# THORIZON’S CARTRIDGE CORE MOLTEN SALT REACTOR

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**Abstract**

Low pressure operation, and elimination of potential escalation by laws of physics, combined with large fuel flexibility, neutron spectrum flexibility, and convenient connection to reprocessing and subsequent fuel production, make molten salt technology the superior basis for next generation nuclear power reactors, aiming to close nuclear fuel cycles. The key challenge of molten salt reactors relates to the structural materials in contact with the primary salt, which are exposed to high temperatures, radiation damage and chemical interaction. Instead of trying to find and qualify materials that can withstand these conditions for the typical lifetime of a nuclear power plant, Thorizon has mitigated material degradation issues by integrating a replacement strategy in the reactor design. The patented Thorizon reactor core concept is modular, consisting of a number of so-called cartridges which can be replaced and maintain nuclear containment at all times. The benefits of this approach, in terms of safety, practical and economic feasibility, qualification, licensing, time to build and the convenient connection to reprocessing facilities will be explained. In addition, a cartridge based experimental validation and qualification strategy will be elaborated, enabling an ambitious timeline to realization of a 250 MWth Thorizon first of a kind.

## NUCLEAR FUEL BEARING MOLTEN SALT REACTOR (MSR) BENEFITS

Molten salt can be used as an effective coolant, heat transport and heat storage medium, and molten salt is foreseen to be used in a variety of different nuclear reactor designs. A specific class of molten salt reactors is formed by systems in which the salt also contains fission and fertile elements in salt form. In that case the molten salt is both fuel and coolant, and is circulated in a closed system from a critical configuration where heat is generated, to a heat exchanger where the heat is transferred to another coolant circuit. Especially these systems offer a lot of advantages in terms of nuclear fuel cycle optimisation and will be addressed in this paper.

For these MSR concepts the following non-exhaustive list of advantages can be noted:

* The primary system is low pressure, i.e. core components are not exposed to high (primary) stresses
* The salt, and therefore the fuel, can expand freely, which leads to lower fuel density in the core when temperatures increase. This negative temperature feedback is an important safety feature of MSR, limiting or avoiding escalation by laws of nature.
* Molten salts generally have high boiling temperatures, providing large safety margins to boiling/evaporation and subsequent system pressurisation, barrier failure and release scenario’s.
* In an MSR, the fuel is the coolant and vice versa. A loss of coolant from the core, therefore leads to fuel removal from the core, reducing or eliminating criticality. This allows the fuel to be relocated to a safe configuration conveniently and passively, without operator action required, enhancing passive safety.
* A fuel in liquid form can absorb radiation without structural damage, and remains homogeneous by circulation induced mixing, unlike solid nuclear fuels. Unaffected by radiation damage, localised burn-up or other localised composition change effects, a liquid fuel can be used in a reactor for a prolonged amount of time. This allows them to sustain longer operations than any solid fuel form might be able to handle, as long as changes in properties are not detrimental for flow, composition stability and chemical (interaction) behaviour.
* Similarly, liquid molten salt nuclear fuels display stable behaviour for a large spectrum of compositions, and can accommodate a large variety of constituents, including fertile, fissile and minor actinide elements, remaining stable and predictable including significant composition changes in the core of a reactor.
* Despite the large variety of compositions and composition changes that need to be evaluated for establishing a full salt behaviour envelope for application in a nuclear reactor, the behaviour of the molten salt is dominated by composition and chemistry, which can be determined without nuclear testing. This greatly facilitates nuclear fuel qualification.
* MSR’s can be developed as thermal, epi-thermal or fast spectrum systems, offering agility in meeting future fuel cycle demands on the same fuel-coolant technology basis.
* With the fuel being also the coolant, MSR’s have the opportunity to be designed with optimal neutronic performance. This enables effective use of nuclear material resources, with the potential to both effectively fission and transmutation reactions, enabling for example minor actinide burning, and establishing closed breeding cycles with fertile Uranium and Thorium.
* Neutronic (burning and breeding) efficiency and molten salt performance can be further improved by online processing and conditioning, enabling:
* optimal neutron economy by removing unwanted neutron absorbing fission products.
* establishing long fuel cycles without salt replacement by adding fissile/fertile materials to the salt.
* corrosion monitoring and control (chemistry optimization).
* removal and safe local storage of fission products that do not dissolve well in the salt, to avoid release from the salt under accidental situations.
* The system operates at a relatively high temperature. This allows the heat generated to be either be used for:
* high efficiency electricity generation
* high quality heat generation for industrial processes for example in the chemical industry and hydrogen production

In short, MSR technology provides an unparallelled perspective on combining maximized safety with optimal usage of nuclear material resources and reduction of long-lived nuclear waste.

## MOLTEN SALT REACTOR BENEFITS IN VIEW OF THE NUCLEAR FUEL CYCLE

A specific advantage of molten salt as fuel form, is that it can be manufactured with chemical processes in liquid form, and can be retrieved relatively conveniently from existing reprocessing facilities. It allows circumventing the relatively complex and costly process for ceramic fuel manufacturing, including (hazardous) powder handling and release during pellet pressing, sintering, centerless grinding and other process steps.

Another key challenge with ceramic fuel is the combination of high temperature gradients, brittle material behaviour, irradiation damage and fission product formation in the ceramic fuel, leading to complex behaviour, and large sensitivity to variations, requiring extensive integral testing for new compositions to be qualified. It also leads to high quality assurance and control standards to be adopted (geometry, surface state, isotope distribution in the pellet), further driving the complexity and costs of ceramic fuel manufacturing. Although salt behaviour and property evolution during operation are by no means easy to assess, properties are expected to be mainly determined by chemical composition and chemical composition change, both for salt properties and salt interaction with structural materials. This needs to be corroborated by irradiation tests, but would allow salt properties and salt-material interaction to be largely determined with conventional non-nuclear chemical tests, enabling convenient and cost effective generation of broad composition envelopes. The quality assurance and control connected to molten salt fuel, is reduced to the determination of chemical and isotopic composition.

Ceramic fuel behaviour complexity and sensitivity to variations, also introduces limits on ceramic fuel compositions thereof, while reprocessing especially when performed repetitively and the need to burn minor actinides, requires a flexible fuel form to accommodate all variations from these waste streams. For example, the amount of minor actinide material like Americium a fuel ceramic can accommodate is too limited for effective burning. Molten salt fuel as a liquid can quite easily accommodate large variation in compositions, as long as chemical stability, decay heat and appropriate properties and property evolution in core can be properly managed.

In fast spectrum systems, the probability/cross-section of neutron induced fission and absorption are relatively low and in the same order of magnitude. For criticality to occur, this therefore requires high fissile and fertile masses in the core, and high neutron flux. Unlike moderated thermalised spectrum systems, this also means that burn-up in fast spectrum systems is relatively limited, but with the benefit that remaining isotope vectors allow for re-use as fuel. This enables nuclear fuel cycle closure, i.e. minimize long-lived nuclear waste, and maximize the effective use of fissile and fertile nuclear material resources. However, this requires repetitive full core reprocessing and fuel remanufacturing. Considering the complexity of ceramic fuels manufacturing and behaviour, and limited flexibility, it is questionable whether full nuclear fuel cycle closure can be economically and even technically achieved by ceramic fuel reactor concepts

Flexibility and manufacturing ease make molten salt the nuclear fuel of choice, related to (repetitive) reprocessing and fuel (re-)manufacturing, supporting advanced fuel cycles and fuel cycle closure.

Molten salt reactors can be designed to in principle allow online reprocessing, but this adds significant complexity to the plant, both from technical, nuclear safety and proliferation point of view. As explained in the following sections, Thorizon therefore adopts a practical replacement strategy, connecting to centralized reprocessing facilities, with initial target to contribute to improvement of light water reactor fuel cycles.

## THORIZON DESIGN DRIVERS

In this section the Thorizon MSR concept is described. Thorizon has made a fundamental reactor concept choice, by which the MSR disadvantages are effectively resolved or compensated by MSR advantages. However, the Thorizon design basis is quite generic (and also patented as such), and offers many different design possibilities.

The Thorizon design is currently driven by deployment on the shortest term possible. This has lead for example to the following choices and decisions:

* Resolve the material degradation challenges of molten salt reactors by practical replacement, taking into account containment, and sizing of the primary components.
* Materials in molten salt reactors are exposed to harsh conditions, such as high temperatures, chemical interaction with molten salt and irradiation. This has been regarded the main reason MSR realization has been pushed to the long-term future by many.
* Focus on licensability and nuclear safety by design, where existing nuclear safety concepts and frameworks are used where possible, such as defence in depth, containment, managing single failure criterion, and by maximally exploiting passive safety potential of molten salt technology.
* Use of existing and nuclear qualified materials where possible, and avoid extensive new material R&D, therefore ensure practical replaceability of materials that are in contact with salt.
* Design for use of existing codes that can be practically validated and are known in the nuclear industry and by regulators. Decouple thermalhydraulics and neutronics as much as possible, by reducing flow degrees of freedom by establishing guided flow, forced by pump. Adopt advanced codes that are not validated or difficult/impossible to validate, as supportive tools only.
* Large salt volumes that allow free salt flow, can necessitate the use of high resolution models for simulation, including all thermalhydraulic-neutronic interactions and coupling, throughout the critical core. These models and the coupling are complex, and difficult to validate.
* Adopt modular approach where possible, with manufacturing of critical components under controlled conditions off-site.
* Avoid (nuclear) complexity:
* Avoiding the need to add front- and back-end complexity to the already challenging scope of developing a nuclear reactor. Connect to parties that are willing to take this responsibility and have the experience.
* Avoiding online processing (adding or removing radioactive materials from the primary system), to facilitate maintaining containment, eliminate chemical processing complexity in the system, and limit potential proliferation concerns.
* Enabling convenient and practical handling and transporting of molten salt volumes whilst maintaining containment.

## THORIZON DESIGN

From the design drivers Thorizon has conceived a modular core design: a core built up out of individually contained, subcritical modules called cartridges. The cartridges are closed before, during and after operation, no material goes in or out, and the cartridges can be introduced and removed individually from the core while maintaining containment. Material degradation is therefore not eliminated, but managed by timely replacement, while maintaining containment. This patented concept has many advantages allowing timely deployment.

Each cartridge contains a primary heat exchanger (from the primary to the secondary salt) and a pump. When the pump is not operated, the top part or core section of the cartridge is filled with gas, and all the salt is in the lower part of the cartridge. When the pump is operated, the salt circulates and displaces the gas to below the core section. This is achieved by a restrictor at the core outlet, establishing core section pressures and flow velocities that block gas up flow. Only when the pump is operated, and an adequate amount of cartridges are placed in proximity, the core sections of the cartridges form a critical configuration. When cartridge pumps are not operated, the molten salt is located in the lower section of the cartridge, not forming a critical configuration. The reactor therefore requires cartridge pumps to be operated to be critical.

The gas volume in the cartridge is relatively large and pressure increase inside the cartridge due to fission gas or other volatile compound release remains acceptably low under all circumstances.

The cartridges are connected to a secondary molten salt coolant system, that takes the heat from the primary heat exchanger in each cartridge, with connections that can be released to allow cartridge removal.

There is no online reprocessing or conditioning of the salt, to avoid complexity and proliferation concerns. Conditioning of the salt is done in cartridge only, and limited to what is needed to secure a minimal lifetime of 5 years. Thorizon has selected containment materials that have been tested for fast reactor application extensively in the past, with appropriate data to support a minimum 5 year lifetime goal as well.

Each cartridge primary containment is encompassed by a secondary containment, providing an additional barrier in case of primary containment failure, separated by a gap in between, which is swept by gas. A high level schematic image of the cartridge concept is shown in Fig. 1, both for pump shutdown and operational modes.



*FIG. 1.* High level schematic image of the cartridge concept.

This gas is analysed for fission products online, to monitor primary containment integrity.

Tritium that has formed in the primary salt and has diffused through the primary containment wall, is also taken with the gas and localised, to avoid further dispersion.

The gas gap also acts as thermal insulation, limiting heat loss during operation, but also facilitating salt melting at start-up.

The cartridges are surrounded by reflector and a radiation shield, forming the so-called core cavity. Control and/or shutdown rods are located in between the cartridges, and can be based on existing designs, as these are not moving in the molten salt environment. The core cavity is cooled by inert gas.

The core cavity cooling system cools actively during operation, but has adequate passive cooling capacity for long term decay heat cooling of the cartridges in a station blackout scenario.

A high level artist impression of a 7 cartridge core has been shown in Fig. 2.



*FIG. 2. A high level artist impression of a 7 cartridge core*

The secondary coolant system transfers heat to a tertiary molten salt cooling system, which is largely conventional and can provide heat to industrial processes directly or can store heat (in molten salt for example), or can convert the heat to electricity, or a combination.

The cartridges are of a transportable size, and instead of a large salt volume and a large primary system, the salt mass has been compartmented in manageable subcritical volumes. An artist impression of the first Thorizon plant, named Thorizon One, is shown in Fig. 3.



*FIG. 3.* Thorizon One*.*

Cartridge size and number have determined the current power of the Thorizon One system of 250 MWth, which can be converted into 100 MWe.

## THORIZON FUEL APPROACH

Thorizon’s cartridge concept combine complexity reduction with practical replacement, and externalize reprocessing to (existing) facilities.

The Thorizon concept facilitates regular salt (re-)processing, conditioning and purification at a central reprocessing location (i.e. not on the reactor site) by regular replacement, avoiding the complexity and proliferation discussions of online salt reprocessing in the reactor environment.

In first instance, Thorizon aims to improve the Light Water Reactor fuel cycle, by burning the long-lived elements in LWR spent fuel.

Future cartridge versions can contain minor actinides, specifically Americium, which is difficult to burn effectively in ceramic fuel concepts, and can be of benefit to reduce long term disposal risks and costs.

Follow-up steps, including further developed cartridges, will allow burn and breed approaches and close nuclear fuel cycles, making optimal use of fertile Uranium and Thorium resources.

## ADDITIONAL ADVANTAGES OF THE CARTRIDGE APPROACH

The modular core and cartridge approach of Thorizon provides additional benefits:

* Without cartridges a Thorizon MSR has no primary circuit, and is largely conventional, and does not require high pressure boundaries. The plant itself is therefore expected to be relatively low cost.
* The primary system is modular, and the cartridges are produced in series, off-site, under controlled conditions, under a proper quality assurance and quality control regime. This allows cost effective, high quality production, independent of local or regional circumstances.
* The cartridges can be continuously improved, for example with new materials for extended lifetime, or in-cartridge salt conditioning systems, to enhance overall system performance and economics with each new replacement
* The Thorizon system can also allow the introduction of different fuels, and could even allow spectrum tuning to serve different fuel cycle and waste reduction strategies. The system therefore is not necessarily designed for one fuel cycle strategy for the decades expected to the plant lifetime. Even a change in neutron spectrum is not excluded in the same plant, by adjusting cartridge designs and reflector.
* A single cartridge represents the whole core. Initial non-nuclear demonstration of manufacturing, thermalhydraulic performance, behaviour under off-normal or accident conditions and corrosion and long-term operation can be assessed effectively by building and testing of single cartridge prototypes.
* The Thorizon concept has a regular replacement approach, providing a recurrent business model, while overall plant costs are minimized.

## SUMMARY

From the Generation IV concepts, molten salt reactor technology offers a unique set of advantages in terms of safety and performance, specifically in relation to closing nuclear fuel cycles and minimizing long-lived waste.

Thorizon aims to exploit the generic benefits of molten salt reactor technology to counter the technical challenges, and targets a practical design, driven by manufacturability, operational feasibility, nuclear safety and licensability, to enable early deployment.

In first instance, Thorizon aims for a complementary role to Light Water Reactors, improving their fuel cycle, by converting longlived elements from reprocessed LWR spent fuel, into short-lived elements and CO2 free heat or electricity.

Thorizon aims for partnerships with nuclear and non-nuclear industry that share this vision, to get support by established experience and accelerate the development.