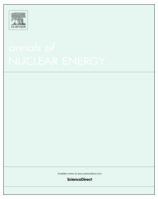
Annals of Nuclear Energy 104 (2017) 1–8

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Conceptual design of a sub-critical Pb-cooled Accelerator Driven System (ADS) fuelled by (Th-LEU)

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ARTICLE INFO

Article history:
Received 24 October 2016
Accepted 5 February 2017

Keywords:
ADS
Sub-criticality
Core design
Reactivity coefficients
Monte Carlo methods

ABSTRACT

The target of this study is to provide information on the actual boundary conditions encountered in the conceptual design of an ADS fuelled by (Th, LEU), as well as their impact on the design itself, on the performances of the system and on the possible solutions from the point of view of the choice of materials, the operating conditions, the neutron design optimization, etc. In this paper rationales and consequences of the (Th, U) fuel cycle adoption, together with the design constraints, are discussed. Identified reference core configuration and the steady state criticality results are also discussed. Stochastic approach for the neutronic evaluations has been adopted.

1. Introduction

The renewed interest in Th relies not only on the neutronic attractiveness of ^{233}U, characterized by some advantages with respect to ^{235}U and/or ^{239}Pu (due to the higher fission and -simultaneously- to the lowest capture cross sections, as well as to the higher neutrons yield per fission event, especially in the thermal reactors) and on the promising physical properties of Th (especially of thorium dioxide), but also on other considerations which constitute foundation of such a renewed interest. They concern: the nuclear market in terms of preservation and medium-to-long term availability of the resources (Anon, 2014), the sustainability of the nuclear option under the Generation-IV criteria (Anon, 2002, 2014), the potential improvement of waste management and potential positive contribution to the proliferation issues.[1] Moreover, the thermo-physical properties of the Th fuels as well as the Front-end and Back-end characteristics of the (Th, U) fuel cycle, could positively impact on operational safety margins and economic competitiveness of the fuel cycle in terms of fuel cycle length, burn-up rates and in “preserving” of U and Pu resources. The benefits and/or the improvements and the consequent challenges, depend on the options of Th utilization in terms of reactor type, time frame of the fuel cycle, strategy on the ^{233}U utilization (burning in situ ≡ long residence-time strategy or its recycling ≡ autonomous Th fuel cycle). Finally, additional issues could have born from particular constraints (e.g. the use of LEU) or the maturity of the reprocessing technology.

This paper is based on a study carried out in the framework of the IAEA Collaborative Work on “Accelerator Driven Sub-critical Systems (ADS) Applications and Use of Low-Enriched Uranium (LEU) in ADS” activities, aimed to investigate the feasibility of a conceptual design of a sub-critical Accelerator Driven System (ADS) fuelled by Th-U solid fuel assemblies, satisfying Proliferation Resistance constraints, i.e.: low enrichment uranium utilization (Anon, 2013). General assumptions, operative conditions, design and materials constraints, neutron characterization and performances, as well as challenging aspects, are some of the objectives of this study.

2. About the (Th, U) cycle

A two β^- decays process, following a neutron capture event, governs the front-end of both (Th, U) and (U, Pu) fuel cycles, i.e.:

$$^{232}Th(n,\gamma)^{233}Th(\beta^-_{22m})^{233}Pa(\beta^-_{27d})^{233}U \tag{1.1}$$

$$^{238}U(n,\gamma)^{239}U(\beta^-_{23.5m})^{239}Np(\beta^-_{2.3d})^{239}Pu \tag{1.2}$$

The couple of isotopes (^{232}Th, ^{233}U) is the analogous of the couple of isotopes (^{238}U, ^{239}Pu). The physical processes described by the Eqs. (1.1) and (1.2) indicate that the “back-end” of the (Th, U)

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[1] The critical mass and heat emission of ^{233}U are really close to the Weapons Grade Pu (WG-Pu) values, while the neutrons spontaneous emission of ^{233}U is about 4 orders of magnitude lower with respect the WG-Pu one.

http://dx.doi.org/10.1016/j.anucene.2017.02.005
0306-4549/

and (U, Pu) fuel cycles are characterized by ^{233}U and ^{239}Pu isotopes respectively, both of them being of major importance in the reactor physics. As indicated below, there are many similarities between ^{232}Th and ^{238}U. Both nuclides are characterized by threshold fission reaction, with the ^{232}Th fission cross-section significantly lower than of ^{238}U (see Fig. 1). This suggests that ^{232}Th critical configurations are practically "impossible"; the criticality will be assured only by mixing with fissile nuclides. The fission probability increases very rapidly around 1 MeV, then decreases rapidly around 5–6 MeV and starts to increase again for neutron energies above 10 MeV. In the same neutron incident energy range, the rapid increase in the fission probability is accompanied by a rapid decrease of the capture probability (see Fig. 2). Beyond the different gradient of the increase of the fission probabilities, the Fig. 1 shows a different impact of the (n, xn) reactions which are in competition with the fission in the high energy region of the spectrum (Fig. 3). It is worth noting that the (n, xn) reactions are multiplication reactions once the neutron is absorbed. Although this effect is modest for critical systems (in the range of 0–20 MeV), in case of neutron population of higher energy (e.g., spallation reactions) this effect could produce important consequences.

It is also worth noting that the ^{232}Th (n, xn) cross section is more than twice the fission cross section in the higher energy range of the neutron spectrum, while the ratio between the respective reaction probabilities is close to a factor of four.

Fig. 4 shows the behaviour of the fission probability, per neutron absorbed, of ^{233}U and ^{239}Pu in comparison with ^{235}U. Among the three fissile nuclides, the ^{233}U tends to maintain its behaviour (and performances) over the whole neutron spectrum.

A reduction of the fission probability is observed in Fig. 4 for ^{233}U as well as for ^{235}U and ^{239}Pu, for incident neutron energies higher than about 5 MeV. This behaviour is a consequence of the competition between (n, xn) and fission reactions; the impact is of minor importance compared with that of the (n, xn) reactions on the fission probability of the fertile nuclides ^{232}Th and ^{238}U.

The processes (1.1) and (1.2) describe physical mechanisms of the two nuclear fuel cycles, as well as the two nuclear conversion processes which allow to achieve the breeding of the nuclear fuel. The nuclear fuel breeding properties constitute a criterion governing the choice of the type of the reactor as a technological solution which may ensure and achieve, beyond other goals, a secure energy supply. The breeding capability of a given reactor, i.e. the neutrons surplus available for creation of fissile isotopes via neutron captures in the fertile ones, relies on intrinsic properties of the fuel isotopes and it concerns the number of the neutrons produced by fission of fissile isotope per neutron absorbed, i.e.:

$$\eta(E) = \nu(E)\frac{\sigma(E)_{fis}}{\sigma(E)_{fis} + \sigma(E)_{cpt}} \tag{2}$$

where ν(E) is the number of the neutrons produced per fission. Well known physical reasons (Waltar and Reynolds, 1981) imply that a reasonable breeding is achievable when the number of the neutrons produced by fission of fissile isotope per neutron absorbed, significantly exceeds the value of 2.

In Fig. 5 the neutron yields per fission event are displayed, confirming the above considerations and showing that from the breeding performances point of view ^{239}Pu is preferable to ^{233}U and ^{235}U in the fast spectrum region, while in the thermal and epithermal spectrum region the choice of ^{233}U is the most appropriate; both options don't depend on the engineering solution since they reside on intrinsic properties of the fuel isotopes.

Being ^{233}U the back-end of the (Th, U) fuel cycle, its neutronic properties, which define the (Th, U) fuel cycle performances, should be taken into appropriate consideration due to their important effect on the strategy of the fuel cycle itself. Actually, such a strategy (as well as many other important parameters of the (Th, U) fuel cycle), it's not taken into account in this phase of the study.

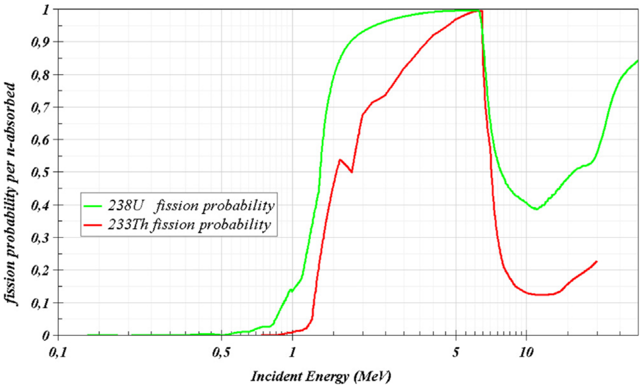

Fig. 1. ^{232}Th and ^{238}U fission probability vs. neutron energy, per neutron absorbed. From JEFF 3.1.2 (Anon, 2014).

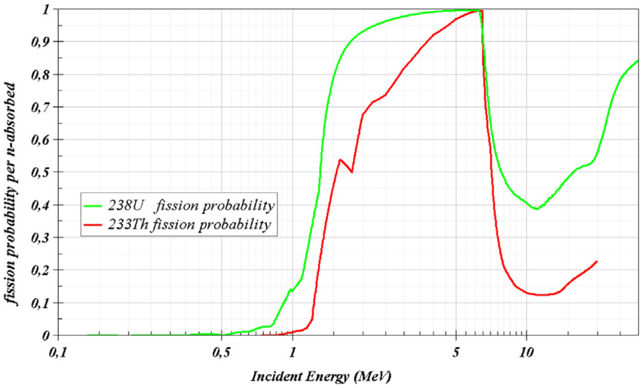

Fig. 2. ^{232}Th and ^{238}U capture probability vs. neutron energy, per neutron absorbed. From JEFF 3.1.2 (Anon, 2014).

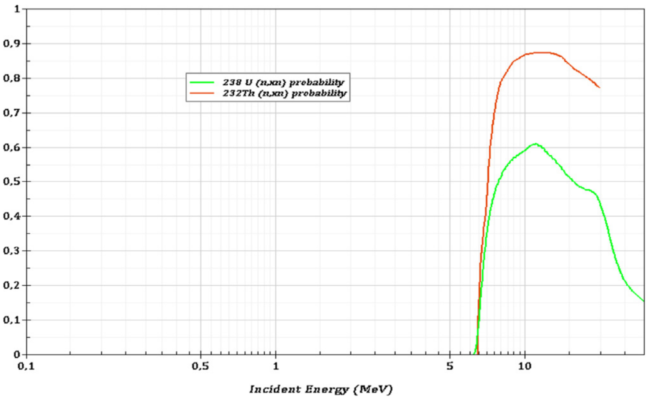

Fig. 3. ^{232}Th and ^{238}U (n, xn) probability vs. neutron energy, per neutron absorbed. From JEFF 3.1.2 (Anon, 2014).

3. Core design assumptions

This paper is based on a study carried out in the framework of the IAEA Collaborative Work on "Accelerator Driven Sub-critical Systems (ADS) Applications and Use of Low-Enriched Uranium (LEU) in ADS" activities, aimed to investigate the feasibility of a conceptual design of a sub-critical Accelerator Driven System (ADS) fuelled by Th-U solid fuel assemblies, satisfying Proliferation