# EvALUATION OF THE MOLTEN SALT REACTOR TEchNoLOGY for the application of floating nuclear power plants

I. KOURASIS

CORE POWER (UK) Inc.

London, United Kingdom

Email: [ioannis.kourasis@corepower.energy](mailto:ioannis.kourasis@corepower.energy)

J. MILES

CORE POWER (UK) Inc.

London, United Kingdom

Email: [jake.miles@corepower.energy](mailto:jake.miles@corepower.energy)

M. EL-SHANAWANY

Nuclear Energy in Maritime Organization

London, United Kingdom

Email: [mamdouhelshanawany@hotmail.com](mailto:mamdouhelshanawany@hotmail.com)

**Abstract**

Floating Nuclear Power Plants (FNPPs) present a promising pathway to broaden the acceptance of nuclear, by addressing critical challenges faced by land-based reactors and streamlining deployment, The paper evaluates the applicability of a liquid-fueled Molten Salt Reactor (MSR) within FNPPs. It specifically delivers an overview of the MSR concept, evaluating its design features and capabilities in the context of the marine environment and the operational profile of floating platforms. Additionally, the research investigates the potential effect of sea water on MSR fuel criticality. The paper is aimed at enhancing the overall understanding of advanced reactors suitability for marine deployment, paving the way for a more cost-effective and easily deployable nuclear power solution.

## introduction to FLOATING NUCLEAR POWER PLANTs

### Floating Nuclear Power Plants

Floating Nuclear Power Plants, FNPPs, have the potential to be one of the main solutions for deploying power generation capacity quickly, economically, and at a large scale. The majority of the global power demand is situated close to the coast where FNPPs can be easily deployed. In addition, FNPPs have access to water for cooling, insensitivity to earthquakes and tsunamis, and greater transportability when compared to terrestrial reactors which make moving nuclear power generation offshore an option worth investigating [1].

FNPPs are not only suited for power generation for remote islands, coastal settlements, and industrial sites but, for instance, also for the powering of offshore facilities which are expected to decarbonize.

All these potential use-cases have been recognized since the 90s [2] and two FNPPs have been successfully deployed in the past, powered by Pressurised Water Reactors (PWR), namely the USS Sturgis [3] and Akademik Lomonosov [4].

Despite the multiple use cases and benefits on paper, FNPPs have not seen widespread development yet. However, the momentum behind FNPPs has risen significantly in the recent years, mostly due to the developments in SMRs and advanced reactor technologies, leading to the 2023 IAEA Symposium on the Deployment of Floating Nuclear Power Plants. Certain Gen IV reactor concepts promise design features that appear to be a great fit for Floating Nuclear applications. To assess how applicable a reactor design is for FNPP deployment, the paper defines 8 key reactor technology evaluation criteria considering a wide range of applications, from a nearshore FNPP powering a port to an off-shore FNPP powering a desalination hydrogen production plant.

### FNPP Reactor Technology Evaluation Criteria

TABLE 1. FNPP REACTOR TECHNOLOGY EVALUATION CRITERIA

|  |  |  |
| --- | --- | --- |
| # | Evaluation Criteria | Rationale |
| 1 | Availability - Fuel Cycle Duration, Refuelling and Planned maintenance frequency | Compared to terrestrial plants, FNPPs are more restricted in terms of space and resources available to transport, handle and store spent and fresh fuel. In addition, planned FNPP reactor outages will have a significant impact on coupled applications like data centers, desalination or hydrogen production plants or the powering of remote areas lacking energy supply. For those reasons, FNPP concepts in general benefit greatly from longer fuel cycles, with planned maintenance and refuelling frequency minimized. In that respect, the Akademik Lomonosov refuelling plan includes entire reactor core refuelling to achieve a maximum of 3.5 years between refuelling (instead of 12-18 months with standard refuelling plans). Reactor technology should be evaluated for its ability to maximize the availability of the plant. |
| 2 | Design Safety for Marine Accident Scenarios | The safety case of FNPPs will have to consider marine related accidents, such as collision and sinking. In these accident conditions the functions of reactor shutdown, reactivity control, radiation shielding, containment and decay heat removal must be performed, with the potential absence of reactor operating crew and the reactor containment partially or fully submerged underwater. Reactor technology should be evaluated for its ability to achieve this reliably |
| 3 | Plant Emergency Planning Zone Size | For FNPP deployment near heavily populated areas like ports, or for coupling with hazardous facilities like hydrogen plants, the extent of the potential radiation exposure in case of severe accidents is an impactful factor for the feasibility of these floating applications. Reactor technology should be evaluated for its inherent safety and ability to minimize the public risk, which is depicted on the size of the emergency preparedness and planning required. |
| 4 | Plant Power output | FNPP applications range from GW scale offshore concepts to 10s of MW scale concepts for powering data centers and desalination barges. Reactor technology should be evaluated against its ability to provide feasible solutions for a wide range of power outputs. |
| 5 | Plant Footprint | FNPP applications will have certain plant footprint limitations that don’t necessarily apply to terrestrial plants. Reactor technology should be evaluated for its ability to produce the required power with limited footprint. |
| 6 | Output Heat Grade | One of the more promising FNPP applications is using the nuclear heat to directly in a chemical process like Haber Bosch [5]. Reactor technology should be evaluated against its ability to provide high grade heat. |
| 7 | Proliferation Resistance | A mobile floating asset is susceptible to an extended set of threats, compared to a terrestrial nuclear plant. Reactors deployed in FNPPs would need increased proliferation resistance to meet international nuclear security standards. |
| 8 | Operation in marine conditions and transients | Marine Conditions include the motions and accelerations experienced by the floating platform. Reactor technology should be evaluated against its ability to operate in these conditions. |
| 9 | Transport in marine conditions and transients | As part of their commissioning and decommissioning, FNPP vessels will be transported via sea or inland waters. Reactor technology should be evaluated for its ability to be transported safely in marine conditions. |

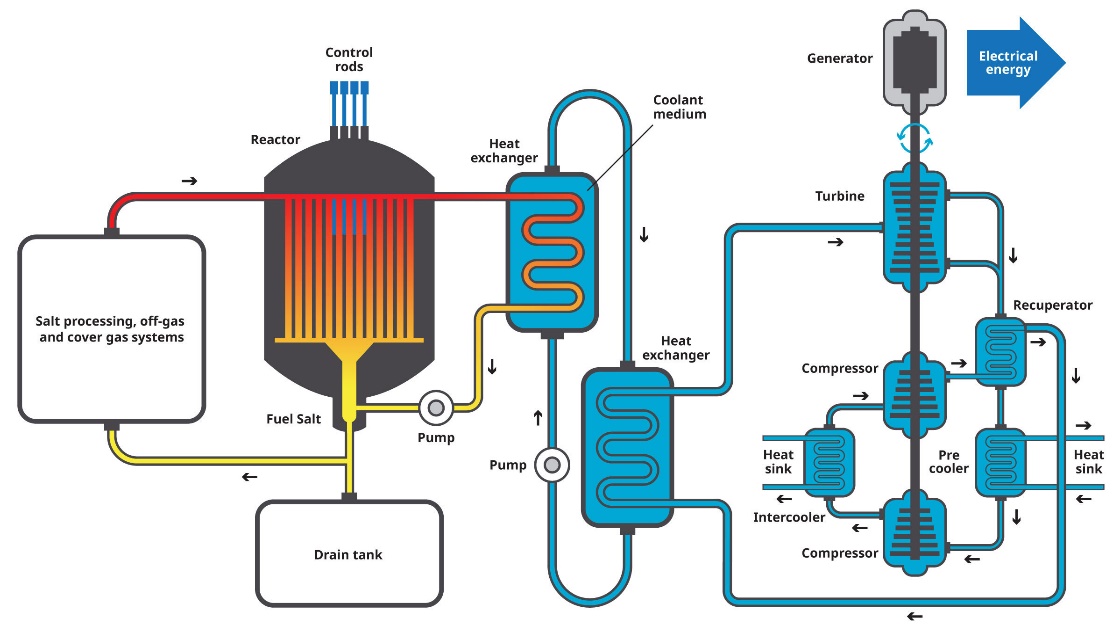
The paper evaluates the liquid-fuelled Molten Salt Reactor concept, against these criteria, to form a better understanding of the applicability of MSRs in FNPPs.

## 

## MOLTEN SALT REACTOR

### Architecture and History

The MSR is a liquid fueled nuclear reactor technology, powered by a circulating molten salt fuel mixture, that can be designed to operate in the thermal or fast spectrum. The fuel salt mixture undergoes fission in the core, is circulated in the primary heat exchangers to extract the heat and then fed back in the core in a closed loop Fig 1. MSRs operate at close to ambient pressure and run at a high temperature, between 500 – 700°C. The heat produced by the fuel salt is usually transferred to an intermediate coolant salt and can then be converted into electricity.



*FIG 1. MSR Schematic based on [6]*

MSRs can be designed to run on Uranium, Plutonium or Thorium, dissolved in Fluoride or Chloride salts, with Fluoride salts preferred for thermal spectrum reactors and Chloride salts for fast spectrum ones. Thermal spectrum MSRs require a graphite monolith to moderate the neutrons in the core, whereas fast spectrum MSRs require the use of a neutron reflecting material, instead of the graphite. The Aircraft Reactor Experiment (ARE) in 1954 followed by the 7 MWth Molten Salt Reactor Experiment (MSRE) in Oak Ridge National Laboratory have demonstrated most of the discussed MSR functions, setting the stage for multiple advanced reactor development programs of MSRs since then.

### Evaluation of MSR Applicability in FNPPs

An evaluation of a generic MSR design against the FNPP reactor design criteria is provided in Table 2.

TABLE 2. EVALUATION OF MSR APPLICABILITY BASED ON FNPP REQUIREMENTS

|  |  |  |
| --- | --- | --- |
| Design Requirement  TABLE 1 Ref # | | MSR Applicability |
| 1 | The liquid nature of the fuel allows for online refuelling, processing and fission product filtering, offering high availability. This could allow for very long intervals (up to decades) between planned reactor outages for refuelling and maintenance. Therefore, the frequency of handling either fresh or spent fuel on board is minimized, in particular when compared to a PWR that requires handling of the solid fuel assemblies every 18 to 24 months on average. This vastly improves the economics of the floating application, enhances proliferation resistance and overall safety. However, storing the fresh fuel required to perform this function as well as the fission products that are being removed, will present added safeguarding and nuclear material accounting and control issues that will need to be addressed according to IAEA standards. | |
| 2 | Liquid fuel can be drained, cooled and solidified in a safely subcritical drain tank, which accommodates decay heat removal. In addition, an in-core MSR shutdown is possible by inserting neutron absorbing rods, or permanently poisoning the salt by dispersing neutron absorbing materials in it. These shutdown methods can be implemented under marine accident scenarios, in the case of operating crew needing to evacuate. The effect that the presence of sea water will have in the criticality of those shutdown configurations needs to be further understood and is investigated in section 3 of the paper. | |
| 3 | MSRs operate at close to ambient pressure. During standard operation, the fuel salts are only under the pressure required for their circulation. The liquid fuel is also very accident tolerant, with an extremely high boiling point and a very strong negative temperature coefficient. In addition, due to some FPs being soluble in the fuel, and the rest filtered, MSRs will have a low fuel source term in paper. Utilizing all these intrinsic safety features, MSR plants could achieve an Emergency Planning Zone at the site boundary, based on the new risk-informed performance based regulatory guidelines [5]. | |
| 4 | MSRs have only been operated successfully up to the 10MWth range. However, the MSR concept has no physical limitations on the power output and can in principle be scaled to achieve outputs to the hundreds of MWs. | |
| 5 | Compared to other reactors, MSRs have a much smaller vessel size and do not require pressure vessels. However, MSRs do require extra space for a cover gas system, fuel tanks and fission product filtering. Overall, judging from the MSRE footprint [7] and overall system architecture, a generic MSR plant footprint is small enough to fit on a floating platform. | |
| 6 | MSR operating temperatures are in the range of 600 – 700 C, providing high grade heat for potential FNPP applications and increasing overall power conversion efficiency. | |
| 7 | In a molten salt core, most of the fission products are soluble in the salt, creating a mixture of actinides and lanthanides. This feature greatly increases proliferation resistance. | |
| 8 | In principle, liquid fuel will be affected by the motions and accelerations experienced in a marine environment. An MSR designed for a marine application should be able to operate at these motions and inclinations, by minimizing free surface and utilizing forced flow systems. MSR designs that are based on natural circulation are not directly applicable for FNPP use. | |
| 9 | Prior to startup, MSR fresh fuel is in a stable solid form, hermetically sealed to prevent oxygen or hydrogen ingress. The paper performs a brief evaluation of the criticality safety of this fissile material in the presence of water. Following reactor shutdown, MSR technology allows for the controlled solidification of the fuel in a subcritical geometry as demonstrated by MSRE [7] with a cooling system required to remove decay heat. In both cases, the fuel will be in a solid state so its geometry will not be significantly affected by marine motions. In addition, fission products that have been separated from the fuel during operation and stored on-site, either solid or gaseous, can be treated and packaged according to nuclear material transport regulations prior to transportation. Overall, MSR technology will allow the plant design to meet international standards for transport safety. | |

### Technical Challenges and areas for development

Molten Salt Reactors have a number of areas that need to be researched and developed in order to achieve technology readiness for large scale commercial deployment, as showcased in Table 3.

TABLE 3. MSR TECHNOLOGY: KEY AREAS OF RESEARCH

|  |  |
| --- | --- |
| MSR Technology Areas of Research |  |
| Salt-facing Materials | MSR requires materials that can operate at high temperatures 700 C, withstanding salt driven corrosion and erosion. Historically, nickel based alloys have been identified to meet these properties, however after a material is identified as a good candidate, tens of thousands of hours of testing and experimentation is needed to collect sufficient data for nuclear licencing. |
| Salt Chemistry | The solubility of minor actinides and lanthanides in molten salts remains uncertain and needs to be researched. In addition, chemistry research is needed in the area of REDOX control, for the purpose of minimizing corrosion of the salt facing alloys. |
| Nuclear Data | More accurate cross section data than what is currently available for high energy neutron reactions with the salt elements is needed to accurately predict MSR core physics and criticality safety. |

In addition, MSRs need multiple ancillary systems to operate, other than the reactor vessel and power conversion system. These include an off-gas/salt processing system that separates non-soluble FPs from the fuel salt, a cover gas system to prevent air from mixing with the salt, fuel storage tanks, piping, pumps and valves that can operate under high temperatures and withstand salt thermal expansion, meeting international nuclear safety standards. Developing the technology readiness of these systems structures and components and integrating them in a marine asset, also designing for an efficient operation and maintenance plan would require significant resources spent in component and materials testing, research and development.

Some exciting upcoming research in these areas is being done by the Molten Chloride Fast Reactor Program, a joint collaboration between TerraPower, Southern Company, CORE POWER and Hyundai Heavy Industries. Under this program, the Integrated Effects Tests is a Thermal-hydraulics testing facility that is performing component testing and operator training with non-fissile molten salts, and the Molten Chloride Reactor Experiment, is a 200 kW fast-spectrum chloride salt experimental reactor that will be built and operated in the following years at Idaho National Laboratory [8].

## evaluating criticality safety of water mixing with fuel salt

As discussed, to licence a reactor for use in marine applications, the reactor should be able to perform the safety function of criticality control under submerged conditions, following marine accidents. For an MSR that is shut down, one of the bounding criticality safety cases that need to be evaluated, especially for the use in FNPPs, is water mixing with the fuel salt. Assuring that an ingress of water into any system does not lead to a criticality accident is essential. As such, this section outlines the preliminary investigation into the effect of the hydrogen-to-heavy-metal ratio (H/HM) on the k-effective of liquid fuels.

### Methodology

Three different liquid fuels are investigated in this study: the uranium-235 Molten Salt Reactor Experiment (MSRE) fuel [9], a thermal spectrum FLiBe fuel salt and a Chloride fuel salt [10]. The composition in terms of number densities (ND) are given in Table 4. Analysis of the fuel-water mixtures was conducted using OpenMC, a Monte Carlo particle transport simulation code [11], with ENDF/B-VIII.0 nuclear data [12], to construct an infinitely reflected volume of liquid fuel. Then, by fixing the amount of each nuclide in the fuel salt, the value for hydrogen and oxygen could be determined and varied to form a mixture with different values of H/HM. For additional analysis, flux and radiative capture spectra were tallied using the ECCO-1968 energy group structure [13].

TABLE 4. FUEL SALT COMPOSITIONS

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| MSRE | | LEU FLIBE | | CHLORIDE BASED | |
| Nuclide | ND (at/barn-cm) | Nuclide | ND (at/barn-cm) | Nuclide | ND (at/barn-cm) |
| U235 | 8.556E-05 | U235 | 4.452E-05 | U235 | 4.880E-04 |
| U238 | 1.743E-04 | U238 | 3.401E-03 | U238 | 3.898E-03 |
| Li6 | 0.000E+00 | Li6 | 9.155E-07 | Cl35 | 1.780E-02 |
| Li7 | 2.057E-02 | Li7 | 4.684E-02 | Cl37 | 5.695E-03 |
| Be9 | 9.341E-03 | Be9 | 4.594E-03 | Na23 | 1.034E-02 |
| F19 | 4.670E-02 | F19 | 4.364E-02 |  |  |
| Zr | 1.572E-03 |  |  |  |  |

### Results

A group of graphs showing different types of data

Description automatically generatedResults of keff vs H/HM for four different fuels are given in Fig 2. A typical LWR fuel (3.5 wt% enriched Uranium Dioxide or UOX) is given to exemplify how H/HM graphs will look in LWRs. For MSRE and FLiBe fuels, their behaviour is analogous to that of the LWR, where the two characteristic regions of under- and over-moderation can be seen, which lie either side of the optimal moderation. On the other hand, the Chloride fuel salt results show that keff decreases with increased moderation, with no amount of moderation leading to a spike.

*FIG 2. k-effective vs. H/HM for different fuel salt compositions*

By investigating spectral changes, the effect of increased moderation can be better understood. Fig 3 displays the total neutron flux spectrum, normalised to a power density of 20MW/MTHM, as in [10]. When there is no water (blue), the spectrum is comparatively harder compared to the other cases. As hydrogen concentration is increased, there is a higher proportion of neutrons being thermalised into and passed the resonance regions. Consequently, there are more neutrons being captured by the sodium and chlorine in the chloride fuel as seen by the increased radiative capture with increased moderation in table 5.

TABLE 5. RADIATIVE CAPTURE IN CHLORIDE FUEL AT DIFFERENT VALUES OF H/HM

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reaction rate [s-1] | No Water | H/M = 0.01 | H/HM = 1 | H/HM = 100 |
| Na-23 (n,γ) | 6.641E+08 | 6.502E+08 | 5.288E+08 | 1.038E+09 |
| Cl-35 (n,γ) | 5.692E+09 | 6.315E+09 | 7.213E+10 | 3.229E+11 |
| Cl-37 (n,γ) | 1.329E+09 | 1.373E+09 | 1.762E+09 | 2.337E+09 |

A graph of different values

Description automatically generated

*FIG 3. Neutron flux spectrum for different values of H/HM*

## COnclusions

The Molten Salt Reactor concept appears as a promising candidate for use in FNPP applications, taking advantage of the liquid fuel and increased passive safety features to achieve competitive economics with online refuelling, increased availability and high-grade heat. In terms of candidates, chlorine-based fuel salts show promising results in the criticality safety bounding case of water-fuel mixing which is an important factor for licencing these technologies in Marine Applications. For achieving commercial deployment of MSRs in FNPPs, significant progress still needs to be made in the development of systems and the testing of salt-facing materials.

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