New breeding gain definitions and their application to the optimization of a molten salt reactor design

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The molten salt reactor (MSR) is an attractive breeder reactor. A graphite-moderated MSR can reach breeding because of the online salt processing and refueling. These features give difficulties when the breeding gain (BG) of the MSR is evaluated. The inventory of the core and external stockpiles have to be treated separately in order to quantify the breeding performance of the reactor. In this paper, an improved BG definition is given and it is compared with definitions used earlier. The improved definition was used in an optimization study of the graphite – salt lattice of the core. The aim of the optimization is a passively safe, self-breeder reactor. The fuel channel diameter, graphite volume and thorium concentration were varied while the temperature feedback coefficient of the core, BG – as defined in the paper – and the lifetime of the graphite were calculated. There is a small range of lattices which provide both negative temperature feedback and breeding. Furthermore, breeding is possible only at low power densities in case of the salt processing efficiencies set in this study. In this range of power the lifetime of the graphite is between 12 and 20 years.

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1. Introduction

In the molten salt reactor (MSR) the fuel – a fluorine salt of actinides – is dissolved in a molten salt carrier. This mixture of salts acts as coolant as well. The fluid fuel is a unique feature of the reactor which provides exceptional transmutation and breeding capabilities because the composition of the salt can be continuously altered by chemical processes during operation. This way the concentrations of various nuclei – actinides and fissile products – can be tailored to optimize transmutation and breeding. The MSR has other advantages on fuel fabrication, neutron economy and high temperature operation as well due to the low absorption, high boiling point and low vapor pressure of the salt. This study focuses on an MSR which is a possible breeder utilizing the thorium fuel cycle.

The fertile isotope of the thorium fuel cycle is $^{232}$Th which forms $^{233}$U after a neutron capture and 2 beta decays. The intermediate products are $^{233}$Th and $^{233}$Pa. The half-life of the two isotopes is 22.3 min and 27 days, respectively. The dynamics of this fuel cycle differs from the uranium cycle because of the relatively long half-life of $^{233}$Pa, while $^{239}$Np, the isotope in the same position in the uranium fuel cycle has a half-life of 2.35 days. This long half-life of $^{233}$Pa results in a high probability of capturing a neutron before the protactinium decays to uranium. If $^{233}$Pa captures a neutron before it decays, the formed isotope will be $^{234}$U, a non-fissile isotope. To avoid this, it is possible in a breeder MSR to extract part of the protactinium from the salt during operation and to store it outside the core (Robertson, 1978). All the removed $^{233}$Pa will decay to $^{233}$U. In this way the $^{233}$U production can be enhanced. Moreover, external stockpiles of protactinium and uranium are formed which are coupled to the reactor. The protactinium stockpile obtains its feed from the reactor while a part of the $^{233}$U formed in the stockpile can be sent back into the core to maintain criticality if needed.

The history of the molten salt reactor dates back to the 1950s. The design was first proposed as the propulsion system of a nuclear-powered aircraft at the Oak Ridge National Laboratory (MacPherson, 1985). After the program finished, the emphasis was put on the research of an MSR running on the thorium fuel cycle. In the 1960s the project focused on the breeding possibilities, resulting in the design of the Molten Salt Breeder Reactor (MSBR) (Robertson, 1978). An experiment, called molten salt reactor experiment (MSRE) (Prince et al., 1968) was carried out from 1965 to 1969. The reactor was operated with $^{233}$U in early 1969. This was the first time $^{233}$U was used as reactor fuel. The salt of this reactor did not contain any thorium because it was intended to simulate only the fuel stream of a two-fluid breeder reactor. The MSBR program was terminated in 1976 although the results of the experiment were promising. The MSR without the complicated chemical removal processes is a converter reactor with high conversion ratio if thorium is added to the fuel (Perry, 1975). The ORNL studies were used as a basis for the molten salt reactor design FUJI.