Status Report – SSR-U

Overview

Full name	Stable Salt Reactor
Acronym	SSR-U
Reactor type	Molten Salt Reactor
Purpose	Commercial
Coolant	Fluoride Salts
Moderator	Graphite
Neutron Spectrum	Thermal
Thermal capacity	750 MW
Electrical capacity	300 MW (formed by eight 37.5MWe modules)
Design status	Conceptual Design
Designers	Moltex Energy
Last update	July 28, 2016

NOTE:

This description was taken from the Advances in Small Modular Reactor Technology Developments 2016 Edition booklet.

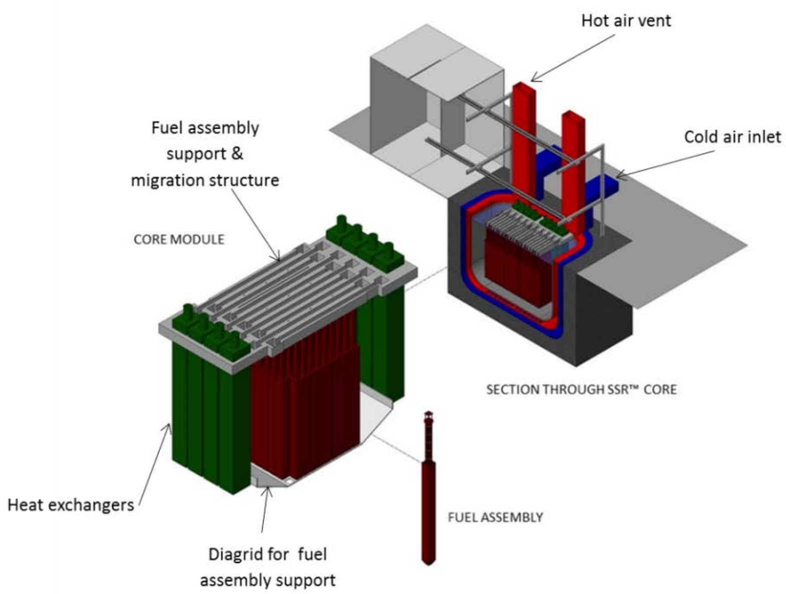


Figure 1: Isometric view of core module and section through reactor (Reproduced courtesy of Moltex)

1. Introduction

The Stable Salt Reactor (SSR) is unique in its use of molten salt fuel replacing solid pellets in conventional fuel assemblies. This brings the major advantages of safe molten salts without the technical hurdles of managing a mobile liquid fuel. This combination should lead to substantially lower capital costs than conventional nuclear power technologies. The SSR is a design platform with two configurations, a thermal spectrum Low Enriched Uranium burner (SSR-U) and a fast spectrum actinide transmuting Wasteburning SSR (SSR-W). Both of these designs can be adapted in the future to breed fuel from thorium. In the thermal versions, the moderator is graphite and forms an integral part of the fuel assembly thus eliminating graphite lifetime concerns. The technology is coupled with large energy storage reserves to increase peak power demand allowing an increase of renewables on the grid. This summary focuses on the details of the thermal spectrum, uranium fuelled reactor SSR-U.

2. Target Application

Stable Salt Reactor technology is initially aimed at mature markets with nuclear expertise. Once deployed and proven to be commercially viable the large market potential is in developing and non-nuclear nations due to the expected low cost and higher proliferation resistance. The high outlet temperatures further allows the plant to be coupled with thermal energy storage reserves in areas where there is grid instability due to fluctuating renewable electricity generation. This will allow a more stable energy market and an expansion of renewable power.

It is envisaged that one Wasteburning SSR-W will be required to burn the spent fuel and transmute the long lived actinides for ten thermal spectrum reactors. Extremely high levels of lanthanide contamination are permitted in the fuel of SSR-W. This enables a simple and economical pyroprocessing method to be used to convert virtually any spent fuel to fuel.

3. Development Milestones

2014	-UK patent granted for use of unpumped molten salt fuel in any reactor. -Independent capital cost estimate complete
2015	-Conceptual design complete and key claims validated by the UK's National Nuclear Laboratories.

4. General Design Description

Design Philosophy

The entire design philosophy is to reduce plant costs by simplifying the design and eliminating instead of containing hazards. This is done by combining the safety and operational benefits of molten salts along with conventional reactor components. Risks to the public are practically eliminated by design, and not merely contained.

The key features of the design are to achieve:

- Virtual elimination of the volatile radiotoxic source term under any conceivable accident, terrorist act or act of war. This would massively reduce the uninsurable liability (~$100 billion) currently born by national governments in the event of a serious release of radioactivity.
- Deployment of the SSR on smaller sites with smaller emergency planning zones as a result of this huge reduction in potential for offsite radioactive releases is expected to be approved by regulators. The probability that this is true is endorsed by the UK's National Nuclear Laboratory (NNL).
- Economic competitiveness to have a capital cost similar to coal fired power stations

but with substantially lower fuel cost. This is partly as a result of the intrinsic safety characteristics and partly due to the absence of pressurised reactor components – see details under Plant Economics.

- Modular design with the reactor assembled from road transportable, factory produced modules creating a single reactor unit of 300MWe. Larger plants of any size can readily be produced for larger demands which drop the Levelised Cost Of Electricity (LCOE) cost further.
- Fuel assembly form is compatible with IAEA Safeguards procedures used in reactors today (unlike other molten salt fuelled reactors).
- The output temperature of the reactor is high at 650-700°C. Thermal stresses are sufficiently low that the proposed standard stainless steels will not suffer creep degradation at these temperatures. The high output temperature has major advantages over the low output temperature of PWR reactors:
    - Use of standard low cost high efficiency superheated steam turbines now produced on a large scale for combined cycle gas turbine plants instead of larger, much less efficient saturated steam turbines which are now rarely produced except for nuclear reactors and which are commensurately more expensive
    - Heat storage using proven technology from solar thermal power plants is possible so electrical generation can be boosted during peak hours while the reactor runs at constant power. This allows carbon free load following to increase the capacity of renewables that the grid can accommodate.
    - SSR process heat has a wider range of commercial uses compared to low temperature nuclear steam.
- To design a reactor system that addresses both the long term sustainability of nuclear energy with the use of thorium and the problem of its resulting long lived radioactive waste.

Power Conversion Unit

A molten salt to steam boiler is proposed to generate steam. The turbine currently being specified for a 300MWe plant is the Siemens SST5-5000. The air cooled generator is Siemens SGen5-1200A-2P 118-55. Steam output temperature is 600˚C.

There will either be a larger turbine of 450MWe installed, to be coupled with the solar salt storage or two turbines of 300MWe and 150MWe. This will depend on the local electricity grid needs and economics.

Reactor Core

The core is made up of fuel assemblies which sit into a diagrid structure located at the bottom. At the top the assemblies sit in a rail system which forms part of the reactor 'lid'. The core is rectangular and the assemblies travel in rows laterally across the core. Each thermal spectrum assembly contains 37 vented tubes containing the fuel salt surrounded by a solid block of clad graphite as shown in *Figure 2*. The coolant passes around the tubes through the centre of the graphite.

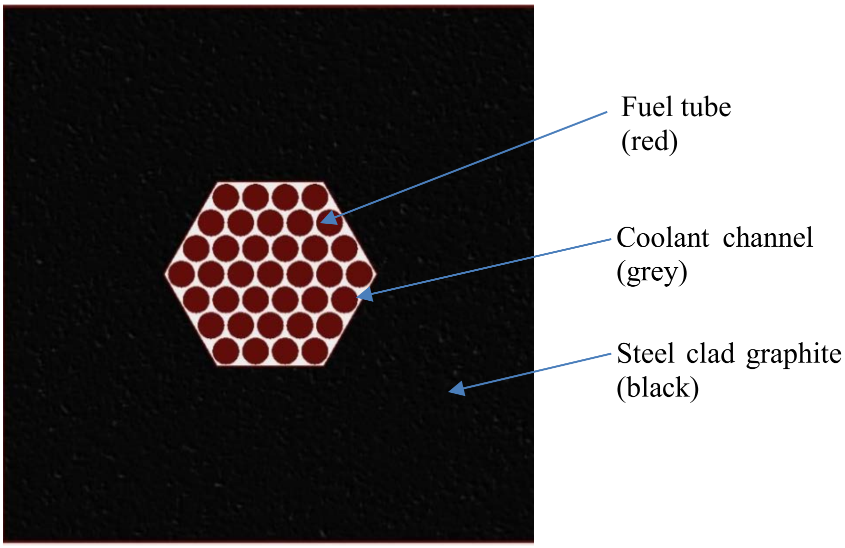
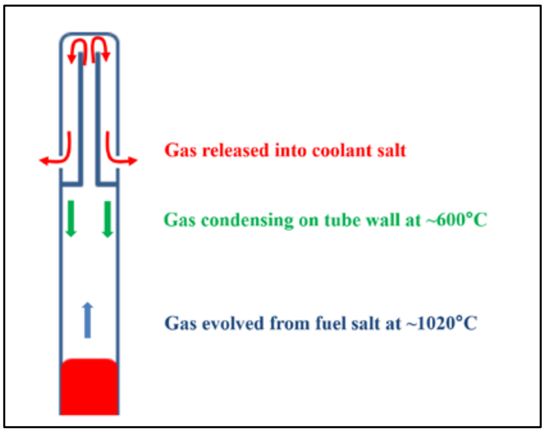


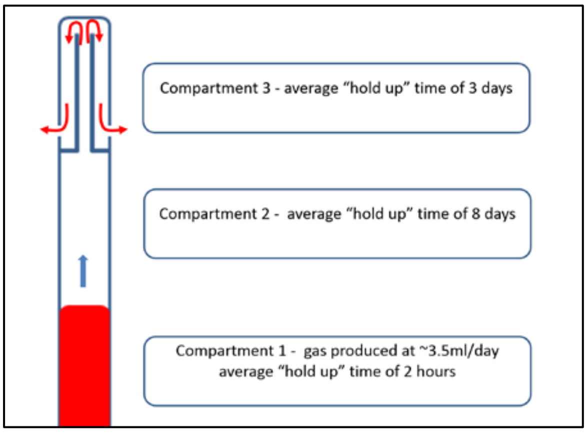
Figure 2: Section through fuel assembly showing the graphite, fuel tubes and coolant flow channel (Reproduced courtesy of Moltex)

The tubes are stainless steel, similar in materials and structures to today's AGR fuel. The tubes are 3m long with 2.6m of fuel and 400mm of gas space at the top which has a venting mechanism as shown in *Figure 3* to allow some gaseous fission products to be released into the coolant salt (most radiologically important fission products are captured in a non-gaseous form). In addition to preventing build-up of pressures within the tubes, the venting mechanism walls are cooler than the gas itself which causes it to condense on the walls and flow back into the fuel. Fission product gases have time to decay to more stable isotopes before entering the pool of coolant salt. Most released fission product gases are furthermore absorbed by the coolant into stable salt forms. Only the noble gases and cadmium migrate through the coolant salt to the argon containment zone above.

Fuel Characteristics

The thermal spectrum fuel is a molten fluoride salt with a eutectic composition of 33%NaF / 30%RbF / 37%UF4 and a melting point of 535˚C. The fuel is prepared in a simple single step reaction from uranium hexafluoride, as is already produced in many parts of the world. Fuel pellets are melt cast from this mixture requiring none of the complex sizing, sintering and machining required for oxide fuel. SSR fuel therefore has the potential to be substantially cheaper than today's fuel. Once the assembly is lowered into the tank of molten coolant salt, the fuel pellets within the tubes will melt. Only then, will they be taken into the core where they will become critical.





Figures 3: Venting mechanism at the top of each fuel tube causes gaseous fission products to condense on the walls ensuring a hold up time before it is released to the coolant salt beyond the tube (Reproduced courtesy of Moltex)

Fuel Handling System

The rectangular core enables lateral fuel shuffling through a rail system without lifting the assembly vertically out of the coolant during a fuel change. The vessel does not need to be flooded as it does in a PWR. The assemblies in alternate rows are moved in opposite directions during reload. This result in a pattern where if fresh fuel is inserted in one end, the two assemblies either side of it are depleted assemblies ready to be removed - they were initially loaded as fresh assemblies from the other side of the core. A new fuel assembly is added to a row every 6 months. At the same time, the assembly at the other end is removed. New assemblies are added to different rows every few days. This is similar in strategy to CANDU fuel shuffling and results in a sufficiently flat power profile across the core.

Once an assembly leaves the core it sits at the edge of the tank until it has cooled sufficiently to be lifted into the argon space above the core to cool down. The fuel quickly solidifies due to the high temperature gradient between itself and the argon. It can then be removed from the reactor and placed into dry cask storage until ready for reprocessing or geological disposal.

Reactivity Control

No excess reactivity needs to be added to the core to compensate for fuel burn up because the combination of frequent on power refuelling and high negative temperature reactivity coefficient allow the core to generate constant power between refuelling steps – the small drop in reactivity is compensated by a small fall in average fuel salt temperature, which is readily compensated by changes in the coolant flow rate.

No reactivity shims or control rods are required at any time under normal operating conditions, eliminating the potential for control failures that can lead to an increase in the core reactivity. The excess reactivity always required at start up is provided either by step by step addition of the final fuel assemblies with the coolant at normal operating temperature or by adding all the fuel assemblies with the coolant at a higher temperature and then carefully lowering the temperature. A combination of the two methods is also practical.

Reactor shutdown is provided by shutdown blades with electromagnetic securing of the control blades. The backup method is a coolant neutron poison system based on sodium fluoroborate which can be released based on a thermally triggered system.

Reactor Containment System

There are no pressurised systems or components within the reactor building. The tank is a stainless steel vessel suspended using anti-seismic suspension fixings. The tank is cooled by air cooling ducts around the perimeter. A thin walled stainless steel liner surrounds the wall and roof of the argon containment zone. This is surrounded by a ~1m blast resistant concrete wall which also acts as a biological shield.

A large airlock allows core modules, fresh and spent fuel assemblies to be moved in and out of the core. Argon venting is done irregularly through the airlock.

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer	Moltex Energy
Country of origin	United Kingdom
Reactor type	Static Fuelled Molten Salt Reactor
Electrical capacity (MW(e))	300MWe (formed by eight 37.5MWe modules)
Thermal capacity (MW(th))	750MWth
Expected capacity factor (%)	91%
Design life (years)	60 years
Plant footprint (m^2)	22500
Coolant/moderator	Graphite as an integral part of fuel assembly
Primary circulation	Forced circulation
System pressure (MPa)	Atmospheric
Core inlet/exit temperatures (^oC)	550˚C - 700˚C
Main reactivity control mechanism	Negative temperature coefficient (net of fuel plus coolant is -5.4pcm/K)
Tank height (m)	4m (H)
Tank Size (m)	18m (L) x 5m (W)
Module weight (metric ton)	<10t per 37.5MWe module excluding salt
Configuration of reactor coolant system	Pool type
Power conversion process	Steam generator to turbine
Cogeneration / Process Heat Capabilities	Yes, possible.
Passive Safety Features:	Large negative temperature coefficients, decay heat removal by passive air cooling ducts, volatile source term reduced by 10^6 in accident scenario (due to the lower partial vapour pressures of volatile fission products in a severe accident with molten salt fuel compared to a uranium oxide fuel pellet).
Active Safety Features:	Shutdown blade SCRAM + fluoroborate poison
Fuel type/assembly array	Molten salt fuel within vented fuel tubes in a conventional style fuel assembly within graphite.
Fuel assembly active length (m)	2.6m
Number of fuel assemblies	1,040 (per 300MWe)
Fuel enrichment (%)	<15% LEU
Fuel burnup (GWd/ton)	>150GWd/tHM
Fuel cycle (months)	~84 months
Approach to engineered safety systems	Reactor has multiple inherent safety features. Inherent features will be given a low probability of failure in the Probabilistic Safety Assessment.
Number of safety trains	Nominally 4 way segregation where applicable
Emergency Safety Systems	Passive Air Cooling Ducts around the tank walls; multiple diverse SCRAM
Residual Heat Removal System	Thermal inertia of tank by natural circulation and passive air cooling ducts.
Refuelling outage (days)	On line regular refuelling – maintenance outage under review.
Distinguishing features	Molten salt fuel constrained in conventional, vented fuel tubes. Thermal energy storage to increase peak electrical capacity.
Modules per plant	8 per 300MWe (no upper limit to number of tanks)
Target construction duration (months)	31 months from start of nuclear concrete
Seismic design	Yes, suspended tank on seismic fixings.
Core damage frequency (per reactor-year)	Expected $<10^{-6}$ (and the consequence / hazard to the public reduced by 10^6)
Design Status	Concept, Preparing licensing pack

Reactor Coolant System
The reactor is a pool type reactor so the primary coolant fills the tank. Use of an RbF based fuel salt means that the coolant must operate between 570°C and 700°C in order to prevent fuel salt freezing. The coolant salt is therefore 39% ZrF_4 / 1% ZrF_2 / 60% NaF with a melting point 500°C.

A secondary coolant salt with additional potassium fluoride to lower the melting point is used to take the heat from the primary heat exchanger to the boiler tubes. Its composition is 10% NaF / 48% KF / 42% ZrF4 and it has a melting point of 385°C. The solar salt thermal tanks are heated through a direct loop into the solar salt tanks. Initial heating of the water/steam from the condenser is done with a small heat exchanger of solar salt to bring the steam temperature to above 435°C.

Steam Generator
The boiler tube design is under review but is being designed using knowledge gained from the concentrated solar industry. Due to the high melting point of the secondary coolant (385°C), a solar salt of lower melting point is used to do the initial heating of the water/steam from the condenser before the steam can enter the main steam generator. This is to ensure there is no freezing of the secondary coolant fluoride salt on the boiler tube walls.

5. Safety Features

Engineered Safety System Approach and Configuration
The molten salts used in the SSR are chemically stable with minimal reactions with air or water. Specific design solutions and material choices prevents corrosion of the fuel clad (with fuel salt) and plant components with the coolant salt. Use of molten salt fuel with the correct chemistry further eliminates the hazardous volatile iodine and caesium source terms which prevents airborne radioactive plumes in severe accident scenarios.

Pool type reactor designs are well established as particularly safe options since natural convection of heat from the core is sufficient to remove decay heat. This design element has been incorporated into the SSR. However, the coolant is chemically non-reactive, under no pressure and has an extremely high boiling point making the pool design even safer than those used in other reactors. This single factor separates the SSR from all other molten salt reactor designs where relatively complex engineered systems are required to assure continued cooling of the fuel.

The non-volatile radioactive fission products are physically contained within the fuel tubes. In the unlikely event of tube rupture the coolant salt has been selected so as to be miscible with the fuel salt. If multiple tubes are ruptured, the large tank of coolant provides a means of massively diluting the fuel rendering the reactor subcritical while maintaining its containment within the reactor tank without relying on drain tank valves.

Below ground construction - The reactor tank is located below ground level in a steel and concrete lined pit. This avoids any potential for a physical loss of coolant sufficient to expose the core and provides protection (in conjunction with above ground concrete shielding) against aircraft impact or other external factors.

Decay heat removal system
Natural convection of the primary coolant salt will continue in the event of a reactor shutdown or pump failure. The primary coolant heats up to a point where radiative heat transfer from the tank walls becomes the dominating factor. A finned air duct to atmosphere

exists around the tank walls which can take decay heat away in this accident scenario.

Emergency core cooling system

The core, heat exchangers and pumps are designed so that natural circulation can continue indefinitely. This ensures the core is continually cooled.

Containment system

See '*Reactor Containment System'* under Section 4 above. There are no internal pressures. The primary containment is the tube wall, secondary is the coolant salt (which absorbs fission products). The third is the tank itself and the fourth is the concrete structure. Above the tank is an argon space which has a stainless steel liner surrounded by a ~1m concrete wall which serves as the biological shield. The concrete above and below grade is designed to be blast resistant. The argon containment zone is at a lower pressure than the air within the reactor building to minimise gas escapes in the event of a breach. However, the composition of the gas within the containment is maintained such that a major release due to massive containment loss would not release hazardous quantities of radioisotopes. The reactor building walls are ~300mm thick reinforced concrete. This serves as building structure and as an initial energy reducer from an external impact of a missile. The building will be aircraft resistant although the consequence of an aircraft impact is substantially lower than in a PWR due to the reduced volatile source term.

6. Plant safety and Operational Performances

The design philosophy is such that no operator access is ever required in the main reactor zone. The substantial reduction in quantity of engineered safety and component systems will substantially reduce the number of operating staff required. The ramp rates of the plant will be driven by the steam side, not the nuclear side. Shutdown and maintenance periods will also be driven by the requirements of the steam turbine.

7. Instrumentation and Control systems

Primary reactivity control will be by the reactivity coefficient of the coolant and fuel. Heat removal driven by the turbine will control the reactivity sufficiently. There will be neutron and temperature sensors above the core area and within the coolant. All components are designed with the facility to be inspected remotely by visual or mechanical means.

There will be radiation and chemical monitoring of the gas space to ensure no unexpected fission products are being released to atmosphere (in the event of a leak or opening of the air lock).

8. Plant Arrangement

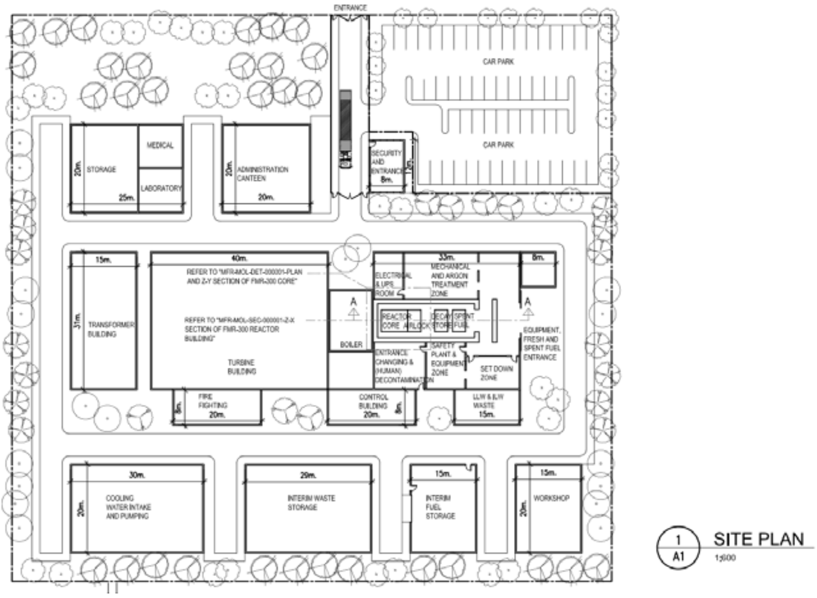


Figure 4: Illustrative site layout for a 300MWe plant (Reproduced courtesy of Moltex)

9. Design and Licensing Status

The focus to date has been on the novel aspects of the reactor including neutronics and chemistry. The majority of the design work has been carried out by various UK consultancies and universities. The current phase of design is at component level where supplier engagement is taking place to specify each component. The Preliminary Safety Case is in preparation to initiate licensing in 2017.

10. Plant Economics

Partly as a result of the intrinsic safety and partly due to absence of pressurised reactor components the overnight cost of the complete nuclear island, including civil works, of a 1GW fast version of the SSR has been estimated independently of Moltex Energy by Atkins Ltd as being £714 per kW ($1,071/kW) capacity. This costing has been used as the basis for estimating full plant cost for a 1GWe thermal spectrum SSR-U of £1,892 per kWe ($2,838/kW). These are based on UK on-site construction costs, potential cost savings for modularised construction is not included. Substantial prelims and contingencies are included. This provides a highly credible case for reactors having comparable capital cost to coal fired power stations but with radically lower fuel cost. Levelised electricity costs are not given at this stage as they are so heavily dependent on the specific financing mechanisms.

The far simpler design of the Stable Salt Reactor compared to PWRs and AGRs and small number of safety critical systems should lead to significantly lower O&M costs. The process for converting enriched uranium hexafluoride into fuel ready for incorporation into fuel assemblies is very much simpler for Stable Salt Reactor fuel than for oxide fuel and is also therefore expected to be significantly cheaper. Subsidies will not be required as the electricity produced by the SSR will be competitive with fossil fuels even without carbon tax.

Appendix: **Summarized Technical Data (SSR-U)**

General plant data		
Reactor thermal output	750 (with 8 units)	MWth
Power plant output, gross	300	MWe
Power plant output, net		MWe
Power plant efficiency, net	40	%
Mode of operation	load following	
Plant design life	60	Years
Plant availability target	>91%	%
Seismic design, SSE	Yes, suspended tank on seismic fixings	g
Primary Coolant material	39% ZrF_4 / 1% ZrF_2 / 60% NaF	
Secondary Coolant material	10% NaF / 48% KF / 42% ZrF_4	
Moderator material	Graphite	
Thermodynamic Cycle	Rankine	
Type of Cycle		
Non-electric application	Possible	
Safety goals		
Core damage frequency (primary loop rupture)	Expected <10^{-6}	/reactor-year
Large early release frequency		/RY
Occupational radiation exposure	0.5mSv	Sv/Person/Y
Operator Action Time	Indefinite	hours
Nuclear steam supply system		
Steam flow rate at nominal conditions	NA	kg/s
Steam pressure/temperature	NA	MPa(a)/℃
Feedwater flow rate at nominal conditions	NA	kg/s
Feedwater temperature	NA	℃
Reactor coolant system		
Primary coolant flow rate	540/module	kg/s
Reactor operating pressure	0.1	MPa(a)
Core coolant inlet temperature	550	℃
Core coolant outlet temperature	700	℃
Mean temperature rise across core	150	℃
Reactor core		
Active core height	2.6	m
Equivalent core diameter	2.5/module	m
Average linear heat rate	36,000	kW/m
Average fuel power density	150kW/l	kW/kgU
Average core power density	7.5	MW/m^3
Fuel material	33%NaF / 30%RbF / 37%UF_4	
Cladding tube material	Stainless – PE16	
Outer diameter of fuel rods	10	mm
Rod array of a fuel assembly	Close packed	
Number of fuel assemblies	120/module	
Enrichment of reload fuel at equilibrium core	15	Wt%
Fuel cycle length	84	months
Average discharge burnup of fuel	150	MWd/kg

Burnable absorber (strategy/material)	None	
Control rod absorber material	None	
Soluble neutron absorber	None	
Reactor pressure vessel		
Inner diameter of cylindrical shell	NA	mm
Wall thickness of cylindrical shell	NA	mm
Total height, inside	NA	mm
Base material	NA	
Design pressure/temperature	Atmospheric/	MPa(a)/℃
Transport weight (of containing Can)		t
Steam generator (if applicable)		
Type		
Number		
Total tube outside surface area		m^2
Number of heat exchanger tubes		
Tube outside diameter		mm
Tube material		
Transport weight		t
Reactor coolant pump (if applicable)		
Type	centrifugal	
Number	4/module	
Head at rated conditions	1.2	m
Flow at rated conditions	0.05	m^3/s
Pump speed	1000	rpm
Pressurizer (if applicable)		
Total volume	NA	m^3
Steam volume: full power/zero power	NA	m^3
Heating power of heater rods	NA	kW
Primary containment		
Type	Pool type	
Overall form (spherical/cylindrical)	Rectangular tank	
Dimensions (diameter/height)	16m x 5m x 4m	m
Design pressure/temperature	100/700	kPa(a)/℃
Design leakage rate	0	Vol%/day
Is secondary containment provided?	Yes	
Residual heat removal systems		
Active/passive systems	Passive air cooling	
Safety injection systems		
Active/passive systems	none	
Turbine (for two module power plant)		
Type of turbines	Superheated steam	
Number of turbine sections per unit (e.g. HP/MP/LP)		
Turbine speed		rpm
HP turbine inlet pressure/temperature	17/566	MPa(a)/℃
Generator (for two module power plant)		
Type		
Rated power		MVA
Active power		MW
Voltage		kV
Frequency		Hz
Total generator mass including exciter		t
Condenser		

Type		
Condenser pressure		kPa(a)
Feedwater pumps		
Type		
Number		
Head at rated conditions		m
Flow at rated conditions		m^3/s
Pump speed		rpm