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A DESCRIPTION OF THE MOLTEN SALT FAST REACTOR AND THE EU SAMOFAR PROJECT

Introduction

The world population has risen seven-fold over the last two hundred years and is expected to reach 11 billion by the end of this century [1,2]. The energy consumption per capita in some countries is no more than 6 kWh per day [3], while this is 120 kWh in the EU today [4]. The combined growth of the population and the energy consumption is expected to lead to a doubling of the global energy demand within several decades from now.

The European Commission recognizes the need for large-scale technologies with a low-carbon footprint in the EU energy system [5,6], and the fact that nuclear power is an outstanding source for base load low-carbon electricity production. The European Union (EU) is currently the largest nuclear electricity generator in the world, and nuclear energy is expected to remain important in the EU as all energy scenarios in the European Energy Roadmap 2050 include nuclear energy [7].

The ultimate aim of nuclear energy research is to develop nuclear energy, which is truly inherently safe and produces no nuclear waste other than fission products. The Molten Salt Fast Reactor (MSFR) described in this article approaches these goals. The liquid fuel salt provides excellent options for reactivity feedback and decay heat removal, and the reactor can operate as a breeder reactor with thorium with in-situ recycling of all actinides, or as a burner reactor incinerating nuclear waste [8].

History

The research into the Molten Salt Reactor (MSR) started at Oak Ridge National Laboratory (ORNL) in the 1950's with the Aircraft Reactor Experiment (ARE), which ran successfully for 100 hours at a power up to 2.5 MWth and an outlet temperature up to 860°C. The ARE showed that the uranium-fluoride was chemically stable and that the gaseous fission products were removed efficiently by the circulation pumps. The fuel salt had a strong negative temperature coefficient, and the reactor power could be manipulated from zero to full power without control rods by changing the power demand only [9,10].

Afterwards the ORNL focused on graphite moderated reactors working with the thorium-uranium fuel cycle. Neutrons leaking from the primary salt were captured in the blanket salt to produce uranium-233, which could easily be recovered by fluorination.

The research at ORNL culminated in the Molten Salt Reactor Experiment (MSRE), which ran successfully for five years until December 1969. The MSRE had a thermal power of 8 MW and operated either with uranium-233, uranium-235 or plutonium-239. However, the fuel salt did not contain any thorium. During operation, uranium was removed from the fuel salt through fluorination.

The experience gained was used in the design of the Molten Salt Breeder Reactor (MSBR) [20], which had a large core to reduce neutron leakage and a low power density to reduce irradiation damage to the graphite moderator. To achieve net breeding, the produced uranium-233 was removed by fluorination, and a process flow sheet was designed to separate the thorium from the lanthanides.

Unfortunately, the development of the MSBR was not pursued, because of its low breeding gain. With current knowledge and technology, the MSR can be designed with a fast neutron spectrum as well, which provides excellent safety features, a high breeding gain, and the capability to recycle all actinides in the fluid fuel salt.

Description of the MSFR

The Molten Salt Fast Reactor (MSFR) is a further development of the graphite-moderated MSBR and is the current reference design studied within the Generation-IV International Forum [12]. It consists of a cylindrical vessel with diameter and height of 2.25 m made of a nickel-based alloy filled with a liquid fuel salt under ambient pressure at operating temperature of 750 °C. The fuel salt in the primary circuit is pumped around in upward direction through the central core zone and in downward direction through the heat exchangers located circumferentially around the core. In between, a container is located filled with a blanket salt containing thorium-fluoride to increase the breeding gain. A schematic view of the primary circuit is shown in Figure 1, while a more detailed view of the MSFR plant layout is shown in Figure 2.

The reactor is designed with a fast neutron spectrum, and can be operated in the full range from breeder to burner reactor. This flexibility is facilitated by the fact that the fuel salt composition can easily be adapted during reactor operation without manufacturing of solid fuel elements.

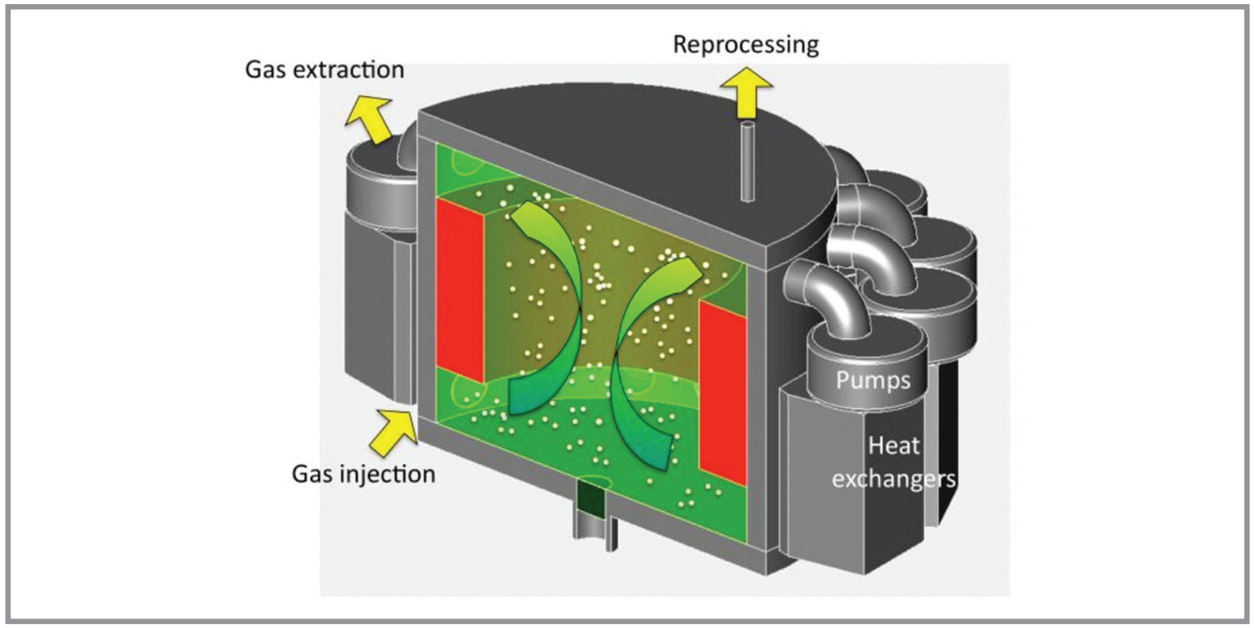

Figure 1. Schematic layout of the MSFR core. The central region (green) is the core surrounded by the annular breeding blanket (red). The heat exchangers are located circumferentially around the vessel [13].

During reactor operation a fraction of the salt is continuously diverted to an ex-core salt clean up unit to extract lanthanides and actinides. The fast neutron spectrum relaxes the requirements for this process considerably [8]. The salt clean-up process is a unique feature of the MSFR and contains two major steps. First, the gaseous and non-soluble fission products like the noble metals are removed from the primary circuit by gas bubbling near the pumps. In a second step the uranium, actinides and some fission products that are strongly bound to the salt, can be separated by pyro-chemical techniques.

Safety Features of the MSFR

The key feature of the MSFR is the liquid fuel salt used under ambient pressure, which provides a unique approach towards nuclear safety, reliability and optimal waste management. Nuclear safety is based on the control of excess reactivity, adequate removal of the (decay) heat from the reactor core, and the safe confinement of the radioactive inventory.

Compared to solid-fuel reactors, the MSFR complies in a completely different way to each of these safety functions. First, the fuel salt provides a strong negative reactivity feedback everywhere in the core due to volume expansion with increasing temperature. This effect is in addition to the nuclear Doppler feedback effect present in all nuclear reactors. Second, the fuel salt in the core is in its most compact and reactive shape and any deformation will lead to a lower reactivity. Third the fuel salt can freely flow through fail-safe freeze plugs into drain tanks beneath the core to bring the reactor in a deep subcritical configuration with passive decay heat removal systems based on natural circulation. Fourth, the liquid fuel salt offers the opportunity to extract fission products from the fuel salt to reduce the decay heat and the parasitic neutron absorption, and to recycle all actinides in the salt until fission.

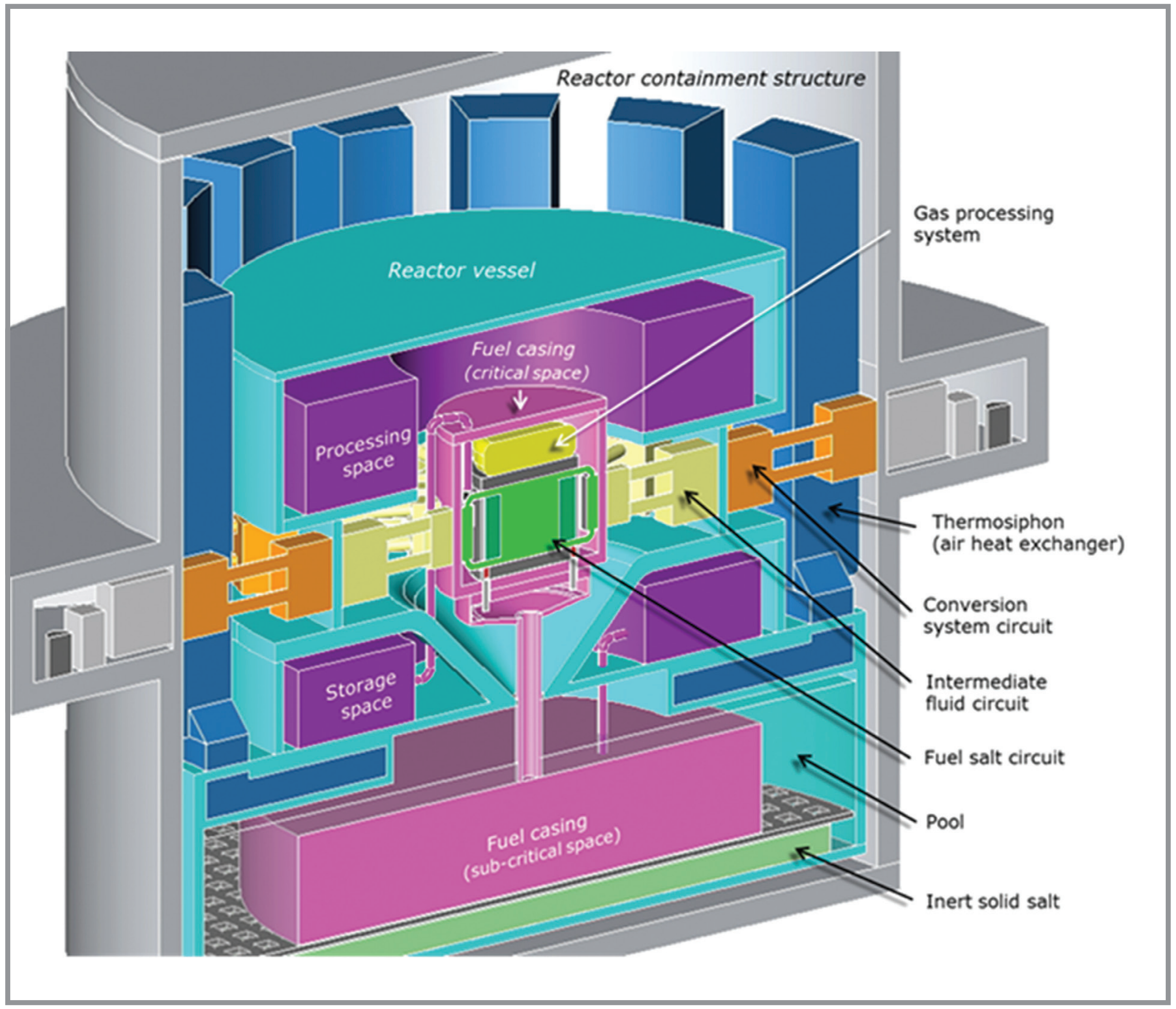

Figure 2. Schematic layout of the MSFR, showing the location of the systems for cleaning and draining of the fuel salt, and the three containment barriers (pink, yellow, grey) [14].

Goals and description of SAMOFAR

The grand technical objective of the SAMOFAR proposal is to prove the innovative safety concepts of the MSFR by advanced experimental and numerical techniques, and to deliver a breakthrough in nuclear safety and optimal waste management.

Besides the Work Package (WP) on Project Management, the SAMOFAR project contains six specialized parts. WP1 deals with the integral safety assessment and the overall reactor design including the chemical plant. WP2 will experimentally determine all safety-related data of the fuel salt. WP3 will experimentally and numerically investigate the natural circulation dynamics of the fuel salt in the primary vessel and drain tanks, and the behavior of the salt in the freeze plugs during a drain transient. WP4 will numerically assess the accident scenarios identified in WP1. These include the normal operation transients and the off-normal accident scenarios. WP5 will experimentally and numerically assess the safety aspects of the chemical extraction processes, and the interaction between the chemical plant and the reactor. WP6 covers the dissemination and exploitation of knowledge and results, among which the education and training of young scientists.

SAMOFAR started in August 2015 and will run for four years. The SAMOFAR consortium consists of 11 partners from the EU, Switzerland and Mexico, each providing a specific own contribution. Besides that various observers participate with in - kind contributions.

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