Chapter 2

Safety and Economics of Small Modular Reactors

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Chapter 2

Safety and Economics of Small Modular Reactors

1. What Are Small Modular Reactors?

Small modular reactors (SMRs) are expected to offer a lower initial capital investment, greater scalability, and siting flexibility for locations unable to accommodate more traditional large-scale reactors. These expectations are not new, since they have been repeatedly researched, developed, and proposed in various international conferences and academic reports over several decades (e.g. International Atomic Energy Agency, 1996). SMRs also have the potential for enhanced safety and security compared to earlier designs. The deployment of advanced SMRs can help drive economic growth.

The US Department of Energy (DOE) describes SMRs as follows: 'Advanced Small Modular Reactors (SMRs) are a key part of the Department's goal to develop safe, clean, and affordable nuclear power options. The advanced SMRs currently under development in the United States represent a variety of sizes, technology options, capabilities, and deployment scenarios. These advanced reactors, envisioned to vary in size from tens of megawatts up to hundreds of megawatts, can be used for power generation, process heat, desalination, or other industrial uses. SMR designs may employ light water as a coolant or other non-light water coolants such as gas, liquid metal, or molten salt. Advanced SMRs offer many advantages, such as relatively small physical footprints, reduced capital investment, the ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. SMRs also offer distinct safeguards, security and non-proliferation advantages.' (DOE, n.d.)

Even SMRs are not perfectly safe, as none of the nuclear reactor concepts are 100% free from the possibility of accidents. One of the major issues concerning the safety of SMRs compared to large-scale light water reactors is 'inherent safety'. SMR vendors often state that SMRs have an 'inherent safety' feature; however, it depends. First of all, the technical term 'inherent safety' should be strictly defined before discussing the inherent safety.

2. Inherent Safety

It can be said that ‘inherent safety’ means that the possibility of danger itself has been eliminated. There are two possible approaches to realising this concept in nuclear power:

(a) Even if a core meltdown occurs and the radioactive materials inside the reactor diffuse outdoors, radiation is generated only to the extent that it does not affect health at all.

(b) Although there is a considerable amount of radioactive material, the core does not melt down, or even if it does, the radioactive material remains in the containment vessel and does not diffuse into the environment. This is called ‘practically eliminated’ (PE), short for ‘the possibility of the radioactivity release could be practically eliminated’.

More detailed explanations of the two approaches are given below.

(a) Control the output

If the output of the core is small, i.e. the amount of radioactive material contained within is small, the amount of radioactive material released during an accident would be extremely limited, and the probability of endangering the health of people outside the site would be extremely low. For example, an experimental reactor with a thermal output of a few kilowatts that is far enough from the site boundary could meet such a condition.

However, how far the output should be reduced to achieve PE or effectively negate the possibility of a large release of radioactive material depends on the characteristics of the core and the design concept of the safety equipment, and it is not clearly determined at present. In other words, just because the amount of radioactive material contained in a nuclear reactor system is small, it does not necessarily mean that the risk of radioactive material release is reduced in proportion to the amount. It is still under debate amongst experts as to what kind of core characteristics and safety designs can be considered as PE.

(b) Eliminate meltdowns

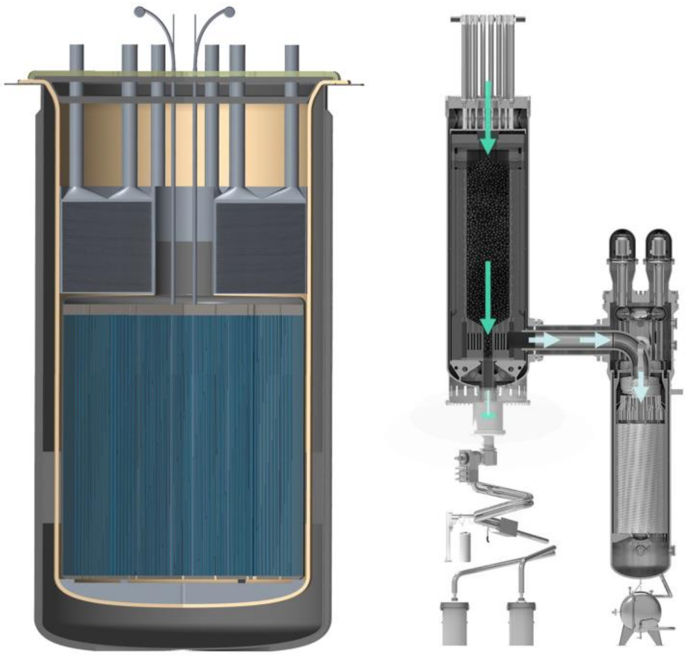
The reactor accidents that have occurred so far can be roughly divided into two categories: reactivity accidents and loss-of-coolant accidents.

Reactivity accidents

The reactors currently in operation run continuously for more than a year, during which no fuel is supplied. The fuel in the reactor is gradually depleted by nuclear fission. Fission becomes critical and continues when there is a certain amount of neutrons, but since the neutrons are generated by the fission of the fuel, the amount of neutrons decreases when the fuel is depleted, and criticality cannot be maintained, which makes continuous operation impossible. To avoid this, a larger amount of fuel is loaded, which generates more neutrons, and the amount of neutrons above criticality is absorbed by burnable poisons, control rods, and boron in water, and the amount of these absorbers is reduced as the amount of the fuel decreases. In the case of control rods, the amount of absorption is adjusted by extracting from the core the rods that have been inserted into it. A reactivity accident is a situation in which such a control device that absorbs neutrons malfunctions or is accidentally removed for some reason, causing a sharp increase in the nuclear reaction, leading to an output surge and sometimes a runaway reaction. Some SMRs, however, are not confined to the existing light water reactor (LWR) concept of ‘no fuel supply during operation’, but have the concept that fuel supply during operation is possible. Since such reactors are not overloaded with fuel, there is no possibility of a reactivity accident even if there is a failure in the control devices.

For example, Terrestrial’s Integral Molten Salt Reactor (IMSR) is a molten salt reactor that can continue operating by adjusting the concentration of liquid nuclear fuel. The IMSR has completed the assessment of compliance with regulatory requirements (Phase 1) of the Canadian Nuclear Safety Commission’s (CNSC) pre-licensing vendor design review (VDR) and is continuing with the assessment for any potential fundamental barriers to licensing (Phase 2) starting in 2018. In addition, X-energy’s Xe-100 is a pebble-bed high-temperature gas-cooled reactor (HTGR), which is based on the concept of supplying spherical nuclear fuel, called tristructural isotropic (TRISO), during operation. The VDR of the CNSC for this reactor also started in 2020. Figure 2.1 shows the design concept for the IMSR and Xe-100.

Figure 2.1. Design of the Integral Molten Salt Reactor and Xe-100



IMSR (200MWe) Xe-100 (75MWe)

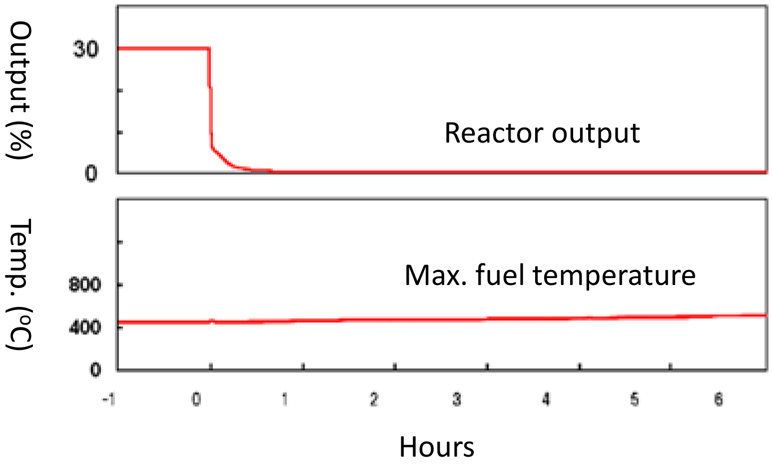
Source: Terrestrial Energy website (https://www.terrestrialenergy.com/technology/molten-salt-reactor) and the X-energy website (https://x-energy.com/reactors/xe-100), accessed 5 April 2021.

Loss-of-coolant accidents

In nuclear power generation, the fuel continues to emit heat, due mainly to fission during operation and the decay heat of radioactive materials generated after fission during shutdown. To remove this heat, the cooling system is always working during both operation and shutdown. If for some reason cooling is not possible, the fuel temperature will continue to rise, and eventually the core will melt, and the radioactive materials locked in the materials and components that make up the fuel will leach out. The high-temperature core raises the temperature of the surroundings. The surrounding materials begin to change into gas, which further expands, causing the pressure inside the containment vessel to build up. If the pressure in the containment vessel exceeds the strength limit, radioactive materials will be released. For this reason, not only the cooling system but also multiple devices to suppress the pressure increase are installed.

One way to prevent such accidents is to use natural convection, i.e. cooling that does not rely on mechanical devices. One example is the High Temperature Engineering Test Reactor (HTTR) (30 megawatts thermal (MWth)) in Japan, where even at 30% power with zero coolant flow, the reactor shuts DON automatically without the insertion of control rods, and heat can be removed without mechanical means by radiation and natural convection to the water-cooled cooling panels outside the reactor. Figure 2.2 shows the results of the zero-coolant test.

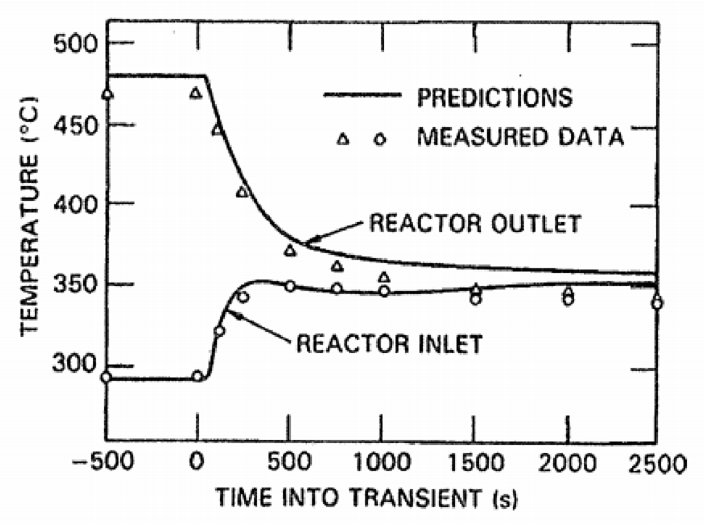
Figure 2.2. Test Results of the High Temperature Engineering Test Reactor



Source: JAEA website (https://httr.jaea.go.jp/S/safe.html), accessed 5 April 2021, translated from Japanese.

The US metal-fuelled fast reactor, the Experimental Breeder Reactor-II (EBR-II, 19 megawatts electrical (MWe)), shows similar results to the above when the coolant flow is set to zero. In addition, it is emphasised that even when the cooling source for the coolant itself is disconnected, the reactor shuts down automatically with the coolant temperature constant at a certain level and the fuel is not damaged. Aurora (4 MWth) by Oklo, which applied for a Combined Construction and Operating License (COL) in 2020, has the same characteristics as the EBR-II.

Figure 2.3. Test Results of the EBR-II



Source: OKLO (2016).

3.Features of Small Modular Reactors

A document published by the International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments*, was issued in 2020 and lists 72 designs of SMRs (IAEA, 2020). These can be grouped into four reactor types with different coolants and core structures as shown in Table 2.1. In addition, some of them are already in operation, some are under review by regulatory agencies, and some are not. Typical examples are as follows:

Existing reactors: KLT-40S (Russia), HTTR (Japan)

Pre-reviewed by the US Nuclear Regulatory Commission (NRC): 4S (Japan), eVinci (US)

Under review by the US NRC: Nuscale (US), Aurora (US)

Phase 2 of the VDR by the CNSC, Canada, or in preparation for it: BWRX-300 (Japan), Xe-100 (US), IMSR (US), SSR-W (US)

Table 2.1. Classification of SMR Designs Mentioned in IAEA (2020)

Reactor Type	Number of Designs Listed	Representative Products
Light water reactor	Land-based: 25 Offshore: 6	NuScale, GE Hitachi BWRX-300, Russia KLT-40S
High-temperature gas-cooled reactor	SMR: 14 MR: 2	X-energy Xe-100, Japan High Temperature Engineering Test Reactor
Fast reactor	SMR: 11 MR: 1	Toshiba 4S, Oklo Aurora
Molten salt reactor	SMR: 10 MR: 1	Terrestrial Integral Molten Salt Reactor, Moltex SSR-W
Others	MR: 2	Westinghouse eVinci

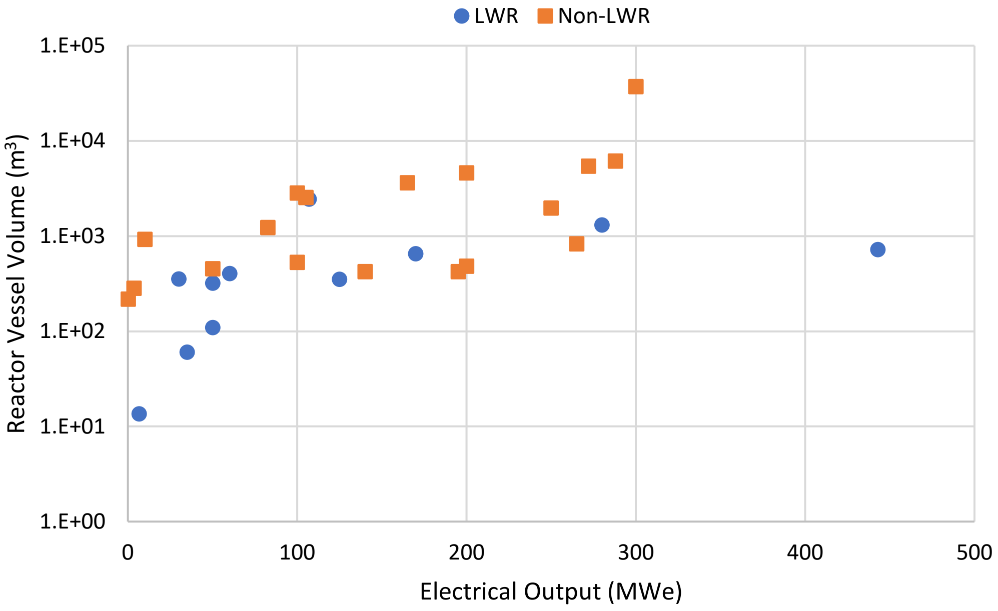
MR = microreactor, SMR = small modular reactor.
Source: IAEA (2020).

Challenges for economies of scale

The IAEA (2020) lists the specifications for a total of 35 SMRs, including eight land-based LWRs, four offshore LWRs, six HTGRs, five liquid metal cooled fast reactors, seven molten salt reactors, and five microreactors. For these 35 SMRs, this research investigated the relationship between the volume of each reactor vessel, which approximates to a cylinder, calculated from the diameter and height and the electric power output (Figure 2.4). It was found that the average reactor vessel volume per unit power output was about 3.05 m^3/MW for the LWRs (12 units), whilst it was about 25.86 m^3/MW for the non-LWR SMRs (23 units). The difference is almost one order of magnitude. The standard volume per unit power output of the third-generation large LWRs is 0.5‐0.7 m^3/MW, so the volume per generation capacity of SMRs, even LWRs, tends to be larger.

Non-LWR SMRs have larger reactor vessels for technical reasons, i.e. the use of graphite as a moderator in the case of HTGRs, and the need for structural materials to prevent chemically active molten salts and liquid metals from coming into contact with air and water in the case of molten salt reactors. A larger reactor vessel has a negative impact on cost, not just because it is harder and more costly to manufacture but also because it is more likely to face transportation constraints. The challenge for the development of non-LWR SMRs will be how to limit the increase in the size of the reactor vessels, which would otherwise offset the advantages of small-size reactors.

Figure 2.4. Electric Power Output and Reactor Vessel Sizes of SMR Designs Mentioned in IAEA (2020)



LWR = light water reactor.
Source: IAEA (2020).

Challenges for modularity of construction

Amongst the equipment of existing LWRs, the typical large-sized items that are manufactured in factories and transported rather than assembled on site are reactor vessels of boiling water reactors (BWRs) and steam generators of pressurised water reactors (PWRs) (the reactor pressure vessels (RPVs) of PWRs are smaller than steam generators). Therefore, the size of NuScale’s integrated containment vessel (CV), which is considered transportable, as well as the size of the BWR reactor vessel and the PWR steam generator, will be a guideline for determining whether modularisation, or factory production, will be possible:

- Example of BWR reactor vessel size: diameter 7.1 m, height 21 m
- Example of PWR steam generator size: diameter 4.1 m, height 21 m

(Example of RPV: diameter 4.4 m, height 12.9 m)

The list of SMR specifications by the IAEA (2020) mentioned previously shows the height and diameter of the reactor vessel of each reactor type. The maximum height is about 30 m, and the diameter is generally within 8 m, except for the Russian BREST-OD-300, which is outstandingly large at about 26 m. Therefore, the reactor vessels of SMRs can be about the same in size as the reactor vessel and steam generator of a large LWR. Therefore, it is unlikely that size will be a technical obstacle to modularisation.

Meanwhile, the largest equipment in an NPP is the containment vessel. Containment vessels are generally much larger than reactor vessels. With a diameter of more than 10 m and a height of more than 30 m, they cannot be transported by ordinary means, such as by trucks on public roads. Although a containment vessel is important equipment for preventing the release of radioactive materials in the event of an accident, it is possible to have a design concept without a containment vessel if the NPP has other equipment that has equivalent functions or safety characteristics. The presence or absence of a containment vessel is another guideline for determining whether modularisation can be achieved.

4.Brief Summary

In this chapter, the research focused on some of the technological issues of SMRs, such as inherent safety, economies of scale, and modularity. As IAEA (2020) shows, there are various designs for SMRs. Many SMR vendors are making efforts to improve the safety, economic efficiency, and modularity of their products. The approaches for improvement are not the same amongst vendors, and the optimal solution for a potential customer could be different from another because of differences in demand and other conditions. Therefore, it is important for customers to make clear their own requirements and to conduct feasibility studies as early as possible. This gives vendors the opportunity to make attractive propositions for their customers.