Federal Office
for the Safety of
Nuclear Waste Management

Small Modular Reactors – What to expect from the new reactor concepts?

Technical Briefing

Executive Summary

- The idea of "small modular reactors" (SMR) dates back to developments in the 1950s, in particular the attempt to use nuclear power as a propulsion technology for military submarines. Today, a wide variety of concepts and developments for SMRs exist worldwide, the vast majority at the conceptual level. In the context of the future of nuclear power, and especially as a measure against climate change, SMRs have been receiving renewed attention for some time now.

- There are many SMR concepts under development worldwide: A total number of over 130 concepts can be identified, some of which date back decades. In 2023, only 8 are in operation and 2 are under construction. Some SMR concepts are planned as mobile units or installed on ships, for example, to provide electricity or heat to remote regions.

- Most SMR concepts are light-water-cooled. Non-light-water-cooled concepts have much higher development risks due to none or less operating experience and new technologies.

- SMRs could potentially have safety advantages over large-capacity nuclear power plants, as they have a lower radioactive inventory per reactor and passive residual heat removal systems, for example. However, the high number of reactors required to produce the same amount of electricity would increase the risk many times over.

- Contrary to the information provided by some manufacturers, it must be assumed that, as far as off-site emergency protection for SMRs is concerned, there is a possibility of contamination extending well beyond the plant site.

- Regulatory challenges include the lack of standardization, adaptation of existing regulations, and the need for internationally agreed safety standards for global SMR deployment.

- Due to the low electrical output, the construction costs for SMRs are higher in relative terms than for large nuclear power plants. A production cost calculation taking into account effects of scale, mass and learning from the nuclear industry suggests that an average of three thousand SMRs would have to be produced for SMR production to become economically viable.

1. Introduction

SMRs are a type of nuclear power plant. Despite the long-standing use of the term "SMR", there is still no internationally standardized definition. It stands for "small modular reactors" or "small and medium reactors". Those descriptions emphasize the limited rated power of the reactor, which is usually understood to be below 300 $MW_{electrical}$, as well as the modular design of the plant. Modern conventional nuclear power plants typically have a capacity of more than 1000 $MW_{electrical}$.

Due to the high relevance of this topic, for example in international organizations, among developers and in the public debate, the German Federal Office for the Safety of Nuclear Waste Management (BASE) commissioned a research project with regard to SMR technologies. The study was carried out by Öko-Institut in collaboration with the Department of Economic and Infrastructure Policy at Technical University Berlin and the Physikerbüro Bremen. It was published in 2022. Unless otherwise stated, the statements in this summary are based on this study[1].

2. Current status: What are the main developments in SMR technology?

The current development of SMRs is largely state-funded and is taking place to a large extent in the USA, Russia, China, Japan, Canada and the United Kingdom. Provided the right conditions are met, SMRs can not only be built in those countries, but also be sold to others.

Industrial and geopolitical motives as well as military interests play a role in the field of SMRs. The majority of countries pursuing SMR development activities maintain nuclear weapons programmes and build nuclear submarines and/or already have a large “civilian” nuclear programme.

In addition to regular power supply, decentralised power supply for industry and households as well as heat for district heating, seawater desalination and industrial processes are mentioned; concepts for military use, such as mobile microreactors, are also being pursued. In Russia, a floating nuclear power plant (Akademik Lomonossow, KLT-40S) is being used to supply remote regions.
In addition to traditional nuclear energy countries, there is growing interest in SMRs from countries with a lack of expertise and infrastructure in nuclear technology.

Of the designs under development, only very few are well advanced. The SMART-SMR concept (this was approved in South Korea in 2012), the NuScale concept (this received design certification in the USA in 2023) and the Aurora powerhouse design (a combined construction and operation application was submitted in 2020, but was denied by the NRC in 2022 due to incomplete information).

1 *https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/berichte/kt/gutachten-small-modular-reactors.html*

Both the NuScale and Aurora Powerhouse concepts were to be implemented in Idaho (USA). However, in November 2023, NuScale announced the termination of a major SMR project for economic reasons[2].

SMRs are also proposed as a solution in the context of combating the threats of climate change and the associated reduction of greenhouse gas emissions for the global electricity supply. SMR electricity production is relevant in this context. Today's new nuclear power plants have electrical outputs in the range of 1,000-1,600 MWe. In contrast, the SMR concepts considered in this study envision planned electrical outputs of 1.5 – 300 MWe. Accordingly, the number of plants required to provide the same electrical output would be 3 – 1000 times larger. Instead of today's approximately 400 reactors with large capacities, this would therefore require the construction of many thousands to tens of thousands of new SMRs. Various safety risks associated with the envisaged plants are largely neglected in the planning, especially questions regarding transport, dismantling and interim and final storage.

3. Technology: Innovations through SMR-concepts?

SMR concepts differ in a number of important technical characteristics from today's large-scale nuclear reactors. These include, for example: The type of coolant used, the nuclear fuel type, the neutron spectrum or the operating temperature. One of the main distinguishing features is the classification into light-water and non-light-water SMR concepts.

Today, light-water reactors make up the vast majority of nuclear power plants in operation worldwide. This means that extensive operational experience and a broadly developed infrastructure are available for such reactors. The majority of the SMR concepts which are currently under development (especially those in an advanced development stage) are also classified as light-water reactors. Such concepts, therefore, have lower development risks compared to non-light-water SMR concepts.

Non-light-water SMR concepts differ in key features from light-water reactors and, therefore, from most of the nuclear power plants that are used today. Possible reactor concepts could be, for example, high-temperature reactors (HTR), lead-cooled reactors (LFR) or molten salt reactors (MSR). There is no or only very limited operating experience for these reactor types, and there are many unresolved questions regarding the deep geological repository of their nuclear waste. Since the use of innovative technological solutions and new materials is planned, significantly longer development periods and higher technological development risks can be expected compared to water-cooled SMR concepts. But developers hope to achieve a number of advantages by utilizing these concepts. For example, higher efficiencies could be achieved through higher operating temperatures.

Other fields of application, in particular the provision of high-temperature process heat, are planned to also become feasible. Many of these concepts are aimed at a so-called closed fuel cycle, with the associated safety risks in the area of fuel development and reprocessing technologies.

2 *https://www.nuscalepower.com/en/news/press-releases/2023/uamps-and-nuscale-power-agree-to-terminate-the-carbon-free-power-project*

SMRs do not necessarily have to be stationary facilities. Most mobile SMRs are primarily used to power ships, such as aircraft carriers, nuclear submarines or nuclear icebreakers. Mobile SMRs that are designed to supply remote areas are also conceivable. For example, the Russian floating nuclear power plant "Akademik Lomonosov", which has two reactors, each with an output of 35 $MW_{electric}$, has been in operation since 2018. Another mobile reactor that is still under development is the eVinci reactor from Westinghouse (5 $MW_{electric}$), which is planned to be transportable by truck (reactors between 1 and 20 $MW_{electric}$ are also known as "microreactors").

4. Safety issues: Are SMRs safer than large-scale nuclear power plants?

To ensure the safety of nuclear power plants, both conventional and SMR, three overarching safety functions must be fulfilled:

- the containment of radioactive substances,
- the control of reactivity, and
- the cooling of the reactor core.

Containment

The principle of defense in depth is used to ensure the safe containment of the radioactive substances in the reactor core. In today's nuclear power plants, these are typically multi-level barriers consisting of the fuel rod tube, the pressurized enclosure (reactor cooling circuit), a containment, and the reactor building. For water-cooled SMRs, similar containment concepts are used as for today's light water reactors. For SMRs that intend to do without a dedicated containment due to special properties of the fuel, further evidence is required to prove that the radioactive inventory is contained safely and reliably.

Control of reactivity

The control of reactivity in a nuclear power plant is achieved by the inherent neutron-physical properties of the reactor on the one hand, and by systems for regulating, shutting down and maintaining subcriticality on the other. Almost all SMR concepts considered today intend for reactivity control to be carried out in a similar way as in today's light water reactors, i. e., essentially via control rods or movable reflectors (the latter are not used in today's LWRs).

Overall, this does not result in any significant differences with regard to reactivity control compared to today's power reactors. In particular, the non-water-cooled SMR concepts often emphasize inherent neutron-physical feedback properties that are advantageous in terms of safety with regard to reactivity control. However, restricting considerations to individual feedback properties is not appropriate. Rather, reactivity must be analyzed and evaluated temporally and spatially under all physical conditions to be considered (also in the case of transients and accidents). As a result, various non-water-cooled SMR concepts, for example, use a second, independent shutdown system.

Cooling

Compared to today's large-scale nuclear power plants, one significant difference regarding the cooling of the reactor core is that options for passive systems, e. g. for residual heat removal or emergency core cooling, are being discussed for SMR concepts. Passive systems can generally lead to increased safety of a reactor system, as possible failure mechanisms of active components can be excluded, and an increased reliability of the function can thus be achieved.

Passive systems are also used to varying degrees in today's nuclear power plants. However, increased reliability cannot be assumed solely on the basis of the characteristics of passivity. Theoretical and experimental proof of the actual reliability of a specific passive residual heat removal system is necessary. Just as necessary are detailed analyses of the operating boundary conditions as assumptions for various possible malfunction and accident scenarios.

The safety characteristics of the reactor must also be analyzed, considering all possible events and incidents. Internal events such as the failure of pumps, the loss of a power supply to equipment, leaks in pipes or fires can play a significant role here. External events such as earthquakes, external flooding or extreme weather conditions must also be considered. Furthermore, civilization-related events such as an accidental or terrorist-motivated plane crash as well as other third-party impacts must also be considered. Design measures such as an integral reactor pressure vessel are intended to rule out certain events in some SMR concepts (in particular a major loss-of-coolant accident) or at least make them less likely.

External events can become more significant for SMRs. The range of possible external events to be considered is typically determined on a site-specific basis. In some cases, SMR concepts are intended for use in remote regions, or to supply industrial plants. In these cases, locations cannot be freely selected. For ocean-based SMR concepts in particular, further questions arise with regard to natural external influences.

Regarding the necessity and size of areas for which radiological contamination must be assumed in the event of an emergency, there are unresolved questions concerning off-site emergency protection (e. g. by the fire department). As a result, complex investigations are still needed, particularly with regard to covering source terms (i. e., the quantities of radionuclides released in the event of an accident) for the individual reactor designs and the possible interactions in multi-unit plants. Contrary to occasional claims of SMR concept developers, it must be assumed that planning areas which extend well beyond the plant site are required for off-site emergency protection.

Overall, SMRs could potentially achieve safety advantages over high-power nuclear power plants, as they have a lower radioactive inventory per reactor and strive for a higher level of safety through simplifications and increased use of passive systems. In contrast, however, various SMR concepts also claim reduced requirements, for example with regard to the level of redundancy or diversity in safety systems. Some concepts even call for waiving current requirements, for example in the area of on-site emergency protection or with reduced planning radii or even a complete waiver of off-site emergency protection planning. As the safety of reactors depends on all of these factors, current knowledge does not warrant the claim that a higher level of safety is achieved with SMR concepts as a matter of principle.

5.
Regulatory requirements: How high is the safety risk for SMRs?

Special application scenarios such as modularity, new manufacturing processes, materials and technological solutions for safety functions often require new regulatory approaches. The planned global spread of SMRs will, therefore, raise entirely new questions for the responsible licensing and supervisory authorities. To date, there are no SMR-specific national or international safety standards. As many SMR developers are aiming for worldwide use of their SMR concepts, an international standardisation of the requirements would become necessary. This is currently not conceivable, especially for established nuclear energy countries. Many of today's nuclear regulatory requirements are basically transferable to SMR concepts. Various regulatory authorities expect light-water SMRs to meet at least the integral safety level that is currently required for new nuclear power plants. However, the industry's interest in a quick international standardization must not compromise the aim for highest safety standards.

This also raises the question of which overall safety level of SMRs will be required, and whether the claim of improved safety compared to today's new nuclear power plants, as advocated by SMR developers, will be implemented in a real plant. In detail, there would be a need to adapt the national regulations for the licensing of an SMR. Today's regulations are generally based on water-cooled reactor concepts. New regulatory approaches may be required for new manufacturing processes, new materials or new technological solutions for safety functions, such as those discussed for SMR concepts. This applies, in particular, to non-water-cooled concepts. This may involve a considerable lead time before SMR concepts can be licensed.

In some cases, technologies are to be used in SMRs for which there is little or no operating experience. In many other cases, suitable verification methods still need to be developed and validated for these technologies. This may also require new calculation methods, new measurement procedures or new inspection technologies. For non-water-cooled SMR concepts, in particular, developers draw on historical experience from demonstration and research reactors. However, the transferability of the findings from such reactors to current concepts must be examined and justified in each case. Licensing authorities still see a considerable need for research and development in this respect.

6.
Access to nuclear weapons-grade material: Do SMRs increase the risk?

Various non-water-cooled SMR concepts envisage the use of higher uranium enrichments or the utilisation of plutonium fuel and reprocessing technology. This has a negative impact on proliferation resistance – i. e. the need to prevent access to or the technology to produce nuclear weapons-grade material.

Another, often-cited key difference between SMR concepts and today's power reactors is the use of systems that have a long service life and would be delivered as a closed system. Sealing them could simplify monitoring and minimise transports. Furthermore, due to the high burn-up, the fissile material will also become unattractive after some time.

Yet, the high quantity of fissile material required at the start of reactor operation will have a disadvantageous effect. An additional aspect concerns the possibilities of fissile material monitoring by the International Atomic Energy Agency. Many of the standard methods for fissile material monitoring are not directly suited to the special features of SMR concepts, and this would pose new challenges.

7. Economic properties: Would SMR production be worthwhile?

In general, the specific costs (€/MW) of a single component or an entire power plant are likely to increase as the total power output decreases. This is due to several factors like fixed cost degression or volume effects. This is therefore likely to result in higher specific costs for SMRs.

On the other hand, the specific costs could decrease as more units are produced. This is due, among other factors, to an increased production efficiency. Developers of SMRs hope that the advantages will overcompensate the disadvantages. Developers argue that, in the long run, SMRs would be more economically viable than current nuclear power plants.

A production cost calculation for light-water SMRs carried out by the Technical University of Berlin, considering effects of scale, mass and learning from the nuclear industry suggests that about 3,000 SMR units would have to be produced to break even. It is therefore unlikely that the cost disadvantage of low-capacity reactors can, in practice, be compensated for by an economy of scale effects. In addition to modularity, another key reason for the development of SMR concepts is the expectation of shorter time horizons, in particular shorter construction times, and possibly also simplified decommissioning. A look at currently planned units under construction or in operation does not confirm this assumption. To the contrary: planning, development and construction times generally exceed the original time horizons many times.

Legal notice

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