Status Report – LFTR

Overview

Full name	Liquid-Fluoride Thorium Reactor
Acronym	LFTR
Reactor type	Molten Salt Reactor
Purpose	Commercial
Coolant	Molten fluoride
Moderator	Graphite
Neutron Spectrum	Thermal
Thermal capacity	600 MW per module
Electrical capacity	250 MW per module
Design status	Conceptual Design
Designers	Flibe Energy
Last update	July 28, 2016

NOTE:

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

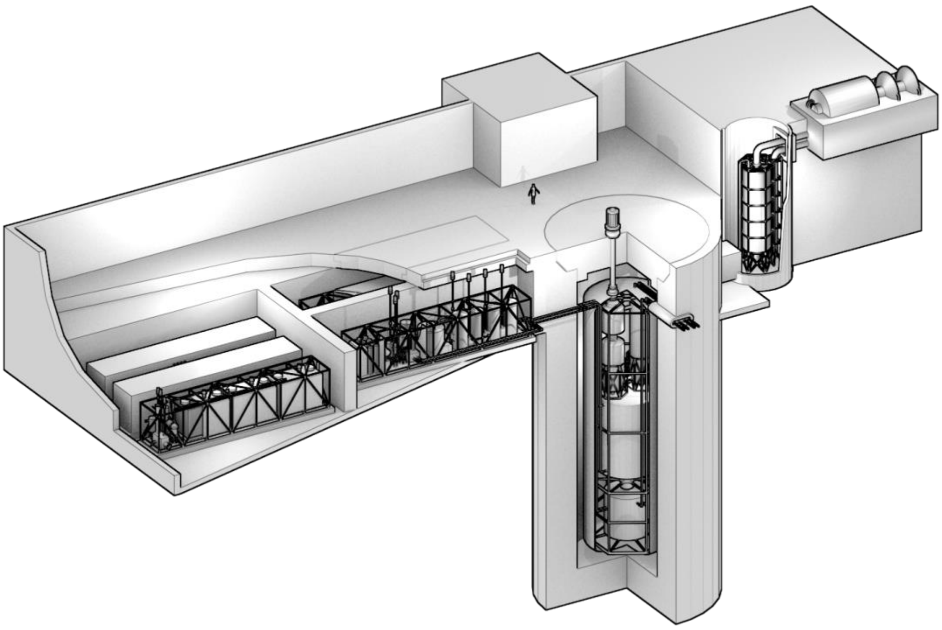

Figure 1: View of the liquid-fluoride thorium reactor (LFTR) plant design (Reproduced courtesy of Flibe Energy)

1. Introduction

The liquid-fluoride thorium reactor (LFTR) design by Flibe Energy is a graphite-moderated, thermal-spectrum reactor with solutions of liquid fluoride salts containing both fissile and fertile materials. Thermal power generated from nuclear fission would drive electrical generation in a closed-cycle gas turbine power conversion system. The objective is to produce electricity at low cost by efficiently consuming thorium.

Mixtures of fluoride salts raised to a sufficient temperature to allow them to liquefy form an ideal medium in which nuclear fission reactions can take place. The ionically-bonded nature of the salts prevents radiation damage to the mixture and allows for operation at high temperature yet at essentially ambient pressure.

The high operational temperatures of the fluoride salts (500-700°C) make them excellent candidates for coupling to a closed-cycle gas turbine power conversion system (PCS). The supercritical carbon dioxide gas turbine employing the recompression cycle is proposed and can generate electricity at high efficiencies (approximately 45%).

The LFTR design has a two-region core (feed / breed) and utilizes a closed fuel cycle based on thorium. The reactor vessel incorporates two plena with a central active core region and the outer blanket area, both filled with fluoride salt. The thorium-232 in the blanket region is ultimately converted to uranium-233 through neutron capture and beta decay. The chemical processing system is used to separate and re-introduce the fertile and fissile material to the two fluoride fuel-salt streams respectively. Utilizing thorium fuel in a thermal neutron spectrum, the reactor is able to extract almost all the energy content thus assuring practically unlimited thorium resources and the associated insignificant basic fuel costs.

2. Target Application

Develop a power-generating nuclear reactor that will produce electrical energy at low cost by efficiently consuming thorium.

3. Development Milestones

2015	Completion of EPRI-funded study of LFTR design

4. General Design Description

Design Philosophy

The objective of the liquid-fluoride thorium reactor (LFTR) design proposed by Flibe Energy [] is to develop a nuclear power plant that will produce electrical energy at low cost. By utilizing thorium fuel in a thermal neutron spectrum, the reactor is able to utilize the energy content of the thorium at a very high efficiency, approaching 100%, at which point the Earth's thorium resources practically becomes unlimited. Some of the main principles followed in the design are (i) inherently safe, with a no meltdown and non-pressurized core; (ii) simplicity, to have an intrinsically stable and self-regulating design; (iii) fuel efficient, and (iv) have the potential to produce far less waste. The general plant layout is shown in *Figure 1*.

Nuclear Steam Supply System

The nuclear heat supply and power conversion system is shown in *Figure 2*. The individual systems are described in more details below followed by other system design descriptions.

Reactor Core

The reactor vessel functions to hold fuel salt, blanket salt, and moderator material together in such a way so as to maintain a critical configuration at the temperatures and thermal power levels required. In addition, it incorporates reactivity control mechanisms both active and passive. The fuel and blanket salts are kept separated in two plena integrated into a single structure within the reactor vessel. Fuel salts are directed into the appropriate channels as it is circulated through the reactor.

The reactor vessel design incorporates several safety functions. In many accident events, a freeze valve, which form part of the vessel and primary loop system, melts and allows fuel salt to drain from the primary loop and the reactor vessel into the drain tank. The separation of the fuel salt from the solid graphite moderator retained in the reactor vessel, assures a subcritical configuration can be established in the drain tank.

The internal graphite structures needs to be replaceable since it subjected to a fast and thermal neutron flux that is greatly in excess of that which will be experienced by the metallic reactor vessel itself, and the replacement of these graphite structures will enable the reactor vessel to continue to operate and serve its function.

Fuel Characteristics

Thorium fuel is introduced as a tetrafluoride into the blanket salt mixture of the reactor. The blanket salt surrounds the active "core" region of the reactor and intentionally absorbs neutrons in the thorium, which leads to the transmutation of the thorium-232 via nuclear beta decay, first to protactinium-233 and later to uranium-233. Both the protactinium and the uranium are chemically removed from the blanket salt mixture and introduced into the fuel salt mixture in the reactor to fission. The fission products are later chemically removed from the fuel salt and in some cases separated and purified before final disposition.

Primary Loop

The function of the primary loop is to direct fuel salt through the primary heat exchanger (PHX) in normal operation, where the fuel salt transfer its heat to the coolant salt. The primary pump provides the necessary forced circulation. The primary loop system begins and ends with its connection to the reactor vessel and includes the primary pump, the PHX, the bubble injection system, and the fuel salt drain tank and its associated external cooling system.

Intermediate Loop

The intermediate loop transfer heat from the primary loop to the PCS The intermediate loop system includes the PHX, the coolant salt pump, the salt side of the gas heater (or intermediate heat exchanger, IHX), the coolant salt drain tanks, and the pressure relief (blowout) valves.

The intermediate loop also isolates the primary loop from the high pressures of the PCS using pressure relief valves. The isolation is an important safety function. In case of a failure in the high pressure PCS it will prevent the transmittal of high pressure back through the coolant salt to the primary loop. The primary loop is not designed for high pressures and without isolation a break in the PCS could cause component rupture and potentially disperse radioactivity into the containment.

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer	Flibe Energy
Country of origin	United States
Reactor type	Molten Salt Reactor
Electrical capacity (MWe)	250
Thermal capacity (MWth)	600
Expected capacity factor (%)	90+
Design life (years)	Undetermined
Plant footprint (m^2)	To be determined
Coolant/moderator	Graphite moderator, LiF-BeF2-UF4 fuel salt
Primary circulation	Forced circulation
System pressure (MPa)	Ambient
Core inlet/exit temperatures (^oC)	500 / 650
Main reactivity control mechanism	Negative temperature coefficient; control rod insertion
RPV dimensions and weight	To be determined
Configuration of reactor coolant system	Loop
Power conversion process	Supercritical CO2 gas turbine
Cogeneration / Process Heat Capabilities (High / Low	Example: Yes, possible with different configuration
Passive Safety Features:	Freeze plug releasing to drain tank; large negative
Active Safety Features:	Motor-driven control rods for shutdown
Moderator type/assembly array	Graphite prisms, triangular pitch
Moderator assembly active length (m)	To be determined
Number of moderator assemblies	To be determined
Fuel enrichment (%)	Not applicable, uses uranium-233 fuel derived from Th
Fuel cycle (months)	Continuous refueling from U-233 produced in blanket
Approach to engineered safety systems	Passive safety implemented throughout
Number of safety trains	Not applicable
Emergency Safety Systems	Not applicable
Residual Heat Removal System	Drain tank in thermal communication with environment
Refuelling outage (days)	Not applicable
Distinguishing features	Complete consumption of thorium resource for energy
Modules per plant	4-6
Target construction duration (months)	To be determined
Seismic design	To be determined
Core damage frequency (per reactor-year)	Not applicable
Design Status	Concept

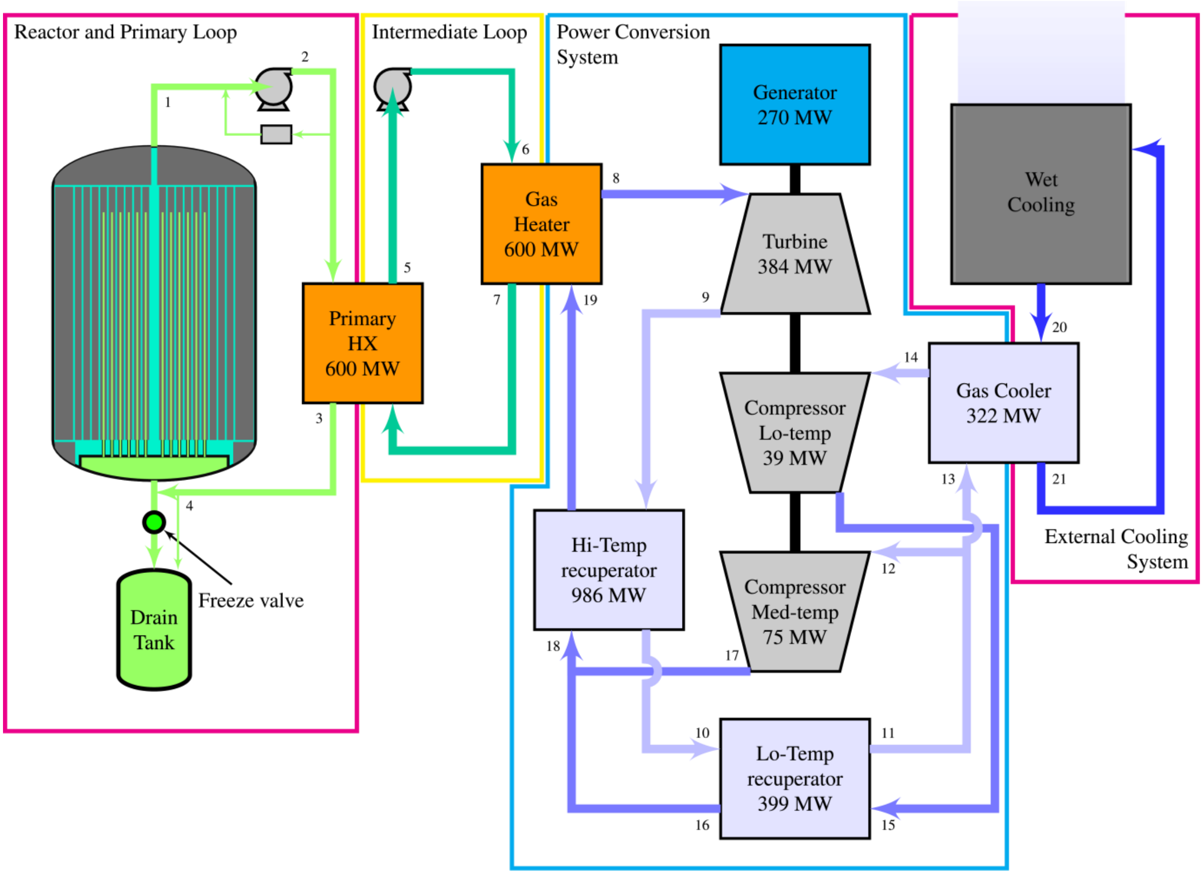

Figure 2: Reactor and primary loop, intermediate loop, power conversion system, and external cooling system simplified flow diagram (Reproduced courtesy of Flibe Energy)

In the event of a failure in the gas heater and the pressurization of the intermediate loop, the pressure relief valves allow coolant salt to leave the loop. This deprives the primary loop of cooling capability and will lead the melting of the freeze valve in the primary loop and the drain of the primary loop fluid contents into the fuel salt drain tank (also see passive shutdown and heat removal later).

The intermediate loop also serves another practical purpose. Since cooling fuel salt with a coolant salt is more compact and effective than cooling fuel salt directly with a gas, the PHX is much smaller and operates at low pressures. It also reduces the fuel salt inventory of the primary loop which reduces the amount of fissile material needed for a given power rating.

Power Conversion System

The function of the PCS is to convert the maximum amount of enthalpy contained in the heated working fluid into shaft work and to reject the remaining enthalpy to the environment in an acceptable manner. The supercritical carbon dioxide gas turbine employing the recompression cycle appears to be the best candidate for coupling to the reactor.

The PCS includes four heat exchangers: the gas side of the gas heater, the gas cooler, and the high-temperature and low-temperature recuperators. It also includes the main turbine, the main compressor, the recompressor, and the electrical generator. The PCS interfaces with the intermediate loop through the gas heater, and interfaces with the external cooling system through the gas cooler.

The PCS and carbon dioxide working fluid in the cycle provides a final barrier to tritium release into the environment. Tritium generation is an inevitable consequence of using lithium and beryllium in the salt mixture and thus the PCS also includes a tritium removal system.

External Cooling System
The function of the external cooling system is to reject the heat that was not converted to shaft power in the PCS to the environment in an acceptable manner. The design shall also prevent the transmission of tritium to the outside environment.

Fuel Handling System
New fissile material can be easily added or removed without resorting to changing the chemical nature of the solvent, and this allows overall reactivity to be held very close to the minimum amount needed to achieve criticality. The fuel salt control is done by the chemical processing system.

Chemical Processing System
The main function of the chemical processing system is to remove uranium and protactinium from the blanket salt and to return uranium to the fuel salt. Its secondary function is to remove fission products from the fuel salt and to further process them into acceptable forms.

The safety-related functions of the chemical processing system mainly involve the safe handling of highly radioactive materials. Drain tanks and cooling systems must be provided for each reaction vessel at each stage of processing through the system. Unfortunately highly chemically reactive gaseous fluorine and hydrogen is needed, to be created just as they are needed from an electrolytic cell using anhydrous hydrogen fluoride as the feed.

Various fission products disperse into the fluid streams of the chemical processing system and some must be handled differently than others. A class of fission products including selenium and tellurium will migrate with gaseous hydrogen and hydrogen fluoride and are handled in a potassium hydroxide neutralization cleanup system. Other fission products are removed from the fuel salt in a reductive extraction column and will exist in a metallic state in bismuth. The high chemical potential of a metal form means that these fission products will need to be oxidized and placed in a disposal form before shipment from the site. The small amounts of material produced means that these disposal plans will not constitute a major issue with reactor operations.

Substantial development work will be needed to prepare for long-term operation of the chemical processing system.

Offgas Handling System
The function of the offgas handling system is to provide a sufficient holdup volume for xenon and krypton generated in the fission reaction, allowing all of their radionuclides to decay to other forms with the exception of krypton-85, which has a 10-year half-life.

Xenon and krypton (and to some degree tritium) are the most mobile radioactive terms in the reactor system. Tritium is subject to chemical reactions but xenon and krypton are not. Fortunately, with the exception of krypton-85, all of their radionuclides are short-lived and a holdup of roughly thirty days is sufficient to allow them to decay to non-mobile forms like caesium, rubidium, strontium, and barium.

The offgas handling system utilizes the fuel salt decay tank as a primary storage volume, allowing the initial and most intense stages of decay to take place there. The passive cooling system of the fuel salt decay tank is utilized to cool the noble gases, providing a continuous test of the efficacy of this crucial subsystem. After initial cooling in the decay tank, gaseous xenon and krypton in a stream of helium pass into a long piping arrangement filled with charcoal (that adsorbs these gases) and cooled by water that provides sufficient holdup volume over time.

After all radioisotopes of xenon have decayed away, the remaining gas stream is cryogenically cooled to separate stable xenon from helium and krypton. Xenon is bottled and could be sold at this stage. Krypton is also bottled and stored because of the continuing slow decay of krypton-85. Helium is recycled and returned to the gas handling system.

Reactivity Control

The reactor vessel accommodates passive and active control rod systems which also have important safety functions. The blanket salt held within the reactor vessel is a strong neutron absorber, and a blanket salt leak from the reactor vessel could lead to the reduction in the blanket salt inventory contained in the reactor vessel, increasing reactivity by removing a neutron-absorbing medium. To compensate for this introduction of positive reactivity, a series of control rods that float in the blanket salt and are thus held outside of the core could be used. An accidental drain of the blanket salt would remove the buoyancy effect of these rods, allowing them to slide down into the core and add negative reactivity to replace and overcome the negative reactivity lost from by the drain of the blanket fluid. These rods would be designed to enter the core passively, without any operator action, in the event of blanket loss. But it is anticipated that there would also be an active drive system present that could drive these rods into the core intentionally in order to have a shutdown effect on the reactor. It would not be possible to start the reactor unless these rods were fully withdrawn from the core due to their strong negative reactivity.

An active set of control rods, of a more conventional design, would also be present in the reactor vessel and would serve a safety function, allowing the operator to control the reactivity level of the reactor. These rods, which would comprise a smaller and less potent source of negative reactivity, would be clustered near the center of the core and provide finer control over reactivity levels. Other possible designs are also considered.

Reactor Pressure Vessel

The reactor vessel shall be constructed from a material that is suitable for accomplishing its functions at the anticipated temperatures, stresses, and neutron fluxes that will exist during operation. Current evidence points to a modified form of Hastelloy-N as the suitable construction material.

At present, it is anticipated that the reactor vessel will incorporate a small heat exchanger exclusively meant for cooling the blanket salt, with the blanket salt flowing throughout the core under the driving force of natural circulation. This heat exchanger has an important safety function in that it cools blanket salt which contains short-lived thorium-233, a significant heating term in the fluid that cannot be chemically removed. If the reactor shut down or if blanket salt chemical processing was terminated for any reason, the reactor vessel would also have to accommodate the heating generated by protactinium decay, but thorium-233 decay would end relatively quickly in this case, since thorium-233 only has a 22-minute half-life.

5. Safety Features

The properties of fluoride salts offer LFTR enhanced safety characteristics. The fluid salt in the core is not pressurized, thus eliminating the fundamental driving force that can release large amounts of radioactivity to the environment. The notion of a “meltdown” leading to reactor failure becomes irrelevant in a reactor designed around the use of liquid fuels. The reactivity of the reactor is self-controlling because any increase in the reactor's operating temperature results in decrease in density of the fuel salt in the core and a reduction of reactor power, thus inherently stabilizing the reactor without the need for human intervention or backup systems.

The reactor is designed with a simple salt plug drain in the bottom of the core vessel to completely shut down the core through gravity. If the reactor should lose power or need to be powered down for any reason, the salt plug is simply allowed to melt and the fluid salt to drain into a passively cooled containment vessel(s) where decay heat is readily removed. This simple feature prevents accidents or radiation releases due to lack of cooling. It also provides a convenient means to shut down and restart the reactor quickly and easily.

The safety function of several of the systems was already described above. Below a few additional safety features of the LFTR are highlighted or further explained.

Fission Product Retention

The integrity of the reactor vessel plays an important role in minimizing radiation hazards by confining radioactive fluids to the flow channels and volumes defined by the vessel and its internal structures. Most fission products, including all of those of greatest radiological concern, form stable fluoride salts that are retained in the overall mixture under all conditions. Fission products gases, whose removal is important from a performance and safety basis, are easily separated from the fluid mixture and allowed to decay to stability in a separate system.

Passive Shutdown and Heat Removal

An important safety function is embedded in the primary loop and is activated when the reactor overheats or loses its coolant flow. A freeze valve is integrated into the primary loop that is maintained frozen by an active coolant system. When this coolant is lost or if the temperature of the system exceeds its cooling capability, the freeze valve fails open and the fuel salt drains out of the primary loop and out of the reactor vessel into the fuel salt drain tank.

The fuel salt drain tank is integrated with a separate cooling system that is passively connected to the outside environment, and provides the necessary cooling for the fuel salt within it.

Fluoride Salt Characteristics

The fluoride salt mixtures in question have high volumetric heat capacity, comparable to water, and do not undergo vigorous chemical reactions with air or water in contrast to many liquid metals.

The components of fluoride salt mixtures have both desirable and undesirable aspects, and the two most important are lithium-7 fluoride and beryllium fluoride. The two natural isotopes of lithium must be separated from one another since lithium-6 (7.5% of natural lithium) is far too absorptive of neutrons to be a suitable component of a reactor fluid. Beryllium fluoride is chemically toxic but has very attractive nuclear and physical properties. The chemical processing and purification of fluoride salt mixtures typically involves using powerful reactants such as gaseous fluorine and hydrogen fluoride which are very toxic and reactive. But the fact that fluoride salt mixtures are processed in a salt form rather than being dissolved into an aqueous solution mitigates issues of accidental criticality considerably, since water is an excellent moderator whereas salts are poor.

Fluoride salts, due to their exceptional chemical stability, have the potential to corrode most structural metal alloys, but some alloys have been developed that hold up very well against any corrosive attack. Invariably these alloys are based on nickel with a variety of other metallic constituents. Fluoride salts moderate neutrons sufficiently on their own to prevent the formation of a truly fast neutron spectrum, but are still insufficiently effective to generate a thermal neutron spectrum. Thus separate moderator materials are necessary for the reactor and graphite has been proven to be very attractive.

Graphite is not wet by the fluoride salts and does not require cladding. If the surface of the graphite is treated so that small pores are closed, most fission product gases can be excluded from the graphite and overall performance will be high. Graphite does experience issues from dimensional distortion over time, but this effect can be quantified and compensated for in reactor design.

6. Plant Arrangement

The plant arrangement has been shown in *Figure 1*. The reactor cavity or silo is below grade and contains the primary circuit

7. Design and Licensing Status

The design is in an early stage of development and licensing activities have not yet been undertaken.

8. Plant Economics

The economic performance of the plant has not yet been modelled in sufficient detail but all indications point towards its performance being strongly competitive with other clean energy sources.

For more information visit: http://flibe-energy.com/

Appendix: **Summarized Technical Data (LFTR module)**

General plant data		
Reactor thermal output	600	MWth
Power plant output, gross	250	MWe
Power plant output, net		MWe
Power plant efficiency, net	45	%
Mode of operation		
Plant design life	Undetermined	Years
Plant availability target		%
Seismic design, SSE	To be determined	g
Primary Coolant material		
Secondary Coolant material		
Moderator material	Graphite	
Thermodynamic Cycle		
Type of Cycle		
Non-electric application	Focus on electricity	
Safety goals		
Core damage frequency (primary loop rupture)	Not applicable	/reactor-year
Large early release frequency		/RY
Occupational radiation exposure		Sv/Person/Y
Operator Action Time		hours
Nuclear steam supply system		
Steam flow rate at nominal conditions		kg/s
Steam pressure/temperature		MPa(a)/℃
Feedwater flow rate at nominal conditions		kg/s
Feedwater temperature		℃
Reactor coolant system		
Primary coolant flow rate		kg/s
Reactor operating pressure	Ambient	MPa(a)
Core coolant inlet temperature	500	℃
Core coolant outlet temperature	650	℃
Mean temperature rise across core	150	℃
Reactor core		
Active core height		m
Equivalent core diameter		m
Average linear heat rate		kW/m
Average fuel power density		kW/kgU
Average core power density		MW/m^3
Fuel material	Molten salt with Thorium and Uranium	
Cladding tube material	none	
Outer diameter of fuel rods		mm
Rod array of a fuel assembly		
Number of fuel assemblies		
Enrichment of reload fuel at equilibrium core	Not applicable	Wt%
Fuel cycle length	Continuous operation	months
Average discharge burnup of fuel		MWd/kg
Burnable absorber (strategy/material)		

Control rod absorber material		
Soluble neutron absorber		
Reactor pressure vessel		
Inner diameter of cylindrical shell	4861	mm
Wall thickness of cylindrical shell	50	mm
Total height, inside	5717	mm
Base material	SS316	
Design pressure/temperature	0.552/704	MPa(a)/℃
Transport weight (of containing Can)	400	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		
Number		
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)		
Dimensions (diameter/height)		m
Design pressure/temperature		kPa(a)/℃
Design leakage rate		Vol%/day
Is secondary containment provided?		
Residual heat removal systems		
Active/passive systems	Drain tank in thermal communication with environment	
Safety injection systems		
Active/passive systems		
Turbine (for two module power plant)		
Type of turbines	Supercritical	
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		
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