Status Report – MSTW

Overview

Full name	Molten Salt Thermal Wasteburner
Acronym	MSTW
Reactor type	Molten Salt Reactor
Purpose	Commercial
Coolant	Molten Salt
Moderator	Graphite
Neutron Spectrum	Thermal
Thermal capacity	270 MW per module
Electrical capacity	115 MW per module
Design status	Conceptual design
Designers	Seaborg Technologies
Last update	July 28, 2016

NOTE:

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

Figure 1: Early model of the underground reactor cave (Reproduced courtesy of Seaborg Technologies).

1. Introduction

The Seaborg Technologies' Molten Salt Thermal Wasteburner (MSTW) is a thermal spectrum, single salt, molten salt reactor, operated on a combination of spent nuclear fuel (SNF) and thorium. It is envisioned to produce 100 MWe, or 115 MWe with a 2 stage turbine, from 270 MWth. The core outlet temperature is 700°C, but can go as high as 900°C for special uses, such as hydrogen production. The MSTW is designed around inherent safety features; no active measures are required to control the reactor under abnormal circumstances. The fully modularized MSTW is suitable for mass production. As a module reaches the end of its lifecycle, it will be extracted and returned for recycling in a central production facility after it has cooled down. The reactor core, including the graphite-based moderator, is projected to have a lifecycle of seven years, while the power plant will operate on the same batch of SNF for the 60 year facility lifetime. The MSTW is in the early design phase and Seaborg Technologies (ST) is focused primarily on neutronics, radiative transfer, computational fluid dynamics (CFD), and the physics of the design. A model of the underground reactor cave is shown in *Figure 1*.

2. Target Application

The MSTW is designed for electricity production, district heating/cooling, sea water desalination, etc. Due to the high outlet temperature it is well suited for synthetic fuel, as well as industrial process heat applications. Its high burnup and the fact that it is fuelled directly with spent nuclear fuel makes it a good option for spent nuclear fuel stockpile reduction. However, it can, without modification, operate on a wide array of different fuels.

3. Development Milestones

2014	Thermal wasteburner concept coined.
2015	Thermal wasteburner neutronic benchmark. Pre-conceptual design (whitepaper).

4. General Design Description

Design Philosophy

The MSTW was originally designed to address the three main concerns that resulted in the Danish ban on nuclear power in 1985, namely safety, waste, and proliferation. As the design has been developed and matured, the following three concepts together have been the essential philosophy around which the other features have been planned and implemented:

Safety: The system is placed in an optimised configuration, whereby any perturbation to such a system - from operator mistakes to major earthquakes - will move the system away from the optimum and thus result in an automatic power reduction and, if the situation is not alleviated, eventually reactor shutdown – see an illustration of one of these principles in *Figure 2*.

Waste: By combining SNF with thorium, the production of transuranic elements (TRU) is lower than the rate at which they are created. The net reduction is roughly five tonnes TRU over the 60 year plant lifetime.

Non-proliferation: To ensure high proliferation-resistance the MSTW is designed to be a single salt reactor wherein the chemical reprocessing system is incapable of extracting specific actinides. Furthermore, no actinide element will have an isotopic composition usable for nuclear weapons at any point in the fuel cycle.

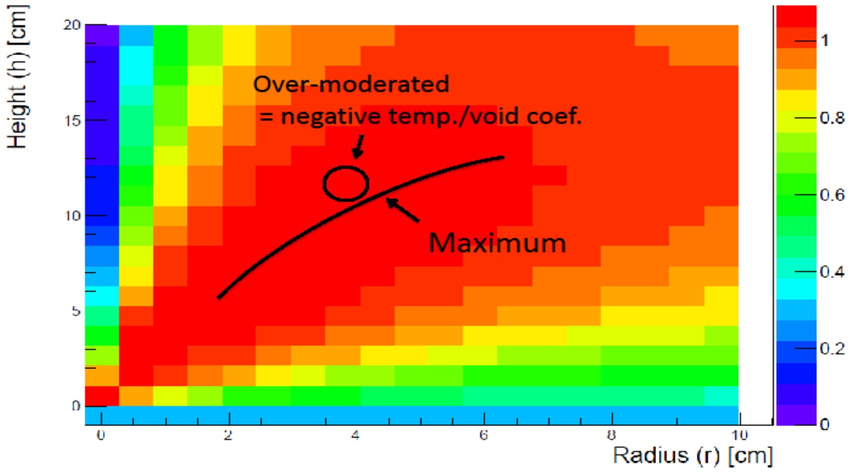

Figure 2: Optimal configuration principle and safety through physics – illustrated through a core geometry optimization of keff (Reproduced courtesy of Seaborg Technologies).

Power Conversion Unit

The MSTW utilizes a coolant salt based on a core-integrated primary heat exchanger system. The coolant salt acts as heat storage and flows through the primary side of the steam generator, which delivers steam at 550°C to the single or two stage turbines (Rankine). The coolant salt and heat exchanger system also serves as core shielding and neutron reflector. The reactor core will passively shut down if overheated (negative thermal coefficient); therefore, loss of coolant accidents (LOCAs) will result in reactor automatically powering down. In case of a continued inability to cool the core, the fuel will eventually drain itself through a freeze plug to a passively cooled dump tank.

Reactor Core

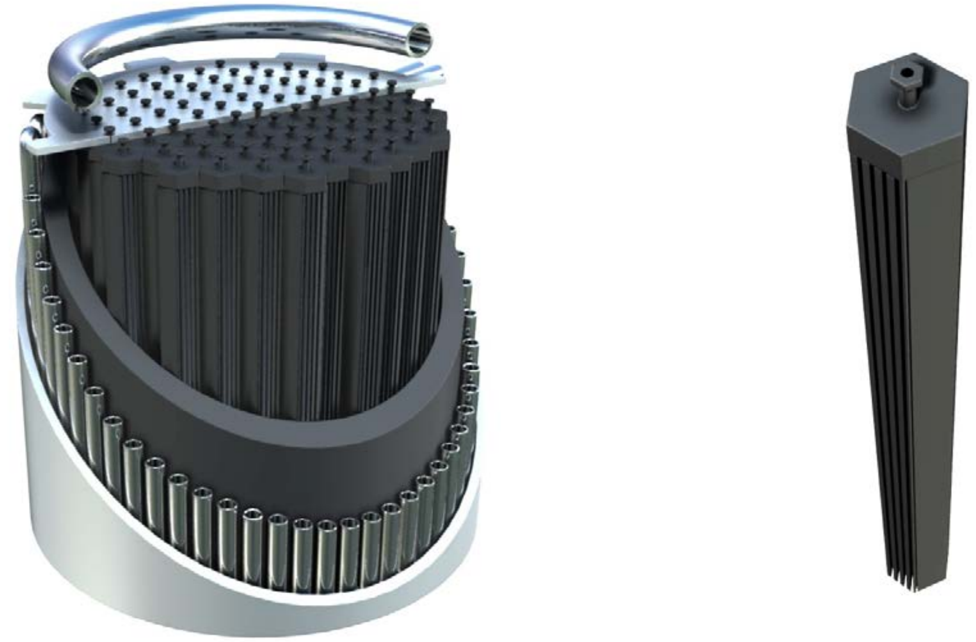

Figure 3: View of the inner reactor core and graphite moderator block (Reproduced courtesy of Seaborg Technologies).

The MSTW core is a graphite-based compound-moderator thermal reactor core as illustrated in *Figure 3*. The core is slightly over-moderated to ensure negative void and temperature reactivity coefficients. The graphite is coated with a metal and corrosion is reduced by regularly circulating the fluoride salt through a fluoride burner and by adding a reducing anode to the fuel salt. The reactor operates at 12 kW per litre core, with a peak power density of 250 kW per litre fuel near the core centre. Swelling and corrosion of the graphite moderator is expected to be the limiting factor for the lifetime of the core module.

Fuel Characteristics

The fuel salt is currently a eutectic sodium-actinide fluoride salt mixture, but sodium-rubidium-actinide or sodium-zirconium-actinide fluoride salts are being considered to reduce the actinide fraction in the salt, which will decrease the power density in the fuel salt and reduce pumping power requirements. Initially the actinide fuel mixture is 93% thorium, and 7% pre-processed SNF (3.5% uranium (1.1% enrichment) and 3.5% reactor-grade plutonium), but over time the plutonium "quality" decreases, and so only SNF is added and the thorium fraction decrease.

Reactivity Control

The strongly negative temperature coefficient ensures a saturation temperature level of the core, thus the power can be reduced by reducing cooling pump speed, or vice versa. The online refuelling slowly feeds fresh SNF into the salt, for continuous operation. Daily adjustment of saturation temperature level is achieved using a series of graphite fine-tuning rods, which can be inserted or extracted from the reactor. Using these rods, the reactor can be maintained critical at its operational temperature for up to two months, without any addition of fresh SNF.

A SCRAM system exists for the operators' convenience and for the 7-yearly core module replacement scheduled for each seven years of operation.

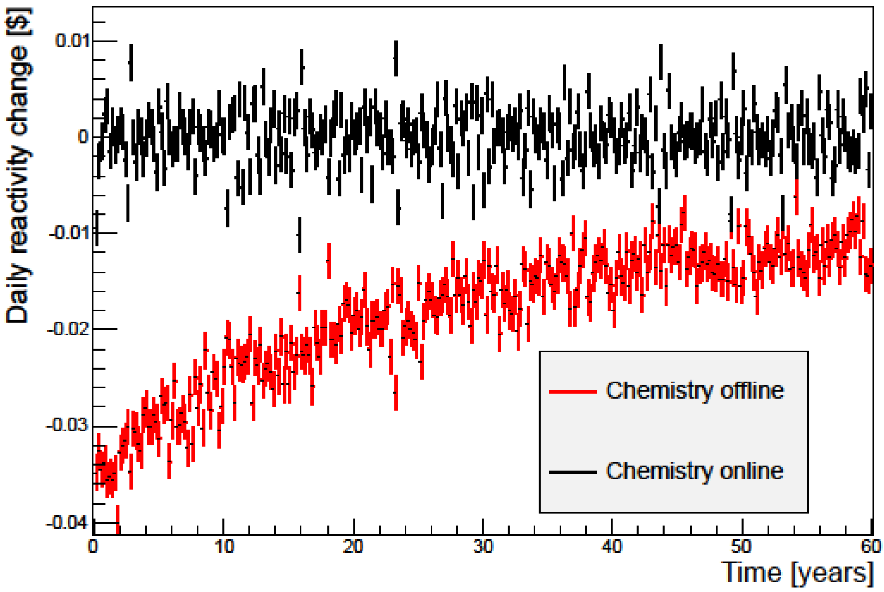

Figure 4: Simulation of reactivity control using the chemical system. New spent fuel is added while fission products are continuously extracted, handled and vitrified. (Reproduced courtesy of Seaborg Technologies)

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer	Seaborg Technologies
Country of origin	Denmark
Reactor type	Molten Salt Reactor
Electrical capacity (MWe)	100 (1-stage turbine) or 115 (2-stage turbine)
Thermal capacity (MWth)	270
Expected capacity factor (%)	97.5%
Design life (years)	7 years component, 60 years plant life.
Plant footprint (m^2)	20000
Coolant/moderator	Graphite based
Primary circulation	Forced circulation
System pressure (MPa)	0.1 (sub-atmospheric)
Core inlet/exit temperatures (^{o}C)	600/700 – or 700/900 in the high temperature configuration
Main reactivity control mechanism	Negative temperature coefficient; graphite control rods
RPV height (m)	5
RPV diameter (m)	4
RPV or module weight (metric ton)	158 (including fuel and coolant)
Configuration of reactor coolant system	Integrated
Power conversion process	Rankine cycle
Process Heat Capabilities (High / Low T)	Different configurations possible (850°C /550°C)
Passive Safety Features:	Many: negative temperature coefficient; freeze plug to drain fuel to passively cooled dump tank; overflow system, etc.
Active Safety Features:	Redundant, but, SCRAM and borofluoride injection installed.
Fuel salt	Sodium-actinide fluoride (93% Th, 3.5% U 3.5% Pu)
Moderator height (m)	2.9
Number of moderator assemblies	91
Fuel enrichment (%)	Pre-processed SNF (U 1.1% fissile, Pu 69 % fissile)
Fuel burnup (GWd/ton)	250 (U and Pu - negligible Th cycle burning)
Fuel cycle (months)	720
Approach to engineered safety systems	Passive
Emergency Safety Systems	Inherent – passive
Residual Heat Removal System	Radiative (core), conduction (dump tank)
Refuelling outage (days)	Not Applicable (60 day module exchange, every 7 years)
Distinguishing features	Thermal spectrum wasteburner; Integrated heat-exchangers; Power production controlled by coolant pump speed
Modules per plant	1 or more
Target construction duration (months)	36
Design Status	Conceptual (mainly neutronics benchmarks done)

Reactor Pressure Vessel and Internals

The reactor operates below atmospheric pressure above the fluid surface. However, the core, chemical unit, dump tank, and other critical components are planned to be contained in an airtight dome, able to withstand a significant pressure, both from internal and external events.

5. Safety Features

In the MSTW safety is guaranteed by physics rather than engineering. The reactor relies on natural convection, radiative heat transfer, and gravity for safety. The neutronics of the reactor is designed to be under optimal conditions. Then, any unexpected change to the system will result in a move away from the optimum, and thus a power reduction or shutdown of the reactor. All active safety systems have been made redundant.

Emergency core cooling system and decay heat removal system

In case of LOCA the core will heat up and the strong negative temperature coefficient will reduce reactivity and terminate power production without any operator interference. After shut down the core will heat up from residual heating, and passive cooling will be ensured through natural convection and radiative heat transfer for a substantial time. However, if main cooling is not restored, the reactor fuel will eventually drain itself (actively or passively) by melting a salt freeze plug. In the drain tank the fuel will solidify and is cooled by conduction to an underground heat sink.

Containment system

With the exception of noble gasses, noble metals, and cadmium, fission products are non-volatile in a fluoride salt. Note that this includes the hazardous caesium and iodine. The MSTW is designed so that critical temperatures are physically unreachable due to a number of reasons including the negative temperature coefficient, and the balancing of residual heating and radiative heat transfer. As such there are no scenarios where large amounts of non-volatile fission products can escape the fluid – even if the entire containment is breached. The remaining volatile fission products are continuously extracted, handled and vitrified, and are therefore never present in significant amounts in the fluid. For this reason, the source term, even during extreme disasters, will be small and will pose a minimal off-site risk.

Despite the inherent safety, the reactor is designed with three barriers, where no irradiated component, coolant or fuel leaves the outer two barriers at any point.

6. Plant safety and Operational Performances

The neutronic optimum design philosophy provides excellent transient behaviour and outstanding inherent safety features, and the plant has outstanding load following capabilities. The heat storage in the coolant salt and the automatic saturation temperature of the reactor enables power production to be turned on and off as fast as the steam generators can be switched on and off. Furthermore, due to the degassing of noble gasses, and the relatively large fuel inventory, the reactor will not experience a poison-out during shutdown or power reduction.

7. Instrumentation and Control systems

The MSTW will have a series of control and monitoring features. Control will be based on a series of fine-tuning moderation rods, which will be placed near the edge of the reactor core so that an ejection event will reduce reactivity (loss of reflector). The reactivity span of these rods will be such that the reactor core saturation temperature can be adjusted within 200°C, and such that critical temperatures are not reachable through intentional or unintentional operator failures.

8. Plant Arrangement

Plant design is not yet finalized. However, all irradiated components, fuel, and coolant salt are contained in an approximately 8 m deep and 12 m wide underground area, covered with 2 m of concrete during operation. The turbine building, control room, and module handling area are placed above ground, above and around the underground area. The plant is envisioned to be operated by two operators, plus maintenance personnel for turbines and other plant components. During module change out, a team from the central manufacturing site will be dispatched to the site.

9. Design and Licensing Status

ST is currently focused on advanced multi-physics, neutronics, and early engineering details. The facility is planned as a green-field concept, and decommissioning considerations feature heavily in the design process, and most component parts are recyclable. Licensing is considered, and a plan has been drafted, however, at this early stage it is of lesser concern.

10. Plant Economics

The design is at a conceptual stage and the details of the plant economics are yet to be assessed. It is our belief that the redundancy of all active systems will result in significant cost reductions, through fewer engineering requirements and general simplicity. Also, the centralized manufacturing and recycling of modules is expected to benefit plant economics. Lastly, the short lifecycle of modules will heavily reduce requirements of materials and engineering. This is expected to significantly reduce the overnight cost, but will come at the expense of a larger over time cost. Postponing a large fraction of the plant cost from the overnight cost will be favourable from an economical point-of-view.

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

General plant data		
Reactor thermal output	270	MWth
Power plant output, gross	115	MWe
Power plant output, net		MWe
Power plant efficiency, net	42.5	%
Mode of operation	load following	
Plant design life	60	Years
Plant availability target		%
Seismic design, SSE		g
Primary Coolant material		
Secondary Coolant material		
Moderator material	graphite	
Thermodynamic Cycle	Rankine	
Type of Cycle		
Non-electric application	Multiple	
Safety goals		
Core damage frequency (primary loop rupture)		/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	/550	MPa(a)/℃
Feedwater flow rate at nominal conditions		kg/s
Feedwater temperature		℃
Reactor coolant system		
Primary coolant flow rate		kg/s
Reactor operating pressure	0.1	MPa(a)
Core coolant inlet temperature	600	℃
Core coolant outlet temperature	700	℃
Mean temperature rise across core	100	℃
Reactor core		
Active core height	2.9	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	Eutectic Sodium-actinide fluoride salt mixture	
Cladding tube material		
Outer diameter of fuel rods		mm
Rod array of a fuel assembly		

Number of fuel assemblies		
Enrichment of reload fuel at equilibrium core		Wt%
Fuel cycle length	720	months
Average discharge burnup of fuel	250	MWd/kg
Burnable absorber (strategy/material)		
Control rod absorber material		
Soluble neutron absorber		
Reactor pressure vessel		
Inner diameter of cylindrical shell	4000	mm
Wall thickness of cylindrical shell		mm
Total height, inside	5000	mm
Base material		
Design pressure/temperature	0.1	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		
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		
Safety injection systems		
Active/passive systems		
Turbine (for two module power plant)		
Type of turbines		
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