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CONCEPTUAL DESIGN OF A MODULAR DUAL–PURPOSE MOLTEN SALT REACTOR

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Abstract: In light of global warming and geopolitical tensions, carbon–emission–free nuclear power has undergone a resurgence, elevating the prominence of small modular reactor (SMR) designs. This study serves as a specific application example, detailing the design process for a 200MWt Molten Salt Reactor (MSR) aimed at hydrogen and electricity generation. The theoretical findings appear promising for future practical applications. Molten salt reactors (MSRs) represent an advanced class of nuclear fission reactors that use molten salts as both coolant and, in some designs, fuel. These reactors offer inherent safety features and high efficiency due to their liquid fuel properties and elevated operating temperatures. A conceptual design for a modular dual–purpose molten salt reactor (MSR) integrates factory–built core units for electricity generation and high–temperature process heat, such as industrial applications or hydrogen production. These designs emphasize replaceable modules, passive safety, and thorium or low–enriched uranium fuel cycles to align with Generation IV goals for sustainability.
Keywords: molten salt, small modular reactor, hydrogen

INTRODUCTION

The imperative for carbon–free energy systems is evident in light of accelerating global warming. Consequently, nuclear energy has gained recognition as a crucial complement to renewable sources, such as solar, marine, and wind power, within the portfolio of alternatives to fossil fuels.

Globally, nations are pursuing diverse strategic approaches to this end. Theoretical and empirical analyses focusing on China, a major force in global production, project a required capacity exceeding 400 GW by 2060. Such scenarios underscore the pivotal role of nuclear energy and emphasize the necessity to accelerate the development of small modular reactors (SMRs) for deployment in inland regions. They further highlight the need for their synergistic integration with renewable energy systems. From this perspective, the commercialization of third–generation reactors, optimizing spatial planning through demand–supply matching algorithms that balance mega projects on the coast with SMR clusters in inland regions, and expanding non–electric applications in hydrogen production and industrial heat supply for emission reduction purposes [1].

A prominent design in the Small Modular Reactor (SMR) category is the Molten Salt Reactor (MSR). Like Pressurized Water Reactors (PWRs), MSRs are fission reactors, but they utilize a fuel salt that is liquid above 500°C. This molten salt coolant, notably FLiBe (a lithium beryllium fluoride mixture), offers significant advantages:

- it operates at low pressure due to its high boiling point,
- possesses high density for substantial thermal energy storage, and
- exhibits exceptional radiation resistance.

This combination of properties, particularly when fuelled with thorium and uranium compounds, makes FLiBe a safe and efficient medium for both transferring heat and sustaining fission reactions [2, 3].

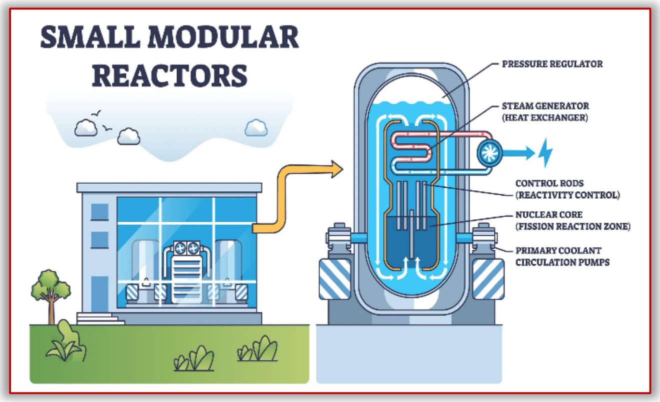

Figure 1. Small Modular Reactor (SMR)

The increase in global energy demand is linked not only to population growth but also to the rise in per capita energy consumption. As increased mechanization on an industrial scale has led to higher electricity consumption, solutions that do not generate carbon emissions have been sought. At this stage, hydrogen production emerges as a new alternative. A study published in 2022 and conducted specifically in Germany revealed that, although hydrogen was not used in the iron and steel, metal processing, glass, mineral processing and paper industries in 2018, taking into account the increase in its use in the refinery and basic chemical sectors, there will be an annual demand of 326TWh in the near future [4].

Hydrogen has gained great importance as one of the climate–friendly energy sources of the future. With this rise, more than 25 countries have announced their hydrogen strategies (roadmaps) in the last year and a half. In addition, various studies and reports have been published by many institutions and organizations to promote the development of the hydrogen economy [5].

Hydrogen strategies and roadmaps are national/regional plans guiding the development and deployment of hydrogen as a clean energy source, focusing on production (green/blue), infrastructure, industry integration, and achieving climate goals like carbon neutrality by setting targets, policies (like the EU's binding targets), and investment frameworks for cost reduction and new value chains. Hydrogen strategies and roadmaps serve as comprehensive frameworks for the production, transport, and use of clean hydrogen to achieve national and regional net–zero goals. As of 2025, over 56 countries have official hydrogen strategies. Key examples are:

- European Union: Strong policy framework with binding 2030 targets for industry/transport, market rules, and focus on renewable hydrogen.
- United States: National Strategy & Roadmap focusing on clean hydrogen production, cost reduction, and deployment through initiatives like the Hydrogen Shot.
- Germany: National Hydrogen Strategy aiming to make green hydrogen a cornerstone of energy transition.
- Asia–Pacific (APEC): Various national roadmaps focusing on cost reduction, strategic frameworks, and clean hydrogen production targets.

When examining the whole of Europe, an assessment of European hydrogen demand in 2050, based on 20 studies exploring decarbonisation pathways, Abid (2024) and colleagues predict that this figure will average 50Mt/year. This figure excludes decarbonisation targets that are intended to be proportionate to Europe's development. Alongside technological development, the decarbonization target should not be forgotten [6].

Forecasts of US industrial hydrogen demand by 2050 vary significantly, from 4 to 22 million tonnes, due to uncertainties in projections of future industrial production. Furthermore, an estimated ~8.3 million tonnes per year of clean hydrogen will be required solely for clean electricity generation, a volume equivalent to a substantial portion of the nation's current renewable or nuclear output. This underscores that scaling up clean electricity production is the principal constraint on using green hydrogen to decarbonize industry. While announced projects propose a total capacity of 17.7 million tonnes per year, potentially sufficient to meet industrial demand, competition from other sectors, such as heavy–duty transport, will complicate allocation and distribution logistics. Consequently, with the widespread adoption of hydrogen, US industrial emissions in 2050 are projected to be only 1.5 to 7.0 percent lower than 2021 levels. An estimated seventy percent of this reduction would be achieved by substituting conventional fuels with clean hydrogen, with the remainder resulting from reductions in overall production [7].

The transition from internal combustion engines to hydrogen fuel cell electric vehicles (HFCVs) has gained importance in the post–Paris Agreement era. Although South Korea has established policies to develop its hydrogen ecosystem, sufficient hydrogen supply plans, annual hydrogen demand for 2040 based on three different scenarios, and daily hydrogen demand per charging station have been the subject of research. By 2040, a hydrogen station is expected to meet a daily demand of 1 to 2.3 tonnes of hydrogen, which is 250 kg/day higher than the current station capacity. If the proliferation of HFCVs follows that of electric vehicles, it is emphasised that although South Korea has hydrogen transport trailers with a capacity of 340 kg, these trailers cannot be used at full capacity due to the 150–litre limitation in containers, highlighting the importance of using tube trailers with a capacity of one tonne [8].

Current hydrogen production remains predominantly reliant on carbon–intensive methods. As of 2020, 59% of global hydrogen was produced via natural gas conversion (steam methane reforming) and 19% from coal gasification. In contrast, low–carbon alternatives constituted a minimal share. Blue hydrogen, produced from natural gas with carbon capture and storage (CCS), accounted for only 0.7% of production. Green hydrogen, produced through water electrolysis powered by renewable energy, represented a mere 0.03%, underscoring the nascent stage of clean hydrogen production [5].

In response to this need, this study presents a conceptual design for a Molten Salt Reactor (MSR) aimed at hydrogen production. A Molten Salt Reactor (MSR) is an advanced nuclear fission reactor that uses a liquid mixture of molten salt as its primary coolant and/or fuel, operating at high temperatures but low pressures. This design offers potential advantages in safety, efficiency, and waste management compared to traditional solid–fueled reactors.

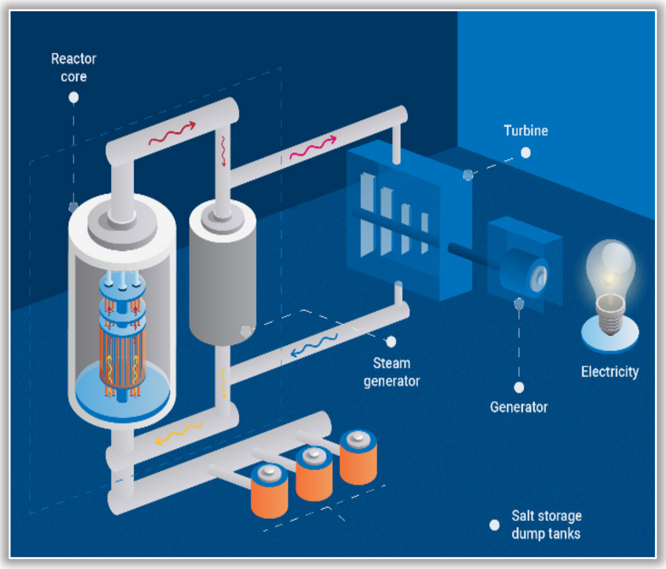

Figure 2. Molten Salt Reactor (MSR)

The design outlines a system with a total thermal output of 200 MWth. The reactor is planned for dual–purpose application, allocating 50% of its thermal power (100 MWth) to hydrogen production and the remaining 50% to electricity generation, thereby offering an integrated approach to clean energy and fuel synthesis.

MATERIAL AND METHODS

Neutronic Analysis

The Monte Carlo method, a powerful computational technique used in reactor physics for simulating neutron transport and fission events, was employed during the reactor design phase of the study. The overall study was modelled using Monte Carlo–based Serpent 2 simulation codes. At this stage, the governing equation is the neutron transport equation, which is the fundamental mathematical formulation describing the spatial, directional, and energetic distributions of neutrons in nuclear reactors, as given in Eq(1).

$$\boldsymbol{\Omega}\cdot\nabla\psi(\boldsymbol{r},\boldsymbol{\Omega},\boldsymbol{E},\boldsymbol{t}) + \sum t(\boldsymbol{r},\boldsymbol{E})\psi(\boldsymbol{r},\boldsymbol{\Omega},\boldsymbol{E},\boldsymbol{t}) = \int 4\pi \int 0 \propto (r, E' \rightarrow E, \boldsymbol{\Omega}' \rightarrow \boldsymbol{\Omega})\psi(\boldsymbol{r},\boldsymbol{\Omega}',\boldsymbol{E}',\boldsymbol{t})dE'd\boldsymbol{\Omega}' + \boldsymbol{S}(\boldsymbol{r},\boldsymbol{\Omega},\boldsymbol{E},\boldsymbol{t}) \quad (1)$$

In this equation, ψ(r,Ω,E,t) represents the neutron flux (r is the position, Ω is the direction, E is the energy, and t is the time). Σt(r,E): The total macroscopic cross section, Σ(r,E'→E,Ω'→Ω) the scattering macroscopic cross section, S(r,Ω,E,t) the source term, Ω·∇ψ: The terms representing the neutron transport.

In the Monte Carlo method, this equation is solved by simulating the paths of individual neutrons and using statistical methods. This approach provides high accuracy for complex geometries and energy spectra [2, 9, 10].

The Bateman equation was used to analyze radioactive decay and isotopic transformations and is given in Eq. (2) as the change in the concentration of an isotope with time.

$$dN_i(t)\ dt = -\lambda_i \cdot N_i(t) + \sum j \neq i\ \lambda_j N_j(t) P_{ji} \quad (2)$$

Here $Ni(t)$ represents the concentration of the isotope at time, λi: the decay constant of the ith isotope, Pji: the probability of transition from the jth isotope to the ith isotope [11–13].

Hydrogen Production Analyses

The principle of decomposition of sulfuric acid (H_2SO_4) was used as an innovative approach for hydrogen production. This chain reaction will occur in three stages. The reaction steps are given below [14, 15].

— Reaction 1 – Decomposition of Sulfuric Acid at High Temperature:

Sulfuric acid (H_2SO_4) decomposes into sulfur dioxide, water, and oxygen at 1147 K (900°C), the ideal temperature for the H2 process, via one second with Eq. (3);

$$H_2SO_4 \rightarrow SO_2 + H_2O + \tfrac{1}{2}O_2 \quad (3)$$

— Reaction 2 – Hydrogen Iodide Production by Catalytic Reaction:

SO_2, iodine (I_2), and water (H_2O) released as a result of decomposition undergo a catalytic reaction to produce hydrogen iodide (HI) and sulfuric acid (H_2SO_4). This reaction takes approximately 5 seconds.

$$SO_2 + I_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (4)$$

— Reaction 3 – High–Temperature Decomposition of Hydrogen Iodide:

The hydrogen iodide (HI) formed decomposes to produce hydrogen gas (H_2) and iodine (I_2) with Eq.(5) in approximately 3 seconds:

$$2HI \rightarrow I_2 + H_2 \qquad (5)$$

Potential losses in the heat exchangers and pipes where the reactions take place must also be taken into account.

RESULTS AND DISCUSSION

The reactor core design used in this study was developed based on an ETR benchmark reactor model found in the Serpent Monte Carlo nuclear code. The designed ETR reactor not only has an innovative geometric structure but also offers a more compact and modular design compared to similar designs by optimising fuel quantity and composition. The graphite moderator and reflector material used in the reactor has also been specially designed in line with the new concept. The two–dimensional layout of the reactor core is shown schematically in Figure 3 [10, 16].

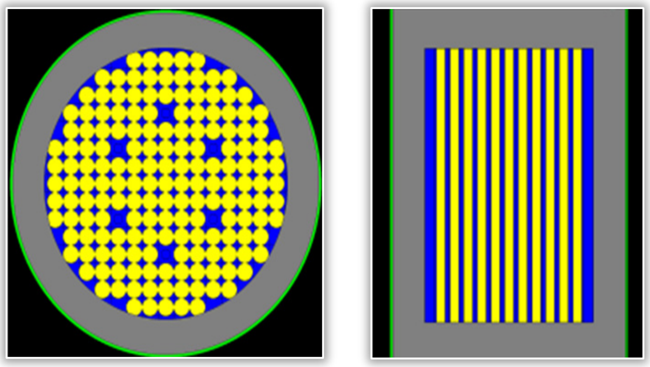

Figure 3. Views of the designed reactor core,
a) Top View b) Side Section View

The yellow, blue, gray, and green areas represent the moderator (graphite), liquid fuel (FLİBE + UF4 + THF4), reflector (BeO), and protection layer, respectively. The design was optimized through numerous simulations with a specific symmetrical arrangement. Reactor Geometry:

≡ Outer Radius of Liquid Fuel / Reflector: 100 / 126cm
≡ Inner Radius of Reactor Vessel: 128 cm
≡ Lower / Upper Reactor Limit: –140 /+140 cm
≡ Graphite Moderator Radius : 6.4999999 cm
≡ Reactor Power / Life : 200 MWt / ≈ 730 days
≡ Fuel Inlet / Outlet Temperature: 1100 / 1200 K
≡ Reactor Core Material: 304 Stainless Steel / Hastellroy
≡ Fuel Specific Heat: ~2.4 kJ/kg K
≡ Fuel Density: 3.3 g/cm³

The simulation results graphed in Figure 4 depict the evolution of the effective multiplication factor (k∞) with fuel depletion. The simulations, performed with 20,000 neutrons per cycle for 200 active cycles, show that k∞ decreases from an initial value of 1.08367 (at a burn up of 13.1 MWd/kgHM) to a final value of 0.941932 at the end of the cycle. This negative reactivity trend is consistent with the expected effects of fuel depletion and fission product poisoning. It is seen that criticality will be maintained for approximately 2 years, including the OFF gas and chemical processing unit.

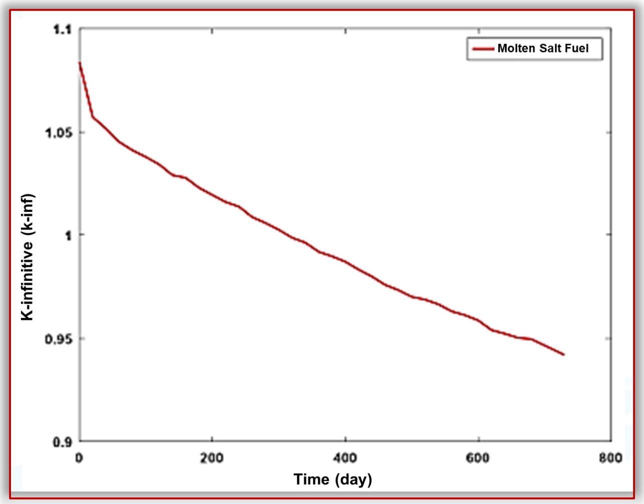

Figure 4. Time dependent k–infinity (kinf) variation
of the designed reactor.

Hydrogen production will occur as a result of a three–step chain reaction. Each of these steps occurs at different times and temperatures. Therefore, a three–stage plant requires a three–stage heat exchanger design. Figure 5 below shows a solid model of the three–stage heat exchanger required for hydrogen production.

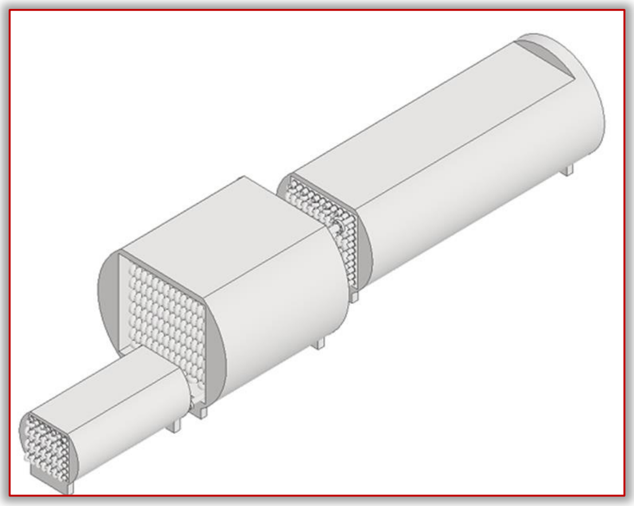

Figure 5. Three–stage heat exchanger required
for hydrogen production.

If the heat entering this exchanger is fuel from the reactor, the hydrogen production facility will be exposed to radioactive contamination. Therefore, the heat must be transferred from the salt + fuel mixture to the salt before passing through this exchanger. For this purpose, a main exchanger should be designed within the insulated area of the reactor vessel. The heat extracted from the fuel and salt mixture entering this exchanger can be used to generate useful work. Calculations for the Power Plant's main exchanger are provided in Table 1 below.

A defining feature of this design is its closed chemical cycle, which requires only water as a consumable input. In the described sulphur–iodine (S–I) process, sulphuric acid (H_2SO_4) and iodine (I_2) are regenerated and reused as catalytic agents, while oxygen (O_2) is produced as a valuable by–product.

Table 1. Design Parameters of main heat exchanger

THE PARAMETERS	VALUES	EXPLANATION
Input/Output Temperature (Salt)	1190 K ⟶ 1100 K (ΔT=90 K)	Molten Salt Heat Exchange
Input/Output of Coolant	310 K ⟶ 900 K	Temperature Difference
Pipe Diameter (d)	0.06 m (6 cm)	Outer Diameter
Pipe Lenght (L)	5 m	
Pipe Radius (r)	0.03 m	
Surface Area of a Pipe	0.942 m^2	Heat Transfer Area
Number of Pipes	2127	
Volume of a Pipe	0.00196 m^2	Inner volume
Heat Exchanger Type	Counter–flow multi–pipe heat exchanger	Design Configuration

This thermochemical process offers significant advantages over conventional methods. Electrolysis suffers from low overall efficiency (30–40%), as a significant portion of the input energy is dissipated as waste heat, exacerbating its environmental impact. In contrast, direct water thermolysis requires impractically high temperatures (~2273 K). The proposed cycle, however, achieves high–efficiency hydrogen production at a substantially lower temperature, as the decomposition of sulphuric acid occurs at 900 K, and subsequent reactions with water proceed at even lower temperatures. It is critical to initiate the process at the correct reaction step to avoid the unproductive accumulation of sulphuric acid as a waste product.

The integrated power plant design allocates the reactor's 200 MWth output equally between hydrogen production and electricity generation. The 100 MWth dedicated to the S–I process is calculated to yield 15.6 tonnes of hydrogen per day. This practical figure, which accounts for efficiency losses between theoretical maximums (~25 t/day) and real–world implementation, remains economically viable.

The remaining 100 MWth is converted to electricity via a two–stage turbine generator system. This dual–stage architecture provides operational flexibility, allowing the entire thermal output to be diverted to electricity generation during periods of high demand, emergency events, or scheduled maintenance of the hydrogen production line. The integration of an Organic Rankine Cycle (ORC) is planned to enhance the efficiency of this conversion, with a calculated electrical output of 40 MWe.

Thermal management calculations confirm the design's feasibility. To deliver 200 MWth of power, the total fuel inventory of $6x10^6$ cm^3 must undergo a temperature drop of 84 K, based on its specific heat capacity. The designed reactor inlet–outlet temperature difference of 100 K provides a sufficient 16 K margin to compensate for heat losses within the heat exchangers.

CONCLUSION

In an era of heightened environmental awareness, green energy is critical to sustainably support global population growth and increasing automation. Nuclear energy remains a key component of the clean energy portfolio due to its low carbon footprint and advancing technology. Recently, Small Modular Reactors (SMRs), particularly innovative Molten Salt Reactor (MSR) designs, have garnered significant interest from national governments for their safety and versatility. Concurrently, hydrogen has emerged as a crucial energy vector and essential feedstock for various industrial sectors.

This study validates the conceptual design of a 200 MWth molten salt reactor facility. The design demonstrates the suitability of utilizing 100 MWth of thermal power for high–yield hydrogen production at a rate of 15.6 tonnes per day, while the remaining 100 MWth is efficiently converted into electricity, showcasing an integrated and efficient approach to dual–purpose energy generation.

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