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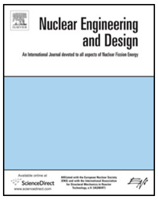

The core design of ALFRED, a demonstrator for the European lead-cooled reactors

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HIGHLIGHTS

- The design for the lead fast reactor is conceived in a comprehensive approach.
- Neutronic, thermal-hydraulic, and transient analyses show promising results.
- The system is designed to withstand even design extension conditions accidents.
- Activation products in lead, including polonium, are evaluated.

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ABSTRACT

The European Union has recently co-funded the LEADER (Lead-cooled European Advanced DEmonstration Reactor) project, in the frame of which the preliminary designs of an industrial size lead-cooled reactor (1500 MW_{th}) and of its demonstrator reactor (300 MW_{th}) were developed. The latter is called ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) and its core, as designed and characterized in the project, is presented here. The core parameters have been fixed in a comprehensive approach taking into account the main technological constraints and goals of the system from the very beginning: the limiting temperature of the clad and of the fuel, the Pu enrichment, the achievement of a burn-up of 100 GWd/t, the respect of the integrity of the system even in design extension conditions (DEC). After the general core design has been fixed, it has been characterized from the neutronic point of view by two independent codes (MCNPX and ERANOS), whose results are compared. The power deposition and the reactivity coefficient calculations have been used respectively as input for the thermal-hydraulic analysis (TRACE, CFD and ANTEO codes) and for some preliminary transient calculations (RELAP, CATHARE and SIM-LFR codes). The results of the lead activation analysis are also presented (FISPACT code). Some issues of the core design are to be reviewed and improved, uncertainties are still to be evaluated, but the verifications performed so far confirm the promising safety features of the lead-cooled fast reactors.

Abbreviations: CZP, cold zero-power; DBA, design basis accidents; DEC, design extension conditions; DPA, deterministic and phenomenological analyses; ELFR, European lead-cooled fast reactor; FA, fuel assembly; HFP, hot full-power; HZP, hot zero-power; ISAM, integrated safety assessment methodology; MA, minor actinides; PLOOP, protected loss of offsite power; PSA, probabilistic safety analysis; RSWG, Risk & Safety Working Group of the Generation-IV International Forum; SGTR, steam generator tube rupture; ULOF, unprotected loss of flow; ULOHS, unprotected loss of heat sink; UTOP, unprotected transient of over-power; WENRA, Western European Nuclear Regulators Association.

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1. Introduction

As it is well known, lead-cooled fast reactors have been selected as one of the possible options for Generation IV reactors (USDOE, 2002). These, as other fast reactors, allow the closure of the fuel cycle and therefore a reduction of about 2 orders of magnitude: of the uranium consumption, of the transuranic waste mass to be disposed in the geological disposal and of the fuel waste long-term radio-toxicity (the reduction factor depending strongly on the amount of the assumed reprocessing losses). Consequently, also the waste disposal volume per unit energy is improved. Some of these aspects can be examined more closely in NEA (2006) and Grasso (2013).

Even if the sodium-cooled reactors represent a much more mature and widespread technology with respect to lead-cooled reactors, the latter ones can have an advantage for the public acceptability of fast reactors. As a matter of facts, lead does not react violently with air and water and, due to the higher density change with temperature, simplifies the design of systems promoting the settlement of natural circulation, even in accidental conditions. These main features allow conceiving a system with safety intimately embedded by design, eventually aiming at downgrading potential safety hazards to investment protection risks. Moreover, they allow a more simplified layout by eliminating the intermediate cooling circuit. The main drawback of lead-cooled systems is represented by the issue related to the corrosive/erosive interaction of lead with the structural materials. A recent discussion about this last topic can be found in Weisenburger et al. (2013).

The European Commission, in its 6th Framework Program, has co-funded in 2006–2010 the ELSY project (European Lead-cooled SYstem), which resulted in a preliminary design of the lead-cooled ELSY reactor of 1500 MW_{th} (Cinotti et al., 2008). Afterwards, in the 7th Framework Program, it has co-funded in 2010–2013 the LEADER project (Lead-cooled European Advanced DEmonstration Reactor), which concentrated on the revision and further development of the ELSY design and on the preliminary design of its demonstrator reactor (300 MW_{th}) (ANSALDO, 2010). The former has been renamed to ELFR (European lead fast reactor), the latter has been called ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator). In the LEADER project 17 different partners from 11 European countries, with research institutions, universities and private companies, led by *Ansaldo Nucleare* (Italy), were involved. The project had a budget of 5.7 million euros.

The goal of this work is to present how the ALFRED core has been designed and characterized in this project, by summing up and discussing the main results described in the detailed project reports.

Firstly, the main technological constraints, goals and safety performances for the core were identified. Then the core has been designed taking into account in a comprehensive approach the impact of these target features on the various and interconnected core parameters, such as the limiting temperatures and the natural circulation (see Section 2). The neutron characterization has been performed then, by 2 independent partners by 2 independent codes: MCNPX and ERANOS (see Section 3). The power deposition calculations were utilized as input for the thermal-hydraulic analysis, performed at the core, fuel assembly (FA) and local level by means of several codes (see Section 4). The reactivity coefficient calculations were utilized as input for the preliminary safety analyses, conducted by means of some of the most assessed system codes (such as RELAP, CATHARE and SIM-LFR), taking into account the most representative DEC accidents, such as ULOF and UTOP (see Section 5). Finally, the lead activation, useful also for the evaluation of the radiological impact of the coolant, has been calculated by means of the FISPACT code (see Section 6).

2. The core design

In order to design the ALFRED core, given the great number of degrees of freedom of the configuration, firstly it was necessary to identify and to fix some main parameters and some priorities. In the following sections the adopted approach and the final chosen core geometry are shown.

2.1. Approach and technological constraints and goals

The main goal of the ALFRED project is to play the role of a demonstrator for the European concept of a LFR, thus proving the safety and reliability – in all operating conditions – of the simple engineering solutions adopted (e.g., the extension of the FA up to the cover gas), while reducing uncertainties in design, construction and operation to the largest possible extent. Since ALFRED and ELFR are characterized by different thermal powers, of course not all their core parameters can be maintained equal. Therefore, the issue arose in the choice, for the sake of the demonstration, of the parameters that are necessarily or conveniently to be kept and those which are not. A detailed discussion about this approach can be found in Grasso et al. (2013a). In particular the fuel enrichment and the breeding ratio are different in the two cores and therefore the closure of the fuel cycle does not represent a goal for the ALFRED core. On the other hand, the materials are the same in the two cores, except for the cladding materials: the expected time required for the full qualification of advanced claddings and coatings in lead (foreseen in the ELFR) is not compatible with the foreseen roadmap for ALFRED (Alemberti et al., 2013). According to the preliminary[1] (yet reliable) results gathered at the beginning of the LEADER project, the temperature limit for the outer wall of the cladding tube is assumed equal to 550 °C. This value turned out to be the same as initially selected during the ELSY project, resulting by averaging the value agreed at the time for the limiting wall temperature of a bare cladding under oxygen control (500 °C) with the one optimistically considered for the on-going experiments on clad coating (600 °C). Concerning the range of temperatures for lead and fuel for ALFRED, it was reckoned they could be chosen the same as for the ELFR, because of the same materials (thus complying with the demonstration aims).

For the coolant flow velocity, the actual physical constraint seems to be related to the component of the lead velocity impinging orthogonally on the structural surfaces, which should be limited below 3 m/s. Translating this physical constraint into a practical one for the flow velocity would require detailed CFD analyses on the specific geometry to be considered. Nonetheless, experimental results typically suggest (Weisenburger et al., 2013) that 2 m/s through the bundle allows withstanding erosion effects: accordingly, this value was chosen as the limit for the maximum coolant velocity.

These values are specified in Table 1, which reports also the main design goals to be achieved, the main technological constraints to be respected and some initial guess parameters, also based on the results of the previous lead-cooled reactor projects (Cinotti et al., 2008).

The fuel assembly has been chosen in ALFRED to be closed by a wrapper – even to the detriment of criticality – mainly to allow for the continuous monitoring of the outlet coolant temperature in each FA, thus providing a means to promptly detect the beginning of flow reduction in case of FA flow area blockage.

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[1] The exact composition and the application procedure of the final coating, the one to be qualified for use in ALFRED, are still being optimized at the time this paper is written (Weisenburger et al., 2013).