Status Report - Stellarium (France)

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1. Overview

- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	--

Reference Plant

Name of Site	--
Link to PRIS	--
Net Power Output (MWe)	110
Gross Power Output (MWe)	--

1.1 Introduction

The Stellarium is a 250 MWth /110 MWe molten chloride salt fast breeder reactor developed by Stellaria, a spin-off of the Commissariat à l'Energie Atomique (CEA, French nuclear energy state agency) and Schneider Electric. It is designed to meet the significant clean energy demands of big industrial sectors, including mines, chemical plants, refineries, factories, data centers and hydrogen production plants, all of which need to decarbonize their energy supply to achieved their goals. The Stellarium can provide direct electricity and/or steam, drawing on decades of R&D experience from CEA in fast neutrons reactors. It is engineered to accommodate various fissile and fertile materials such asUranium, Thorium, Plutonium and Minor Actinides, contributing to the closing of the fuel cycle by enabling the continous breeding and burning of these materials.

The Stellarium reactor targets energy-intensive industries and utilities aiming to utilize their plutonium inventories and reduce waste. Built in pairs for maximum economic efficiency, a Stellarium plant can generate 220 MW of electricitywith supercritical steam turbines (~50% efficiency) or 500 MW of 600°C superheated steam. The output can be adjusted to provide a mix of steam and electricity, catering to specific applications, such as foundries that need both steam for pre-heating metals and electricity for melting alloys. Stellarium can use various fuel cycles, always combining fertile and fissile materials,

including Thorium/Plutonium, Thorium/Uranium, Uranium/Plutonium. Different grades of plutonium or HALEU can be used, along with the option to consume minor actinides. Utilities that choose reprocessing can employ Stellarium to consume plutonium, breed plutonium or uranium 233, and destroy minor actinides.

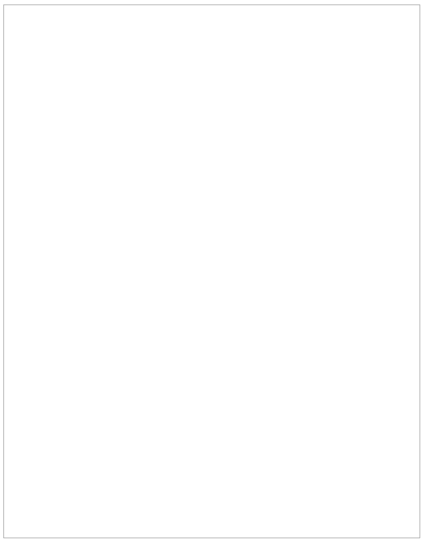


Figure 1. Stellarium design concept

1.2 Development Milestones

2023	Completed preliminary studies and technological innovation (using previously developed patents).
2024	Completed pre-conceptual design phase and technology validation
2026	Conceptual Design phase (and preparation for pre-licensing) will be completed
2028-2030	Basic Design Phase
2028	Planned first criticality of critical experiment
2033	Target first criticality for the FOAK plan
2036	Target first criticality for the first NOAK plant

1.3 Design organization or vendor company

1.4 Links to designer/vendor website

1.5 Design Description

The Stellarium is designed to satisfy the criteria of a XXIst century GEN IV to ensure high performances and public acceptance. Then the reactor must have : low radioactive rejects in case of severe accident (< 1 mSv a site fence), easy decommissioning even after accident, easy operation (low number of systems, low pressure, complexity…), in-core capacity to close the fuel cycle (iso-generation or breeding), in-core capacity to burn large amounts of minor actinides, capacity to be built almost everywhere (earthquake

resistance and size of components allowing road transports), high technological maturity, high dispatchability (equivalent of gas turbine).

1.6 Licensing Application Support Documents

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Prototype/FOAK	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Non-electric (Target energy-intensive industries and utilities aiming to utilize their plutonium inventories and reduce waste)	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Inland	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)		e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	Molten Salts	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	30 MWth <= Thermal power < 1000 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth
Reactor Type	MSR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR

Neutron Moderator	None	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout		e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced	e.g. Forced (# pumps), Natural
Thermodynamic Cycle		e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid		e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Liquid Fuel/Coolant	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Other	e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Molten Salt	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Fast	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	60	Years
Lifetime Capacity Factor		%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages

Major Planned Outages		# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources		# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design		n Units/Modules
Capacity to Electric Grid	110	MWe (net to grid)
Non-electric Capacity		e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint	45000	m2 (rectangular building envelope)
Site Footprint		m2 (fenced area)
Emergency Planning Zone		km (radius)
Releases during Normal Operation		TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed		x – 100%, % per minute
Seismic Design (SSE)	0.45	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	0.13	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	0.4	MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)		kg
Nominal Coolant Flow Rate (primary)		kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	550	ºC
Core Outlet Coolant Temperature	750	ºC
Available Tempeature as Process Heat Source		ºC

NSSS Largest Component	Reactor vessel	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	7000	mm
- NSSS Largest Component Diameter	2300	mm
- NSSS Largest Component Thickness		mm
- NSSS Largest Component Weight	30	tonne
Reactor Vessel Material		e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design		e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory		kg
Pressurizer Design		e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume		m3 / m3 (total / liquid)
Containment Type		Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume		Years of full-power operation / m3
Non Electric Application		-
Core Delta Temperature	200	ºC
Fuel/Core		
Single Core Thermal Power	250	MW(th)
Refuelling Cycle	240	months or “continuous”
Fuel Material	Molten Uranium, Plutonium Chloride (optional minor actinides)	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	< 8% PuCl3 or 16.5% HALEU	%
Average Neutron Energy		eV
Fuel Cladding Material		e.g. Zr-4, SS, TRISO, E-110, none

Number of Fuel “Units”		Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit		kg
Total Fissile Loading (initial)		kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation		Applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge		%
Core Discharge Burnup	100	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding/Conversion Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing		e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Control rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		n/(cm²*s)
Max. Fast Neutron Flux		n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active/Passive	- / - / -
- core injection	Active/Passive	- / - / -
- decay heat removal	Active/Passive	- /- / -

- containment isolation and cooling	Active/Passive	- / - / -
- emergency AC supply (e.g. diesels)	Active/Passive	- / - / -
DC Power Capacity (e.g. batteries)		Hours
Events in which Immediate Operator Action is required		e.g. any internal/external initiating events, none
Limiting (shortest) Subsequent Operator Action Time		Hours (that are assumed when following EOPs)
Severe Accident Core Provisions		e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)		x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)		x/reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)		Months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort		Person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C]/%[M&E]	
- Site Development before first concrete		(e.g. 25/10) (30/40) (20/25) (20/10) (5/15) (----------) (to add up to 100/100)
- Nuclear Island (NSSS)		
- Conventional Island (Turbine and Cooling)		
- Balance of Plant (BOP)		
- Commissioning and First Fuel Loading		

Factory / On-Site split in [C&C] effort		%/% of total [C&C] effort in PY (e.g., 60/40)
Nuclear System		
System Steam Flow Rate		kg/s
System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s
System Feedwater Temperature		ºC
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/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

The typical power plant includes a reactor building housing two 250 MWth reactors each producing 110 MWe. The steam generators are in an adjacent building, supplying steam to the turbine building. The reactor building is 70 meters long, 30 meters wide and half burried with 15 meters above ground. Cooling options include river cooling, wet cooling tower, dry cooling towers. For industrial steam or heat production the layout may include additional buildings.

Figure 2. Plant layout

4.1 Site Requirements during Construction
4.2 Site Considerations during Operation
4.3 Grid Integration

5. Technical NSSS/Power Conversion System Designn

SUMMARY FOR BOOKLET

Nuclear Steam Supply System

The Stellarium is built with four different loops. By convention the first loop containing the molten salt fuel is labelled “fuel loop”. The primary loop extract the heat form the fuel salt by entering an heat exchanger inside the vessel. As this primary salt will be lightly activated a secondary circuit is needed to avoid any radiological hazard outside the reactor building. Then a Rankine supercritical steam turbine is used to convert heat into electricity with high efficiency (~50%). Steam can be directly used after the steam generator to power industrial processes.

Reactor Core

The reactor core is a critical cavity inside the reactor vessel, the salt is circulated thanks to natural convection produced by the self-heating. The internal heat exchanger is located above the core to facilitate the movement. Around 60 tons of fuel salt are contained inside the vessel, which accounts for ~5 tons of plutonium and ~30 tons of depleted uranium. The breed and burn process allows for 20 years of autonomy, each fission producing energy and neutrons, the later being used to fertilize the uranium.

Reactivity Control

The reactivity control is ensure by control rods. The need for antireactivity being modest because the breeding allows for low excess reactivity.

Reactor Pressure Vessel and Internals

The reactor vessel functions at atmoshperic pressure and is made of Inconel to resist corrosion, irradiation and high temperature. By design its life is limited to 10 years, hence all components are fully

exchangeable and easily replaceable. A second, slightly larger vessel encloses the reactor vessel to ensure that any leak is contained.

Reactor Coolant System and Steam Generator

The reactor has a main system for its cooling with the two primary and secondary loops with molten salt coolant (chloride) leading to the steam generators. The steam generators are equivalent to those used in the thermal solar industry. Two specific system are used to remove the decay heat. The first is active and placed on the secondary loops. It uses one small pump on the primary loop and one in the secondary loop. The second is also active and is used to cool the reflector. In case of accident the second system can work in natural circulation and uses water from two big tanks inside the reactor building.

Pressuriser

No pressure inside the different loops except for hydrostatic. A special system allows for the extraction of fission gases from the reactor vessel.

Primary pumps

No pumps inside the reactor vessel and on the fuel loop, the primary and secondary loops have pumps.

Instrumentation and Control Systems

Thanks to the deep partnership of Scheider Electric the I&C systems of the Stellarium will be state-of-the-art and include the latest innovations. Nuclear instrumentation technologies relevant to fast neutron molten salt reactors have been developped in the past for sodium fast reactors. All nuclear instrumentation is ex-core. The conventional instrumentation is taken from thermal solar technology.

5.1 Primary Circuit
5.2 Reactor Core and Fuel
5.3 Fuel Handling
5.4 Reactor Protection
5.5 Secondary Side
5.6 Containment/Confinement
5.7 Electrical, I&C and Human Interface
5.8 Unique Technical Design Features (if any)

6. Technology Readiness

SUMMARY FOR BOOKLET

Testing Conducted for Design Verification and Validation

Stellaria is conducting tests on molten salts loops to verify the thermo-physical properties of selected molten salts and performing chemistry studies in a dedi c ated lab. A critical mock-up will be built by

2027, aiming for criticality by 2028. In the early 2030's, a 50 MWth Firsk-of-a-Kind (FOAK) vessel will be constructed for reactor-scale demonstration, with plans to replace it later with a full-size vessel (250 MWth) connected to the grid.

Design and Licensing Status

The consortium made of Stellaria, Orano and the CEA has been awarded by the French governement with a 10-million grant (France 2030 phase 1) and has begun discussion with French ASN in the preliminary screening framework. Preliminary design phase is over as end of september 2024. Preliminary design for the critical experiment and conceptual design for the reactor are due to begin by end of Q3 2024

6.1 Deployed Reactors
6.2 Reactors under Licensing Review
6.3 Reactors in the Design Stage

7. Safety Concepts

SUMMARY FOR BOOKLET

Engineered Safety System Approach and Configuration

The goal is to reach the 1 mSv at site border in case of severe accident. Thanks to the behavior of molten salt fuels and the absence of pressure the safety approach can be really efficient. In fact only a small number of systems are needed to deal with accidents. Molten salt have really strong negative reactivity coefficient of temperature, which leads to passive shutdown in case of temperature raise. This feedback phenomenon removes all reactivity-induced accidents. For the decay heat removal, the Stellarium has two diversified systems, to cool the salt in the reactor vessel. If the salt has been drained, the subcritical tanks are also cooled. From the containment side, metallic and soluble fission products as well as fertile and fissile materials are trapped in the salt (fusion point at 450°C) and volatile fission products are removed from the reactor plenum thanks to cold traps. The four barriers are at atmospheric pressure.

Safety Approach and Configuration to Manage DBC

The Stellarium exhibits favorable physical responses to most transient. Reactivity insertion accidents (such as the instant withdrawal of all control rods) lead, after a transient power peak, to a controlled salt temperature increase (<100°C) without damage to the main vessel; loss-of flow and loss-of heatsink transients, even unprotected, lead to a similarly reasonable temperature increase, after which the vessel can be cooled for more than 72h by radiation to the passively-cooled reflector. In the case of a main vessel leak, salt flows into the surrounding guard vessel : salt then flows from this vessel to the underlying drain tanks. In all cases the reactor can be restarted after (at most) a vessel change.

Safety Approach and Configuration to Manage DEC

In more severe transients (such as a main vessel leak followed by a guard vessel leak), a majority of

the salt can be drained through the connection to the drain tanks. The remaining salt can then be cleaned in the leak-tight reactor pit.

Containment System

The reactor uses 4 barriers to contain the radioactivity inside the reactor building. First is the reactor vessel, second is the guard vessel. The reactor pit is leak-tight and filled with argon to ensure containment and detection of leaks. These three barriers use pressure cascades to avoid passive leaks. The last barrier is the reactor building itself. The reactor is burried and only the hall is above ground.

Spent Fuel Cooling Safety Approach / System

The spent fuel is drained by gravity in the crypts under the reactor pits. Several subcritical heated and cooled tanks are there to wait for the fuel to be able to be transported. After one year the fuel can be safely transported away to the reprocessing plant. A special tool is brought to the reactor site to allow the removal of the subcritical fuel tanks.

Plant Safety and Operational Performances

The Stellarium reactor is design to fit inside the existing french Autorité de Sûreté Nucléaire (ASN, French nuclear regulator) framework. Studies are ongoing at the European level to harmonize parts of the differents existing frameworks and Stellaria will include the conclusions to the design. The Stellarium is also design to be built everywhere in Europe and in the majority of the countries. That means that stronger design earthquakes have been taken into account. A standard power plant will include two reactors with a 100-people staff including guards. The plant layout is optimized to accommodate all requirements regarding safety, security, safeguards, and environmental protection. The reactor vessel is replaced every 10 years during a 6-months outage period corresponding to the 10-yearly visit. The reactor is refueled every 20 years thanks to its core breeding ratio of 1.

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

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Fuel Cycle Approach

Stellaria's fuel cycle philosophy emphasizes closing the fuel cycle through advanced reprocessing capabilities. The Stellarium reactor is designed for flexibility, allowing it to use various fuel types, including plutonium from PWR/BWR/PHWR spent fuel, depleted uranium, and minor actinides. Stellarium can manage different plutonium qualities and incorporate up to 30% minor actinides in its fuel mix. After 20 years of operation, the reactor is unloaded, and the fuel is sent to a reprocessing plant, where fission products are extracted, leaving the plutonium mass largely unchanged. This allows the cycle to be closed by creating new fuel salt with only depleted uranium make-up. The plutonium

can then be reused in Stellarium or other reactor types. For countries without plutonium, Stellarium can be started with HALEU, eventually transitioning to a closed uranium-plutonium cycle after a few cycles. Additionally, the reactor can also be initiated with HALEU and thorium or plutonium and thorium for countries interested in using thorium.

Waste Management and Disposal Plan

As the Stellarium burns the minor actinides the only waste management needed concerns : structural materials (vessels…), effluents and fission products. The Stellarium is designed to fit inside the existing French ecosystem with the fuel reprocessing separating useful materials (uranium, plutonium, thorium) from the wastes (fission products and minor actinides). The minor actinides being separated from the fission products in the next plant (La Hague 2, 2045), they will be burnt inside the Stellarium. Then only vitrified fission products will be sent to the Deep Geological Repository (DGR).

The vessel weights approximately 30 t and is replaced every ten years. This metal will be heavily irradiated and will be cut off and compacted into standardized container to fit in a DGR.

8.1 Fuel Cycle Options
8.2 Resource Use Optimization
8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

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9.1 Safeguards
9.2 Security
9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

10.1 Project Preparation and Negotiation
10.2 Construction and Commissioning
10.3 Operation and Maintenance