Annals of Nuclear Energy 99 (2017) 471–483

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Physical model of the nuclear fuel cycle simulation code SITON

Á. Brolly[a,*], M. Halász[b], M. Szieberth[b], L. Nagy[b], S. Fehér[b]

[a] Centre for Energy Research, Hungarian Academy of Sciences, Budapest, Hungary
[b] Institute of Nuclear Techniques, Budapest University of Technology and Economics, Budapest, Hungary

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 14 June 2016
Accepted 3 October 2016
Available online 19 October 2016

Keywords:
Nuclear fuel cycle
Simulation
Discrete event
Cross-section parametrization

ABSTRACT

Finding answers to main challenges of nuclear energy, like resource utilisation or waste minimisation, calls for transient fuel cycle modelling. This motivation led to the development of SITON v2.0 a dynamic, discrete facilities/discrete materials and also discrete events fuel cycle simulation code. The physical model of the code includes the most important fuel cycle facilities. Facilities can be connected flexibly; their number is not limited. Material transfer between facilities is tracked by taking into account 52 nuclides. Composition of discharged fuel is determined using burnup tables except for the 2400 MW thermal power design of the Gas-Cooled Fast Reactor (GFR2400). For the GFR2400 the FITXS method is used, which fits one-group microscopic cross-sections as polynomial functions of the fuel composition. This method is accurate and fast enough to be used in fuel cycle simulations. Operation of the fuel cycle, i.e. material requests and transfers, is described by discrete events. In advance of the simulation reactors and plants formulate their requests as events; triggered requests are tracked. After that, the events are simulated, i.e. the requests are fulfilled and composition of the material flow between facilities is calculated.

To demonstrate capabilities of SITON v2.0, a hypothetical transient fuel cycle is presented in which a 4-unit VVER-440 reactor park was replaced by one GFR2400 that recycled its own spent fuel. It is found that the GFR2400 can be started if the cooling time of its spent fuel is 2 years. However, if the cooling time is 5 years it needs an additional plutonium feed, which can be covered from the spent fuel of a Generation III light water reactor.

1. Introduction

Modelling the nuclear fuel cycle has gained increasing importance in the last decades. It has been recognised that although irradiation in the reactor has the most important effect on the fuel composition, out-of-pile processes also have to be taken into account. The two most evident examples are radioactive decay and chemical separation. Significance of these processes increases in a recycling scenario, in which operation of the reactor is directly influenced by the ever-changing composition of the fresh fuel. This means that answers to main challenges of nuclear energy—like natural uranium utilisation or waste minimisation—also depend on the route that material covers between reactors not only on the spectrum of reactors.

Furthermore, it has also been identified that transient fuel cycle analysis is as important as the equilibrium one since transition from a current reactor park to a future equilibrium one can be hindered by several factors, for example lack of raw material, capacity limitation of plants or cooling time of spent fuel intended for reprocessing. These bottlenecks can only be identified by transient fuel cycle modelling.

Among other things, the above mentioned observations initiated the development of SITON v2.0, a SImulation TOol for modelling the Nuclear fuel cycle. The code is a result of a co-operation between the Hungarian Academy of Sciences Centre for Energy Research (MTA EK) and the Budapest University of Technology and Economics Institute of Nuclear Techniques (BME NTI). The fuel cycle model was developed in MTA EK; BME NTI developed the burnup module to evaluate the discharge composition in the 2400 MW thermal power design of the Gas-Cooled Fast Reactor (GFR2400).

This paper describes the physical model of SITON v2.0. Section 2 summarises characteristics of the nuclear fuel cycle and modelling possibilities. Section 3 presents the physical model of SITON in general, while subsequent sections from Sections 4–8 describe the components of the physical model in detail. Section 9

* Corresponding author.
E-mail address: brolly.aron@energia.mta.hu (Á. Brolly).

http://dx.doi.org/10.1016/j.anucene.2016.10.001
0306-4549/

illustrates capabilities of the code and finally, Section 10 outlines future developments.

2. Modelling the nuclear fuel cycle

An interesting feature of the nuclear fuel cycle is its discrete nature. An obvious example is that number of reactors is an integer number, therefore commissioning of new reactors increases the installed capacity of a reactor park in finite steps. Another feature is that reactors are refuelled in batches, which results discrete material flow between facilities. Furthermore, reactors, plants operate in cycles, i.e. their input and output flows in and out at well defined time points. As a result, time advances in finite, variable length steps. Last but not least, the operation of reactors and plants is driven by an external energy or material demand, respectively.

Existing fuel cycle simulation codes model these features in different ways. VISION treats facilities in discrete manner, while it tracks material flow continuously; simulation time is advanced in predefined, equal length steps (Jacobson et al., 2010). GENIUSv2 and its successor CYCLUS model both facilities and material transfer in discrete manner and they advance time in fixed-length steps. Connection of facilities in these codes is based on matching material requests to material production (Oliver et al., 2009; Huff et al., 2011). COSI is also a discrete facilities/discrete materials code taking into account facility needs. Facilities are connected according to the path of material in the fuel cycle (Boucher and Grouiller, 2006; Meyer and Boucher, 2009). NFCSim belongs to the group of discrete facilities/discrete materials codes. It advances time using a simulation clock and matches demands of facilities during the simulation, which results in slight undershoot of the demands (Schneider et al., 2005).

3. General presentation of the physical model

The authors aimed to develop a general purpose fuel cycle simulator that is not linked to specific reactor types, reprocessing methods or recycling strategies and that includes the important features of the nuclear fuel cycle outlined in the previous section. Consequently, the physical model of SITON v2.0 has the following components:

- facilities, which are treated as discrete objects, and the physical model of their operation;
- material transfer between facilities, which is represented as transfer of discrete packages;
- connections between facilities, description of which is stored in the packages that facilities process;
- discrete events, which describe both material requests and material transfers;
- the FITXS burnup method (Szieberth et al., 2015, 2014; Perkó et al., 2015), which is used for reactors with varying fresh fuel composition.

Our model includes those facility types which are important from the point of view of natural uranium utilisation and waste generation, i.e.: reactor, fuel fabrication plant, enrichment plant, spent fuel reprocessing plant, material stock and spent fuel interim storage facility. A simulation can include several facilities of one type each with different user-defined parameters; the number of facilities of one type or the total number of facilities is not limited.

Packages transferred between facilities can have two types: material or fuel; the composition of packages is stored by nuclide. Transfer of packages between facilities is treated uniformly, whereas packages inside a facility are treated as material or fuel according to the operation of the facility. Chemical form of the material or fuel (e.g. UF_6 or UO_2) is not taken into account, i.e. SITON tracks only fissile, fertile and fission product elements.

The novelty of our model is that the front-end facilities do not store information about their connections since that would result in static connections. Instead, the packages themselves store their path in the front-end, as a result of which front-end facilities are connected by the packages they process. The benefit of this solution is the dynamic linking of front-end facilities and the flexible routing of front-end material streams. In addition, facility models can be developed without information about the connections between facilities.

SITON describes operation of the fuel cycle, i.e. material requests and transfers, through discrete events. As a novelty, facility requests are surveyed and collected in advance of the simulation during a phase called planning. In the planning all facilities formulate their requests as events and triggered events in the past are tracked. This ensures that all requests are taken into account at the proper time. Subsequently, in the simulation the events are processed, i.e. requests are fulfilled and their composition is calculated. In case of a broken scenario, in which some requests cannot be fulfilled, SITON does not search for alternatives (raw materials or plants), the user has to tune the scenario parameters to obtain a working scenario. During the simulation time is advanced using the time of the events, which results in variable length time steps and the simulation clock is not necessary.

SITON uses the newly developed FITXS burnup method to calculate the irradiated composition of spent fuel in reactors using varying composition fresh fuel. The FITXS method fits one-group microscopic cross-sections as polynomial functions of the fuel composition. Using the atomic densities of important actinides and fission products as fitting parameters makes it possible to determine the spent fuel composition for a wide range of initial compositions with high accuracy at low computing time. Currently, the SITON implementation of the FITXS method works only for the 2400 MW thermal power design of the Gas-Cooled Fast Reactor (GFR2400).

The driver of our model is the electrical energy demanded from each reactor to be produced, while the result is the time-dependent material flow—annual and cumulative—between facilities by nuclide.

SITON v2.0 was coded in Fortran 95—with some additional Fortran 2003 features—using object-oriented techniques. Although this standard does not support all features of object-oriented programming, for example run-time polymorphism, we complemented these gaps with additional coding to emulate them.

The following sections present the physical model of SITON v2.0 in detail.

4. Facilities

Operation of each facility type is taken into account only with respect to material composition change and waste production. Facility types can have several inputs and outputs according to the physical model of their operation; and they have several user-adjustable parameters.

A common feature of all facility types is that they record received packages in their input history and they also put them into their internal buffer called inventory; output packages are recorded in the output history. Each buffer stores packages individually; histories are used for post-processing. When a facility works firstly it removes one or more packages from its inventory. Plants, reactors remove complete packages, whereas storage facilities (a material stock or a SFIS facility) may split packages and remove only part of a package. Then the facility unwraps the package(s) to obtain material (or fuel) stored in the package(s). Next, the