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Modelling fuel behaviour in a reactor park using fuel cycle kinetics

J.A.B. van Rhijn, S.A. Christie *, D. Lathouwers, J.L. Kloosterman

Delft University of Technology, Department of Radiation, Radionuclides and Reactors, Physics of Nuclear Reactors, Mekelweg 15, 2629 JB Delft, The Netherlands

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ABSTRACT

The theory of fuel cycle kinetics is re-examined. This theory is a powerful tool to describe the time-dependent fuel behaviour of large populations of nuclear reactors. The aim of this paper is to verify the fuel cycle kinetics theory and use it to find a pre-determined asymptotic growth of nuclear reactors based on an expected growth of energy demand. The theory is based on the principles of a reactor park and an analogy to point kinetics. A reactor park is the description of the interconnections between a population of nuclear reactors with various designs. In the fuel cycle kinetics theory, point kinetics is used as a model to simplify space-, energy-, and time-dependent burn-up equations of the reactors in a park to a set of only time-dependent equations, called the fuel cycle kinetics equations. Reducing the problem to being only time-dependent makes it possible to research complex reactor systems in a short time and at low computational cost. The theory is also used for a new application, adjusting reactor parks to match given growth rates.

1. Introduction

Predictions show the world electricity demand growing the most strongly of all final forms of energy (IEA, 2010) in the coming years. Combined with the goal of reduced global CO_2 emissions, countries have to change their energy policies. Due to this a global shift to nuclear power, renewables and low-carbon technologies is expected. The energy strategy that a country chooses is of great influence on the growth of nuclear power. The World Nuclear Association show in their World Nuclear Outlook (WNA, 2008) the number of nuclear reactors now in operation and give upper and lower predictions for the upcoming century. New innovations are needed to research such large and complex reactor scenarios.

One candidate for use in this kind of research is fuel cycle kinetics. The theory of fuel cycle kinetics was first developed in the 1970s (Maudlin, 1979; Maudlin and Ott, 1979). The theory projects the behaviour of a population of reactors due to their designs and fuel cycles without the use of detailed calculations. This article re-examines this theory and tests its use in predicting reactor park behaviour. The scenarios studied are a single deployment of FBRs and symbiotic deployments of PWRs and FBRs. The solutions of the fuel cycle kinetics equations found are compared to TRITON (DeHart, 2009) calculations on the same systems. The theory is then used to adjust the growth rates of reactor parks to required levels.

2. Reactors designs and fuel

Throughout this paper two types of reactor will be used for describing a reactor park, the light water reactor, LWR, and the fast breeder reactor, FBR. The LWR that is used is a pressurised water reactor, PWR. The design of the FBR that is used is similar to the one used in (Ott and Borg, 1980). The PWR is described with a three zone block model, loosely based on the European Pressurised Water Reactor (EPR).

Both types of reactor will use mixed oxide fuel, MOX. Only the growth of plutonium is considered here, so the fuel used is composed of Pu and ^{238}U oxides only. The composition of the fuel changes over time, but eventually reaches an equilibrium. An illustration of this behaviour in the core of an FBR is shown in Fig. 1.

3. Reactor park

A reactor park consists of multiple reactors of different designs which are interconnected by an external fuel cycle, see Fig. 2. The single quotation mark, double quotation marks, etc., indicate that a reactor is at a different time in its life and therefore has a different fuel composition. The charge ξ and discharge κ terms are explained in detail below. The reactors do not have to be in the same geographical location to be part of a reactor park, they only have to be linked by their external fuel cycles. The fuel behaviour of a reactor park can be described by considering the burn-up equations of single reactors of every type.

* Corresponding author. Tel.: +31 0 15 27 84182; fax: +31 0 15 27 86422.
E-mail address: S.A.Christie@tudelft.nl (S.A. Christie).

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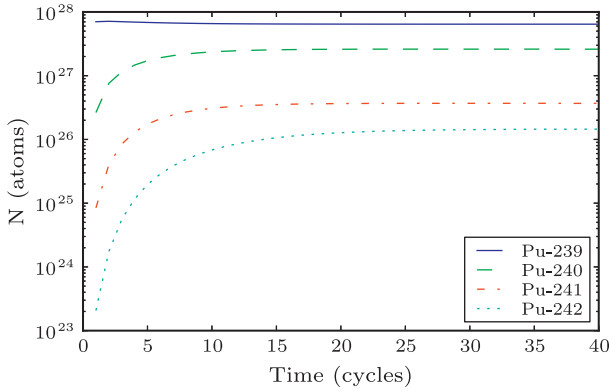

Fig. 1. Average core composition per cycle for an FBR.

3.1. Single reactor

In general the change of fuel in a reactor is given by the fuel balance equation, Eq. (1). From the equation we can see that the change in the amount, N_i, of an isotope i depends on a production term $P(\vec{r},t)$, a loss term $L(\vec{r},t)$, a discharge term $\kappa(\vec{r},t)$ and a charge term $\xi(\vec{r},t)$.

$$\frac{dN_i(\vec{r},t)}{dt} = P_i(\vec{r},t) - L_i(\vec{r},t) - \kappa_i(\vec{r},t) + \xi_i(\vec{r},t) \tag{1}$$

Integrating Eq. (1) over the volume of the core and averaging over the fuel cycle period, Δt, gives the change of N_i per cycle. Eq. (1) can also be written in vector notation, which will be used from here onwards.

$$\frac{d\vec{N}_T(t)}{dt} = \vec{P}_T(t) - \vec{L}_T(t) - \vec{\kappa}_T(t) + \vec{\xi}_T(t) \tag{2}$$

where T is the index for the reactor type.

3.2. Fuel accumulation

To describe fuel evolution in a reactor park the behaviours of the individual reactors have to be taken together. This can be described by taking the sum of the balance equations, Eq. (2), of each reactor of the same type in the park. Mathematically the accumulation of fuel isotopes can be described as follows

$$\hat{\vec{N}}_T = \sum_R \vec{N}_{TR}(t), R = 1, 2, \ldots, R_T(t) \tag{3}$$

where $\wedge$ represents accumulation and R is the index for each reactor that is included. The sum for the accumulation is only taken for reactors of the same type. $R_T(t)$ is the total number of reactors of type T in a park at time t. This accumulation can be used to describe the changes of accumulated fuel in a set of reactors of type T in a reactor park. This gives

$$\frac{d\hat{\vec{N}}_T(t)}{dt} = \hat{\vec{P}}_T(t) - \hat{\vec{L}}_T(t) - \hat{\vec{\kappa}}_T(t) + \hat{\vec{\xi}}_T(t) \tag{4}$$

which is the rate of change of isotopes in reactors of type T in a reactor park.

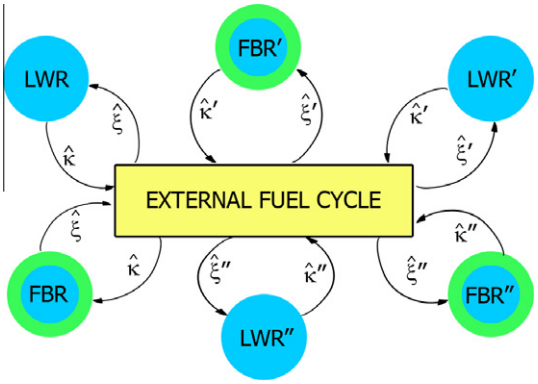

Fig. 2. Illustration of a reactor park.

3.3. External fuel cycle

The external fuel cycle is a general term for those parts of the nuclear fuel cycle that take place outside the reactors. Every burn-up equation is coupled to the external fuel cycle by its discharge and charge terms. This is shown schematically in Fig. 2. Here a closed fuel cycle is used, with fuel being discharged from a reactor, reprocessed, and then charged into the next reactor. The amount of fuel that is in the external fuel cycle can be written

$$\frac{d\hat{\vec{N}}_x(t)}{dt} = \sum_{T'} \vec{\kappa}_{T'}(t) - (1-\vec{\varepsilon}) \sum_{T'} \vec{\kappa}_{T'}(t-\tau) \tag{5}$$

where the index x indicates the external fuel cycle and T' indicates the discharge from a reactor of type T in the previous cycle. The time taken for reprocessing and the delay before the fuel is charged into a new reactor is called the fuel cycle lag time τ. During the reprocessing, losses ε can occur. These losses are a result of the chemical treatment used for reprocessing and natural decay. The accumulation of fuel in the external fuel cycle does not play a role in the total fuel accumulation, as fuel is only in the external fuel cycle during reprocessing. The treatment of fuel that has been reprocessed but not yet returned to a reactor is discussed in the next section.

3.4. Temporary storage pool

To create a continuous model for the accumulating fuel, all fuel must be accounted for at all times. This means that the fuel that is not charged to a reactor immediately after reprocessing must be included. This fuel accumulates outside the reactors waiting until there is enough fuel to charge a new reactor. This is done by creating a temporary storage pool, which is described as

$$\frac{d\hat{\vec{N}}^0_T(t)}{dt} = (1-\vec{\varepsilon}) \sum_{T'} \vec{\kappa}_{T'}(t-\tau) - \sum_{T'} \vec{\xi}_{T'}(t) \tag{6}$$

with the index 0 indicating the temporary storage pool. The change of fuel isotopes in the storage pool is the sum of the accumulating discharge, after reprocessing losses, minus the charge into the reactors. For every type of reactor there exists a storage pool, as the different stocks of materials must be tracked separately.

The fuel behaviour of a reactor park can be described for every reactor type by adding the fuel present in every reactor, the core and the blanket, plus the fuel that is present in the temporary storage pool and external fuel cycle.

$$\hat{\vec{N}}_T(t) = \sum_T \hat{\vec{N}}_{TC}(t) + \sum_T \hat{\vec{N}}_{TB}(t) + \sum_T \hat{\vec{N}}^0_T(t) + \hat{\vec{N}}_x(t) \tag{7}$$

with C indicating core and B blanket.

4. Fuel cycle kinetics

Using the description of the fuel behaviour of a reactor park and point kinetics theory from Ott and Neuhold (1985), the fuel cycle