UNIQUE NUCLEAR HEAT: BLUE CAPSULE’S

SINGULAR APPROACH TO DESIGN

SIMPLIFICATION AND INTEGRATION IN

SMALL MODULAR REACTORS

EDOUARD HOURCADE

Blue Capsule Technology

Aix-en-Provence, France

Email: edouard.hourcade@bluecapsule-technology.com

ALEXEY LOKHOV

Blue Capsule Technology

Saclay, France

MATHIEU CAREY

Blue Capsule Technology

Saclay, France

DOMNIN ERARD

Blue Capsule Technology

Aix-En-Provence, France

**Abstract**

## With nuclear energy poised to play a more prominent role in global decarbonisation efforts, small modular reactor (SMR) innovators are seizing the opportunity that reduced use of fossil fuels implies. Currently, 10 per cent of global greenhouse gas emissions are a direct consequence of fossil fuel combustion to produce heat for industrial processes, so companies like Blue Capsule, a spin-off from France’s CEA, are proposing a reactor design that maximises the production of industrial-grade heat (air at up to 700°C) for new markets; namely onsite co-location at hard-to-abate industries such as ammonia and soda ash production. For this to work, the modularity of a Blue Capsule is allied with a simplified cross-over of two mature technologies: the TRISO-based prismatic fuel from high-temperature reactors (HTRs), and the coolant of sodium-cooled fast neutron reactors. This paper explores the resulting reactor concept, identifying both the simplification and integration facets of this SMR as a unique proposition to Europe’s SMR ecosystem. The paper finds that Blue Capsule’s design can bring new insights to well-known difficulties associated with nuclear technologies, and new challenges in relation to new usages: (i) safety, regulatory and physical issues (i.e. cold source availability); (ii) capacity to connect with versatile end users with new energy vectors; (iii) reducing the level of complexity to significantly lower initial capital expenses.

## INTRODUCTION

Since well before this decade began, many economies were already faced with the twin imperatives of decarbonisation and keeping industries competitive; in line with global climate objectives under the UNFCCC, and the need to keep jobs and communities alive. In the current geopolitical context, these imperatives have gained even more importance, as we urgently seek solutions to both challenges.

Innovative nuclear technology is ideally placed to deliver on both fronts. Where CO2 emissions from industry are concerned, the quest to phase out coal and gas has already begun. Currently, 10 per cent of global greenhouse gas emissions are a direct consequence of fossil fuel combustion to produce heat for industrial processes. In terms of final energy demand, process heat accounts for more than 20% of demand in the world today – both a problem and opportunity for new technologies. It is hoped that solutions such as small modular reactors (SMRs) could go some way to replacing the 75% of industrial heat fuelled by oil, coal and natural gas.

The opportunity is there, and the market is there. The global market for heat stands at some 57,000 TWh (of which around half is accounted for by industrial demand) [1]; equivalent to 1.5 times Chinese final energy consumption, and more than 20 times the final consumption of energy in France. Specifically, there is a growing demand for air heated above 400°C, in addition to high-temperature steam and electricity for onsite processes. In the European Union alone – where reports of de-industrialisation have routinely made the rounds in the media -, the demand for industrial heat stands at around 1,290 TWh. Reliable nuclear technologies may yet help reduce CO2 emissions from industrial sites and keep them competitive and maintain jobs.

This is the rationale behind SMR designs such as Blue Capsule, a spin-off of France’s CEA, that aims to deploy a cross-over of sodium-cooled and high-temperature reactor (HTR) technology, featuring TRISO fuel. With a maximum capacity of 150 MWth, each capsule is slated to produce air above 700°C, in addition to steam and electricity (50 Mwe). The subterranean capsules would be co-located at industrial sites, for example, chemical installations for the production of ammonia or soda ash.

Other technologies have been designed in this vein, usually high-temperature reactor models with varying coolant technologies such as helium or molten fluoride salt. But the concept of a simplified cross-over of sodium-cooled and HTR technologies means that both technologies are already mature, well understood, and benefit from existing supply chains – notably as concerns their development in France and the European Union. Part of the rationale for this design concept from mature technologies is the likelihood that regulatory and safety hurdles could be easily overcome – again, notably in France and the European Union. Indeed, the use of singularly robust TRISO fuel would also enhance the safety credentials of this design concept.

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. This paper addresses these elements below.

## INTEGRATION WITH EXISTING INDUSTRIAL SITES

Historically, nuclear power was not designed to connect to customers other than electrical grids. In this case, the typical feedback from the customer would come from network frequency regulation that directly impacts core power fine tuning. This type of coupling on large power grids does not require large and/or sudden variation of power production; variation that could be envisaged with smaller grids (including a limited number of local customers; local loops). Equally, in the past nuclear power plants were never installed close to industrial sites. As such, potential external hazards rarely included hazardous initiators coming from other industries – a point that must be specifically addressed when physical interface between both systems (nuclear and non-nuclear) is defined.

In some conventional pressurised water reactor (PWR) circuits that are used for district heating, open circuits are a feature (i.e. no physical feedback from final user to the plant), but the power grade is very low in terms of both pressures and temperatures. As such, the challenge for Blue Capsule is to provide high temperature-grade power very close to the final user. Consequently, a safe connection must be made available very close to the reactor itself. A safe connection can be defined as such:

* No radioactive content should be present in the so called “coupling fluid” which can be defined in this case as the fluid exiting the nuclear installation and entering the non-nuclear installation (this fluid must not be activated).
* No event on a conventional site (either normal or incidental) should have an impact on reactor safety functions, i.e. cooling, but more generally the global physical integrity of plant.

These two features can a have strong impact on design options, both on the reactor core and the energy transfer system, which is to say: a number of leak-tight structures between fuel and coupling fluid; the “design” of possible feedback from conventional installation to the nuclear island, and so forth.

In this regard, the potential industrial market for Blue Capsule can be described as three types of end users:

— “Plug-in” type end users. In this case the final product that comes from Blue Capsule can perfectly replace existing technologies without a change of interface. This is the case for industries using pressurised high temperature steam up to 650°C. For example, soda ash plants using the Solvay process enter this category.

— “Multi-vector” type end users. These can be industrial clusters using versatile energy vectors: electricity, hot air, steam, or hydrogen (see Fig. 1). A co-generation of these three vectors can be provided with ad-hoc interface modules that can easily be plugged in to main coupling fluid without interfering with the nuclear island safety or security case. Examples include: water electrolysis plants using both steam and electricity, or; chemical clusters using electricity, steam and gas/hydrogen grids.

A diagram of a steam plant

Description automatically generated— “Pre-heating” end user processes. In this final case a new interface has to be designed. This is typical for glass, steel or fabrication of ceramics.

Fig. 1: Blue Capsule facilitates the production of hydrogen through high-temperature electrolysis.

## design AND OPERATION SIMPLIFICATION

The objective of Blue Capsule is to decarbonise industrial heat, and in this regard, the choice was made to use sodium as the core coolant as already experienced with NSRE and Halam projects [2] . This choice 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 accidental events.

As concerns the sodium boiling point, around 883°C at atmospheric pressure, this means that Blue Capsule has the capacity to offer offers high temperatures for the customer – up to 700°C –, with no pressuriser. The latter is always a complex component.

The core of Blue Capsule is derived from the HTTR design [3], with fuel compacts (Fig. 2; brown hereunder) made of TRISO particles placed in a graphite matrix, with a packing fraction around 30%. The main physical difference between the Blue Capsule core and the HTTR core is that Blue Capsule fuel is encapsulated in ceramic cylinders (Fig.2; purple hereunder), that separate the fuel compact from sodium flow, in order to protect graphite from interaction with sodium.

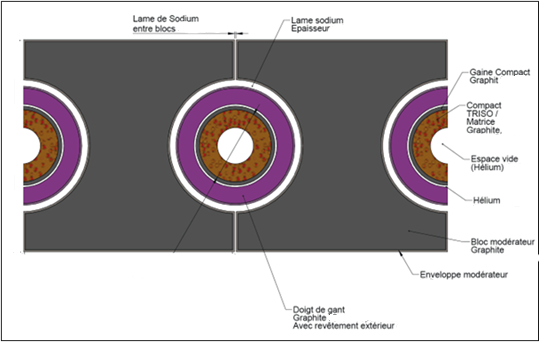


Fig. 2: Blue Capsule’s core pattern

This physical separation provides significant benefits. First, this design allows for simple fuel handling, since the assembly is not in contact with the sodium and, consequently, there is no need for rinsing and drying operations. A side effect of this design option is that, even if minimized, there exists a gap between the tube and the fuel assembly, creating a thermal barrier. This leads to medium assembly power density, around 50MW/m3 (~5 times higher than the HTTR).

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. Given both the sodium temperature of 750°C at the core outlet, and the power density, thermal transfer between fuel and sodium could be reached by simple thermal conduction.

The neutronic weight of the fuel assembly is small which allows for simple online refueling (i.e. at full power), without strong neutronic perturbations. Indeed, this online refueling is a major advantage of the Blue Capsule design, allowing for increased availability of the installation, and reducing risks inherent to refueling operations by reducing the timing pressure on this critical operation.

The characteristics of TRISO also allow to obtain dry storage in racks, only cooled by venting, then by radiation once placed in casks, few weeks after core unloading.

Fig. 3: Options taken by Blue Capsule designers, leading to design, safety and exploitation benefits.

Simplicity also relies on design sizing methodology, and mainly on the margin taken in order to limit constraints on operation and manufacturing. Core components are complex mechanical parts and must be produced as much as possible with industrial standards, which requires robust design without outstanding manufacturing tolerances. For instance, non-concentric positioning between fuel compact and cylinder must be acceptable; the leak of sodium inside the cylinder should also be included as an incident with only slight consequences on the exploitation.

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, see §3.

## LICENSING SIMPLIFICATION

Blue Capsule aims to achieve a reactor that ensures the highest level of safety. This involves considering, from the early stages, the major design options that naturally lead to a controlled operation of the installation.

**3.1. Prevention**

Firstly, as illustrated in Figure 3, 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, no pressurisation, and no continuous purification 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 actions of the operators 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 (see §1), the reactor building is placed at subterranean level for protection.  
  
**3.2. Accidental transients**

During accidental transients, the design incorporates favorable physics to slow down effects and limit variations (reactivity, temperature, etc.). Regarding reactivity accidents, the low neutron weight of core components helps limit power variations. For example, a design that restricts reactivity insertions to 100pcm allows for tolerating the consequences without needing to shut down the reactor. In other words, the new operating point reached becomes part of the extended operating domain and can be sustained before operator intervention to return to a controlled state – either in power or shutdown, depending on the initiating failure.

Accidents related to the loss of the cold source lead to a temperature increase resulting in quick power reduction. The design objective is to benefit a physical stop of the nuclear reaction before reaching the boiling point of sodium in the core for all design basis conditions.

All these considerations are possible due to the significant fuel temperature margins (around 400°C) with respect to TRISO robustness, which allows time for physical feedback to be completely effective. For instance, in the event of a core temperature increase, natural circulation will boost primary flow rate and reduce the impact of this increase by approximately 50%.

In the case of leak/breach transients, the design featuring a double tank and the altimetric distribution of sodium volumes above the core effectively prevents its drainage, ensuring a sufficient level for internal natural circulation between the inner and main tanks, which acts as the cold point of the core in fallback state (see below).

The inertia of the various core components allows for time to manage accidents. Leveraging a temperature rise in the concrete due to tank radiation allows for nearly 6 hours before reestablishing the backup heat sink, achieved by a simple ventilating system. It's worth noting that approximately 24 hours after reactor shutdown, the temperatures of the different structures have returned to values close to normal operation, with maximum values reached after about 6-12 hours.

**3.3. Fallback state**

In the event of a situation where the core cannot return to normal operation, the fallback state relies on the following: (a) a sub-critical state caused by the control rods dropping; (b) natural internal circulation within the boiler, enabling the transfer of power from the core to the sodium and the boiler structures, and (c) forced convection evacuation through the backup ventilation of the containment pit. Control of this state is straightforward and depends on only a few active systems. Moreover, the potential for natural ventilation of the containment pit is being studied. This simple approach significantly helps in complying with post-accident procedures.

The core's natural behavior 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.

**3.4. Safety demonstration / thermal hydraulic conformity**

The safety demonstration is based on methods and data developed in the Phenix [4], Superphenix [5], and Astrid [6] projects. The modeling of single-phase liquid transients involves simple physical models, with the main complexity lying in describing natural circulation in open areas using Computational Fluid Dynamic tools. These will be validated during the experimental program at the laboratory scale in 2025-2026 (proof of concept) and at the reactor scale (non-nuclear prototype) by 2030.

## CONCLUSION

From the outset, the Blue Capsule design has aimed to address typical challenges known to the nuclear energy sector as regards the construction and operation of installations – Gen. IV or otherwise. It is intended that the innovative Blue Capsule design, and its combination of sodium-cooled and HTR technologies featuring TRISO fuel, will lead to advancements that benefit both operator and end user.

As concerns safety, regulatory, and physical issues, Blue Capsule’s simplification of multiple nuclear installation features means that in target markets such as France and the European Union, this reactor should not face insurmountable licensing hurdles. Safety considerations such as prevention, accidental transients, fallback state and thermal hydraulic conformity attest to the pursuit of the highest levels of safety in this design.

Blue Capsule’s singular approach to integration with existing industrial sites, on a “plug-in” basis or otherwise, means that in future, vast industrial heat markets that have been largely untapped – in terms of CO2 emissions reductions – can now be addressed as part of concerted global efforts to reduce this sector’s dependence on fossil fuels such as natural gas and coal.

Design simplification in SMRs also means taking into consideration the typically high level of complexity that has, at times, led to elevated initial capital expenses. Blue Capsule features such as the simplification of the primary circuit – and near absence of pipelines, valves and pumps – means that safety and licensing advantages transcend into capital expense reductions; ‘getting built on time and on budget’ as per an industry maxim.

In these regards, Blue Capsule’s singular approach to design simplification and integration with industrial sites means that the prospective reactor has the potential to decarbonise hard-to-abate industries, and do so in a manner which assures safety, simplicity, and regard for both industrial clients and the advancement of fourth generation nuclear energy and nuclear science more broadly.

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