Small Modular Reactors

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Background

Small modular reactors (SMRs), as defined by the International Atomic Energy Agency (IAEA), are reactors with less than 300-MW-electric (MWe) output. SMRs are being explored as a technology that can decarbonize power and steam, although cogeneration (electrical + steam) is an evolving subject with challenges. Most SMRs are derived from large reactors, but with some important differences as mentioned below.

– SMRs are intended for manufacture in fabrication shops and then shipped to the site. This standardizes the manufacture of SMRs in a controlled environment and mitigates cost overruns and schedule delays, which typically plague large reactors. For example, the Vogtle AP-1000 reactors 3 and 4 (1.1 gigawatt-electric [GWe] each) were delayed by many years with a final cost of over $30 billion, up from an original budget of $8 billion.

– Multiple modules can be installed to increase the plant output.

– The low thermal power of a module enables the use of passive safety features, such as gravity or natural circulation.

– SMRs can be coupled with steam as a heating medium, or as a cogeneration plant.

– SMRs are applicable when the grid capacity is low and cannot absorb a large gigawatt (GW)-scale reactor.

The major types of SMR technologies acknowledged by the IAEA are:

– Water cooled (including light water, heavy water, and boiling water — 32 designs)

– High-temperature gas cooled (17 designs)

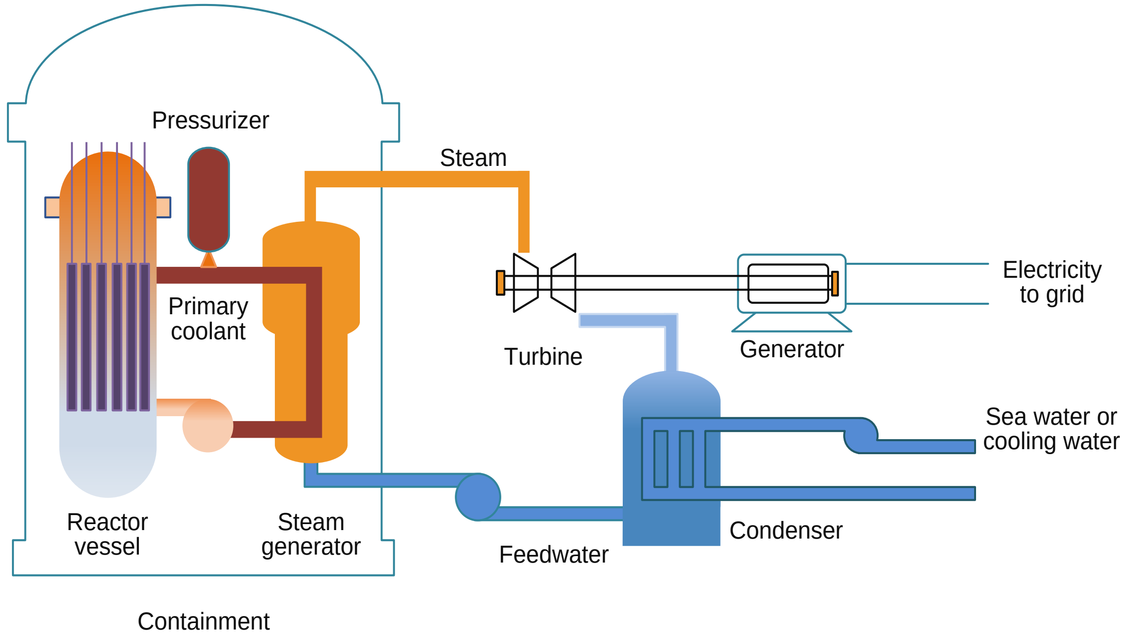
– Fast neutron spectrum (8 designs)

– Molten salt (13 designs)

– Micro modular reactors (12 designs)

Most large power reactors operating worldwide are water cooled. Of the 442 operating reactors, more than 95% are water cooled. This gives the water-cooled technology a head start, considering that regulations, the operating experience, and the supply chain are already developed. Light-water reactors (LWRs) are the most common type of reactors worldwide. They can be categorized into two types: pressurized water reactors (PWRs), which produce steam for the turbine in separate steam generators, and boiling water reactors (BWRs), which use the steam produced inside the reactor core directly in the steam turbine. All LWRs require fuel that is enriched in the fissile isotope, U-235.

Figure 1 Nuclear power plant operation



As of June 2024.
Source: S&P Global Commodity Insights.

The safety systems developed in the 50 years of operation are also advantageous for the water-cooled reactors. The three major incidents (Three Mile Island, Chernobyl, and Fukushima) have provided lessons, which have found their way into safety regulations worldwide.

The major differences in the technologies are highlighted in Table 1.

Table 1 Reactor technologies

	PWR	BWR	HTGR	SFR
Power density, kWth/l	100	51	6	280
Fuel	UO_2	UO_2	UO_2	U + Pu
Cladding	Zr	Zr	TRISO	SS
Fuel form	Rods	Rods	Pebbles/prismatic	Rods
Primary coolant, P (bar)/T (°C)	150/300	69/285	70/750	1/500
Secondary coolant, P (bar)/T (°C)	60/276	NA	150/750	150/500

Data compiled June 2024.
BWR = Boiling water reactor; °C = Degree Celsius; HTGR = High-temperature gas-cooled reactor; kWth/l = Kilowatt-thermal per liter; NA = Not available; P = Pressure; PWR = Pressurized water reactor; SFR = Sodium-cooled fast reactor; SS = Stainless steel; T = Temperature; TRISO = Tristructural isotropic.
Source: S&P Global Commodity Insights.

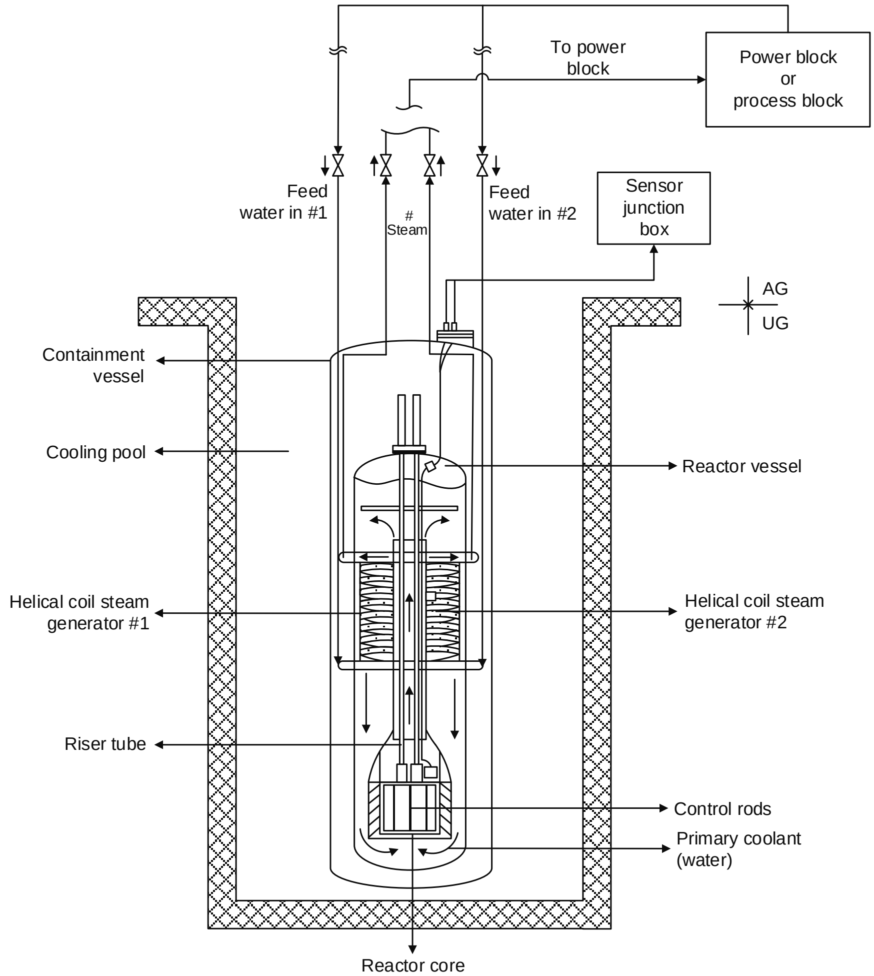
All nuclear reactors generate heat, which is cooled by a primary coolant, and the heat is transferred to a steam generator. The steam is used in a Rankine cycle to generate electricity in a steam turbine generator or can be potentially exported as process steam. This method of generating electricity implies that the thermal efficiency of the nuclear plant is about 33% to 40%. Hence, about two-thirds of the generated heat needs to be dumped into a heat sink, which is usually the cooling tower.

'Modular construction' refers to a technique in which modules are constructed off-site in a controlled environment and shipped to their destination, where they are assembled in a building. The major parts of the reactor vessel can be shop fabricated, which mitigates quality, schedule, and cost overrun, compared with 'stick-built' construction. Modular fabrication is well-adapted in the oil and gas sector, both midstream and downstream. This has been used widely where the weather conditions only permit a few months of site work. However, it has associated risks. For instance, it requires more intense detailed engineering to ensure that the module sits exactly as designed when transported to the site. The freedom of site adjustment, for example, small bore piping or flexible cable routing cannot be expressed.

A typical SMR may have the following features:

- Modular construction, as much as possible.
- A single module limited in power. A number of modules can be combined.
- Passive safe systems may be deployed.
- The reactor vessel can be integral with a steam generator, pressurizer, coolant pumps, and control rods. This is named as an 'integral' design.

Figure 2 Schematics of a typical integral SMR



As of June 2024.
AG = Aboveground; SMR = Small modular reactor; UG = Underground.
Source: [US 20230287583] Tsang, F et al., "Small Modular Nuclear Reactor Integrated Energy Systems for Energy Production and Green Industrial Applications," NuScale Power LLC, Sept. 14, 2023.

Although several SMR designs have been under consideration, only two reactors were in operation at the time of writing. KLT-40S was deployed in Russia as a floating nuclear power plant. Russia's *Akademik Lomonosov* was connected to the grid in 2019 and started commercial operation in May 2020. The floating nuclear power plant has two KLT-40S reactor modules, capable of generating 70 MWe of deployable power, with each reactor module rated at 35 MWe. The other one is in mainland China — a high-temperature gas-cooled modular pebble bed (HTGR-PM) reactor demonstrator, which is helium cooled at 70 bar and 750°C outlet temperature. The steam is generated at 133 bar and 567°C (superheated). The plant is 2 × 250 megawatt-thermal (MWth) (210 Mwe). The safety feature includes ensuring that the decay heat is passively removed from the core under any designed accident conditions by natural mechanisms, such as heat conduction or heat radiation, and keeping the maximum fuel temperature below 1,620°C to contain nearly all the fission products inside the silica carbide layer of the tristructural isotropic (TRISO)-coated fuel particles. This eliminates the possibility of core melt and large releases of radioactivity into the environment. Another feature of the HTGR-PM design is the long period of accident progression because of the large heat capacity of the fuel elements and graphite internal structures. The fuel elements require several days to reach the maximum temperature when the coolant is completely lost.

The onstream factors of the two SMRs, described above, have been reported to be very low.

The applicability of SMRs for decarbonizing refineries and chemical plants can hinge upon the following major features. Using electricity to decarbonize the power requirements is a facile application. The other major application in a chemical plant is the process of heat, and depending on the temperature, this can be difficult to decarbonize. If the SMR runs as a cogeneration plant, it is possible to use the steam as a heat source in the chemical plant. However, this arrangement necessitates the nuclear plant to be adjacent to the chemical plant to avoid long runs of steam lines. Another major consideration is the level of heat needed in the chemical plant. Depending on the SMR technology, the temperature supplied can be 300°C for a typical PWR or as high as 750°C for an HTGR. Even lower temperatures can be used efficiently in many applications. The typical maximum temperature limits used in many of the process units are listed in Table 2.

Table 2 Maximum temperature used in various processes

Refinery process	Typical maximum temperature, °C
CDU	350
VDU	350
Hydrotreating	345
Hydrocracking	450
Catalyst reforming	520
Catalyst cracking	530
Steam methane reforming	800
Coking	500

Data compiled June 2024.

CDU = Crude distillation unit; °C = Degree Celsius; VDU = Vacuum distillation unit.

Source: S&P Global Commodity Insights.

Therefore, for a refinery, meeting the maximum temperature from a PWR using the steam generated will be difficult. However, there are some uses of lower-temperature steam within the refinery. The Process Economics Program (PEP) team has analyzed many crude oil to chemicals (COTCs), and a typical case, which uses steam, is listed in Table 3 below.

Table 3 Process design

Location	USGC	
Reference	PEP Report 303D Case-0	PEP Report 303D Case-1
Integration level	**Fuels refinery**	**COTC with 27% chemicals**
Steam, 42 barg/250°C (saturated), t/h	651.2	530.2
Electricity, MW	261.36	422.29
Total number of modules needed	6	7
OOM capital cost, $ millions	9,300	10,850
Annual operating cost (including fuel), $ millions	100	100
CO_2 abated annually, MMt	1.76	2.08
Cost of CO_2 abatement, $/t	145	135
% CO_2 abated	31	27
Basis		
1. Capital cost amortized linearly over 60 years.		
2. Capex @ $20,000/kWe.		
3. CO_2 abated (a) Electricity @ 0.39 t/kWh and (b) Steam @ 0.187 t/t.		
4. CO_2 abated is location dependent.		
5. Each PWR SMR module is assumed to be 77 MWe/250 MWth.		
6. Only 600# steam and electricity are abated. Process and fuel for heaters not abated.		

Data compiled June 2024.

barg = Bar gauge pressure; CAPEX = Capital expenditure; COTC = Crude oil to chemicals; °C = Degree Celsius; $/kWe = Dollars per kilowatt-electric; $/t = Dollars per metric ton; MMt = Million metric tons; MW = Megawatts; MWe/MWth = Megawatt-electric/Megawatt-thermal; MWth = Megawatt-thermal; OOM = Order of magnitude; PWR = Pressurized water reactor; t/kWh = Metric tons per kilowatt-hour; t/h = Metric tons per hour; t/t = Metric ton per metric ton; USGC = US Gulf Coast.

Sources: S&P Global Commodity Insights; PEP Report 303D *Crude Oil Conversion to Chemicals* (December 2021).

There are some interesting conclusions from this analysis. As the integration with chemicals rises, the complex generates fuel gas, which can be used in-house. At a COTC integration of about more than 30%, the complex is in excess of the fuel gas. The majority of the carbon emissions are from process heaters operating at higher temperatures or from process emissions. These cannot be substantially mitigated by a PWR SMR, although an HTGR may cover some needs.

The ability to decarbonize electricity and steam is possible. Although some SMR technology suppliers claim that steam supply at 500°C is possible, running a 109-bar steam line all over the plant has its own risks. Steam hammering at this pressure can be quite devastating. The high temperature will also need expensive material, and the length of steam piping in a typical plant can make this cost prohibitive.

An SMR plant can be designed for 40 or 60 years of life duration, but a typical chemical complex is designed for 20 years of life, although some operate longer, up to 30 to 40 years. Therefore, one needs to take into consideration that a nuclear plant will outlast the chemical complex it serves. Alternate arrangements of evacuating only power to the grid must be considered.

The cost of abating one metric ton of carbon is about $140, which is not far away from a typical carbon capture and sequestration (CCS) cost. If the SMR replaces electricity generated from a coal plant, then the cost of abatement can fall below 100 dollars per metric ton ($/t) of CO_2.

Both CCS and SMR have their challenges when it comes to application to carbon abatement.

CCS:

- Needs a large footprint.
- The sequestration site may not be conveniently nearby, leading to high CO_2 transportation costs.
- Needs a considerable amount of steam and electricity, which, if not sourced from a renewable source, can reduce the net decarbonization.
- The amount and cost of CO_2 captured depends on the CO_2 partial pressure, and in most cases, it will not be 100% of that emitted.

SMR:

- Needs regulatory approval, which can be onerous.
- The negative safety image of a nuclear plant can bring resistance from local voices.
- A significant footprint is also needed to adhere to the emergency planning zone.
- The storage of fresh and spent fuel could bring large radioactive inventories and be inconvenient.
- The integration of steam as process heat with the chemical complex steam system could be difficult.
- The shutdown needs for an SMR for refueling will require careful planning to coincide with that of the chemical complex.
- An SMR will not be able to supply the high-level heat needed in most applications.

Conclusions

SMR is being touted as an alternative low-carbon technology to supply electricity and heat for decarbonization, and much of this is justified. This is a unique solution for baseload operations, vis-à-vis renewable power, which needs to be offset for its intermittency. The modular approach implies that much of the plant can be manufactured in a controlled environment, limiting field cost and schedule overruns, which have plagued much of the nuclear power industry. The low cost of operation (a fuel cost of about 6 dollars per megawatt-hour [$/MWh]) is attractive. Smaller modular plants have easier grid integration, and the inherent safety features of SMRs mitigate some safety concerns.

However, the challenges, which are anticipated, also need to be acknowledged:

- The relatively higher cost of carbon abatement, much of which is capital cost related, can be a stumbling factor.
- The regulatory process is not much different than a typical nuclear plant and can take time.
- The thermal heat provided by the dominant technology PWR is limited to about 300°C, which precludes some high-temperature applications.
- The life of a nuclear plant easily exceeds that of a process chemical plant and needs to be planned accordingly.
- The safety concerns prevalent among the public need to be addressed comprehensively.

Overall, SMR is an interesting solution for decarbonization but needs to be carefully evaluated and planned for this approach to mature.

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