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Safety and design concepts of the 400 MW_{th}-class EFIT accelerator driven transmuter and considerations for further developments

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ABSTRACT

European R&D for ADS design and fuel development is driven in the 6th FP of the EU by the EUROTRANS Programme. In EUROTRANS, the longer-term EFIT development, the european facility for industrial transmutation, aims at a generic conceptual design of a full transmuter. A CERCER U-free fuel core with an MgO matrix and a CERMET core with a Mo-92 matrix have been designed. Both the CERCER and the CERMET EFIT concept were optimized towards: a high transmutation efficiency, high burn-up, low reactivity swing, low power peaking, adequate subcriticality, reasonable beam requirements and a high level of safety. Protected and unprotected transients which are initiated by a mismatch of power-to-flow or resulting from a beam disturbance or overpower situation were analyzed. Potentials which can lead to the introduction of positive reactivity into the core were identified, as e.g. the steam generator tube rupture (SGTR) accident or the pin failure with a gas release from the fission gas plena. Both for the CERCER and the CERMET fuelled core the design and safety analyses are close to completion in EUROTRANS and thus a first preliminary résumé can be drawn on the achieved design and safety goals. In addition, scenario studies in the framework of the PATEROS CA project of the 6th FP highlighted the specific needs on transmutation machines serving in countries with different nuclear options. Based on these studies in the 6th FP first reflections can be performed on needs or options for further optimizing an EFIT type ADS.

1. Introduction

The 6th EU FP EUROTRANS Programme [1], which drives the European R&D for ADS design, fuel and technology development, has developed the EFIT, the european facility for industrial transmutation. To a high level of detail a generic conceptual design of a full transmuter [2–4] has been matured. The EUROTRANS Domain DM1 (DESIGN) was responsible for the development of the conceptual reference design of the whole plant, including core and target. The EFIT, a 400 MW_{th} ADS, utilizes a U-free CERCER fuel with MAs and Pu embedded in an MgO matrix. The core coolant, allowing a fast spectrum, is pure lead, as well as the windowless target for the 800 MeV proton beam. The reference sub-critical level has been postulated to be $k_{eff} = 0.97$. The EUROTRANS Domain DM3 (AFTRA) has been responsible for the fuel development within EUROTRANS. In AFTRA also various core designs have been developed to allow the assessment of the different fuel forms and matrices. Fuel forms comprised composite fuels as CERCER (CERamic–CERamic) and CERMET (CERamic–METal) and also cores with Zr based solid solution fuels. The main focus of the accelerator driven transmuter (ADT) fuel development concentrated on the oxide route in line with the European experience. The DM1 design work concentrated mainly on the CERCER core. One reason was the better neutronic performance of the MgO. Within AFTRA the work focussed on a CERMET core, after a ranking procedure based on a number of criteria, ranging from fabrication, reprocessing via economics to safety. The composite CERMET fuel $(Pu_{0.5},Am_{0.5})O_{2-x}$–$^{92}Mo$ (93% enriched) has been recommended by AFTRA as the primary candidate for the EFIT [5] fulfilling adopted criteria for fabrication and reprocessing, and especially providing superior safety margins. The higher thermal–mechanical resistance against beam-trips was e.g. an argument for the CERMET choice. Disadvantages include the cost for enrichment of ^{92}Mo and higher neutron absorption. The composite CERCER fuel $(Pu_{0.4},Am_{0.6})O_{2-x}$–MgO has been recommended as a backup solution as it might offer a higher consumption rate of minor actinides, and can be manufactured for a lower unit cost. The main CERCER disadvantage is the low dissociation temperature which gives reduced margins during some severe transients.

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Reprocessing of the fuels currently favoured for the EFIT (CERCER and CERMET) has been confirmed within the FUTURE program (5th FP of the EU, [6]) and the PYROREP program (5th FP of the EU, [7]). These innovative fuels are still under scrutiny with the results of the irradiation campaigns which started within EUROTRANS [1] still awaited. Investigations in FUTURE concern the fabrication process and fuel behavior under nominal and transient conditions (and consequently the material limits are set up according to safety criteria). For what concerns reprocessing, one relies in the findings of the PYROREP program for which Pu–Am are co-extracted from the fission products and the MgO ceramic or light Mo metal. During the fabrication process, missing MA being burnt in the previous cycle is added to the reprocessed fuel. The core is designed to keep the reactivity constant through that process but an adjustment is still possible by using an increased matrix fraction. Still to be solved however – although several possible solutions are existing – is how to keep the MgO ceramic or light Mo metal out of fission products stream and re-use them at the fuel fabrication stage. The scenario envisaged is not put into question by this point but might have an impact on the amount of low waste. Wet reprocessing are discarded for this plant, not because the two processes PUREX and DIAMEX lead to separate streams of MA and Pu (quite degraded Pu vector which cannot be of any use for weapons) but because of the fuel heat and radioactivity.

The detailed neutronic design calculations for both the CERCER and CERMET core have been performed with the deterministic codes ERANOS [8], DANTSYS [9], SIMMER-III [10,11] and C4P-TRAIN [12] and with the Monte Carlo code MCNPX [13].

In Refs. [2–4] and [14,15] the CERCER EFIT variant has been extensively explained and described. The current paper focuses in its design part more on the CERMET core, while for the safety assessment both results of the CERCER and CERMET analyses are given and compared. First analyses which were performed in close line with the CERCER design showed a lower transmutation performance of the CERMET core. However changing the design, especially utilizing the larger flexibility in the pin design revealed a good and similar transmutation performance as the CERCER core [16]. An important advantage of the CERMET fuel lies in its high thermal conductivity. An increase of the pin diameter or even an upgrade of the core to higher power densities and higher ratings is possible. Scenario analyses on integrating the EFIT into efficient transmutation strategies showed that this could be a point of interest (PATEROS [17])). The EFIT designed by DM1 [2,3] represents an efficient 'MA burner" where new MAs are used for refueling and the Pu mass share remains unchanged. The CERCER EFIT start-up core has been designed to fit the so-called "42:0" approach [2,14]. The fission rate is $\sim$42 kg/TWh$_{th}$, representing the 200 MeV/fission which is a physical constant. The '42' fissioned can be differently split between MA and other heavy nuclides as Pu. In the pair of numbers 42:0 the first one indicates the overall MA disappearance (either fissioned or transmuted), the second one is an indicator of new Pu production, with their difference being in any case $\sim$42. The EFIT fundamental choice of the inert matrix implies that new Pu production has to be avoided. Therefore the Pu balance should be 0, that leads to the "42:0" pair. This has been accomplished with a fuel enrichment of Pu/(Pu + MA) = 45.7%. It is important to note that, with the Pu content rather constant over the cycle, the reactivity swing will not be large. A low reactivity swing is of high importance as the EFIT will be designed with a non-variable beam power.

The safety objectives for the EFIT are that all reasonably practicable measures are taken to prevent accidents, and to mitigate their consequences. This is achieved based on the defense-in-depth concept. The demonstration of the adequacy of design with the safety objectives is structured along three kinds of basic conditions: The design basis conditions (DBC – structured in four categories), design extension conditions (DEC – limiting events, complex sequences and severe accidents) and residual risk situations [18]. For innovative reactors such as the ADS, cliff-edge effects should be identified and excluded. The fuel limits for the CERCER and CERMET fuels have been specified by AFTRA according to the various accident categories. At the end of the EUROTRANS programme, in-pile experiments planned within AFTRA as FUTURIX [19] should provide information on the irradiation behavior, and the HELIOS [20] and BODEX [21] experiments will provide information on helium release potentials. Selected results from the overall safety analyses both for the CERCER and CERMET EFIT obtained with the SIMMER-III code are presented. The CERCER and CERMET core safety behavior will be demonstrated for typical transients as the unprotected loss of flow (ULOF). The protected over power (PTOP), the unprotected blockage accident (UBA) and the steam generator tube rupture (SGRT) accident are used to provide some important findings on the EFIT safety behavior. An key safety parameter in this respect is the positive void worth of the CERCER and CERMET cores and the strong production of He via the transmutation process. While coolant boiling can be excluded because of the high boiling point of the lead coolant, pin failures could lead to a gas blow-down from the plena, to local voiding and reactivity addition. Another route to voiding may be the ingress of steam via a steam generator tube rupture accident (SGTR). Based on the analyses some proposals are made for further increasing the flexibility of an EFIT for specific reactor and waste strategies and also for further improving the safety potential of an ADS.

2. The CERCER reference core and the CERMET core design

In the following the CERCER and the CERMET core a briefly characterized.

2.1. The CERCER reference core design

In a paper for the PHYSOR 2008 conference [3] a detailed description of the EFIT CERCER three-zone core with MgO as inert matrix has been given. Some highlights are reported here, for details we refer to the full paper [2]. One key decision in designing the core has been the definition of a unique enrichment that fits the "42:0" approach. The Pu content is rather constant in the cycle, resulting in a low reactivity swing which allows to keep a rather constant proton current. The isotopic compositions of the used Pu and MA have been obtained as a result of a mixing of MA coming from the spent UO_2 fuel (90%) and the spent MOX (10%) of a typical PWR unloaded at the burn-up of 45 MWd/kgHM, then cooled down for a period of 30 years. Plutonium is extracted from the same spent UO_2 but with the storage period of 15 years. With these vectors the enrichment fitting the pair goal "42:0" has been evaluated and found to be 45.7%. The maximum linear power turns out to be 203 W/cm in the inner zone (close to the spallation source) and the average homogeneous power density is 70.7 MW/m^3. The power deposition in the target will not exceed 9 MW$_{th}$. The "42:0" approach defines the enrichment, therefore the active fuel volume fraction has been increased along the radius for power flattening. That has been achieved by either increasing the fuel/matrix ratio keeping the same pin diameter (from inner to intermediate zones), or by increasing the pin diameter keeping the same fuel/matrix ratio (from intermediate to outer zones). In the operating conditions, the mean coolant inlet temperature is 400 °C and the outlet temperature is 480 °C. The chosen structural material is Ferritic–martensitic steel T91. For the EFIT clad and structural materials an FeCrAl – aluminization treatment with a GESA type technique is foreseen [22]. Consequently, no thermal conductivity reducing oxidation layers on the cladding surface