Experience and Prospects of Nuclear Heat Applications

District heating, process heat, seawater desalination

by G. Woite, T. Konishi, J. Kupitz, International Atomic Energy Agency

Abstract

Relevant technical characteristics of nuclear reactors and heat application facilities for district heating, process heat and seawater desalination are presented and discussed. The necessity of matching the characteristics of reactors and heat applications has consequences for their technical and economic viability. The world-wide operating experience with nuclear district heating, process heat and seawater desalination is summarised and the prospects for these nuclear heat applications are discussed.

Contents

1. Introduction

Nuclear Energy is playing an important role in electricity generation, producing 17% of the world's electricity. Nuclear power plants (NPPs) are proven to be safe, reliable, economic and have only a minimal impact on the environment when they are properly designed and operated. Most of the world's energy consumption, however, is in the form of heat. Nuclear energy can provide a clean alternative to the burning of fossil fuels for the production of industrial process heat, for district heating and for seawater desalination. This would provide energy supply diversification and reduction of environmental and climatic impacts which occur from combustion of fossil fuels. In several countries nuclear heat is already being used for district heating, process heat and seawater desalination. But the nuclear option could be better deployed if it would provide a larger share of the heat market.

There are now about 60 reactors and over 500 reactor years of operational experience with nuclear district heating (DH), industrial processes and seawater desalination. There appear to be no major technical or safety concerns with nuclear heat application systems. The design precautions to prevent the carry-over of radioactivity into the heating network or into the desalted water have proven to be effective. These findings are important for future applications of nuclear heat for district heating, process heat and seawater desalination.

Nuclear economics usually favour large units. This has led to the development and predominant deployment of large-size reactors in industrialised countries with large interconnected electrical grid systems. However, integration of large reactors in small or medium electric grids would not be viable. Thus, there has been and there continues to be a market for small- and medium-sized power reactors (SMRs). Most SMR designs currently under development are not scaled down versions of large commercial reactors, and they are intended to be economically competitive. SMRs would in many cases fit the requirements of countries with small or medium electric grids and nuclear heat applications better than large reactors. The IAEA is therefore closely following up the development of SMR designs and applications [1,2].

2. Characteristics of reactors and heat applications

In the following, characteristics of heat applications and nuclear reactors are highlighted which are important for their coupling. These include:

- Siting aspects
- Magnitude of demand for heat, electricity and/or desalted water
- Availability and load factor of the reactor and heat consumer
- Temperatures of heat supply and application process

Siting: Nuclear reactors are usually constructed at a considerable distance to densely populated areas, both for regulatory and public acceptance reasons. On the other hand, heat must be supplied from a nearby source (usually less than 10 km) because of the high cost of heat transport. The need for a pipeline, thermal insulation, pumping, and the corresponding investments, heat losses, maintenance, and pumping energy requirements make it impractical to transport heat beyond distances of a few kilometres or, at most, some tens of kilometres. There is also a strong size effect. The specific costs of transporting heat increase sharply as the amount of heat to be transported diminishes. Compared to heat, the transport of electricity from where it is generated to the end-user is easy and cheap, even to large distances measured in hundreds of kilometres.

Since water transport costs less than heat transport, seawater desalination plants may be sited more distant to population centres than district heating plants and the same applies to industrial complexes. In these cases, the siting requirements are easier to match with those of a reactor.

Magnitude of demand: Due to the economies of scale, the magnitude of the heat, electricity and/or desalted water demands is very important for the economic viability of the application. Cogeneration of electricity and heat is the most frequent supply option. Power reactors in the cogeneration mode are in most cases optimised for the generation of electricity as the main product, with district heat or process heat as a by-product (usually less than 10% of total energy generation). SMRs would in many cases fit the requirements of small or medium electric grids and nuclear heat applications better than large reactors.

The required **availability** and achievable **load factor** of the reactor and heat consumer are another important criterion for matching. The required availability of the heat source varies among the applications: Close to 100% availability are required for industrial process heat and, during the heating season, for district heat. The required availability may be less for desalination where potable water can be stored and/or be obtained from other sources at times when the heat source is not available. The achievable load factors are close to 100% for industrial process heat and less than 50% for district heat.

Nuclear power plants have achieved average lifetime availability factors of 70% to 80%. The frequency and duration of unplanned outages can be kept very low with good preventive and predictive maintenance. Availability and reliability of a reactor, however, can never reach the nearly 100% required by most industrial heat users and district heat systems (in winter). Consequently, as for fossil-fuelled heat sources, redundancy is needed. Multiple unit cogeneration-generation power plants, modular designs, or back-up heat sources are suitable solutions.

Nuclear reactors are capital intensive and have relatively low fuel costs. The influence of the fixed cost component is predominant in the final cost of energy. Therefore, base-load operation with load factors as high as achievable is needed for competition with alternative sources. This is only possible when the demand of the heat market to be supplied has base-load characteristics, or when the combined electricity and heat market enables overall base-load operation of a nuclear cogeneration-generation plant.

Regarding the **temperature** ranges available from reactors, up to about 300°C are obtained in light- and heavy-water reactors, up to 540°C in liquid metal-cooled fast reactors, up to 650°C in advanced gas-cooled reactors, and up to about 1000 °C in high temperature gas-cooled reactors.

The temperature requirements of applications range from about 70-130°C for desalination and 100-150°C for district heating to over 1000°C for some industrial processes. The lower process heat range up to about 200 to 300°C includes the pulp and paper as well as textiles industries. Chemical industry, oil refining, oil shale and sand processing, and coal gasification require temperatures up to 500 - 600°C. Non-ferrous metals, refinement of coal and lignite, and hydrogen production by water splitting require temperatures between 600 and 1000°C. The range above 1000°C is dominated by the iron and steel industry.

3. Operating experience

The technical viability of using nuclear heat for the supply of hot water and/or steam for district heating and industrial processes has been demonstrated both in dedicated nuclear heating plants and in heat and power cogeneration plants. Nuclear heat application systems have been in service for over 20 years without any serious problems. Extensive experience has been accumulated, mainly in the low temperature range, with district heating, seawater desalination and process heat supply.

3.1 Nuclear district heating systems

Dedicated nuclear heating systems were designed and some built and operated in Canada, China and Russia. The plants in Canada (Slowpoke-3) and China (NHR-5) were for demonstration purposes, whereas the Russian plants are to supply settlements in northern Russia.

Most of the nuclear reactors supplying district heat at present are cogeneration plants, in which the main product is electricity and only a fraction of the reactor power is used for nuclear heat applications. The heat output capacities range from about 20 to 240 MW(th). For thermodynamic reasons, the extraction of low temperature/low pressure steam from the turbine leads to low heat cost to consumers, provided the cost of transmission and distribution is not a dominating factor. Nuclear cogeneration plants for electricity and district heating were built and operated in Bulgaria, Germany, Hungary, Russia, Slovakia, Switzerland and Ukraine. Over 500 reactor-years of quite satisfactory and encouraging operational experience has been accumulated. The plants have operated safely and reliably. No incidents involving radioactive contamination have been reported.

The NPP Kozloduy in Bulgaria has supplied heat to the town of Kozloduy since 1990. The Kozloduy NPP consists of four WWER reactors of 408 MW(e) and two WWER reactors of 953 MW(e). The reactors had some problems of safety and reliability; however, no relevant problems with district heating were reported.

The Greifswald NPP in Germany (former GDR) has supplied up to 180 MW(th) for district heating until its decommissioning in 1990.

The Paks Nuclear Power Plant in Hungary consisting of four WWER-440 reactors is supplying heat to the town of Paks. The secondary circuit steam leaving the steam generators is monitored by gamma detectors. The water pressure in the heat exchanger is kept higher than the steam pressure to prevent contamination of the hot water system.

The Bohunice Nuclear Power Plant in Slovakia produces electrical energy and low temperature heat for heating and industrial purposes. It is shown by operating experience that the heat supply from the nuclear power plant to the town of Trnava is reliable, safe and economically competitive.

The district heat extraction from the Beznau NPP (2 x 360 MW(e) PWR) has been operated reliably and successfully since its commissioning in 19983/84. The peak heat load is about 80 MW(th). The district heating system supplies about 2100 private, industrial and agricultural consumers. Since the consumers are spread over a relatively wide area, the heat cost to them is higher than with individual oil heating, but is largely accepted as a contribution to environmental protection.

The most extensive experience with district heat supply from nuclear cogeneration plants has been gained in the Russian Federation. A research reactor at Obninsk has supplied heat since 1976 and is still in operation. The NPPs of Bilibino, Belojarsk, Balakovo, Kalinin, Kola, Kursk and Sankt Petersburg are supplying heat from steam turbine bleeders through heat exchangers to district heating grids of towns with typically about 50 000 inhabitants, situated between 3 and 15 km from the NPP site. The heat output capacities range from about 50 to 230 MW(th).

In Ukraine, the NPPs Rovno and South Ukraine have supplied heat to district heating grids since 1982 and 1983, respectively. The design characteristics and operating experience are similar to the NPPs and heating grids in the Russian Federation.

The design precautions to prevent the transfer of radioactivity into the district heating grid network have proven to be effective in all these countries. These design features include one or more barriers to radioactive substances, e.g., in the form of a leak-tight intermediate heat transfer loop at a pressure higher than that of the steam extracted from the turbine cycle of the nuclear plant. These loops are continuously monitored, and devices are provided to isolate potentially contaminated areas.

District heating systems require a back-up heat source when the main heat source is unavailable. Therefore, at least two nuclear power units or a combination of nuclear and fossil-fired units are used for district heating grids.

3.2 Nuclear desalination systems

Integrated nuclear desalination plants have been operated in Kazakhstan and Japan for many years.

In Aktau, Kazakhstan, the liquid metal cooled fast reactor BN-350 has been operating as an energy source for a multi-purpose energy complex since 1973, supplying regional industry and population with electricity, potable water and heat. The complex consists of a nuclear reactor, a gas and/or oil fuelled thermal power station, and Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF) desalination units. The seawater is taken from the Caspian Sea. The nuclear desalination capacity is about 80 000 m^3/d. A part of this capacity has now been decommissioned.

In Japan, all of the nuclear power plants are located at the seaside. Several nuclear power plants of the electric power companies of Kansai, Shikoku and Kyushu have seawater desalination systems using heat and/or electricity from the nuclear plant to produce feedwater for the steam generators and for on-site supply of potable water. MED, MSF and reverse osmosis (RO) desalination processes are used. The individual desalination capacities range from about 1000 to 3000 m^3/d. The experience gained so far with nuclear desalination is encouraging.

3.3 Nuclear process heat systems

Experience with nuclear process heat systems was gained in Canada, Germany and Switzerland.

In Canada, steam from the Bruce Nuclear Power Development (BNPD) is supplied to heavy water production plants and to an adjacent industrial park at the Bruce Energy Centre. The nuclear steam and electricity generating complex BNPD has operated successfully for over 20 years. It includes eight CANDU nuclear reactors, the world's largest Heavy Water Plant, and the Bruce Bulk Steam System (BBSS). The BBSS can produce 5350 MW(t) of medium pressure process steam. The cost of steam is reported to be significantly lower than the cost of heat from burning natural gas, which is the closest competitor. In 1995, Unit 2 of the Bruce A NPP was laid up. Because of lack of demand for heavy water and technical problems with Bruce A, the heavy water plant and units 1,3 and 4 of Bruce A will be laid up in 1998.

The six private industries established at the Bruce industrial park are (1) a plastic film manufacturer, (2) a 30 000 m^2 (7.5 acres) greenhouse, (3) a 12 million litres/year ethanol plant, (4) a 200,000 ton/year alfalfa dehydration, cubing and pelletizing plant, (5) an apple juice concentration plant and (6) an agricultural research facility.

In Germany, the Stade NPP PWR, 1892 MW(th), 640 MW(e) supplied steam for a salt refinery which is located at a distance of 1.5 km since December 1983. The salt refinery requires 45 t/h process steam with 190^{o}C at 1.05 Mpa, i.e. 30 MW(th) or 1.6% of the thermal output of the NPP. Since 1983, the steam supply by NPP Stade had very high time availability, and the operating experience with process steam extraction is very good.

In Switzerland, the 970 MW(e) PWR of Gösgen provides process steam for a nearby cardboard factory since 1979. The process steam (1.37 MPa, 220^{o}C) is generated in a tertiary steam cycle by live steam from the PWR. It is then piped over a distance of 1750 m to the cardboard factory. A maximum process steam extraction of 22.2 kg/s is possible which corresponds to about 54 MW(th) or about 2% of the total thermal power of the PWR.

4. Prospects

The prospects of future nuclear heat application are specific to geographic areas, fields of application, and reactor types and sizes.

Nuclear district heating will only be viable in very cold climate, i.e. parts of North America, Europe and Asia. Nuclear desalination could become viable mainly in North Africa [3], the Near and Middle East, and in some other water-scarce regions of southern Europe, China and American Continents. Vital preconditions for the viability include access to nuclear technology and at least a basic nuclear infrastructure. Public acceptance must be obtained, too. Besides internationally accepted safety precautions, some additional design features must be adopted for nuclear plants intended for seawater desalination or district heating to prevent the ingress of radioactive substances into the product water or the heating grid.

Concerning reactors, the usual approach for large size reactors is to build multiple unit stations. When used in the cogeneration-generation mode, electricity would always constitute the main product. Such plants have to be integrated into the electrical grid system and optimised for electricity production. For reactors in the SMR size range, the possible share of process heat supply would be larger, and heat could even be the predominant product. This would affect the plant optimisation, and could present more attractive conditions to the potential process heat user. SMRs are more suitable for countries with small or medium electric grids and could be better adapted to cogeneration-generate electricity and process heat than large reactors.

4.1 Economics

At cogeneration plants, which constitute the vast majority of nuclear heat supplying plants, the main product is electricity. Heat delivery amounts usually to less than 10% of the total thermal power. The cost of the nuclear electricity will thus be decisive for the economic viability of a nuclear cogeneration project, with heat supply as a by-product. The energy cost attributable to heat supply is usually calculated from the lost electricity generation and the electricity generation cost. This power credit method is also applied in a computer spreadsheet developed at the IAEA [4]. Besides the heat and/or water production cost, the cost of transport must be evaluated and compared to alternatives. The cost of distribution will be the same for the alternatives.

Nuclear heat applications were found economic in a number of study cases, but not under all circumstances. The energy cost due to lost electricity production in cogeneration plants is usually low, but the heat transport system and other necessary installations may be quite costly. Among other conditions, a large and fairly steady demand for heat or desalted water is favourable for economic nuclear heat application.

In spite of the positive experience with operating nuclear district heating systems, new projects were found uneconomic in several cases (e.g. in the Czech Republic), mainly because of the high investment and operating cost of the required hot water pipelines from the NPPs to the consumers.

4.2 Current development activities

Long and extremely cold winters have led the Russian Federation to early deploy nuclear district heating. It is now using its extensive experience to develop advanced heating reactor design concepts. The construction work at Voronez and Tomsk, both using AST-500 heating reactors, was suspended. Some nuclear cogeneration plants may be constructed to replace existing district heating plants which are approaching the end of their design life. The modular transportable nuclear power-and-heating reactor design ANGSTREM would use a fast nuclear reactor cooled by a lead-bismuth eutectic. The project may include seawater desalination and/or refrigeration. In China a demonstration plant using an NHR-200 is being constructed in the North East region of China. More information on heating reactor designs is contained in [5].

Freshwater shortages in arid and semi-arid regions as well as in rapidly growing coastal areas necessitate improved water management and deployment of additional resources, including seawater desalination. In the field of nuclear seawater desalination, there are currently relevant ongoing development activities in Canada, China, Egypt, India, the Republic of Korea, Morocco and the Russian Federation. Canada is promoting the coupling of a RO desalination facility with feedwater preheating to a CANDU reactor. Morocco and China are studying the use of a small 10 MW(th) heating reactor from China for the production of about 8000 m^3 of potable water per day in Morocco via a MED process. Egypt is studying the feasibility of nuclear desalination on its Mediterranean coast. In the Republic of Korea, the design of a 330 MW(th) advanced reactor is in progress as a cogeneration demonstration nuclear plant for electricity generation and seawater desalination. In India a hybrid MSF/RO desalination unit is planned to be coupled to an existing PHWR. In the Russian Federation a small floating nuclear desalination plant is under development using a nuclear reactor originally developed for icebreakers. India, Korea and Russia are offering their projects for international co-operation.

An International Nuclear Desalination Advisory Group (INDAG) was established in September 1997 to provide advice and guidance on the Agency's activities in nuclear desalination. A Coordinated Research Programme (CRP) on 'Optimization of the Coupling of Nuclear Reactors and Desalination Systems' was initiated to address relevant technical issues of nuclear desalination.

Temperatures between 500 and 1000°C are required by a number of industrial processes, including chemical processes, oil refining, oil shale and tar sand processing, coal gasification, non-ferrous metals, refinement of coal and lignite, hydrogen and methanol production. Research and development to use nuclear heat for such processes were performed in Germany and USA but are limited to the laboratory or small scale demonstration. Although some experience is available from these early high temperature reactor (HTR) developments, significant research and development is still required for their large-scale deployment.

Such R&D efforts are underway in Japan and China which are currently constructing HTR test reactors to investigate high temperature applications. Initial criticality of the Japanese High Temperature Engineering Test Reactor (HTTR) is expected in mid-1998. The Chinese High Temperature Reactor (HTR-10) is scheduled to go critical in 1999. The Russian Federation is undertaking a design study of a modular helium cooled reactor with an outlet temperature of 750-950^{0}C. Indonesia and South Africa are also interested in utilising high temperature gas reactors. The IAEA is coordinating three research projects in this field: (1) Heat transport and afterheat removal for GCRs under accident conditions, (2) Design and evaluation of heat utilization systems for the HTTR, and (3) Evaluation of High Temperature Gas Cooled Reactor Performance.

5. Conclusions

Most of the world's energy consumption is in the form of heat. Several countries have implemented programmes to use nuclear heat from dedicated heating reactors and cogeneration plants. This is an environmentally benign alternative to the burning of fossil fuels for district heating, seawater desalination and industrial process heat. There are no technical or safety impediments with using nuclear heat. An additional future potential is high temperature process heat generation for industrial purposes such as coal conversion and hydrogen production.

The IAEA is continuing activities in nuclear heat application, in particular concerning SMR development and nuclear desalination. This includes international information exchange in order to facilitate the sharing of knowledge and experience, performing studies and assisting Member States in building nuclear infrastructures and implementing demonstration projects.

References

[1] IAEA, Design and development status of SMR systems 1995, IAEA-TECDOC 881, 1996
[2] IAEA, Introduction of SMRs in developing countries, IAEA-TECDOC 999, 1998
[3] IAEA, Potential for nuclear desalination as a source of low cost potable water in North Africa, IAEA-TECDOC 917, 1996
[4] IAEA, Methodology for the economic evaluation of cogeneration/desalination options: A user's manual, Computer Manual Series No.12, 1997
[5] IAEA, Design approaches for heating reactors, IAEA-TECDOC 965, 1997