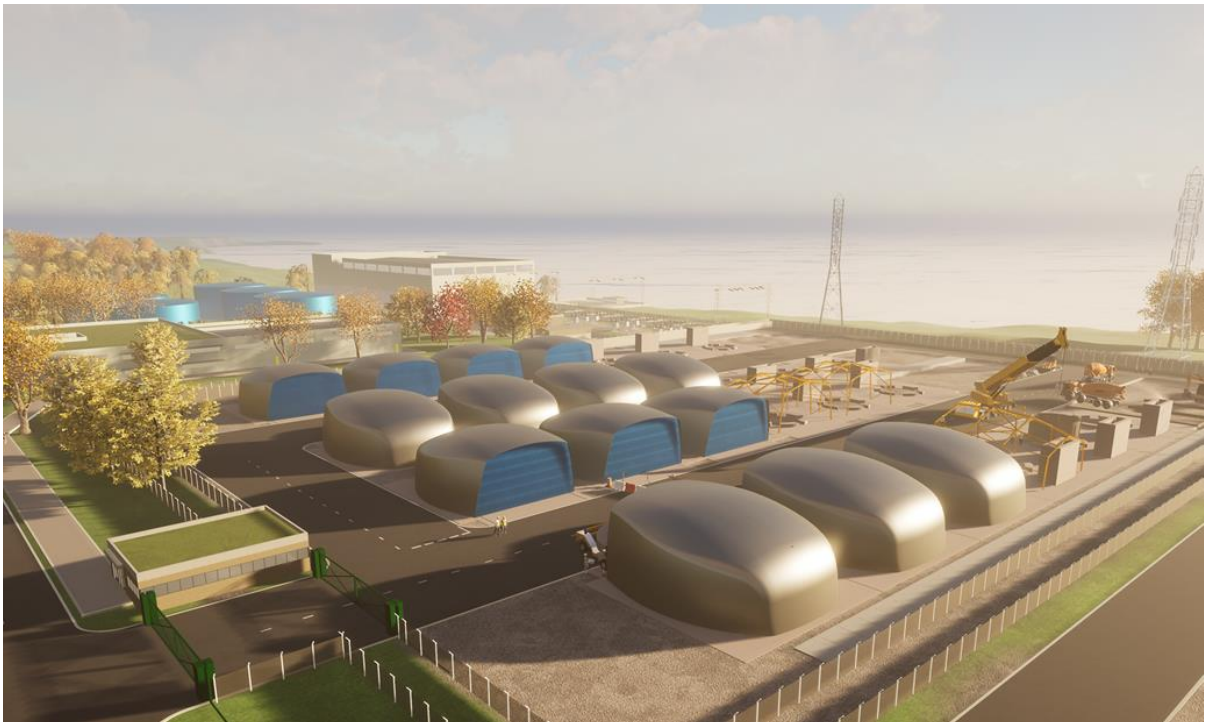
Stable Salt Reactor – Uranium (SSR-U)

Technical description



A flexible, scalable and simple advanced modular reactor delivering low-cost, clean energy for electricity and high-temperature heat for industry

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OUR PHILOSOPHY

The SSR-U is a 40 MW (thermal energy) molten salt reactor with a high temperature output of approximately 700°C. Its simplicity offers a low-cost alternative to fossil fuels. The design is based on Moltex's patented concept of containing the fissile molten salt in vented tubes whilst using a different molten salt as the primary coolant. The reactor uses 6% low-enriched uranium, and will provide power for 16 to 20 years before it requires refueling.

Simple

The SSR-U is designed with simplicity in mind. It is small and modular, allowing most components to be factory-produced and readily transportable, reducing on-site work, increasing speed of construction, and minimising overall costs. Wherever possible, the SSR-U uses materials and technology that are proven in the nuclear industry, making safety and design substantiation easier and quicker by eliminating the need for long research programmes. The key development intent is to bring the SSR-U technology to market quickly, and to make it easily and rapidly deployable worldwide.

Low-cost

Conventional nuclear power plants have become expensive to build and operate due to the systems and procedures needed to keep them safe – in particular, the redundant active safety systems, and also through the requirement for high integrity claims on components, such as the containment system required with pressurised reactors. By contrast, the SSR-U is a low-pressure system which substantially reduces the cost of containment, and its operational safety is ensured through inherent and passive safety systems which drastically reduce capital and operating costs. At a fraction of the size of a conventional nuclear power plant (NPP), the SSR-U is designed to provide a cost competitive alternative to burning fossil fuels. Furthermore, the high thermal output of the SSR-U offers the potential for higher efficiency energy conversion.

Complements renewables

The SSR-U design complements intermittent renewable energy by being available on demand. Most people acknowledge that the new baseload should be provided by renewable energy sources, and the SSR-U provides dispatchable generation to address shortages in renewable energy supply. For economic reasons, it is impractical to provide this flexibility through conventional NPPs, and the resulting gaps in supply are often filled by using fossil fuel generation. The high output temperature of the SSR-U, however, allows cost-effective storage of thermal energy for extended periods using molten salt, as already used in the solar energy industry, which can be released when demand outstrips supply.

Inherently safe

Our safety philosophy is based on the elimination or reduction of many of the fundamental hazards through inherent characteristics of the technology and design, and the use of passive safety provisions to manage residual risks. In normal operations, the SSR-U does not require any active provisions to maintain nuclear safety. This approach makes a significant difference to the basis of the safety argument when compared with other reactor technologies, where a much higher degree of reliance is normally placed on the provision, maintenance and operation of active safety systems.

The SSR-U concept designs out many of the hazards and eliminates the risks, as opposed to providing engineered solutions to control the risk presented by the hazard. The SSR-U is therefore, safe by design.

Multipurpose heat

The SSR-U produces 700°C heat, which can be used to decarbonise energy usage in several ways:

- Production of on-grid and off-grid electricity.
- Direct use of heat in industrial processes or for district heat, as up to 2/3 of all heat use in European industry is below 700°C.
- Input to high-temperature electrolysis, a moderately efficient way of producing clean hydrogen. The temperature is also high enough to support the more efficient thermochemical production of hydrogen. The hydrogen itself can then be used in several ways:
  - as a direct substitute for gas in industry;
  - for fuel cells for heavy transport; and
  - as a feedstock for synthetic fuels, including ammonia as a bunker-oil substitute for shipping.
- As a power source for desalination plants.

Additionally, the SSR-U has the potential to be marinised for ship propulsion.

THE SITE

A typical site will contain several individual reactors, each with the thermal power of 40 MW. As an example, an array of 32 units may be deployed in combination with the thermal storage facility (Grid Reserve) to deliver 512 MWe of reactors supporting a 1.5 GWe x 8 hours/day electricity peaking plant.

The heat output from the reactors will be collected in a system of molten storage salt pipes and transferred to large tanks (Grid Reserve). Hot storage salt can then be taken from the tanks and used to generate superheated steam to drive conventional turbines. The storage tanks and heat processing facilities can be located outside the nuclear site boundaries and work independently. This configuration is possible because, unlike conventional reactor designs, the safety of the SSR-U is completely independent of the heat sink provided by the heat storage and power generation plant. The decay heat removal system is completely passive and utilises natural convection with no need for mechanical components. Additionally, because no safety-related operations and maintenance are required, the number of access points to a typical SSR-U site can be minimised, reducing vulnerability.

Figure 1 The site

THE REACTOR

The SSR-U differs in many respects from more conventional reactor designs in its concept, construction and operation. Both the fuel and primary coolant consist of molten salt, and corrosion issues are controlled by managing the chemistry of the salts to prevent oxidation and leaching. The fuel salt is contained in steel tubes, each of which is placed in a separate channel in a graphite matrix moderator, forming the reactor core. The core and primary heat exchangers sit within the reactor tank vessel, which is filled with primary coolant. The reactor tank vessel is placed in a concrete pit underground and covered from the top with a concrete shield.

The initial fuel load remains in the reactor for approximately 16 years, with a further two fuelling cycles resulting in the total reactor lifetime of about 50 years. During normal operation, the heat generated by the fuel is removed from the reactor via primary and secondary coolant loops by natural convection-driven circulation. If this functionality is lost, the reactor heats up and reactivity and power decrease due to inherent features of the core. Residual decay heat is continually removed by natural circulation of air around the reactor tank. These passive control measures mean that, unlike conventional reactor designs, no active systems or pumps are required for heat removal or shutdown.

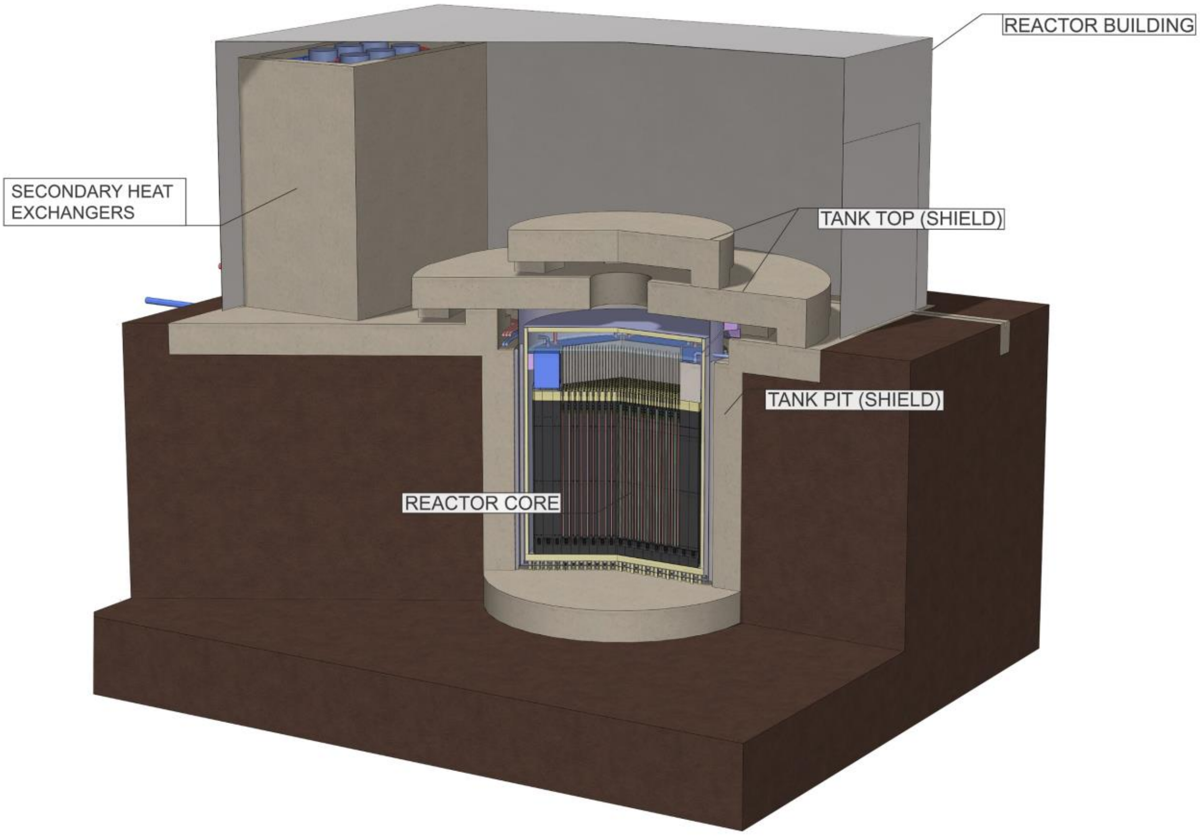

Figure 2 The reactor

THE FUEL

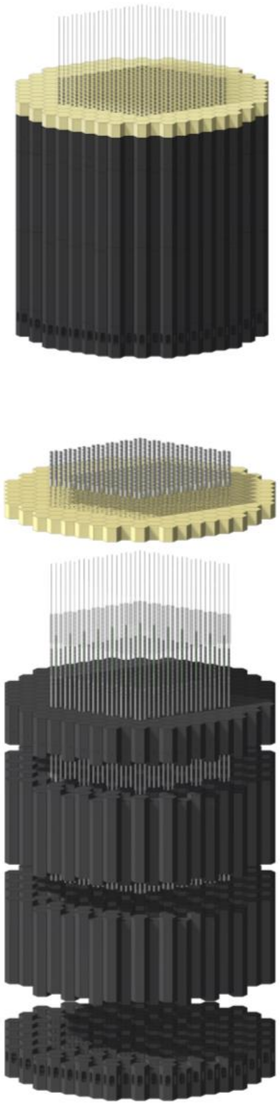

Figure 3 The core

The reactor core comprises an array of fuel tubes in a graphite matrix, which fills most of the tank. Each tube sits in a separate channel, within which a molten salt primary coolant circulates.

Fuel salt

The SSR-U is a fluoride salt reactor with separate fuel and coolant salts. The fuel is in the form of molten low-enriched uranium fluoride salt (6% enrichment), which is contained at low pressures by the patented vented fuel tube. The molten fuel salt circulates within the fuel tube by natural convection, which facilitates heat transfer through the tube wall to the coolant surrounding the tube. The fuel salt chemistry is redox-stabilised by a combination of uranium oxidation states acting as a redox buffer in a eutectic mixture with sodium fluoride diluent. The redox buffer enables maintenance of redox potential and neutralisation of potentially corrosive fission products generated throughout the reactor's lifespan.

The fuel salt is not in contact with the graphite and does not require pumping outside the reactor core into the heat exchangers. It is completely encapsulated by the body of the fuel tube, whose cooling and geometry eliminate the possibility of bubble formation within. This is very important, as bubbles can lead to undesirable rapid changes in reactivity. Any liquid system carries this risk, but the SSR-U is designed to eliminate it.

The miscibility of fuel and coolant salt has a fundamental impact on the concept of core damage. In a conventional reactor, core damage can cause the reactor to move to a substantially more hazardous state. In the SSR-U, similar scenarios are tolerable because even severe core damage moves the reactor to a safer state. For instance, breach of the tube wall caused by the tube melting, would lead to a reduction in core reactivity, as the fuel salt would be diluted in the large coolant volume. As a result, core damage does not cause an increase in probability of radiation exposure to workers or the public.

Fuel tube material

The fuel tube material is the same as that used in the UK's fleet of Advanced Gas Cooled Reactors (AGRs) and experiences comparable neutron irradiation, carburising environment and temperature exposure. This enables us to use proven nuclear materials, significantly de-risking the design, reducing costs, and allowing earlier deployment through accelerated licensing.

Fission gas venting

Many of the fission gases are immediately captured as non-volatile salts and remain contained in the fuel salt within the fuel tube. The volatile fission gases that are not immediately captured in the fuel salt pass through a series of bubble traps, subsequently emerging from the top of the fuel tube into the gas space at the top of the tank vessel. The major hazardous fission gas produced is xenon-137, which decays to the very hazardous caesium-137. The holdup of the gases in the series of bubbler ensures that essentially all of this hazardous material is trapped in the series and does not leave the fuel tube.

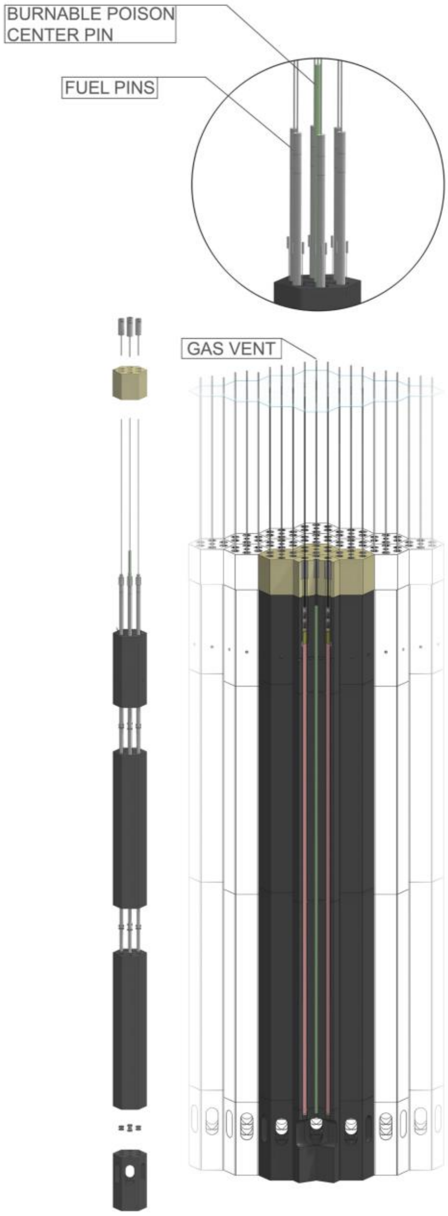

Figure 4 The fuel

The major radioactive gas that does emerge from the bubble traps is krypton-85. This accumulates in the gas space of the reactor over its lifespan. With a half-life of 10 years, much will still be present at decommissioning. Since it is a noble gas, which does not bioaccumulate, it is currently normal industry practice for krypton-85 to be discharged into the atmosphere – where it is diluted to trivial concentrations. Our intention, however, is that the gas will instead be trapped and stored until it has almost completely decayed, in about 50 years.

Fuelling cycle

Most commercial reactors require regular refuelling. These periods are times of increased hazard, as even with a delay of weeks between shutting down the reactor and fuel pin removal, the spent fuel is extremely radioactive. The SSR-U will operate for a period of 16 to 25 years on one fuel load, with a further 2 fuelling cycles totalling the reactor lifetime of 50 to 75 years.

THE PASSIVE CONTROL SYSTEMS

In the SSR-U, the bulk of the excess reactivity present immediately after fuelling is neutralised through a fixed, burnable absorber in inserts within the graphite matrix. Any residual excess reactivity is neutralised by pellets of neutron absorber, which are soluble in the coolant salt and added to the primary coolant by using a periodic injection system. This neutron absorber burns out slowly and is replenished at intervals of several weeks or months.

Fine reactivity control, for reactivity changes during power demand shifts, is provided by a patented novel mechanism akin to a conventional mercury thermometer, but instead filled with liquid neutron absorber. The “bulb” of the thermometer sits in the hot coolant salt exiting the fuel tube channel; the stem extends down through the graphite matrix towards the centre of the core. An increase in heat demand from the reactor causes a drop in primary coolant temperature and, as a result, the bulb of the thermometer cools, causing the neutron absorber to be withdrawn from the stem of the thermometer, increasing reactivity and power output. Conversely, when heat demand is reduced, the temperature of the primary coolant rises, heating the thermometer bulb, driving the neutron absorber down the stem, thus reducing reactivity and power.

THE HEAT REMOVAL SYSTEMS

The fuel tubes facilitate the heat transfer between the fuel and the surrounding coolant, which operates at up to 800°C at full power conditions, and rising further at minimum power. The low-pressure coolant utilises natural convection to rise through the channels to the reactor top as it is heated. The primary heat exchangers, which are mounted above the core inside the reactor vessel, facilitate the heat transfer between the primary and secondary molten salt coolants. The primary coolant, which becomes denser as it cools, consequently returns to the base of the reactor and circulates back up through the fuel tube annuli to repeat the cycle. No moving parts are involved in the circulation of the coolant salt.

The energy transferred in the primary heat exchanger to the secondary coolant is carried by the coolant to the secondary heat exchanger located outside the reactor tank and shield. Similar to the primary coolant, the secondary coolant is a molten salt which circulates between the heat exchangers by natural convection, with no moving parts required. The purpose of the secondary loop is to avoid the radioactive primary coolant leaving the reactor tank while also preventing exposure of the storage salt to neutron irradiation.

The high-temperature output of the SSR-U enables coupling with molten salt energy storage which operates between 500°C and 700°C (GridReserve). The storage salt is pumped from the tanks outside the nuclear site through the secondary heat exchanger, ultimately harnessing the energy from the reactor. One of the many benefits of this system is that the flow of the storage molten salt requires no control inputs from the reactor operators. Because the reactor passively regulates its output, it can autonomously modulate in response to heat demand.

The stored hot salt can be used to produce steam, and hence electricity, using a conventional power plant outside the nuclear site, with the benefit of the power plant being subject only to normal industrial safety standards. The thermal storage system, combined with the SSR-U, is highly attractive for supplementing other generation when energy demand cannot be met with intermittent energy sources such as renewables.

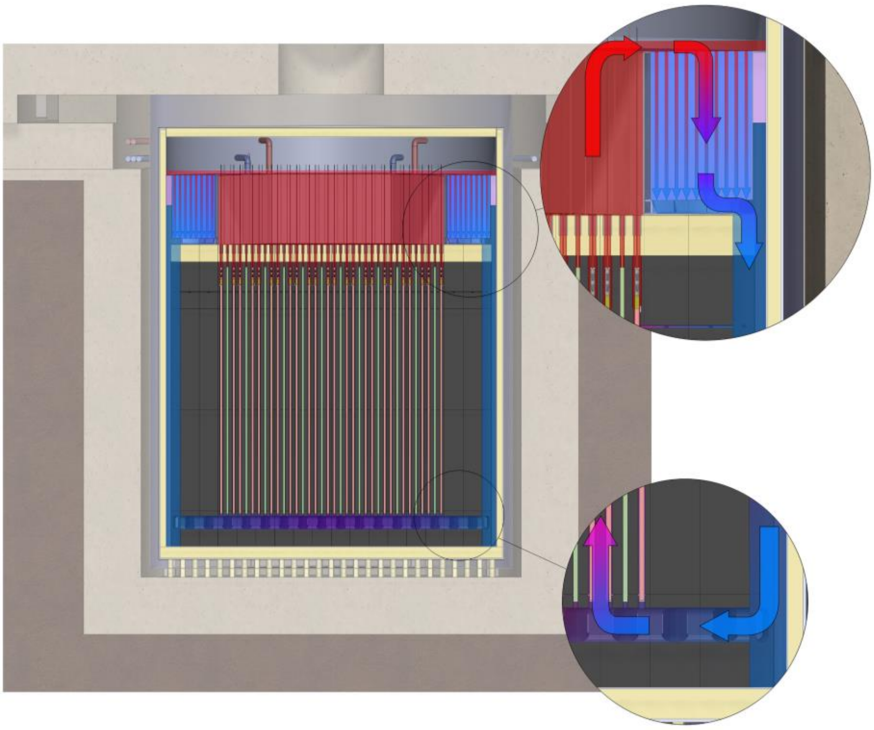

Figure 5 The primary coolant

Coolant salts

The coolants used in existing nuclear reactors carry serious safety hazards. When water is used, it can undergo a potentially hazardous phase change if pressure is lost, for instance through a breach of containment; historically, extreme pressures have contributed to some major reactor accidents. In other designs, using sodium as the coolant has been shown to cause sodium fires. Any pressurised gas cooled reactor must include safety systems to manage the consequence of a breach of the pressure boundary and consequent loss of core cooling. Thus, the main learning outcome from existing reactors has been to use a chemically and physically stable and unpressurised coolant, as provided by a salt.

The SSR-U uses fluoride eutectic salts as both the primary and secondary coolants. Tritium production is avoided by eliminating lithium and beryllium from the chemistry. Both coolant salts are compatible with graphite and mix safely with the fuel salt.

Corrosion of metals by molten salts is a long-standing problem in the industry. This is prevented in the coolant salt by adding a proprietary redox control agent that scavenges any oxygen that leaks into the reactor before it can attack the metal.

Residual heat

The SSR-U’s passive residual heat removal system (RHRS) operates continuously to remove 0.5% of full reactor power. This is a worthwhile compromise for achieving a completely passive system, which utilises natural convection of air to cool the bottom, sides, and top of the reactor tank outer layer. The local temperatures are limited to 300 to 400°C. The space between the outer tank and the wall of the reactor pit is divided into inner and outer air ducts, producing an inlet and outlet for the cooling air. The air is subsequently vented into the reactor building.

If heat withdrawal from the reactor stops entirely while it is at full power, the initial high decay heat causes the reactor to heat to approximately 50°C above its normal operating temperature. After that, the continuing loss of 0.5% of full power through the RHRS cools the reactor until the temperature is sufficiently low to return to criticality as the reactivity thermometers respond to the reduction in operating temperature. The reactor then settles at a level of 0.5% of full power until there is demand for more heat from the power plant operators.

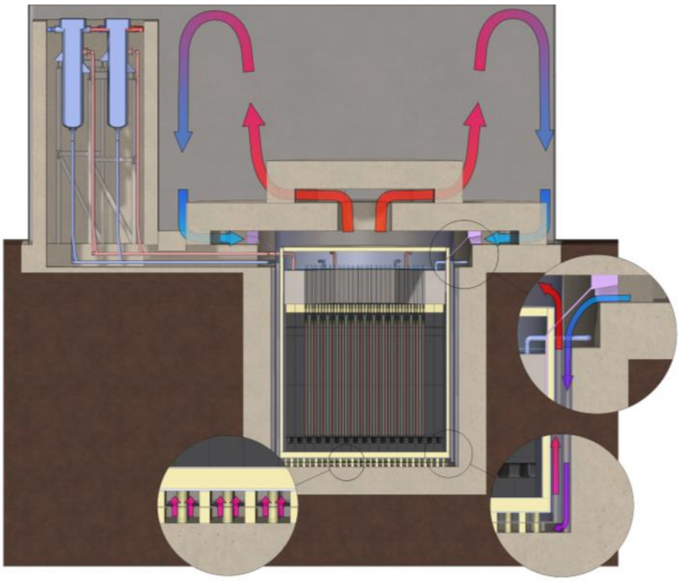

Figure 6 The residual heat removal system