

## Post Irradiation Examination Techniques for Fuel Performance Evaluation

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### Abstract

Various techniques can be used for characterizing fuel behaviour after irradiation in power plants. For example the pellet volume swelling is determined by combination of gamma scanning, profilometry and EC oxide thickness measurement. The results show that the pellet swelling follows the well established relation of 0.7% / 10MWd/kgU up to a burnup of around 70 MWd/kgU. At higher burnup the swelling is stronger. The results are supported by optical microscopy.

Axial gamma scanning of fuel rods indicates different features of the reactor core i.e. irregularities in the assembly distances.

**Keywords:** *gamma scanning, profilometry, pellet swelling, reactor core geometry*

### Introduction

A number of LWR fuel rods have been examined after irradiation to about 70 MWd/kgU. The purpose was to evaluate the fuel performance up to this relatively high burnup. The fuel type was the same for all rods and they were irradiated in one assembly for three cycles and in another assembly for the last cycle. The only difference between the rods was their locations in the assemblies.

The pellet volume matrix swelling is normally regarded as linear versus the burnup after the initial densification period. The relation is 0.6-0.8% / 10 MWd/kgU.

### Experimental evaluation techniques

The pellet volume swelling evaluation requires knowledge of the dimension changes in the radial and in the axial direction. The swelling can be determined as:

Swelling =  $\Delta V/V_b = (L_a/L_b) * (D_a/D_b)^2 - 1$ , where

$\Delta V$  = Volume change [mm<sup>3</sup>]

$V_b$  = Volume before irradiation [mm<sup>3</sup>]

$L_b, L_a$  = Length before, after irradiation [mm]

$D_b, D_a$  = Diameter before, after irradiation [mm]

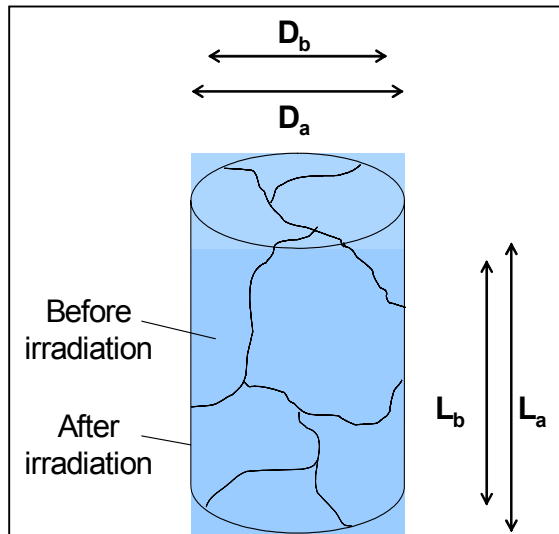
This includes the effect of pellet relocation, where thin cracks within the fragmented pellets slightly increase the total volume.

Assuming that the swelling is isotropic it can be determined as:

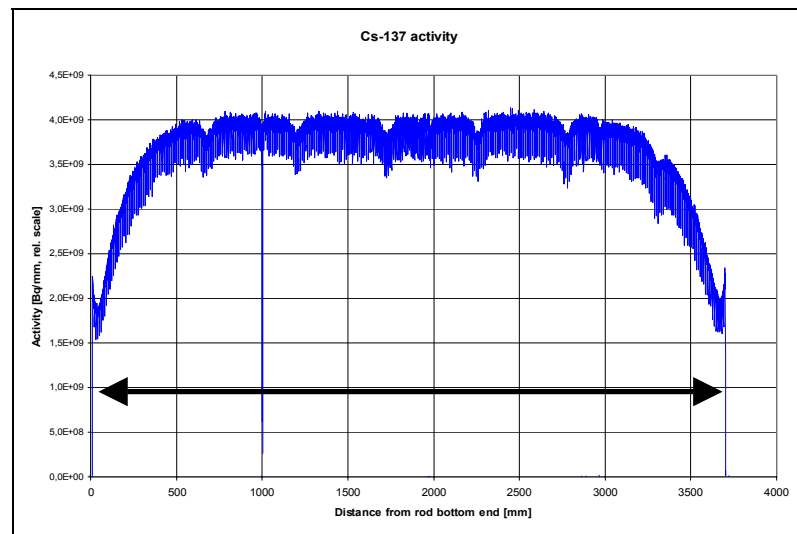
Swelling =  $(D_a/D_b)^3$  or  $(L_a/L_b)^3$

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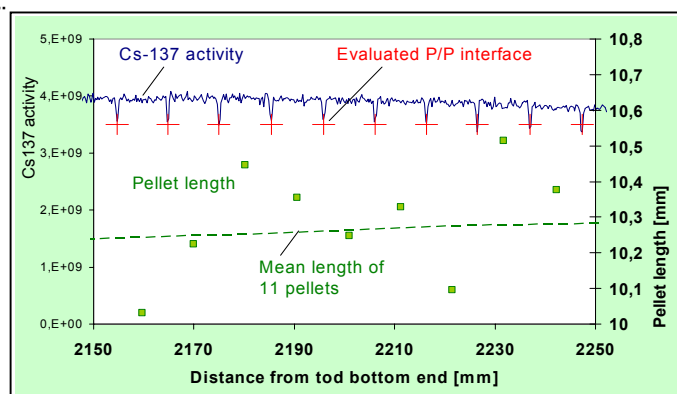
**Fig. 1** Dimensional pellet change during irradiation



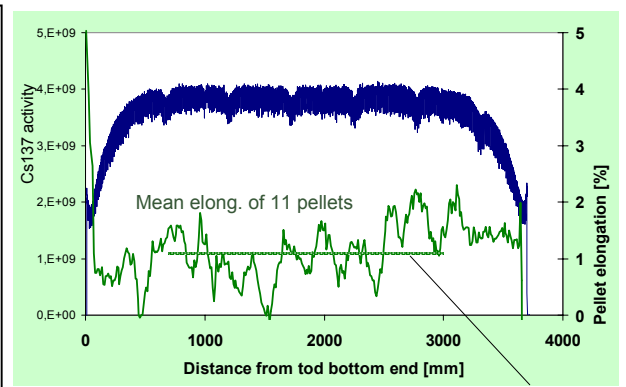
**Fig. 2** Pellet stack length after irradiation

The lengths and diameters before and after the irradiation can be measured in different ways:

The pellet elongation can be approximately evaluated from the pellet stack length after irradiation according to the gamma scanning curve (see Fig. 2) in combination with the as-manufactured pellet stack length. The length of each pellet can also be evaluated from the characteristic pellet/pellet dips in the gamma scanning curve, and comparison with the manufactured pellet length gives the individual pellet elongation. Fig. 3 shows the results from the central part of a rod and Fig. 4 shows the pellet elongation along a whole rod.



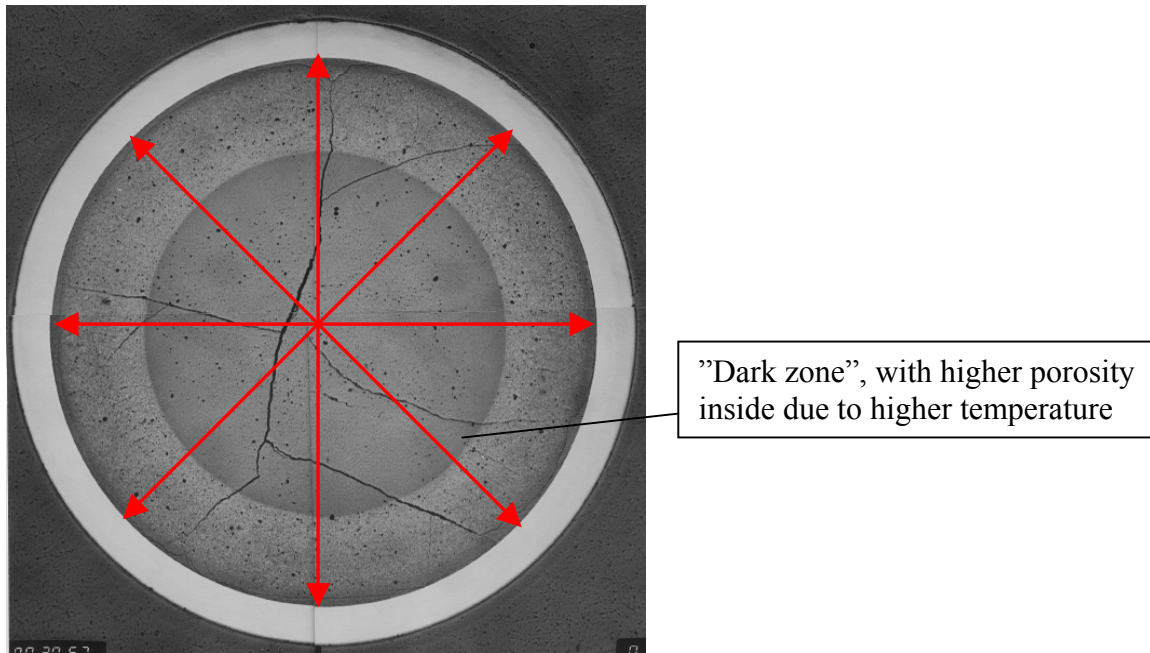
**Fig. 3** Pellet / pellet interfaces and pellet lengths



**Fig. 4** Pellet elongation along the rod

Mean elong., central part = 1.10%

The pellet diameter can be determined on separate microscopy samples, by measurement in the microscope. The diameter is given by the average of four measurements, 45° in between each (see Fig. 5). The local elongation can be assumed as similar to the diameter change.



**Fig. 5** Pellet diameter measurement on a ceramography sample

The diameter of the pellets can also be determined from the profilometry and oxide thickness measurements. At burnup around 70 MWd/kgU there is total pellet / cladding contact and the pellet diameter can be evaluated according to:

$$D_p = D_c - 2 * Ox_o * (1-1/PB) - 2 * t_c - 2 * Ox_i * (1-1/PB)), \text{ where}$$

$D_p$  = Pellet diameter

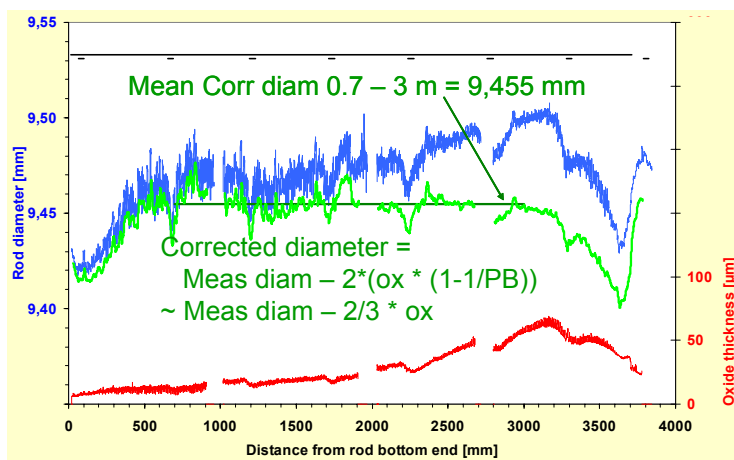
$D_c$  = Measured cladding outer diameter incl the oxide

$t_c$  = Cladding thickness

$Ox_o, Ox_i$  = Outer and inner oxide thickness

PB = Pilling-Bedworth ratio describing the density and volume difference between metal and oxide. At an oxide porosity of 10% PB = 1.68

Fig. 6 shows the results of profilometry and oxide thickness measurement of the same rod as in Fig. 2.



**Fig. 6** Profilometry and oxide thickness results

The corrected diameter, which shows a “hypothetical” cladding outer diameter if no oxidation had occurred, has a quite even level along the central part of the rod. The mean value of this is 9.455 mm, corresponding to a pellet diameter of 8.30 mm. The pellet diameter change is thus 8.30/8.16%=1,7%. The values of the axial elongation and the diametral change give the total pellet volume increase.

Gamma scanning of fuel rods gives a good overview of the rod shows any pellet / pellet gaps, shows the burnup profile of the pellet stack, etcetera. A qualitative view of the burnup profile is given by the activity of Cs-137 that has a long half-life of 30 years. By selecting isotopes with shorter half-life periods at the end of irradiation can be studied. If the Cs-137 activity of the rod is compared with the Cs-activity and of a reference rod with known burnup are compared, the absolute burnup can be determined.

## Results

The pellet diameter was measured on 12 ceramography samples, which were cut out from three of the rods. The sample positions were selected both from the central parts and from the upper and lower ends to cover ranges in LHR, burnup, and oxide thickness. The result is given in Fig. 7, which shows the pellet total swelling as a function of the local burnup for the samples.

The figure shows that the volume change follows the matrix swelling relation of 0.7 %/10 MWd/kgU up to a burnup of 70-75 MWd/kgU. Above that the volume change has a stronger dependence on the burnup.

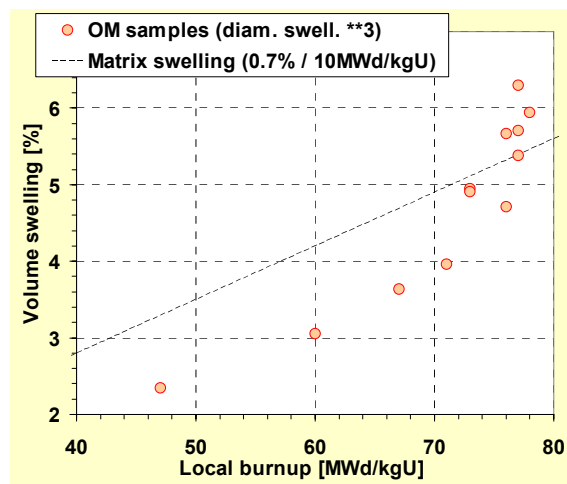


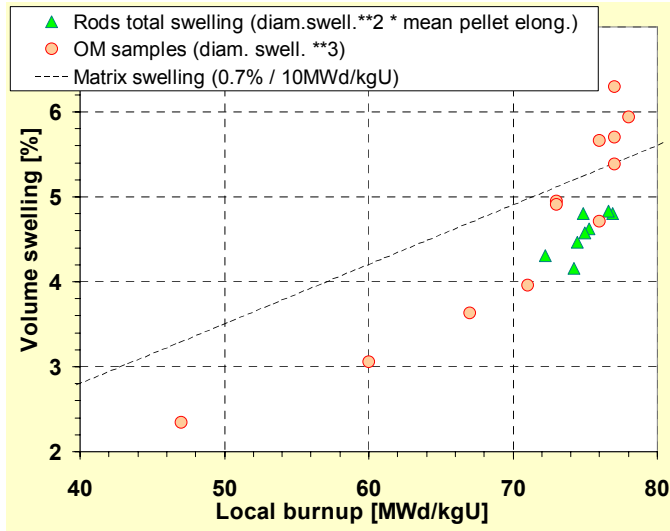
Fig. 7 Pellet volume swelling vs local burnup of the ceramography samples

The gamma scanning, the profilometry and the oxide thickness measurement of the rods gave elongation, diameter change and volume change according to table 1.

Table 1 Rod elongation, diameter change and volume change

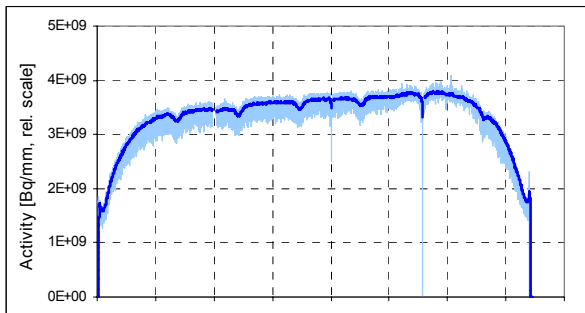
	1	2	3	4	5	6	7	8
Elongation [%]	0,93	1,07	0,94	1,31	1,10	1,14	1,08	1,22
Diameter change [%]	1,6	1,6	1,9	1,7	1,8	1,7		1,59
Volume change [%]	4,2	4,3	4,8	4,8	4,8	4,6		4,5
Local burnup [MWd/kgU]	74,3	72,3	76,9	74,9	76,6	75,3	75,0	74,5

These volume change values are compared with the ceramography values in Fig. 8. They seem to have the same relation to the burnup. The slightly higher ceramography values might be due to the assumption that the swelling in the axial direction is similar as in the diametral.

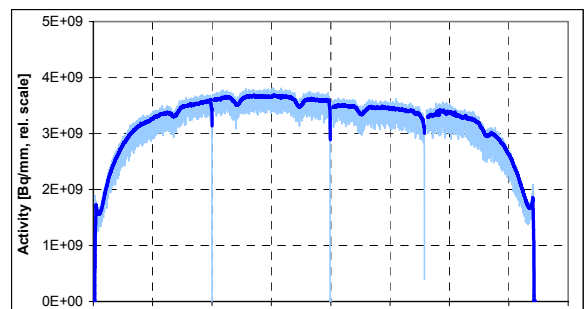


**Fig. 8** Pellet volume change as a function of local burnup

Among the rods examined in this study there are two rods, which were peripheral during the last cycle and located on opposite faces of the assembly. While the other rods had quite flat Cs-137 activity profiles along the central part of the rod (1-3 m), these two were top peaked and bottom peaked respectively, see Figs. 9 and 10.

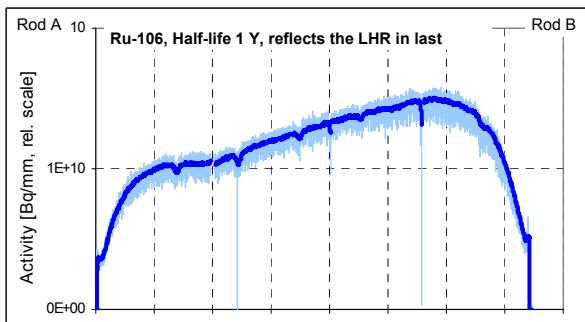


**Fig. 9** Cs-137 activity profile reflecting the top peaked burnup profile of the peripheral rod A

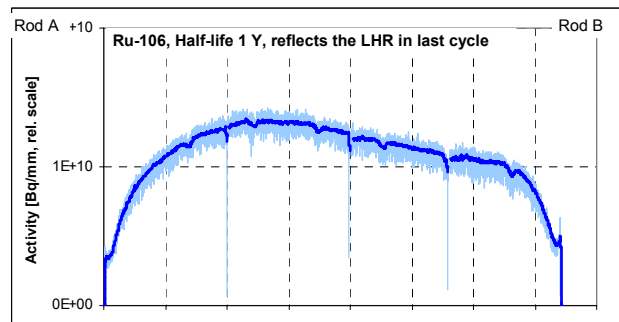


**Fig. 10** Cs-137 activity profile reflecting the bottom peaked burnup profile of the peripheral rod B

The activity curves of the Ru-106 with half-life of 90 days reflect the fissions during the last 6-12 months, as the Ru-106 formed earlier has already decayed. It is clear that the LHR profile was top peaked for rod A and bottom peaked for rod B.



**Fig. 11** Ru-106 activity profile reflecting the top peaked last cycle LHR profile of the peripheral rod



**Fig. 12** Ru-106 activity profile reflecting the bottom peaked last cycle LHR profile of the peripheral rod

## **Discussion**

The change of pellet swelling behaviour at 70-75 MWd/kgU is probably related to increasing porosity all over the sample. At lower burnup high porosity is mainly found in the rim zone at the pellet periphery. At higher burnup also the inner part of the pellet has higher porosity, for example inside the "dark zone" where the porosity is higher due to higher temperature.

The profiles with opposite LHR peaking from the opposite faces of the assembly might be related to some type of unevenness in the assembly geometry.