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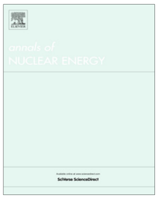

Neutron shielding studies on an advanced molten salt fast reactor design

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ABSTRACT

The molten salt reactor technology has gained some new interest. In contrast to the historic molten salt reactors, the current projects are based on designing a molten salt fast reactor. Thus the shielding becomes significantly more challenging than in historic concepts. One very interesting and innovative result of the most recent EURATOM project on molten salt reactors – EVOL – is the fluid flow optimized design of the inner reactor vessel using curved blanket walls. The developed structure leads to a very uniform flow distribution. The design avoids all internal structures. Based on this new geometry a model for neutron physics calculation is presented. The major steps are: the modeling of the curved geometry in the unstructured mesh neutron transport code HELIOS and the determination of the real neutron flux and power distribution for this new geometry. The developed model is then used for the determination of the neutron fluence distribution in the inner and outer wall of the system. Based on these results an optimized shielding strategy is developed for the molten salt fast reactor to keep the fluence in the safety related outer vessel below expected limit values. A lifetime of 80 years can be assured, but the size of the core/blanket system will be comparable to a sodium cooled fast reactor. The HELIOS results are verified against Monte-Carlo calculations with very satisfactory agreement for a deep penetration problem.

1. Introduction

In the today's view molten salt reactors have a long history, based on the somewhat curious idea of the early phase of nuclear development in the late 40ies and early 50ies, the nuclear aircraft. "The idea of using molten fluoride salts and thus liquid nuclear fuel in a reactor is rather old. Molten salt reactors were already proposed during the post-World War II attempt to design the nuclear powered aircraft. The Aircraft Reactor Experiment, a small thermal reactor (2.5 MW) using circulating molten salt, operated for several days in 1953" (MacPherson, 1985). This first experiment has been followed by a larger scale experiment with 8 MW thermal, the Molten Salt Reactor Experiment (MSRE). "Design of the MSRE started in the summer of 1960 and construction started 18 month later, at the beginning of 1962. The reactor went critical in June 1965, and was briefly at full power a year later "(MacPherson, 1985). A major step in the MSRE was the demonstration of the use of thorium as fertile material and U-233 as fissile material. The reactor was operated until December 1969 and the U-235 fuel salt was successively replaced with U-233. Finally, the reactor was operated based on U-233 fuel for several months. It was the first time U-233 has been used as reactor fuel. (MacPherson, 1985).

The molten salt reactor technology has gained some new interest nowadays (Waldrop et al., 2012). This interest has been focused in the EURATOM project MOST – Review on Molten Salt reactor Technology (Renault and Delpech, 2005; Mathieuet et al., 2005). Following the MOST project, two recent important projects have been launched EVOL (EVOL – Evaluation and Viability of Liquid Fuel Fast Reactor, 2010; Renault and Delpech, 2010) and MOSART (Ingatiev et al., 2012, 2007). This renewed interest can be explained by some really interesting features of molten fluoride salts. "Molten fluoride salts have some beneficial characteristics, like the wide range of solubility of uranium and thorium, the thermodynamic stability and the resistance against radiologic decomposition, the low vapor pressure at operation temperature and the compatibility with nickel based alloys which are traditionally used as construction material (MacPherson, 1985). In contrast to the MSRE launched in the 60ies, both projects focus on the development of a molten salt reactor with fast neutron spectrum.

In "In addition molten salt fast reactors (MSFRs) exhibit large negative temperature and void reactivity coefficients. This is a unique safety characteristic not found in solid-fuel fast reactors (Mathieu et al., 2009)" (Generation IV International Forum, 2009). This unique safety characteristic and the specific features of the fluoride salts described above lead to superior inherent safety characteristics. MSFR systems have been recognized as a long term alternative to solid-fuelled fast-neutron systems with unique favorable features (negative feedback coefficients, smaller fissile inventory, easy in-service inspection, simplified fuel cycle, etc.) (Generation IV International Forum, 2009). In the frame of the development of future energy resources and an improved nuclear waste

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management, the molten salt reactor concept offers a large capability of different operational regimes. Molten salt reactors are one of the six concepts selected by the Generation IV International Forum (GIF) Generation IV International Forum, 2009 for further study. In contrast to molten salt reactors previously studied, the specificity of the MSFR is the removal of any solid moderator from the core. This choice is motivated by the study of parameters such as feedback coefficient, breeding ratio, graphite lifespan, and U-233 initial inventory (Mathieu et al., 2009). This change results in a fast neutron spectrum molten salt reactor (Merle-Lucotte et al., 2011).

The EVOL MSFR is proposed to be operated in the Th/U-233 fuel cycle with fluoride salts. Since U-233 does not exist in nature, it is foreseen to start the reactor with plutonium and minor actinides (TRUs or transuranium isotopes) as fissile material which is produced in currently operating light water reactors (Merle-Lucotte et al., 2009).

One very interesting and innovative result of the EVOL project is the fluid flow optimized design of the inner reactor vessel using curved blanket walls (Rouch, 2012a,b; Rouch et al., submitted for publication). The developed structure which leads to a very uniform flow distribution without using internal flow guiding structures is an important step forward in the design of molten salt fast reactors. The absence of internal structures avoids the significant problems due to the high mechanical stress and the exposition to very high fast neutron flux. This high fast neutron flux would lead to a rapid material degradation caused by irradiation damages.

Based on this new geometry a model for neutron physics calculation is presented in this publication. The major steps are: the modeling of the curved geometry in the unstructured mesh neutron transport code HELIOS and the determination of the real power distribution for the new geometry. The developed model is then used for the calculation of the neutron fluences in the inner and outer wall of the system. In a final step, an optimized neutron shielding strategy for the molten salt fast reactor is developed to keep the fluence in the safety related outer vessel below the limit values over an operation time of 80 years.

2. Known problems in MSRE and new challenges

Some special problems with the materials in molten salt reactor already appeared in the MSRE. "Hastelloy N used for the MSRE was subject to a kind of “radiation hardening due to accumulation of helium at the grain boundaries…it is still desirable to design well blanketed reactors in which the exposure of the reactor vessel wall to fast neutron radiation islimited" (MacPherson, 1985). This described problem with the fluence of fast neutrons will be significantly increased in a MSFR due to several reasons. There are some major differences in the design of a MSFR compared to the MSRE:

- significantly increased power density, thus significantly higher neutron flux level in the core;
- the neutron spectrum in MSFR is significantly harder since there is no moderator existing, thus a higher share of neutrons above 1 MeV appears;
- the fission reactions happen everywhere in the vessel of a MSFR, in contrast to the very well defined core in a thermal molten salt reactor given by the graphite moderator;
- the consequences is that fast neutron are born directly at the wall, no real slowing down can appear before the neutrons hit the vessel wall.

3. The model

The basic arrangement of the main components of a molten salt reactor is given in Fig. 1. All main reactor components (core with blanket, heat exchanger, pumps, and draining tanks) are located in a surrounding steel vessel. The molten salt is fed into the core (area inside the fertile blanket) through perpendicular arranged pipes. This salt is configuring the reactor core by forming a critical mass. In this area the majority of the fission reactions take place. The hot salt is withdrawn at the top of the core and pumped into the heat exchanger and from there back into the core. This basic arrangement has been improved significantly in the frame of the EVOL project. The improved proposal contains of a curved wall geometry with optimized flow conditions. This curved wall separates the blanket from the core. The core and the blanket have to be surrounded by an outer vessel. The reduced 2D geometry for the HELIOS modeling consists only of the core and the blanket surrounded by the outer vessel. All other structures like heat exchanger, pumps, and surrounding reactor vessel are not considered for the neutronic simulation. The 2D geometry is a vertical cut through core and blanket.

The basis for the determination of the fluences which appear in the walls of the inner and outer vessel is a detailed model of the curve wall geometry of the inner vessel and the whole core including fuel, blanket, and outer vessel. These neutron fluences are used for the determination of the feasible operation time of the inner and outer vessel.

For the calculations of the neutron field the HELIOS 1.10 code system with the internal 47 energy group library is used (HELIOS, 2003). The code is a 2D spectral code with wide unstructured mesh capabilities and a transport solver, based on the current coupling collision probability method (Villarino et al., 1992). The staring point for the development is a 15 by 15 cm grid in the center of the system. This grid is surrounded by some compressed cells in the blanket area to open the possibility to increase the blanket size for the shielding studies. The model consists of 37 times 21 cells. Additionally, the curve blanket wall like it has been invented by Rouch and Vu (Rouch, 2012a,b; Rouch et al., submitted for publication) is inserted using the unstructured mesh capabilities. This leads to over all 922 HELIOS calculation regions. The curved wall is approximated by straight line segments. The coordinates for the reproduction of the curved wall are determined with the help of CAD. The visualization of the 2D model forming a vertical cut through core and blanket is given in Fig. 2. The core region with the mix of fuel and fertile salt is given in red. This area is surrounded by the curve blanket wall with a constant thickness of

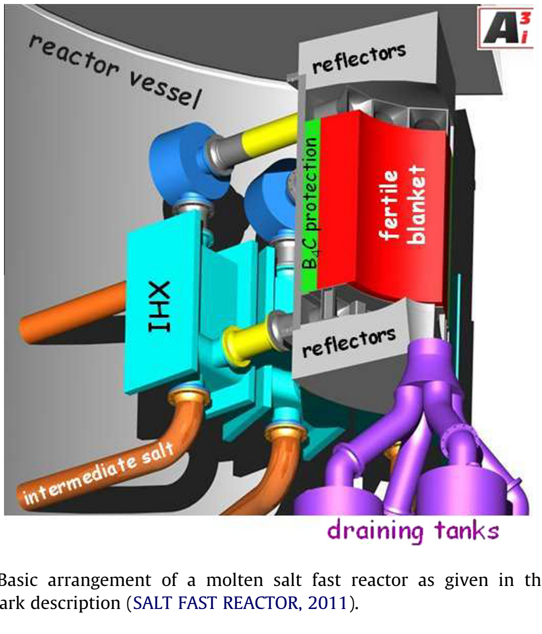

Fig. 1. Basic arrangement of a molten salt fast reactor as given in the EVOL benchmark description (SALT FAST REACTOR, 2011).