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# Original Article

# Experimental simulation of activity release from leaking fuel rods



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#### ABSTRACT

The Leaking Fuel Experiment test facility was designed to simulate the activity release from spent leaking fuel rods under steady state and transient conditions in the spent fuel pool. The experimental rig included an electrically heated fuel rod with different defects and a cooling system. The fission product transport was simulated by potassium-chloride. The conductivity changes of the water in the cooling system were measured to provide information about the amount of released solution. Defects of different sizes and positions were applied, together with a wide range of rod powers to simulate decay heat. The produced data can be used for predicting the activity release from leaking fuel under storage conditions and for the interpretation of fuel examination procedures.

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# 1. Introduction

The fuel rods in a nuclear power plant have to withstand the continuous neutron flux, high mechanical and thermal loads, corrosion and other effects associated with the structural changes caused by the irradiation. Modern fuel rod designs can guarantee that most of the fuel rods would keep their integrity during several years of operation in nuclear reactors. The fuel failure is a rare event, according to the statistics one out of one-hundred-thousand fuel rods loses its integrity during normal operation [1]. The typical mechanisms leading to failure are the corrosion, formation of hydrides in the cladding, fretting by debris or spacer grid, pellet-cladding mechanical interaction and fabrication defects.

The presence of leaking fuel rods in the core is indicated by the increase of coolant activity since through the defect some of the radioactive fission products can be released from the fuel rod into the coolant. The power plants are equipped with water purification system, which is able to keep low activity levels in the primary coolant even with leakers in the core [2].

Using the coolant activity concentration the number and some other characteristics of leaking fuel rods (e.g. burnup), and the amount of fissile material contamination on the core surface can be estimated [3–6]. Most nuclear power plants have special devices (e.g. sipping equipment) using which the leaking fuel assembly can be identified during the refueling period [2].

Leaking fuel assemblies are handled in different ways at nuclear

power plants. They can either be stored together with the intact ones in the spent fuel pool, can or be placed into special canisters or after further examinations the leaking fuel rods can be removed from the assembly.

The decision on the placement of the leaking fuel assembly in a normal position or in a special canister in the spent fuel pool can be based on the expected contamination of the pool by the leakers.

For the period of storage, the inhermetic fuel rod leaks into the pool. The amount of released activity depends on the size and position of the damage, on the burnup and the linear heat rate of the fuel, and also on the time spent in the reactor between failure and removal. The potential release from the leaking fuel rods in the spent fuel pool can be estimated by carrying out special measurement programmes with leaking assemblies stored in the pool [7,8]. Such measurements are very useful, however, they are representative only for the given leaking fuel rods stored in the pool. In order to cover a wider range of parameters (e.g. fuel rod power, defect size and position) additional measurements may be needed. The development of numerical models used for the simulation of leaking fuel can only be performed if supported by experimental data.

Experiments with real irradiated VVER fuel have been carried out at the MIR reactor, Russia [8]. Those experiments were representative for reactor operation conditions. In case of spent fuel pool the decay heat of the fuel rods is much smaller, new fission products are not produced since the chain reaction was stopped and the temperature of the fuel is much lower, which slows down the migration of isotopes inside the pellet. On the other hand, due to low temperature condensation of steam will take place, the gas volume of the fuel rod will be filled by water, which can facilitate

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the diffusion of soluble fission products from the fuel rod into the coolant.

The main objective of the Leaking Fuel Experiment (LEAFE) experimental programme was to support decision making on the storage mode of VVER-440 fuel assemblies at Paks NPP. A special measurement programme was performed at Paks NPP with one leaking fuel assembly in the spent fuel pool [9]. The activity concentrations were regularly measured and beyond the standard water purification system additional sampling of coolant from different positions in the pool were taken. The measurement programme included transient phenomena (e.g. water level change, periodic operation of water purification system, lift-up and sipping of the leaking fuel assembly). The capabilities of a numerical model [10] developed for the simulation of leaking fuel assembly in the spent fuel pool including sipping tests could be extended with data characterizing the decay heat, position and size of the defect. The inactive simulation of such phenomena is much simpler compared to the testing of irradiated fuel rods.

# 2. Materials and methods

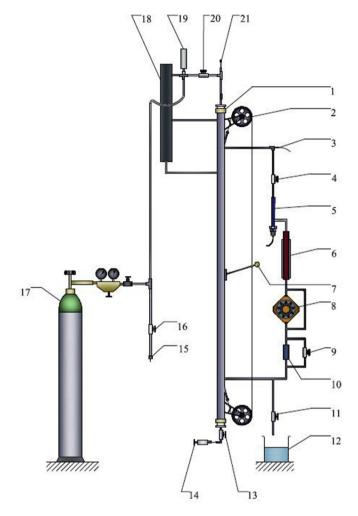
### 2.1. The experimental set-up

The LEAFE experimental rig was a full scale mock-up for one single fuel rod.

The design parameters of the facility were selected in order to establish experimental conditions that can be considered representative for the leaking spent fuel in the storage pool. The geometry of the fuel rod (length, diameter) was comparable to the typical VVER-440 fuel rod design. The characteristics of alumina pellets were similar to that of UO<sub>2</sub>. The free gas volume inside of the fuel rod on one hand had to be similar to that of real fuel rods, and on the other hand must be changeable to simulate different conditions. Heating of the fuel rod was applied to the full length in order to create uniform power distribution, and the heating power could be change. Furthermore, the linear heating rates typical for fuel rods in the spent fuel pool had to be reached. The circulation loop did not simulate the water purification system of the spent fuel pool. For the applicability of the LEAFE test facility to transient tests, the fuel simulator rod could be pressurized to simulate sipping tests or lifting the fuel assembly.

The test section included an electrically heated fuel rod which had special defects on the cladding. The defects could be opened individually by external manipulators. The fuel rod was placed into a large diameter tube filed with water, which simulated the spent fuel storage pool surrounding the leaking assembly. The external water was circulated through a pipe connecting the bottom and the top of the large diameter tube, as shown in Fig. 1.

The geometry of the rod was similar to the VVER-440 fuel rod (Fig. 2). The cladding was made of stainless steel with 8.00 mm inner diameter and 9.15 mm outer diameter. The length of the cladding tube was 2554.5 mm. The pellets were made of Al<sub>2</sub>O<sub>3</sub>, this ceramic behaves similarly to UO<sub>2</sub>. The diameter of the pellets was 7.52 mm and that of the central hole was 3 mm. The total free volume inside the fuel rod simulator was 21 cm<sup>3</sup>. Decay heat was simulated by a heating wire (diameter 2.8 mm) installed in the central hole of the pellets. In each experiment one single defect was applied. It was located in the middle (1228 mm from the bottom of the rod), at the top (218 mm from the top of the rod) or at the bottom (218 mm from the bottom of the rod (Fig. 2). The size of the defect varied between 180 µm and 5 mm (Fig. 3). The defects are circular holes and the size of the defect is the diameter of the hole. 180 µm size was chosen as the smallest technically feasible defect. 5 mm defect was chosen on the basis that the debris could cause some millimeters defect on the rod.



**Fig. 1.** Main components of the experimental rig (1: rod, 2: wire control disc, 3: thermometer, 4: tap, 5: conductometer, 6: heater, 7: valve opener, 8: pump, 9: bypass, 10: throttle, 11: drain: 12: vessel, 13: valve, 14: injector, 15: throttle, 16: drain, 17: argon gas cylinder, 18: buffer tank, 19: pressure gauge, 20: drain, 21: K-type thermocouple).

The temperature was measured at three different positions. One K-type thermocouple was installed inside the fuel rod and one Pt-100 temperature sensor was placed at the top of the loop. The conductivity measuring instrument had also a temperature output which was in the middle of the cooling system.

The coolant flowrate was measured with a differential pressure transducer. The typical flowrate was around  $3.5~\rm dm^3/h$  and the total circulated water volume was between  $2.15~\rm dm^3$  and  $2.5~\rm dm^3$  depending on the experiment. With the chosen parameters, the ratio between the flowrate and the water volume corresponds to the conditions at Paks NPP. The pressure was measured in the loop with pressure transducer.

### 2.2. The test matrix

The main objectives of the LEAFE programme covered both steady state and transient conditions.

- In the steady state tests the rod power and the defect size were varied in order to obtain information on the effects of these parameters on the intensity of leaking.
- The transient tests simulated the telescope sipping and canister sipping type testing of leaking fuel rods with different defect

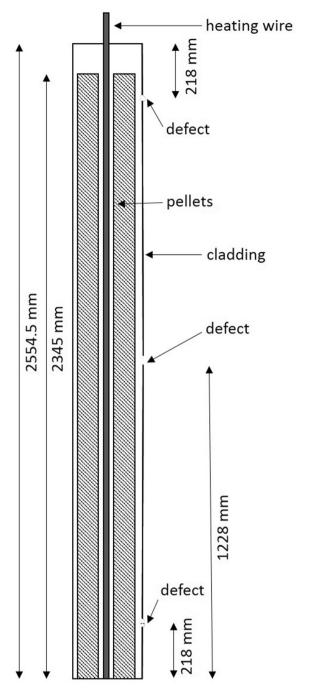


Fig. 2. The schematic view of the fuel rod.

locations and defect sizes. The effect of initial gas volume in the leaking fuel rod was also investigated. One test was performed at 80  $^{\circ}\text{C},$  while the other measurements were taken at room temperatures.

The test matrix (Table 1) was set up in order to gain as much information about the leaking fuel as possible from this group of experiments.

The first six experiments were carried out under steady state conditions, the rest of them were designed to simulate transient sequences occurring during the telescope sipping and canister sipping type examinations of the leaking fuel. The experimental programme included on the whole 19 measurements.

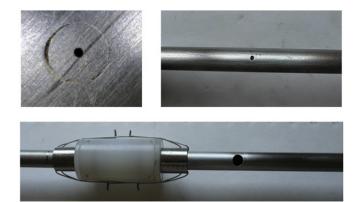


Fig. 3. View of the 180  $\mu m$  defect (upper left), 1.2 mm defect (upper right) and the 5 mm defect with opening sleeve (bottom).

#### 3. Execution of tests and main results

# 3.1. Steady state tests

At the beginning of the test the fuel rod was filled up with KCl-containing water and the specified gas volume was established at the top of the fuel. The volume surrounding the fuel rod was filled up with ultra-high purity water. The KCl-containing water was released from the fuel rod during the tests and the change of KCl-concentration outside the rod was monitored.

The conductivity of the coolant was measured on-line and the concentration change could be recorded. It was important to carry out the measurements without taking samples from the loop because that would have influenced the results.

The opening of the leak was carried out with a manual mechanical device (Fig. 3) after the initial conditions were reached both inside of the fuel rod and in the cooling system.

The facility was running for 3 h to reach constant temperature before start-up of the steady state tests. After the heating period the defect was opened and data recording started. It was intended to perform the tests under isothermal conditions (the main part of the facility was insulated but not everywhere), but some temperature changes occurred because the laboratory temperature changed few degrees during the day.

The fuel rod could communicate with its surrounding environment only through the defect. The water level was always the same in the fuel rod and in the coolant at the start of the tests. Levels could not be monitored but valves were installed to check that the levels were at the same elevation at the beginning of the experiment.

In Fig. 4 the recorded data are shown for test No. 3. The curve with square symbols shows the rod temperature, the curve with triangle symbols visualizes the coolant temperature at the top of the loop, the curve with diamond symbols displays the temperature recorded by the conductivity-measuring equipment. All of the temperatures are in °C. The curve without symbol shows the measured conductivity in  $\mu$ S/cm. Conductivity is always corrected to 25 °C. For all the steady state experiments similar plots are available.

In Fig. 4 the 1.2 mm defect was in the middle of the rod (test No. 3). The rod power was 20 W/m and the gas volume was 2 cm<sup>3</sup>. The experiment was carried out at room temperature and lasted for four days.

In Fig. 5 the concentration of KCl in the storage pool is plotted versus time for tests No. 1–6. For the experiment with 180  $\mu$ m defect and 5 W/m linear heat rate (solid line) the fractional release

**Table 1**Test matrix of LEAFE experiments.

| No | . Rod<br>power | Position of defect in the rod | Size of<br>defect | -          | Initial over-pressure in fuel rod | Initial gas<br>volume | Final gas<br>volume | Simulated scenario                 |
|----|----------------|-------------------------------|-------------------|------------|-----------------------------------|-----------------------|---------------------|------------------------------------|
| 1  | 5 W/m          | middle                        | -<br>180 μm       | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   | Steady state leaking in spent fuel |
| 2  | 20 W/m         | middle                        | 180 μm            | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   | pool                               |
| 3  | 20 W/m         | middle                        | 1.2 mm            | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   | •                                  |
| 4  | 20 W/m         | middle                        | 5 mm              | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   |                                    |
| 5  | 5 W/m          | middle                        | 5 mm              | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   |                                    |
| 6  | 10 W/m         | middle                        | 5 mm              | Room temp. | 0 bar                             | 2 cm <sup>3</sup>     | 2 cm <sup>3</sup>   |                                    |
| 7  | 5 W/m          | middle                        | 180 μm            | Room temp. | 1 bar                             | 1.2 cm <sup>3</sup>   | 2.4 cm <sup>3</sup> | Telescope sipping                  |
| 8  | 5 W/m          | middle                        | 180 μm            | Room temp. | 1 bar                             | 3 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 9  | 5 W/m          | middle                        | 1.2 mm            | Room temp. | 1 bar                             | 1.2 cm <sup>3</sup>   | 2.4 cm <sup>3</sup> |                                    |
| 10 | 5 W/m          | middle                        | 1.2 mm            | Room temp. | 1 bar                             | 3 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 11 | 5 W/m          | bottom                        | 1.2 mm            | Room temp. | 1 bar                             | 3 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 12 | 5 W/m          | upper                         | 1.2 mm            | Room temp. | 1 bar                             | 1.2 cm <sup>3</sup>   | 2.4 cm <sup>3</sup> |                                    |
| 13 | 5 W/m          | middle                        | 180 μm            | Room temp. | 5 bar                             | $0.4 \text{ cm}^3$    | 2.4 cm <sup>3</sup> | Canister sipping                   |
| 14 | 5 W/m          | middle                        | 180 μm            | Room temp. | 5 bar                             | 1 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 15 | 5 W/m          | middle                        | 1.2 mm            | Room temp. | 5 bar                             | 0.4 cm <sup>3</sup>   | 2.4 cm <sup>3</sup> |                                    |
| 16 | 5 W/m          | middle                        | 1.2 mm            | Room temp. | 5 bar                             | 1 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 17 | 5 W/m          | bottom                        | 1.2 mm            | Room temp. | 5 bar                             | 1 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 18 | 5 W/m          | upper                         | 1.2 mm            | Room temp. | 5 bar                             | 1 cm <sup>3</sup>     | 6 cm <sup>3</sup>   |                                    |
| 19 | 5 W/m          | middle                        | 180 μm            | 80 °C      | 5 bar                             | 1 cm <sup>3</sup>     | 6.8 cm <sup>3</sup> |                                    |

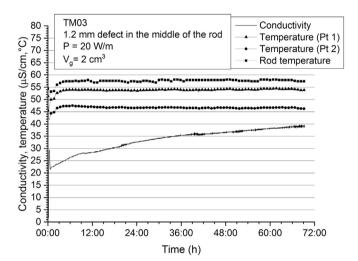


Fig. 4. Leaking under steady state conditions with 1.2 mm defect in the middle of the rod.

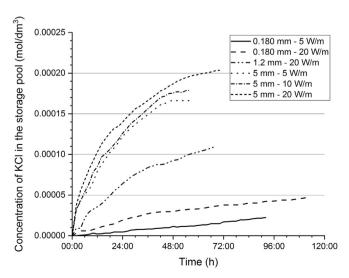


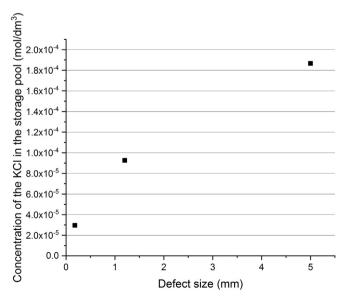
Fig. 5. Concentration of KCl in the storage pool versus time for test 1-6.

rate was approximately constant over the experiment. During the other tests at the beginning of the experiment the release was faster and after 2 days it has started to become slower due to dilution. The highest release was observed at the high power rod (20 W/m) and with biggest defect size (5 mm).

Fig. 5 shows that KCl concentration also increases with the linear heat rate. So the release rate is lower when the linear heat rate is lower. The measured concentration highly depends on the defect size: the KCl concentration with 5 mm defect is about ten times higher compared to cases with 180 μm defects.

Fig. 6 shows the concentration change with the defect size for tests with 20 W/m power. The release rate is clearly increasing with the size of the defect.

Using the measured KCl concentrations in the external tube after 48 h and knowing the water volumes and the initial KCl concentration inside the fuel rod simulator (0.1 mol/dm3) the release rates for two days can be calculated. Fig. 7 shows the release rates for the steady state experiments. In case of small defect (180  $\mu$ m) the release rate was less than 5%. The large defects



**Fig. 6.** Concentration of the KCl in the storage pool versus defect size (rod power 20 W/m).

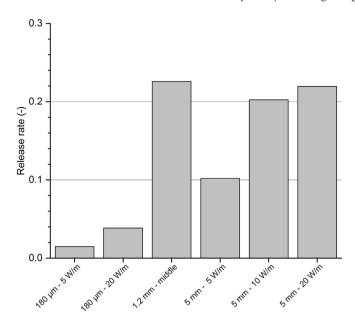


Fig. 7. Release rate versus rod power, defect size and position.

resulted in 10-20% release during this period.

On the basis of the measured steady state data a correlation was fitted for release rate as function of rod power and defect size and it was built into a numerical model used for the simulation of leaking VVER fuel [10].

# 3.2. Transient tests

The identification of leaking fuel assemblies is carried out by sipping techniques at the NPPs. During telescope sipping due to the lift-up of fuel assemblies the hydrostatic pressure changes inside of the leaking fuel rod and the expansion of the gas volume results in the release of fission products solved in the water or gas volume inside the rod. In the canister sipping technique the assembly is placed into the canister, inside of which the pressure is artificially increased and decreased leading to compression and expansion of the gas volume and resulting in activity release. In the LEAFE facility both techniques were simulated setting 1 bar overpressure for telescope and 5 bar overpressure for canister sipping scenarios.

At the beginning of transient tests the fuel rod was filled with KCl solution and the required gas volume was kept above the liquid. The pressure inside the fuel rod was increased. The simulation of the transient started with the manual opening of the defect. The overpressure resulted in the expansion of gas volume and the release of corresponding amount of solution from the fuel rod through the defect.

The conductivity history is illustrated in Fig. 8 for a 1 bar overpressure case with 3 cm<sup>3</sup> initial gas volume in the fuel rod. Following the depressurization of the fuel rod, a large peak of conductivity was observed. After that, the conductivity decreased and converged to a value which was about half of the peak conductivity. This history showed that there was a large release after the opening of the defect, but later only the mixing of the coolant in the circulating loop played a role in the change of conductivity measured in a local position. Similar behavior was observed for the simulated scenarios with 5 bar overpressure, too (Fig. 9).

The released volume of water from the fuel rod can be predicted by the gas law if the pressure and gas volume are known in the fuel rod. The released volume can be estimated also on the basis of measured conductivity data.

In Fig. 10 the release rate predicted by gas low (straight line) and

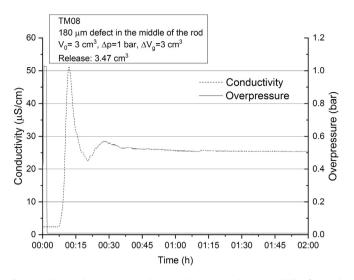


Fig. 8. Leaking under transient conditions with 180  $\mu m$  hole in the middle of the rod.

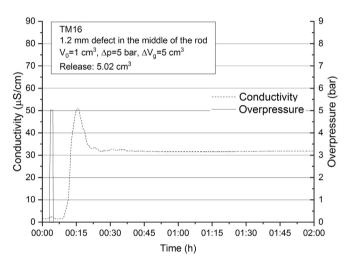


Fig. 9. Leaking under transient conditions with 1.2 mm hole in the middle of the rod.

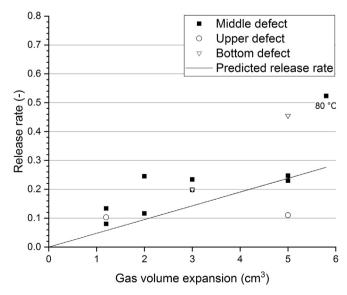


Fig. 10. Predicted and measured release rates as function of gas volume expansion.

the release rates based on measured data are shown. The gas volume expansion is the volume change compared to the original value at the beginning of the experiment. The predicted and measured release rates are in the same order of magnitude. The best agreement can be observed for cases with middle defect (marked with black squares). In case of upper defect the measured release was below the predicted one, while the bottom defect showed higher release compared to the theoretical value. This difference can be explained by the axial distribution of KCl in the fuel rod. Probably the concentrations were higher in the bottom of the rod, that is why the lower defect was characterized by higher release rate. The highest measured release rate was detected at test No. 19, which was performed at 80 °C. The higher temperature could cause higher release rate, since the solubility of gases is decreasing with temperature and the dissolved gases could increase the gas volume.

#### 4. Conclusion

A test facility was installed for inactive experimental simulation of leaking fuel rods in the spent fuel storage pool. Both steady state and transient sequences could be simulated. 19 tests were performed with different defect sizes and positions, power and pressure histories.

The experiments indicated that the leakage rate for steady state conditions highly depends on the size of the simulated defect and monotonically increases with the power of the fuel rod. The transient tests showed that the release from the rod correlates well with the expansion of the gas volume inside of the fuel rod and temperature but it does not depend on the hole size.

The produced data can be used for predicting the activity release from leaking fuel under storage conditions and for the interpretation of fuel examination procedures.

#### References

- Review of Fuel Failures in Water Cooled Reactors, IAEA Technical Reports, No. NF-T-2.1, IAEA, 2010.
- 2] Leaking fuel impacts and practices, NEA/CSNI/R, vol. 10, 2014. OECD (2014).
- [3] M.H. Chun, N.I. Tak, S.K. Lee, Development of a computer code to estimate the fuel rod failure using primary coolant activities of operating PWRs, Ann. Nucl. Energy 25 (1998) 753-776.
- [4] B.J. Lewis, R.J. Green, C.W.T. Che, A prototype expert system for the monitoring of defected nuclear fuel elements in Canada deuterium uranium reactors, Nucl. Technol. 98 (1992) 307–321.
- [5] V. Likhanskii, I. Evdokimov, A. Sorokin, V. Kanukova, V. Zborovskii, Taran, M. Ugrumov, A., Riabinin Yu, Development and using computer codes for improvement of defect assembly detection on Russian VVER NPPs, in: Proc. 8<sup>th</sup> Int. Conf. WWER Fuel Performance, Modelling and Experimental Support, Bulgaria, 2009, pp. 148–157.
- [6] Z. Hózer, Simulation of leaking fuel rods in a VVER reactor, Ann. Nucl. Energy 70 (2014) 122–129.
- [7] Marek Miklos, Miroslav Bozik, Daniel Vasina, Leak tightness testing system for nuclear fuel assemblies in wet conditions of interim spent fuel storage, Int. J. Nucl. Energy Sci. Technol. 3 (3) (2007) 220–235.
- [8] A. Sorokin, et al., Modeling in support of experiments in the MIR reactor to assure safe operation of nuclear fuel of advanced design, 11, in: International Conference on WWER Fuel Performance, Modelling and Experimental Support, 2015 (Bulgaria).
- [9] T. Burján, Failed (leaking) spent fuel management and storage in Paks NPP, in: Proc. 9th Int. Conf. WWER Fuel Performance, Modelling and Experimental Support, 2011, pp. 132–139.
- [10] P. Szabó, Z. Hózer, K. Kulacsy, B. Somfai, R. Nagy, T. Burján, I.B. Varjú, T. Pintér, Numerical simulation of the telescope sipping of a leaking VVER fuel assembly, Ann. Nucl. Energy 99 (2017) 345–352.