The FLEX reactor

A technical description

The FLEX reactor can meet the global demand for clean, low-cost flexible energy

December 2023

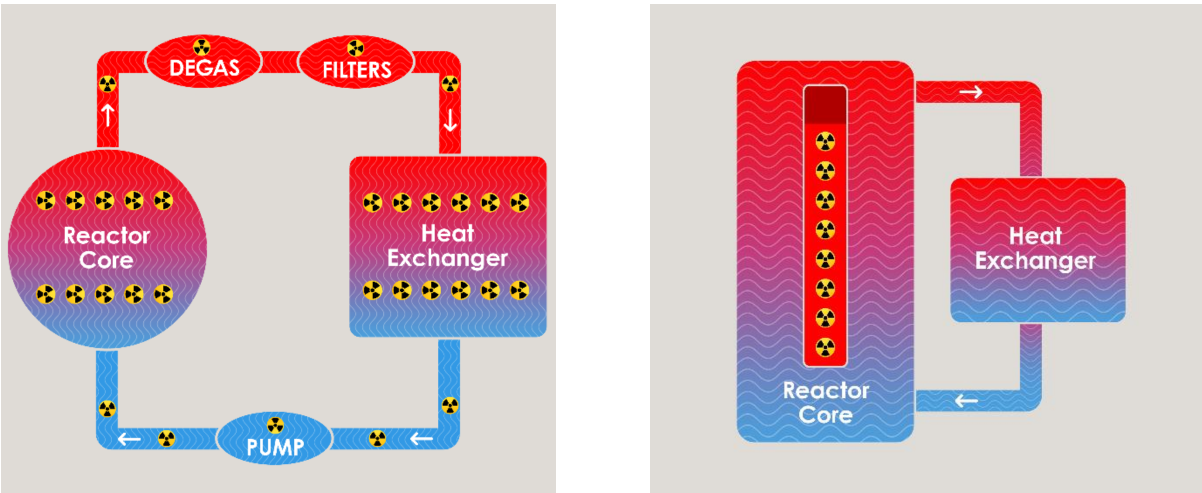
OUR CORE TECHNOLOGY

The FLEX reactor is the thermal neutron (moderated) version of Moltex Energy Limited's globally patented stable salt reactor technology. This technology is shared with MoltexFLEX's sister company, Moltex Energy Canada Inc., which is developing the fast neutron version of the stable salt reactor.

Stable salt reactors differ fundamentally from all other molten salt reactors under development around the world in that they restrict the highly radioactive fuel salt to fuel tubes, similar to those in conventional reactors. A separate, non-radioactive molten salt transfers heat from the reactor core to heat exchangers.

In other molten salt reactors, where the fuel is also the coolant, the complex fuel salt circulation system – with pumps, filters, conditioning units, and heat exchangers – is exposed to the intensely radioactive fuel salt. This puts severe demands on these components and makes monitoring and maintenance very challenging. Figure 1 illustrates this key difference between the molten salt reactor types.

Conventional MSRs | **Stable salt reactor technology**



Conventional MSRs:

- **Molten salt fuel pumped between reaction chamber and heat exchanger**
- **Intensely radioactive and still fissioning fuel salt exposed to pumps, valves, degassing system, filters, and the heat exchanger**

Stable salt reactor technology:

- **Fuel salt in tubes with heat transfer to tube wall by natural convection**
- **Separate non-radioactive coolant salt transfers heat to heat exchanger**

Figure 1: Difference between conventional molten salt reactors and stable salt reactors

OUR PHILOSOPHY

Simple

The FLEX reactor is designed with simplicity in mind, with approximately 10% of the systems of a conventional nuclear reactor (e.g., a PWR). It is small and modular, allowing most components to be factory-produced, facilitating transportability, reducing on-site work, and expediting construction, all of which minimise overall costs. Wherever possible, the FLEX reactor uses established materials and technology already proven within the nuclear industry, making safety and design substantiation easier and quicker by eliminating the need for extensive research programmes. MoltexFLEX's mission is to rapidly bring the FLEX reactor to market and deploy fleets worldwide.

Low-cost

Conventional nuclear power plants have become expensive to build and operate, mainly due to the safety management systems and procedures needed to control risk. By contrast, the FLEX reactor is inherently safe, employing a low-pressure system, which substantially reduces containment costs. Its operational safety is ensured through inherent and passive safety systems, which drastically reduce capital and operating costs. The FLEX reactor is designed to provide energy at a cost lower than unmitigated coal or natural gas, without assuming any carbon tax. Furthermore, the high-temperature output of the FLEX reactor offers the potential for higher-efficiency conversion of heat to electricity than a conventional nuclear power plant.

Complements renewables

The FLEX reactor design supports intermittent renewable energy through its rapid responsiveness to changes in demand. A FLEX reactor power station can flexibly generate electricity on a comparable basis with conventional fossil fuel plants. For technical and economic reasons, conventional nuclear power stations are less capable of providing this flexibility. Therefore, it can fill supply gaps caused by dips in solar or wind generation that until now were mostly filled by gas or other fossil fuel-powered generators.

The high output temperature of the FLEX reactor allows for cost-effective storage of thermal energy in the GridReserve© system for hours or days, using molten salt (as already used in the solar energy industry). This energy can be released when demand outstrips supply, further enhancing the flexibility of the FLEX power plant.

During longer periods of high renewable generation, the FLEX reactor can simply move passively into idle mode, producing just enough heat to keep the reactor at operating temperature. The low capital cost of the reactor makes this economically practical.

Inherently safe

Our safety philosophy is centred on the reduction or elimination of many of the primary hazards through the fundamental characteristics of the technology, along with passive safety provisions to manage residual risks. In normal operations, the FLEX reactor does not require any active provisions to maintain nuclear safety. This approach offers a considerable safety advantage over other reactor technologies, where a much higher degree of reliance is normally placed on the provision, maintenance, and operation of active safety systems.

The FLEX reactor concept designs out many of the hazards, thus eliminating the risks, as opposed to providing engineered solutions to control or mitigate them. Therefore, the FLEX reactor is fundamentally safe by design.

Multipurpose heat

The FLEX reactor generates heat at 700°C, which can be directly used for on-grid and off-grid electricity generation or additional downstream applications, including:

- direct input heat for industrial processes or district heating (as much as two thirds of all heat use in European industry is below 700°C);

- input to high-temperature electrolysis, a reasonably efficient way of producing clean hydrogen; the temperature is also high enough to support more efficient thermochemical production of hydrogen, and the hydrogen itself can then be used:
  - as a direct substitute for gas in industry,
  - for fuel cells for heavy transport, or
  - as a feedstock for synthetic fuels, including ammonia as a bunker-oil substitute in shipping; and
- as a power source for desalination plants.

Additionally, the FLEX reactor can be reconfigured for marine applications, principally for ship propulsion.

POWER GENERATION SITE

A typical site may contain any configuration of modular FLEX reactors, each with a thermal power of 60 MW, equivalent to 24 MWe. For example, an array of 32 units (768 MWe) may be deployed in combination with the GridReserve© thermal storage facility to deliver 2,304 MWe during the most demanding eight hours of each day.

The heat output from the FLEX reactors is transported in molten salt via a system of pipes to the GridReserve© storage tanks, located outside the nuclear island. This stored molten salt can be called upon to generate superheated steam to drive conventional turbines. This configuration is possible because, in contrast to conventional reactor designs, the safety of the FLEX reactor 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 uses natural convection, with no need for mechanical components. Additionally, because no time-sensitive safety-related operations and maintenance are required, the number of access points to a typical FLEX reactor site is lower than in conventional nuclear power plants, reducing security risks.

Figure 2: Artist's impression of a power station with a 32-module reactor array, GridReserve© and turbine hall

THE REACTOR

The FLEX reactor differs in many respects from conventional reactor designs in its concept, construction, and operation. Both the fuel and coolant consist of molten salt, with corrosion controlled through the careful choice of the chemistry of the salts to prevent oxidation and leaching. The fuel salt is contained in steel tubes, each placed in a separate channel in a graphite matrix moderator, forming the reactor core. The core sits within the reactor tank vessel, which is filled with coolant salt. The reactor tank vessel is placed in a concrete pit underground and covered with a concrete shield.

The fuel tubes remain in the reactor for up to 15 years of operation, with partial refuelling approximately every five years to deliver the 60-year lifetime of the reactor. During normal operation, the heat generated by the fuel is removed from the reactor core by natural convective circulation of the coolant salt that fills the reactor tank. Residual decay heat is continually removed by natural circulation of air around the reactor tank. These passive heat transport mechanisms ensure that no active systems or pumps are required for heat removal or shutdown.

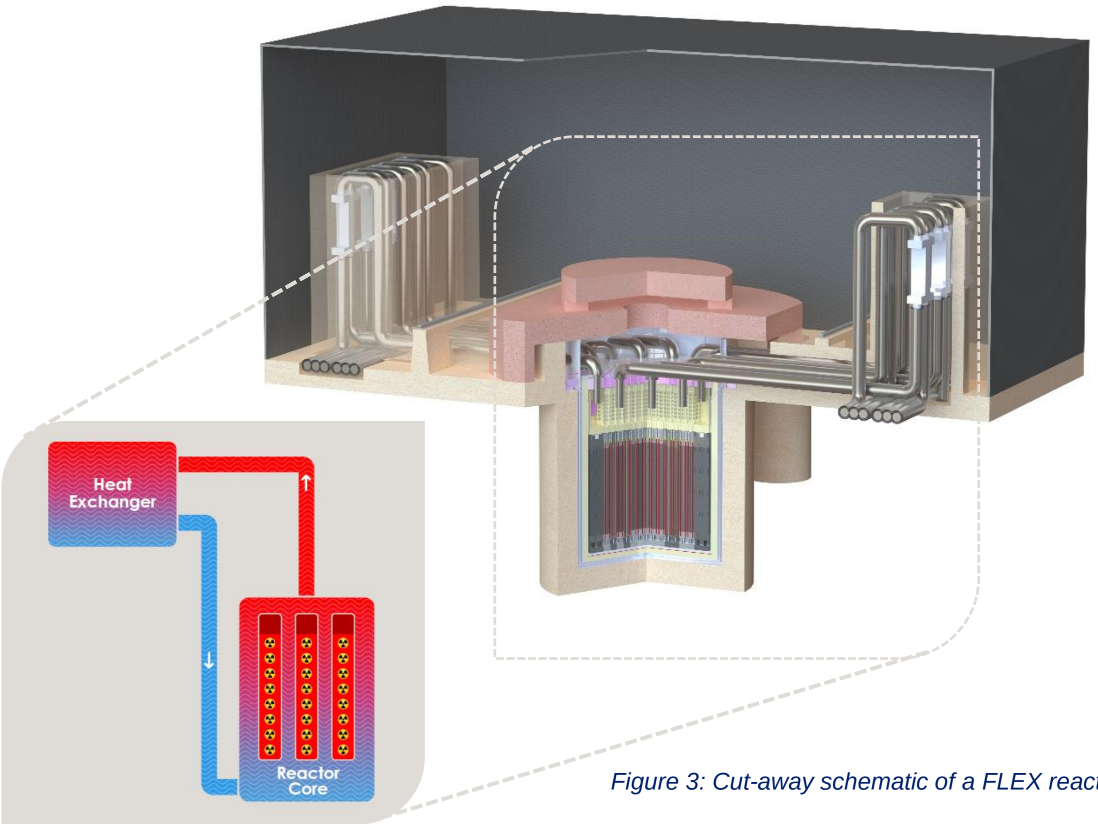


Figure 3: Cut-away schematic of a FLEX reactor

THE FUEL

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

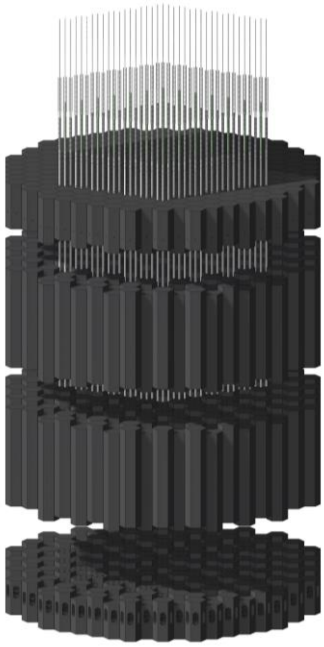


Figure 4: Graphite matrix and fuel pins inside the reactor core

Fuel salt

The FLEX reactor's fuel is a molten low-enriched uranium fluoride salt (5% enrichment), held in patented vented fuel tubes. The molten fuel salt circulates within the fuel tube by natural convection, which facilitates heat transfer through the tube wall to the coolant surrounding it. 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. This redox buffer enables the maintenance of redox potential and neutralisation of potentially corrosive fission products generated throughout the reactor's life.

The fuel salt does not come into contact with the surrounding graphite and does not require pumping from the reactor core into the heat exchangers.

The fuel salt is also kept separate from the coolant salt, which is another fluoride salt used to transfer heat from the reactor. However, they are miscible, which fundamentally changes the effect of core damage. In a conventional reactor, core damage causes the reactor to move to a substantially more hazardous state. In the FLEX reactor, even severe core damage would move the reactor to a safer state. For example, breach of the tube wall caused by tube melting would lead to a reduction in core reactivity, as the fuel salt would become diluted within the large coolant salt volume. As a result, core damage would not escalate beyond a release of fuel salt into the coolant salt.

Fission gas venting

In the FLEX reactor, most of the fission products 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 in which the shorter-lived radioactive isotopes decay; their decay products are trapped in the salt. Almost all of the most hazardous radioactive fission gas (xenon-137, which decays to hazardous caesium-137) is contained within the bubble traps.

The major radioactive gas that does escape from the bubble traps is krypton-85. This accumulates in the gas space of the reactor over its life. With a half-life of 10 years, a significant amount will still be present at decommissioning. Because it is a noble gas that does not bioaccumulate, standard practice for krypton-85 is to discharge it into the atmosphere, where it is diluted to trivial concentrations. However, MoltexFLEX's preference, is to capture and store the gas until it has almost completely decayed, which will take about 50 years.

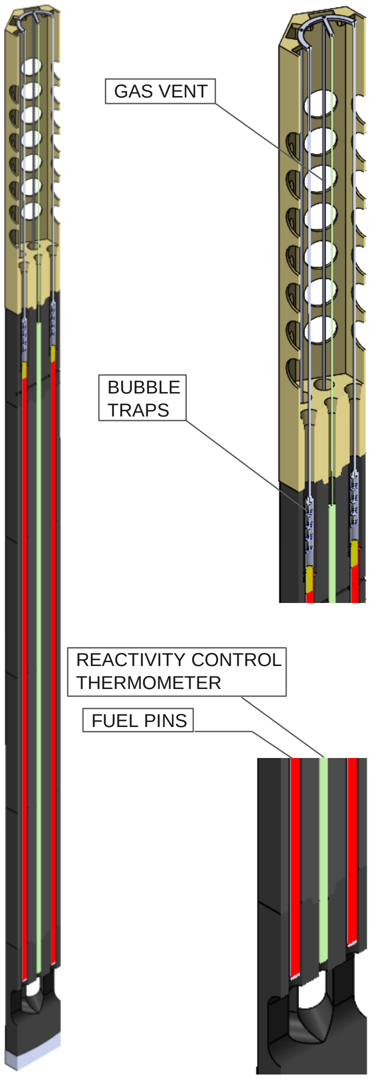


Figure 5: The fuel pin assembly

THE PASSIVE CONTROL SYSTEMS

The majority of the excess reactivity present in the FLEX reactor immediately after fuelling is neutralised through burnable neutron absorber in the reactor core. Any residual excess reactivity is neutralised by another neutron absorber, which is soluble in the coolant salt and added to the coolant through a periodic injection system. This neutron absorber burns out slowly and is replenished at intervals of several weeks or months.

Fine control over changes in reactivity, in response to shifts in power demand, is achieved by a patented novel mechanism similar to a conventional mercury thermometer but filled with liquid neutron absorber. This mechanism passively reduces the core reactivity as the coolant temperature rises, providing the reactor with the ability to respond safely to changes in heat removal from the reactor to the heat exchangers, without any operator action required.

THE HEAT REMOVAL SYSTEMS

The fuel tubes facilitate heat transfer between the fuel salt and the surrounding coolant salt, which operates at up to 795°C. As it is heated, the coolant salt rises through the channels in the graphite to the top of the reactor, through natural convection. The hot coolant salt then passes to heat exchangers, and the cooled salt returns to the base of the core, all by passive natural convection.

The FLEX reactor's high-temperature 795°C output is transferred to GridReserve©, a thermal storage system that stores the reactor's thermal energy output in large tanks of molten salt, providing 700°C usable heat. This salt can later be used to produce steam, and consequently, electricity using a conventional power plant that is outside and isolated from the nuclear island and is therefore subject to normal industrial safety standards. GridReserve© allows the power plant to output several times the reactor's power during times of the day when electricity demand is high.

One of the many benefits of this system is that the flow of the storage molten salt requires no control inputs from the reactor operator because the reactor passively regulates its output. Therefore, power plant operators do not need to be concerned about the impact of changing or stopping the power generation of the power plant on the nuclear reactor.

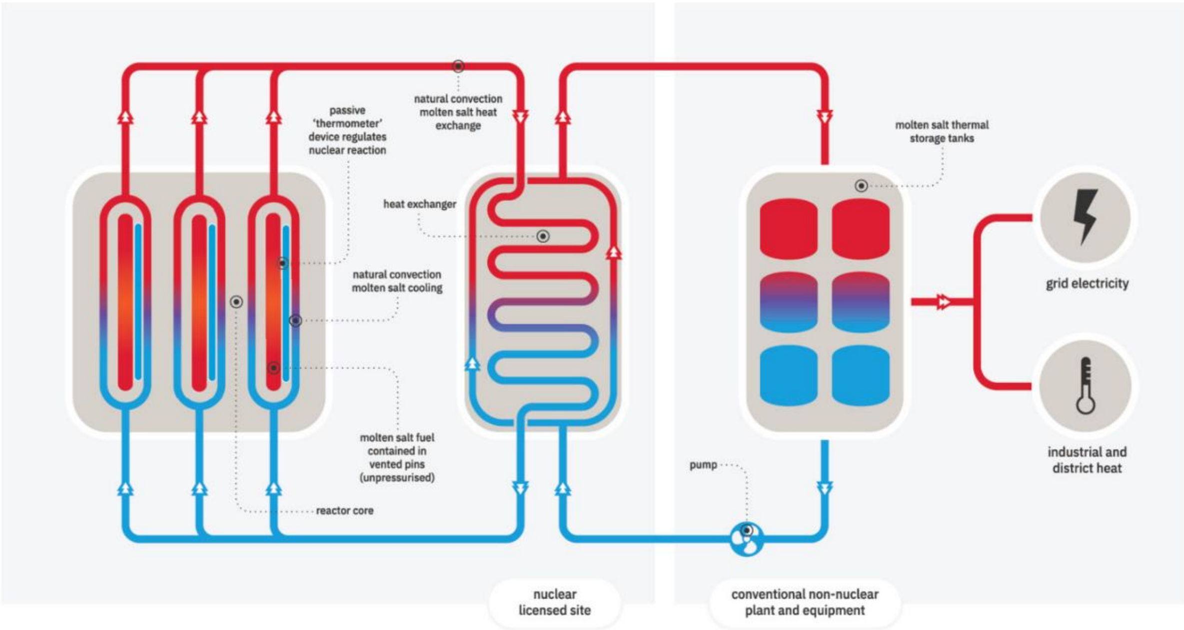


Figure 6: Heat removal from the FLEX reactor

Coolant salts

The coolants used in conventional nuclear reactors pose serious safety hazards. For example, water can explode into steam when pressure drops due to component failures. In other reactor designs, the use of sodium as a coolant has caused fires. Any pressurised gas-cooled reactor must include safety systems to manage the consequences of breaching the pressure boundary and the subsequent loss of core cooling. Thus, the main learning outcome from existing reactors is the importance of using a chemically and physically stable, unpressurised coolant, such as molten salt.

The FLEX reactor uses a patented eutectic mixture of aluminium fluoride and sodium fluoride as its coolant. Similar salt mixtures have seen decades of use in the aluminium smelting industry, giving high confidence in their lack of interaction with the graphite moderator.

Corrosion of metals by molten salts has long been a challenge in the industry. To prevent this issue in the coolant salt, small amounts of aluminium are added, which scavenge any oxygen that might potentially leak into the reactor before it can corrode the metal.

Residual heat

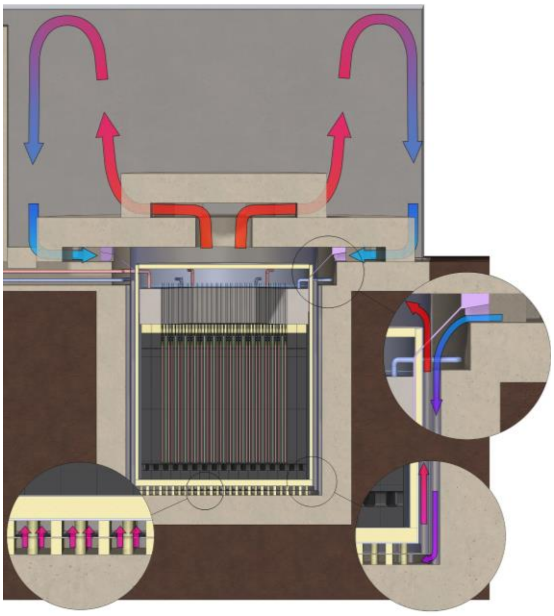


Figure 7: The residual heat removal system

The passive residual heat removal system (RHRS) operates continuously to remove 0.5% of full reactor power. This is a worthwhile compromise to achieve a completely passive system, which uses natural convection of air to cool the bottom, sides, and top of the reactor tank's outer layer. 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 then 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 up 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 low enough 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.

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