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A Review of District Heating Reactor Technology

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Summary

District heating using fossil fuels is a major contributor to CO_2 emissions in Finland, and there is considerable pressure to move from coal-fired plants to low-carbon technologies, such as biofuels and heat pumps. The possibility of using nuclear reactors for heating applications has also become a hot topic for public discussion. The viability of the nuclear option is currently being evaluated in a research project coordinated by VTT. This report provides a short review of the developed technologies and the characteristic features of heating reactors.

There exists considerable practical experience in the use of nuclear power reactors for co-generation, in particular in Russia. Reactor types specifically developed for low-temperature heating applications have also been studied since the 1970's, and the technology is expected to be commercialized in China in the 2020's. The advantages of dedicated heating reactor technology include small unit size and low operating temperature and pressure, which may considerably reduce the manufacturing costs of reactor components. The main challenges and open questions are related to urban siting, since it may not be very cost-effective to transfer low-temperature heat over long distances.

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1. Introduction

The majority of global CO_2 emissions originate from the energy sector, i.e the production of heat and electric power. Industrial process heat constitutes a major part of fossil fuel consumption worldwide, and residential heating is a large contributor to carbon emissions in countries with cold winter climate. In Finland, low-carbon technologies already cover some 80% of electricity production, so the largest potential for climate action lies in heating applications.

District heating is the most common form of residential heating in Finland, covering almost 50% of the market. In large cities the share is even higher, exceeding 90%. The most common heating fuels are coal, natural gas and peat. Even though one third of the production is already covered by biofuels, there is considerable pressure to reduce the dependence on fossil fuels. In 2018 the Finnish government proposed a ban on the use of coal for energy production beginning from 2029. The schedule is extremely ambitious, considering the fact that the scalability of bioenergy is still a subject of debate.

During the past few years there has been serious public discussion on the use of nuclear energy for district heating. The idea itself is not new, since several conceptual reactor technologies were developed for this purpose already in 1970's, when the oil crisis raised concerns on the availability of cheap heating fuels. There is also considerable practical experience in co-generation of heat and power using nuclear reactors, especially in Russia. This report provides a review of the developed technologies and the characteristic features of heating reactors.

2. Heat reactor technology

District heating networks in Finland are designed for temperature range 65–120 °C, depending on season and weather. Heat supply is typically provided by large base-load stations used for co-generation, with additional peak load units to compensate for the difference between production and demand during the coldest winter days. Base load generation usually covers around 50% of peak demand, which is sufficient for 80–90% of operating time.

2.1 Technical requirements

The temperature range of the district heating network also determines certain boundary conditions for reactor design. The maximum output temperature on the secondary side should reach 90–120 °C, depending on how the network is structured, and whether the reactor is intended to be used for base-load operation only, or also to satisfy peak demand. The reactor is connected to the grid via heat exchangers, which means that the operating temperature must be somewhat higher. Reaching temperatures above 100 °C requires elevated pressure. The boiling point of water as function of operating pressure is plotted in Figure 1.

Reactors designed for district heating are typically small compared to conventional power reactors, which require almost 3 units of fission power to produce one unit of electricity. The thermal output of the DHR-400 prototype reactor (see Sec. 3.4), for example, is 400 MW, but it

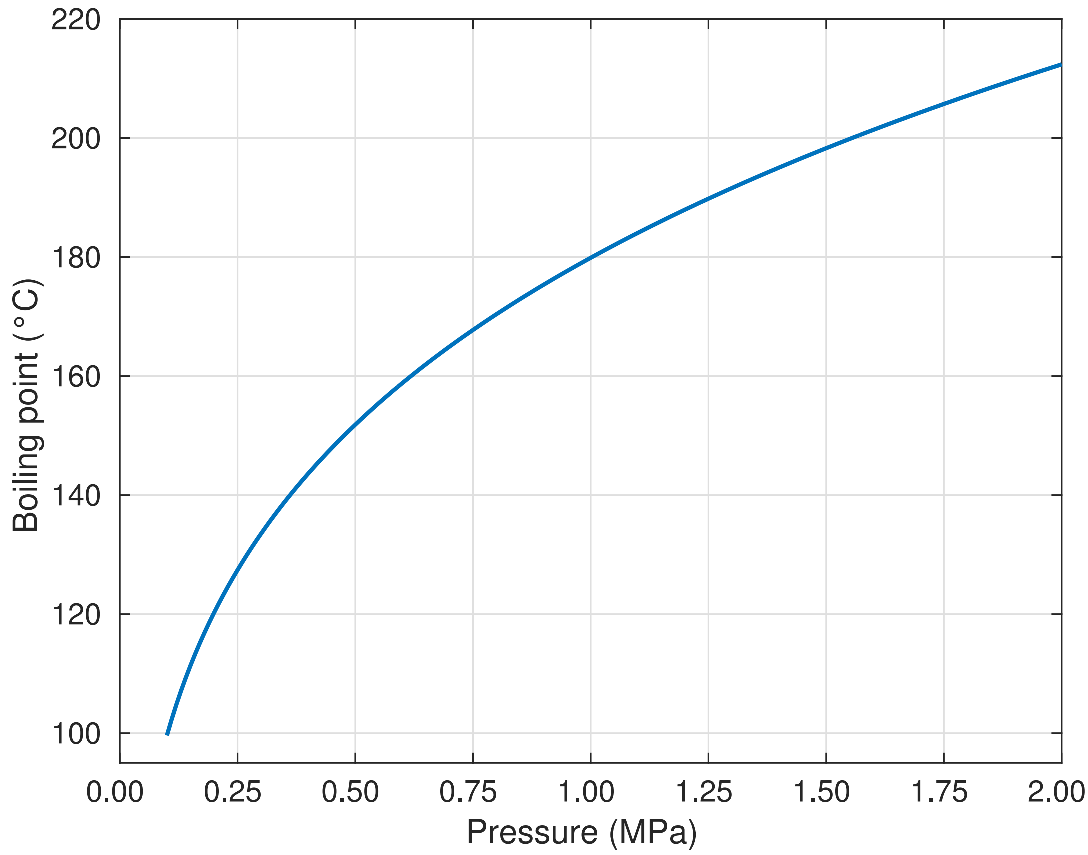

Figure 1. Boiling point of water as function of pressure for conditions relevant for low-temperature reactor applications. Atmospheric pressure at sea level is 0.1 MPa. Conventional BWRs and PWRs operate at around 7 and 12–15.5 MPa pressures, in which the boiling point is 286 °C and 325–345 °C, respectively.

is anticipated that there exists commercial market for reactors in the 25–50 MW range as well. For comparison, the thermal power of the 1600 MWe EPR is 4500 MW.

Heat demand of district heating networks varies considerably between seasons, and large base-load units accommodate by reducing their output during the Summer months. In the fuel cycle studies carried out for the Swedish-Finnish SECURE reactor concept (see Sec. 3.3) it was assumed that the number of effective full-power days (EFPD) for the 200 MW base load unit was 182. The Chinese DHR-400 is expected to be operated 150 EFPD per year to cover the district heating needs in northern China. This type of operation differs from conventional power reactors, which are usually run at full power for the duration of the entire cycle.

Short-term variation in heat demand is generally slow and predictable, depending mostly on the outside temperature. The district heating network has high thermal capacity and relatively broad operating regime. The operational requirements differ considerably from electricity production, in which the tolerances for voltage and frequency are strict, and fast changes in both demand and production are not uncommon, especially when large capacity of wind power is connected to the grid. Slow changes in fission power can be managed by control rods, soluble boron, or (at least to some extent) utilizing the natural load-follow capability of nuclear reactors.

2.2 Advantages of low operating temperature and small unit size

Temperatures relevant for district heating applications can be achieved even below 1 MPa pressure, which is comparable to a household espresso machine. To hold this pressure, the reactor vessel needs to be only a few centimeters thick. In the 1974 study (see Sec. 3.2) the working group at VTT estimated that a 10–11 mm thick stainless steel vessel is sufficient to withstand an over-pressure of 1.6 MPa. For comparison, the thickness of the EPR pressure vessel shell is 246 mm. Reduced wall thickness implies significantly lower manufacturing costs, simplified quality control and a wider supply of industrial companies capable of performing the work.

Low operating temperature also means that the amount of energy stored in the primary circuit as latent heat is considerably lower compared to conventional LWRs. This is reflected in the safety design, as the reactor containment needs to be able to withstand the pressure increase caused by primary coolant flashing into steam. Since reactors designed for district heating are at least a factor of ten smaller than typical large power reactors, the amount of decay heat released after reactor shut-down is also much lower. A small 25 MW reactor unit produces less than 400 kW of decay heat one hour after the fission power is cut off.

Since pressure vessel size is not as strictly limited by economics, some of the heat reactor concepts have been designed with a relatively low power density. This reduces mechanical and radiation stress in the materials, and increases cycle length as the fuel is depleted at a slower rate. Low power density also reduces the fuel and cladding temperatures. Average UO_2 temperature in a district heating reactor is around 300–400 °C, which is hundreds of degrees lower compared to typical PWRs and BWRs. Low temperature reduces fission gas release from cladding defects, and increases the margin to various safety limits [1].

In general, small low-temperature district heating reactors are naturally well suited for passive safety, and eliminating the need for complicated and multi-redundant active systems may be another factor that significantly reduces the construction costs.

2.3 Safety challenges

Nuclear industry is among the most highly regulated industries in the world, and all reactors are subject to strict safety requirements. Even though passive heat removal and other attractive features discussed in the previous section can be considered major advantages when it comes to safety design, there are also entirely new challenges associated with district heating applications.

One of the fundamental issues is related to urban siting. Existing regulatory guidelines are historically based on the idea that nuclear power plants can be constructed far from densely populated areas, and mitigating the consequences of severe accidents by limiting public exposure is part of the defense-in-depth principle. In practice this is accomplished by defining large emergency planning zones (EPZ) around the site.[1] Since it is not cost-effective to transfer heat over large distances, reactors designed for district heating have to be constructed closer to consumption. In practice this means that the overall safety has to be demonstrated without resorting to the EPZ concept, which may require re-evaluating some of the fundamental licensing principles.

[1] Emergency planning zone is a region where rapid evacuation may be necessary to protect the population, and radioactive contamination may require long-term limitations to land use and cultivation. There are regions inside the EPZs of the Fukushima Daichi nuclear power plant that are still under evacuation orders following the 2011 accident.

Nuclear power plants are also subject to strict limits when it comes to radioactive emissions during operation. Small amounts of fission products escape from leaking fuel rods. Corrosion products and other impurities circulating with the primary coolant are activated in the reactor core, and radioactive tritium is produced from hydrogen in water (via conversion of ^{2}H), and boron used for reactivity control. It is likely that limiting the emissions of these radionuclides becomes even more pronounced for reactors operating closer to population. Radioactive inventory is proportional to unit size, and low power density, temperature and burnup may reduce the amount of fission products leaking from the fuel rods. Contamination of the district heating network is eliminated by separation from the primary circuit with an intermediate water loop.

Some district heating reactor concepts are designed to be constructed underground, which provides some natural protection against aircraft crash and other external threats. Even though the safety benefits are significant, they are limited to relatively unlikely events. On the other hand, underground siting may turn out to be more challenging when it comes to protection against fires and flooding. In severe accidents there is also a chance that the local ground water basin becomes heavily contaminated by radioactive emissions, which may become another limiting factor for reactor siting.

Small district heating units are operated remotely without regular on-site staff. There is no prior experience on remotely operated nuclear reactors, at least for civilian applications, which brings new challenges when it comes to securing the site against physical and cyber threats.

3. Review of historical and on-going projects

The oil crisis of 1973 can be considered a major milestone in the development of urban district heating systems, as concerns on the availability of cheap heating fuels forced several countries to re-evaluate their national energy strategies. This was especially the case for the Nordic countries with cold winter climate. The interest in the use of nuclear energy for heating applications also rose in the aftermath of the oil crises. In addition to co-generation using existing reactor technologies, various concepts dedicated to low-temperature heat production without any turbine cycle were introduced at that time.[2] The use of nuclear energy for district heating was foreseen as an attractive and economically viable option also in Finland and the Scandinavian countries. Even though decreasing coal and gas prices and the accidents at Three-mile Island (1979) and Chernobyl (1986) eventually put an end to a promising start, it is worthwhile to take a closer look at some of the historical projects.

More recent development has been carried out in China, and co-generation of heat and electric power has always played a major role in the Russian nuclear industry.

3.1 Ågesta

The Ågesta heavy water reactor commissioned in 1964 in the Farsta suburb of Stockholm was the first commercial nuclear power plant in Sweden [2]. The purpose of the project was to pioneer the "Swedish line", i.e. technology based on natural uranium from domestic resources. The low content of fissile ^{235}U required using heavy water as the neutron moderator. The

[2] A good overview of the historical projects can be found in volume 38 of Nuclear Technology (American Nuclear Society, 1978), which is devoted to papers presented at the Topical Meeting on Low-Temperature Nuclear Heat in Espoo, Finland, on August 21-24, 1977.

reactor was operated for ten years until 1974, producing 10–12 MW of electricity and 55–68 MW of district heat.

Since the reactor was designed for co-generation, the operating temperature was above 200 °C, which is relatively high compared to later heat reactor designs, albeit low compared to modern LWRs. The primary circuit was pressurized to 3.3 MPa. Heat for the local district heating network was obtained by direct connection to the turbine condenser. The supply temperature was 78–115 °C and return temperature 55–60 °C. Excess heat removal could also be accomplished using a cooling tower, which enabled full-power operation all year round, including the warm season when the demand for district heating was low.

The Ågesta reactor was the first large-scale district heating application for nuclear energy. Even though the project was relatively short-lived, it provided an important demonstration that connecting a nuclear reactor to an urban district heating network is technically feasible. The reactor type may no longer be considered particularly relevant, as the availability of enriched fuel and the global success of LWR technology made natural uranium fueled heavy water reactors obsolete in most countries. The project was not a commercial success story either, as the original budget (35 million SEK) was exceeded by a factor of four. It should be noted, however, that the early development of nuclear technology in Sweden had connections to a secret weapons programme, which is why it may not be entirely fair to compare the economics of the Ågesta project to the civilian nuclear industry.

3.2 Heat reactor studies in Finland in 1971–1973

The first academic studies on heating reactors in Finland were carried out in 1969, and three years later a national project on the viability of using nuclear energy for district heating was launched. The project was carried out in 1971–1973, and coordinated by Technical Research Centre of Finland (VTT). Other project partners included Oy Finnatom Ab with its member companies, Ekono Oy, Imatran Voima Oy (predecessor of Fortum), Teollisuuden Voima Oy (TVO) and Institutt for Atomenergi from Norway. The results of the project are summarized in a final report from 1974 [3].

The main purpose of the study was to evaluate the cost of nuclear-based district heating, by designing a conceptual mid-size power plant using existing technology and engineering standards. Since nuclear energy is associated with high capital and low fuel costs, the reactor was designed for base-load operation. The reference 100 MW reactor plant was accompanied by two 75 MW oil-fired boilers, which served as peak-load units and back-up when the reactor was down. The scenario assumed that the first prototype could be constructed in 4 years, and the following units in 3 years, making the technology commercially available in the 1980's. The potential market covered the 12 largest cities in Finland,[3] and some specific case studies were carried out for the city of Tampere.

To ensure safety and reliability without excessively high R&D costs, the reactor design borrowed many of its features from conventional LWRs. The main components included the reactor vessel, pressurizer and two primary coolant loops with circulation pumps. The main difference to conventional PWRs was that the steam generators were replaced with heat exchangers connected to the district heating network via an intermediate water loop. The entire primary

[3]The criterion was that the district heating network served at least 50,000 customers. Cities that fulfilled this criterion at the time of the study were Helsinki, Tampere, Lahti, Espoo, Vantaa, Oulu, Jyväskylä, Kuopio, Vaasa, Lappeenranta, Hämeenlinna and Pori. The city of Turku was not included for reasons not apparent from the report.

circuit was enclosed inside a double-wall containment, with an inner gas-tight stainless steel dome, and an outer concrete shell for protection against external threats.

The reactor pressure vessel was 3.8 meters high and 1.8 m in diameter, and made from stainless steel. The maximum design pressure was 1.6 MPa, which for the given dimensions would have required wall thickness of 10–11 mm. In the cost analyses it was assumed, however, that some extra thickness was required for protection against external damage, so the calculations were made based on 20 mm wall thickness. The reactor was designed to operate at 1.35 MPa pressure and 160 °C average coolant temperature. The core was comprised of 57 standard PWR fuel assemblies (10×10 rods in rectangular lattice), shortened to 110.4 cm length. The equivalent core diameter was 119.3 cm. Apart from the operating pressure and temperature, the design parameters, such as power density and burnup, were similar to standard PWRs of the time. This was also the case for the 12-month fuel cycle length.

Reactor control and protection systems represented standard PWR technology, with control rods and boron shim. It was pointed out in the report that reactivity control by boron dilution was particularly well suited for district heating applications, in which the changes in reactor output are usually slow. The possibility of natural load-follow, taking advantage of physical reactivity feedbacks, was also considered. Emergency cooling systems were designed according to the 1970's regulatory requirements, with large-break loss of coolant accident (LOCA) as the most limiting case. It was noted that the importance of reliable back-up power becomes pronounced for heating reactors without any on-site electricity production. Station blackout was considered a major initiating event, which reflects the fact that passive heat removal had not yet become the cornerstone of safety design for heating reactors.

The study followed a somewhat conservative approach to reactor design, without taking advantage of passive safety features that would most likely be implemented if the technology was developed today. The work produced a very comprehensive estimate of the overall costs. The analyses included not only the main reactor components, but also auxiliary systems, buildings, and practically the entire power plant. Connection to the district heating network included the construction of a 6 km long transmission pipeline.

Realistic cost estimates were obtained from component manufacturers. The overall price tag for the 100 MW reactor and two peak load / back-up boilers was 98.7 million Finnish marks, which in today's currency is about 97 million euros. It was concluded that nuclear based district heating would be a competitive option compared to fossil fuels, second only to peat in locations where the fuel supply was available near the site.

3.3 SECURE

SECURE (Safe Environmentally Clean Urban REactor) was a low-pressure, low-temperature light-water reactor concept [1, 4, 5] developed as Swedish-Finnish collaboration in 1976–1977 by four partner organizations: Ab ASEA-Atom, Ab Atomenergi, Oy Finnatom Ab and VTT. The possibility of using waste heat from large nuclear power stations for district heating was extensively studied at the time, and the SECURE reactor provided an alternative that could be placed closer to city centers and other densely populated areas. The reactor was designed for base-load heat production for large and medium-size district heating networks, with a 200 MW thermal output at 95 °C temperature. A larger variant with design parameters increased to 400 MW and 160 °C was also studied.

One of the primary design criteria for SECURE was to eliminate the need for large emergency planning zones, which is a practical necessity for urban siting. The means to accomplish this was to minimize the dependence on engineered systems and rely on inherent safety features and passive cooling. Physical protection was provided by underground siting. The reactor core, primary cooling circuit and all safety-related auxiliary systems were placed in an underground rock cavern, which also served as the primary containment. Secondary heat exchangers with connection to the district heating network were placed in a reactor building above ground, and a small cooling tower was used to dissipate residual heat in the atmosphere in normal shut-down conditions. The station was designed for remote operation, and required no on-site staff.

The reactor was fueled with standard low-enriched LWR fuel, with assembly height reduced to about 2 meters.[4] The 200 MW core was 1.8 meters in diameter, and contained 144 assemblies. The larger 400 MW core was comprised of 288 assemblies and had a diameter of 2.6 m. Fuel cycle was based on estimated 182 effective full-power day operation per year. Cycle length was two years, after which 1/4 of assemblies were replaced with fresh fuel. Power density in the fuel was 15 kW/kgU, which is less than half compared to modern PWRs. Discharge burnup was also relatively low, only 22 MWd/kgU.

The reactor core was placed in a 1200 m^3 cylindrical pool made of pre-stressed concrete. The system was pressurized to 0.7 MPa, which raises the boiling point of water to 165 °C. Coolant circulation was maintained with pumps. The core outlet temperature was 115 °C (200 MW variant), and the inlet temperature varied depending on output. Average fuel temperature was low, only 370 °C. Low fuel temperature, low power density and low discharge burnup were considered important design features, lowering the probability of fuel failures.

Reactivity control was accomplished by adjusting coolant boron concentration. The variation in normal operation was estimated to be between 80 and 145 ppm, which is quite low compared to modern PWRs with beginning-of-cycle concentrations exceeding 900 ppm. The reactor had no control rods, but small boron steel spheres poured into the moderator channels inside the fuel assemblies provided enough negative reactivity for long-term shut-down. The same system was used as a diverse scram mechanism for emergencies.

The reactor was designed with unique passive safety functions based on the PIUS principle (Process Inherent Ultimate Safety), which was introduced by ASEA-Atom in the 1970's [6]. The reactor had two pump-driven primary cooling circuits, and an additional passive loop, in which the water in the reactor pool was circulated through the core by natural convection. The primary circuits were open to the pool, but forced circulation created flow conditions that prevented the pool water from entering the core. Any disruption in the primary flow would brake the pressure balance, and start the natural circulation. The pool water had high boron concentration (1000 ppm), so that the fission power would be effectively stopped if coolant flow was disrupted and borated water sucked into the core (for a detailed description, see Ref. [4]). The primary mechanism for reactor shut-down was to trip the circulation pumps.

The large volume of the reactor pool provided enough heat capacity to confine decay heat for at least 24 hours after reactor shut-down. Natural circulation through heat exchangers was sufficient to maintain the temperature below boiling point. The residual heat was discharged to an above-ground cooling tower. Pressure build-up resulting from a loss of coolant accident was considered small due to low operating temperature and pressure, and the large volume of the rock cavern acting as the primary containment. The surrounding rock also provided an effective heat sink, eliminating the need for containment spray cooling systems. In case all cooling functions were lost, the reactor core was estimated to remain covered for 1–2 weeks before make-up water needed to be supplied into the pool.

[4] 8×8 ASEA-Atom BWR fuel with a central moderator channel occupying the positions of 8 rods. Fuel enrichment in the equilibrium core was 2.58% ^{235}U, and excess reactivity was compensated by burnable absorber (Gd_2O_3).

The SECURE reactor concept was developed more than 40 years ago, but many of the design features are still relevant today. The suitability of the design to modern Finnish safety standards is discussed in Ref. [7]. Passive safety features independent of on-site power can be considered a major advantage. On the other hand, the fact that the defense-in-depth principle and severe accident management were not fully applied in the design is a clear reflection of out-dated 1970's safety philosophy.

3.4 Heat reactor development in China

The first commercial power reactors were not commissioned in China until the early 1990's, but considerable experience on nuclear technology was gained much earlier from experimental reactors. Work on heating reactors was also started already in the 1980's. The technology has been developed in particular at the Institute of Nuclear Energy Technology (INET) at Tsinghua University in Beijing.

The Chinese low-temperature heat reactor development has followed two separate lines of technology. A small 5 MW prototype reactor NHR-5 was commissioned at Tsinghua University in 1989 [8]. The reactor is based on a traditional pressure vessel type design, with operating pressure and core outlet temperature of 1.37 MPa and 186°C, respectively. Primary coolant circulation is based on natural convection inside the reactor vessel, and heat transfer is handled through two heat exchangers and an intermediate water loop. The primary vessel is placed inside a larger steel tank, which acts as the reactor containment.

During the first four years of its operation the NHR-5 achieved a remarkable 99% availability factor. The success of the first prototype prompted the development of NHR-200, a commercial size reactor based on the same general concept [9]. Thermal output was increased to 200 MW and primary system pressure to 2.5 MPa. The reactor is designed to be operated in conventional PWR mode with core outlet temperature of 210°C, or allowing some coolant boiling (BWR mode), which increases the outlet temperature to 224°C.[5] Reactivity control is achieved using hydraulically operated control rods, and primary coolant circulation and residual heat removal systems are based on natural convection.

The preliminary design of the pressure vessel type NHR-200 was completed already in 1995, and the plan was to commercialize the technology by the late 1990's. The original schedule did not hold, but the China General Nuclear company (CGN) is currently conducting a feasibility study with Tsinghua university on the construction of a demonstration nuclear heating plant based on a revised design (NHR200-II).

The second line of technology is based on experience from the 1980's, using pool-type research reactors to provide space heat for the nearby buildings. The deep pool reactor (DPR) concept developed at Tsinghua university [10] utilizes hydrostatic pressure to obtain outlet temperatures compatible with the district heating network. In the 120 MW DPR-3 design the reactor core is placed at the bottom of a 25 m deep pool, which increases the operating pressure and temperature to 0.29 MPa and 110°C, respectively. The larger 200 MW DPR-6 concept applies additional pressurization using the primary coolant pumps, which allows increasing the core outlet temperature to 132°C. Reactivity is control is achieved by movable control rods.

The advantages of the pool-type design are similar to the SECURE concept, i.e. low operating pressure and temperature, and large thermal inertia of the pool water. The design practically

[5] In the VTT heat reactor study from 1974 [3] it was noted that coolant boiling at low temperature and pressure may create unstable flow conditions that are difficult to predict. However, there is no mention of such issue in the NHR200 paper [9] published two decades later.

eliminates the possibility of loss of coolant accidents and control rod ejection. The reactor is operated without soluble boron, which also eliminates reactivity-induced accidents caused by boron dilution. Coolant circulation during operation is maintained with pumps, but residual heat removal from the core is based on natural convection.

In November 2017 the China National Nuclear Corporation (CNNC) announced the development of a 400 MW pool-type DHR-400 heating reactor, after a successful 168-hour trial run using the “49-2” test reactor at the China Institute of Atomic Energy. The technology, sometimes referred to as “Yanlong”, is based on the earlier DPR studies. The first DHR-400 reactor unit is expecting a construction license in early 2019, making the technology commercially available in the early 2020’s. In addition to district heating, the reactor is planned to be used for refrigeration and desalination of sea water, as well as material irradiation and isotope production.

3.5 Co-generation using power reactors

Co-generation of heat and electric power becomes economically feasible when the generating station is located sufficiently close to a major population center. An IAEA report from 2000 [11] lists 49 reactors in Bulgaria, Hungary, Russia, Slovakia, Switzerland and the Ukraine, that were primarily constructed for electricity production, but have also been used to serve district heating needs. The electric output of these reactors varies between 385–953 MWe, and heating capacity from 20 to 240 MW. Since high thermal efficiency for electricity production requires temperatures in the 300 °C range, the supply temperatures for the district heating network are also high, up to 150 °C.

Remarkably, almost all of the reactors used for co-generation are of Russian VVER- or RBMK-type (with the notable exception of two Westinghouse PWRs in Beznau, Switzerland). Heating applications were included in the nuclear energy programme in the Soviet Union already in the 1950’s, and facilities to provide heat for on-site use and nearby towns were part of the standard design. In fact, of the 29 power reactors that operated in Russia at the time the IAEA report was written, Novovoronezh unit 5 was the only one not included on the list. The realized capacities have remained relatively low, but in the 1990’s there were ambitious plans to supply almost 3000 MW of heat from the Kola NPP and 7000 MW from the Novovoronezh NPP to cities and towns located up to tens of kilometers from the sites [12].

Russia is also developing floating reactor technology. The Akademik Lomonosov floating nuclear power station was constructed at the Baltic Shipyard in Saint Petersburg. The ship was transferred to Murmansk, where the reactors were loaded with fuel. The first criticality was achieved in November 2018. The power plant is comprised of two modified KLT-40 naval propulsion reactors, originally developed for nuclear powered ice breakers. The reactors are capable of producing 70 MW of electric power and 60 MW of low-temperature heat for remote locations in the arctic Russia.

In Finland, the possibility of providing district heating to the Helsinki metropolitan area from the Loviisa NPP site was investigated by Fortum in 2008–2010, in preparation for the application for the decision-in-principle for the Loviisa-3 reactor [13]. The reactor candidates were rated at 1200–1700 MWe, with the estimated district heating capacity of 1000 MW. Supplying heat from an existing nuclear power station would have solved the problems related to urban siting. On the other hand, distance of 75 km between supply and consumption raised concerns about the economics. The application was turned down by the government in 2010.

Desalination of sea water for human consumption and irrigation can be accomplished in a temperature range comparable to district heating. Nuclear co-generation plants have been used for desalination in Japan and Kazakhstan. The six Japanese reactors listed in the previous IAEA report are of the PWR type, and used for on-site water supply with a capacity of 1000–3900 m^3 per day. The BN-350 reactor in Kazakhstan is a prototype fast breeder reactor, that was used in 1973–1999 to supply 135 MW electricity and 120,000 m^3 of fresh water to the city of Aktau located on the east bank of the Caspian sea.

4. Summary, conclusions and discussion

Using nuclear energy for low-temperature applications has been studied for several decades, and there exists considerable practical experience in the co-generation of electricity and district heat, in particular in Russia. Several reactor concepts dedicated to low-temperature applications without any turbine cycle have also been developed, and the construction of two Chinese heating reactor prototypes (NHR200-II and DHR-400) is expected to start within the near future. If realized according to schedule, the technology could become commercially available in the 2020's, which makes nuclear energy a potential option for reducing the CO_2 emissions of district heating in Finland as well.

The operating temperature of district heating networks (65–120 °C) can be easily achieved with conventional LWR technology. If the reactor is designed exclusively for heating applications, the operating temperature and pressure can be considerably reduced from the range typically used in PWR- and BWR-type power reactors. This leads to lower manufacturing costs for the reactor pressure vessel and other primary circuit components. Heat supply is not limited by thermodynamical efficiency, which implies smaller unit size compared to reactors designed for electricity production. Lower rate of decay heat production and low operating pressure and temperature may considerably simplify the safety design. Residual heat removal can be easily accomplished by passive systems, which is another factor lowering the construction costs.

Even though there are several similarities to conventional LWRs, the operating conditions of district heating reactors are so different, that they should be viewed as a separate technology. Coolant pressures and temperatures in the conceptual designs range from 0.3–2.5 MPa and 110–224 °C, respectively. Output temperatures below 100 °C are achievable even in ambient pressure, but the heating plant may require additional boilers to satisfy peak demand during the coldest winter days. Primary coolant flow can be accomplished by forced or natural circulation. Residual heat removal usually relies on passive systems.

The developed technologies can be divided into pressure vessel and pool-type designs. In addition to operating temperatures and pressures, there are also some differences in reactivity control. The SECURE concept relied entirely on soluble boron, which was chosen in part because the changes in heat demand are usually slow and predictable. The Chinese heating reactors, on the other hand, apply control rods without any boron shim. This simplifies the water chemistry, reduces tritium production, and removes yet another complicated system from the reactor design.

Specific power density in district heating reactors is usually low compared to conventional LWRs. This, together with a lower operating temperature, reduces the probability of fuel failures and increases the margin to various safety-related limits. Slower fuel depletion rate increases the refueling interval, and since the utilization factor for district heating is in any case relatively low compared to electricity, it may be possible to design the core for very long cycle length. Minimizing the need for maintenance and handling of radioactive materials may become another economic advantage, especially for small reactors, for which the specific operating costs may be somewhat higher.

District heating reactors should be well suited for serial production, which is generally considered one of the factors favoring the development of SMR-scale technology. The primary circuit components, especially for small 25-50 MW units, could most likely be mass-produced even in conventional workshops. The use of nuclear energy for district heating was considered an economically viable option in the 1970's, and similar conclusions were drawn in a recent study at VTT [14], even without taking full credit of dedicated reactor technology. The broad range of operating parameters brings flexibility in reactor design.

In addition to technical and economical considerations, other boundary conditions are dictated by licensing requirements. The characteristic features of district heating reactors were simply not considered when the current legislation was first drafted for large NPP's. Passive decay heat removal and other inherent safety features considerably simplify the plant design, which could allow more streamlined licensing procedures to be applied as well.

The major open questions are related to urban siting and remote operation. The current licensing practices rely heavily on the concept of emergency planning zones in the mitigation of the consequences of severe accidents. The licensing of an urban reactor may require some revision of these basic principles to account for the fact that if a major radioactive emission can be ruled out, there is no need for large-scale evacuation procedures under any accident scenario. These, and other issues related to the licensing of small reactors are addressed at the IAEA SMR Regulators' forum.[6]

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