



ANALYSIS OF THE NUCLEAR HEATING REACTOR AND ITS POSSIBLE APPLICATION IN SEAWATER DESALINATION

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Abstract

In order to mitigate the problems of the energy shortage, environmental pollution caused by coal burning and the transport burden in China, the Institute of Nuclear Energy Technology (INET), Tsinghua University, under the support of the state, began the research and development (R&D) of nuclear heating reactor (NHR), which is one of the national key R&D projects in China since the 1980's. Since a 5MW test NHR was completed in November 1989, a lot of experiments have been carried on the NHR-5. The NHR-200 is developed on the experience gained from the design, construction, start-up and operation of the NHR-5. It is designed with a number of advanced and inherent safety features. The main technical and safety features of NHR-200 are: a vessel type light water reactor with the integrated arrangement, full power natural circulation, self-pressurized performance and dual vessel structure. The hydraulic driving system of the control rods is adopted. The design of the NHR-200 insures that the reactor core can be always covered by coolant at any LOCA conditions and the possibility of rods ejection event is excluded by using hydraulic control rods driving system. The excellent performance of the NHR-200 shows that it is suitable to the coupling with a seawater desalination plant from both technical and economic stand. According to the systematic analysis and comparison of economy, technology and safety, the selected coupling design of desalination plant with the NHR-200 are: the steam generator plus multi-effect distillation (MED) process for single water production and the steam generator plus turbine system plus MED process for cogeneration of water-electricity. The economic analysis based on the above mentioned two coupling designs has been conducted. The desalinated water price and its influential factors are determined under present technological circumstances. And some specific proposals of which system to select are given.

1. Introduction

The energy supply has been one of the major problem which strongly impacts the socio-economic development in China. Coal plays an important role in China's primary energy supply systems. According to a study on the energy strategy of China, about 75% of the primary energy consumption is contributed by coal. Enormous consumption of coal leads the very serious problems in environmental pollution, which will become unacceptably serious in some cities if no action is taken immediately. In addition, since the coal production district is highly concentrated in the North and Northwest China, while the main consumption district is located in Northeast, East and Southeast China, the produced coal must be usually transported after a long distance to the end user. Coal transportation takes up more than 40%, 25% and 20% of the railway, highway and waterway freight capacity. It aggravates the serious situation of communications and transportation.

In order to mitigate the problems of the energy shortage, environmental pollution caused by coal burning and the overburdened transportation systems, the Institute of Nuclear Energy Technology (INET), Tsinghua University, under the support of the state, has begun the research and development (R&D) of nuclear heating reactor (NHR), which is one of the national key R&D projects in China, since the 1980's.

The INET conducted successful tests of nuclear district heating using the existing pool type research reactor in 1983 and 1984. The project of a 5MW test NHR (NHR-5) was started in 1984 and begun to construction in 1986 and completed in 1989. In November 1989 the test reactor went the first criticality.

Since then, It has been successfully operated for district heating and a lot of experiments have been carried on the NHR-5. On the basis of the successful of NHR-5, a commercial sized NHR with output of 200MW thermal power (NHR-200) has been developed by INET^[1]. Several cities and large enterprises are interested in introducing NHR into their local energy system. The application for the construction permit of the first demonstration NHR-200 was submitted to the National Nuclear Safety Administration in December 1995 with the attached documents and now the preparation of the project is in progress. At the same time, the other three projects are planning. One is to provide process steam for the new developing district in Shanghai, China. The other two are used as energy source to couple with desalination plant in Dalian, China and in Morocco.

2. Main technical and safety features of NHR-200

The NHR-200 is developed on the experience gained from the design, construction, start-up and operation of the NHR-5. It is designed with a number of advanced and inherent safety features, including integrated arrangement, natural circulation, self-pressurized performance, hydraulic control rods driving and passive systems. It could be used in district heating, air conditioning, seawater desalination and other industrial processes. The main design parameters of NHR-200 and NHR-5 are listed in Table I.

Table I Main design parameters of the nuclear heating reactor

		NHR-5	NHR-200
Thermal power	MW	5	200
Primary system pressure	MPa	1.5	2.5
Core inlet/outlet temperature	°C	146/186	140/210
Ave. linear heat rate	kW/m	5.6	7.67
Volumetric power density	kW/L	26	36.23
Number of fuel assemblies		16	96
Number of control rods		13	32
Active core height	m	0.69	1.9
Active core diameter	m	0.57	1.9
Inventory of UO ₂	t	0.51	14.87
Enrichment of initial core	%	3	1.8/2.4/3.0
Refueling enrichment	%	3	3
Intermediate circuit temperature	°C	102/142	95/145
Intermediate circuit pressure	MPa	1.7	3.0
Heating grid temperature	°C	90/60	130/80

2.1 Technical description of the NHR-200

The NHR-200 is a vessel type light water reactor. The main technical features can be briefly summarized as follows^[2].

a) Integrated design. Both reactor system and the primary circuit, including primary heat exchangers (PHEs), are arranged into the reactor pressure vessel (RPV). The core is located at the bottom of the RPV, and six PHEs are arranged within the annular space between the riser and vessel wall. The riser with height of 5.1m above the core outlet is to enhance the capability of natural circulation. Spent fuel assemblies are stored in the racks around the core. All of the penetrations are on the upper part of the RPV and the biggest diameter of the penetrations of coolant pressure boundary is $\phi 50\text{mm}$. Fig.1 shows the reactor structure.

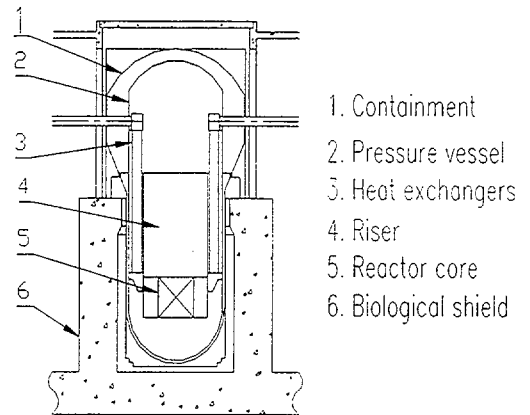


Fig.1 Reactor structure of NHR-200

b) Full power natural circulation cooling. The coolant circulates due to the density difference between hot and cold regions inside the RPV at all power levels so that the primary circulating pumps can be eliminated and the higher system reliability can be ensured. The decay heat is removed also by natural circulation and a special test, which was conducted on NHR-5, indicates that this kind of residual heat removal system is effective even if the natural circulation in the primary circuit is interrupted.

c) Hydraulic driving system of the control rods. This system meets the requirement of “fail-safe” principle i.e. control rods will drop into reactor core automatically by gravity under lose of power supply, depressurization of RPV, pipe break and pump shut down events. This design simplifies the reactor structure and eliminates the accident of rapid rod ejection. There is no boric acid in the coolant during normal operation. Gadolinium oxide as a burnable poison is used to control the reactivity along with the B_4C control rods. In addition, a boric acid injection system as a secondary shutdown system will be operated when anticipated transient without scram occurs.

d) Self-pressurized performance. The primary pressure, composed by the saturate steam pressure corresponding the core outlet temperature and a certain inventory of nitrogen, regulates itself very stable at the designed level.

e) Dual vessel structure. A tight steel containment is equipped around the RPV. The containment vessel will ensure the flooding of the reactor core without any emergency cooling actions in case of a very unlikely failure of the RPV. A secondary concrete containment is adopted to mitigate the mental fear of some resident on the nuclear energy.

2.2 Safety concepts of the NHR-200

The design of the NHR-200 insures that it is operated under the low temperature, low pressure, low power density and low radioactivity content in primary coolant. The main safety features can be briefly summarized as follows^[3].

a) A number of passive safety measures. That the core is always covered by coolant is one of the fundamental design criteria for the NHR-200. This result is caused by the follow measures, integrated design to exclude the possibility of large LOCA, on the upper parts of the vessel and small bore of all penetrations limits the loss of coolant, dual vessel design and huge subcooled water inventory. In addition, except full

power natural circulation cooling, a passive pattern used in the residual heat remove system, hydraulic driving system for control rods and dual vessel design, all of these above mentioned, low power density and large negative feedback as well as quite large margin of DNBR in the accident condition can maintain the integrity of fuel cladding at any transients and accidents. The results of accident analysis for the NHR-200 indicates that the accident of $\phi 50$ penetration pipe break outside the steel containment followed by failure of isolation is the most serious LOCA accident. The results of LOCA analysis for the NHR-200 are listed in Table II. The main results of the safety analysis based on any design basis accidents can be summarized as follows. DNBR_{min} is always greater than safe limit. Peak pressure in primary system is far below its design pressure and the integrity of coolant pressure boundary will be maintained properly. The core will never be uncovered. The maximum fuel enthalpy is much lower than safe limit and the release of radioactivity is much less than the prescribed limit.

b) The effective isolating heating grid or fresh water from radioactivity. The multi-barriers including fuel cladding, reactor pressure boundary, steel containment and secondary containment compose the multi-defenses against the release of radioactive substance. In addition, the nuclear steam supply system (NSSS) is composed by triple loops, i.e. the primary circuit in the reactor pressure vessel, a intermediate circuit and the heating grid or the steam circuit. The working pressure in the intermediate circuit is higher than that in the heating grid or in the steam circuit, so the pollution of radioactivity can be prevented from and the safety of the heating grid or the produced water can be ensured.

Table II Results of LOCA analysis for NHR-200

Events*	Accident circumstances		
	Ultimate pressure in the reactor pressure vessel MPa	Amount of water lost t	Amount of water remained above the core t
1	1.68	23.6	69.3
2	~0.12	45.3	47.6
3	1.04	34.2	58.7
4	0.60	8.25	84.65
5	1.70	11.4	81.5

- * Event 1 $\phi 50$ pipe break inside the steel containment
- Event 2 $\phi 50$ pipe break outside the steel containment followed by failure of isolation
- Event 3 Small crack ($\sim 1\text{cm}^2$) at the bottom of the RPV
- Event 4 Safety valve stuck open
- Event 5 ATWS initiated by loss of off-site power and safety valve not reclosing

3 Seawater desalination with NHR-200

3.1 Option of desalination process

The excellent performance of the NHR-200 shows that it is suitable to the coupling with a seawater desalination plant. Among the various existing desalination processes worldwide, the following have been selected for the present study as the most interesting for nuclear desalination: reverse osmosis (RO), multi-effect distillation with vapour compression (MED/VC), multi-effect distillation (MED), and multi-stage flash distillation (MSF). And all of these are proven by experience. Among them, MED and MSF may come into consideration to couple with NHR-200. The energy input is mainly in the form of low temperature heat and some electricity for the two distillation processes. But the energy consumption of MSF is greater than MED.

Based on an evaluation of the technological status of the two distillation processes, INET selects MED process for desalination study using NHR-200 or other scale NHR.

In order to match different user's requirements, several scales of the NHR desalination plant are included in the INET's study program, including NHR-200 desalination plant, NHR-10 desalination plant and NHR-5 desalination plant. The pre-feasibility study on the NHR-10 desalination plant in Morocco is in progress.

3.2 Coupling of desalination plant with NHR-200

The main parameters of NHR-200 perfectly match the requirements on the heat source for seawater desalination processes. Based on the study of the technological features of NHR-200 and the MED process, the selecting principles of the coupling plan of desalination plant with NHR-200 are realizable in technology, reliable in safety and optimum in economy. Two kind of interface design between NHR-200 and MED plant was conducted, one is to produce water only and another is to co-generate water and electricity. The choice among these two designs is depended mainly on site features, the design of water production only can gain a larger gain-output ratio (GOR), and the design of water and electricity co-generation can satisfy the requirement for electricity consumption of the NHR-200 and of the MED plant.

According to the analysis on the 8 coupling plans^[4] for the water production only, the best one is: steam generator + MED plant. The system diagram of this coupling design is shown in Fig.2 and main parameters are listed in Table III. Within this design, the low pressure steam generated in the intermediate circuit steam generator will be directly introduced to the MED plant. A GOR of 20.76 is designed and the daily fresh water production will be 165,052m³.

The purpose of the heat/electricity co-generation design is to ensure the supply of fresh water and not to intensify the shortage of electricity supply. The basic demand for this purpose is that the generated electricity shall be used for the self-consumption both for the reactor and for the desalination process, and that the output of fresh water shall be greater than 120,000m³/d. After comparing the other 8 coupling plans for the cogeneration^[4], the selected optimum interface is: steam generator + turbine system + MED plant. Fig.3 shows the system diagram of this interface and key design parameters are listed in Table 3. The steam will first be used for electricity generation. And then, the steam extracted from the last stage of the turbine with lower temperature and pressure will go to the MED system. The maximum fresh water output will be 127,583m³/d with a GOR of 17.89 and the generated electric power will be 14.42MW.

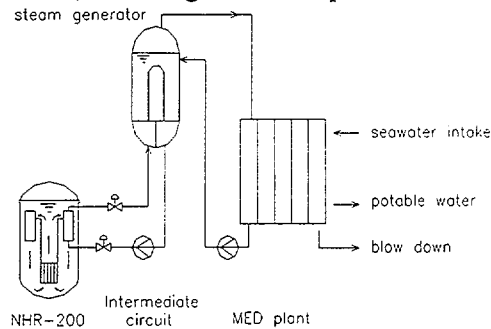


Fig.2 Simplified system diagram of water production only

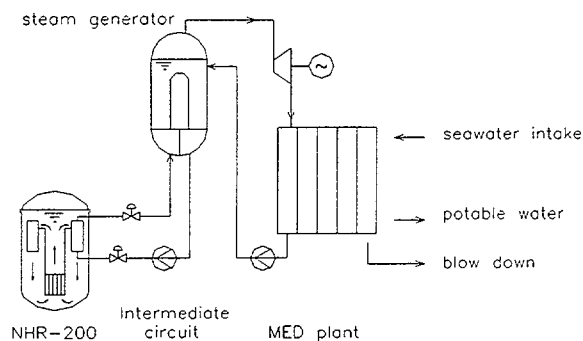


Fig.3 Simplified system diagram of co-generation

Table III Main parameters of the two coupling designs

Design parameters		Water only	Co-generation
Reactor thermal power	MW	200	200
Pressure in primary loop	MPa	2.5	2.5
Core inlet/outlet temperature	°C	154/213	154/213
Intermediate loop inlet/outlet temperature	°C	135/163	135/163
Ratio of investment and power of the reactor	\$/kW	552.0	552.0
Steam generator outlet steam temperature	°C	130	145
Inlet steam temperature of MED process	°C	130	102
Unit capacity of MED plant	m ³ /d	48,000	48,000
Number of unit		4	3
Number of effect		30	23
Gain-output ratio (GOR)		20.76	17.89
Efficiency of the turbine generator	%	—	72.7
Electric power	MW	—	14.42
Self-consumption of electricity	MW	—	13.36
Maximum fresh water production	m ³ /d	165,052	127,583
Interest rate	%	8	8
Material cost factor*		0.8	0.8
Price of water	\$/m ³	1.188	1.206

* The material cost factor is the ratio of the other two ratios, one is the ratio of investment and produced water using low temperature material and high temperature material respectively and another is using high temperature material only under the condition of the same number of effect in MED process.

3.3 Economic analysis

Several advantages can be gained using a NHR for seawater desalination. Compared with a fossil-fueled plant, a NHR desalination plant may not only save large amounts of valuable coal and oil resources and decrease environment pollution but will also be competitive economically under some certain conditions. Due to the inherent and passive safety features of the NHR itself, the NHR desalination plant can be constructed near big cities and industrial consumers. It would lead to a decrease in the cost of the water pipe network.

On the basis of the data provided in IAEA-TECDOC-666, the water prices both of the water production only and water/electricity cogeneration using NHR-200 have been analyzed with the method of output cost per unit and the method of effective credit. Water storage, transport and distribution facilities are not included. The result indicates that the main part of the water price is constituted by the annual fixed capital charge of water plant and heat charge. The water price listed in Table 3 are slightly higher, but the water price may reduced to 0.93\$/m³ for water production only and 0.955\$/m³ for cogeneration in case of the 5% interest rate. The most sensitive factor, which has influence on the water price, is the load factor of the water plant and the reactor. In addition, the following factors have the more influence on the water price: output of water, investment and service life of water plant, investment and service life of the reactor. The main influence factors on water price are listed in Table 4. The result of sensitivity analysis on the water price indicates that the water price will be dropped in case of the low interest rate and investment of NHR desalination plant as well as high availability of the plant.

Table IV Main influence factors on water price^[5]

Sensitive factors	*Change of water price, %	
	Water production only	Co-generation
Interest rate	0.632	0.559
Electricity price	0.109	0.020
Load factor of NHR-200	-0.710	-0.779
Load factor of MED plant	-0.885	-1.035
Service life of NHR-200 (20~30 year)	-0.092	-0.189
Service life of NHR-200 (30~40 year)	-0.035	-0.041
Service life of MED plant (20~30 year)	-0.201	-0.182
Service life of MED plant (30~40 year)	-0.071	-0.057
Investment of NHR-200	0.208	0.287
Investment of MED plant	0.485	0.401
Amount of water production	-0.387	-0.451
Efficiency of turbine generator	—	-0.068

* The percentage of water price change is calculated at the conditions which assume the sensitive factor increase of 1%, others keeping constant

The scale of the NHR-200 desalination plant is more suitable for the demand of potable water about a hundred thousands m³/d. Under the suitable condition, several NHR-200s could be combined to supply heat and electricity to a large scale seawater desalination plant for cities and industrial districts with large fresh water requirements. The combined NHR-200s desalination plant can not only ensure the continuity of the water production but also improve the economy by sharing of common facilities and service systems including infrastructure, maintenance facilities, reduction of staffs and so on.

4 Conclusion

The safety is a very important factor into the nuclear seawater desalination in the fields of the safety of the reactor itself and the pollution prevention of the produced water. The NHR-200 is designed with a number of advanced and inherent safety features, which have been proved by the successful operation and the results of special experiments carried on the NHR-5. And the technical measures adopted in the NHR-200, such as dual vessel, secondary containment and intermediate circuit, can guarantee the produced water against radioactivity. The NHR-200 can be considered as the new generation nuclear reactor.

The large nuclear power plant may produce cheaper fresh water due to its lower heating price at the present. But the long distance transport would lead to an increase in the cost of water. Due to the excellent performance of the NHR-200, the MED desalination plant coupled with NHR-200 can be located in the vicinity of the consumer, which will bring about reduction of the water price. And the NHR-200 desalination plant or other scale NHR desalination plant may be more suitable for developing countries in respect of its smaller scale, simpler system, easier component manufacture, maintenance and operation.

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