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Computational and experimental study of an irradiation rig with a fuel heater for the BOR-60 reactor

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Abstract

Advanced core materials and components for nuclear reactors of a new generation are tested in the BOR-60 reactor. A novel irradiation rig (IR) with a fuel heater is used for high-temperature tests of material samples. The irradiation rig features a number of advantages over ampoule-type irradiation rigs commonly used nowadays. Computational and experimental studies on an IR with a fuel heater have been conducted in the BOR-60 reactor core. The results of a dedicated methodical experiment have proved that it is possible to provide the required temperature conditions for irradiation of tested samples. MCU-RR, a precision code, was used for neutronic calculations, and thermohydraulic calculations were performed using the ANSYS CFX software system. A comparison of calculated temperature values against experimental data has shown a fit in the experimental error limits which confirms the applicability of the selected codes, models and procedures. Computational and experimental studies have also been conducted for the temperature distribution in the IR with a fuel heater following the withdrawal of the IR from the reactor and its placement in a dry cooling channel. The decay power in the IR fuel pins were calculated using the AFPA code and the temperature fields were calculated based on ANSYS CFX. It has been shown that the permissible temperature value on the fuel cladding is not exceeded in the IR withdrawn from the reactor following two-day cooling after the reactor shutdown.

Keywords: Reactor; Irradiation rig; Samples; Fuel pins; Heat rate; Power; Temperature; Thermocouple; Nuclear fuel; Enrichment; Coolant.

Introduction

The BOR-60 reactor [1] is used for an extensive scope of experimental studies and diverse irradiation programs to justify the feasibility of new advanced materials and designs for some of the reactor components, the possibility for increasing the maximum burn-up of nuclear fuel, and the achievability of threshold neutron fluences and damaging doses, as well as to study the regularities involved in the radiation-induced change in the behavior of different materials [2]. Different types of irradiation rigs (IR) are used for in-pile tests.

Generally, the positions the samples of test materials are placed in are limited by the reactor core height (45 cm), though positions at the level of the end blanket regions (upper blanket—100 mm, lower blanket—150 mm) are also possible. Radially, the sample positions are limited by the assembly casing's inner flat-to-flat dimension (42 mm). Besides, a double-casing IR design is used in most cases to thermally insulate test samples from adjacent assemblies, in which case the casing's inner flat-to-flat dimension is 38 mm. The diameter of the sample-containing ampoules is normally 32–38 mm.

Normally, non-fissionable materials (steels, alloys, absorbers, and moderators) are tested at high temperatures (400 °C and 700 °C and more) in ampoule-type IRs, with samples placed in sealed ampoules, while the required sample

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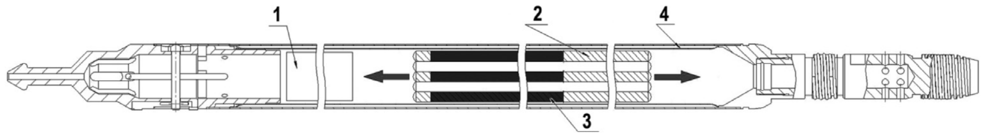

Fig. 1. An IR with a fuel heater (a longitudinal cut): 1—experimental volume for accommodation of test material samples; 2—fuel pins bundle; 3—fuel column; 4—IR wrapper.

temperature is ensured by selecting the dimension of the heat-insulating gap between the walls and the composition of the gas to fill in the gap (argon, helium, neon or mixtures thereof). Inside ampoules, samples may be contained in different environments (sodium, lead-bismuth, lead, gas and so on).

The major drawbacks of ampoule-type IRs are:

- highly non-uniform temperature distribution;
- a much smaller net volume for the test material accommodation;
- samples cannot be withdrawn from sealed ampoules for substitution or intermediate out-of-pile examination;
- the sample temperature can be only calculated (and normalized against measured values of performance parameters);
- the sample temperature is sensitive to variations in the reactor thermal power due to being weakly dependent on the coolant flow rate through the IR;
- the temperature conditions in the fabricated IR can be changed only through its relocation within the core;
- there is a risk of a gas leak not being detected by standard reactor equipment but leading to a sharp decrease in the sample temperature.

An IR with a fuel heater can be used for high-temperature tests (at 400 °C–650 °C) of the samples [3].

Irradiation rig with a fuel heater

Fig. 1 presents a longitudinal cut of an IR with a fuel heater. Arrows show the potential directions for the fuel pins bundle displacement.

The required temperatures of samples are achieved in an IR of this type thanks to the heating of sodium on the fuel pins bundle in the IR's lower part. The heating level is ensured through the adjustment of the nuclear fuel load, the fuel enrichment, the axial arrangement of fuel pins and the sodium flow rate. Standard BOR-60 fuel can be used in the heating fuel pins. An IR with a fuel heater lacks most of the above drawbacks which are inherent in ampoule-type irradiation rigs. Thus, for example,

- test samples are contained in a reactor-grade sodium fluid heated to the given temperature, which enables uniform distribution of temperatures;
- heating fuel pins may be positioned at the level of the bottom blanket region of standard FAs and lower, this enabling test material samples to be placed along the entire core height (there are no double-wall ampoules and it is possible to eliminate the double-wall casing for an increased sample accommodation volume);
- samples are contained in a dedicated suspension withdrawable from the IR independent of the fuel bundle;
- the sample temperature is equal to the heated coolant temperature measured by thermocouples;
- the temperature of sodium and, accordingly, of samples depends on the ratio between the reactor power and the sodium flow rate which remains nearly invariable during the reactor operation at a power level close to the rated value;
- the temperature irradiation conditions can be changed both through the relocation within the reactor core and by moving the fuel heater along the IR axis;
- a potential loss of sealing in the heating fuel pins is detected by the fuel cladding integrity monitoring system. In this case, the reactor is shut down and the samples are transferred into the IR with a new fuel heater.

It should be noted that an IR with a fuel heater is more expensive to fabricate and more difficult to handle outside the reactor than an ampoule-type IR.

Therefore, an IR with a fuel heater makes it possible to achieve different sample irradiation temperatures (up to 650 °C), periodically regulate the power density in fuel pins as the fuel burns up, and, accordingly, keep the sample temperature in the given limits, and change the temperature as specified by the experiment program.

The use of this IR type in the BOR-60 reactor requires the validity of calculation programs and procedures used to calculate the in-pile IR test conditions (power density and temperature) and the IR parameters outside the reactor to be confirmed experimentally.

Programs and procedures

Different programs and procedures described below were used for computational and experimental studies.

The BOR-60 reactor's data and measurement system (DMS) includes transducers the signals from which are processed in the computer system, stored in a special file and displayed as necessary. The DMS supports monitoring, in real time, of many reactor parameters (about 1000), as well as filing of all parameters. The DMS implements certified procedures for determination of the reactor power, the sodium flow rate and temperature, and so on. The DMS makes it possible to increase the number of measuring channels and introduce new measuring subsystems, specifically, thermocouples (TC) installed inside the IR. The DMS data are used to analyze directly measured and calculate unmeasurable reactor parameters, as well as to calculate the IR characteristics.