NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 4(1): 21–26
DOI 10.3897/nucet.4.29838

Research Article

Measurement of the spent fuel rod cladding temperature during the in-pile testing at 500–900°C*

Oleg I. Dreganov[1], Vitalij N. Shulimov[1], Irina V. Kiseleva[1], Aleksandr V. Alekseev[1]

1 *JSC "State Scientific Center – Research Institute of Atomic Reactors", 9 Zapadnoye shosse, Dimitrovgrad, Ulyanovsk Reg., 433510, Russian Federation*

Corresponding author: *Oleg I. Dreganov* (sokratik9@yandex.ru)

Academic editor: *Yury Korovin* ♦ **Received** 18 September 2018 ♦ **Accepted** 19 September 2018 ♦ **Published** 17 October 2018

Citation: Dreganov OI, Shulimov VN, Kiseleva IV, Alekseev AV (2018) Measurement of the spent fuel rod cladding temperature during the in-pile testing at 500–900°C. Nuclear Energy and Technology 4(1): 21–26. https://doi.org/10.3897/nucet.4.29838

Abstract

This paper deals with the problem of measuring the VVER-1000 burnup fuel cladding temperature in a 500–900°C range in the process of experiments in a channel of the MIR research reactor to obtain data on the fuel element behavior under the influence of the parameters typical of the maximum design-basis loss-of-coolant accident (LOCA). Studying the burnup fuel cladding deformation pattern requires measurements of the cladding temperature with no (thermal, mechanical and other) impacts on the cladding in the maximum deformation region.

For dynamic experiments in the MIR reactor channel with fuel testing in a vapor-gas environment, a cladding temperature measuring unit has been developed, in which the cladding is not subjected to external impacts in the maximum deformation region. In the process of being installed into the spacer grid, the thermoelectric transducer (TET) has its hot junction forced against the cladding making it possible to prevent the external impact on the cladding. The thermometric characteristic of the TET attachment, which is associated with the impact of the grid as such on its thermal condition, was studied using a laboratory facility. This technique was used in an in-pile experiment to study the fuel cladding deformation pattern.

Keywords

Laboratory facility (LF), experimental fuel element (EFE), electroheated fuel element simulator (EHFES), cladding, spacer grid (SG), thermoelectric transducer (TET), hot junction, temperature, heat-up rate, MIR reactor, loss-of-coolant accident (LOCA).

Introduction

To study the behavior of the VVER-1000 reactor fuel elements during normal operation and anticipated operational occurrences, there is a whole class of reactor experiments (Alekseev et al. 2007a; Alekseev et al. 2006a, b; Alekseev et al. 2012), in which the item of interest shall be tested in a strictly defined temperature range. This is especially true in the event of a fuel element test in conditions of a loss-of-coolant accident (LOCA) (Goryachev et al. 2004, Alekseev et al. 2009, Salatov et al. 2013, Goryachev et al. 2004a), in which the cladding temperature varies in a temperature range of 700–900°C for different experiments with an accuracy of not more than 2–5%. If this value is exceeded, an additional factor may occur, which influences the property under investigation and

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2017, n.4, pp. 50–60

cannot be taken into account in the interpretation of the experiment results.

Such experiments require the cladding temperature to be known at any given time with such accuracy as is sufficient for the interpretation of the results.

The temperature estimation in such experiments (Shulimov and Kiseleva 2004) does not lead to a successful result since the nonuniform power densities existing in the research reactor channel and the complexity of heat transfer in the vapor-gas environment the item is tested in under the LOCA conditions do not make it possible to achieve the acceptable calculation accuracy. The only way of temperature determination is online measurements. What is meant here is the measurement of the VVER-1000 burnup fuel cladding temperature since the testing of fresh fuel elements is of no practical interest.

Methods for the TET attachment to the burnup fuel cladding used in in-pile experiments

Literature contains data on two ways to install a hot junction on the burnup fuel cladding: by means of remote spot welding performed in a shielded box (Askeljung et al. 2012) and using a special collar (Kekkonen Laura 2008) which is also installed remotely. The first of the methods was used for experiments in the Halden reactor channel, and the second technique for the TET hot junction attachment was used in shielded-box experiments.

The above-noted methods for the TET attachment to the irradiated fuel cladding are used remotely and are hard to employ. Moreover, they may not be technologically feasible for some reactors. Certain problems occur when installing the communication lines between the sensor and the secondary transducer. For the channels of the MIR research reactor (Research Reactors of RIAR 1991), it is not technologically feasible due to the specific reactor design.

If the list of the major properties to be studied includes the fuel cladding deformation pattern, then the attachment principle as such is an essential drawback of the said techniques because of the cladding subjected to mechanical and thermal impacts expected to affect the nature and the absolute magnitude of the deformation process.

Spent fuel cladding temperature measuring unit for experiments in the MIR reactor channel

For dynamic experiments in the MIR reactor channel (Shulimov et al. 2015; Izhutov et al. 2015; Alekseev et al. 2016; Goncharov et al. 2016; Alekseev et al. 2017a, b) where the item of interest is tested in a vapor-gas environment, a thermometric unit has been developed to measure the irradiated fuel cladding temperature, in which the cladding is not subjected to external impacts in the maximum deformation region. Such experiments include the VVER-100 fuel testing in the LOCA conditions.

A distinctive feature of the developed technique consists in the TET being installed into a spacer grid of a specific design such that the TET has its hot junction automatically forced against the fuel cladding when the spent fuel element is loaded remotely into the device. A major advantage of such attachment technique is that it does not require a remote operation in the process of the device assembly. The TET and the communication lines between the TET and the secondary transducer are installed at the manufacturer's assembly stand.

Spacer grids (SG) with a pitch of 200 mm were used to install the fuel element with the kernel length of 1000 mm into the device for the LOCA experiments. The TET hot junction position may be both inside of the SG and at a distance of 5 to 7 mm from the SG upper end. Both options require the TET hot junction to be forced against the fuel cladding by means of the TET attachment structure.

Laboratory facility to determine the thermometric characteristic of the TET attachment to the burnup fuel cladding

The extended surface of the SG and a major loss of heat from this surface to the environment lead to the SG's substantial impact on the fuel cladding axial temperature distribution. This impact is especially marked in dynamic experiments. Without knowing the quantitative SG impact on the cladding temperature distribution and the system of corrections for determining the cladding temperature between the grids, this method cannot be used to install the TET into the devices designed for experiments in the research reactor channels. It is obvious that the thermometric characteristics of the assembly with different TET hot junction positions will differ from each other. Therefore, the corrections for the TET readings in the SG shall be determined separately for each option. These corrections were determined experimentally using a laboratory facility being a precise replica of the active part of the device for dynamic reactor experiments with simulation of the VVER-1000 LOCA parameters in the test channel. A fuel element simulator with an internal electric heater was used as the heat flux source in the facility.

Fig. 1 shows the overall view of the laboratory facility and the layout of its central part with the spacer grid (SG) and TET locations. Inside of the device, electric heaters (EH) are installed on the side face of the shroud tube to create the external temperature conditions on the fuel element that are typical of operation in a multielement fuel assembly.

In the central part of the laboratory facility (the volume with the EHFES), the TETs are installed:

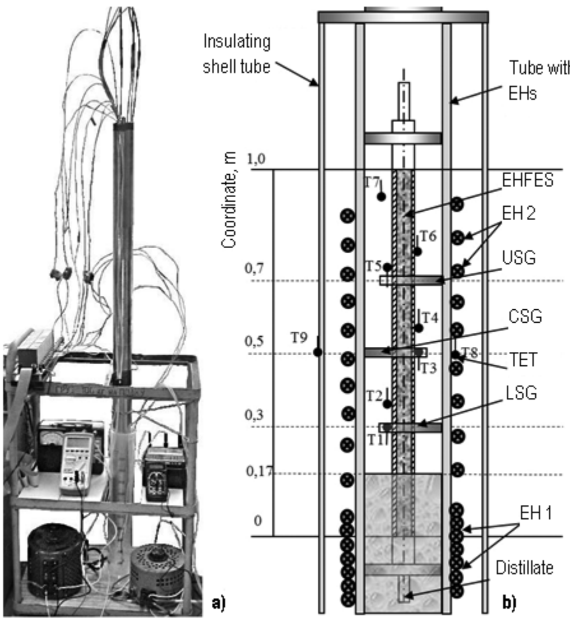

Figure 1. Laboratory facility: a) – overall view; b) – SG and TET arrangement in the LF

- inside of three spacer grids (T1, T3, T5) for the readings of which corrections are to be determined;
- on the EHFES cladding at three points at different heights (T2, T4, T6) not connected to the SG; the coordinates of the TET hot junction attachment to the cladding are above the SG;
- on the shroud tubes and in the coolant.

The TET locations are shown in Fig. 1b. The TET hot junction is at a distance of 5 to 7 mm from the SG's upper end in the upper spacer grid (USG), and inside of the SG in the central spacer grid (CSG) and in the lower spacer grid (LSG).

Wire binding was used for the TET attachment to the EHFES cladding. All TETs were connected to the information and measuring system (IMS) with a recording frequency of 1 Hz. For the temperature measurements both at the laboratory facility and in the reactor experiments, cable TETs (tolerance class 2.0) were used with a thermocouple of the chromel-alumel type (K-type), the steel (12Kh18N10T) shell diameter of 1.5 mm, a magnesium oxide insulation, and a joint hot junction of the

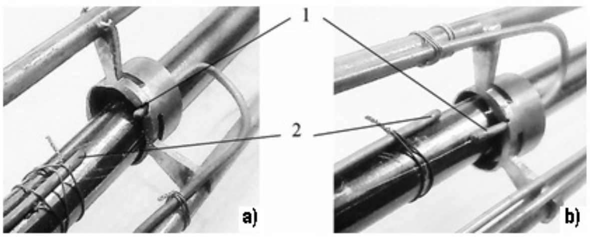

Figure 2. TET hot junction attachment points: a) – in the SG plane ; b) – 7 mm above the SG plane; TET forced against the SG cladding (1), TET forced against the cladding by means of wire binding (2)

thermocouple wires with a diameter of 0.27 mm. Before the experiments, all TETs were certified under GOST R 8.585–2001, for which the correction value is in a range of –0.7 to –1.5°C. For the TET certification, the correction allowed for the thermoelectric nonuniformity, as well as for the communication between the temperature sensor and the secondary transducer (a signal converter). The TET time constant does not exceed 0.500 s.

Fig. 2 shows the points of the TET attachment to the EHFES cladding.

Experimental determination of corrections to the TET readings

The values of the corrections for the TET readings in the SGs ($T_2 - T_1$, $T_4 - T_3$, $T_6 - T_5$) depend on the temperature of the TET attachment and the value of the heat flow from the EHFES cladding (cladding heat-up rate) in the SG installation area. For this reason, the EHFES power was varied during the experiment.

We shall give the parameters of two EHFES heat-up modes with the minimum and maximum heat-up rates as can be achieved using this equipment. Please note that the maximum heat-up rate corresponds to the value specified for the reactor experiment.

Mode 1 – EHs 1 and 2 are on (each heater has a power of 350 W), the EHFES power is increased in steps (16, 62, 135, 235, 377, 545 W).

Mode 2 – EH 1 (340 W) and EH 2 (300 W) are on, stepwise EHFES power increase in two steps of 790 and 900 W with intermediate cooling of the EHFES cladding to 500°C.

In each EHFES heat-up mode, each further power increase step was preceded by a time delay for achieving a steady-state thermal condition.

Table 1 shows values of the differences in the TET readings for each SG and the rates of the growth in the TET readings which are interconnected. Both parameters were determined in an on-line experiment.

The spacer grid had the greatest effect on the TET readings with the hot junction being inside of the SG (Fig. 2a), as was the case with the LSG and the CSG. In this case, the difference between the TET readings inside of the SG and on the EHFES cladding may exceed 100°C with high EHFES heat-up rates (over 3°C/s). If the TET contacts the SG but the hot junction is outside of the SG (Fig. 2b), the spacer grid effect is much smaller. For each mode, in this case, the difference between the TET readings inside of the SG and on the EHFES cladding did not exceed 30°C. A quantitative SG effect in each TET installation option was determined in an experiment on the laboratory facility.

Fig. 3 presents the value of the difference in the TET readings inside of the SG and on the EHFES cladding as a function of the growth rate for the two hot junction locations: inside of the SG (for the CSG) and at a distance of about 5 to 7 mm (for the LSG).

Table 1. Values of temperature differences for $T_2 - T_1$, $T_4 - T_3$, $T_6 - T_5$ and growth rates of the TET readings.

LSG region			CSG region			USG region		
$T_2 - T_1$, °C	Rate, °C/c		$T_4 - T_3$, °C	Rate, °C/c		$T_6 - T_5$, °C	Rate, °C/c	
	in LSG	above LSG		in CSG	above CSG		in USG	above USG
Mode 1								
72	0.22	0.43	30	0.29	0.46	13	0.37	0.48
83	0.34	0.57	33	0.39	0.57	13	0.5	0.62
79	0.29	0.51	27	0.4	0.55	15	0.45	0.6
84	0.41	0.7	25	0.54	0.75	18	0.64	0.83
Mode 2								
166	1.96	3.24	96	2.8	3.84	22	2.97	3.2
90	1.38	2.77	50	1.78	3	8	0.91	0.78

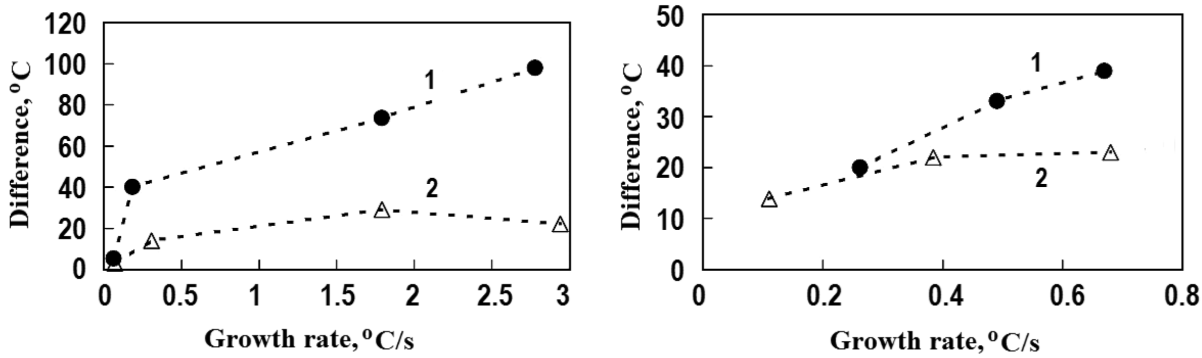

Figure 3. Variation of the difference in the TET readings for $T_4 - T_3$, $T_6 - T_5$ as a function of the rate of growth in the TET readings in the CSG (1) and in the LSG (2) at 300°C (a) and 600°C (b)

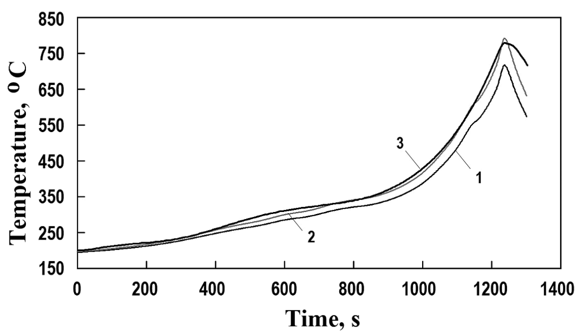

Figure 4. Time-temperature curve for experiment 1: TET readings (1); cladding temperature values determined using the TET readings with corrections taken into account (2); calculated cladding temperature values (3)

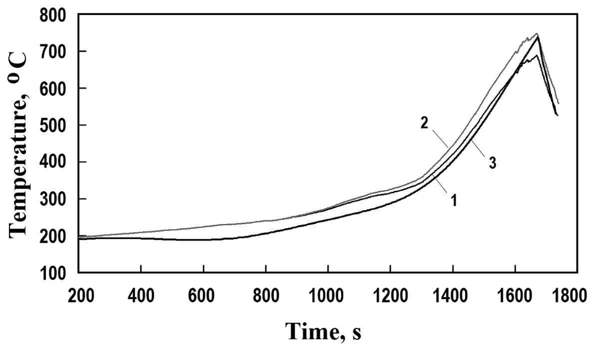

Figure 5. Time-temperature curve for experiment 2: TET readings (1); cladding temperature values determined using the TET readings with corrections taken into account (2); calculated cladding temperature values (3)

According to the data shown in Fig. 3 and Table 1, the option with the TET hot junction being above the SG plane is the preferred one since the corrections to the TET readings are smaller in this case.

The values of the corrections to the TET readings with the hot junction installed:

– inside of the SG: 80–100°C for the growth rate of the TET readings in the limits of 2.0–3.0°C/s;
– 5 to 7 mm above the spacer grid plane: 20–30°C for the growth rate of the TET readings in the limits of 0.5–3.0 C/s.

Use of the results obtained in computational modeling of the reactor experiment parameters

The results obtained were used to determine the temperature of the high burnup fuel cladding in experiments (Shulimov et al. 2015; Izhutov et al. 2015; Alekseev et al. 2016; Goncharov et al. 2016; Alekseev et al. 2017a, b) in the MIR research reactor channels with simulated parameters of the LOCA accident in the VVER-1000 reactor (Spasskov et al. 1998; Alekseev et al. 2007b). The experimental results correlated well with the data obtained in the post-test examination of the tested fuel and were confirmed by computational modeling of the data.

Figs. 4 and 5 show the results of two experiments (Alekseev et al. 2016; Goncharov et al. 2016; Alekseev et al. 2017a): the maximum cladding temperature in the first experiment was 805°C, and the maximum cladding temperature in the second experiment was 760°C. Additionally, computational modeling results obtained for the CSG installed in the maximum power density region are presented.

The height coordinate, at which the maximum cladding temperature is reached, coincides with the coordinate of the maximum circumferential deformation measured in the shielded box.

Conclusions

The procedural aspects of measuring the burnup fuel cladding temperature, successfully implemented in the experimental practice in the MIR reactor channels, have been analyzed, in which one of the major parameters studied is deformation of the cladding in a temperature range of 700–900°C.

The results of studying the thermometric characteristic of the TET attachment in a spacer grid are presented. Using a laboratory facility, in which a fuel element simulator with internal electroheating was employed, a system of corrections was determined for determining the cladding temperature.

The reliability of the burnup fuel cladding temperature determination results has been confirmed by results of post-test examinations and by results of the experimental data computational modeling.

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