Examination of an Irradiated Fuel Pin Segment by Laser Scanning Profilometry, Gamma Spectrometry and Neutron Radiography

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Abstract. Paul Scherrer Institute (PSI) conducts post irradiation examinations (PIE) on fuel pins irradiated in nuclear power plants. During pool-side inspections of the nuclear fuel at one of these plants, an intact fuel pin showed a small deviation in diameter along several mm of the axial elevation. The pin was added to the fuel delivery transport to PSI in the frame of a surveillance program. To detect the exact dimensions of the pin section, a laser scanning profilometer was adapted for hot cell use by mirroring the laser beam. The examined length of the found clad necking matched the nominal length of one fuel pellet, indicating a missing or diameter reduced pellet. Axial gamma spectrometry confirmed the match of the neckings's length with the pellet gaps indicated by higher cesium count rates. The azimuthal variation in cladding diameter was confirmed by gamma spectrometry angle-dependent mappings. To investigate the pellet integrity without destructive methods, a neutron radiography was decided for. After cutting a segment of the pin, the radiography at the PSI neutron irradiation facility SINQ revealed one pellet with variations in diameter, but without abnormal structural defects. This paper outlines the combination of the three non-destructive methods as well as technical descriptions of the methods and some results of the examinations.

1. MOTIVATION

To improve the economy of nuclear fuel assemblies, further development of cladding alloys and assembly designs is aimed for by utilities, suppliers and vendors. To confirm the effectivity of the developments as well as the compliance with safety margins, Paul Scherrer Institut (PSI) Hotlab conducts a post irradiation examination (PIE) program, where fuel pins irradiated at swiss commercial plants are characterized on a regular basis since 25 years. The fuel pin positions are chosen based on fuel assembly design changes and heat generation or burn-up criteria and PSI offers the complete range of non-destructive and destructive analyses. During pool-side inspections of the nuclear fuel at one of these plants, an intact fuel pin showed a small deviation in diameter along several mm of the axial elevation. This paper describes a set of three non-destructive tests delivering the basic information to choose the position for destructive analyzing in case of this fuel imperfection.

2. CONDITIONS

The non-destructive testing is performed in the 1st cell of a hot cell chain built in the beginning of the 1960‘s and refurbished 1985–87 to conduct PIE of fuel pins irradiated in commercial power plants.

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Equipped with 90 cm of steel-encased concrete shielding and remote handlers „Wälischmiller A100“, the gamma dose rate at the different measurement systems can reach up to several $kGy \cdot h^{-1}$. As the dose rate and accumulated dose in the cell is steadily increasing due to higher burn-up and earlier delivery of pins after their end of life, modern measurement systems with integrated electronics installed inside the cell required additional shielding. They replace the older systems based on mechanical principles or more robust, conventional electronics. Regarding the limitations of criticality and geometry for Hotcell 1, 37 UO_2 or 23 MOX fuel rods with a maximum enrichment of 5% and 7%, respectively and a rod length up to 4300 mm can be handled. The fuel pin movement is automated and programmable, allowing smallest stepwidths of 0.1 mm in axial and 1° in azimuthal direction.

3. EXAMINATION

An intact rod, examined in the frame of the regular PIE program 2010 showed a very small azimuthal necking in diameter, hardly to be detected by visual inspection. The fuel manufacturer and the plant operator decided to investigate the cause. A non-destructive examination was chosen to avoid any impact to the material and to define the axial level of metallo-ceramography.

3.1 Profilometry

The exact dimensions of the necking were determined by laser scanning profilometry. The method detects the amount of light received from an oscillating laser beam after shadowed by the measured sample.

Properties and abilities of the method:

- Deviation from the calibrated diameter with accuracy and reproducability of 0.3 μm.
- Minimum axial step width of 0.3 mm.
- Measuring time for an axial rod profile of about 4 m length in approximately two hours.
- Rotational profiles , indicating the surface contour of the cladding.

This unique adaptation of an industrial system (Mitutoyo LSM) to highly radioactive ambience was achieved by mirroring of the laser beam. Therefore, shielding of emitter and receiver by ~10 half-value layers of lead was possible. The laser beam is distracted by a rotating polygonal mirror, thus oscillating along the position of the moving fuel pin. By exactly positioning of the additional mirrors, the accuracy of the encapsuled system was kept in the same order. Roughness and cleanliness of the mirrors are checked by the oscilloscope signal.

The system can be removed from the outer shielding for repairs or cleaning. Maintenance is negligible compared to the earlier used system with LVDTs as there is no mechanical wear.

The axial and azimuthal scanning of the fuel rod confirmed that the axial length of the necking matches the height of a single fuel pellet while the diameter was varying in circumferential direction with a pronounced minimum at one side of the rod (Fig. 3.1).

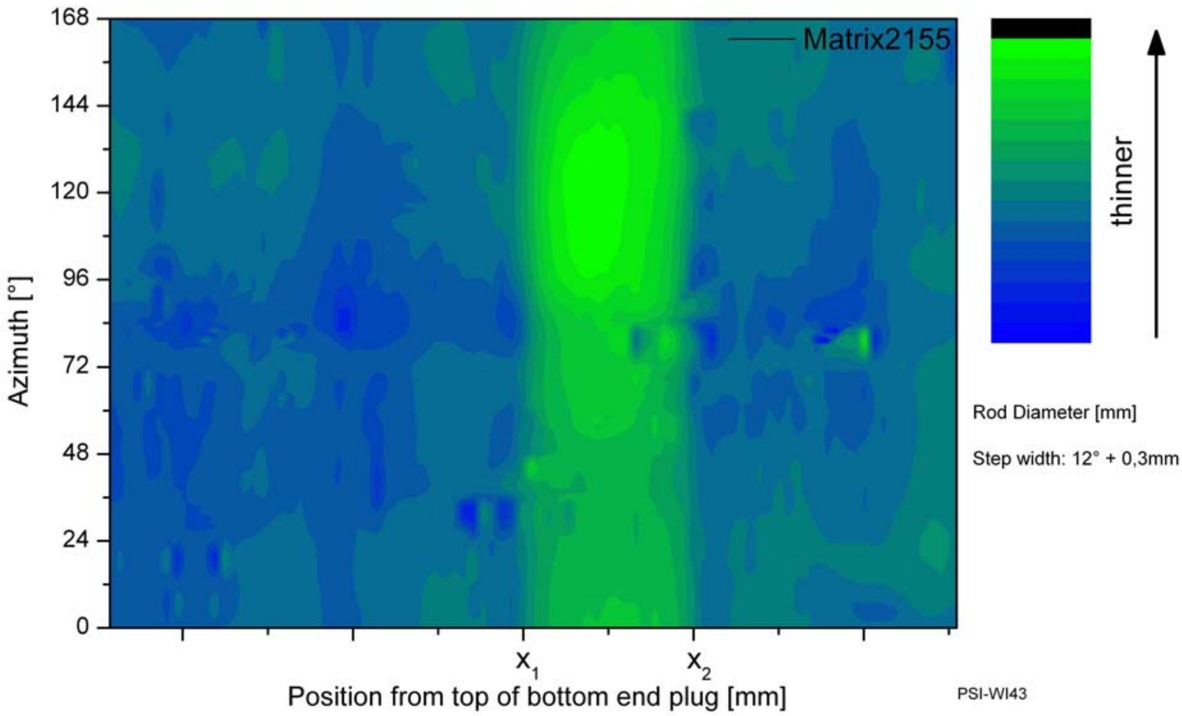

FIG. 3.1. Azimuthal diameter plot of the fuel rod necking; axial length determined to one pellet [x_1;x_2] and pronounced on one side of the rod.

3.2 Gamma spectrometry

Knowing the length of the clad necking matches one pellet, gamma spectrometry was applied to confirm the positions and conditions of the fuel pellets. The method is an energy dispersive measurement of fission and activation products with positioning of the fuel pin equal to profilometry. Volatile and fixed species detected allow for conclusions regarding temperature and fission rate gradients in the fuel column, i.e. positions of the pellet gaps and possible fuel inhomogenities. The gamma beam is collimated with a slit width of 0.3 mm, the collimator itself is integrated within the hotcell shielding wall. The nitrogen cooled HPGe-Detector delivers a spectrum of 4096 energy channels, which correlates to a resolution of about 0.5 keV if used over the full energy range. Very high count rates up to 4E5 cps are accepted by the hardware due to digital amplification and loss free impulse counting; the spectrum analysis software (Canberra Genie 2K) is remote controlled by a LabView based two-axis drive system moving the fuel pin.

As the volatile cesium accumulates at positions of lower temperature, pellet gaps and areas of better thermal conductivity or lower heat generation are indicated by higher count rates. As ruthenium is kept fixed in the fuel matrix, inhomogenities in the fuel are detected. The plots of count rate against fuel rod elevation of these nuclides are compared in Fig. 3.2. The observed pellet gaps matched perfectly with the area of reduced diameter of the necking, and the higher count rates of ^{134}Cs and ^{137}Cs observed at mid pellet height can be attributed to positions of closer contact of pellet and cladding. On the other hand, the quite stable count rate of ^{106}Ru indicates no hint for fuel imperfection.

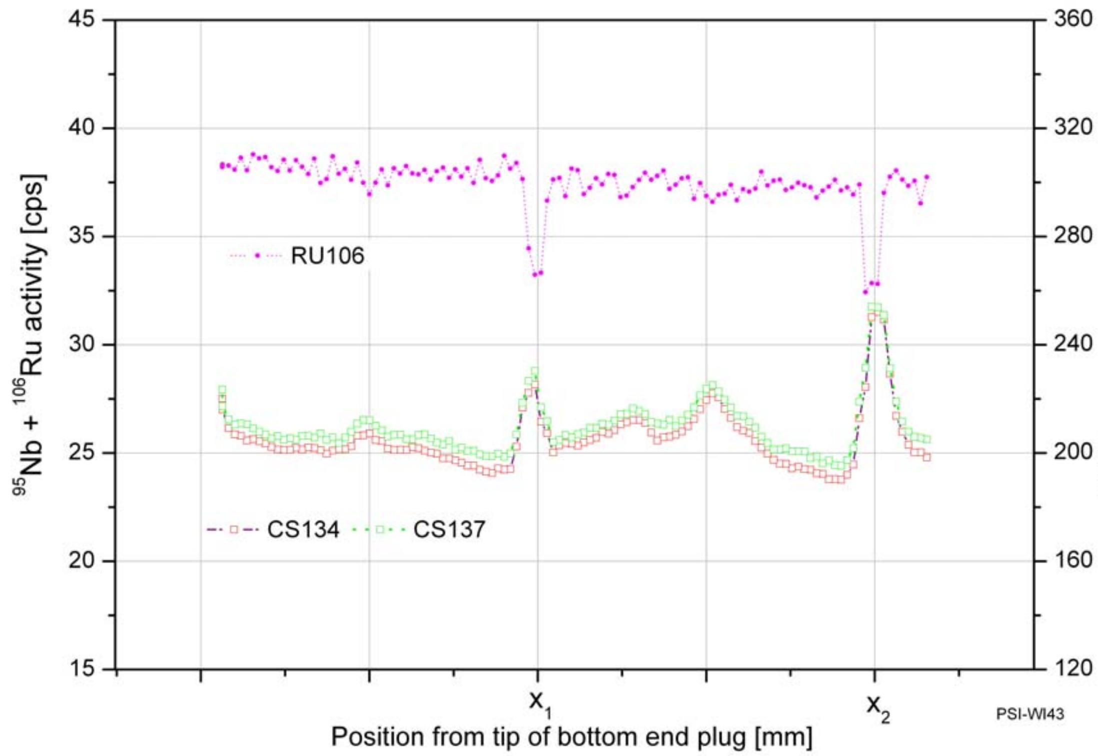

FIG. 3.2. Plot of axial count rate of cesium and ruthenium, indicating the gaps between the pellet matching the necking position.

3.3 Neutron radiography

Now that the cause for the necking was identified in one certain fuel pellet, the obvious next step was ceramographic examination. But, proceeding directly with metallo-ceramography would imply a lot of grinding levels and possible influence of sample preparation on the defect. Decision was taken to "have a look first" by neutron radiography despite the effort and cost. The PSI Spallation Neutron Source is equipped with the station NEURAP, which allows non-destructive imaging of radioactive samples by 25 meV thermal neutrons at a flux of 1×10^{14} cm^{-2}.

After cutting the fuel pin, the 200 mm long segment to be examined was encased in an aluminum tube, referencing the azimuthal orientation by polyethylene markers. Said tube can be drawn into a shielded manipulation and transport cask which is connectable to both the cell at the hot laboratory and the beamline shielding at NEURAP. The relative attenuation of neutrons by the relevant materials zirconium, aluminum and polyethylene is given with ~0.01; ~0.1 and ~3.5, respectively. Thus, the neutron beam crossing the fuel segment is hardly hindered by the Zr and Al in contrast to the azimuthal mark made of PE. After passing the sample, the beam enters the detector slot, there exposing an imaging plate. The imaging plates contain a photoluminescent compound and a neutron absorber. While the plate is excitated during exposure by gamma rays from the fuel, the absorber is activated by the attenuated neutron beam. After exposure, the plate is erased by light, followed by self-exposure through the activated absorber. Final readout is done by a laser scanner with 50 µm squared raster. This procedure was repeated 12 times, each time turning the fuel segment by 15°. Fig. 3.3 shows as an example one aspect irradiated at 0–180°.

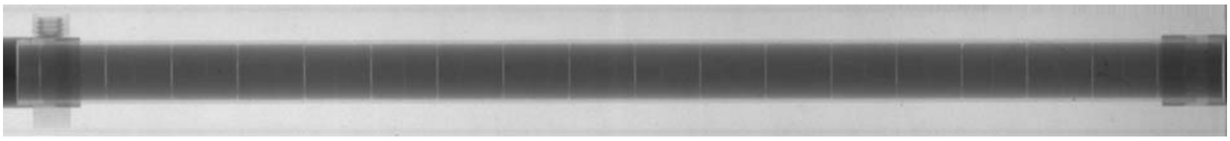

FIG. 3.3. Aspect of neutron radiography, total length of examinated segment.

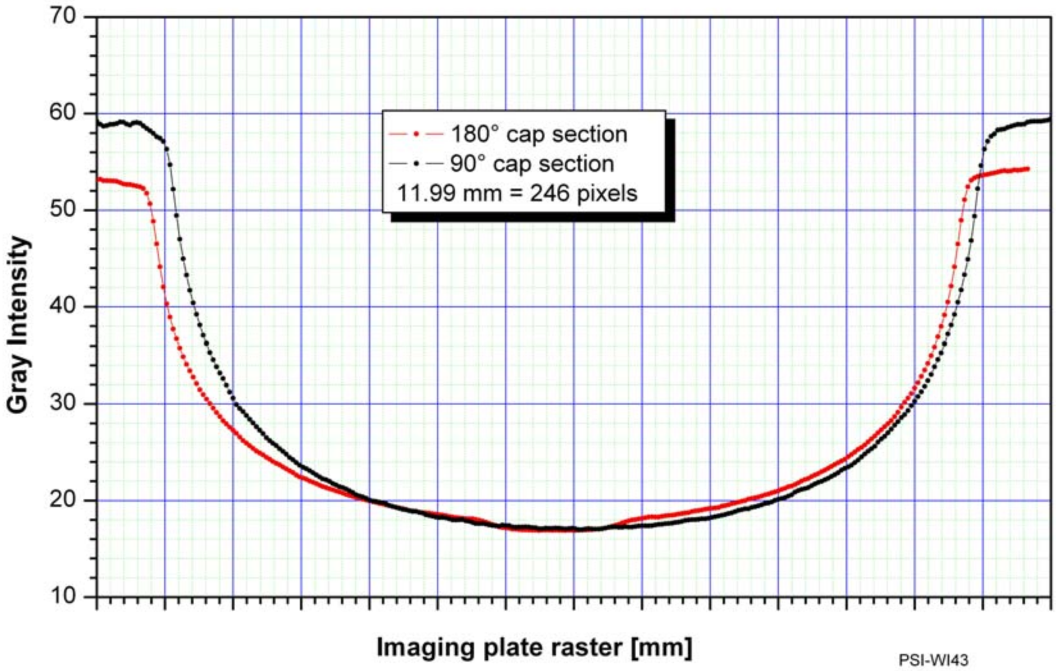

FIG. 3.4. Diametral grayscale intensity of segment end cap, used for scaling the neutron image.

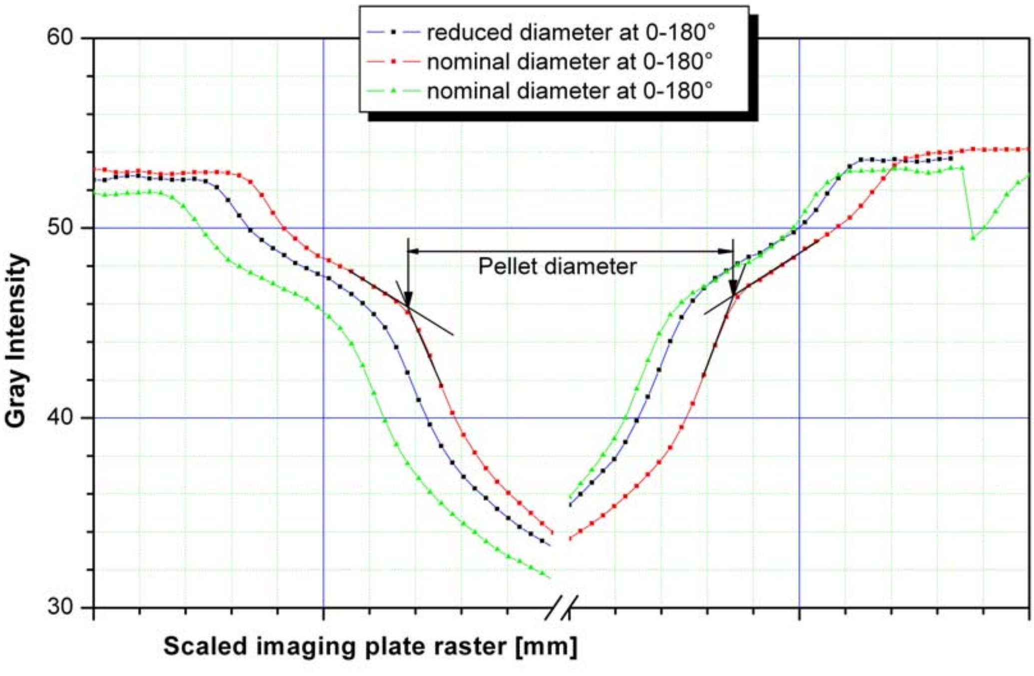

FIG. 3.5. Fuel pellet diameter determination by neutron radiography. Gray intensity levels of imaging plates exposed by the attenuated neutron beam allow the distinction between fuel and cladding.

Different image manipulation techniques like conversion to black/white and shifting the respective threshold values or enhancing the contrast and shifting the histogram values, showed no major defects inside the pellet. Consequently, the examination focused on the diameter of the pellet. The slight magnification of the images due to the collimation ratio of the neutron beam was accounted for by scaling against the known diameter of the segment end caps. Scaling was possible by counting the number of pixels of the diametral grayscale value, where the neutron beam was attenuated by solid material (Fig. 3.4). Regarding the examined pellet, the gray intensity of diametral lines was measured at different segment elevations comprising the neighbouring pellets (Fig. 3.5). Clear distinction was possible between cladding and fuel, allowing the determination of the pellet diameters. Although the resolution was restricted to 50 µm by the readout raster, a reduction of diameter at the considered pellet was confirmed. Through analyzing the radiographs at different beam angles, a picture of the pellets outer shape and its position in the cladding was derived.

4. RESULT AND CONCLUSIONS

The necking of diameter found at one elevation of an intact LWR fuel pin irradiated in a commercial power plant was explained by combination of three non-destructive methods:

- Laser profilometry and gamma spectrometry showed compliance of the position and length of the cladding constriction and one certain pellet.
- Neutron radiography imaging revealed no major flaw in the fuel but a slightly smaller and irregular diameter of the pellet.
- The combination of the three methods allowed the choice of a specific ceramography level followed by cutting of the segment without the possible influence on the cause of the defect.

Comparison of the results of the three non-destructive methods reveals a minimum diameter of the pellet at a certain rod elevation. The cladding tube has creeped down to the fuel surface with closest contact at positions of higher cesium count rates (Fig. 4.1). Neighbouring areas of the imperfect pellet are confirmed to be in a state as expected regarding the rod's burn-up. The elevation of highest deviation in diameter was chosen as level for ceramography, and the ongoing investigations indicate an irregularity of the manufacturing process.

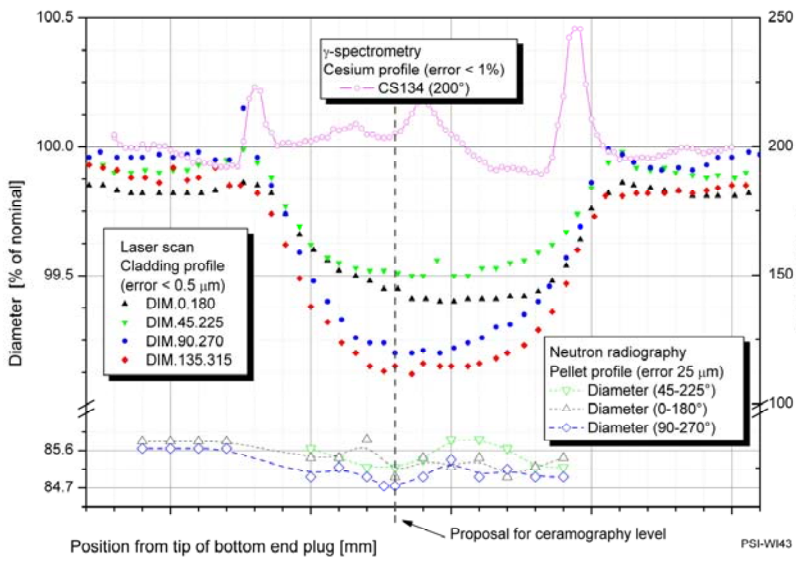

FIG. 4.1. Combined laser profilometry, gamma spectrometry and neutron radiography measurements.