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T/H and transient analyses to confirm EFIT preliminary design

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ABSTRACT

One of the main objectives of the EUROTRANS Integral Project is the design of a several hundreds MWth transmutator based on the accelerator driven system (ADS) concept. The preliminary layout of European Facility for Industrial Transmutation (EFIT) has started with a set of basic options derived from the previous ADS demo design (PDS-XADS) with the adoption of U-free fuel instead of MOX and taking into account the economic requirements needed for an industrial power plant. To support the project, a thermal-hydraulic numerical model of the reactor has been developed for the RELAP5 system code with the support of multidimensional SIMMER code to improve the representation of the natural circulation paths in the reactor vessel. The presented analyses, addressed to verify the capability of EFIT to face up the high power densities and temperatures, have allowed a first positive evaluation of the inherent safety behavior of the plant mainly relying on the natural circulation.

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1. Introduction

Within the EURATOM Sixth Framework Program (FP6), the EUROTRANS integrated project [1] is expected to provide a significant contribution to the demonstration of the industrial transmutation through the ADS route. The goal will be reached in two phases: the advanced design of a 50–100 MWth experimental facility LBE cooled to demonstrate in the short term the technical feasibility of Transmutation in Accelerator Driven Systems (XT-ADS) and the conceptual design (several 100 MWth) of the lead-cooled European Facility for Industrial Transmutation (EFIT) to be realized in the long term.

Starting from the 80 MW LBE-cooled XADS design studied in FP5 [2], which showed the feasibility of coupling an accelerator and a subcritical system with a high degree of safety, several modifications have been introduced to correctly address a detailed design of an industrial demo able to produce energy at reasonable cost maintaining as much as possible the high safety level.

The elimination of intermediate loops, the installation of heat exchangers inside the primary vessel and the implementation of mechanical pumps for forced nominal circulation lead to a more compact primary system with higher core power density.

Pure molten lead is used as primary coolant instead of LBE. In fact, high operating temperatures improve the plant yield and are required for embrittlement issues. On the other hand to reduce the risk of structural material corrosion the plant will operate with low core ΔT. Moreover, the amount of activated products, such as Polonium should be rather reduced.

An uranium free fuel is adopted in order to obtain an acceptable burning efficiency. A general system simplification and easy refueling are also pursued to reduce the maintenance costs.

A numerical T/H model of the reactor has been developed with the RELAP5 Mod 3.2.2β version modified to treat HML systems to investigate the safety issues and to confirm the neutronic design.

2. Numerical model of the preliminary design

The main features of the preliminary design are reproduced as much as possible in the 1-D RELAP model. The reactor has a pool type configuration with a lead forced circulation in nominal condition by means of four pumps placed in the hot collector at SGs inlet on the high part of the vessel (Fig. 1).

In the model [3] the lead mass inventory distribution and the major flow paths are correctly represented (Fig. 2). The primary pumps are simulated by means of time dependent junctions to impose forced flow and alternative flow paths for natural convection. Eight once-through, helical-coil and straight tube bundle SGs (2 units per pump) are completely described with lead outside the tubes and superheating conditions in the four secondary loops that are imposed by boundary conditions. The reactor core [4] has three U-free fuel zones (CERCER oxide composite $(Pu,MA)O_2 + MgO$), which are modeled with average and hot channels for each core zone with equivalent flow areas coupled with the corresponding pin thermal structures.

The Target Unit, that derives from the previous PDS-XADS design opportunely scaled up, is not still simulated. The Decay Heat is removed by natural circulation through four independent loops with secondary side diathermic oil. The model is limited to the

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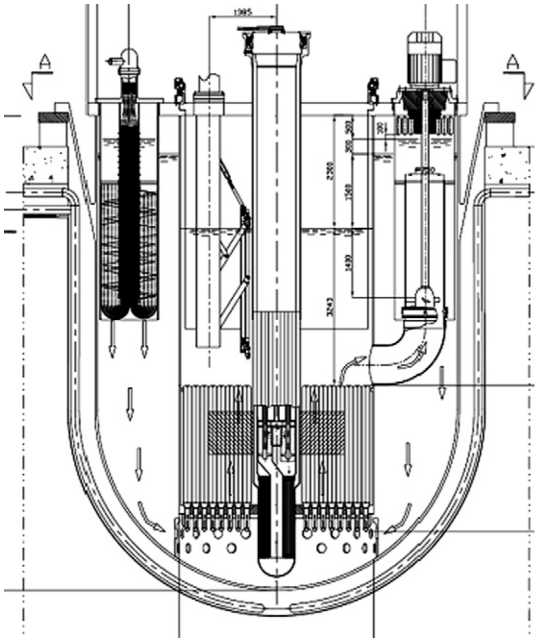

Fig. 1. Vertical section of EFIT preliminary layout.

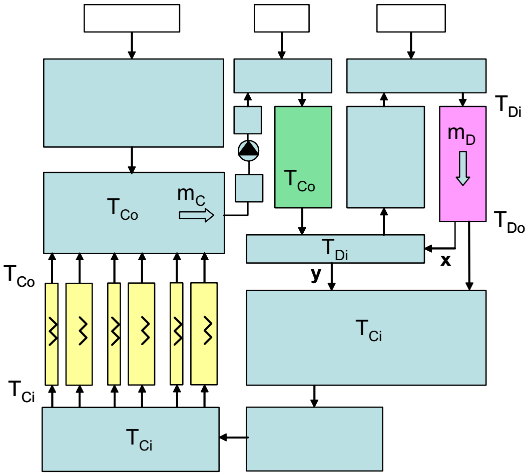

Fig. 2. Scheme of RELAP5 model for EFIT.

Table 1
EFIT main T/H parameters

Primary and secondary conditions			
Power (MWth)			379
Mass flow rate (kg s^{-1})			24 000
Temperature at the core inlet (°C)			400
Temperature at the core outlet (°C)			480
Total pressure drop (kPa)			43
Core pressure drop (kPa)			36
Secondary steam pressure (MPa)			14
Secondary steam temperature (°C)			450
Feedwater temperature (°C)			335
Decay heat removal power (MW)			26.6
Core parameters	Inner	Middle	Outer
Fuel assemblies	42	66	72
Power (MW)	96	142.3	140.5
Fuel matrix (% MgO)	57	50	50
Pellet diameter (mm)	7.1	7.1	8
Gap thickness (mm)	0.16	0.16	0.16
Clad thickness (mm)	0.6	0.6	0.6
Pitch (m)	13.63	13.63	13.54

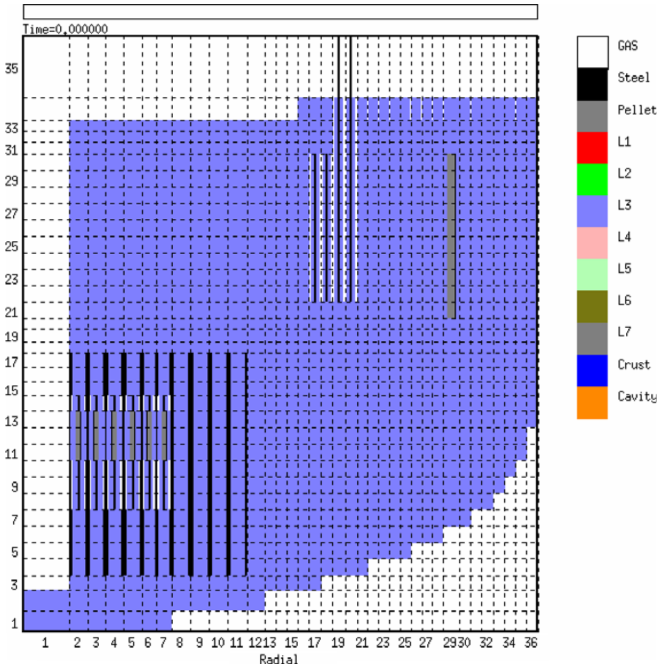

Fig. 3. Scheme of SIMMER model for EFIT.

HX primary side by imposing the exchanged power as a function of the lead temperature.

Table 1 shows the main parameters for EFIT.

In order to set up the natural convection paths for the DHR circuit a 2-D simulation in cylindrical geometry was performed with SIMMER-III (Fig. 3). The core is represented by 6 radial fuel rod rings plus the reflector and by-pass zones, and meshed in 14 axial nodes. The primary pump section, the steam generators and the DHR heat exchangers are represented by annular zones with equivalent cross flow area. RELAP results have been tuned to the SIMMER ones in case of DHR operation conditions (Fig. 4) by imposing suitable singular pressure drops in the natural circulation flow paths.

3. T/H and transient analysis results

The core design has been verified with respect to the following safety limits for the design basic conditions in category 1: 550 °C for the ferritic–martensitic steel (T91) cladding considering an aluminium coating, 1380 °C for the fuel due to the risk of dissolution of the ceramic matrix and 1500 °C for the coolant. Table 2 summarizes the results for the three zones of the core. All the safety limits are met for the three zones only by introducing orifices at the core inlet of the middle and outer zones in order to increase mass flowrate in the Inner one, thus levelling the lead outlet temperatures.

Two accidental scenarios that represent a meaningful challenge to the safety characteristic of the EFIT design have firstly been analyzed.

A protected loss of heat sink (PLOHS) at BOC with beam and pump trip when the average outlet core temperature exceeds 500 °C and DHR degraded conditions (3 out of 4) is analyzed to verify the effectiveness of DHR system in natural circulation conditions.

An unprotected loss of flow (ULOF) at BOC with SGs full capacity and without reactivity feedback (constant core power) is analyzed to assess the inherent safety behavior of the primary layout.

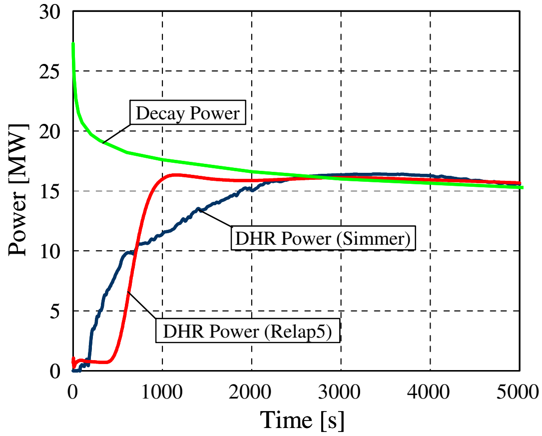

Fig. 4. Comparison of the decay power removed by DHR in SIMMER and RELAP5 codes.

Table 2
Temperatures at steady-state conditions

Param\zone	Inner		Middle		Outer	
Power form factors	Axial 1.14		Axial 1.16		Axial 1.17	
	Rad. 1.12		Rad. 1.13		Rad. 1.24	
Temperature (°C)	Avg	Hot	Avg	Hot	Avg	Hot
Central fuel	1151	1251	1216	1331	1094	1286
Surf fuel	822	874	807	860	737	819
Inner clad	523	538	520	536	508	534
Outer clad	513	526	510	525	501	525
Lead	482	492	482	493	482	502

The PLOHS results in Figs. 5 and 6 show how after some initial oscillations (free levels movements) both core and DHR mass flow rates became stable and the DHR attains maximum performance (20 MW per 3 units) after 600 s.

The peak clad temperature reaches 585 °C in the hot channel of inner core zone, then in a few seconds all temperatures fall down the operational values. This behavior is acceptable for an accident in DBC 4 category, where the clad temperature can remain between 550 and 600 °C for 600 s.

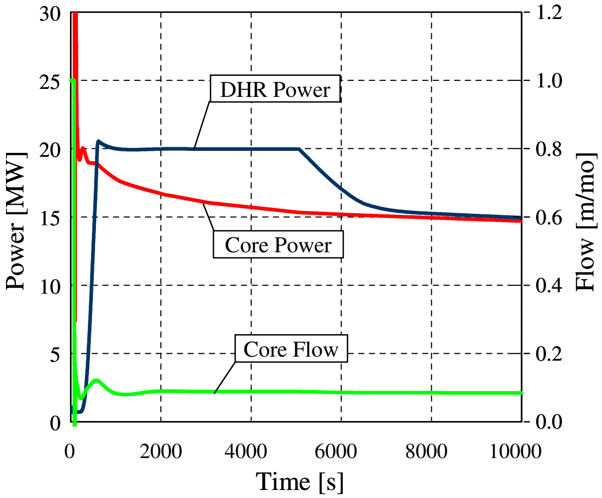

Fig. 5. Power and flow transient in PLOHS condition.

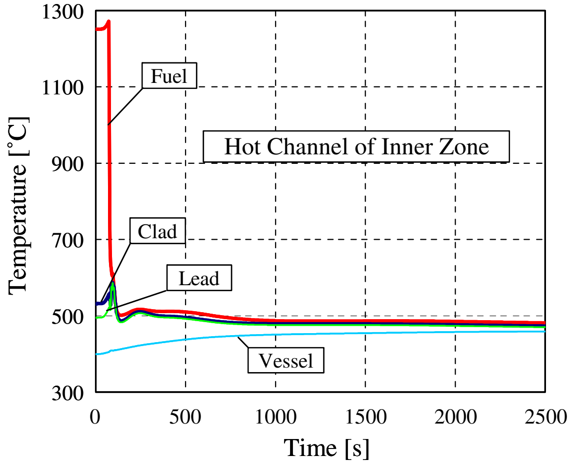

Fig. 6. Temperatures transient in PLOHS condition.

In the ULOF calculation after pumps stop the natural circulation rapidly stabilizes the core mass flow rate at about 35% of the nominal value (Fig. 8). Maximum peak clad and fuel temperatures

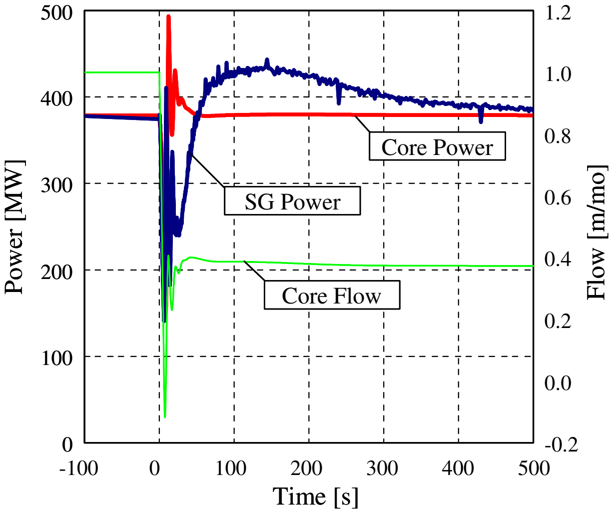

Fig. 7. Power and flow transient in ULOF condition.

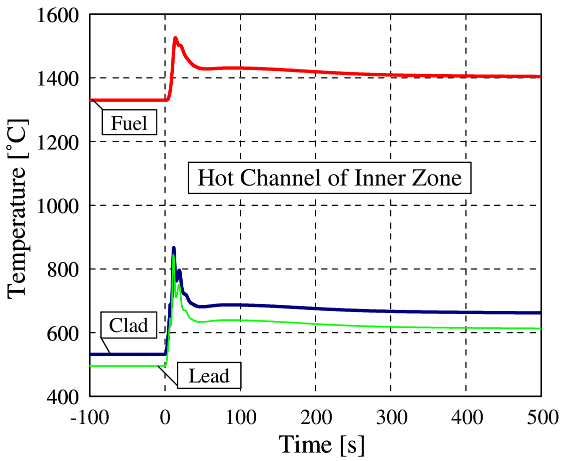

Fig. 8. Temperatures transient in ULOF condition.

(Fig. 7) reach, respectively, about 870 °C and about 1525 °C just after pump stop, than they quickly stabilize at values well below the failure temperatures. The relatively high temperatures calculated during a few seconds are considered acceptable for design extension conditions (DEC) transients.

4. Conclusions

RELAP5 analyses of the EFIT behavior have concerned the T/H design of the core and the inherent safety behavior of the primary system layout.

The steady-state calculations at nominal conditions confirm the capability of a suitable design of the U-free core to face up higher temperature and power density respect to previous ADS design.

The transient analyses focused on DHR design and DEC scenarios have confirmed the DHR System design relying on natural circulation and predicted a good intrinsic safety behavior of the plant.

Acknowledgements

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