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Fuel burnup analysis of the TRIGA Mark II reactor at the University of Pavia

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ABSTRACT

A time evolution model was developed to study fuel burnup for the TRIGA Mark II reactor at the University of Pavia. The results were used to predict the effects of a complete core reconfiguration and the accuracy of this prediction was tested experimentally. We used the Monte Carlo code MCNP5 to reproduce system neutronics in different operating conditions and to analyze neutron fluxes in the reactor core. The software that took care of time evolution, completely designed in-house, used the neutron fluxes obtained by MCNP5 to evaluate fuel consumption. This software was developed specifically to keep into account some features that differentiate low power experimental reactors from those used for power production, such as the daily ON/OFF cycle and the long fuel lifetime. These effects can not be neglected to properly account for neutron poison accumulation. We evaluated the effect of 48 years of reactor operation and predicted a possible new configuration for the reactor core: the objective was to remove some of the fuel elements from the core and to obtain a substantial increase in the Core Excess reactivity value. The evaluation of fuel burnup and the reconfiguration results are presented in this paper.

1. Introduction

The TRIGA Mark II reactor at the Applied Nuclear Energy Laboratory (L.E.N.A.) of the University of Pavia is a pool type reactor with a nominal power of 250 kW. It was brought to its first criticality in 1965 and since then it was used for several scientific activities, such as radioisotope production, material analysis via neutron activation and reactor physics studies.

The reactor core is shaped as a right cylinder featuring 90 slots, distributed over 5 concentric rings, which can contain either fuel elements, graphite (dummy) elements, control rods or irradiation channels. The fuel consists of a uniform mixture of uranium (8% wt., enriched 20% wt. in ^{235}U), zirconium (91% wt.) and hydrogen (1% wt.). The Fuel Elements (FEs) used in the current core configuration belong to different manufacturing series that were designed by General Atomics over the years. The 101-type FEs are characterized by aluminum cladding, 1:1 atomic ratio between zirconium and hydrogen and two burnable poison disks containing samarium. The 103-type and 104-type FEs have stainless steel cladding, 1:1.6 ZrH ratio and a zirconium rod at the center of the fuel; furthermore, a burnable poison disk containing molybdenum is present in the 104-type FEs.

In the recent years, the TRIGA Mark II reactor of Pavia was characterized in detail by means of both neutron activation measurements in different irradiation facilities (Borio di Tigliole et al., 2014; Chiesa et al., 2014a; Chiesa et al., 2014b; Chiesa et al., 2015) and development of proper simulation tools for modeling the neutronics, the dynamics and the thermal-hydraulics of the system (Alloni et al., 2014; Borio di Tigliole et al., 2010; Cammi et al., 2016; Cammi et al., 2013; Sartori et al., 2014).

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In particular, to study the reactor neutronics, we developed a Monte Carlo model based on MCNP5 (The X-5 Monte Carlo Team et al., 2005). We chose this code thanks to its general geometry modeling capabilities, correct representation of neutron transport effects and continuous-energy cross section treatment. This model was extensively tested and validated by reproducing the experimental results obtained in 1965, during the operations that followed the reactor first startup (Cambieri et al., 1965). This analysis included the reproduction of control rod calibration curves and the evaluation of the criticality coefficient (k_{eff}) in several reactor configurations both at low power (~ 10 W) and full power (250 kW) conditions (Alloni et al., 2014; Cammi et al., 2016).

In this initial configuration (Fig. 1) all the fuel elements were new and did not contain significant amounts of neutron poisons. Therefore, in the MCNP5 simulations, we could model the fuel using the data of the original isotopic composition provided by the manufacturer.

In this work, through the analysis of the fuel burnup, we aim to characterize the TRIGA reactor in its present configuration, after many years of operation. Moreover, this analysis is important to study the fuel cycle and determine the amount of long-lived radioactive waste which are produced in a reactor after a certain operating time.

2. Reactor fuel evolution

In order to characterize and model the current configuration of the TRIGA Mark II reactor, we must take into account several aspects related to fuel burnup. First of all, the consumption of the fissile isotopes and the buildup of neutron poisons affects the system reactivity. Therefore, in order to simulate the criticality condition of the reactor, it is crucial to know the fuel composition as function of time. Moreover, since the fuel burnup is not homogeneous within the core, also the neutron fluxes and the power distributions change over time. In addition, we must consider that, during the operations of refueling and core reconfiguration, some fuel elements are replaced, added or moved to different locations.

For this reason, to evaluate the fuel composition as function of time, the whole history of the nuclear reactor must be followed, reproducing all the different configurations of the core and collecting the data concerning operating times and powers.

In order to analyze and simulate the fuel burnup in the TRIGA Mark II reactor, we decided to develop a time evolution software which couples the historical data of reactor operating time and core configurations with the information about effective cross sections and neutron fluxes, evaluated through the MCNP5 model. This software was completely developed in-house to take into account some features that differentiate low power experimental reactors from those used for power production and to provide additional flexibility in our model:

- inclusion of the effects of the daily ON/OFF cycle (roughly 6 h of operating time per day) and of the shutdown during weekends;
- a database containing information on all available fuel elements (FEs). This allows us to keep track of all the FEs that were ever used in the reactor, some of which were never removed from the core across 48 years. This also lets us correctly account for radioactive decay in FEs that were pulled out of the reactor core and reinserted years later;
- the possibility to evolve and store in the database the samarium (for the 101-type FEs) and molybdenum (for the 104-type FEs) poison disks;
- fully customizable list of isotopes that need evolution.

The historical data about the critical configurations of the core can then be used as a benchmark for validating the MCNP5 model after each step of the burnup calculation. In this way, at the end of the simulation process, we aim to obtain a reliable and benchmarked simulation model for the current reactor configuration.

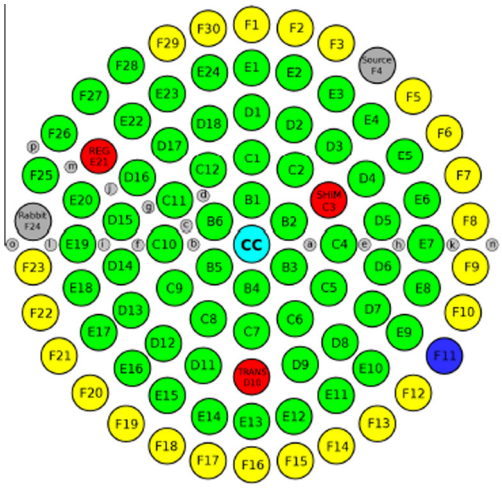

Fig. 1. Core configuration in 1965. Fuel rods are represented in green, graphite rods in yellow, control rods in red, irradiation channels in gray and an empty channel in blue. CC = central irradiation channel (or central thimble). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Burnup calculation strategy

The simulation model for the fuel burnup is based on the solution of a coupled set of differential equations, whose variables are the concentrations of all the isotopes in the fuel (Stacey et al., 2007). Although all the nuclear reactions and decays should be considered for an exact calculation of the fuel evolution, the main relevant processes to be modelled in order to ensure a good accuracy in the neutronics simulations are fission, neutron capture and radioactive decays.

The isotopic concentration $n_j(t)$ of a fission product species j, characterized by λ_j decay constant and σ_a^j neutron absorption cross section, evolves in time according to this generic formula (Stacey et al., 2007):

$$\frac{dn_j}{dt} = \sum_k \gamma_j^k \Sigma_f^k \Phi + \sum_i \left(\lambda^{(i\to j)} + \sigma^{(i\to j)}\Phi\right) n_i - \left(\lambda^j + \sigma_a^j \Phi\right) n_j, \qquad (1)$$

where the sum $\sum_k$ is performed over all fissionable nuclei, γ_j^k is the fission yield of isotope j, Σ_f^k is the macroscopic fission cross section, Φ is the integral neutron flux intensity, $\lambda^{(i\to j)}$ is the decay rate of isotope i to produce isotope j and $\sigma^{(i\to j)}$ is the transmutation cross section for the production of isotope j by neutron capture in isotope i.

In order to take into account the reaction rate dependence on the neutron spectrum, the cross sections in Eq. (1) must be calculated as effective ones, i.e. average cross sections weighted by the energy distribution of the neutron flux. The time evolution of the elements belonging to the original fuel composition (U, Zr and H) or produced exclusively through neutron capture can still be described by Eq. (1) by setting the fission yield value γ_j equal to 0.

Eq. (1) must be integrated to determine fuel composition changes over its lifetime. In order to carry out this calculation, however, the time dependence of the neutron flux must be known. To overcome this issue, the 48 year period is divided in several time intervals in which the neutron flux distribution is assumed to vary negligibly. In order to find optimal time intervals, we ran some dedicated MCNP5 simulations.

At first, we ran the model with 27 time steps, one for each core reconfiguration occurred between 1965 and 2013. We compared