Nuclear heat applications: World overview

by Juergen Kupitz and Milan Podest

Nuclear power has long played an important role in the safe and reliable generation of electricity, and today carries considerable potential to contribute to overall energy supplies needed in the future.

The major part of the world's primary energy currently is consumed in the form of heat by various branches of industry or for heating homes. Industrialized countries now consume about 70% of their primary energy as heat and only 30% as electric power.

Nuclear reactors could supply energy in the form of heat – and thereby contribute to the necessary substitution of fossil fuels, whose prospects include expected shortages, rising prices, and uncertain availability in the long term.

In general, heat consumption can be divided into two temperature levels:

- Low-temperature heat, which includes hot water or low-quality steam for district heat, desalination, and other purposes.
- High-temperature process heat, which includes process steam for various industrial applications (aluminium production, chemicals) or high-temperature heat for conversion of fossil fuels, hydrogen production, and so on.

Various types of reactors can produce these different temperature levels. Water-cooled reactors (light-water and heavy-water) can produce hot water or steam up to about 300°C. Gas-cooled reactors cooled by helium or carbon dioxide can produce process steam up to 540°C and the high-temperature gas-cooled, graphite-moderated reactor (HTGR) can produce process heat up to 950°C.*

Status of low-temperature applications

Low-temperature nuclear heating has been demonstrated in practice to be technically feasible and commercial introduction could be based either on electricity/steam cogeneration power reactors or on specialized low-temperature nuclear heating stations.

Economic studies on the use of heat from light-water reactors (LWRs) have shown that nuclear power plants are, in principle, suitable for the generation of low-temperature district and process heat. However, a disadvantage is that, for safety reasons, these nuclear power plants must be located a suitable distance from densely populated areas, which causes an increase in distribution costs.

In Czechoslovakia and Finland, the decoupling of heat for district heating from nuclear power plants (existing, under construction, or planned) equipped with the Soviet WWER-440 or WWER-1000 pressurized-water reactor (PWR) is highly elaborated. Plans for using decoupled heat from the PWRs are being made in the German Democratic Republic, Hungary, and Yugoslavia. Good results with the decoupled heat for district heating were achieved in the USSR at the Bilibino cogeneration plant, which now has been operating for nearly 10 years.

As previously mentioned, the siting of nuclear power plants at longer distances from population centres – motivated by safety requirements – may negatively affect economies of heat supply. In this respect, several projects show that transmission distances of about 30 to 40 kilometres are quite satisfactory. An exception is seen in a Finnish study on possible heat supply from the future Loviisa WWER-1000 reactor, which would have an 80-kilometre transmission line. This was still found to be economically competitive with an alternative coal-fired plant.

Nuclear heat stations

Another approach in nuclear heat supply – especially for district heating – is the use of specialized nuclear heat stations. On the one hand, with a view to efficiency and economy, it is necessary to locate these nuclear units as close as possible to the population areas. At the same time it is, of course, necessary to take all achievable safety measures. The so-called system of inherent reactor safety is of particular interest for this application. The most important design objective for this purpose is to make it technically impossible for the core to melt for any possible operation condition of the reactor.

Based on these principles, the nuclear heat station AST-500 was developed in the USSR and is now under construction in the cities of Gorky and Voronezh. These units are rather large and correspond to the demands of heat in several parts of the USSR. The Soviet study covering heat estimates for the whole

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* See the proceedings of the Technical Committee Meeting and Workshop on Nuclear Heat Applications, Cracow, 5–9 December 1983 – published by IAEA in September 1984 – for a detailed description of the state-of-the-art of nuclear heat reactors and process-heat applications.

USSR economy lead to the conclusion that altogether 600 nuclear heat stations, each 1000 megawatt (MW), should cover the country's demand. Nuclear heat stations called AST-300 (derived from the Soviet AST-500) are planned to be applied for district heating of two cities in Czechoslovakia by approximately 1995.

The result of the Asea-Atom study in Sweden was the Secure reactor design, operating at low power density, temperature, and pressure. Safe shutdown of the reactor and reliable core cooling are its essential safety features. The principle of securing these functions by inherent means is designated the PIUS philosophy (Process Inherent Ultimate Safety).

In France the CAS-300 (PWR) is now under consideration for heat supply, although no decision has been taken so far for its practical application.

In Canada, Atomic Energy of Canada Limited (AECL) has developed a small pool-type nuclear reactor (2 to 20 MW thermal) for heating buildings, called Slowpoke-3, based on the design of the previous experimental reactor Slowpoke-2. Six Slowpoke-2 reactors have been installed in Canadian cities and are licensed to operate unattended, but remotely monitored. Low-temperature leads to simplicity, safety, and low cost, while small unit size eases adaptability to the large but dispersed space-heating market.

A typical example of nuclear heat applications for industrial processes is the Canadian Bruce Bulk Steam System. For more than 10 years, medium-pressure steam for the nearby heavy-water plant has been delivered from the Candu nuclear reactors. By 1988, there will be eight Candu power reactors operating at this site, each with a capability of supplying 800 MWe of electricity – plus an additional 13% of full-rated output for process steam.

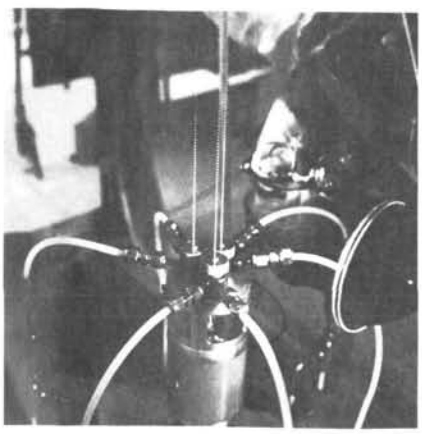
In the Federal Republic of Germany, the nuclear power plant Stade of Nordwestdeutsche Kraftwerke AG has supplied – since the end of 1963 – 60 tonnes of steam per hour at a pressure of eight bar and at a temperature of 270°C. About 95% of the steam – transported by pipeline over approximately 1.5 kilometres – returns in the form of condensate. The economics for this steam supply is better than that of a conventional process using heavy oil.

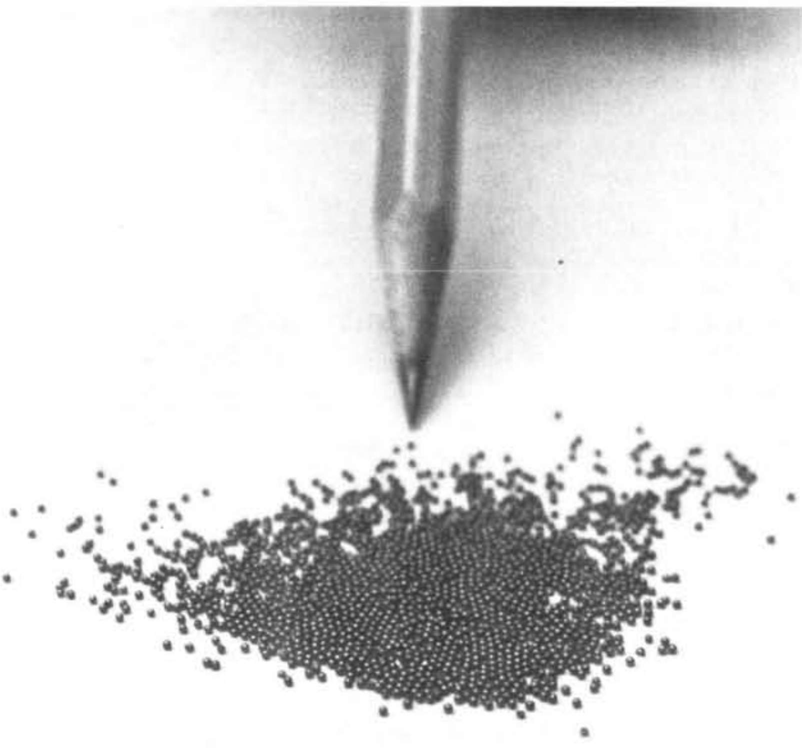
A unique example of the use of a fast reactor for cogeneration is the BN-350 located in Shevtshenko, USSR. The electrical output of this reactor is 120 MW, whereas a major part of the reactor heat is extracted from the third circuit and is used in a sea-water desalination station that is supplying 50 000 cubic metres of distilled water per day.

Status of high-temperature applications

High-temperature nuclear heat applications can be subdivided into two fundamentally different techniques – the use of steam up to temperatures of 540°C, and the direct use of the heat transferred through a heat-exchanger at up to temperatures of 950°C.

To help reduce dependence on fossil fuels for heat and power supplies, high-temperature gas-cooled reactors (HTGRs) are being developed to produce electricity and process heat up to 950° C from small coated uranium/thorium fuel particles such as the ones shown here close-up and in production. (Photos courtesy of GA Technologies, Inc.)





Process-steam applications. Gas-cooled reactors with primary-coolant temperatures of 650°C (AGR) to 750°C (HTGR) or higher can produce process steam comparable to that from fossil-fired steam generators, for example 540°C and 180 bar. This high-quality steam is well suited for fulfilling the needs of a number of industrial and chemical complexes. Potential areas for industrial applications of nuclear process steam include:

- Aluminium production
- Steelmaking
- Chemical industry
- Oil recovery
- Shale oil recovery
- Tar sand oil recovery
- Coal gasification by the Lurgi or Exxon gasification process

These processes, based on existing technology, presently provide process steam by burning fossil fuels. Most of these energy-intensive processes require considerable amounts of steam and electric power, making cogeneration an economic solution to meet requirements.

The gas-cooled reactors are well suited for cogeneration, since they can deliver high-quality steam that can either be used directly for industrial processes or be expanded through a turbine to cogenerate electric power and supply process steam.

In the United Kingdom, several AGR units for electricity production are in operation or have reached an advanced stage of construction. The HTGR is entering the market introduction phase in the USA and in the Federal Republic of Germany.

In the USA, the Fort St. Vrain prototype for electricity generation has been in operation since 1976, and in the Federal Republic of Germany the thorium high-temperature reactor (THTR) – also an electricity generating plant – will begin its first power test in early 1985.

In both countries, HTGRs have been designed for process-steam production and cogeneration of electricity. In the USA, for example, a number of studies have been performed that indicate a large market potential for cogeneration of process steam and electricity.

Process-heat applications. Progress made in the development of HTGRs has led to investigations in a number of countries – such as Austria, the Federal Republic of Germany, France, Japan, USA, and USSR – on the use of high-temperature thermal energy of these reactors for gasification of lignite and hard coal.

Direct coal gasification requires process heat at temperatures of 800 to 950°C. Nuclear coal gasification reduces coal consumption by a factor of 1.6 to 1.7 in comparison with conventional methods, increases production efficiency, reduces the cost of the end products, and considerably improves the environmental impact. Pollution by sulphur dioxide, nitrogen oxides, and ash can be avoided completely, as the accompanying table shows.

Comparison of environmental impact of coal power stations and gasification plants

Process	Waste heat (%)	CO_2 (%)	SO_2 (%)	NO_x (%)	Dust (%)
Coal power station	100	100	100	100	100
Gasification					
Autothermal	53	57	20	25	20
Nuclear process steam	63	31	0	0	0
Nuclear process heat	37	31	0	0	0

Several coal-conversion processes have been selected as candidate processes. Semi-technical and pilot coal-gasification plants with a throughput of up to 200 tonnes of coal per day are under construction or already in operation.*

The products of these processes are either substitute natural gas (SNG), which can be directly fed into existing gas networks or synthesis gas, a mixture of carbon monoxide and hydrogen. Synthesis gas is an important raw material for various industrial processes, such as direct iron ore reduction, the production of ammonia, and of liquid secondary energy carriers which can be used as a substitute for gasoline.

Another potential application for nuclear process heat is long-distance energy transport by gases. The main principle is the combination of an endothermic chemical reaction (steam reforming of methane to carbon monoxide and hydrogen) taking place at the location of the HTGR, and the reverse exothermic reaction (methanation) at the location of an area of energy and heat consumption. Thus, the energy of the HTGR is transported as later-bound chemical energy to a consumer.

Temperatures of up to 600°C can be produced by the recombination of carbon monoxide and hydrogen to methane and water. Most work on this process is being done in the Federal Republic of Germany, USA, and the USSR.**

* See IAEA's *Status of and Prospects for Gas-Cooled Reactors*, Technical Reports Series No.235 (April 1984) for further details.

** See *Status of and Prospects for Gas-Cooled Reactors* for a description of the EVA II/ADAM II demonstration plant (30 MW), a closed-cycle, nuclear long-distance energy system, in operation at the Nuclear Research Centre (KFA)-Jülich, Federal Republic of Germany.

High-temperature process-heat application also opens the door for novel energy systems, such as the "Horizontally Integrated Energy System", which is based on the principle of decomposing the hydrocarbon feedstock prior to combustion. This results in three principle products (carbon monoxide, hydrogen, and oxygen), which can be combined in various proportions to meet consumer demand for final energy. The advantage of this energy system is that there is only a negligible burden on the environment, even if low-grade fossil fuel resources are used as feedstock.

As a long-term option, hydrogen can be produced by thermochemical watersplitting; high-temperature nuclear process heat will provide for the necessary thermal energy. The large-scale introduction of this process – which is studied and operated at an experimental scale in several laboratories such as in the Federal Republic of Germany, Italy*, Japan, and the USA – would allow for nearly unlimited energy since water and uranium are abundantly available.

The feasibility of high-temperature process-heat production has been demonstrated by the successful operation of the AVR, a pebble-bed HTGR of 45 MW(thermal), in operation since 1967 on the grounds of the Kernforschungsanlage (KFA)-Jülich. The heat-exchanging components needed to decouple the hot helium from the reactor still require further research and development work for commercial application.

Emphasis of international programmes is now put on further qualification of high-temperature metallic materials and the design, fabrication, and testing of heat-ducting and heat-exchanging components in large helium test rigs. Remarkable progress has been made in these fields during the past few years. High-temperature materials have been developed that can resist stresses at 950°C. Material test programmes in the Federal Republic of Germany have reached a stage that allow for component lifetime predictions of up to 70 000–100 000 hours. Helium/helium intermediate heat exchangers of 10 MW and steam reformers of 5 MW have reached an advanced stage of construction and will be tested in 1985.

Results of these tests will form a basis for a decision to be taken regarding type and size of a future prototype plant for generating nuclear process heat. In general, the coal-conversion technology is expected to be ready for market introduction in the 1990s.

Potential for key role

Ten years ago, the expectation of scarce resources of cheap oil and gas was an important motivation for the introduction of new technologies aimed at replacing or saving these energy carriers. Since then, reduced economic growth and the emphasis of energy conservation have led to a lower energy demand than expected. As a result, there seems to be at the present time an abundance of energy, and the need for new technologies has less emphasis than formerly.

But one should not think only about the present and the very near future. When the economy begins to prosper again, growing demand will confront us and energy supply shortages can be expected to arise. In contrast to physical resource assumptions, it is almost impossible to forecast events that may affect energy supply. It is therefore an important task for all nations to seek alternative sources of energy. With regard to the future national and global security of energy supply, nuclear heat can begin to play a key role in the 1990s and beyond.

* At the Ispra-Euratom Joint Research Centre in Varese, Italy.