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Research Article

Identifying the key development areas for small nuclear power plants*

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Abstract

The paper considers the key characteristics of the small nuclear power plant (SNPP) modular design, demonstrates the possibility for reducing the construction cost and time for this class of plants due to factory fabrication, the effect of series manufacturing, and less redundant safety systems. It has been shown that it is possible to extend considerably the fields of application for nuclear technologies thanks to modularity and the possibility of ensuring high safety indicators. Potential applications for SNPPs have been analyzed, including power supply to remote (Arctic) territories, switchover from (renovation of) coal-based electricity generation, high-potential heat and hydrogen production for commercial consumers, and other applications. Rationale has been provided for most typical consumer requirements that define the greatest efficiency of the SNPP application in the given field. The need has been shown for developing and introducing a new technology platform for the SNPP-based nuclear power to decarbonize globally the world economy thanks to expanding greatly the application of nuclear power technologies in addition to the technology platform currently developed for the CNFC with fast reactors (addressing the objective of fuel supply and waste recycling) and the controlled nuclear fusion technology platform (addressing the objective of long-term global energy supply). The new platform needs to be based on an extensive international cooperation involving the formation of international consortiums. It has been proposed that a test site be set up to elaborate hydrogen (heat) production technologies for an individual commercial consumer (captive production) and other technologies for the practical use of SNPPs based on a pilot demonstration nuclear power plant.

Keywords

The Arctic, small nuclear power plants, energy storages, synthetic zero-carbon fuel, new technology platform, hydrogen

Introduction

Since the publication in 1990 of the first report by the Intergovernmental Panel on Climate Change (IPCC), which placed emphasis on the immediate threat of climate change from the emission of greenhouse gases, diplomatic efforts have been focused on searching for an international framework to regulate such emissions. These efforts crystallized into the UN Framework Convention on Climate Change (1992), the Kyoto Protocol (1997), and the Paris Climate

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Agreement (2015) that defined the objectives for the global greenhouse gas emission reduction. Notions of low-carbon and decarbonized economy and a call for global decarbonization have appeared (Clark et al. 2020). For all that time, technological efforts have largely been aimed at evolving 'green' power based on renewable energy sources (RES), as well as energy saving and energy efficiency technologies. Many countries have declared a reduction or even full abandonment of nuclear generation not believed to be 'green'. Meanwhile, the energy crises of 2020 and 2021 in the USA and Europe have shown RES-based power to be incapable in principle to ensure, at the same time, both a major reduction in the emissions of greenhouse gases, and the energy reliability of power systems, in connection with which much attention is given now to nuclear power recognized to be 'green' by the overwhelming majority of the world community. The existing nuclear power is evidently expected to contribute to the global decarbonization, but this contribution is likely to be limited, first, by problems involved in fuel supply and spent nuclear fuel (SNF) disposal, the solution of which is currently achieved through developing energy technologies of the closed nuclear fuel cycle (CNFC) with fast-neutron reactors (BR), and, second, by the use of the existing high-capacity nuclear power being systemically confined only to electricity generation. There is a need for extending globally the deployment of nuclear power to the niches of human life activities beyond the reach of high-capacity power, namely, expanding geographically the application of nuclear power and spreading it to nonelectrical applications in industry, communal services, medicine, etc. Small generating facilities are required for such applications but featuring a better safety performance so that SNPPs could be deployed immediately in the vicinity of the consumer.

Modular design of SNPPs

The world community has long referred to this class of nuclear facilities as *small nuclear power plants* (SNPP) which include, according to the IAEA classification, plants with an equivalent electric power of below 300 MW (IAEA-TECDOC-1485 2006, IAEA-TECDOC-1536 2007, IAEA-TECDOC-1652 2010). Reactors of such power level formed the basis for nuclear power at its early evolution stages but a trend prevailed later for increasing power (to achieve the economic advantages offered by economy of scale), which has led to nuclear power plant designs of 1000 to 1600 MW(el) forming currently the basis of modern world nuclear power.

As part of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) established in late 2000, investigations were undertaken into the SNPP legal and institutional support issues (Kuznetsov 2009, Kuznetsov and Opanasyuk 2013), which introduced the term "Transport Nuclear Power Plants (TNPP)", which are described as "SNPPs whose lifecycle is based on a single transport platform, as well as SNPPs assembled of factory-made transportable modules on prepared sites and removed from these sites in the same way". This definition is a special case of the definition "Small Modular Reactors" (SMRs) proposed in the course of the Sixth INPRO Dialog Forum in the summer of 2013 to identify small power facilities of industrial serial fabrication (Small Modular Reactors 2016, 2021).

The modular design defines the following advantages of SNPPs:

- construction cost and time reduced thanks to a larger share of factory fabrication, and the effect of series fabrication and the construction site work scope reduction, including at the expense of underground or buried deployment;
- better safety performance (including natural safety) due to a shift in the energy balance between the bulk release of energy and the surface heat removal in beyond-design-accident modes;
- reduced construction cost and time due to abandoning excessive safety systems thanks to using an integral (unitized) layout of the primary circuit, and enabling complete removal of residual heat, and so on;
- reduced construction cost and time due to abandoning the infrastructure for the fresh nuclear fuel (FNF), spent nuclear fuel (SNF) and radioactive waste (RW) handling on the deployment site (if defined in the project) and the SNPP transport for carrying out such operations at the manufacturer's site;
- a concept of the SNPP delivery to the consumer in an 'undismountable' form and transport to the manufacturer's site for the fuel handling operations makes it possible to justify the possibility for such plants to be exempt from the IAEA safeguards that limit the fuel enrichment and increase so the fuel life;
- feasibility for being more flexibly integrated into the existing grids and the consumer demand;
- a shorter period for the return on investments to start due to phased deployment of energy modules;
- possibility for a public/private partnership thanks to less investments in the power unit construction and a shorter time of return;
- increased reliability of power supply thanks to a smaller risk of complete shutdown for a multi-module station;
- smaller cost of green-field decommissioning due to the possibility for modules to be removed to the factory for disposal;
- possibility for expanding the market for the peaceful use of nuclear power through the incorporation of those segments where no nuclear power technologies are used at the present time, including thanks to the possibility of deployment in the immediate vicinity of the consumer with increased safety characteristics.

SNPP evolution trends

Globally, there are a number of promising trends for the evolution of SNPP designs depending on their purpose, specific customer features, and consumer requirements.

SNPPs for heat and electricity supply to remote territories

This application is topical largely for Russia, Canada and island states (including in the Arctic region), and isolated towns and installations. For example, the establishment of international cross-polar aircraft corridors over the Russian territory which are commercially promising due to a shorter route. Thus, the Toronto-Hong Kong air route can be shortened by 20% if run over the polar latitudes, and the time reduction for the Vancouver-Delhi air route, if run transpolarly, is 3 hours and a half with a saving of $36,000. The commercial efficiency of transpolar routes has been demonstrated for 40 pairs of cities as a minimum. To date, however, no air flights over the Northern latitudes are properly tracked so there are no practically such flights made on a commercial scale. This requires continuous radar surveillance and communication along the entire route provided by ground air traffic control services in addition to satellite navigation, this leading to the need for reliable and cost-effective power sources. And the payment for the air flight ground tracking is up to 1$ per km.

The key requirements to these plants are:

- operation for the local or district power supply sectors in enhanced power maneuvering modes (*local* means here a power supply sector isolated from grids and other power sources, and comprising one source and one or more consumers (a power center); and *district* means a centralized power supply sector isolated from the unified grid and comprising several sources and consumers);
- a maximally possible long refueling interval of 10 to 20 and more years;
- cogeneration of electric and thermal power;
- cost effectiveness as compared with other possible power sources (largely with diesel-based generation) deployed on the given site;
- availability of emergency backup facilities in case of failures;
- operation with as small number of operating personnel as possible or no personnel involved in remote access control;
- no onsite fuel handling infrastructure and transport to the manufacturing site for refueling, largely for very small plants (plants with an equivalent electric unit power of below 10 MW are also referred to as very small nuclear power plants).

The line of single generating facilities in highest demand is that with an equivalent electric power of 200 kW to 100 MW.

This concept is expected to include an economically justified use of chemical (hydrogen) energy storages to support cost-effective maneuvering modes (Tarasenkov and Shkolnikov 2009) for very small plants. And the accumulated hydrogen can be used to produce zero-carbon synthetic motor fuel for transport (e.g., to produce ammonia from hydrogen and nitrogen contained in the air) or using hydrogen directly in transport with hydrogen fuel elements which is of a great importance for remote towns and installations, specifically in the Arctic region where this function allows excluding in full the delivery of fuel and improving the environmental situation (Klimentyev and Klimentyeva 2017). Such storages are also expected to serve as an emergency source of power in the event of an accident or a failure.

SNPPs to substitute (renovate) coal generation

This is the most topical evolution trend for Russia (CIS countries), Europe, China, India, etc. in terms of substituting the existing coal-fueled thermal power plants (TPP).

There are two potential concepts for this application:

- the reactor plant substitutes only the coal boiler with the rest of the key components (turbines, heat regeneration systems, power generators, network facilities, etc.) remaining in service, this reducing to a great extent the capital costs;
- full substitution of the key components, including the turbine island, while using the site infrastructure built (roads, railway tracks, etc.) and auxiliary equipment (power delivery systems, buildings, structures, etc.).

The key requirements are as follows:

- possibility of generating superheated steam or supercritical-pressure steam (depending on the TPP type);
- operation in maneuvering modes as part of a single centralized power network;
- improved safety performance to enable deployment in the immediate vicinity of the consumer (within large cities as a rule) while excluding in full offsite protective measures;
- reduction of the levelized cost of energy (LCOE) to the level that ensures economic efficiency;
- tightly scheduled greenfield decommissioning.

The greatest demand is for single-unit facilities of 100 to 200 MW(el).

SNPPs to substitute centralized units of a large unit power with several small modular units, including for distributed generation (deployment at a number of sites as part of one grid)

This application is topical primarily for developing countries with not enough power facilities and underdeveloped power transmission lines. Extra economic advantages for this application are small grid installation costs and smaller grid losses (in the event of distributed generation) (Zaychenko et al. 2008, Maykov and Direktor 2011), a higher capacity factor (CF), and improved safety performance. The key requirements to these plants are in line with the requirements to large nuclear plants provided the LCOE is reduced to a level comparable with that for large NPPs (Projected Costs 2020). The LCOE determination requires taking into account the decommissioning cost, this being much smaller for modular SNPPs in the event of a concept with the delivery of modules to the manufacturing site to be further recycled. One also needs to take into account the fact that, for the small generation case, the insurance premium amount for the nuclear damage in the event of an accident is enough to cover in full the damage caused, while this damage for a large station will have to be partially reimbursed for by the NPP hosting state (Amelina and Kutumov 2011).

This application is being evolved by Rolls-Royce jointly with BNF Resources UK and Exelon Generation which plans to build 16 SMRs in England to replace large NPPs in 2030–2050. These plants are also expected to be equipped with chemical (hydrogen) energy storages, and the accumulated hydrogen will be also used to produce synthetic motor fuel.

The highest demand is for single-unit facilities of 100 to 300 MW(el).

Small industrial nuclear power plants (SINPPs) for production of high-grade heat and captive hydrogen for commercial consumers

Industries consume much high thermal energy (above 700 °C) in processes; these are largely metallurgy, chemical and petrochemical industries, etc. At the present time, this thermal energy is produced largely at the expense of burning mineral hydrocarbon fuels (coal, gas, oil fuel, etc.), which leads to the environment heavily polluted both by greenhouse gases and other mineral fuel combustion byproducts. Many commercial consumers in metallurgy (e.g., production of superpurity metals, direct technology of producing steel by forward recovery from ore by hydrogen), chemistry and petroleum chemistry (oil refining), pharmaceutics, etc., use much hydrogen in process cycles. At the present time, the required hydrogen is produced predominantly at a large commercial consumer site by methane steam conversion method with 50% of methane combusted to achieve the required process temperatures, this accompanied by emission of substantial amounts of greenhouse gases (Ball and Wietschel 2009, Zhuravlev et al. 2021). The capacity of such facilities for captive production of hydrogen (that is, for auxiliary consumption) at a commercial consumer site is 10 to 150 thsd t/g, which can be perfectly well substituted with SINPPs:

- 2017 – OOO Gazprom Neftekhim Salavat, 17.7 thsd t/g;
- 2018 – Omsk PNZ Gazprom Neft, 12.3 thsd t/g;
- 2014–2017 – Ufa, Bashneft Oil Company, 153 thsd t/g.

Using SINPPs for supplying high-grade heat and hydrogen to large commercial consumers is economically justified for the following reasons.

- No discharge into the environment both globally (greenhouse gases the emission of which is expected to be stringently quoted soon by international law), and locally (contamination of the nearby residential areas, mainly large industrial cities, and the surrounding territory with toxic mineral fuel combustion byproducts and ash dumps which are limited by federal and regional laws).
- Insignificant fluctuations in the world prices for nuclear fuel leads to stable, predictable and better planned industrial activities both technologically and economically. This application is topical for Russia, China, India, and other industrial countries.
- With centralized production of hydrogen, hydrogen storage and transport operations account for most of the final price for hydrogen because of its physical properties (low density, lower liquefaction temperature, etc.), so the most effective way will be to exclude these operations from the flowchart and produce hydrogen immediately in the vicinity of the consumer.

Economically, the nuclear source of high thermal energy and the hydrogen production facility need to be deployed immediately on the commercial consumer site (a hazardous installation) deployed as such, predominantly, in the immediate vicinity of big industrial cities. Such deployment, as well as the deployment of a potentially hazardous production facility near an NPP is prohibited today both by international nuclear safety standards and by Russian standards and regulations. Therefore, a nuclear source of high thermal energy is required to be safer than the existing units to be certified for deployment in the immediate vicinity of the commercial consumer.

Apart from the above SNPP key evolution trends, there are other applications with their own requirements to plants, e.g., SNPPs for desalination of seawater (Rouillard and Rouyer 1992), power supply to offshore oil platforms (topical for China) (Collection of Works 2015), substitution of coal boiler houses, SNPPs for medical applications (neutron capture and neutron collision therapy directly at a medical institution) (Levchenko et al. 2003), SNPPs for combustion of minor actinides, etc.

To date, there are some 50 different SNPP designs worldwide at different stages of consideration, which can be divided technologically into two applications (IAEA 2018, 2020).

- Evolutionary development of water-cooled water-moderated nuclear power technologies of

generation III+ (including boiling water reactors), not meeting in full the consumer requirements but offering reference capacity and capabilities for a faster market access.
- Development based on generation IV power technologies (molten salt, liquid metal, etc.) meeting consumer requirements in terms of properties, specifically increased safety requirements, with a capability to operate as part of the CNFC, but having no sufficient reference status and differing with a longer period to the finished commercial product.

Conclusion

The development of the required SNPP line is a highly diversified, challenging and sufficiently costly task that cannot be solved by Rosatom State Corporation alone. Similar strategic programs need to be undertaken based on an extensive international collaboration with the establishment of international consortiums as was proposed by Academician Ye.P. Velihkov at the IAEA way back in 2008 (IAEA 2008).

And the actual SNPP deployment in present-day market conditions can take place only as part of actual and large-scale projects in which SNPPs will not be an end in itself but a tool for addressing in an efficient manner global infrastructural objectives. A practicable solution appears to be to build a test range to fine-tune technologies for the captive hydrogen (heat) production for commercial consumption based on a pilot and demonstration industrial nuclear power plant with a high-temperature gas-cooled reactor with a thermal power of 50 to 100 MW, a coolant temperature of 950 to 1000 °C. This test range can be used to fine-tune the following technologies:

- a high-temperature gas-cooled reactor for cogeneration of zero-carbon hydrogen (heat) and electricity for industries;
- hydrogen production by high-temperature electrolysis of water and thermochemical cycles of water decomposition;
- direct production of iron by forward recovery from ore using hydrogen and a technology to obtain pure metals and alloys;
- radiation thermal cracking, hydrogen cracking and hydrogen oil refining;
- zero-carbon technologies for production of synthetic motor fuel from hydrogen (ammonia, methanol, etc.);
- lifting of heavy oil and renovation of used wells, etc.

For centralized zero-carbon commercial production of hydrogen, it will be practicable to consider for a long term the use of a high-temperature sodium-cooled reactor with a sodium temperature of 950 to 1000 °C at the core outlet for production of hydrogen by high-temperature electrolysis of water or by high-temperature thermochemical cycle of water decomposition.

We shall note the advantages of the high-temperature sodium technology as compared the high-temperature gas technology (with outlet coolant temperature of 750 °C) being developed presently in Russia.

- A higher power density in the core, up to 400 MW(th)/m^3 (up to 9 MW(th)/m^3 for a high-temperature gas-cooled reactor), a much higher efficiency, and low cost of hydrogen production (economy of scale).
- Much smaller dimensions of the reactor unit (smaller capital costs).
- Low pressure in the coolant circuit (less consumed materials).
- Reliable method for residual heat removal.
- Higher level of nuclear safety and no contamination with carbon-13.
- Possibility for operation in a closed nuclear fuel cycle.

Therefore, full-scale deployment of the SNPP line in different spheres of human life activities for the purpose of substituting technologies based on using organic raw materials for the global decarbonization of the world economy and a major reduction of the greenhouse gas emissions offers an individual new technology platform for nuclear power. This platform adds to the currently developed technology platform for a CNFC with fast-neutron reactors to address the objectives of fuel supply and waste disposal, and to the technology platform for controlled fusion to address the objectives of long-term global power supply. The establishment of a new technology platform based on the SNPP line requires the development and adoption of Rosatom State Corporation's Strategic Program for this field of application.

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