Status Report - BLUE CAPSULE (France)

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1. Overview

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

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	2029

Reference Plant

Name of Site	--
Link to PRIS	--
Net Power Output (MWe)	50
Gross Power Output (MWe)	--

1.1 Introduction

Blue Capsule is a 150 MWth reactor that allows onsite co-location at hard-to-abate industries and is designed to maximise the production of industrial-grade heat in the form of air at temperatures up to 700°C. This output can be used directly for preheating components or materials, transformed into high-grade steam at 650°C, or converted into electricity up to 50 MWe per unit. The innovation lies in deploying a cross-over of sodium-cooled and high-temperature reactor (HTR) technology, featuring TRISO fuel and primary loop at atmospheric pressure. The ultimate heat sink is ambient air in an open circuit, with the air passing through the sodium-air heat exchangers and then directed towards the conventional, versatile part of the system, which interfaces with the final user facility.

Blue Capsule targets three key end users: (1) decarbonizing existing industrial sites using a "Plug-in" approach, with high-temperature steam up to 650°C, (2) Supporting “Multi-vector” type end users with co-generation capabilities, and (3) integrating into “Pre-heating” end user processes like glass, steel, or the fabrication of ceramics.

Figure 1. Design concept of BLUE CAPSULE Core and Na-air heat exchanger

1.2 Development Milestones

2023	Preliminary studies and technological innovation (using previously developed patents).
2026	Pre-conceptual design phase and technology validation
2027	Conceptual Design Phase (and preparation for pre-licensing)
2028	Basic Design Phase
From 2027	Commercialisation
2028-2030	Detailed Design Phase
By 2029	Target first concrete for the FOAK plant

1.3 Design organization or vendor company

1.4 Links to designer/vendor website

1.5 Design Description

Blue Capsule combines two mature technologies: that of high-temperature gas-cooled reactors (HTRs) with its inherently safe TRISO fuel, and that of sodium-cooled fast reactors. Using sodium as the core coolant and graphite moderator – as already experienced with the NSRE and Halam projects – Blue Capsule offers several possibilities linked to key design options. First, the high thermal conductivity of sodium allows for a high thermal exchange capacity that, in turn, allows cooling of the core power by natural circulation. This

implies a simple, robust means to cool the core during both normal and abnormal conditions. In addition, with the high mass density of sodium (compared with HTR cooling with pressurised helium), the transients are slow – giving time for the operators to cope with potential events. As concerns Blue Capsule's potential competitiveness (i.e. vis-à-vis industrial heat sources such as natural gas), this stems from the cost-driven design and "plug-in" integration with industrial sites.

Figure 2. Options taken by Blue Capsule designers leading to design, safety and exploitation benefits

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	Commercial – Electric/Non-Electric	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload, Non-electric ("Pre-heating" end user processes like glass, steel, or the fabrication of ceramics.)	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	Na	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	Others	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR
Neutron Moderator	Graphite	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	Natural	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	Coated Sphere	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant

Fuel Lattice Shape	Hexagonal	e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Oxide	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Pre-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	Thermal	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	50	MWe (net to grid)
Non-electric Capacity		e.g. MW(th) heat at x °C, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint	690 (reactor building only)	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)		g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	0.1	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	0.5	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	400	ºC
Core Outlet Coolant Temperature	750	ºC
Available Tempeature as Process Heat Source		ºC
NSSS Largest Component		e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length		mm
- NSSS Largest Component Diameter		mm
- NSSS Largest Component Thickness		mm
- NSSS Largest Component Weight	130	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	"Pre-heating" end user processes like glass, steel, or the fabrication of ceramics.	-
Core Delta Temperature	350	ºC
Fuel/Core		
Single Core Thermal Power	150	MW(th)
Refuelling Cycle	continuous	months or "continuous"
Fuel Material	UO2	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	5	%
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	30	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	N/A	- / - / -
- decay heat removal	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

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The logic of the plant building's layout is based on the following principles: proximity of the reactor building to the consumer processes, as well as shared utilities and support functions. For multiple capsules co-located on an industrial site, the intention is to share all functions that are not present in the reactor buildings of each capsule, including electrical supply, support network supply, support buildings, fire service, physical protection, storage for spare parts: for parts not subject to physical protection, conventional network (secondary, turbine, alternator, compressor, etc.), temporary construction and heavy maintenance area. It is assumed there will be road access to facilitate the delivery of large equipment.

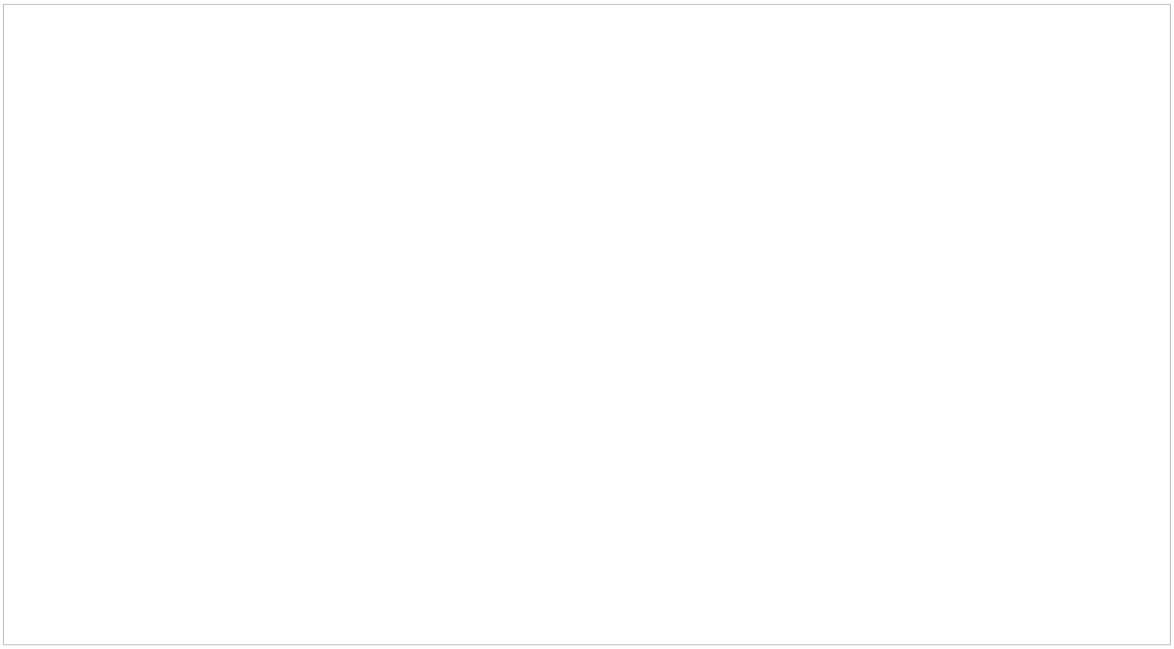


Figure 3. Plant layout

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

5. Technical NSSS/Power Conversion System Designn

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Power Conversion System

The heat from the assemblies is evacuated by conduction through the fuel, graphite, and thermal binder to the ceramic housing structure, which is then cooled by sodium in natural circulation. The sodium coolant is not in direct contact with the fuel; its outlet average temperature is 750°C. The sodium is directed towards five identical sodium/air heat exchangers upon exiting the core. The Blue Capsule secondary circuit is versatile, meaning that any transformation of the energy flow (hot air, various steam flows, electricity) downstream of the reactor does not affect its design or operation. This characteristic is central to adapting the reactor to the different industrial heat usage scenarios by end users. This versatility is achieved by using an "open" energy conversion cycle.

Reactor Core

The core of Blue Capsule is similar to a core of gas-cooled HTRs. The fuel compacts Blue Capsule's core pattern made of TRISO particles with UO2 kernels (enrichment 5% in 235U) placed in a graphite matrix, with a volume packing fraction around 30%. The main physical difference between the Blue Capsule core and gas-cooled HTRs is that Blue Capsule fuel is encapsulated in ceramic cylinders (Blue Capsule's core pattern – not at scale) that separate the fuel compact from sodium flow, to protect graphite from interaction with sodium. Thus, Blue Capsule fuel is in a dry zone, separated from the sodium flow.

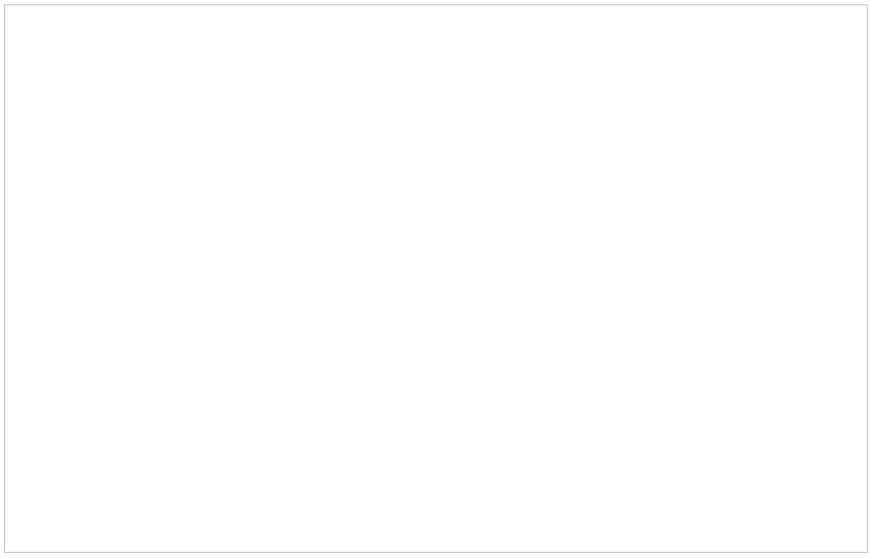


Figure 4. Core pattern

Reactivity Control

Reactivity is managed using control rods from the reactor hall above the core. These rods are made of neutron-absorbing material and regulate both the level of reactivity and the power output. Nuclear power is intended to remain constant, with any variability in the final product being managed through a heat storage system, if necessary. The control rods are placed in sleeves like those housing the fuel assemblies. Their positioning within the core will allow for flux distribution adjustment.

Reactor Internal and Main Vessels and Internals

The reactor core is enveloped by a non-pressurised main vessel containing hot sodium. It directs the ascending flow under natural convection and the descending flow of sodium. The fluid is distributed laterally to the heat exchangers in the upper section. Once cooled in the heat exchangers, the sodium descends into the annular space between the inner and main vessels, reversing direction in the lower section and rising back into the core. The main vessel is suspended from the reactor deck, and the inner vessel rests on top of it. A safety vessel is located around the main vessel in case of mechanical failure. The entire core and these vessels are situated within the vessel pit.

Reactor Coolant System

After exiting the core, the sodium is directed towards sodium/air heat exchangers. These are located on the deck above the core within the reactor hall. The currently preferred option for the heat exchangers is shell-and-tube type, in two cylindrical sections, allowing for double-pass cooling. This design also helps reduce the height of these components, improving seismic performance. It also provides a high point that facilitates the easy installation of an expansion tank. The heat exchangers' design and positioning – as close as possible to the core minimise the piping length – reduce the risk of leaks.

Pressuriser

There is no pressuriser in the reactor; it operates at atmospheric pressure.

Primary pumps

The reactor operates under natural convection without primary pumps.

Instrumentation and Control Systems

Reactivity is managed using control rods from the reactor hall above the core. These rods are made of neutron-absorbing material and regulate both the level of reactivity and the power output. Nuclear power is intended to remain constant, with any variability in the final product being managed through a heat storage system or variation in end products, if necessary. The control rods are placed in sleeves like those housing the fuel assemblies. Their positioning within the core will allow for flux distribution adjustment.

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

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Testing Conducted for Design Verification and Validation

The design of Blue Capsule revolves around several experimental installations that are integral to the development plan and timeline:

- A laboratory-scale experimental loop, “proof of concept”, is specifically designed to demonstrate the heat removal performance of the Blue Capsule reactor core through a natural convection circuit, and will be put in operation at the beginning of 2026.
- A non-nuclear prototype scheduled for the first half of 2029 includes a complete thermohydraulic representation of Blue Capsule, with the output connected as an industrial heat source to test the representative processes for the final uses of the Blue Capsule nuclear solution. This prototype ensures that Blue Capsule is ready for commercial deployment by thoroughly testing and validating all key aspects before full-scale nuclear operation.

This structured approach ensures that the Blue Capsule design is rigorously tested and validated at every stage.

Design and Licensing Status

Blue Capsule conducted the sketch and feasibility study phase in 2022-2023, with the Preliminary Design phase starting in early 2024 and expected to finish by mid-2026. The reactor benefits from mature technological components and successful licensing experiences in France and internationally. Preliminary discussions with French nuclear authorities have begun. The reactor design combines sodium-cooled and HTR technologies, both of which are mature and well-understood, facilitating easier regulatory and safety approvals, especially in France and the European Union. The use of singularly robust TRISO fuel further enhances safety. Safety demonstrations (in France) will use methods developed for more complex sodium cooled fast reactors (Blue Capsule is a thermal-spectrum concept), such as Phenix, Superphenix, and Astrid projects. The design will be validated through an experimental program, including the laboratory scale testing starting in 2025-2026 (representative sodium loop) and at the reactor scale (non-nuclear prototype) by 2030.

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

7. Safety Concepts

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Engineered Safety System Approach and Configuration

Blue Capsule takes advantage of the best properties of sodium as a coolant, and of TRISO particles,

both in terms of safety and performance. Using liquid sodium as a coolant allows to keep the maximal fuel temperature of 1250°C in normal operation and to keep the fuel temperature below the TRISO failure limit in all conditions. The sufficient resilience of sodium boundaries, such as the shells of sodium-gas heat exchangers, the reactor deck, or the safety vessel, prevents significant off-site chemical risks. Blue Capsule uses air as the ultimate source term, and since no water is involved, sodium-water reaction is avoided by design. The Blue Capsule safety and security approach could be summarised as: generalised loss of the first barrier eliminated; core uncover eliminated; no risk of sodium release into the atmosphere; no risk of depressurisation; fuel qualification in accidental conditions covered by normal operation, and; maximum sodium temperature = 880°C.

Safety Approach and Configuration to Manage Design Basis Condition

Firstly, the low neutronic weight of the fuel assemblies and the neutron absorbers allows for the implementation of slow automation, ensuring stable operation. Core cooling is based on a primary circuit with natural circulation, designed to ensure a wide range of physical stability. Furthermore, the compact design of the primary circuit with the positioning of the heat exchangers just above the core – so no pressurisation – leads to an almost complete absence of pipelines, valves, and tee-branch. This greatly limits the risks of accidents related to the primary circuit. Ventilation plays a central role as it ensures the cooling function of the primary vessel as well as the heat evacuation of the stored irradiated fuel, but redundancies on sensitive sub-systems and components will be put in place to reduce the probability of initiating events.

In general, the operators' actions are very limited, greatly reducing the risk of errors, and the algorithms rely on a level of redundancy to achieve significant reliability. Concerning external threats, especially considering co-location with the industrial customer site, the reactor building is placed at subterranean level for protection. The core's natural behaviour plays a major role in the safety of the installation, provided that the design parameters make the best use of this capacity. Coupled with the high robustness of the TRISO fuel, this eliminates significant fuel degradation and practically prevents substantial radioactive releases.

Safety Approach and Configuration to Manage Design Basis Earthquake

Blue Capsule – and in particular the reactor core and safety systems – is being designed so that potential seismic events are being considered.

Containment System

No credible scenario leads to a generalised failure of the first barrier (TRISO). In the event of particle failure, the primary circuit, the vessel pit, the loading bubble, and the biological shield ensure containment.

Spent Fuel Cooling Safety Approach / System

The Blue Capsule core can be unloaded completely during operation, and the interim storage inside the reactor building is designed accordingly. When considered alongside the thermal robustness of TRISO, this allows a cooling by radiation during irradiated fuel handling – even with high residual power – immediately after the fission reaction stops.

The refractory features of TRISO also allow to obtain dry interim storage in racks, only cooled by air circulation, then by radiation once placed in casks, shortly after unloading from the core. The limited

size of the fuel assemblies also leads to lower risks of significant radioactive releases during fuel handling, which is a strong safety asset, in addition to the impossibility of general fuel failure.

Plant Safety and Operational Performances

The target capacity factor is 90% (thanks to online refuelling), the thermal power output is 150 MWth, and the outlet temperatures are 750°C primary and secondary: 700°C air, 650°C steam, and 50 MWe. This means that Blue Capsule's output is versatile and can be adapted to the client's needs.

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

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Fuel Cycle Approach

TRISO-based fuels are traditionally considered for use in an open cycle. However, experiments have been conducted to recycle TRISO fuels and small-scale industrial capabilities for recycling non-irradiated TRISO fuels do exist internationally. Blue Capsule is already considering options for nuclear fuel reprocessing at the preliminary design phase. Since HTR/TRISO fuels are excellent at burning materials, Blue Capsule is also exploring options for using MOX-based TRISO and options for treating and recycling spent fuels.

Waste Management and Disposal Plan

Blue Capsule's waste management and disposal plan is designed to consider the French national framework for waste classification and management.

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

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