IN-REACTOR CREEP BEHAVIOR OF ZIRLO® AND OPTIMIZED ZIRLO™ CLADDING

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ABSTRACT

The in-reactor creep properties of ZIRLO® and Optimized ZIRLO™ [1] alloys were extensively analysed in the Vogtle Program by measuring the diameter change from multi-cycle irradiation of pressurized tube samples, located inside the fuel assembly thimble tubes. The Vogtle program included test material with different fabrication parameters (tin content and microstructure) and different inner pressure (hoop stress).

Since Vogtle samples are non-fuelled tubes, their irradiation condition might be different from the fuel cladding, especially the temperature. Therefore, a devoted Post-Irradiation-Examination (PIE) Program on actual fuel rods with ZIRLO and Optimized ZIRLO cladding was performed to study the in-reactor creep of both alloys.

Three fuel rods with very high backfill pressure were irradiated in the Spanish Almaraz Nuclear Power Plant (NPP) for only one cycle so that the combination of high backpressure and short irradiation would allow the pellet-clad gap to remain open during their operation. Thus, the cladding creep down of both alloys can be assessed from the outer diameter change values measured on the rods without the effect of the pellet-cladding interaction.

A complete set of manufacturing characterization, irradiation follow-up and hot-cell examination was performed on the fuel rods. Afterward, the rods were modelled by fuel rod thermomechanical code PAD4 comparing code predictions with measurements for the rod internal pressure, void volume and outer diameter, showing very good agreement for the three rods independent of the alloy and backfill pressure. The pellet-clad gap status is determined by the thermomechanical code along each rod length in combination with a relocation model. As a result, the ZIRLO and Optimized ZIRLO rods with higher pressure keep the gap open. Therefore, the hot-cell profilometry measurements of these rods are utilized to derivate the creep value for both cladding alloys.

As a conclusion, Almaraz and Vogtle data together build a full picture of in-reactor creep behaviour of ZIRLO and Optimized ZIRLO rods demonstrating that both alloys show the same in-reactor creep behaviour.

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1. Introduction and Background

The creep phenomenon is a time-dependent deformation under a certain applied load. It is usually affected by the changing condition in loading and temperature, especially at high temperature – the thermal creep. But creep deformation may be produced in other conditions for certain materials. In the case of the zirconium alloys used as PWR nuclear fuel clad, the creep produced during irradiation is a combination of the conventional thermal creep with the irradiation creep - the deformation to account for the fast neutrons impact on the zirconium lattice. As a result, the rod diameter changes throughout the irradiation period due to the cladding material creep.

The deformation due to the thermal creep component shows a marked dependence on the cladding temperature and stress, which is induced by the difference between internal rod pressure, contact pressure due to pellet cladding mechanical interaction and the system pressure. On the other hand, the deformation as a result of the irradiation creep is less sensitive to these parameters but it largely depends on the neutron flux and the deformation mechanics created in the zirconium lattice, clearly specific to the clad material chemical composition and microstructure.

The determination of the proper dependence of so many different factors in the creep model for a specific fuel rod cladding requires extensive measurements of diametral deformation for irradiated fuel under very controlled conditions. The in-reactor creep properties of ZIRLO and Optimized ZIRLO alloys were extensively analysed in the Vogtle Program by measuring the diameter change from multi-cycle irradiation of pressurized ZIRLO and Optimized ZIRLO tube samples, located inside the fuel assembly thimble tubes. The Vogtle program included test material with different fabrication parameters (tin content and microstructure) and different inner pressure (hoop stress), as discussed in Reference [1].

However, Vogtle samples are non-fuelled tubes so that the irradiation condition experienced by Vogtle samples might be different from the fuel cladding, especially the temperature. Therefore, a Post-Irradiation-Examination (PIE) Program on actual fuel rods with ZIRLO and Optimized ZIRLO cladding is needed to study the in-reactor creep of both alloys as fuel rod cladding.

The Almaraz Program with creep measurement on fuelled rods is presented in this paper along with Vogtle program to build the whole picture of the in-reactor creep behaviour of ZIRLO and Optimized ZIRLO rods.

2. Materials and Tests performed in the Almaraz Post-Irradiation Program

Three fuel rods with ZIRLO and Optimized ZIRLO cladding were fabricated with a high backfill pressure, one rod with ZIRLO clad and 450 psia of backfill pressure and the other two rods with Optimized ZIRLO clad and pressures of 450 and 365 psia. They were irradiated for only one cycle in Nuclear Power Plant (NPP) Almaraz Unit 2.

The purpose of the specific high backfill pressure, higher than in the standard fuel rod, and irradiation was to make sure the pellet to clad gap along the most part of the fuel rod length remain open during operation. Thus the deformation measurements correspond only to the metallic clad without the contribution of the pellet expansion and therefore the in-reactor creep behaviour of ZIRLO and Optimized ZIRLO clad can be measured. Tables 1 and 2 collect respectively the main manufacturing characteristics (including tin content and microstructure of the clad) and the operational conditions.

Rod	Clad Material	Back. Press (psia)-(MPa)	Enrich . (w/o)	Active length (mm)	Plenum length (mm)	Cladding OD/ID (mm)	Tin (%) / Microstructure*
O16	ZIRLO	450 - 3,1	4,69	3663,4	188,9	9,49/8,36	0,95 / SRA
C16	Optimized ZIRLO	450 - 3,1	4,69	3619,0	218,6	9,50/8,35	0,67 / PRXA
P16	Optimized ZIRLO	365 - 2,5	4,69	3621,5	216,1	9,50/8,35	0,67 / PRXA

* SRA (stress-relief annealed), PRXA (partial recrystallization annealed)

Table 1: Main manufacturing characteristics

Parameter	Value		
Reactor Thermal Power (MWt)	2947		
Average Linear Heat rate (kW/m)	18,93		
System Pressure (psia)-(MPa)	2250 - 15,51		
Average temperature (ºC)	306,9		
Cycle length (Effective Full Power Hours EFPH)	10765,2		
Avg. Burnup (MWd/kgU)	**O16**	**C16**	**P16**
	22,73	22,71	22,47

Table 2: Operation conditions

In addition to the characterization during manufacturing and the irradiation follow-up, the three rods were inspected at site after irradiation (visual, corrosion and axial growth), showing a good oxide condition. Oxide thickness and axial growth values were meeting performance expectations.

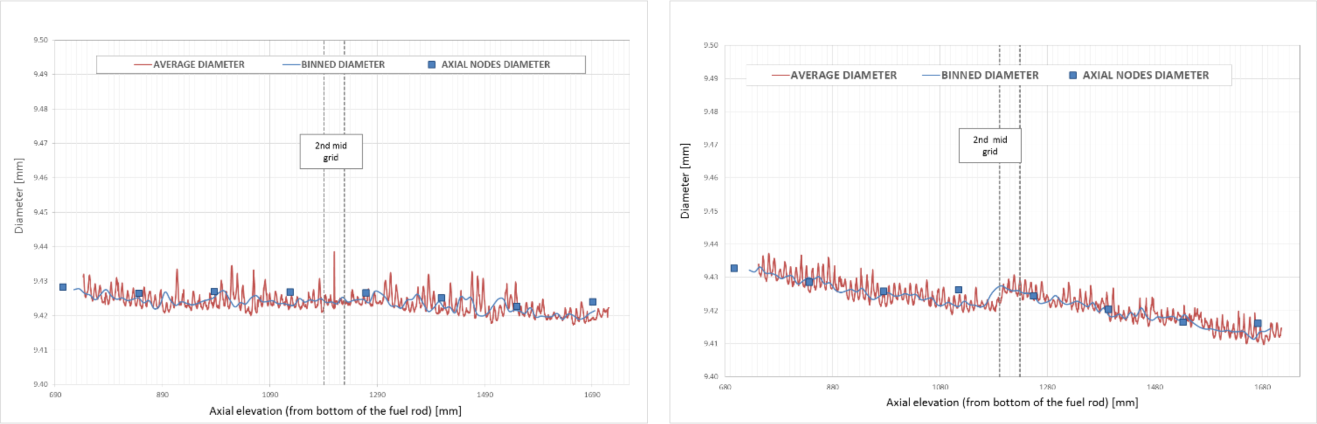
Finally, the fuel rods were sent to Studsvik for hot-cell PIE program. Table 3 summarizes the tests performed in the Almaraz program from which the results have been considered in the analysis presented in the following sections.

	Test	Material
Manufacturing	Dimensional characterization	Pellet, Clad and Fuel rods O16, C16, P16
	Physic characteristics	Pellet (density, pores distribution, etc.), Clad (%Sn content)
	Backfill pressure	Fuel rods O16, C16, P16
Irradiation Follow-up	Power, thermo-hydraulic conditions, coolant chemistry during time irradiation	Almaraz 2 NPP
	Detailed fast fluence, burnup and power during time irradiation	Fuel rods O16, C16, P16
On-site Inspection	Corrosion, axial growth inspections	Fuel rods O16, C16, P16
Hot-cell PIE	Internal pressure and void volume measurements	Fuel rods O16, C16, P16
	Profilometry (4 generatrixes)	Lower segment of rods O16, C16, P16

Table 3: Summary of information of the Almaraz Program

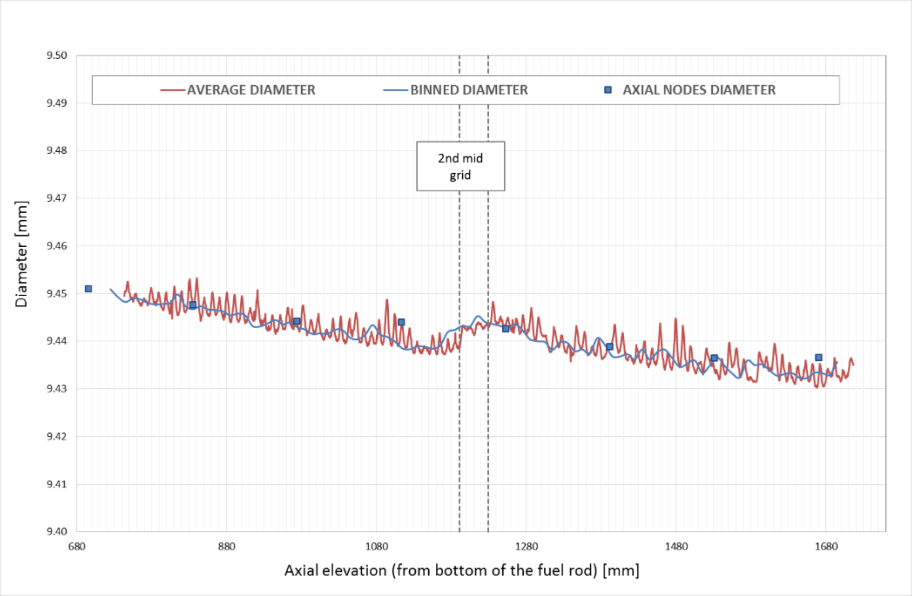
The Almaraz hot-cell PIE program consisted of a puncture test and a profilometry. The puncture test measured the rod internal pressure (RIP) and the free void volume at both 0ºC and 20ºC. The profilometry was performed on one segment of about 1 meter cut from each fuel rod in the lower part of every rod, approximately between 680 mm and 1680 mm from the bottom of the fuel rod, comprising the two spans lower and upper of the second mid grid. Here, it is expected according to fuel rod design predictions to have simultaneously a very flat thermal gradient and an open pellet-clad gap, the conditions needed to measure the irradiation component of the clad creep.

The outer diameter including the oxide thickness was measured at four generatrixes - 0º, 45º, 90º and 135º of the segment in Figure 1 for each rod. The three rods show very low variability in any of the generatrixes so that the average outer diameter value for each elevation was utilized in the analysis.



Rod O16 (ZIRLO,450 psia)

Rod P16 (Optimized ZIRLO, 365psia)



Rod C16 (Optimized ZIRLO,450 psia)

Figure 1: Data treatment of the outer diameter measurements

After correcting the axial elevation of the segment by the end plug length and making smoother the diameter profile eliminating the spikes corresponding to the pellet-to-pellet interfaces positions (where the in-reactor creep is obviously not considered), the average smoothed diameter is normalized according to the axial mesh of the thermo-mechanical code. Thus, eight (8) average outer diameter values are obtained for each fuel rod, as shown in Figure 1. The diameter elastic deformation recovery due to the de-pressurization rod after puncturing is also taking into account for these eight values.

Finally, the measured creep values including the oxide thickness, are obtained as the difference between the irradiated and the un-irradiated outer diameter (Table 1), both measured at room temperature. The eight measured creep values for each rod can be, therefore, directly compared with PAD4 predicted creep values since modelling of the creep includes the pool cooling period before the shipping to the hot-cells, cancelling the effect of the thermal expansion of irradiated clad.

3. Methodology and hypothesis

The standard Westinghouse Fuel Rod Design methodology with PAD4 code is applied to analyse the rod internal pressure as well as the void volume for the three rods. As inputs to the modelling of rods during operation, very precise manufacturing parameters characterization data as well as specific power histories and operational conditions are used. As a part of the accurate modelling process, the models for the oxidation and the axial rod growth were adjusted to incorporate the measurements performed on-site for the three fuel rods and summarized in Table 3.

In addition to oxidation and irradiation growth, those models with a remarkable impact in the pellet to cladding gap are considered whereas the other fuel rod performance models without significant contribution to the outer diameter change are fixed at its best estimate conditions. It should be noted that the needed accuracy of the Westinghouse densification model has been already demonstrated in Reference [2] by an extensive comparison of the hot-cell measurements and PAD4 predictions for UO_2 pellets.

With the purpose of assessing the predicted creep values and quantifying the predictability of ZIRLO and Optimized ZIRLO cladding creep behaviour, *Best Estimate* condition (current PAD4 ZIRLO and Optimized ZIRLO model) and *Adjusted* condition (scaled to Zr-4 creep rate) were applied in the creep model.

Finally, as an hypothesis to evaluate the dependency between the secondary creep rate and the circumferential stress in the tube, once it is determined that the gap is open and, thus, the stress state is due to the rod internal pressure, it is assumed the stress keeps mainly constant along the irradiation time supported by the small increment of the internal pressure, as it was measured, in only one cycle of irradiation.

4. Evaluation and results

4.1. Rod internal pressure and Void volume

Figures 2 and 3 depicts the comparison of the PAD4 results for rod internal pressure and void volume with the hot-cell measurements respectively for both the Best Estimated and Adjusted creep cases for all the rods regardless its burnup. There is a good coherence between measured and predicted values, with an improvement in the predictability, overall for the void volume, for the *Adjusted* creep case.

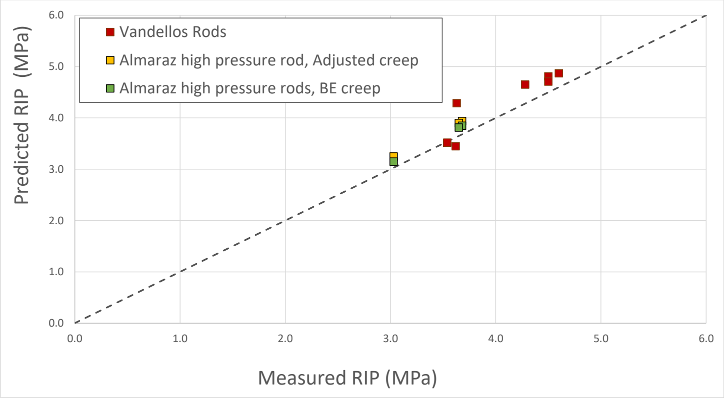


Figure 2: Rod internal pressure

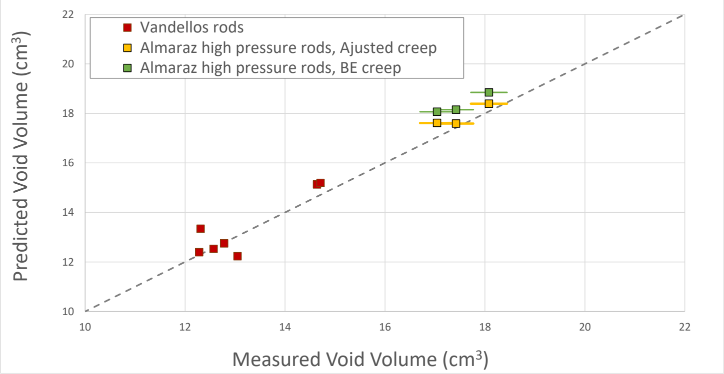


Figure 3 Void volume

With the measurements obtained in the Almaraz Program, it is able to complete the database of previous hot-cell program, presented in Reference [2] (Vandellos Program). Figure 4 shows the evolution along the irradiation of the fuel rod internal pressure and void volume.

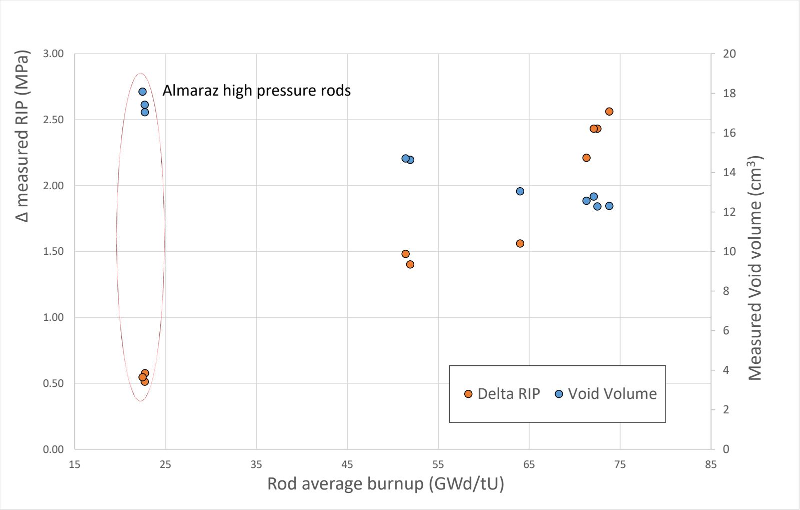


Figure 4 RIP and void volume measurements data base

4.2. Outer diameter change induced by irradiation creep

The comparison of the measured creep values and the predicted ones by PAD4 for all the rods, regardless its initial backfill pressure and cladding material, shows an under-prediction in the outer diameter change due to inward creep when the *Best Estimate* creep model is applied as shown in Figure 5. Indeed, this under-prediction has been already addressed in the following version of the thermo-mechanical code, PAD5, based on extensive measurements from several hot-cell programs, as discussed in Reference [3]. Thus, the agreement of the measured and predicted values improves when the creep of ZIRLO and Optimized ZIRLO clad is increased in the performance creep model, the *Adjusted* creep case illustrated in Figure 5.

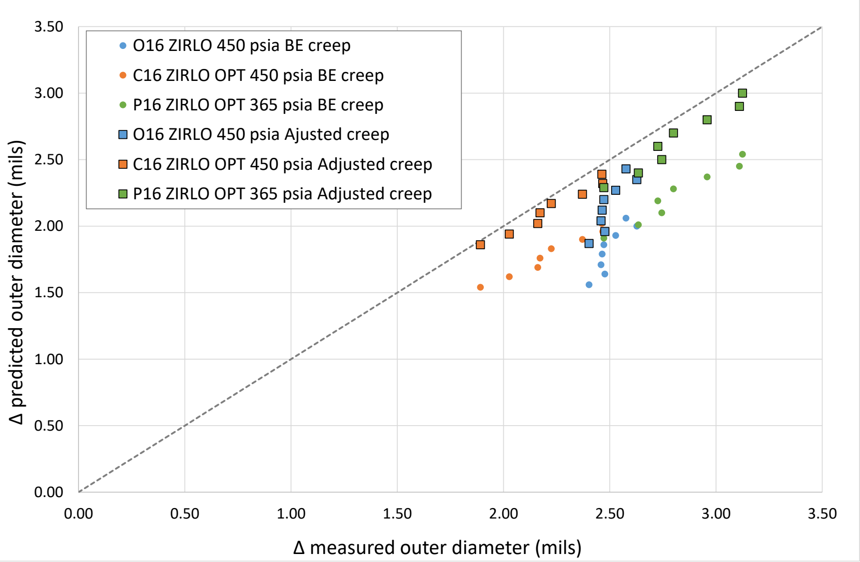


Figure 5: Creep behaviour of Almaraz program rods

4.3. Pellet-clad gap evaluation

An essential key of the analysis of the Almaraz program is to make sure that the outer diameter changes are due to metal clad deformation induced by creep effect, without contribution of the pellet radial expansion. Even if the pellet interfaces contact points between pellet and clad are produced, which are called the *primary ridges*, the contact may be soft enough so that the cladding deformation is derived from the metal clad creep effect, being essentially the pellet-clad open in the central zone of the pellet.

As the pellet-to-clad gap closure cannot be determined experimentally by hot-cell tests, the analysis was performed with the thermo-mechanical code PAD4 based on the very accurate prediction of the void volume for the *Adjusted* creep case for each of the fuel rods. Figure 6 depicts the gap size along the fuel rod length according to PAD4 results. The position of the segment examined in the hot-cells is also indicated in the figure. Coherently, the gap size is lower for the Optimized ZIRLO rod with the lower backfill pressure (P16).

The gap presented in Figure 6 is the minimum PAD4 value along the axial length for each fuel rod at the end of the irradiation (not in the pool), i.e., corresponding to the maximum burnup (table 2) so that all the thermal effects (densification, swelling, creep) are considered, resulting in the maximum values for the radial expansion of the pellet and inner diameter of the clad. Additionally, the calculation's scope has been extended in order to take into account, besides the thermal effects on pellet and cladding, the cracking and relocation of the fuel fragments, which are not explicitly modelled in the PAD4 models and could produce a reduction or even the closure of the gap.

The relocation model utilized is documented in Reference [4] that provides with the gap reduction depending on the pellet burnup and with several constants adjusted to both, out-of-pile and in-pile experiments. Thus, a conservative minimum predicted gap size for each rod is obtained. These conservative gap sizes are also presented in Figure 6. For the examined segments, the gap for the higher pressure rods (450 psia) is still open for both ZIRLO and Optimized ZIRLO rods, while it is closed at least along the most part of the segment length for the rod with lower backfill pressure (365 psia, Optimized ZIRLO).

As a conclusion, the measured creep values at hot-cell (the eight values depicted in Figure 1) for the two rods with highest backfill pressure (450 psia) of both ZIRLO and Optimized ZIRLO alloys, are those considered **for** the further analysis of the in-reactor creep behavior.

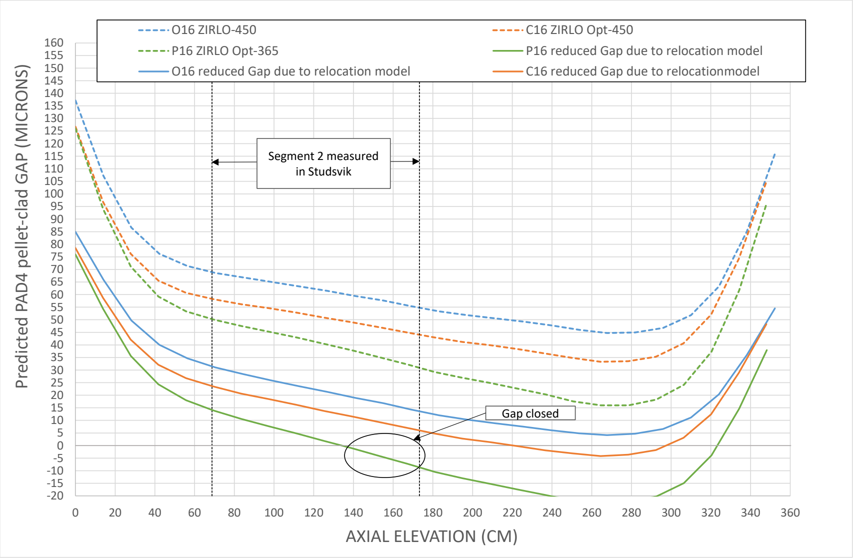


Figure 6: Gap size with & without relocation model

4.4. Correlation of the in-reactor creep data of Almaraz and Vogtle programs

Along the development of Optimized ZIRLO cladding, the thermal treatment was modified in order to recover part of its creep resistance due to the tin content reduction. The purpose was to obtain creep behaviour equal to ZIRLO alloy, so a partial recrystallization annealing treatment was chosen based on extensive un-irradiated material tests.

Moreover, in order to confirm the expectations of similar in-reactor creep for both ZIRLO and Optimized ZIRLO clad alloys, the Vogtle program was designed and performed providing with the creep behaviour for both materials (including also the Low Tin ZIRLO variety, with 0.75% tin) through a wide range of measurements of the diametral change in samples of pressurized non-fuelled tubes irradiated at guide tube positions. Reference [1] presents the results of the Vogtle program detailing measurements, results analysis and discussion.

Once it is determined that ZIRLO and Optimized ZIRLO rods with higher backfill pressure, (O16 and C16 respectively) keep the pellet-clad gap open so that the measured deformation on the outer diameter is induced only by creep, its measured outer diameter deformation values are compared with the Vogtle program results, following several assumptions:

- Firstly, the measured creep values in O16 and C16 fuel rod segments (the average of the eight values displayed in figure 1) are corrected with the diametral change induced by irradiation growth, in coherence with the Vogtle program, and that is proportional to the irradiation axial growth.

- Secondly, the Almaraz creep results are normalized in order to take into account the different hoop stress at the clad of Almaraz rods and the Vogtle samples. As mentioned above, there is no significant error to assume a constant hoop stress state in the clad due to the small increment in the internal pressure of these rods.

Figure 7 depicts the diametral change induced by creep as a function of the tin content for both programs, Vogtle and Almaraz, where there is a remarkable alignment between the results. The findings lead to the conclusion that ZIRLO and Optimized ZIRLO alloys have the same in-reactor creep behaviour.

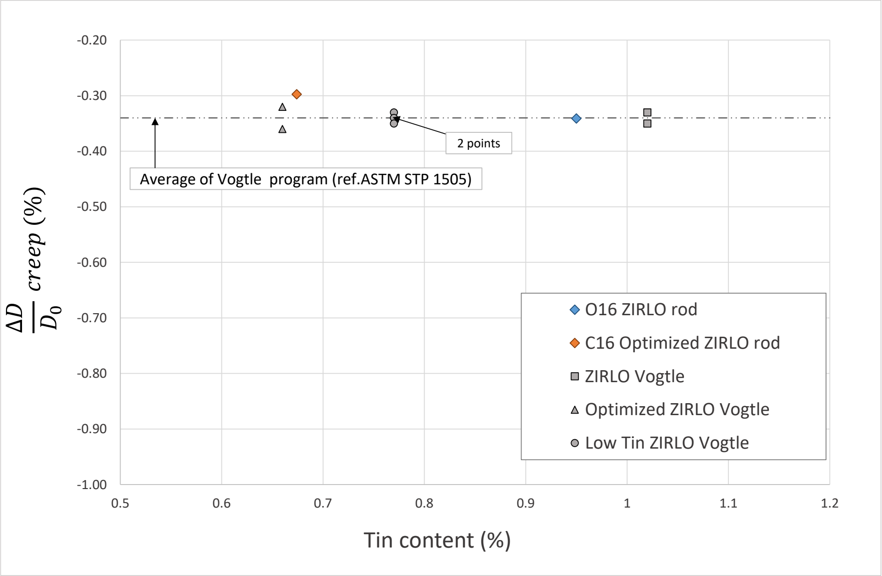


Figure 7: ZIRLO and Optimized ZIRLO Creep Rate

5. Conclusions

The Almaraz PIE program has been completed for three fuel rods, one rod with ZIRLO clad and high initial backfill pressure of 450 psia and other two rods with Optimized ZIRLO clad and two levels of high pressure, 450 and 365 psia. The measured data for variables including rod internal pressure, void volumes and outer diameter along with the manufacturing and irradiation parameters characterization and the on-site inspection measurements, have constituted the vast information needed to analyse the in-reactor creep behaviour of both alloys.

The evaluation of the data has consisted firstly the comparison of the measured internal pressure and the void volume of the three rods from Almaraz PIE with the thermo-mechanical code PAD4 predictions, showing very good agreement. The accuracy of the predictions is improved when the creep of both clad materials is adjusted to the outer diameter measurements in the hot-cell. In addition, Almaraz program data along with data from previous programs provided reasonable dependence of the internal pressure and void volume on the fuel rod burnup.

With very conservative assumptions, including the gap reduction due to a cracking pellet and the relocation of the fuel fragments, the two rods with the highest backfill pressure were determined to have the open gap during irradiation and the clad deformation values are only induced by the cladding creep, without contribution of the pellet radial expansion. The outer diameter change values measured on these two rods of the Almaraz program are compared with the ones measured in the Vogtle program. Almaraz and Vogtle data together build a full picture of in-reactor creep behaviour of ZIRLO and Optimized ZIRLO rods and it is concluded that both alloys have the same creep performance during the irradiation.

6. Acknowledgments

The authors gratefully acknowledge the contributions of Studsvik, for testing, modelling and discussions of the results. The contributions of the Spanish utilities involved in the program and especially the Almaraz site where the test was irradiated are gratefully acknowledged.

7. References

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