THE ROLE OF NUCLEAR ENERGY IN REDUCING THE ENVIRONMENTAL IMPACT OF CHINA'S ENERGY UTILIZATION

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ABSTRACT

It is presented in this paper the current status of China's energy market and the projections of its future development. China's energy market, currently and in the next decades, is mainly characterized by rapidly increasing demand and dominant role of coal which is directly related to serious environmental pollution. The role of nuclear energy utilization in improving the primary energy infrastructure is addressed. Status and development of nuclear power generation are described. Potential of introducing nuclear energy into heat market is discussed. An overview of the research and development work of water cooled low temperature heating reactors and gas-cooled high temperature gas cooled reactors in China is given and the technical and safety features of these two reactor types are briefly described.

1. PRESENT STATUS OF CHINA'S ENERGY MARKET

China's national economy and energy consumption have experienced rapid growth in the last years. In the period 1991~1995, the average economical growth rate reached 11.8%[1]. In 1995, consumed primary energy was 1,312 Mtce (Million tons of coal equivalent). Average growth rate of primary energy consumption over 1991-1995 was 6.0%. To the 1,312 Mtce primary energy consumed in 1995, 74.6% is contributed by coal, 17.5% by oil, 1.8% by natural gas, 6.1% by hydro-power and 0.4% by nuclear power. In 1995, a total of 1,290 Mtce was produced so that China's energy production roughly balances its consumption. But China is now a net importer of oil.

Since 1990, annual power generation capacity installation of about 15GWe has been considerable large. In 1995, a total generation capacity of 215GWe was installed, and a total of 1,002 TWh electricity was produced, of which 79.8% is from fossil fuels, primarily coal, 18.9% from hydropower and 1.3% from nuclear.

China has a huge population: in 1995, it reaches 1.211 billion, of whom about 70% live in rural areas. All the above facts characterize China's energy market with the following features: 1) coal plays the dominant role in energy production and consumption, 2) energy consumption per capita is still considerably low although the total consumption ranks the second right after the USA on the world list, 3) energy consumption intensity per GDP value of about 2.0 kgce/US$ in 1994 is several times higher than the world average, 4) the dominant role of coal exerts great transportation burden and causes serious environment pollution, both are serious problems in the social and economic development.

It is expected that the national economy and energy consumption will continue to grow. Table 1 and Table 2 give respectively baseline scenarios of annual primary energy demand and CO_2 emission and electricity

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[1] The statistical data in this section on energy economy are taken from CHINA ENERGY YEAR BOOK 1997, unless a specific reference is given.

generation capacity, cited from a study performed by the Institute of Nuclear Energy Technology (INET) of Tsinghua University for the first twenty years of the next century [1]. It can be seen from the tables that both primary energy demand and electrical power generation capacity show continuous increase, and coal still plays the dominant role. Although hydropower and nuclear power are expected to increase considerably, still the share of hydropower remains almost constant and that of nuclear power accounts for only a few percent. The dominant role by coal is not changed. In the next century, CO_2 issue might become a more important weighing factor in China's energy economy. This can lead to alternative scenarios where carbon-free energy forms are more intensively utilized, in particular nuclear and hydropower, both capital intensive.

Table 1 Baseline scenario of annual primary energy demand and CO_2 emission of China

Energy Forms and CO_2 emission	2000		2010		2020	
	Mtce	%	Mtce	%	Mtce	%
Coal	1,169	74.8	1,617	72.3	2,065	70.7
Oil	247	15.8	361	16.2	470	16.1
Natural gas	44	2.8	85	3.8	121	4.1
Hydropower	94	5.4	125	5.6	161	5.5
Nuclear	6	0.4	43	1.9	84	2.9
Renewable	2	0.1	4	0.2	19	0.7
Sum	1,562	100	2,235	100	2,920	100
Total CO_2 emission (Mt-C)	915		1,320		1,695	
Per capita CO_2 emission (kg-C)	707		952		1,134	

Table 2 Baseline scenario of installed power generation capacity of China

Power forms	2000		2010		2020	
	GW	%	GW	%	GW	%
Fossil fired	219.7	75.8	386	74.2	558	73.4
Hydropower	68	23.5	114	21.9	162	21.3
Nuclear power	2.3	0.79	20	3.9	40	5.3
Sum	290	100	520	100	760	100

Electrical power takes only about 30~40% of the total commercial energy consumption, so that non-electrical applications imply a big market potential. Utilization of nuclear energy in non-electrical sectors would contribute greatly to the improvement of energy economy structure, in particular to the mitigation of environmental pollution caused by coal burning.

2. THE ROLE OF NUCLEAR ENERGY

China's energy demand will, along with the economical growth and the improvement of people's living standard, considerably increase in the next decades. Meeting the demand will be mainly challenged by energy supply capacities and the environmental impact of energy production and consumption. From these perspectives, nuclear energy should make a much more important contribution than it does now.

Due to large amount of coal combustion, urban air pollution has become a serious problem. In 1996, SO_2 emission in China was 13.6Mt. SO_2 concentration in many cities and their suburbs exceeds $20\mu g/m^3$. In some urban regions, the value is above $150\mu g/m^3$ and even worse during space heating period. Moreover, the rainfall pH values in some cities like Chongqing and Guiyang are lower than 5, which causes acid rain damages.

The eastern coastal areas with a higher level of economic development and population density face, in particular, the great challenge of environmental protection. The national air protection regulations put strict limitations on pollutant emissions. More crucial measures have to be taken to meet these limitations. More developed coastal provinces, which face more serious problems of power shortage, are also in shortage of primary energy resources. Therefore, transportation capacity have to be expanded or newly built to establish the fuel supply systems for the newly installed capacities. Nowadays, already 48% of the railway and 25% of the land-road transportation capacities are used for the transportation of power generating coals. Transportation capacity increase means great amount of investment. The erection and operation of emission abatement facilities would also contribute to generation costs.

The importance of nuclear energy has been realized by both governmental decision-making agencies and the power generation industries. As environmental considerations become more popular and related regulations become more stringent, nuclear energy will expectedly gain increasing importance.

There have been vigorous programs for nuclear power development. Currently, there are three commercial nuclear power reactors in operation with a capacity of 2.1GW. Eight units of a total capacity of 6.4 GW are under construction or have been planned for construction in the near future. It is generally expected that nuclear generating capacity installation would reach 20GWe till 2010 and 40GWe till 2020. Although the nuclear share in the total power generation capacity is still rather small, its significance in mitigating environmental pollution is important.

Besides the development of nuclear power generation, 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 low temperature applications. Technology development of High Temperature Gas-cooled Reactors (HTGR) is also being conducted both for electrical and non-electrical applications. The following sections will be mainly devoted to discussions of these technologies.

3. PROSPECTS AND REQUIREMENT FOR NON-ELECTRICAL APPLICATIONS OF NUCLEAR ENERGY IN CHINA

Non-electrical applications, as meant in this paper, deal with heat applications. Heat is not suitable for transportation over long distances. Nuclear reactors for heat supply purposes should be built near industrial or densely populated areas. Therefore, these reactors should show an extremely high level of safety. Emergency planning outside the nuclear heat supplying plants should be made unnecessary by plant designs. Nuclear heat supply systems should also be made economically competitive over fossil fuels.

In the efforts to develop NHR and HTGR, high level of nuclear safety is much emphasized and realized by integrating inherent and passive safety features into the reactor and plant systems, so that these reactors show extremely good safety performance even beyond the design basis. Safety and technical features of the pertinent reactors will be discussed more in the next section.

The development of NHR is mainly aimed at providing heat for district heating and for low temperature process heat applications like seawater desalination. There exists a huge district heating market in North

China. The main issue is the economy of nuclear heating systems. Studies have been made to compare the economy aspects of district heating by NHR and by coal-fired boilers. An NHR of 200MWth developed by INET (see the next section) and a coal-fired heating plant without desulfuration facilities are taken as references. The main reference data are listed in Table 3.

Table 3 Main reference data of a nuclear heating plant and a coal-fired heating plant

Nuclear heating plant	Coal-fired heating plant
Thermal power: 200 MW	Thermal power: 233 MW
Life time: 30 years	Life time: 20 years
Specific investment: 350 US$/kW(th)	Specific investment: 100 US$/kW(th)
Average burnup: 30,000 MWd/tU	Thermal efficiency: 85%
Fuel price: (3% enrichment): 1.0 MUS$/tU	Coal price: 35 US$/t

The investment costs are considerably higher with the nuclear option, but the fuel costs are much lower with nuclear. The impact of these factors on the levelized heat costs is influenced primarily by the discount rate and the load factor. Figure 1 and Figure 2 show respectively the dependence of heat costs on the load factor and the discount rate. Nuclear heating systems with NHR are economically competitive over coal-fired boilers under certain combined conditions of discount rates and load factors. At a load factor of 50%, nuclear heat would be cost competitive when the discount rate is not higher than about 7%. Current studies could not taken much into account the pollution penalties on fossil fuels. As China puts more stringent regulations on environmental protection, the economy balances will also change.

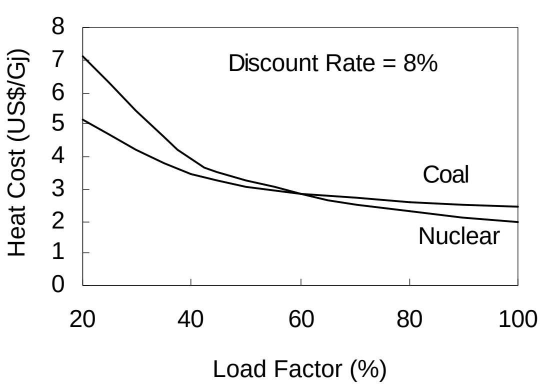

Figure 1 Heat costs vs load factors

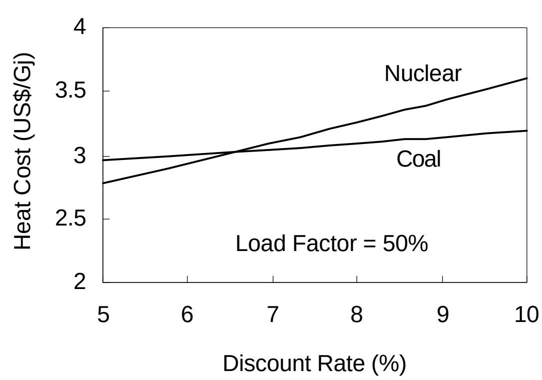

Figure 2 Heat costs vs discount rates

Higher load factors will favor nuclear heat in terms of economy. This is usually the case with process applications like seawater desalination. China is a country with fresh water shortages. The per capita fresh water resources account for only 27% of the world average. The coastal areas of China are densely populated and economically more developed. Just these areas are lack of both fresh water and energy resources. Along with the economical development and improvement of living standard, the problem of water shortage will become increasingly serious. Studies have been made to investigate the feasibility of nuclear desalination with NHR. A 200MWth NHR coupled with an MED process can generate about 160,000 m^3/d at the cost of 0.7~1.0 US$/$m^3$.

The HTGR has a wide range of applications. The pebble bed HTGR which China pursues can provide high temperature process heat up to 950°C. This reactor type is suitable for both electricity generation and a variety of process applications. Pebble bed modular reactors coupled with a direct helium turbine cycle can generate electricity very cost effectively, as studied by South African electricity utilities[2]. According to their investigations, the power generation costs by modular pebble bed HTGRs with helium turbines, constructed in series, are 0.014US$/kWh.

Heat applications with HTGR in China have been considered mainly in the following areas: process steam supply for petrochemical plants, heavy oil recovery, coal conversion, seawater desalination and space heating. Techno-economical studies have been made for applications in petrochemical plants and heavy oil recovery. Once again, the main issue of introducing HTGR into the heat supply market is the economical competitiveness. Because of less experience in the construction and operation of modular HTGR, the economical data pertinent to HTGR reactor systems vary in different studies. If the South African studies will be demonstrated by real projects, HTGR will show economical viability in many application areas.

4. RESEARCH AND DEVELOPMENT OF NHR AND HTGR IN CHINA

4.1 NHR

INET has been developing water-cooled nuclear heating reactors since the 1980s. 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, air conditioning and desalination with nuclear energy. 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.

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 and the primary heat exchangers are integrated into the pressure vessel. This 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 3 shows the overall design of 200 MW demonstration reactor, while the key design parameters of the two heating reactors are listed in Table 4.

Table 4 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

4.2 HTGR

Under the support of the Chinese government, INET of Tsinghua University started in the 1970's to develop HTGR technology. 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. The future roles of HTGR and the development work were defined. It is projected to establish before the year 2000 a 10 MWth test module reactor (HTR-10) at the site of INET. The HTR-10 project is to be carried out in two phases. In the first phase, the reactor is coupled with a steam turbine system which works on co-generation basis. In the second phase, a closed cycle gas turbine is planned for additional coupling to the reactor for the development of nuclear gas turbine technologies. The HTR-10 reactor is now being constructed. It is expected that commercial HTGR demonstration plants will be projected if the HTR-10 proves to be a success.

Design of the HTR-10 test reactor (Table 5, Figure 4) 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. Fuel elements used are spherical fuel elements (6 cm in diameter) with coated particles. Fuel elements go through the reactor core in a “multi-pass” pattern. 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.

Table 5 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
Nuclear fuel		UO_2
Heavy metal loading per fuel element	g	5
Enrichment of fresh fuel element	%	17
Number of fuel elements in reactor equilibrium core		27,000

With respect to 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 reactor cavity which works on the natural circulation principle.
- A vented confinement instead of a gas-tight 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

The Chinese energy economy is mostly characterized by the dominant role of coal both in the primary energy production/consumption and in the electricity generation. This brings two adverse problems with it: transport burden and environmental pollution, both are serious problems in the social and economical development of China. It is generally believed that both primary energy demand and electricity demand will continuously increase at a relatively high rate. By the constraints of resources and economic competitiveness, coal is expected to continuously play an important role in the energy supply systems. Environmental factors will definitely gain increasing importance in the economical development, which will influence the economical competitiveness of different energy forms. Nuclear energy is regarded as a clean and safe energy source. It is the only energy form which can substitute for coal on large scales in the next decades. China has planned vigorous programs for nuclear power development. Since China is just at the start of its nuclear program, the share of nuclear energy in the overall energy production will be limited in the next two decades. Nevertheless, the significance of nuclear energy utilization in terms of mitigating environmental pollution is important.

Introduction of nuclear energy into the heat application market would considerably enlarge the application potential of nuclear energy. There is a variety of application possibilities. China has supported the development of reactor systems, i.e., water-cooled low temperature heating reactors and high-temperature gas-cooled reactors, which are suitable for heat applications. These two reactor types are strongly characterized by their excellent safety features. These advanced reactors are, generally speaking, economically viable.

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