# Óbuda University

Theses of doctoral (PhD) dissertation

# Experimental and numerical investigation of plastic deformation of fuel claddings in nuclear power plants at different time scales

Author: Richárd Nagy

Supervisor: Dr. Zoltán Hózer

**Doctoral School on Materials and Technologies**

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# I. Preliminaries of research

The fuel of water-cooled reactors in nuclear power plant (including the current and under construction Paks units) contains $^{235}U$ isotope-enriched uranium dioxide pellets housed in a zirconium alloy enclosure [1]. Cladding of fuel elements allows the heat, which is generated in fuel pellet, to be carried toward the coolant. Cladding prevents the escape of radioactive and toxic materials from fuel. The cladding material of the fuel rods of VVER type reactors (Paks) is an alloy containing 99% zirconium and 1% niobium [2]. The Russian acronym of this cladding family is E110, which, in addition to being abrasion-resistant, high-strength, and resistant to the medium in the reactor at operating temperatures.

The basic goal of research on nuclear power plants is to learn about the processes that take place in fuels, to establish safety criteria for fuels used, and to provide data for the development and validation of numerical models of fuel behavior codes, which are used for reactor safety analyzes. Hungarian fuel research is mainly carried out by the Centre for Energy Research (EK). Experimental work focuses on the examination of fuel claddings [3] [4]. During my doctoral work, I participated in two projects in the EK, in which we examined the damage to the fuel cladding on different time scales:

• The pellet-cladding mechanical interaction (PCMI) occurs when the gap between the pellet and the cladding closes in the fuel and when transients are performed in the reactor during which the power increases [5]. Thermal expansion of the pellet can then create significant stress in the cladding. The magnitude of loading and the actual condition of cladding material determine whether the loss of integrity of cladding tube might occur. To investigate the phenomenon, we developed a segmented mandrel test [6].

• Burst of cladding can occur during loss of coolant accidents, when pressure of cooling media drops caused by structural failure. The temperature of the dry fuel cladding significantly exceeds the operating temperature [7]. Difference between external and internal pressure, and high temperature cause plastic deformation of the cladding, which can lead to ballooning and burst of cladding tube. Ballooning and burst experiments are performed in high temperature facility such that the internal pressure of the specimens is significantly higher than the external pressure [8].

# II. Objectives

In 2013, I joined to the group of EK Fuel and Reactor Materials Department. Since then, I have participated in several research programs related to the safe operation of the Paks Nuclear Power Plant in the field of nuclear fuel investigation. As experimental and numerical modeling, I had to solve several tasks that were necessary for comprehensive examination of zirconium cladding, which is used in power plants.

In connection with the research presented in the doctoral dissertation, we expressed the following objectives, with my colleagues:

1) A segmented mandrel measuring device had to be designed to study pellet cladding mechanical interaction. Numerical simulation had to be performed to optimize the number and size of the segments. After completing the measurement program, finite element model had to be developed and to be used for detailed evaluation of the measured data on as-received and hydrogenated fuel claddings.

2) In order to measure the high-temperature cracking of the zirconium cladding, an electronic regulator panel had to be designed to perform experiments at different predetermined pressure increment rates. To observe the crack propagation, in detail, it had to be solved to be able to connect optical devices to the furnace in which the ballooning and burst of the fuel elements can be examined.

3) During the ballooning and burst tests, the samples were loaded from inside, in an electric heated tube furnace, at high temperature by high-pressure argon gas. The ballooned samples eventually burst as the pressure increased. Based on the fast-camera measurement data, it was necessary to evaluate the dynamics of the inflation of the cladding tube before the rupture and the geometrical changes that accompany the process.

4) Based on the fast camera measurement data, the characteristic duration of the crack opening had to be determined (time elapsed between the appearance of the crack and the fully opened burst region).

5) Based on visual measurement, hot spot had to be examined by a thermal camera measurement, whether local heating occurs during the crack formation, and if so, with what magnitude.

# III. Investigation methods

### Numerical modeling of mandrel measurement

For finite element modeling, I used MSC Marc, a general-purpose implicit finite element calculation program. Pre- and post-calculations of this were performed with Mentat code. Mentat allows us to build elementary geometric shapes from points, the curves that connect points, and the surfaces bounded by curves. Elemental shapes can be extended into spatial bodies. Bodies can be rotated, shifted, magnified, or combinations of these transformations can be used. With this program, bodies touching each other can be easily and well defined, and the surfaces are separated during the calculation.

In the simulated system, I defined pressing needle, the mandrel segments and the zirconium ring under investigation with a separate unit, with detailed geometric description and a network. During the runs, the mandrels were stretched apart by a pressure pin pressed evenly between them. During the development of the model, I used a homogeneous, isotropic material property distribution. The plasticity calculations were interpreted on the zirconium tube sample only. The effective coefficient of friction was set so that the maximum value of the calculated axial force corresponded to the maximum value of the measured compressive force. Based on fitting of the measured data of the differently hydrogenated samples, I determined a parameter with which the simulation returned the measured parameters by transforming the basic plastic yield curve.

### Optical devices for monitoring cladding

To measure the high-temperature ballooning and burst of the fuel cladding tubes, a special measuring facility had to be built, consisting of a high-temperature tube furnace, an optical system, and a pressure control system. The furnace was a vertically arranged electrical tube furnace, which could provide a uniform and constant heat profile of 300 mm in length for the measurements. The isothermal nature of the furnace is impaired by the less insulated spout, a strong heat flow can start outwards, which distorts the symmetry of the heat profile of the furnace. Therefore, the monitoring of the inflation and rupture of the fuel element was performed using a uniquely designed closed-tube optics.

The change in the diameters of the sample during the ballooning in the furnace was determined by video measurement. For this purpose, I designed an aperture within the furnace insulation, into which an image-extracting optical telescope can be mounted. The double-walled tube allowed the lenses to not move or shatter during cooling after the furnace was turned off during thermal expansion cooling phase. The telescope was able to take a high-quality image of the 6 cm image, which was 50 mm away from it, using a camera. The telescope remained focusable at 1000 ° C. I connected different cameras to the optical system during the measurements.

- Conventional color (DSLR), 4000×4048 (HD) camera capable of 60 fps (frames per second) time resolution.
- A high-speed camera (CMOS) capable of a resolution of up to 100,000 fps, capable of capturing images with a spatial and temporal resolution appropriate to the size of the light output and the observed spatial range (typically 500×200 pix resolution).
- InfraTec Image IR-5300 HP camera with 300mm diameter *f / 3* bright germanium lens and QWIP-type Peltier-cooled InSn 2-5 micron CMOS infrared detector with 350 fps time-lapse and 512×640 pix with spatial resolution.

**Pressure control for cladding rupture measurements**

In most of the experimental programs with Paks fuel claddings, isothermal measurements were performed with linear pressure increment. In order to keep the pressure increase rate constant, I designed a control electric and program panel that regulated the needle valve in the pressure system using a stepper motor, based on the measured pressure data. Opened or closed by a six-pole unipolar stepper motor (Sanyo StepSyn 103-770-4243) attached to the needle valve stem. I used custom-programmed Virtual Instrument (VI) modules, created in the National Instruments LabView® program, to control the output analogue channels of a Measurement Computing UBS-2408 D/A converter. The full-stepping of the stepper motor was determined by the minimum and maximum values of the pressure increment rate, which was given by the user, in relation to the measured pressure difference quotient. Opening and closing took place five times per second, and pressure surges and oscillations in the buffer tank were equalized, so that adequate accuracy in the pressure increment rate could be achieved. Any pressure increment rate between 0.02 bar / s and 6 bar / s could be set, and that rates the controller could maintain.

# IV. New sientific results

1. I have developed a finite element model of the mandrel device, which contains mesh and relationships describing the plastic deformation. Based on the analyzes, I proposed the number of segments of the shear-steel mandrels and their size, to be able to withstand the loads occurring, without deformation and failure, during the mandrel measurement. I found that by increasing the number of mandrel tools, the load on the inner surface of the sample is more “even”. Using the finite element model of the mandrel equipment, I successfully reproduced the “needle displacement versus force” curves, which was obtained during the measurement of as-received and hydrogen charged samples with different hydrogen content. Measured and calculated curves fit appropriately [T1, T2, T3].
2. For ballooning and burst measurements of the cladding, I designed control and data acquisition devices, that made it possible to follow the assumed damage of the nuclear power plant fuel elements during a loss of cooland accident. I designed and fabricated a stepper motor control that fits into a computer virtual instrument and is able to move a needle valve dispensing high-pressure argon gas so that the pressure in the sample increases linearly, in a range of 0.02 bar/s up to 6 bar/s, with a relative accuracy of 0.998. I have successfully designed and constructed an optical device with an image that is distortion-free up to 75% of the full field of view and that does not break up at 1000 ° C due to thermal expansion and a large ambient temperature gradient. The tube of the telescope can be fitted to the retort of the furnace, and the telescope can easily be focused at operating temperature and any optical instrument or camera can be fitted to the exit pupil of this telescope [T4]. Thus, in the course of this work, I designed, built, and tested the measurement data acquisition, pressure regulator, and optical components of an entirely new, complex measuring device that ultimately provided the opportunity to measure ballooning and burst and its optical observation.
3. Based on the video measurement data of ballooning and burst performed by the experimental facility presented in Thesis 2, I established that the ballooning consists of two, well-separable stages. The diameters of 10 optically observed samples of alloys E110 and E110G, which inflated at about 800 ° C, within the α-β phase transition range, and a rate of pressure increment of about 0.5 bar/s: firstly a diameter grown slowly along the entire length of the sample, up to about 60-85 % of burst pressure. At 96-99% of the burst pressure, a local ballooning occurred, during which the largest diameters of the sample increased

abruptly with similar kinetics, prior to burst. Simultaneously, with local ballooning, the axes of the samples in the locally inflated region were bent [T5, T6].

4. Using a conventional camera, I observed that a hot spot appeared in the “inner half” of the curvature of the curved-axis sample, in each case recorded with a camera, and the crack opening of the sample occurred at location of the hot spot. Three burst have seen by the high-speed camera, which confirms that. Based on the data from the high-speed camera image series, I pointed out that the crack formation on the crack opening at a pressure increment at around 800 ° C, with a 0.5 bar/s pressure increment rate, lasted 0.1-0.12 milliseconds. Crack propagation for one sample was recorded by high-speed camera [T5, T6, T7].
5. Based on the data of thermal imaging measurements, I proved that the hot spot appearing on the convex side of the inflated, bent sample is not only an optical phenomenon, but appears during the instability of the plastic deformation, and shows a real local heat-up related to the high-speed deformation of the metal. I measured the temperature of that hot spot. It have also shown that the hot spot appears on the propagating tips of the crack. The tube sample with low heat capacity remains at a constant temperature in the furnace with a very high thermal inertia, except at the point where the sample opens up [T8].

## V. Possible use of results

The created finite element numerical method can be applied for the simulation of other materials. It could be used for the simulation of oxidized Zr rings with several radial layers. Other geometry (e.g. thin wall cladding) cases could be also analysed.

The ballooning and burst measurement facility is appropriate and will be used for testing of new thin wall E110G cladding and other accident tolerant fuel design claddings, which are under development in foreign laboratories.

The optical system developed for the ballooning tests could be used for the observation of breakaway oxidation phenomena in high temperature steam atmosphere.

Both the numerical and experimental information can be used for the development of FRAPTRAN 2.0 transient fuel behaviour code.

# VI. Scientific publications related to theses


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[T8] **R. Nagy**, M. Király, P. Petrik, Z. Hózer: Infrared Observation of Ballooning and Burst of Nuclear Fuel Cladding Tubes, **Nuclear Engineering and Design** IF(2022): 1,869, 371 Paper: 110942, pages 9, (2020)

## VII. Further sientific publications

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[T11] G. Mayer, **R. Nagy**, I. Nagy, An e*xperimental Study on Critical Heat Flux in Vertical Annulus Under Low Flow and Low Pressure Conditions*, **Nuclear Engineering and Design** IF(2022): 1,869, 310 pp 461-469 (2016)

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