Nuclear energy for heat applications

Co-generating electricity and heat is a promising application

by H. Barnert, V. Krett and J. Kupitz

As the World Energy Council has noted, energy supplies will have to increase in years ahead, especially in the electricity sector, to meet the needs of the world's growing population. At the same time environmental problems, including the greenhouse effect linked to emissions of carbon dioxide and other gases from the burning of fossil fuels, pose serious challenges in the view of the Intergovernmental Panel on Climate Change and other bodies.

Nuclear energy has the potential to contribute to solutions of such problems. It already has become a valuable energy source with important environmental benefits. Its share of the world's electricity production is now about 17%.

Yet only part of its potential is being realized. The technology can play an even greater role in assuring adequate energy supplies by producing both electricity and heat for residential, industrial, and other purposes.

Characteristics of energy use

Worldwide, about 30% of total primary energy is used to produce electricity. Most of the remaining 70% is either used for transportation or converted into hot water, steam, and heat. This shows that the non-electrical market, in particular that for hot water and steam, is rather large.

Nuclear energy is now being used to produce electricity in more than 24 countries. Some 423 nuclear plants with a total capacity of about 324 gigawatts-electric (GWe) are operating and just over 80 plants with a total capacity of about 80 GWe are being built. Only a few of these plants are being used to supply hot water and steam. The total capacity of these plants is less than 5 GW thermal (th) and they are operating in just a few countries, mostly in Canada and the USSR.

There are many reasons for the disparity in electricity and heat production from nuclear energy. They include a fragmented co-generation market, electrical grid sizes, low costs of alternate energy sources for heat production, and high costs of transportation and distribution.

For heat applications, specific temperature requirements vary greatly. *(See graph on next page.)* They range from low temperatures, just about room temperature, for applications such as hot water and steam for agro-industry, district heating, and sea water desalination, to up to 1000° Celsius for process steam and heat for the chemical industry and high-pressure injection steam for enhanced oil recovery, oil shale and oil sand processing, oil refinery processes and olefine production, and refinement of coal and lignite. The process of water splitting for the production of hydrogen is at the upper end. Up to about 550° Celsius, the heat can be supplied by steam; above that, requirements must be served directly by process heat, since steam pressures become much higher than 550°. The upper limit of 1000° for nuclear-supplied process heat is set on the basis of the long-term strength capabilities of metallic reactor materials.

Of course, there are industrial processes with temperature requirements above 1000°; for example, steel production. Such processes can utilize nuclear energy only via secondary energy carriers, such as electricity, hydrogen, and synthesis gas.

Capabilities of reactors

At all nuclear plants, the primary process in the reactor core is the conversion of nuclear energy into heat. Therefore, in principle, all nuclear reactors could be used to produce process heat. However, in practice, two criteria

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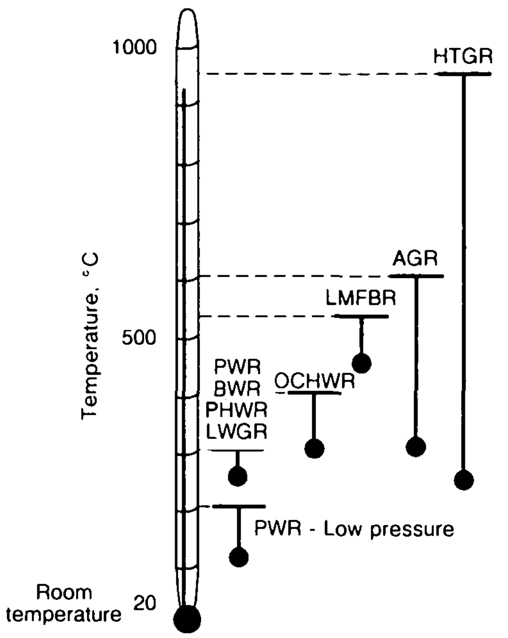
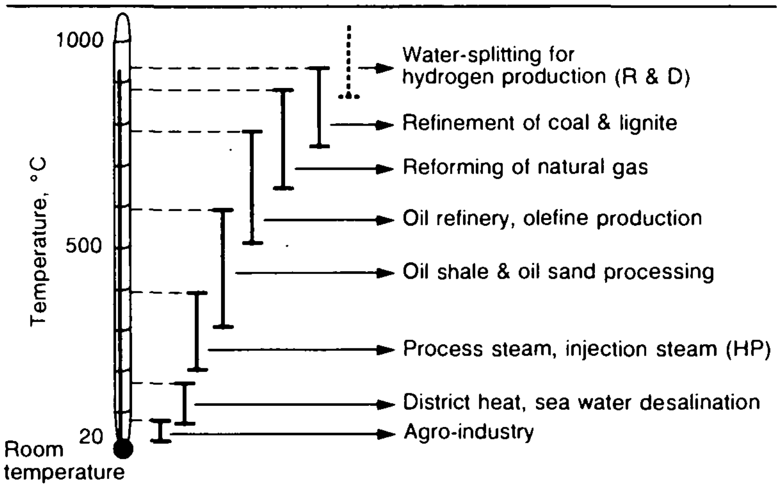
Temperature capabilities of reactor types



are decisive: the temperature of the produced heat (of primary coolant); and the pressure of produced steam (in some cases).

Regarding the first factor, water-cooled reactors offer heat up to 300° Celsius. These types of reactors include pressurized-water reactors (PWRs), boiling-water reactors (BWRs), pressurized heavy-water reactors (PHWRs), and light-water-cooled, graphite-moderated reactors (LWGRs). Organic-cooled, heavy-water-moderated reactors (OCHWRs) reach temperatures of about 400°, while liquid-metal fast breeder reactors (LMFBRs) produce heat up to 540°. Gas-cooled reactors reach even higher temperatures, about 650° for the advanced gas-cooled, graphite-moderated reactor (AGR), and 950° for the high-temperature gas-cooled, graphite-moderated reactor (HTGR). *(See graph.)*

Temperature regions of heat consumption for typical industrial processes



In addition to the maximum temperature of the primary coolant, another important consideration is the temperature difference between coolant inlet and outlet.

The pressure of the produced steam is important when it comes to applications in the field of enhanced oil recovery: The deeper the oil resource, the higher the injection steam's pressure must be. Here, reactor types that have primary coolants other than water — the OCHWR, LMFBR, AGR, and HTGR — have advantages. They easily can produce injection steam with a higher pressure (for example, 10 MPa) for an oil field depth of about 500 metres. For water-cooled reactors, attainment of such pressures would require the additional step of steam compression.

Thermodynamics of electricity and heat generation

As noted before, the primary conversion process in a nuclear reactor is the conversion of nuclear energy into heat.

This heat can be used in a "dedicated" mode of operation for direct heating purposes. In this case, no electricity is produced.

The other mode is co-generation of heat and electricity. Parallel co-generation is achieved by the extraction of some of the steam from the secondary side of the steam generator, before the entrance to the turbine. Series co-generation is achieved by the extraction of some or all of the steam at some time during steam expansion in the turbine when it has the right temperature for the intended application. During this cycle, the extracted steam also has been used for electricity production. Series co-generation is ideally suited to industrial processes related to district heating, desalination, and agriculture.

Examples of existing applications

Currently, a number of countries have nuclear plants that are being used for the production of hot water and steam. The total capacity amounts to less than 5 GWth.

Significant experience in the co-generation of electricity and heat has been gained in these countries, notably in the Soviet Union. This experience encompasses reactors at Beloyarsky, Kursk, Novovoronezh, Rovno, and Kol'skaya in the Soviet Union; Tsinghua University in China; Bruce Nuclear Power Development in Canada; Bohunice in Czechoslovakia; Goesgen and Beznau in Switzerland; and Stade in Germany.

A brief technical overview of some of these applications follows.

Heat reactor in China. At the Institute of Nuclear Energy Technology (INET), Tsinghua University, Beijing, a nuclear heat reactor with the capacity of 5 MWth started operations during the winter of 1989–90. Used to supply heat to the INET centre, the reactor's operating experience has been very good. Its design principles follow that of a PWR. The design pressure of the primary circuit is 1.5 MPa (about 10 times smaller than in a usual PWR) and temperature conditions in the primary loop are 186/146 degrees Celsius. Temperatures in the intermediate loop are 160/110° at 1.7 MPa, and in the heat grid, 90/60°.

Parallel co-generation of process steam and heat in Canada. One of the largest uses of process steam occurs at the Bruce Nuclear Power Development Facility in Ontario, Canada. The Candu PHWRs at this site are capable of producing over 6000 MWe of electricity as well as process steam and heat for use by Ontario Hydro and an adjacent industrial energy park.

The Bruce-A nuclear station consists of four 825-MWe units that are generating electricity. Additionally, the plants supply steam to a steam transformer plant. This plant generates 720 MWth of process heat and steam for heavy water production plants; 70 MWth for the Bruce energy centre; and 3 MWth for side services.

The cycle is typical for parallel co-generation. Nuclear heat generated in the reactor is transferred to the steam generator via the primary heat transport loop. Steam is extracted from the secondary side of the steam generator, in parallel with the steam supply to the turbine and then fed directly to the steam transformer plant. The extracted steam is not used to produce electricity.

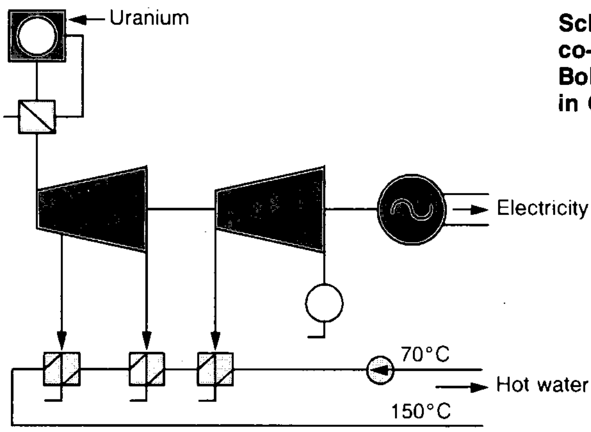
Series co-generation of hot water for district heat in Czechoslovakia. The Bohunice nuclear power station consists of two Soviet-designed VVER-440/230 units, and two VVER-440/213 units. All units are in service. Each one consists of the reactor with a thermal power of 1375 MWth, six horizontal steam generators, and two condensation turbines. The plants co-generate electricity and low-temperature heat for heating, industrial, and agricultural purposes in the area near Trnava.

In the series co-generation cycle, water is heated to temperatures of 70° and 150° Celsius; the turbines are capable of supplying 60 MWth of heat. *(See the simplified flow diagram.)*

Series co-generation for sea water desalination in the USSR. Exploiting natural resources in the arid regions of West Kazachstan in the USSR became possible once water and electricity supply problems were solved. An important contributor to this effort has been the Shevchenko complex. It includes a fast breeder reactor, type BN-350, three thermal power stations, and a desalination plant with thermal distillation equipment. The complex constitutes the world's first, and for the time being the only, demonstration plant where a nuclear reactor is used in desalination of sea water.

In the process, the BN-350's steam generators and a boiler unit supply steam to several different turbines. Steam from the BN-350 unit at 4.5 MPa and 450° Celsius is directed to the back-pressure turbines and to the condensing turbine. Steam from the back-pressure turbines is directed towards the desalination units and the industrial enterprises of the town.

The Shevchenko complex is the largest centre of commercial thermal desalination in the USSR. There are 12 operating desalination units at the complex with a total capacity of 140 000 cubic metres a day of distillate.



Schematic of co-generation at Bohunice in Czechoslovakia

Economics of nuclear co-generation

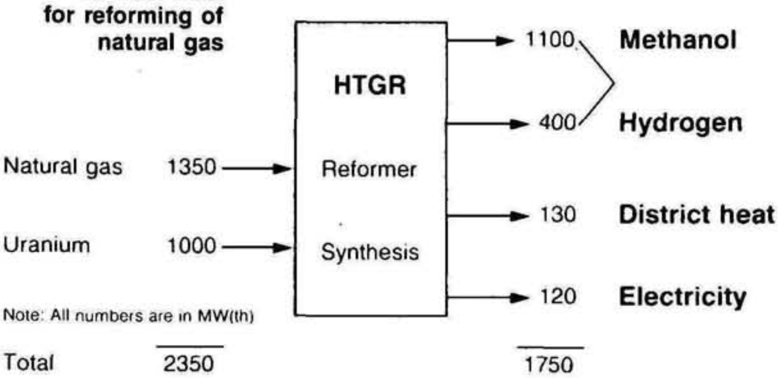
Nuclear electricity generation, as well as the infrastructure for the transportation and distribution of hot water and steam, are capital-intensive technologies. While nuclear power plants have proved to be economically competitive for electricity generation alone, different cost factors are involved for co-generation and heat production modes.

The following rule of thumb can be used: the cost of co-generated heat is equal to the electricity cost divided by the coefficient of plant performance, a factor which depends on the type of reactor under consideration and other parameters.*

* The coefficient of performance is specifically defined as $c = H_b/\Delta E$, in which H_b is the produced heat and ΔE is the difference between electricity in the pure electricity-production mode and in the co-generation mode of operation.

Using that rule, cost figures for co-generation have been calculated, as an example, for a modular high-temperature gas-cooled reactor (MHTGR) in Germany. In this example, the cost of electricity equals 5 US cents per kilowatt-hour-electric, the cost of steam equals 1.7 US cents per kilowatt-hour-thermal, and the cost of hot water equals 0.5 US cents per kilowatt-hour-thermal. These costs are the levelized costs for the 40-year lifetime of an MHTGR.

Nuclear heat for reforming of natural gas



Note: All numbers are in MW(th)

Integration of nuclear and fossil energy

More than 80% of the world's energy use is based on fossil energy sources, namely coal, oil, and gas. Burning these fuels is known to cause serious environmental problems from emissions of sulphur oxides, nitrogen oxides, and carbon dioxide.

To help solve such problems, one approach that has been proposed is the integration of energy systems. A typical example for one future integration is the application of nuclear heat for the reforming of natural gas. *(See diagram.)* Synthesis gas, methanol, hydrogen, heat, and electricity would be produced from natural gas and uranium using what is known as the HTGR-reforming process. In the process, natural gas is decomposed into mainly hydrogen and carbon monoxide. The main products are methanol, a liquid hydrocarbon, and hydrogen. Side products are heat and electricity.

Another example of this integrated approach is seen in the oil industry. Several studies have been done on the use of nuclear power as a heat source for heavy oil exploitation. They have shown that under favourable oil market conditions, the nuclear option presents economical and environmental benefits as compared to conventional methods.

A third example is the integration of coal and nuclear energy in the steel industry. From the technological point of view this is the most ambitious integration. It involves gasification of hard coal heated by hot helium from an HTGR. The intermediate products are synthesis gas and coke, which is used for iron ore reduction. The final products are methanol and pig iron.

Promising potential

There is considerable incentive to make use of the capacity of most nuclear plants to provide steam and heat for residential and industrial purposes.

In a number of countries, co-generation and heat production using nuclear reactors is already an effective way to meet different types of energy needs. The potential for applying this technology more widely appears promising. Interest at the international level is again emerging as environmental and other problems raise concerns about the burning of fossil fuels.

As part of its work, the IAEA convened a meeting of experts in 1990 to review the status of nuclear-based co-generation and heat systems. A technical document on nuclear applications for steam and hot water supply also has been prepared for publication to broaden the exchange of experience in this field.

As energy needs increase, this technology, among others, may merit even closer consideration.