FAST REACTOR R&D IN PIONEER
Fuels, Materials, Design and Safety Support Analyses

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INTRODUCTION: In the Dutch 'Program for Innovation and cOmpetence development for NuclEar infrastructurE and Research' (PIONEER) [1], sustainability of the nuclear fuel cycle is addressed through R&D towards solid fuel fast reactors efficiently using uranium and plutonium and towards liquid fuelled molten salt reactors using uranium, plutonium and/or thorium fuel. For both routes, fuel and materials R&D takes place with irradiation experiments in the 45 MW(th) High Flux Reactor (HFR) which is operational since 1962. Currently, the construction is underway for the PALLAS reactor which should replace the HFR. The PALLAS reactor aims to be operational at least for some time alongside the High Flux Reactor to ensure a smooth transition of activities. In addition, design and safety support analyses are being performed for a number of Liquid Metal Fast Reactor and Molten Salt Reactor designs which is accompanied by development and validation of various numerical tools, models, and approaches. The extended abstract will provide an overview of the variety of R&D being performed in the PIONEER program with respect to fuels, materials and design and safety support analyses.

1. FUEL IRRADIATION TESTS

In the field of fast reactor fuel development, PIONEER activities deal with various aspects of the fuel cycle. First of all, emphasis was put on reduction of transuranic elements, plutonium and/or minor actinides like americium, neptunium and curium. This can be achieved with oxide fuels, however, also nitride fuels have been studied. The targeted irradiation tests are being performed in the HFR. Such tests can consist of (semi-)integral tests through irradiation of reduced size fuel pins, so called fuel rodlets, or of separate effect tests. These latter tests for example focus on fission gas release or irradiation creep. Table 1 provides an overview of different fuel compositions irradiated in the HFR which have recently been analyzed.

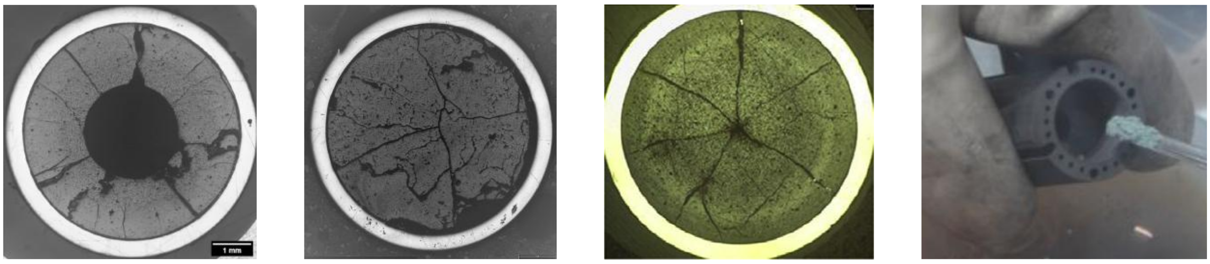

FIG. 1. Micrographic images of TRABANT [2], MARINE [3] and SPHERE [5] pellet fuels after irradiation and filling of the SALIENT graphite capsule with molten salt thorium bearing fuel (courtesy of P.R. Hania).

The references provided in Table 1 will provide the reader much more information on the irradiations performed. Exemplary micrographic images of the three fast reactor fuel pellets are shown in FIG. 1 alongside with a picture of the filling of a graphite crucible with the molten salt fuel specified in Table 1.

TABLE 1. RECENTLY ANALYSED HFR IRRADIATION EXPERIMENTS

Irradiation Experiment	Fuel type	Reactor Type	Reference
TRABANT	MOX with 40% Pu	LMFR	[2]
MARINE	UO_2 with 15% Am	LMFR	[3]
SPHERE	MOX with 3% Am	LMFR	[4] [5]
SALIENT	78% LiF 22% ThF_4	MSR	[6]

2. MATERIAL TESTS

The influence of irradiation damage on construction materials is being investigated through a series of irradiation experiments in the HFR under the name ENICKMA [7]. This facility contains a set of tensile/low cycle fatigue and stress relaxation samples irradiated in inert atmosphere at representative temperatures in the range of 650 to 750°C. Tested materials include nickel-molybdenum-chromium alloys like Hastelloy N, Hastelloy 242, MONICR and GH3535, and a 316 L(N) steel developed within the French sodium fast reactor program. In parallel, the same materials are separately only being exposed to the high temperature. In this way, the irradiation effects can be separated from the high temperature effects.

3. PROCESSING

Reprocessing of irradiated fast reactor or molten salt fuel is an important step in the fuel cycle. As part of the post irradiation examination, fuel pins are cut and made available for a dissolution study. If the well-known PUREX process is followed, the fuel is dissoluted in hot nitric acid. However, not all fuels can be treated in this way. Therefore, alternatives are being investigated using hot concentrated nitric acid with and without hydrofluoric acid, or oxidation with in-situ chemically generated silver.

For molten salt fuels, new processing methods need to be developed for reprocessing as well as disposal, starting from the molten salt irradiated fuel in the PIONEER program. Several options were reviewed, both for fluoride as well as chloride salts. From this literature survey, it is concluded that dehalogenation and vitrification probably work well. Subsequently, various glass types are being investigated for this application and discussions with the Dutch waste organization have been initiated.

4. DESIGN AND SAFETY ANALYSES

Traditionally, design support and safety assessments are being performed using system thermal hydraulics simulation codes. However, with increasing computer power, more detailed Computational Fluid Dynamics (CFD) analyses are now becoming common in design support and start to be integrated in the safety assessments. And profiting from both strengths, the possibility of multi-scale analyses, coupling system thermal hydraulics codes to CFD codes, is being investigated, as well as the possibility of solving for more than one physics aspect in a single simulation, either through coupling codes or by monolithic approaches in which all solvers are integrated in a single code. All the above mentioned approaches are being studied in the PIONEER program. Table 2 provides an overview on pool and system analyses for LMFR and MSR systems for various test cases, experiments, reactor designs, and actually operated reactors. Some examples are provided in FIG 2. The reader is referred to the references for more information and explanation.

Apart from the above mentioned pool and system simulations, also much effort has been put in core thermal hydraulics CFD analyses, i.e. the analysis of the heat transport from the core by the coolant for LMFRs. Since the fuel assembly design can be very different, both grid-spaced designs and wire-wrapped designs are being studied. It is recognized that a lot of knowledge on nominal conditions is available in correlations for system and subchannel codes, however, the study of nominal is being used as a step towards non-nominal conditions. With that, the influence of deformed fuel assemblies on the heat transport, eccentrically places bundles in their wrapper, inlet blockages, and internal blockages are being studied [8]. A summary of studies on internal blockages has recently been published [9]

Finally, the fundamental difference between turbulent heat transfer in CFD from air or water and liquid metals or molten salts is subject of study within PIONEER. For such fluids, the analogy between the momentum and energy field, which is valid for fluids like air or water, is not valid. Therefore, new models are under development to overcome this shortcoming which might effect the accuracy of CFD simulations significantly in some cases. A novel local algebraic heat flux model has been developed [10] and is being tested.

TABLE 2. POOL AND SYSTEM LMFR AND MSR SIMULATIONS

Application	Description	Simulation	Reference
ALFRED	Steady-state	STH, CFD	[8]
ASTRID	Loss-of-Flow	STH	[8]
Cavity	Separate Effect Tests	Multi-physics	[9]
CIRCE-ICE	Steady-state, Loss-of-Flow-and-Heat-Sink	CFD	[8]
CIRCE-HERO	Steady-state, Loss-of-Flow-and-Heat-Sink	STH, CFD, Multi-scale	[8] [11]
EBR II	Loss-of-Flow	STH, Multi-scale	[8] [11]
ELSY	Start-up, Shut-down, Sloshing	STH, CFD	[8]
ESCAPE	Steady-state, Asymmetry, Loss-of-Flow, Loss-of-Heat Sink	STH, CFD, Multi-scale	[8] [11]
ESFR	Loss-of-Flow, Transient Overpower, Sloshing	STH, CFD	[8]
FFTF	Loss-of-Flow	STH	[8]
MSFR	Nominal Conditions	Multi-physics	[11]
MSRE	Steady-state, Natural Convection, Start-up, Coastdown, Reactivity Insertion	STH, CFD	[1] [8] [12]
Phénix	Dissymmetric Loss-of-Flow	STH, Multi-scale	[8] [11]
SEALER-Arctic	Steady-state, Transient Overpower	STH, CFD	[8]
SEALER-UK	Steady-state, Asymmetry, Loss-of-Flow	CFD	[8]
TALL3D	Steady-state, Loss-of-Flow	STH, CFD, Multi-scale	[8] [11]

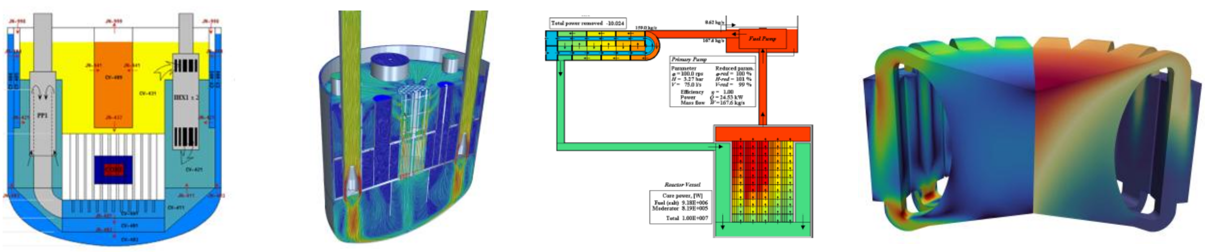

FIG. 2. Left-to-right: STH model of the sodium-cooled Phénix reactor [8], CFD model of the lead-bismuth cooled ESCAPE facility [8], STH model of the molten salt reactor MSRE [8], and 3D multi-physics model of the molten salt reactor design MSFR [11].

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