



NUCLEAR REACTOR DEVELOPMENT IN CHINA FOR NON-ELECTRICAL APPLICATIONS

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Abstract

In parallel to its vigorous program of nuclear power generation, China has attached great importance to the development of nuclear reactors for non-electrical applications. The Institute of Nuclear Energy Technology (INET) in Beijing has been developing technologies of the water-cooled heating reactor and the modular high temperature gas-cooled reactor. In 1989, a 5 MW water cooled test reactor was erected. Currently, an industrial demonstration nuclear heating plant is being projected. Feasibility studies are being made of sea-water desalination using the INET developed nuclear heating reactor as heat source. Also, a 10 MW high temperature gas-cooled test reactor is being constructed at INET in the framework of China's national high-tech program. The paper gives an overview of China's energy market situation. With respect to China's technology development of high temperature gas-cooled reactors and water cooled heating reactors, the paper describes some general requirements on the technical development, reviews the national programs and activities, describes briefly the design and safety features of the reactor concepts, discusses aspects of application potentials.

1. Introduction

China's national economy and energy consumption have experienced rapid growth in the last years. From 1991 to 1995 which is the National Eighth Five-Year Plan period, the average economical growth rate reached 11.8%. In 1994, consumed primary energy was 1227 Million Tons Coal Equivalent (Mtce). Average growth rate of primary energy consumption over 1991-1994 was 5.6%. It is expected that the national economy and energy consumption will continue to grow. China implements the policy of self-reliance for energy production, so that meeting the energy consumption demand by capacity installation and efficiency enhancement remains a challenging task.

Of the 1227 Mtce primary energy consumed in 1994, 31.5% is consumed in the form of electricity, the rest part is consumed for non-electrical applications. To the total of energy consumption in 1994, 75.0% is contributed by coal, 17.4% by oil, 1.9% by natural gas, 5.3% by hydro-power and 0.4% by nuclear power. The energy consumption and production in China is dominated by coal. This fact brings two problems with it: transportation burden and environment pollution. Both are serious problems in China's rapid social and economical development.

Nuclear energy has been recognized in China as a clean, safe and economical energy source. There have been vigorous programs for nuclear power development. Currently, there are three commercial nuclear power reactors in operation with a capacity of 2.1 GW. Eight units of a total capacity of 6.4 GW are under construction or have been planned for construction in the near future. Besides the development of nuclear power generation, great importance is also attached to the development of nuclear energy technology for non-electrical applications. The vessel type water-cooled reactor with low core outlet temperatures (Nuclear Heating Reactors - NHR) has been developed for district heating or other lower temperature applications. Technology development of High Temperature Gas-cooled Reactors (HTGR) is being conducted both for electrical and non-electrical applications. The development work, technical and safety features as well as application potentials of these two reactor types will be presented in the following sections.

2. General requirements on developing heat supplying reactors

Heat is not suitable for being transported over long distances. Nuclear reactors for heat supply purposes should be built near industrial or densely populated areas. Therefore, these reactors should have an extremely high level of safety and should be economically competent over fossil fuels. Following design philosophies are applied to the development of NHR and HTGR in China.

Safety. In the development of heat supplying reactors, nuclear safety is to be improved through the following approaches:

- To improve the reactor's inherent safety. Through appropriate design and proper selection of material's type, quantity and properties, the reactor can be endowed with certain capability of self-protection or will be free of certain potential adversity
- To adopt passive system design. Instead of depending on the operator's action or the effect of external machinery and power, the safety system employs certain natural phenomena such as natural circulation, heat conduction, radiation, internal energy preservation and others to realize its function and thereby to ensure its reliability and effectiveness
- To ensure negative temperature coefficient of reactivity under all conditions by proper nuclear design and to ensure enough negative reactivity to be introduced for reactor shutdown
- To ensure safe removal of decay heat by proper reactor and system design
- To lessen the dependence on the operator's response capacity
- To iron out the influence of internal and external events on the reactor safety
- To further decrease the radiation dose of the operating personnel and the public

Operational reliability. One of the important goals of developing heat supplying reactors is to enhance their operational reliability so as to increase its availability and load factor. In order to accomplish this, the following measures should be taken:

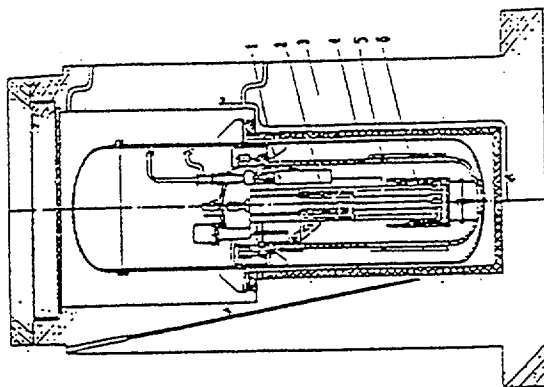
- Simple design
- Accessibility for maintenance and inspection
- Use of proven technology
- Adoption of standard design

Economy. To have a better economy, nuclear reactors for heat supply are required to have the following features achieved by design, construction and operation:

- Longer operational life-span
- Shorter construction period
- Lower operational and maintenance costs
- Lower decommissioning costs
- Smaller investment risk

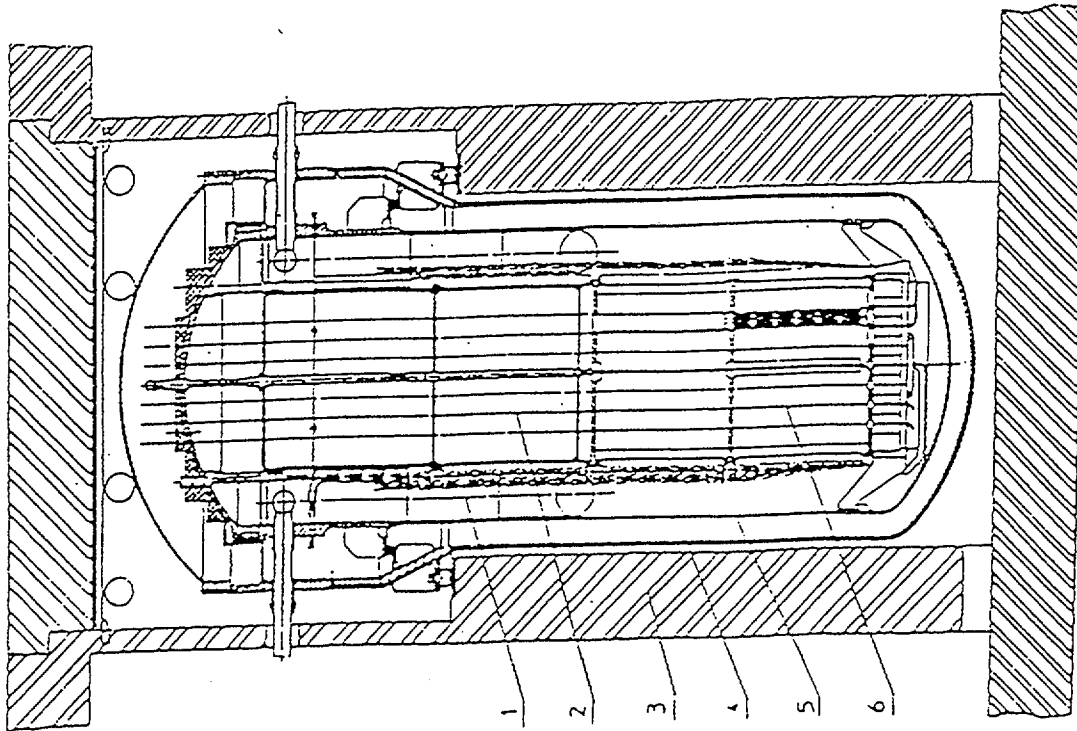
3. Development of NHR in China

The Institute of Nuclear Energy Technology (INET) of Tsinghua University in Beijing has been developing water cooled nuclear heating reactors since the 1980's. In 1983 and 1984, INET conducted successful tests of nuclear district heating using the existing swimming pool type research reactor. In 1984, INET began the project of erecting a 5 MW test NHR on the site of the institute which is about 40 km away to the north of Beijing city. The construction of the 5 MW NHR started in 1986 and was finished in 1989. In November 1989 the test reactor went critical. Since then, the reactor has been successfully operated. For research and development to make more use of NHR, experiments have been conducted on the 5 MW test reactor such as co-generation of electricity and heat, air conditioning and desalination with nuclear energy.



5MW test heating reactor

- 1. Primary heat exchanger
- 2. Riser
- 3. Biological shield



200MW demonstration heating reactor

Fig. 1. The 5 MW test NHR and the 200 MW demonstration NHR.

Table I Key design parameters of the nuclear heating reactors

Reactor		NHR-5	NHR-200
Thermal Power	MW	5	200
Primary pressure	MPa	1.5	2.5
Core inlet / outlet temperature	°C	146 / 186	140 / 210
Height of the active core	m	0.69	1.90
First core UO ₂ loading	t	0.508	14.5
Enrichment of the first core loading	%	3.0	1.8/2.4/3.0
Enrichment of the reload fuel	%	3	3
Intermediate circuit pressure	MPa	1.7	3.0
Intermediate circuit temperature	°C	102 / 142	95 / 145
Heating grid temperature	°C	90/60	130/80

Table II Key design parameters of the HTR-10 test reactor

Reactor thermal power	MW	10
Primary helium pressure	MPa	3.0
Reactor core diameter	cm	180
Average core height	cm	197
Average helium temperature at reactor outlet	°C	700
Average helium temperature at reactor inlet	°C	250
Helium mass flow rate at full power	kg/s	4.3
Main steam pressure at steam generator outlet	MPa	4.0
Main steam temperature at steam generator outlet	°C	440
Feed water temperature	°C	104
Main steam flow rate	kg/s	3.47
Number of control rods in side reflector		10
Number of absorber ball units in side reflector		7
Nuclear fuel		UO ₂
Heavy metal loading per fuel element	g	5
Enrichment of fresh fuel element	%	17
Number of fuel elements in reactor core		27,000
Fuel loading mode		multi-pass

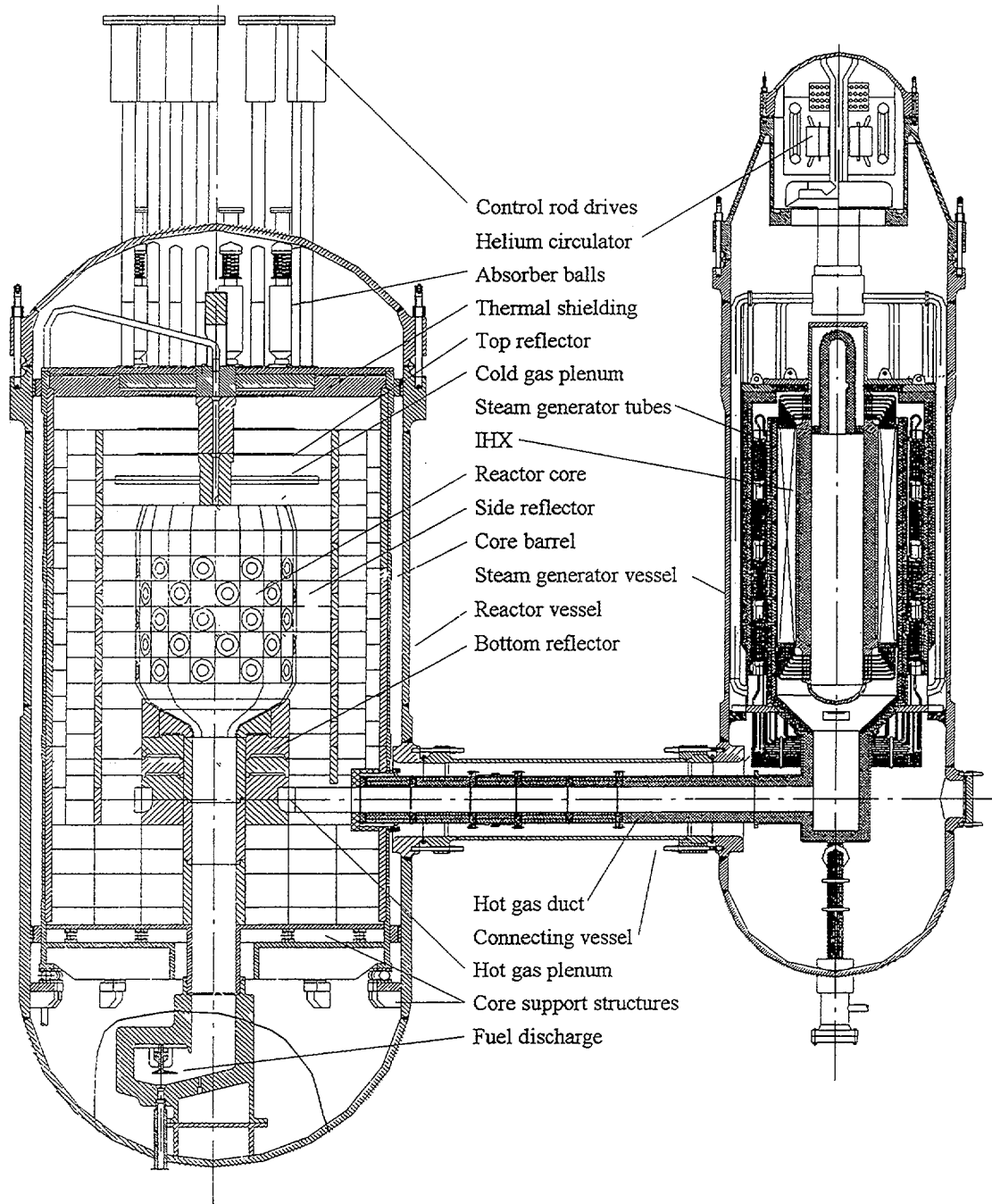


Fig. 2. The HTR-10 reactor and steam generator.

On the basis of the successful 5 MW test reactor, several cities and large enterprises have showed their strong interests in building NHRs. INET is now projecting a 200 MW commercial demonstration nuclear heating reactor which will be built in the northeast part of China.

Technical and safety features of the NHR. Both the 5 MW and the 200 MW heating reactor are of water cooling, vessel type design. Their main technical and safety features are briefly summarized as follows:

- Integrated design. Both the reactor system and the primary heat exchangers are integrated into the pressure vessel. This compact integrated design minimizes the probability of large LOCA accidents.
- Full power natural circulation cooling. At all power levels, the reactor power is designed to be carried out by means of natural circulation, eliminating circulating pumps and ensuring higher system reliability. This is also true for the reactor decay heat removal.
- Duel vessel design. The steel containment vessel is designed closely surrounding the pressure vessel. In case of a very unlikely failure of the pressure vessel, the containment vessel will ensure the immersion of the reactor core without any emergency cooling actions.
- Hydraulic driving mechanism of the control rods. A new driving mechanism of the control rods by hydraulic means has been developed and utilized. This design simplifies the reactor structure design and eliminates the accident of rapid rod ejection.
- Primary pressure self-regulation. With the help of a certain inventory of nitrogen in the primary loop, the primary pressure regulates itself very stable at the designed level.
- Low parameters. The design parameters are chosen which are suitable for district heating purposes and they are much lower than those of large electricity generating reactor. This brings more safety advantages and makes the reactor operation simpler and easier.

Figure 1 shows the overall design of the 5 MW test NHR and the 200 MW demonstration NHR, while the key design parameters of these two reactors are listed in Table I.

4. Development of HTGR in China

Under the support of the Chinese government, INET of Tsinghua University started in the 1970's to develop HTGR technology. A lot of R&D work was performed in the fields of reactor design methodology, system and component technology, coated particle technique, helium technology, graphite materials, treatment of irradiated fuel, etc.

Since 1980's, R&D work in China has been concentrated on the modular reactor concept and process heat applications of HTGR. In 1986, R&D of HTGR was integrated in the National High-Technology Program (NHTP). The future roles of HTGR and the development work were defined. It is projected in the NHTP to establish before the year 2000 a 10 MWth test module reactor (HTR-10) at the site of INET. The HTR-10 is now being constructed. It is expected that commercial HTGR demonstration plants will be projected if the HTR-10 proves to be a success.

Following objectives are expected to be achieved through the establishment of the 10 MW test module reactor:

- Acquiring the key technologies of the modular HTGR with respect to design, construction and operation
- Demonstration of the safety features of modular HTGR
- Demonstration of electricity/heat co-generation
- Demonstration of power generation with gas/steam combined cycle
- R&D of high temperature process heat application, e.g., coal gasification and liquefaction as well as steam reforming
- Providing an irradiation facility for fuel element and material experiments.

Technical and safety features of the HTR-10. Design of the HTR-10 test reactor (see Figure 2) represents the features of modular HTGR design. Reactor core and steam generator are housed in two steel pressure vessels which are arranged in a “side-by-side” way. The two vessels are connected to each other by a connecting vessel in which the hot gas duct is designed. All these steel pressure vessels are in touch with the cold helium of about 250°C coming out from the circulator which sits over the steam generator tubes in the same vessel.

Fuel elements used are the German type spherical fuel elements (6 cm in diameter) with coated particles. The reactor core contains about 27,000 fuel elements forming a pebble bed which is 180 cm in diameter and 197 cm in average height. Spherical fuel elements go through the reactor core in a “multi-pass” pattern. Graphite serves as the main material of core structures which mainly consist of the top, bottom and side reflectors. The ceramic core structures are housed in a metallic core vessel which is supported on the steel pressure vessel. Side reflector is 100 cm thick. In the side reflector, cold helium channels are designed in which helium flows upward after entering the reactor from between the connecting vessel and the hot gas duct. Helium flow reverses at the top of reactor core into the pebble bed, so that a downward flow pattern takes place in it. After being heated in the pebble bed, helium enters into a hot gas chamber in the bottom reflector, and from there it flows with reactor outlet temperature through hot gas duct to the heat exchanging components.

The steam generator is composed of a number of modular helical tubes which are arranged in a circle between two insulation barrels inside the steam generator pressure vessel. The place inside the inner barrel is foreseen for an intermediate heat exchanger which is to be installed in the second phase of the project.

On the wall of the concrete housing, a surface cooling system is designed. This system works on the principle of natural circulation of water and it takes the decay heat via air coolers to the atmosphere. In fact, this surface cooling system is designed to protect the vessel and concrete structures more than the ceramic reactor core from being overheated by decay power.

There are two reactor shutdown systems, one control rod system and one small absorber ball system. They are all designed in the side reflector. Both systems are able to bring the reactor to cold shutdown conditions. Since the reactor has strong negative temperature coefficients and decay heat removal does not require any circulation of the helium coolant, the turn-off of the helium circulator can also shut down the reactor from power operating conditions.

With respect to reactor safety, the 10 MW test reactor is characterized by the following features:

- The overall temperature coefficient of reactivity of the reactor core is always negative. All reactivity transients during power operation can be compensated by the negative temperature coefficient which leads to the self-shutdown of the reactor.
- The decay heat removal requires no circulating coolant systems. It can disperse to the outside of the reactor pressure vessel through heat conduction and radiation within the reactor internals. The dispersed residual heat will be taken away through a surface cooling system on the wall of the concrete cavity which houses the reactor.
- Because of the good capability of coated fuel particles to retain fission products, the primary helium is of low level radioactivity and is allowed to be released unfiltered to the atmosphere at system depressurization, without causing irradiation effect beyond specification. Therefore, a vented confinement instead of a gastight containment is designed for an organized and controlled release of gases in the facility, which serves as the last independent radioactivity barrier following the defense-in-depth principle.

5. Summary and perspective

In China, great importance has been attached to the development of advanced reactor types such as NHR and HTGR. These advanced reactor types are of advantageous safety features and have application potentials in heat supply.

The NHR can be used for district heating and air conditioning in densely populated areas. This can save a great amount of coal consumption and thus ease the associated problems with coal burning. It can also be used to provide low temperature process steam for industrial applications like seawater desalination. With respect to the serious situations of fresh water supply in many coastal areas in the world, there is a good prospect for the NHR to be used for this application.

The HTGR can be used to provide process heat at various temperature levels up to 950°C. With HTGR, process steam can be produced for example for heavy oil recovery and crude oil refinement process. HTGR is the only reactor type which can provide high temperature process heat used for coal liquefaction or gasification. Considering the problems with coal burning and the shortage of liquid fuel supply, the application of HTGR to convert coal into liquid form energy carriers is of special interest in the future energy market.