Status Report – MSR-FUJI

Overview

Full name	Molten Salt Reactor FUJI
Acronym	MSR-FUJI
Reactor type	Molten Salt Reactor
Purpose	Commercial
Coolant	Fluoride Salts
Moderator	Graphite
Neutron Spectrum	Thermal
Thermal capacity	450 MW per module
Electrical capacity	200 MW per module
Design status	Conceptual design
Designers	International Thorium Molten-Salt Forum: ITMSF
Last update	July 28, 2016

NOTE:

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

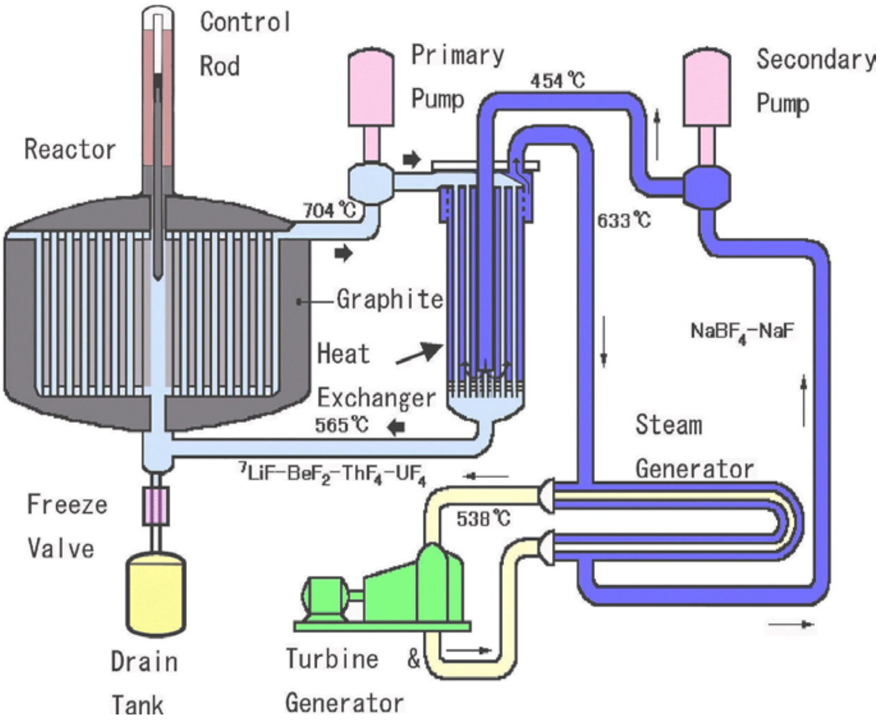

Figure 1: Schematic diagram of MSR-FUJI (Reproduced courtesy of ITMSF)

1. Introduction

The Molten Salt Reactor (MSR) uses molten salt, in general molten fluoride salt, as liquid fuel and coolant. MSR was originally developed at Oak Ridge National Laboratory (ORNL) in 1960s, and three experimental MSRs were constructed. One of them was operated for 4 years without severe problems. Thus, it is verified that the MSR technology is feasible.

MSR-FUJI was developed since the 1980s by a Japanese group (now, International Thorium Molten-Salt Forum: ITMSF), based on the ORNL's results with the view to deploy it widely in the world [1,2].

Molten salt is a liquid, which is in general a melted chemical compound of acid and alkali at high temperature. Molten salt is stable and inert at high temperature, and can be used at very low pressure. Since core meltdown or steam/hydrogen explosion is impossible, high safety can be achieved.

MSR-FUJI is size-flexible as from 100 MWe to 1000 MWe. But, a latest and typical design (FUJI-U3) is 200 MWe, which can be categorized as small-sized reactors with modular designs (SMR). The thermal output of FUJI-U3 is 450 MWt and thus a 44% thermal efficiency can be attained. In addition to the expected high efficiency the simple core structure and high fuel efficiency should facilitate a favourable economic performance.

A schematic diagram of the MSR-FUJI is shown in *Figure 1.*

Molten fuel salt can contain thorium (Th) as fertile material and ^{233}U as fissile material, and based on this the FUJI-U3 design can attain a self-sustaining fuel cycle with a conversion factor of 1.0. Since MSR-FUJI applies the Th-cycle, generation of plutonium (Pu) and minor actinide (MA) is very small compared with Light Water Reactors (LWR). Furthermore, it can consume Pu as the fissile material, and can thus contribute to reduce the proliferation risk caused by Pu from LWR spent fuel. It can also be used to transmute long-lived MA to shorter ones.

2. Target Application

MSR-FUJI can be applied not only to electricity generation, but also to transmutation of Pu and/or MA. Besides these purposes, it can be used as a heat source for water supply by desalination of seawater or for hydrogen production, utilizing its high exit temperature of 704 °C.

3. Development Milestones

1980's	Conceptual designs of MSR-FUJI have been started
1980's	Accelerator Molten-Salt Breeder (AMSB) design for a large production of fissile material (similar to Accelerator Driven System ADS)
Until 2008	Several designs, such as a pilot plant (mini-FUJI), a large-sized plant (super-FUJI), a Pu-fueled plant (FUJI-Pu),
Recent	The latest SMR plant (FUJI-U3), The MSR-FUJI as in this text refers to the 200 MWe FUJI-U3 design

4. General Design Description

Design Philosophy

The design philosophy of MSR-FUJI is to achieve a high level of safety, good economic performance, contributing to non-proliferation, and to achieve fuel cycle flexibility.

MSR-FUJI is based on the ORNL's results, and has been optimized as a small sized plant and further simplified by removing the online reprocessing facility. Based on the operating experience at three experimental MSRs in ORNL, it has been verified that MSR-FUJI is feasible. The steam generator (SG) is however a major unverified component but it can be developed based on Fast Breeder Reactor (FBR) experience and the recent supercritical power station technology.

MSR-FUJI adopts a passive safety system to improve the safety, reliability as well as the economics. Molten fuel salt can be drained to a sub-critical drain tank through a freeze valve. Since gaseous fission products (FP) are always removed from molten fuel salt, the risk at accidents is minimized. MSR-FUJI is operated at very low pressure (0.5 MPa), and a thick reactor vessel and pipes are not required. There are no fuel assemblies or complex core internal structure with the only component within a reactor vessel being the graphite moderator. Based on these design principles in-factory fabrication would be simple.

Nuclear Steam Supply System

The nuclear steam supply system (NSSS) consists of a reactor core, pipes, pumps, a heat exchanger (HX), and a steam generator (SG), which supplies steam to a turbine/generator (T/G), as is shown in *Figure 1*. This figure shows only one loop, but a loop can be redundant depending on a plant size or a need for flexibility.

MSR-FUJI is designed to produce an exit temperature of 704°C in molten fuel salt, and its heat is transferred to the secondary salt through a HX. Then, its heat produces 538°C supercritical steam at a SG, and generates electricity by a supercritical T/G. Owing to its high temperature, MSR-FUJI can achieve 44% thermal efficiency.

Since molten salt is used as fuel and coolant, loss of coolant accident (LOCA) may need a new definition for MSR. In case of pipe break, leaked molten salt is drained to an emergency drain tank without passing through a freeze valve. Even in this case, a molten salt loop returns to atmospheric pressure when a pump stops, and a pressurization accident is incredible, owing to its low vapor pressure. Therefore, an emergency core cooling system (ECCS), containment cooling system (CCS), makeup water pools, and automatic depressurization system (ADS) are not required.

The primary loop (molten fuel salt loop) is operated with forced circulation by a centrifugal pump during normal operation. The system also has a natural circulation capability in emergency conditions.

MAJOR TECHNICAL PARAMETERS

Parameter	Value
Technology developer	International Thorium Molten-Salt Forum: ITMSF
Country of origin	Japan
Reactor type	Molten Salt Reactor
Electrical capacity (MWe)	200
Thermal capacity (MWth)	450
Expected capacity factor (%)	75% for daily load-following operation
Design life (years)	30
Plant footprint (m^2)	<5000 (R.B. + SG.B. + TG.B.)
Coolant/moderator	Molten fluoride / Graphite
Primary circulation	Forced circulation by pump
System pressure (MPa)	0.5 (by pump head)
Core inlet/exit temperatures (^{o}C)	565 / 704
Main reactivity control mechanism	Control rod, or pump speed, or fuel concentration
Reactor Vessel height (m)	5.4 (inner)
RV diameter (m)	5.34 (inner)
RV weight (metric ton)	60 (made of Hastelloy N)
Configuration of reactor coolant system	Primary loop and secondary loop
Power conversion process	Rankine Cycle
Cogeneration / Process Heat Capabilities (High / Low T)	Possible, utilizing high exit temperature
Passive Safety Features:	Freeze valve to drain tank.
Active Safety Features:	Control rod scram. ECCS is not required
Fuel type/assembly array	Molten salt with thorium and uranium
Fuel assembly active length (m)	No fuel assembly
Number of fuel assemblies	No fuel assembly
Fuel enrichment (%)	2.0 equivalent (0.24%^{233}U + 12.0%Th). Pu or LEU can be used.
Fuel burnup (GWd/ton)	No mechanical limitation for burnup
Fuel cycle (months)	Continuous operation is possible
Approach to engineered safety systems	Passive safety
Number of safety trains	ECCS/CCS/ADS are not required
Emergency Safety Systems	Ditto
Residual Heat Removal System	Passive cooling without electricity (required at drain tank)
Refueling outage (days)	<30 (Refueling shutdown is not required)
Distinguishing features	High safety, high economic performance, contribution to non-proliferation, and fuel cycle flexibility
Modules per plant	(Not decided)
Target construction duration (months)	(Not decided)
Seismic design	Same as LWRs
Core damage frequency (per reactor-year)	Core meltdown is impossible
Design Status	3 experimental MSRs were built. Detailed design has not started

Reactor Core

A reactor vessel is cylindrical in shape. The core structure is made up by hexagonal shaped graphite moderator blocks. The blocks contain holes that serve as the flow paths of the molten fuel salt that flow upwards through the blocks circulated by the primary pump. The molten fuel salt then goes to a heat exchanger to transfer the heat to the secondary coolant salt.

The concentration of the fuel composition can be adjusted at any time through the fuel concentration adjustment system. Since there are no fuel assemblies in the core, refueling shutdown is not required, and continuous operation is possible. In order to achieve a core conversion factor of 1.0 it is recommended to refresh the fuel salt every 7 years. Periodic maintenance shutdown will of course be required as in any power plant.

Fuel Characteristics

The molten fuel salt is a liquid form of fluoride ($LiF-BeF_2$) with ThF_4 and a small amount of $^{233}UF_4$. A typical composition is $LiF-BeF_2-ThF_4-^{233}UF_4$ (71.76-16-12-0.24 mol%).

Molten fluoride can be used at very low pressure owing to its very high boiling temperature and very low vapor pressure. The melting temperature of the above fuel composition is 499°C. It can dissolve uranium (U) or Pu as fissile material so that low enriched uranium (LEU) or Pu can be used. Owing to unique features of molten fuel salt, fuel assembly fabrication is not required, and radiation damage or fuel cladding failure does not occur.

Reactivity Control

Reactivity control for long-time operation can be performed anytime by a fuel concentration adjustment system. In normal daily operation, reactivity or power level can be controlled by core flow or by core temperature. Control rods are withdrawn in normal operation and are inserted by gravity in case of emergency shutdown.

Reactor Vessel and Internals

The reactor vessel is made of Hastelloy N. Since the operating pressure is very low (0.5 MPa) a "pressure" vessel is not required and the reactor vessel wall thickness is about 5 cm. Only one component, the graphite moderator blocks, is present within the core internal region.

Secondary salt loop

The secondary loop adopts molten salt of $NaBF_4$-NaF. This secondary loop is circulated by a centrifugal pump and removes heat from the primary loop through a heat exchanger to the steam generator. Since the pressure of both the primary and secondary loop is very low, the danger of rupture is minimized. In case of a pipe break molten salt is drained to a drain tank.

Steam Generator and Turbine Generator

A steam generator (SG) of MSR-FUJI adopts a shell and tube design. A U-shaped shell contains a secondary salt flow, and steam flows inside of multiple tubes within a shell. The secondary salt loop at 633°C provides heat to the SG that generates 252 kg/cm^2 steam at 538°C fed to the supercritical turbine generator (T/G) to produces 200 MW electricity.

5. Safety Features

The MSR-FUJI design has very favourable safety characteristics that essentially exclude the possibility of severe accidents based on the following unique features:

- The primary and secondary loops are operated at a very low pressure, which essentially eliminates accidents such as system rupture due to high pressure.
- The molten salt is chemically inert, that is, it does not react violently with air or water,

and is also not flammable. The corrosion of Hastelloy N can be minimized by the appropriate chemical control and maintenance of the molten salt.

- Pressure increase in a primary loop is incredible, because a boiling temperature of the fuel salt is very high (about 1,400°C) compared with the operating temperature (about 700°C).
- Since there is no water within the containment, there is no possibility of high pressure by steam generation, and therefore no possibility of hydrogen explosions at any accidental conditions.
- The fuel salt is drained to a drain tank through a freeze valve, if required. In case of a rupture in the primary loop, the spilled fuel salt is drained to an emergency drain tank without passing a freeze valve.
- The fuel salt only reaches criticality within the graphite core (with the appropriate moderation). In an accident the fuel salt is drained to a drain tank designed so that a re-criticality accident does not occur.
- MSR has a large negative reactivity coefficient of a fuel salt temperature that can suppress an abnormal change of the reactor power. Although a temperature coefficient of graphite is positive, it does not affect the safety, because the heat capacity of graphite is large enough.
- Since gaseous fission products (FP) can be removed by separation from the fuel salt, the danger due to the release of radioactivity from the core at accidental conditions can be minimized.
- Since fuel composition can be adjusted when necessary, the excess reactivity and the reactivity margin to be compensated by control rods are small. Therefore, reactivity requirements for control rods are also small.
- The delayed neutron fraction of ^{233}U is lower than that of ^{235}U and some of delayed neutrons are generated outside the core. However, safe control of the reactor is possible because of a large negative reactivity coefficient and limited potential reactivity insertion.
- Since there is no airflow and no heat source within the core when the fuel salt is drained at accidental conditions, self-sustained graphite oxidation does not occur.

Engineered Safety System Approach and Configuration

Many of the safety features were described above. Therefore, redundant and diverse emergency core cooling systems (ECCS), makeup water pools, and automatic depressurization system (ADS) are not required. In order to protect against a freeze accident in a molten fuel salt loop, a high temperature containment is equipped.

Decay heat removal system

In normal shutdown condition, decay heat is transferred to a secondary loop and a steam-line loop, and disposed to the ultimate heat sink (seawater for example). If all pumps in a primary or secondary loop stop, fuel salt is drained to a drain tank through a freeze valve. Decay heat at the drain tank is cooled by a passive heat removal system, and finally its heat is disposed to the outside environment through an air-cooled system that does not require electricity.

Emergency core cooling system

As is explained above, redundant and diverse emergency core cooling systems (ECCS) and makeup water pools are not required. This would simplify the plant, and eliminate concerns of failures in safety systems.

Containment system

Since the risk of pressurization accidents is incredible, the containment size can be minimized. Although molten salt is not flammable, inert gas (N_2) is enclosed within a containment in order to maintain fuel salt purity in case of a pipe break accident. The MSR-FUJI design has three levels of containment. The first is the reactor vessel and pipes made of Hastelloy N. The second is a high temperature containment composed of three layers, which contains a reactor vessel, pipes, and a heat exchanger, as is shown in *Figure 2*. In order to avoid a freezing accident, this containment is equipped with heaters. The third level is a reactor building composed of two layers. As explained above, a pressurization accident is incredible due the low vapor pressure. Therefore, a containment cooling system (CCS) and makeup water pools are not required.

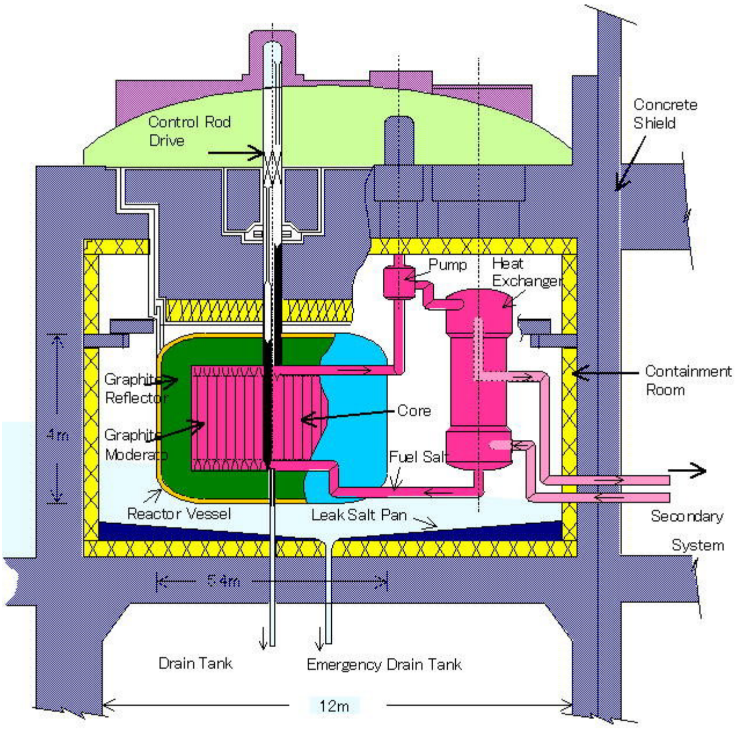

Figure 2: Vertical cross section of primary system of MSR-FUJI (Reproduced courtesy of ITMSF).

6. Plant safety and Operational Performances

Overall safety is described above. In case of a station blackout (SBO: Loss of all AC electricity) the MSR-FUJI can be shut down and cooled without electricity. Core meltdown or steam/hydrogen explosion is physically excluded by design and no ECCS is needed. As for long-time operation, reactivity can be controlled anytime by a fuel concentration adjustment system.

In normal daily operation, the power level can be controlled by core flow or by core temperature control. That is, load following is easily performed without using control rods. Control rods are withdrawn in normal operation, and are inserted by gravity in case of emergency shutdown.

7. Instrumentation and Control systems

Instrumentation and control (I&C) systems in the MSR-FUJI design are the same as for recent LWR designs. It must support operators in making decisions and efficiently operating the plant during plant start-up, shutdown, normal operation, surveillance testing, and accidental situations. It adopts the man-machine interface more useful, and expands the scope of automatic control.

I&C systems include an alarm system, an information processing system, a reactor protection system, an engineered safety equipment control system, power and process control systems, sensors and instrumentation, an radiation monitoring system, and so on.

8. Plant Arrangement

Major buildings of MSR-FUJI are a reactor building, a steam generator building with a main control room, and a turbine-generator building as shown in *Figure 3*. An auxiliary building is not shown.

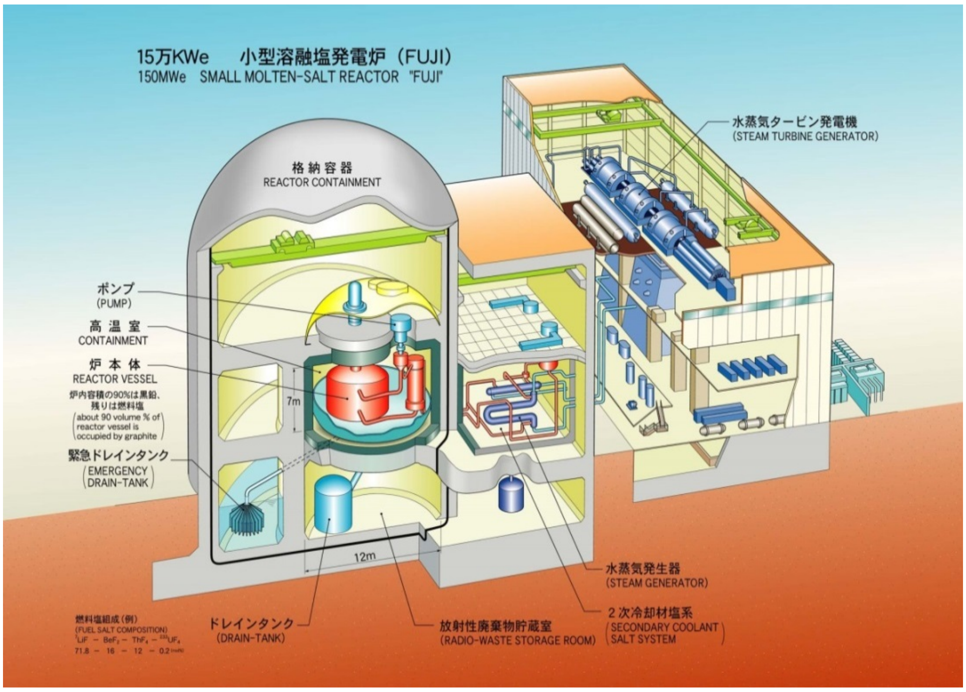

Figure 3: Bird-eye view of MSR-FUJI (Reproduced courtesy of ITMSF).

Reactor building

The reactor building contains a high temperature containment, drain tanks, a radio-waste storage, and other facilities required for the reactor. This reactor building is a cylindrical shape with a hemispherical dome, which is made of concrete with steel liner as its inner layer. The reactor building is founded on a common base-mat together with other buildings.

Control building

The main control room (MCR) is located at a steam generator building, which is next to a reactor building. The MCR is a key facility to cope with normal and emergency situations, so it is designed to ensure that plant personnel successfully perform the tasks according to the proper procedures.

Balance of plant:

Turbine Generator Building

The turbine generator (T/G) building contains the supercritical turbine and generator, which produce electricity. Also, it contains condensers for disposed steam. The condensers use outside water (for example, sea water) for cooling.

Electric Power Systems

These systems include the main generator, transformers, emergency diesel generators (EDG), and batteries. MSR-FUJI is equipped with two external electric sources for operation, and EDGs are required for backup. In case of station blackout (SBO: Loss of all AC electricity), it can be shut down and cooled without electricity.

9. Design and Licensing Status

Preliminary designs for various applications have been completed [3]. Three experimental MSRs were constructed, and one of them was operated for 4 years without severe problems. The detailed design has not yet started. Safety criteria and guidelines for MSR licensing are proposed [4].

10. Plant Economics

MSR-FUJI can achieve higher thermal efficiency owing to its high exit temperature. It has the potential to be operated for longer periods with a high availability factor since it does not require refueling shutdown. Also, fuel cycle advantages and cost saving can be realized due to its self-sustaining fuel cycle and no need for fuel element manufacturing. A plant construction cost for the 1000 MWe MSR-FUJI (super-FUJI) is estimated as less than $2000/KWe and the total electricity generation cost about 3 cents/KWh. In general the economic performance of a smaller plant may be expected to be worse than that of a larger plant. This factor has not been evaluated till now.

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[1] Furukawa, K. et al. “Molten Salt Reactor for Sustainable Nuclear Power – MSR FUJI”. p.821-856 of *IAEA-TECDOC-1536* “Status of Small Reactor Designs Without On-Site Refueling”, 2007

[2] Yoshioka, R. “Nuclear Energy Based on Thorium Molten Salt”, Chapter-23 of the book “*Molten Salts Chemistry: From Lab to Applications*“ edited by F. Lantelme and H. Groult, Elsevier Inc., USA, 2013

[3] Yoshioka, R., Kinoshita, M. “Liquid Fuel, Thermal Neutron Spectrum Reactors”, Chapter-11 of the book “*Molten Salt Reactor*”, Elsevier Inc., USA, to be published in 2017

[4] Yoshioka, R., Mitachi, K., Shimazu, Y., Kinoshita, M. “Safety Criteria and Guidelines for MSR Accident Analysis”, *PHYSOR-2014*, Kyoto, Japan, 2014

Appendix: **Summarized Technical Data (MSR-FUJI module)**

General plant data		
Reactor thermal output	450	MWth
Power plant output, gross	207	MWe
Power plant output, net	200	MWe
Power plant efficiency, net	44.4	%
Mode of operation	load following	
Plant design life	30	Years
Plant availability target	90	%
Seismic design, SSE	Same as LWRs	g
Primary Coolant material	LiF-BeF$_2$-ThF$_4$-^{233}UF$_4$	
Secondary Coolant material	NaBF$_4$-NaF	
Moderator material	Graphite	
Thermodynamic Cycle	Rankine	
Type of Cycle		
Non-electric application	Multiple	
Safety goals		
Core damage frequency (primary loop rupture)	Core meltdown is impossible	/reactor-year
Large early release frequency	Core meltdown is impossible	/RY
Occupational radiation exposure	tbd	Sv/Person/Y
Operator Action Time	> 1 week	hours
Nuclear steam supply system		
Steam flow rate at nominal conditions	252	kg/s
Steam pressure/temperature	tbd/538	MPa(a)/℃
Feedwater flow rate at nominal conditions	tbd	kg/s
Feedwater temperature		℃
Reactor coolant system		
Primary coolant flow rate	2400	kg/s
Reactor operating pressure	0.5	MPa(a)
Core coolant inlet temperature	565	℃
Core coolant outlet temperature	704	℃
Mean temperature rise across core	139	℃
Reactor core		
Active core height	4.66	m
Equivalent core diameter	4.72	m
Average linear heat rate	n/a	kW/m
Average fuel power density	n/a	kW/kgU
Average core power density	5.5	MW/m^3
Fuel material	Molten salt with thorium and uranium	
Cladding tube material	n/a	
Outer diameter of fuel rods	n/a	mm
Rod array of a fuel assembly	n/a	
Number of fuel assemblies	n/a	
Enrichment of reload fuel at equilibrium core	2	Wt%
Fuel cycle length	Continuous operation	months

Average discharge burnup of fuel	No mechanical limitation	MWd/kg
Burnable absorber (strategy/material)	None	
Control rod absorber material	B_4C	
Soluble neutron absorber	None	
Reactor pressure vessel		
Inner diameter of cylindrical shell	5340	mm
Wall thickness of cylindrical shell	50	mm
Total height, inside	5400	mm
Base material	Hastelloy N	
Design pressure/temperature	0.5/704	MPa(a)/℃
Transport weight	60	t
Steam generator (if applicable)		
Type	Shell and tube	
Number	tbd	
Total tube outside surface area		m^2
Number of heat exchanger tubes		
Tube outside diameter		mm
Tube material	Hastelloy N	
Transport weight		t
Reactor coolant pump (if applicable)		
Type	Centrifugal pump	
Number	2	
Head at rated conditions		m
Flow at rated conditions		m^3/s
Pump speed		rpm
Pressurizer (if applicable)		
Total volume		m^3
Steam volume: full power/zero power		m^3
Heating power of heater rods		kW
Primary containment		
Type		
Overall form (spherical/cylindrical)	Cylindrical	
Dimensions (diameter/height)	12/7	m
Design pressure/temperature	tbd / 538	kPa(a)/℃
Design leakage rate	Tbd	Vol%/day
Is secondary containment provided?	No	
Residual heat removal systems		
Active/passive systems	Passive cooling without electricity	
Safety injection systems		
Active/passive systems	ECCS is not required	
Turbine (for two module power plant)		
Type of turbines	Super-critical	
Number of turbine sections per unit (e.g. HP/MP/LP)		
Turbine speed		rpm
HP turbine inlet pressure/temperature		MPa(a)/℃
Generator (for two module power plant)		
Type	tbd	
Rated power		MVA
Active power		MW
Voltage		kV

Frequency		Hz
Total generator mass including exciter		t
Condenser		
Type	tbd	
Condenser pressure		kPa(a)
Feedwater pumps		
Type	None	
Number		
Head at rated conditions		m
Flow at rated conditions		m^3/s
Pump speed		rpm