NHR-5 has excellent inherent and passive safety features. The reactor will be shutdown passively even in the described ATWS case.



1. reactor power 2. flow rate through intermediate heat exchanger
3. core inlet temperature 4. core outlet temperature
5. outlet temperature in the 2nd of primary heat exchanger
6. inlet temperature in the 2nd of primary heat exchanger

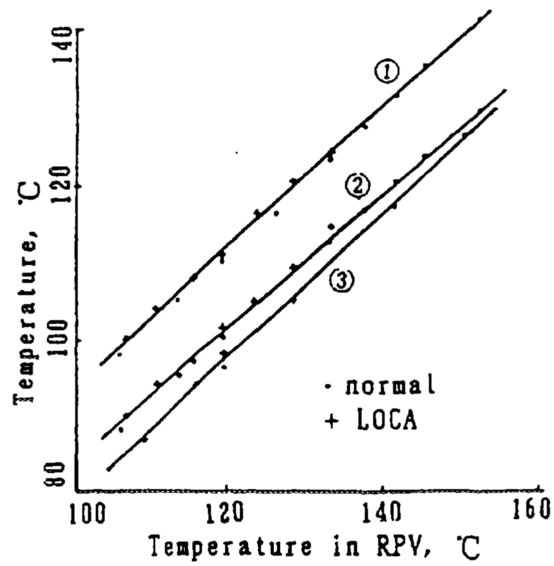
Fig.10 The transient behaviour of loss of main heat sink without scram

4.4. Residual heat removal after interruption of natural circulation in the primary circuit

When a loss of coolant accident (LOCA) occurs in the primary circuit, the water level inside the RPV will decrease. Due to the integrated arrangement of the primary circuit, and due to the feature that all penetrations of small pipes are located at the upper part of the vessel, the reactor core will never be uncovered. But as a result of the water level decrease the natural circulation of the water in the primary circuit might be interrupted. In this case the residual heat of the reactor will be transported by vapor condensed at the uncovered tubes of the primary heat exchangers.

To demonstrate the capability of residual heat removal under LOCA conditions a special experiment was made at the NHR-5 in March 1992. After reactor shut down the water in the reactor vessel was discharged by opening the valve to the blowdown tank. The water discharge rate was 1.6m^3/hr and an amount of 2.4 m^3 water was drained off. The water level in the reactor vessel decreased below the entrance of the primary heat exchanger and the water-phase natural circulation was interrupted. In this case the residual heat removal was mainly realized by condensation of the vapor. Due to the discharge of 2.4 m^3 water the partial pressure of nitrogen reduced from 0.29 MPa to 0.022 MPa, so that the water subcooling of the reactor outlet temperature decreased from 12°C to 2°C.

The reduction of subcooling enhanced the vaporization - condensation process. Figure 11 shows the comparison of the residual heat removal capabilities during LOCA conditions and under the normal operation. From the results of the comparison it can be shown that the procedures of both LOCA and normal operation are almost the same. The decay heat can be reliably removed by means of vapor condensation on the primary heat exchanger under LOCA conditions.



1. inlet temperature of vaporizer 2. outlet temperature of vaporizer
3. inlet temperature of aie-cooler

Fig.11 The comparison of the capability of residual heat removal

5. SUMMARY

During four winters of NHR-5 heating operation, the reactor has been known as a valuable tool for a number of experiments on operational behavior and safety features. The operational and experimental results have successfully demonstrated the inherent and passive safety characteristics of the NHR-5. It was proven that the design concept and technical measures of NHR are suitable to meet the requirements for district heating in northern cities, cogeneration and air condition in the middle cities of China, as well as the requirements for seawater desalination.

REFERENCES

[1] Wang Dazhong et al, The 5MW Nuclear Heating Test Reactor, Nuclear Engineering (in Chinese), Vol. 11, No.5, May 1990

[2] Zhang Dafang et al, The Initial period Heating Operation at Tsinghua 5MW Experimental Heating Reactor, Journal of Tsinghua University (in Chinese), Vol.30, No.S2,1990

[3] Zhang Dafang, et al, The Experimental Study for Residual Heat Removal System in 5MW District Heating Plant, Nuclear Engineering (in Chinese) vol.12, No.2, 1991

[4] Final Safety Analysis of NHR-5, INET-Document March 1988

[5] Wang Dazhong et al, Experimental Study and Operation Experience of the 5MW Nuclear Heating Reactor, Nuclear Engineering and Design 143 (1993) 9-18

[6] Zhang Dafang et al, The Experimental Study of the Operation Features at Tsinghua 5MW Test Heating Reactor, Atomic Energy Science and Technology (in Chinese), Vol. 24, Nov.1990

[7] Xin Renxuan et al, Water Chemistry in NHR-5, INET Report, Nov. 1993

[8] Dietmar Bittermann, et al, Design Aspects and Pertaining Development Work for the KWU 200MWth Nuclear Heating Reactor, Nucl. Engery Des. 108 (1988) 403-417

[9] Feng Yuying et al, Evaluation of Environmental Radiation Monitoring For Two Operation Years in NHR-5, INET Report, April 1991