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Evolution of the CYCLE code for the system analysis of the nuclear fuel cycle

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Abstract

The CYCLE code is intended to simulate mathematically the operation of a nuclear power system (NPS) with thermal and fast reactors in an open or closed nuclear fuel cycle, to develop scenarios of efficient nuclear power evolution in Russia and to analyze trends in global nuclear power. The code is based on a well-known software program, WIMSD-5B, broadly used for the design of thermal reactor cells, and on a 2D multi-group software system, RZA, for the fast neutron reactor simulation. The CYCLE code was developed at IPPE in Obninsk. This paper presents a brief review of the capabilities and information on the current status of the CYCLE code. The code allows simulation of key facilities of the external fuel cycle (fuel fabrication and reprocessing facilities, SNF storage, uranium, plutonium, neptunium, americium and curium stores, RW long-term storage sites), nuclear reactors, including RBMK-1000 reactors, existing and advanced VVER reactors (using different fuel types), and fast reactors (both existing and innovative). As an important feature, the CYCLE code allows the evolution of the fuel's nuclide composition both in reactors and at the external fuel cycle phase to be considered in details. Offered as an extra option is the capability to calculate a variety of the nuclear fuel cycle cost parameters for nuclear power plants with thermal and fast reactors. For years, the code has been successfully used as part of INPRO, an international innovative nuclear reactor and fuel cycle project. The results of studies into the Russian NPS evolution scenarios were presented at Global 2011. Some other of the CYCLE-based simulation results were presented at Global 2015.

Keywords: Fuel cycle; Simulation; Modeling; Code; Scenario; Thermal reactor; Fast reactor; Nuclide composition; Recycling; Plutonium equivalenting; Store; Minor actinides.

Introduction

The CYCLE code is intended to simulate mathematically nuclear fuel cycles, develop scenarios for effective evolution of nuclear power in Russia, and analyze trends in global nuclear power. The system has been successfully used in international studies as part of INPRO, an innovative nuclear reactor and fuel cycle project. A great deal of emphasis was placed in the development of the CYCLE code on the description and consideration of peculiarities inherent in simulation of a closed nuclear fuel cycle (CNFC) with fast and thermal reactors. The code was developed at IPPE in Obninsk. The initial development stage of the CYCLE code ($CYCLE_{TR}$) was described in [1]. The activities at that stage were limited to the simulation of the VVER-type reactor fuel cycle (NFC) with the fuel isotopic composition and radiological and environmental characteristics tracked in the following chain: mining of natural uranium – conversion – enrichment – fuel assembly (FA) fabrication – reactor – spent nuclear fuel (SNF) pool – interim storage – SNF long-term storage (or disposal). It was also possible to simulate VVER reactors partially loaded with MOX fuel, with a constant isotopic composition of loaded plutonium. Since then, the functionality of the code has been expanded drastically and is described herein.

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Evolution of the CYCLE code

Presently, the CYCLE code allows modeling a two-component nuclear power system (NPS) the model of which, in addition to thermal reactors with uranium oxide (UOX) fuel, includes fast reactors and enables multiple recycling of plutonium, uranium and minor actinides. It is also possible to use mixed uranium-plutonium oxide (MOX) fuel or nitride fuel with a variable uranium and plutonium content for thermal reactors. A fuel cycle with a fuel processing capability, including the use of natural, depleted and reprocessed uranium, plutonium, neptunium, americium and curium stores, is considered.

The simulation results for the fuel cycle of thermal reactors with UOX fuel (TR_{UOX}), involving the formation of uranium, plutonium and MA stores, are used as the input for the simulation of the plutonium fuel reactor operation as part of a nuclear power system.

Plutonium fuel reactors are started both using plutonium generated in power reactors and plutonium obtained from other sources. The latter suggests that the initial characteristics of the given plutonium store should be given rather than calculated. Different physical and logical topologies of plutonium stores are possible. Thus, it is possible to simulate the evolution of nuclear power based on combined operation of TR_{UOX}, thermal reactors with a partial MOX fuel load (TR_{MOX}) and fast reactors. And thermal reactors with a partial MOX load are assigned the role of plutonium burners, while fast reactors (FR) enable degradation of the plutonium isotopic vector to be stopped during plutonium recycling in thermal reactors. A simplified flowchart of the NFC simulated in the CYCLE code is presented in Fig. 1.

Calculation results

The major calculation results are the time dependence of material flows at the NFC stages and the evolution of isotopic vectors. Besides, the following characteristics are calculated: fuel activity (Bq), radiotoxicity by air (Sv), radiotoxicity by water (Sv), neutron source due to spontaneous fission of actinides (n/s), neutron source due to oxygen-based (α, n) reaction (n/s), total neutron source (n/s), actinide heat (kW), fission fragment heat (kW), total decay heat.

The nuclide list includes all heavy nuclides with a half-life of over 46 days, including stable isotopes of lead and bismuth. The rest of the nuclides are assumed to be in equilibrium with their precursors. The concentrations thereof are taken into account for the calculation of other fuel characteristics: activity, radiotoxicity, neutron source and heat.

Reactor commissioning

Reactors of the specified type are commissioned and decommissioned in accordance with the given time dependence and reactor operating time. In the process of operation, it is possible to convert thermal reactors with uranium fuel to a partial MOX fuel load for burning the plutonium built up in the system.

Fuel cycle's pre-reactor stages

The fuel is enriched uranium or mixed fuel. The pre-reactor stages are: uranium mining, conversion, enrichment, FA fabrication (for uranium fuel), retrieval of fuel components from stores, repeated removal of americium from plutonium, and FA fabrication (for mixed uranium-plutonium fuel).

Annual and integral values are determined for the following:

- consumption of natural uranium and other fuel components;
- separative work;
- accumulation of depleted uranium;
- accumulation of americium from its possible repeated removal from plutonium;
- consumption of mixed fuel components from stores;
- demands for UOX and mixed fuel fabrication.
- uranium, plutonium and MA losses at the above fuel cycle stages.

For reactors with mixed uranium-plutonium fuel, retrieval of fuel components from uranium, plutonium, neptunium, americium and curium stores is modeled. It should be noted that components may be retrieved starting from "older" or fresh batches or evenly. The content of plutonium in the fabricated fuel, in the event its nuclide composition differs from the base composition, is adjusted. The adjustment is based on the condition of maintaining the reactor cycle duration in accordance with the plutonium equivalenting procedure [2] or by use of direct calculations.

The following is taken into account in the fuel fabrication

- a change in the nuclide composition of the fuel components in the course of storage;
- possible repeated removal of americium from the plutonium retrieved from the plutonium store;
- losses of components during factory-based fuel fabrication;
- a change in the nuclide composition of fuel from the time of the fabrication till the loading into the reactor.

The losses of fuel components are shipped for disposal.

Fuel cycle's reactor stages

- Calculation of the heavy metal quantities loaded annually for the reactor startup and refueling as specified by the given scenario.
- Calculation of the spent fuel nuclide composition in a range from thorium isotopes to curium isotopes.
- The input and output nuclide compositions may be given as initial data.