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A Review of Halden Data on Gap Closure and Mechanical Behavior of UO_2 Fuel Rods

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Abstract

This paper extensively reviews representative experimental data obtained by the Halden Project for last about twenty years to investigate gap closure and pellet-cladding mechanical interaction (PCMI) in UO_2 *fuel rods. The purpose of the present paper is to supplement the previous reviews of Halden data by reference to more recent experiments. The experiments are grouped into sections describing gap closure, PCMI, clad response to variable load conditions and clad failure by stress corrosion cracking. The new data complement the previous findings, extending the conclusions to higher burnup and different operating regimes.*

1. Introduction

Commercial and test reactor experience has shown that at some time during the irradiation there is inevitably a mechanical interaction between the cladding and the enclosed pellets. In order to quantify the pellet-cladding mechanical interaction (PCMI) and provide adequate data for its modeling, numerous experiments have been performed in the Halden reactor using in-pile diameter and length gauges. Experiments have been performed to investigate the influence of design variables like pellet-to-clad gap, rod length, pellet length to diameter ratio and changes to pellet properties, e.g., grain size, density, geometry and additives. Also investigated has been the effect of irradiation history, the effect of single power ramps and the effect of multiple power ramps or power cycling.

Two reports have already been written compiling and reviewing the experimental findings, Vilpponen et al. [1] and later, Kolstad et al. [2]. The reports reviewed the data describing gap closure by fuel swelling and clad creep-down, the onset power for interaction and relaxation effects during hold time at high power. Of particular interest was the comparison made by Vilpponen et al. between simultaneous diametral and elongational strain measurements. They showed that there was a good correspondence between the in-pile and PIE measured elongation, and that diametral and axial strains were correlated linearly. In the latter case this implied that elongation, which is more easily measured than changes in rod diameter using movable diametral gauges, is a good indicator of the state of total PCMI. Recently Sim et al. [3] continued the review to supplement the previous reviews by reference to more recent experiments. This paper presents the review of Sim et al. with some improvements.

2. Gap Closure

Before any interaction can take place between pellet and cladding, it is necessary for any residual diametral gap to be closed by thermal expansion, clad creep-down or fuel swelling. It follows that the smaller the gap, the earlier PCMI occurs during the irradiation and the lower the power is for its onset. It is important therefore to be able to estimate the rate of gap closure as a function of time in reactor and irradiation conditions.

2.1 Gap Meter Rig, IFA-522

A series of experiments were performed in IFA-522 [4] where at several points during irradiation, a measurement of the gap could be obtained by compressing the clad onto the underlying pellet. The different loadings contained short rods of different specification and the progression of the gap closure was measured for different rod variants.

Major observations in IFA-522 were: (1) Relocation and densification are processes competing with each other early in life, with driving forces due to temperature gradient and absolute temperature, respectively. (2) The strength of cracked pellets is weak as long as fuel fragments are not pushed firmly to form a solid cylindrical body, and therefore, even in the case of the gap closure, only small cladding strains are imposed when there is still free volume distributed across the pellet.

2.2 Densification and Swelling, IFA-409.2

The experiment IFA-409.2 [5] was designed to study restrained densification/swelling phenomena in the reactor, and hence fuel rods were prepared to cover a wide range of fabrication parameters such as fuel density, grain size and pore morphology.

A correlation of swelling rate as a function of fuel density was developed from the observations.

2.3 Fuel Densifications in Different Fuels, IFA-503

The experiment IFA-503 [6] was the base irradiation for the comparison of standard WWER-400 and PWR type fuel. Both fuels were different in the power conversion (ADU for the PWR; IDR for the WWER), sintered fuel density (95% for the PWR; 97% for the WWER) and grain size (9 μm for the PWR; 7 μm for the WWER).

The result showed more densification in the WWER fuel than the PWR fuel due to different grain size and pore size distributions. But both fuels showed a similar swelling rate.

3. Pellet-Cladding Mechanical Interaction

The ideal situation of a fuel stack aligned concentric with the cladding forming a well-defined annular gap does not occur in practice. Even before pellet cracks form due to the radial temperature gradient, each pellet in the stack is randomly offset from the centre and from its neighboring pellets. Thus, an irregular gap is formed which varies both randomly and systematically up the length of the fuel rod. This picture is qualitatively unchanged once cracking occurs. As a consequence, PCMI takes place rather earlier and more strongly than predicted with the idealized geometry as is evident in the experimental observations. Firstly, on increasing power, the expected two stage elongation comprising extension at a rate due to free clad thermal expansion followed by a sharp change to extension at a rate due to fuel thermal expansion is not observed. Instead, elongation starts at low power at a low rate of extension that increases gradually, only reaching that of the pellet thermal expansion at high power. Because of the miss-aligned pellet stack, the first ramp also produces relative high interaction resulting in unexpectedly large clad stresses and hence clad elongation. Such effects are also noted on re-starting after shutdowns, particularly if the fuel has been moved. The consequence for commercial reactor operators is a restriction on the rate of power raising after reloads in order to prevent rod failure. The first ramp during startup appears to re-align the pellet stack such that on decreasing the power, the pellet stack is more concentric with the clad. The second and subsequent ramps are more like to the ideal situation and exhibit the two-stage elongation. From this type of behavior, the onset of interaction is more easily discernible, and it can be seen that this onset occurs at progressively lower power as burnup accrues.

3.1 Effect of Pellet Locking, IFA-552

Eight fuel rods contained in the test rig IFA-552 [7] were subjected to a base-irradiation where heat ratings were below 25 kW/m. Two different diametral gap widths, 130 and 180 μm, were used.

All rods showed the same overall shape and rate of elongation; expansion due to PCMI appeared as peaks on changing power. But, one rod showed exceptionally large cladding elongation that was about 6 times that of the other rods. This behavior was more like that of a rod with a much smaller gap, even though the rod had an as-fabricated 180 μm gap width. Therefore, the strong PCMI of the rod was believed to be attributed to trapped pellets.

3.2 Hollow versus Solid, IFA-509.2 & .3

Two fuel rods were loaded in the 3-rod diameter rig IFA-509 [8,9]. The differences between the two rods were enrichment and inner hole of the pellet. The hollow fuel had a 3.0 mm diameter hole in the pellet centre, and therefore it was designed to have a higher enrichment in order to compensate for the lower fuel weight and to have the same heat ratings.

Experimental results showed a much greater change in diameter in the solid rod compared to the hollow rod when ramped at the same power at the burnup 3 MWd/kgUO$_2$. This behavior was reflected in the fuel stack length changes, but strangely, the residual clad elongation measured at hot stand-by was the same in both rods.

3.3 Power Cycling

3.3.1 Effect of Power Cycling and Remedy Fuels, IFA-519

Three test rods were base-irradiated at powers in the range of 30-40 kW/m to burnups to about 29 MWd/kgUO$_2$, and then loaded into the rig IFA-519 [10]. The test rods were one BWR standard rod (R-23), one annular pellet rod with graphite coating inside the clad (ACP-29), and one vipac fuel rod (SP-33). Here, the gap size was the same, 260 μm, in both the R023 and ACP-29 rods. After conditioning, the test rig suffered 14 cycles of daily load following.

No difference in performance between the three fuel rod designs was observed.

3.3.2 Effect of Gap Size, IFA-550.2

Test rods R-23 (BWR standard rod) and ACP-29 (annular pellet + graphite coating) in the test IFA-519 [11] were irradiated together with the rod 509/4 which was BWR small-gap fuel rod and had been irradiated at low ratings to 30 MWd/kgUO$_2$. These three rods were further base-irradiated to 41 MWd/kgUO$_2$ and experienced load following operation.

The small-gap rod showed more strong and earlier PCMI than the standard rod. The measured clad elongation of the standard rod and the remedy fuel rod was about the same as the free expansion up to the power level where hard PCMI occurred in the standard rod. In the standard rod, from this power level the clad expanded of the same rate as the UO_2 stack.

3.3.3 Power Overshooting Effect, IFA-512

Three test rods of the same design (rods 402.3, 402.4 and 402.6) were base-irradiated at 25 kW/m to 7.2 $MWd/kgUO_2$. After that, these were reloaded in the rig IFA-512 [10], and were subjected to a high power (~51 kW/m) excursion, followed by two daily load-follow operations of 14 and 8 cycles, respectively. The high and low powers in these cyclic operations were about 47 and about 30 kW/m. Subsequently the rods were operated at powers in the range of ~50 kW/m to a burnup of ~18.4 $MWd/kgUO_{2.}$ Rod 402.2 was replaced with a new one, designated as 402.1, which had been base-irradiated at 25 kW/m to 15.7 $MWd/kgUO_2$. These three rods were conditioned at 30 kW/m and exposed to the third daily load-follow, where power was changed from 29 to 46 kW/m and 14 cycles were achieved. Then, the rod 402.1 was replaced with another new one, designated as 402.5. All three rods experienced the fourth daily load-follow which was performed in the same manner as the third load-following.

Significant radial deformations were observed on rod 402.5 compared to others after the fourth cyclic operation. This was attributed to the power overshooting effects. For rods 402.4 and 402.6, the conditioning power levels before the third and fourth load-follow sequences were too short (1.2 days) to cause re-conditioning, and therefore, actual power overshooting did not exist as in the first and second load-follow sequences. While, for rod 402.5, the base irradiation power was lower than the high power in the cyclic operation, and therefore the power overshooting from the base irradiation power significantly affected fuel rod deformation. Another important observation was that clad strains on rods 402.3, 402.4 and 402.6 were within the range of measurements during stable power periods at about the same power level in fuel rods with similar design features. This implies that the cyclic power operation may not lead to an enhancement of the diametral clad deformations.

3.3.4 Comparison of Cycling with Hold, IFA-520 and 525

The third series LWR simulation tests [12] were performed with four BWR type rods and two PWR type rods. These tests were extended to investigate the effect of power cycle on the thermal and mechanical behavior of pre-irradiated fuel rods, while only ramp effects were emphasized in the earlier series LWR simulation tests. In particular, tests with PWR type fuel rods were designed to provide comparative information of fuel behavior at between a power cycling and a conventional ramp. Total operation time at high power (45 kW/m) in the power cyclic operation was the same as the holding period in the conventional ramp test with the ramped power 45 kW/m. Both PWR type fuel rods were of the same design.

No influence of cyclic operation was observed in the fission gas release as well as mechanical responses of test rods.

3.4 High Burnup Effect, IFA-597.3

Within the program to study integral behavior at high burnup, three segments from a standard BWR fuel rod discharged from a commercial reactor at 59 MWd/kgUO_2 have been re-instrumented and re-irradiated in IFA-597.2. One rod failed during the start-up ramp, and that failed rod was replaced with the third segment in IFA-597.3 [13]. Both test segments were further irradiated to 61.5 MWd/kgUO_2. Rod heat ratings increased to ~32 kW/m in the early days of the test period and then gradually decreased to ~21 kW/m at the end of the test.

The high degree of PCMI decreased progressively during the first part of the irradiation, showing relaxation of clad stress and strain. After ~0.6 MWd/kg$UO_{2,}$ and despite a slowly decreasing power, there was a gradual increase in clad length at the rate of fission product swelling of the fuel matrix.

4. Clad Response to Variable Loading Conditions
- Clad Creep under Stress Reversal Conditions, IFA-585

The response of the Zircaloy cladding to the stress imposed by the expanding pellet can be categorized into: recoverable elastic strain, and non-recoverable plastic and creep strain. The first increment of strain in response to a change in stress is elastic that is time independent and non damaging; Damage, and progression to failure only occurs by plastic deformation, crack initiation and growth.

Three rodlets were in the rig IFA-585 [14] in the order of BWR rodlet (Recrystalized Zry-2, pre-irradiated), lower PWR rodlet (Cold-worked & stress-relieved Zry-4, fresh) and upper PWR rodlet (Cold-worked & stress-relieved Zry-4, fresh). The fuel-clad gap widths were large so that a considerable creepdown could be accommodated without any PCMI. When the assembly was in the reactor at power, the external coolant pressure was constant and the lower PWR rodlet was held at constant internal gas over-pressure. Stress was varied in the other two rodlets (i.e., BWR rodlet, and upper PWR rodlet) by altering internal gas pressure. On-line measurements of clad diameter over its whole length were performed at the same time for three rodlets by moving the gauges up and down along the axial extent of the cladding materials. The test rodlets have been subjected to water coolant at pressures and temperatures typical of LWR conditions. During this time the test rodlets have accumulated about 14,400 hours at power, and have been subjected to a fast neutron dose of about $1.6\text{x}10^{21}$ n/cm^2. For the variable stress rods, the internal pressure was changed several times throughout the experiment in order to provide the required stress history. Both internal and external pressures were monitored and used for the determination of the stress state in the clad.

Experiment results showed: (1) The cladding elastic behavior was identical in tension and compression; (2) The secondary creep rate was proportional to the absolute stress, i.e., the secondary creep rate in tension was 1.7-1.8 times larger than in compression; (3) The primary creep strain under variable loading conditions was not proportional to the absolute level of stress, but rather to the change in stress from the previous period.

5. Clad Failure

Post irradiation inspection of fuel rods that have failed by PCMI during an over power transient show that the failure site is an axial crack. The morphology of the crack shows that is transgranular and characteristic of a low strain brittle failure. In some cases the crack morphology changes part way through the clad thickness to more ductile failure mechanism.

There have been many studies of this failure mechanisms, both in-pile and laboratory experiments. The brittle nature of the failure size has lead to a general consensus that although stress is the primary initiator, progression of the crack is chemically assisted, thus the process is termed Stress Corrosion Cracking (SCC). Despite an understanding of the principles involved, there has been little success at modeling the failure mechanism.

There have been three experimental assemblies irradiated at Halden with the aim of clarifying various specific aspects of the SCC phenomenon. These are described in this section. In addition, in-pile ramp tests at very high burnup are also described in terms of failure thresholds compared to those previously obtained at small and intermediate burnups.

5.1 SCC Experiments

5.1.1 First Single Effects SCC Experiment, IFA-413/517

This experiment was performed to investigate which would be the critical process in controlling in-reactor fuel failure due to PCI/SCC, crack initiation or crack propagation.

Six fuel rods were contained in the rig IFA-413 for a base irradiation, three with and three without fatigue-induced pre-cracks in the cladding. The pre-cracks had depths ranging from less than 0.05 mm to 0.3 mm. The rods had 10 pre-cracks each. The pellet stack was made up in such a way that some of pre-cracks were located at pellet-pellet interfaces, while others were at mid pellet position. All six rods loaded in the rig IFA-413 were base-irradiated to a burnup of 11.6 MWd/kgUO_2 at power levels between 20 to 30 kW/m. After that, two pairs consisting of one smooth rod and one pre-cracked rod were transferred to the rig IFA-517 [15] for ramp tests. A stepwise ramp started after 20 hours conditioning at ~30 kW/m with 4 steps and a ramp rate of 2 kW/m-min. at each power step and hold times of 1 hour.

All test rods failed due to SCC at pellet-pellet interface positions in that part of the rod that experienced the highest power levels and power steps due to axial power shape in the ramp rig. In the first pair of rods all the pre-cracks were located at mid pellet positions and therefore were not coincide with the actual defects. In the second pair of rods a through wall defect was observed but did not coincide with any one of the pre-cracks, even though a pre-crack was located at the axial position experiencing the same heat rating as that of the final crack. Furthermore, the pre-crack did not show SCC growth. Based on these observations, it was concluded that crack initiation is more likely the critical process in controlling in-reactor fuel rod failure due to PCI/SCC.

5.1.2 Second Effects SCC Experiment, IFA-516

This experiment was performed to investigate possible degradation with time of the effectiveness of freshly released fission products in the SCC process. Four smooth fuel rods were used in the experiment IFA-516 [16]. Wide gap was prepared in all the rods to avoid any influence of PCMI on the eventual failure. The cladding wall thickness of four smooth rods was reduced to ~0.4 mm at the middle part of the rod and increased monotonically from the reduced value to a standard thickness of 0.8 mm at the both ends of the rods. This reduced the rod internal pressure required to produce the necessary clad hoop stress (at the middle part) whereas the thicker cladding at lower and upper ends guaranteed against mechanical failure. Base irradiation was performed at ratings ~30 kW/m. and the average burnup reached a value of 14 MWd/kgUO_2. After the base irradiation, high power ramping was started to give fresh fission product, and subsequently the power was lowered to a level at which no more release took place. Immediately, two rods were pressurized to determine their SCC failure level with fresh fission products. Ten days later, the other pair of rods was pressurized to investigate the role of the aged in the SCC process.

All four rods indicated failure in the pressure tests. The first pair with fresh fission products failed within a short time (0-7 min.) after reaching a clad hoop stress of 390 MPa, implying that a short period aging (i.e., 0.6 to 6 hours) may not degrade the effectiveness of the fission product or that the necessary concentration of fresh fission products in much lower. The second pair with the old inventory of fission products in the gap also failed at the same hoop stress. Bit in this case the total failure process lasted about one hour. This implied that SCC failure can occur in the presence of a sufficient inventory of fission products aged for 10 days, or that the required concentration of fresh fission products is very small, i.e., in the order of the fresh release concentration coming from athermal release mechanisms (0.01-0.1 cc STP per rod).

5.1.3 Third Effects SCC Experiment, IFA-567

This experiment was performed to investigate the effects of quantifying and age of fission products on the SCC process and the propensity for cladding failure. A single cluster of eight nominally identical fuel rods of BWR dimensions was contained in the IFA-567 rig [17], and was base-irradiated to a burnup of ~15 MWd/kgUO$_2$ at low powers such that there was little fission product release from the fuel. The test rods were pressurized with gas entering through gas lines attached to the both ends of the rod from the external. For pressurization in the first test, the destination pressure 35 MPa was chosen to produce a clad hoop stress of 450 MPa, adequate to induce failure by SCC. The fuel rods were treated as pairs (Pair 1 for low FP inventory; Pair 2 for high inventory of fresh FPs; Pair 3 for high inventory of aged FPs), and the difference between pairs was achieved by the choice of filling gas in the pressure ramp tests. Pairs 1 and 3 were intact, and only one rod (Rod 7) of Pair 2 was believed to fail showing a long axial crack in the region close to the position of maximum power. The intact rods were further base-irradiated and subsequently suffered a high power ramp. After this the rods were linked to the pressurization system for the second test. Two rods were for low inventory of fresh FPs (Rod 4-retest, Rod 2-retest), and other two (Rod 1-retest, Rod 6-retest) was for high inventory of FPs. One of each pair of rods (Rod 2-retest, Rod 6-retest) was pressurized after one day aging, while the other was pressurized immediately after the high temperature period. As a consequence, Rod 6-retest was failed, even though Rod 1-retest was most likely to be failed due to high inventory of fresh FPs.

Based on the observations, it was found that the availability of freshly released FPs is not a necessary requirement to promote SCC, and that the quantity of FPs at potential failure sites is critical for the SCC process to occur.

5.2 LWR Failure Thresholds

5.2.1 Failure at Medium Burnups, IFA-531

The rig IFA-531 [18] consisted of five segmented BWR rods of standard 7x7 and 8x8 designs base-irradiated at peak ratings less than 26 kW/m in commercial reactors. Each rod was fast-ramped individually using a combination of rapid pressure changes in He-3 coils and slow reactor power level changes. The ramping started after a pre-conditioning period of 6 hours at 26 kW/m. and proceeded with 6.6 kW/m/min step each hour until failure, or the maximum desired power (56-60 kW/m) was reached.

In four rods failure occurred at locations close to the peak flux, and the failure powers were in accord with the power versus burnup failure threshold derived from ramp tests performed elsewhere.

5.2.2 Failure at High Burnup, IFA-597.2

The original fuel rod was irradiated at low ratings below 20 kW/m to a rod average burnup 52 MWd/kgUO_2 in a commercial reactor, and two segments (whose local burnup was 58.5 MWd/kgUO_2) were taken out to re-build two test rods for IFA-597.2 [19]. The two test rods were designated as Rod 2 and Rod 5. The rig IFA-597.2 was loaded in the HBWR and was subjected to three short calibration power cycles, followed by one planned reactor scram. After that, the rig was eventually power-ramped and held for 6 hours. (Hereafter this operation is called as the fourth cycle.) The ramped power during the fourth cycle was 26 kW/m for Rod 2 and 31 kW/m for Rod 5.

Rod 5 was failed at a relatively low rating of ~28 kW/m. Despite the presence of a fuel-clad bonding layer and a pronounced pellet ‘rim’ structure, this was consistent with the extrapolation of the PCI/SCC failure threshold, derived at low burnup.

6. Conclusions

The purpose of this paper is to supplement the previous reviews by reference to more recent experiments. The experiments have been grouped into sections describing: *Gap Closure*, *PCMI* including new start-of-life and very high burnup data, *Clad Response* including data on the effect of stress reversal for compressive to tensile, and finally, a review of a series of experiments to investigate *Clad Failure* by SCC. Major observations were as follow:

(1) Initial rates of gap closure are affected by relocation or densification, independently, according to fuel temperature conditions. Subsequent rate of gap closure agrees with estimates based on solid fission product swelling of the pellet. In addition, at high powers and burnup where fuel temperatures are in excess of the fission gas release threshold, there must be some fission gas swelling, and this, along with thermal feedback from the poisoned gap conductance would be responsible for sudden reduction in gap size.

(2) Strong clad elongation is usually observed in pre-irradiated segments on the first rise to power, and this is thought to occur as a result of trapped pellets or their fragments causing premature PCMI. The onset power and degree of interaction on the second and subsequent ramps is much reduced.

(3) Hollow pellets seemed more beneficial to PCMI than solid pellets. Benefits of graphite layer could not be proven in the experiment.

(4) Load follow experiments and inverse load follow experiments showed that clad

deformation responded to the maximum power achieved, whether it was during the conditioning period as in load following or as the conditioning power as for inverse load following.

(5) During cycling, the diameter and length changes gradually reduce. A similar result was found in ramp and hold tests with dimensional changes reducing during the hold at maximum power.

(6) In the in-pile creep experiment, the cladding elastic behavior was identical in tension and compression. The secondary creep rate was proportional to the absolute stress, while the primary creep strain under variable loading conditions was proportional to the change in stress from the previous period.

(7) Experiments to investigate the mechanism of SCC failure indicate that crack nucleation and not crack growth rate to be the rate controlling process. It is also indicated that quantity of released fission product is important for promoting failure, while the influence of their age still remains unclear.

From the above, it is concluded that the new data complement the previous findings extending the conclusions to high burnup and different operating regimes.

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