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Nuclear Energy and Process Heating

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K.S. Kozier

Paper presented at the Canadian Nuclear Society Climate Change and Energy Options Symposium, Ottawa, Ontario, 1999 November 17-19

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Office of the Chief Engineer
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L'ÉNERGIE NUCLÉAIRE ET LA PRODUCTION DE CHALEUR INDUSTRIELLE

par

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RÉSUMÉ

L'énergie nucléaire produite dans les réacteurs de fission est un produit polyvalent qui peut, en principe, satisfaire à tous les besoins énergétiques du monde entier par des moyens directs ou indirects. En plus de son utilisation actuelle principale pour la production d'électricité, et, à un degré moindre, la propulsion marine, l'énergie nucléaire a été et peut être utilisée pour les applications de chaleur industrielle, comme le chauffage des locaux, le chauffage industriel et le dessalement de l'eau de mer. En outre, une grande variété de types de réacteurs a été employée à cette fin dans divers pays. En se fondant sur cette expérience, deux méthodes de conception surgissent pour le chauffage industriel nucléaire : extraction d'une partie de l'énergie thermique d'une centrale nucléaire (c.-à-d. création d'une centrale de production conjointe de chaleur et d'électricité) et transport à l'utilisateur ou implantation de centrales calogènes ou de production de chaleur nucléaire en général plus près de la charge thermique. Si l'expérience de production de chauffage industriel nucléaire repose en grande partie sur la première méthode, un intérêt considérable a été manifesté récemment pour la deuxième, mettant généralement en jeu de petites centrales innovatrices présentant des caractéristiques améliorées et à sûreté passive. L'accent mis sur les caractéristiques de sûreté nucléaire inhérentes à ces types de réacteurs traduit la nécessité d'éviter toute exigence relative à l'évacuation du public en cas d'accident, ainsi que le désir d'un fonctionnement durable et d'une protection des investissements à coût minimum.

Étant donné qu'approximativement 67 % de l'utilisation principale d'énergie du monde entier ne dépendent pas de l'électricité, un vaste marché potentiel existe pour les systèmes de production de chaleur nucléaire, particulièrement aux températures d'utilisation finale faibles à moyennes nécessaires pour le chauffage des habitations et pour plusieurs applications industrielles. Bien qu'uniquement 0,5 % de la production d'énergie nucléaire du monde entier soit actuellement utilisée pour les applications de production de chaleur industrielle, un rôle élargi au XXI[e] siècle semble être inévitable, en partie comme mesure de réduction des émissions de gaz à effet de serre et d'amélioration de la qualité de l'air. Bien que les aspects techniques de nombreuses applications de production de chaleur nucléaire soient considérés comme étant bien éprouvés, un effort déterminé serait nécessaire pour pouvoir l'utiliser à court terme de façon plus importante. L'opportunité et l'ampleur de cette mise en œuvre dépendront bien sûr de l'indice d'actualisation du prix des combustibles fossiles, de la disponibilité locale des sources d'énergie de remplacement et du degré général de confiance du public dans la technologie nucléaire.

Le présent document examine les débouchés des systèmes de production de chaleur industrielle nucléaire, et notamment la nature du marché potentiel, certains choix de types de réacteurs de production de chaleur nucléaire prometteurs présentant actuellement un certain intérêt et l'expérience canadienne et mondiale.

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ABSTRACT

Nuclear energy generated in fission reactors is a versatile commodity that can, in principle, satisfy any and all of mankind's energy needs through direct or indirect means. In addition to its dominant current use for electricity generation and, to a lesser degree, marine propulsion, nuclear energy can and has been used for process heat applications, such as space heating, industrial process heating and seawater desalination. Moreover, a wide variety of reactor designs has been employed to this end in a range of countries. From this spectrum of experience, two design approaches emerge for nuclear process heating (NPH): extracting a portion of the thermal energy from a nuclear power plant (NPP) (i.e., creating a combined heat and power, or CHP, plant) and transporting it to the user, or deploying dedicated nuclear heating plants (NHPs) in generally closer proximity to the thermal load. While the former approach is the basis for much of the current NPH experience, considerable recent interest exists for the latter, typically involving small, innovative reactor plants with enhanced and passive safety features. The high emphasis on inherent nuclear safety characteristics in these reactor designs reflects the need to avoid any requirement for evacuation of the public in the event of an accident, and the desire for sustained operation and investment protection at minimum cost.

Since roughly 67% of mankind's primary energy usage is not in the form of electricity, a vast potential market for NPH systems exists, particularly at the low-to-moderate end-use temperatures required for residential space heating and several industrial applications. Although only about 0.5% of global nuclear energy production is presently used for NPH applications, an expanded role in the 21st century seems inevitable, in part, as a measure to reduce greenhouse gas emissions and improve air quality. While the technical aspects of many NPH applications are considered to be well proven, a determined effort would be needed to achieve more significant near-term use. The timing and extent of this implementation will of course depend on the rate of escalation of fossil-fuel prices, the local availability of alternative energy sources, and the general level of public confidence in nuclear technology.

This paper reviews the prospects for NPH systems, including the nature of the potential market, some of the promising NHP reactor design options of current interest, and Canadian and global experience.

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1. INTRODUCTION

As an energy source, nuclear fission has several characteristics of strategic significance:

- no oxygen is consumed and no oxides of carbon, sulfur and nitrogen are produced,
- nuclear fuel has an extremely high energy content, allowing for low fuel fabrication and transportation costs, and small waste volumes,
- nuclear fuel resources are currently plentiful, and options such as advanced fuel cycles or seawater extraction of uranium assure their availability for thousands of years, and
- a wide range of materials, configurations, operating conditions and engineering options can be employed in various fission-reactor designs, providing flexibility to adapt to particular missions and circumstances.

The versatility of nuclear-fission-reactor technology has enabled its use for applications as diverse as submarine propulsion and spacecraft power generation. Indeed, at least in principle, nuclear energy could satisfy any and all of mankind's energy needs through direct or indirect means. Examples of the latter include the production of electrolytic hydrogen from a nuclear power plant (NPP) for use as a transportation fuel and the production of ^{238}Pu to power "nuclear batteries" for heart pacemakers.

Today, nuclear reactors are predominantly used for electricity generation, supplying about 17% of global demand. The global nuclear generating capacity is about 352 GW_e from 442 reactors in 32 countries. In addition, there are about 250 nuclear powered vessels (a decline from over 400 in 1989), including eight civilian icebreakers and a transport barge, powered by more than 400 small reactors.

An expanded role for nuclear energy in the 21st century seems to be inevitable given the strong growth in demand expected for all forms of energy, especially as a consequence of population growth and economic progress in developing countries, and the need to address the local and global problems of air quality and climate change. Besides building more NPPs of current and advanced design, an expanded use of nuclear energy could take several forms:

- greater use of nuclear process heating (NPH). Currently more than 60 reactors supply about 5 GW_t for residential and district heating, industrial processes and seawater desalination, and over 500 reactor years of experience has been accumulated [1],
- new ways of bringing nuclear energy to market, such as barge-mounted NPPs [2], and
- new applications, such as using nuclear submarine technology for undersea mining of oil and gas deposits [3].

This paper reviews the prospects for NPH systems, including the nature of the potential market, some of the promising NPH reactor design options of current interest, and global experience on a country-by-country basis.

2. THE NUCLEAR PROCESS HEAT MARKET

At present about 67% of total primary energy is consumed as heat for residential and industrial purposes, and for transportation. More than 50% of primary energy is used for either hot water or steam production. Virtually all of the heat market is supplied by burning coal, oil, gas and wood. Thus, the main societal benefits of using nuclear energy to generate an increasing share of this heat are energy-supply diversification and reduction of the environmental and climatic impacts from fossil-fuel combustion.

Unlike electricity, transporting heat is difficult and expensive, requiring piping, insulation, pumps, heat exchangers and maintenance. Consequently, heat is rarely transported over distances of more than a few kilometres — at most a few tens of kilometres. The specific cost of transporting heat depends strongly on the amount transported and increases rapidly for small systems. Storage of large quantities of heat would be expensive.

Thus, heat sources tend to be small in terms of total thermal power output, located close to the user, operated according to immediate needs, and isolated from other heat source and distribution systems. Since the consequences of loss of heat supply can be severe, high availability is required, necessitating redundant or alternate sources as backup.

For dedicated NPH systems (i.e., a single-purpose nuclear heating plant, or NHP), these market requirements necessitate the design of small reactor systems (less than about 500 MW_t) that can be licensed for use close to population centres and near industrial activities that may present non-negligible external hazards to the NHP. Hence, the design of modern NHPs emphasizes passive safety features, such as natural coolant circulation, and inherent nuclear safety characteristics, such as negative temperature reactivity feedback coefficients, that do not require operator action and rely instead on natural processes like gravity. While the prime safety objective is to avoid any requirement for evacuation of the public in the event of an accident, these design measures enhance investment protection and reduce operating costs.

Unlike nuclear-generated electricity, with NPH systems it is theoretically possible to transport radioactive contamination along with the heat. Consequently, additional protective barriers are imposed between the reactor and the consumer, including intermediate heat-transport loops; pressure gradients are used to prevent the spread of potential contamination; and heat-transport circuits are monitored continuously to ensure compliance with radioactivity concentration limits.

District Heating

A cooperative heating system makes sense when a group of users shares common or complementary needs and economies of scale provide benefits concerning efficiency, operation and maintenance, environmental emissions and unit energy cost. District heating provides >25% of all space heating in Germany, Denmark, Sweden and Finland. Several towns in northern Europe obtain ~70% of their heat demand from district heating.

In Canada, the total capacity of existing district heating systems is only about 1.5 GW_t and includes systems ranging in size from 3.7 to 276 MW_t. About 86% of these systems have capacities <100 MW_t and account for about 54% of the total energy usage. A typical user is a major university or large hospital complex.

District heating systems range in size from about 600 to 1200 MW_t in large cities and from 10 to 50 MW_t in towns and villages. Load factors vary with the length of the heating season and can reach 50%. District heating systems provide energy for space heating as well as domestic hot water. A key feature is fuel flexibility, particularly using surplus heat from combined heat and power (CHP) systems and cogeneration from industrial facilities.

District heating uses hot water or steam distribution systems at supply temperatures ranging from about 85 to 220°C, typically 100 to 150°C. The temperature of the return line is usually about 50 to 70°C. The modern trend is toward low-temperature hot water for new or replacement heat distribution systems for economic reasons. One way to improve the load factor of the distribution network is to provide cooling with chilled water during the summer air-conditioning season.

Since district heating systems are capital-intensive, the main near-term market for nuclear district heat sources is as replacements for existing fossil-fuelled sources.

An obstacle for the widespread introduction of dedicated NHPs is the difficult and often lengthy process of establishing new nuclear facilities. Public confidence in the safety and reliability of nuclear technology and appreciation of its environmental and economic benefits are prerequisites to overcome the not-in-my-backyard (NIMBY) syndrome.

Industrial Process Heating

Industrial users require a high degree of reliability and availability approaching 100% for large installations and energy-intensive processes. The energy demands typically have base-load characteristics and are not very sensitive to climatic conditions.

About 50% of industrial users require <10 MW_t of heat and an additional 40% require between 10 and 50 MW_t [4]. About 99% of industrial users are in the 1 to 300 MW_t range and account for 80% of the total energy consumed.

In Germany, about 65% of industrial heat is provided at temperatures >800°C and only about 21% is required at temperatures <300°C [4]. Temperature ranges pertain to industry as follows:

- <300°C: seawater desalination, pulp and paper, textiles, agribusiness,
- 300 to 600°C: chemical industry, oil refining, oil-shale and oil-sand processing, coal gasification,
- 600 to 1000°C: non-ferrous metals, refinement of coal and lignite, hydrogen production by water splitting, and
- >1000°C: iron/steel industry, glass and ceramics.

Seawater Desalination

About three quarters of the world's population lack safe drinking water [5], particularly in the Middle East and parts of Africa, South America and Southeast Asia. The consequences of poor water quality are sobering: contaminated water causes 80% of the disease in developing countries and kills 5.3 million people each year [6].

In Tripoli, Libya, the cost of potable water is >U.S. $3 per m^3. In some oil-producing countries the cost of a gallon of gasoline is less than a gallon of water.

Seawater desalination is a good solution to shortages of potable water in many areas; however, it is an energy-intensive process. Desalination processes include multistage flash (MSF) and multi-effect distillation (MED) and reverse osmosis (RO); MSF and MED mainly require energy in the form of steam, while RO primarily uses electricity. The most energy-efficient desalination process is RO, which requires 4 to 7 $kW_e{\cdot}h/m^3$ of electrical energy, depending on water quality requirements, feed seawater salinity and temperature, and plant configuration.

3. CHARACTERISTICS OF NPH SYSTEMS

NPH systems comprise several reactor types, varying in operating temperature, primary coolant, and design configuration:

- **water-cooled reactors:** comprising pressurized heavy-water reactors (PHWRs) and light-water reactors (LWRs), the latter including pressurized water reactors (PWRs), boiling-water reactors (BWRs) and graphite-moderated systems (e.g., RBMKs). The maximum temperature at which heat can be delivered is about 300°C; higher temperatures can be achieved with advanced, supercritical-water-cooled designs or by adding fossil-fuelled peaking systems. The main types of dedicated NHPs include:
  - ⇒ **pool-type LWRs**: simple, low-capital-cost, unpressurized systems, similar in design to many research reactors and delivering low-temperature hot water at ~85°C. The main design feature is a large pool of light water that serves as the neutron moderator, heat-transfer medium and radiation shield. The key safety feature is elimination of the possibility of a rapid loss-of-coolant accident (LOCA) caused by depressurization of the primary circuit.
  - ⇒ **integral PWRs (IPWRs):** the primary heat exchangers or steam generators are included within the reactor pressure vessel, thereby eliminating the possibility of a pipe-break LOCA. Numerous designs have been considered [7].
- **liquid-metal-cooled reactors:** are capable of delivering heat at temperatures up to about 540°C and include sodium- and lead-bismuth-cooled systems.
- **gas-cooled reactors:** are capable of delivering heat at temperatures up to about 1000°C and include carbon-dioxide- and helium- (He) cooled systems.

High-temperature reactors (HTRs, ~500 to 1000°C output temperature) are at an earlier stage of development and commercialization than water-cooled systems. However, HTRs offer the potential of high energy-conversion efficiency for electricity generation, are well suited to use in arid regions with waste heat rejection to air, and have the flexibility to address a range of process heat applications directly.

CHP systems can be configured in either a parallel or series arrangement. In parallel cogeneration, a portion of the steam from the steam generators is diverted to the process heat application, while in series cogeneration steam is bled from a suitable point in the steam turbine cycle of the secondary loop, usually at the high-pressure/low-pressure crossover. In the latter arrangement, up to about half of the heat removed to the condenser of an NPP can be used for process heating, increasing the overall energy efficiency of the plant to about 60%.

For current nuclear CHP systems, the cogenerated heat represents less than 10%, and in most cases less than 5%, of the overall power output. Hence, the produced heat is essentially a by-product and the economics of the plant are dominated by the generation of electricity. The cost of nuclear process heat is usually calculated from the lost electricity generation and electricity generation cost (power credit method).

Siting considerations are similar for NHP and NPP systems, although it is economically desirable to site the former much closer to the user. For hot-water district heating systems, delivery over distances of up to 60 km is technically and economically feasible. For steam heat, the maximum delivery distance is about 20 km.

Irrespective of reactor type, modern NHPs incorporate similar enhanced safety features to enable their use close to the user, such as:

- large operating margins: low power density, low operating pressure/temperature,
- elimination of large pipe-break LOCA events,
- natural circulation of primary coolant,
- self-actuating reactivity shutdown mechanisms, negative reactivity coefficients,
- large primary-coolant inventory and thermal heat sink,
- long station-blackout capability,
- passive decay heat removal,
- dual containment, and
- low operator response requirements (e.g., self-regulation, slow thermal response).

4. GLOBAL NPH EXPERIENCE

Global experience with NPH systems is reviewed on a country-by-country basis in alphabetical order, including actual operating experience and some recent studies.

Argentina

The 27-MW_e (100-MW_t) CAREM-25 IPWR is being developed by the Atomic Energy Commission (CNEA) and INVAP SE for electricity generation, industrial steam production, seawater desalination or district heating. One application studied is the production of electricity and process heat for the extraction and purification of sodium sulfate at a remote mine site in the Northwest Puna region of Argentina [1].

Bulgaria

The Kozloduy NPP consists of four VVER-440 (408 MW_e each) and two VVER-1000 (953 MW_e each) units. Since 1990, up to 230 MW_t of steam has been extracted from the turbine cycle and used to generate hot water for district heating in the nearby town of Kozloduy. The safety requirements include: continuous radiation monitoring of the water in the boiler and heat distribution circuits and weekly laboratory analysis, similar weekly analysis of the specific activity of corrosion products in the boiler circuit, and maintenance of a minimum positive pressure differential of 1.5 kg/cm^2 between the output of the hot-water loop and the steam-extraction circuit [4].

Canada

From 1979 to 1985, a portion of the heat output (~13 to 15 MW_t) from the 60-MW_t WR-1 research reactor was used to heat the plant site at Atomic Energy of Canada Limited's (AECL's) Whiteshell Laboratories (WL) in Pinawa, Manitoba, saving a total of 21 million litres of fuel oil. WR-1 was a small prototype of the CANDU* OCR (organic-cooled reactor) concept, in which the heavy-water coolant inside the pressure tubes was replaced by a mixture of partially hydrogenated terphenyls. The heat-transport circuit used for process heating operated at a relatively high temperature of about 345°C, but at a moderate pressure of only 2.4 MPa. .

At AECL's Chalk River Laboratories (CRL) in Chalk River, Ontario, low-temperature effluent heat from the heavy-water-cooled and -moderated 125-MW_t National Research Universal (NRU) reactor has been recovered on occasion and used to preheat building ventilation air and make-up water to various systems. Also, waste heat from the separate, high-temperature U2 experimental loop (~4.5 to 8 MW_t) has been used to supply process steam to the CRL site.

The SLOWPOKE Energy System 10-MW_t (SES-10) [8], pool-type heating reactor was developed by AECL in the 1980s as a source of low-temperature (85°C) hot water for building complexes, institutions and municipal heating systems. One SES-10 unit would heat 150 000 m^2 of floor area or about 1500 individual apartments. The cost of heat energy from the SES-10 system is sensitive to the annual load factor; at an 80% load factor this was estimated to be about U.S. $0.02 per $kW_t{\cdot}h$ (in 1990) [4]. A similar 2-MW_t unit, the SLOWPOKE Demonstration Reactor (SDR), was built at WL and operated briefly in 1987 for physics and thermalhydraulics tests.

* CANDU: CANada Deuterium Uranium; registered trademark of AECL

AECL also studied a novel, heat-pipe-cooled, solid-core reactor concept known as the Nuclear Battery [9], which would have been capable of generating about 600 kW_e of electricity for remote communities or 2.4 MW_t of steam heat at about 500°C (e.g., for the in situ recovery of bitumen from the Alberta Oil Sands using the high-pressure Cyclic Steam Stimulation (CSS) or "huff and puff" process) for 15 full-power years.

The use of CANDU PHWRs for process heat applications was reviewed recently by Meneley et al. [10]. Notably, the recently developed Steam Assisted Gravity Drain (SAGD) process for bitumen recovery in the Alberta Oil Sands using parallel horizontal wells is compatible with the medium-pressure steam available from CANDU [11].

The Bruce Nuclear Power Development (BNPD) operated by Ontario Power Generation (OPG, formerly Ontario Hydro) is one of the world's largest energy centres, containing two 4-unit CANDU NPPs (904 MW_e gross per unit), the Bruce heavy-water plant (BHWP), a low-level radioactive waste storage facility, a nuclear training centre, central stores and maintenance facilities, and the Bruce bulk steam system (BBSS). Besides meeting OPG's steam needs, the BBSS serves the adjacent Bruce Energy Centre (BEC). Steam is extracted from the steam generators in a parallel cogeneration arrangement.

The BBSS is capable of producing 5350 MW_t of medium-pressure steam and was originally built to service the nearby heavy-water production plants. It operated as the world's largest NPH system from 1977 to 1998, when the Bruce A units were laid up as part of OPG's performance improvement program and the BHWP was mothballed. During operation, the typical demand for steam included 750 MW_t for the BHWP, 15 MW_t for the internal needs of the Bruce NPP, 3 MW_t for the training centre and 72 MW_t for the BEC. The total length of the steam delivery system is about 6.4 km.

The customers at the BEC include: (1) a 30 000 m^2 greenhouse, (2) a 12 million L/a ethanol plant using locally grown corn, (3) a plastic film production plant, (4) a 90 000 tonne/a alfalfa dehydration, cubing and pelletizing facility, (5) an apple-juice-concentration plant, and (6) an agricultural research facility. In the early 1990s, the cost of steam produced from natural gas was about 38% higher than that from the BBSS.

CANDESAL Inc. of Ottawa, Ontario, has looked at the coupling of an RO desalination unit with a CANDU [12] as well as a Russian reactor [2]. Besides using nuclear-generated electricity to power the RO units, waste heat from the turbine condensers is used to preheat the feedwater to the RO units, thereby improving their efficiency.

China

Energy used as heat at temperatures <150°C accounts for about 25% of the total energy consumption in China.

R&D work on NHP systems has been underway since 1982 at the Institute of Nuclear Energy Technology (INET) at Tsinghua University, about 40 km north of Beijing. Starting in 1983, a demonstration of nuclear heating was carried out over two heating seasons using an existing, pool-type experimental reactor. A Deep Pool Reactor (DPR) concept [13] and an IPWR were studied for further development.

In 1986, construction began on the Nuclear Heating Reactor 5-MW_t (NHR-5) IPWR at INET. Key design features include natural circulation of the primary coolant at full power, dual vessel design, hydraulic in-vessel control-rod drive mechanisms, self-regulation of primary system pressure and low process parameters. The NHR-5 system has been in operation since 1989 November and is currently the world's only dedicated NHP. Experiments have been conducted to study electricity generation with low-pressure steam in a cogeneration mode, air conditioning using a lithium-bromide heat-absorption process to produce chilled water at 7°C, and seawater desalination [1].

The commercial-scale Nuclear Heating Reactor 200-MW_t (NHR-200) design was developed by INET with assistance from Siemens/KWU of Germany. The size selected was based on analysis of the market demand for district heat. The annual base-load heating requirement varies from 3000 to 5000 h in North and Northeast China; combined use for heating and air conditioning could increase the annual load in Central and South China to about 4000 h. The first demonstration plant is under construction in Daqing City in Northeast China. Operation is possible with either fully pressurized primary coolant conditions or slight boiling, the latter mode enhancing coolant circulation.

The use of the NHR-200 NHP to produce 150 000 m^3/d of potable water has been studied for Dalian City. The production cost is estimated to be U.S. $1.2 per m^3 [14].

Construction of the 10-MW_t High Temperature Reactor (HTR-10) is nearing completion at INET based on pebble-bed reactor technology developed in Germany. It will deliver He at 950°C for the demonstration of electricity generation (steam cycle), electricity/heat cogeneration, gas/steam combined-cycle electricity generation, and NPH applications such as coal gasification/liquefaction and steam reforming [15].

Germany

The Stade NPP consists of a 630-MW_e (1892-MW_t) PWR. Since 1983, it has supplied about 30 MW_t of steam heat to a salt refinery located 1.5 km away, and has supplied about 10 MW_t for space heating at the Schilling oil-fired power station and an adjacent tank storage facility.

The Greifswald NPP consists of four VVER-440 model V230 PWRs. It supplied up to 180 MW_t for district heating, but was shut down in 1990 following German reunification.

Hungary

The Paks NPP consists of four VVER-440 model V230 PWRs. Since 1977, up to 55 MW_t of hot water from the NPP has been transported a distance of 6 km to the town of Paks. The heating system uses basic and peak heat exchangers in series. The basic heat exchanger heats the returning water to 100°C using steam extracted from the low-pressure turbine. The peak heat exchanger increases this to 130°C using steam from the high-pressure turbine. The heating system of one reactor supplies the internal needs of the NPP, while any of the other three units can supply the full heating load of the town.

India

A 425-m^3/d MSF desalination facility has been operated at the Bhabha Atomic Research Centre (BARC) in Mumbai since 1984. A 6300 m^3/d hybrid plant (MSF/RO) is planned for the Madras Atomic Power Station (MAPS) PHWR in Kalpakkam [1].

Japan

Since 1973, Japan has used PWRs at the Ohi, Ikata, Genkai, and Takahama NPPs for nuclear desalination. Feedwater for the steam generators and on-site potable water is produced using RO, MSF or MED plants of 1000 to 21 000 m^3/d capacity [1].

The 30-MW_t High-Temperature Engineering Test Reactor (HTTR) at the Oarai Research Establishment of the Japanese Atomic Energy Research Institute (JAERI) achieved initial criticality in 1998 November. The HTTR uses a prismatic-block-type graphite core with TRISO (triply isotropic) coated-particle fuel. It will be the first nuclear reactor to be connected to a high-temperature process-heat utilization system, supplying heat at ~850°C. About 60% of Japan's total energy needs are for heat at temperatures $<$1000°C.

JAERI is developing a thermochemical method to produce hydrogen from water using an iodine-sulphur (IS) process (first proposed by General Atomics) that recycles the chemical components and generates no carbon dioxide [1,15]. JAERI is also studying heat transport over long distances using tiny encapsulated particles containing phase-change materials (PCMs). For HTR applications, the PCM would likely be a molten salt with inorganic coatings similar to the TRISO particles.

Kazakhstan

The Aktau NPP at the Mangyshlak Atomic Energy Complex on the Caspian Sea consists of a 750-MW_t BN-350 liquid-sodium-cooled, fast breeder reactor. It is a multipurpose experimental facility and the world's first demonstration plant for nuclear desalination, in service since 1973 using the MED process. It produces up to 125 MW_e of electricity, up to 80 000 m^3/d of desalted water (some of which is used as feedwater for the nuclear plant), and supplies hot water for district heating.

Morocco

Morocco is presently involved in a pre-project study of a 10-MW_t NHR-10 NHP from China to produce 8000 m^3/d of potable water using a MED process at the Tan-Tan coastal site in South Morocco [1].

The Netherlands

In 1996-97, the Ministry of Economic Affairs funded a pre-feasibility study of a small 40-MW_t, He-cooled, pebble-bed CHP design known as INCOGEN (Inherently Safe Nuclear Cogeneration), capable of producing 16.8 MW_e and 18.2 MW_t of process heat at 150°C. It was found that the concept, while feasible, may not be economical where natural gas is inexpensive [15]. Additional studies are being performed on a similar 40-MW_t HTR concept known as ACACIA (Advanced Atomic Cogenerator for Industrial Applications) that is capable of producing 13.6 MW_e and 17 tons/h of steam at 220°C.

Republic of Korea

The Korea Atomic Energy Research Institute (KAERI) has studied using a 330-MW_t IPWR, known as SMART (System Integrated Modular Advanced Reactor), as a CHP system for seawater desalination that is capable of producing up to 40 000 m^3/d [1].

Romania

The 700-MW_e Cernavoda-1 CANDU 6 NPP went into commercial operation in 1996. It supplies steam to a district heating system for about 60% of local residents [16].

Russia

All operating NPPs in Russia have associated heating systems for space heating, air conditioning and hot-water supply for the power station and nearby towns. Typically, these towns have populations of 40 000 to 50 000, are located 3 to 15 km away, and have heat loads of 100 to 200 MW_t [1].

NPH systems are especially attractive in the extreme north and northeast part of Russia, where about 80 to 90% of the cost of fossil fuel is determined by transport costs, and where the cost of electricity and heat are 10 to 20 times higher than in other regions.

The 5-MW_e (30-MW_t) water-cooled, graphite-moderated AM reactor (First NPP) at the Institute for Physics and Power Engineering (IPPE) in Obninsk was the world's first reactor to produce significant quantities of electricity, beginning in 1954 June 27. In 1976 its turbine was dismantled and 10 MW_t of steam heat was instead distributed to local industries and to a district heating system in Obninsk. It is still operating today.

IPPE has studied a pool-type NHP known as RUTA, ranging in size from 10 to 55 MW_t; a 30-MW_t unit has been proposed as a replacement for the AM plant and would supply 85% of the annual heating load at IPPE. An underground NHP consisting of four 55-MW_t RUTA reactors has been proposed for the town of Apatity in the Kola peninsula.

The Bilibino Nuclear Cogeneration Plant (BNCP) in Chukotka consists of four 62-MW_t water-cooled and graphite-moderated reactors that each supply 12 MW_e plus 19 MW_t as heat. It has been in operation since 1974. The cost of electricity and heat from the BNCP is 2.0 to 2.5 times lower than fossil-fuelled alternatives. Three advanced channel-type ATU-2 reactors (40 MW_e plus 58 MW_t) are planned to replace the BNCP units.

At the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad, two pilot-scale plants, the VK-50 50-MW_e (250-MW_t) BWR and the BOR-60 12-MW_e (60-MW_t) sodium-cooled fast reactor, produce electricity and heat that is sold to the surrounding region, including nearby greenhouses. A larger 250-MW_e (750-MW_t) VK-300 plant has been proposed for district heating and electricity supply.

Starting in about 1958, water-cooled, graphite-moderated plutonium (Pu) production reactors of the AD and ADE types were used to provide electricity and heat to "closed" cities at the Tomsk-7 (now Seversk) and Krasnoyarsk-26 (now Zheleznogorsk) sites in Siberia. The remaining reactors at those sites are scheduled to be shut down in 2000 and various advanced reactor plants have been proposed as replacements.

The AST IPWR NHP design was developed by the Experimental Machine Building Design Bureau (OKBM) in sizes ranging from 50 to 500 MW_t. In 1983-85, construction started on a 500-MW_t AST-500 unit at Nizhny Novgorod (formerly Gorky) and on two units at Voronezh, but was later interrupted. In 1996 construction resumed at Voronezh. Twin AST-500 units have been proposed as replacements for the Tomsk-7 reactors; it is planned to use some of the components previously delivered to the Gorky site.

A 290-MW_e (600-MW_t) Gas Turbine - Modular Helium Reactor (GT-MHR) design developed jointly by General Atomics, OKBM and the Kurchatov Institute has been proposed as a replacement for the Tomsk-7 and Krasnoyarsk-26 reactors that would destroy weapons-grade Pu while providing electricity and energy for district heating [17]. The reactor would heat He to 850°C at 7.02 MPa and achieve a conversion efficiency of 47% in a direct Brayton cycle using a helium gas turbine.

Russia has about 150 reactor years of experience with lead-bismuth-cooled systems (45% Pb - 55% Bi), such as those used for submarine propulsion. Based on this experience, the small 30-MW_t ANGSTREM design has been developed as a modular, transportable power source for cogeneration, district heating or seawater desalination.

A floating NPP system, known as APWS-80 and consisting of two KLT-40 loop-type PWRs (up to ~160 MW_t), has been designed based on more than 150 reactor years of experience for marine propulsion. The system has been proposed for electricity generation at Pevek in Northern Siberia as well as for seawater desalination in North Africa. The APWS-80 could deliver up to 80 000 m^3/d of desalted water or combinations such as 58 MW_e and 20 000 m^3/d. The estimated cost of potable water is U.S. $1.0 to $1.5 per m^3. Similar floating NPPs have been considered using the ABV IPWR.

Russia has over 20 years of successful experience with more than 50 small nuclear desalination plants of 60 to 120 m^3/day capacity on its civilian nuclear-powered ships [2].

Slovakia

At the Bohunice V-2 NPP in Slovakia, steam has been extracted from the turbine cycle of two of the four VVER-440 type V-213 reactor units since 1987, to supply heat to the town of Trnava, about 23 km away. The maximum capacity of this system is 240 MW_t. Heat delivery has increased gradually from 478 TJ in 1988 to 1104 TJ in 1995 [1]. Nuclear heat supplied about 60% of the total heat required by the district heating system in 1995 at about 60% of the cost of heat from fossil fuel.

South Africa

ESKOM, the state electricity utility in South Africa, is developing the 103-MW_e (228-MW_t) Pebble Bed Modular Reactor (PBMR) based on technology developed in Germany. Although the primacy focus is low-cost, high-efficiency (~47%) electricity generation via direct coupling to a helium gas turbine, application for industrial purposes such as hydrogen production is also being evaluated. A half-scale model of the PBMR achieved criticality in 1999 June at the Kurchatov Institute's Astra facility [18].

Sweden

From 1963 to 1974, heat from the 12-MW_e (68-MW_t) heavy-water-cooled and -moderated Ågesta CHP plant was delivered to Farsta, a suburb of Stockholm.

Switzerland

The Beznau NPP consists of two 365-MW_e (1130-MW_t) PWRs located about 35 km northwest of Zurich and is operated by the utility NOK (Nordostschweizerische Kwaftwerke). Starting in 1983, heat was supplied to two nuclear research institutes: EIR (Eidgenössisches Institut für Reaktorforschung) and SIN (Schweizerisches Institut für Nuklearforschung), located 1.8 km from the NPP. The capacity of this system was expanded progressively to 80 MW_t. In 1997, 141 $GW_t \cdot h$ of heat was delivered by the REFUNA (Regionales Fernwärmenetz Unteres Aaretal) district heating grid.

Steam for district heating is extracted at 128°C from two of the four turbines between the high and low pressure portions. Initially this caused a loss of electricity generation at a rate of 0.161 MW_e/MW_t; however, the addition of a second heat-extraction stage at 85°C in Beznau I and new steam generators in 1993 reduced the loss rate to 0.12 MW_e/MW_t.

The REFUNA system supplies about 2160 private, industrial and agricultural customers through 35 km of main piping and 85 km of local distribution pipes. The cost to customers is somewhat higher than with individual oil heating, because they are spread over a wide area; however, most accept this as a contribution to environmental protection.

The temperature of the hot-water grid is adjusted from 75 to 120°C to meet seasonal requirements. The heat losses at full power are about 6% in the main piping and 6-12% in the local networks (about 15% overall). Normal water losses are about 1.0 to 1.5 m^3/d.

The Gösgen NPP consists of a 970-MW_e PWR located 35 km southeast of Basel. Since 1979, steam has been extracted in a simple, parallel-cogeneration arrangement using a tertiary steam loop and piped over a distance of 1.75 km to the Niedergösgen cardboard factory. In 1997, 142 $GW_t{\cdot}h$ of heat was delivered.

Ukraine

Extensive nuclear district heating systems are associated with the multi-unit NPPs at Zaporozhe (capacity 1165 MW_t), South Ukraine (534 MW_t) and Rovno (291 MW_t) [1,4].

United Kingdom

The first of the four 60-MW_e (originally 41 MW_e from 225 MW_t), CO_2 gas-cooled, Calder Hall MAGNOX power reactors operated by British Nuclear Fuels Limited (BNFL) at Sellafield, in Cumbria, opened in 1956 October, supplying process steam heat to a neighbouring fuel reprocessing plant and electricity to the grid. The reactor is still operating and is licensed to the year 2006.

United States

An RO desalination plant of 2200 m^3/d capacity has been operated at the Diablo Canyon NPP at San Luis Obispo in California for on-site water supply since 1985 [1].

The technical feasibility of very small nuclear reactor plants to produce heat, electricity and fresh water for local energy systems in remote locations was demonstrated in early development efforts, such as the U.S. Army "packaged" reactor program [19]. A variety of reactor designs were deployed in this program and operated from the mid-1950s to the early 1970s in Alaska, Antarctica, Greenland and at several locations in the continental U.S. The thermal power used for space heating ranged from 0.3 to 13 MW_t.

5. FUTURE PROSPECTS

Presently, NPH is predominantly derived from CHP systems as a minor local byproduct of NPP operation — a bonus to surrounding communities and industries, and a means to increase the overall energy efficiency of the plant. Typically, NPH systems are put in place somewhat after operation for electricity generation. Expanded use of NPH in this manner, therefore, mainly depends on the continued success of (water-cooled) NPPs competing in the market for new power-plant construction. Enhanced use of NPH also requires systems in place to distribute the heat, and nearby customers; such factors should be considered in the siting and design of new NPPs or the construction of replacements.

The development of new industrial processes better matched to the output characteristics of existing water-cooled reactor designs, such as the SAGD process for bitumen recovery in the Alberta Oil Sands, could accelerate the introduction of substantial NPH systems where heat is the dominant product.

The end of the Cold War has given impetus to the development of new NPH systems, particularly in Russia. Firstly, resources previously occupied with the construction of military nuclear-powered vessels have been liberated to pursue commercial opportunities for floating nuclear CHP systems and desalination units. Secondly, the cessation of weapons-Pu production and the implementation of Pu-dispositioning projects have created a unique opportunity to demonstrate new NHP designs.

While NPH systems are by nature very localized and justified on a case-by-case basis, interest in their use is global — spanning all continents except Australia, and all reactor types. Two trends of note are the commonality of design concepts in several countries, such as the numerous IPWR-based systems, and the transfer of technology between countries, especially for HTR systems, assuring continuous, evolutionary development.

A small additional type of cogeneration market exists where waste heat (if available at sufficient temperature and with a compatible duty cycle) from reactors designed to generate neutrons for research purposes, isotope production, medical therapy, or as engineering-test and prototype facilities, can be used for local institutional needs. Some examples were noted in Section 4. Such systems have a natural synergism with nuclear research centres, major technical universities and hospitals, where substantial technical expertise, infrastructure, energy distribution systems and appropriate safety culture are already in place; hence, the possible merits should be considered when constructing new or replacement facilities.

The near-term prospects for dedicated NHPs are somewhat less certain, since those systems are in a demonstration or first-of-a-kind engineering-prototype phase, while fossil-fuel prices have remained low. A determined effort will likely be needed to demonstrate the economic effectiveness of the technology, address public-perception issues concerning the siting of new reactor systems, and develop the necessary supporting infrastructure. Interest is high for specific projects, particularly in China and Russia, where the potential economic and societal benefits are clear, but it remains to be seen whether a near-term market for a sufficient number of units will emerge to attract the capital investment needed to have a significant energy impact.

In the longer term, successful deployment of NPH systems capable of higher operating temperature than existing systems could accelerate the use of NPH for a broader range of industrial applications. Based on the current level of construction of new research and development facilities and the number of active projects in several countries, it appears that helium-cooled HTR technology may be well positioned to play a significant future role in the expanded commercial use of nuclear energy, for electricity and process heat. Prime industrial roles for NPH are oil recovery from oil shale and oil sands, the transformation of fossil fuels into more convenient forms (e.g., coal into methanol [20]), and hydrogen production.

6. CONCLUSION

After more than 45 years of practical use, nuclear energy remains underutilized, even though it could address many of mankind's growing energy needs in a safe, economical, environmentally responsible and sustainable manner. An expanded role for nuclear energy in the form of process heat for district heating, industrial processes, and seawater desalination is certainly feasible, based on the successful demonstration of such uses with various reactor designs and in numerous countries, and would contribute to the achievement of greenhouse-gas-reduction targets. A vast potential market for NPH exists, since roughly two thirds of global energy consumption is not in the form of electricity. While existing NPH systems are dominated by CHP arrangements where heat is only a minor byproduct of NPP operation, there is substantial interest in NHPs that are specifically designed to match the needs of the process heat market, especially in China, Japan and Russia. The low-temperature end of this market appears to be best served by water-cooled reactors, either low-cost pool-type reactors (combined if necessary with fossil-fuelled peaking systems) or reactors with pressurized coolant, having adequate safety provisions to enable siting close to the user. In the longer term, successful deployment of higher-temperature reactor systems could provide a flexible means of addressing a wide range of industrial uses for process heat and further enhance the efficient use of nuclear energy.

7. REFERENCES

1. Nuclear heat applications: Design aspects and operating experience, IAEA-TECDOC-1056, Vienna, 1998 November.
2. Floating nuclear energy plants for seawater desalination, IAEA-TECDOC-940, 1997 May.
3. N. Ponomarev-Stepnoi, Nuclear Power of the 21st century, Nuclear Engineering and Design, 173, 1997, pp.21-31.
4. Nuclear applications for steam and hot water supply, IAEA-TECDOC-615, Vienna, 1991 July.
5. J. Kupitz, Nuclear's potential role in desalination, Nuclear Engineering International, 1992 December, p.41.
6. T. Spears, Global water plan far from developed, The Ottawa Citizen, 1999 April 14, p.A12.
7. Integral design concepts of advanced water cooled reactors, IAEA-TECDOC-977, Vienna, 1997 November.
8. J.W. Hilborn and G.F. Lynch, SLOWPOKE - Heating Reactors in the Urban Environment, AECL report AECL-9736, 1988 June.
9. K.S. Kozier and H.E. Rosinger, The Nuclear Battery: A Solid-State, Passively Cooled Reactor for the Generation of Electricity and/or High-Grade Steam Heat, AECL report AECL-9570, 1988.

10. D.A. Meneley, R.B. Duffey and D.R. Pendergast, CANDU Co-Generation Opportunities, paper presented at the IAEA Technical Committee Meeting, Prospects of Non-Electrical Applications of Nuclear Energy, Beijing, 1999 April 20-23.
11. J.K. Donnelly and D.R. Pendergast, Nuclear Energy in Industry: Application to Oil Production, 20th Annual Conference of the Canadian Nuclear Society, Montreal, Quebec, 1999 May 30 to June 2.
12. J.R. Humphries, K. Davies, T.D. Vu, N.A. Aryono and Y. Peryoga, A Technical and Economic Evaluation of Reverse Osmosis Nuclear Desalination as Applied at the Muria Site in Indonesia, 19th Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, 1998 October 18-21.
13. T. Jiafu, Y. Fu and Z. Zhaoyi, Deep Pool Reactors for Nuclear District Heating, Progress in Nuclear Energy, Vol. 33, No. 3, 1998, pp.279-288.
14. Y. Zhang, D. Zhang and D. Dong, Analysis of seawater desalination with NHR-200, Nuclear Energy, Vol. 38, No. 1, 1999 February, pp.21-29.
15. J. Nedderman, HTGR is alive and being relaunched, Nuclear Engineering International, 1998 October, pp.49-55.
16. M. Stiopol, Romanian N-Plant Set to Ease Winter Fuel Bills, European Nuclear Society, NucNet, The World's Nuclear News Agency, 1999 September 6, News No. 361.
17. C. Rodriguez, D. Pfremmer and A.J. Neylan, Simulation helps to make the case for the GT-MHR, Nuclear Engineering International, 1994 October, pp.74-77.
18. A. MacLachlan, Pebble Bed Model Goes Critical Moving ESKOM Closer to Decision, Nucleonics Week, Vol. 40, No. 29, 1999 July 22, p.1.
19. R.L. Loftness, "Nuclear Power Plants: Design Operating Experience and Economics", D. Van Nostrand Co. Inc., 1964, pp. 127-138.
20. S. Sato, H. Nagata, R. Notomi, I. Minatsuki and S. Uchida, A Study of a New Electrical Energy Storage System in which Nuclear Energy is used for Methanol Production, Progress in Nuclear Energy, Vol. 29 (Supplement), 1995, pp. 217-223.

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