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Neutronics calculations for denatured molten salt reactors: Assessing resource requirements and proliferation-risk attributes

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A R T I C L E I N F O

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A B S T R A C T

Molten salt reactors (MSRs) are often advocated as a radical but worthwhile alternative to traditional reactor concepts based on solid fuels. This article builds upon the existing research into MSRs to model and simulate the operation of thorium-fueled single-fluid and two-fluid reactors. The analysis is based on neutronics calculations and focuses on denatured MSR systems. Resource utilization and basic proliferation-risk attributes are compared to those of standard light-water reactors. Depending on specific design choices, even fully denatured reactors could reduce uranium and enrichment requirements by a factor of 3–4. Overall, denatured single-fluid designs appear as the most promising candidate technology minimizing both design complexity and overall proliferation risks despite being somewhat less attractive from the perspective of resource utilization.

1. Introduction

Molten salt reactors (MSRs), in which fissile and fertile nuclear materials are dissolved in a liquid carrier salt, were originally proposed in the late 1940s. Oak Ridge National Laboratory under Alvin Weinberg later spearheaded the research and development effort and first conceived MSRs as a compact, relatively light-weight reactor design to power airplanes.[1] Following the termination of the aircraft-propulsion project in 1961, Oak Ridge continued its research into molten salt reactors for electricity production, which led to the Molten Salt Reactor Experiment (MSRE, 8 MWt, 1965–1969) (Haubenreich and Engel, 1969) and the concept for a prototype Molten Salt Breeder Reactor (MSBR, 1000 MWe) (Kasten et al., 1966), which was never built but would have been based on the thorium fuel cycle. Research on the technology was terminated in 1976 due to a lack of government funding. No other molten salt reactors were ever operated in the United States or elsewhere after shutdown of the MSRE 45 years ago, and no MSR ever used thorium fuel.

Several technical challenges would have to be resolved before molten salt reactors could be deployed commercially. These challenges include handling the highly radioactive coolant circuit, controlling the carrier salt chemistry, and demonstrating the irradiation behavior and longevity of in-core structural components. There are currently few incentives for the nuclear industry to embrace new types of reactors and fuels that are fundamentally different from those designs currently licensed and used. Despite these obstacles, several research groups, private companies, and independent developers continue to explore MSRs because of their potential to offer important advantages vis-à-vis existing reactors. These include, for example, the IMSR (LeBlanc, 2013), the Fuji MSR (Mitachi et al., 2007), the LFTR (Hargraves and Moir, 2010), and the Waste-Annihilating MSR (Massie and Dewan, 2013; Transatomic Power, 2014). These newer designs are often envisioned as small modular reactors with power levels on the order of 200 MWe. Enhanced safety and significantly better fuel utilization are two important features attributed to MSRs compared to currently deployed nuclear technologies. The use of denatured fuel, i.e., elemental and isotopic fuel compositions that are considered non-weapon-usable at all times, has previously been suggested as a strategy to improve the proliferation resistance of MSRs in the case of a global deployment of the technology (Bauman et al., 1977).

This paper studies the resource requirements and some proliferation-risk attributes of two notional single-fluid (SF) and two-fluid (TF) denatured MSRs with long-lived cores. An extensive Oak Ridge National Laboratory (ORNL) study on the performance of denatured single-fluid MSR, performed towards the end of the R&D effort on MSRs at the laboratory, concluded that a once-through fuel cycle without on-line fuel processing would be the "most reasonable choice for development," taking into account fuel resources, cost, and R&D needs (Engel et al., 1980). On the other hand, the two-fluid MSR, where the uranium fuel is separated from

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[1] The Aircraft Reactor Experiment (ARE, 2 MWt) was conducted at Oak Ridge from 1953 to 1954 and evolved to the 60 MWt Aircraft Reactor Test. The program was canceled in 1961, just before the second reactor was completed (Anon., 1963).

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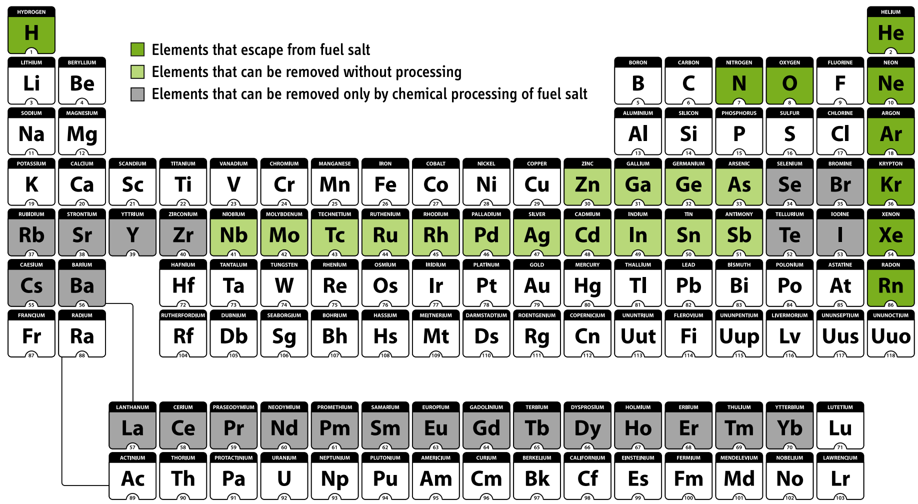

Fig. 1. Processing options for molten salt reactor fuels. Adapted from chart courtesy of Nicolas Raymond, www.freestock.ca.

a thorium-blanket salt, offers the advantage of simplified removal of fission products in the absence of thorium as well as better neutron economy due to reduced neutron capture in protactinium (LeBlanc, 2010). Further details on the design specifications and features of the single-fluid and two-fluid MSR are examined below. This paper adds two new elements to the discussion on the prospects of MSRs: first, a comparative analysis of proliferation risks and resource requirements between SF-DMSRs and TF-DMSRs systems; and second, a similar analysis between notional DMSRs and SMRs based on light-water reactor technology. For reference purposes, we use a power level of 200 MWe (500 MWt) for the MSR concepts studied throughout this paper.

2. Design principles and options for MSRs

Molten salt reactors are typically (but not necessarily, see e.g. Holcomb et al., 2011; Krepel et al., 2014) designed as thermal systems facilitated by the low-Z constituents of common salts. The core itself contains additional moderating material, typically graphite, which ensures that the salt reaches criticality only within the core. Since the fuel is in liquid form, there is great flexibility with regard to fuel choice and reactor configuration. Many types of fuel can operate within MSRs, but most designs envision a thorium fuel cycle, in which natural thorium is used to breed fissile uranium-233, because of the excellent neutron economy of thermal uranium-233-fueled systems.[2] Initially, designers sought to optimize the breeding ratio of MSRs in order to match the performance of sodium-cooled fast neutron reactors. As discussed in more detail below, additional design options become available, if a breeding ratio of less than one is accepted.

All MSR designs involve varying levels of online fuel processing. At a minimum, volatile gaseous fission products escape from the fuel salt during routine reactor operation and must be captured. Most designs also call for the removal of rare earth metals (using a gas-sparging system) from the core since these metals act as neutron poisons. Some designs envision more complex processing schemes (Fig. 1), including the temporary removal of protactinium from the salt or other adjustments of the actinide inventory in the fuel.

More so than perhaps for any other type of reactor, there is uncertainty in the broader energy debate about the potential of molten salt reactors—and, more generally, about the potential of thorium as a reactor fuel. The following discussion highlights the main design features and options for two notional MSRs.

2.1. Single-fluid and two-fluid designs

There are two fundamental classes of molten salt reactors: single-fluid (Haubenreich and Engel, 1969) and two-fluid designs (Robertson et al., 1970). In a single-fluid design, a single type of molten salt flows through the core. This salt contains both the fissile material and any fertile material for breeding. In contrast, in a two-fluid design, the fertile material is separated into a second molten salt. The two salts need to be placed in close proximity to achieve adequate breeding ratios. Fissile material that is produced in the blanket salt is regularly or quasi-continuously extracted and transferred to the fuel salt, while new fertile material is added to the blanket. Typically, the two fluids are separated by a graphite structure, which serves as a barrier and a neutron moderator. Single-fluid and two-fluid designs both have tradeoffs in terms of complexity, performance, and proliferation risk.

The main advantages of two-fluid designs are higher breeding ratio and simplified fuel processing. More importantly, since breeding occurs outside the fuel salt, protactinium-233 produced from neutron capture in thorium-232 does not have the same poisoning effect as it does in a single-fluid design. Therefore, two-fluid designs do not require the removal of protactinium from the blanket salt; it can simply be left in the salt to decay into uranium-233. In contrast, in the original single-fluid reactor aiming for the highest possible breeding ratio, the protactinium is immediately removed after it is produced following neutron capture in thorium. Protactinium is then left to decay to uranium-233 outside the core ($T_{1/2} \approx 27$ days) before it is reintroduced into the salt. Essentially, two-fluid designs can decrease the fuel processing requirements of MSRs over single-fluid designs at the expense of design complexity and cost.

In either case, a basic thorium-fueled MSR can run on virtually pure uranium-233 for its fuel, except for a startup period during which enriched uranium (e.g. uranium enriched to 10–20% uranium-235) may be used. Uranium-233 is a weapon-usable material with a small critical mass and low neutron background (Kang and von Hippel, 2001). Under routine operating conditions, no stockpiling of uranium-233 is envisioned, but in principle, uranium-233 could also be extracted and set aside for weapons purposes while another make-up fuel is used to keep the reactor running. Unless

[2] On average, U-233 emits 2.3 neutrons after absorption of a thermal neutron, which is higher than the respective values for U-235 (2.0) and Pu-239 (2.2).