END OF LIFE INSPECTION OF FUEL THAT HAD EXPERIENCED TRANSIENT DRYOUT IN FORSMARK 2

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ABSTRACT

In June 2008 a disturbance in the external grid propagated into the Forsmark 2 electrical system and caused a fast runback of the main recirculation pumps. As a consequence a small number of fuel assemblies were calculated to have experienced a short transient dryout. All the fuel assemblies that were calculated to have potentially experienced dryout were removed from the core for one cycle. Following poolside inspection of the bounding assembly, and detailed hot cell PIE of the peak rod in the assembly, the other assemblies were reloaded into the core for further operation without any additional restrictions. These assemblies operated to their design EOL burnup without any problem. One of these assemblies was inspected visually after being discharged, focusing on the elevation where the brief dryout would have occurred. There were no signs of dryout or abnormal oxide appearance and the fuel appeared to be in good condition.

1 Introduction

In June 2008 a disturbance in the external grid resulted in the tripping of all the recirculation pumps in Forsmark 2, a BWR with internal recirculation pumps. The flywheel-driven backup energy supply to the pumps did not function correctly, resulting in a rapid pump rundown. Since the core design had been based on the assumption that the fly-wheel backup would guarantee a controlled pump ramp-down, this (all-pump trip) transient was not covered in the core design. After the recirculation pumps stopped, the core flow decreased from ~10500 kg/s to about 2800 kg/s within about one second causing a void increase. The negative void feedback decreased the thermal neutron flux giving a rapid drop in power to about 20 %. Since the heat transfer from the fuel pellets to the coolant lags the neutronic power, it takes a few seconds before the stored energy in the pellets falls to a corresponding level. Calculations showed that during this brief time about 84 fuel assemblies fell below the SLMCPR (Safety Limit Minimum Critical Power Ratio) and 18 of these briefly experienced dryout (calculated CPR < 1.0).

All 84 assemblies, either in their first or second annual cycle, that were calculated to have fallen below the SLMCPR were discharged from the core following the event. They were subject to verification of fitness for further use before reloading into the core. Out of the 18 fuel assemblies calculated to have experienced dryout (calculated CPR < 1.0), four were GE14 assemblies and the other 14 were Atrium 10B, all of them in their first annual cycle.

A programme was implemented to verify the condition of the affected fuel for further operation [1]. The objective of the programme was to verify, beyond any reasonable doubt, the methodology used to ensure that the fuel subjected to the transient dryout event was fit for further operation without any special restrictions. The fuel needed to fulfil all the conditions and assumptions in its existing (licensed) design documentation, thereby permitting continued operation according to the existing design bases. Following the successful completion of the verification programme, all 84 affected assemblies were reloaded in the core for continued operation until their planned end-of-life (EOL).

Two of the assemblies are still in operation at the time of writing, while the other 82 assemblies have been discharged, after reaching their planned EOL, without any fuel failures or other observed operational problems. One of these assemblies has now been inspected following its discharge, and the results of the inspection are presented in this paper.

2 Previous work

The analysis of the core and fuel response to the transient, as well as the verification programme to justify the reloading and continued operation of the affected fuel assemblies, have been described previously 7[1]. This previous work is summarised here as a background to the new inspection reported in this paper.

The first part of the verification programme consisted of calculations of the transient and its impact on the fuel. It was decided to use best estimate, nominal, data for the core and safety system performance, or other known data where available. In addition to in-house analysis performed by Forsmark/Vattenfall, independent calculations of the event were also performed by the fuel vendors Genusa and Areva using different codes than those available within the Vattenfall group. The most important objectives of the analyses were to assess the peak cladding temperature histories during the transient, and to identify the most limiting fuel assembly and fuel rod in the core (in terms of cladding temperature history).

The second part of the verification programme consisted of physical post-irradiation examinations (PIE), focusing on the single (limiting) bundle and fuel rod, representing the most affected fuel in the core, which had been identified in the detailed analysis of the event. Both Atrium 10B and GE14 experienced similar peak cladding temperature histories and since the fuel behaviour is basically the same for both fuel types under the conditions of the transient, it was sufficient to perform the PIE on only the limiting bundle and fuel rod.

2.1 Analysis of transient

Shortly after the dryout event, simulations and calculations were performed to evaluate any possible impact on the cladding integrity during the event or during later operation. The first analyses were performed in order to identify which assemblies had experienced a minimum CPR below the SLMCPR. Following this, further analyses were performed in-house and by the fuel vendors, Areva and Genusa. The codes POLCA (static core 3-D simulator) and BISON (transient code) were used for the in-house analyses and the fuel vendors used their own codes.

The first objective was to simulate the event with BISON and compare calculated global parameters (neutron flux and core flow) with the measurements recorded during the event to verify that BISON could simulate the overall event with adequate accuracy. The agreement between the measured and calculated neutron flux was excellent and the agreement between measured and calculated core flow was also reasonable. Having verified that BISON could simulate the event adequately, calculations of CPR and peak cladding temperature were performed with the same code for individual fuel assemblies. For the identified leading Atrium 10B and GE14 fuel assemblies respectively more detailed calculations were performed, including pin-power reconstruction to rank the cladding temperature histories of individual fuel rods in the assemblies. This result was then used to choose a single fuel rod as representative of the most limiting rod (bounding the cladding temperature histories of the entire core during the transient) for hot cell PIE. The leading assembly was identified as Atrium 10B assembly F20081 and the limiting rod as h2 (the fuel assembly coordinates are shown in Figure 4.) The analyses have been presented previously [1].

2.2 Poolside inspection immediately after the transient

A number of phenomena were identified as potential impacts of the short transient dryout (see section 2.3 below). Unfortunately, it was not judged feasible to assess the three most likely and limiting phenomena with a poolside inspection. Therefore, the objective of the poolside inspection was limited to the verification of the absence of any gross damage to the fuel assembly. It should also be borne in mind that some of the fuel rods, which were subjected to the brief dryout, are located in the interior of the bundle. The inspection of the fuel assembly F20081 identified as the limiting assembly in the core has been described earlier [1]. No indications of abnormal behaviour or appearance attributable to the transient were seen in the inspection, where the leading hottest fuel rod (h2) was withdrawn from the bundle for hot cell PIE.

2.3 Hot cell

The possible effects on the fuel rods due to the brief dryout event were assessed and the following phenomena were identified, in decreasing order of probability:

1. Recovery (annealing) of the irradiation hardening in the cladding. A best estimate calculation predicted zero recovery, but with more conservative transient analyses a partial recovery of up to about 30% was predicted. This was the most likely and most limiting potential effect of the transient on the fuel and could thus be used to exclude the possibility of any other impact on the future behaviour of the cladding.

2. Collapse or creep-down of the cladding. The best-estimate peak cladding temperature history was expected to result in <<1 µm creep-down. Creep-down of ~5 µm was experimentally measurable and could thus indicate a higher PCT than expected; above ~10 µm creep-down could potentially have an impact on the fitness for further operation.

3. Other effects on the cladding (corrosion and hydrogen pickup during the transient, hydrogen redistribution, changes in the cladding corrosion resistance) were considerably less likely, i.e. require considerably higher temperatures/times than the above two phenomena and could be excluded if the first two were within an acceptable range.

4. Any significant impact on the fuel pellets was ruled out since the peak pellet temperature in this event did not exceed that during normal operation, and the local temperature variations in the outer part of the pellet were too low for any significance.

The hot cell examination focused primarily on assessing items (1) and (2) above with a high level of experimental precision. The irradiation hardening was determined by microhardness measurements both at the elevations where the transient heating due to dryout would have occurred as well as in lower positions of the rod with a similar fast neutron fluence. No measureable recovery was found, where the estimated detection limit was well under 10 %. The cladding diameter (average of 9 generatrices) was subtracted from the as-manufactured cladding tube diameter profile in order to determine the net change during operation (creepdown). It was very clear that there was no local decrease in diameter just below the 7th spacer, which is where a local creepdown due to the dryout transient would have occurred in the event that the peak cladding temperature had been high enough.

Following the verification of fitness for operation, further studies were performed in order to more precisely estimate an upper bound on the temperature that the fuel rod cladding might have experienced during the short transient event [2]. These studies involved measuring the recovery of irradiation hardening following simulated short temperature transients in cladding samples from the bounding rod as well as irradiated cladding samples from another fuel vendor, in order to establish the highest credible temperature history that the fuel could have experienced in the pump trip transient.

3 Operating history to end of life

All 84 assemblies that reached a minimum CPR below SLMCPR (1.06) were unloaded from the core after the event for one cycle, awaiting the results of the verification (described above). All of these assemblies were either in their first or second annual cycle of operation (the transient occurred late in the cycle). Since the results of the inspection cleared the assemblies for further operation all but two were reloaded in the core during the 2009 outage. They were operated with no additional restrictions a further four to six cycles after the dryout event and discharged during the outage in 2013 to 2015, without experiencing any fuel failures or other problems.

The bounding assembly F20081 from which the fuel rod for hot cell PIE had been extracted was not reconstituted until later, so that assembly and its symmetry sibling were only reloaded later. F20081 and its symmetry are still in operation.

An inspection at end of life (EOL) had been planned already at the time of the verification of fitness for further operation, in order to provide additional confirmation that the short transient dryout had not led to any deterioration in fuel performance later in life. In particular, it was of interest to check for any possible impact on the cladding corrosion behaviour later in life (point 3 in the list of identified potential effects of the transient). When selecting a suitable assembly for the EOL inspection, the ten fuel assemblies that had experienced the highest calculated local peak cladding temperatures during the transient were considered. The Atrium 10B assembly F20075 was selected for this inspection. In its first cycle it had a very similar operation to assembly F20081 (selected as the bounding assembly for the initial verification programme). The calculated minimum CPR the F20075 experienced during the transient was 0,981 (fairly close to that of F20081) with a best-estimate peak cladding temperature during the transient of about 417 °C.

When it was unloaded after the pump trip transient near the end of its first cycle of operation assembly F20075 had a burnup of 11,5 MWd/kgU. Following its reinsertion in the core in 2009 the assembly was operated for a further four cycles to a final EOL burnup of 41,5 MWd/kgU at the time of discharge in 2013. The assembly operated at a higher power than the core-average power over essentially all of its lifetime apart from the very end of its life, see **Error! Reference source not found.**. Its positions in the core for each cycle are shown in **Error! Reference source not found.**. In its first cycle (when the transient occurred) it had a similar core position and relative power to the assembly F20081 identified as the limiting assembly in the core, see Figure 3.2.

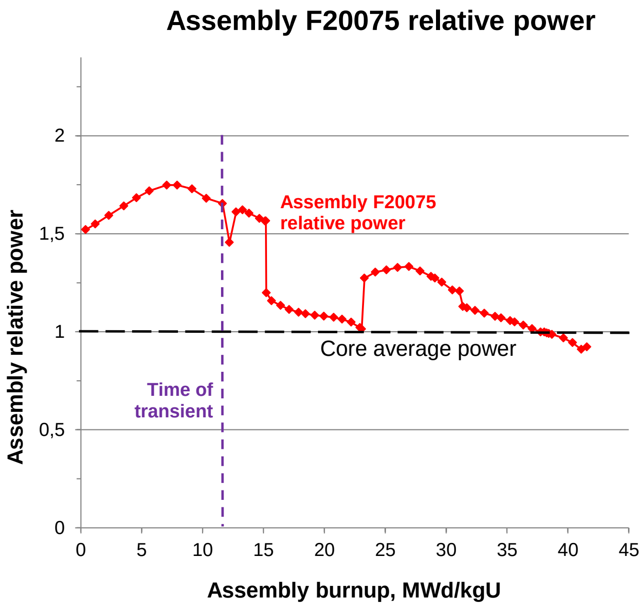

Figure 3.1 The relative power in fuel assembly F20075.

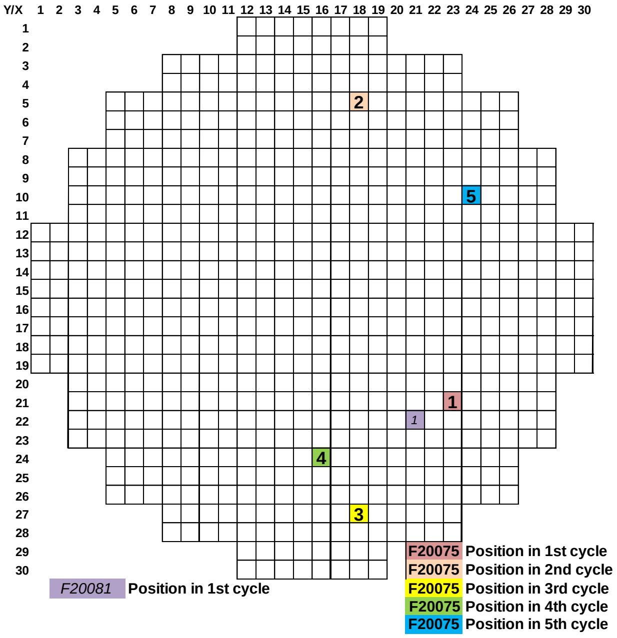

Figure 3.2 The position of FA F20075 in the core during every cycle (bold) and FA F20081 during its first cycle (italic).

4 End of life inspection

4.1 Objectives

The objective of the inspection was to verify that there had not been any impact on the fuel cladding from the transient early in life leading to deterioration in the fuel performance later in life. There was no expectation of seeing any negative impacts from the dryout event. Therefore, the inspection was limited to verifying the absence of any apparent abnormality in the fuel bundle. It should also be borne in mind that some of the fuel rods, which were potentially subjected to the brief dryout, are located in the interior of the bundle.

1. Visual inspection of the de-channelled bundle focussing on the top of the bundle, in order to verify the absence of unexpected differential fuel rod growth which could potentially be indicative of accelerated hydriding of the fuel cladding in affected fuel rods.

2. Visual inspection of the outer surface of the peripheral fuel rods, especially below the two upper spacers and in the span (between the top two spacers) at the axial level where the calculated CPR was lowest during the transient. The objective was to verify the absence of any indications of increased local cladding corrosion or other visible damage to the cladding in these locations.

3. Visual inspection through the fuel rod gaps, ensuring focal depth, to check for unexpected fuel rod bowing or gap closure in both the peripheral rods and the interior of the bundle. In particular, this was performed at the level of the inter-spacer span where the calculated CPR was lowest during the transient, and included the rods with the calculated highest peak cladding temperature history during the transient. The objective was to verify the absence of any unexpected large local rod bowing which could indicate an impact of the dryout on the fuel geometry. Even if the bowing itself is within the allowable limits, the occurrence of significant local bowing could indicate local cladding overheating during the event.

4.2 Inspection method

The inspection was performed by the plant personnel using their own equipment in one of the pools in the reactor hall. The fuel bundle was dechannelled and placed in front of an underwater camera (Ahlberg). The camera could be moved vertically and also had variable pan, tilt and zoom. During the inspection the fuel bundle was held in the fuel handling crane, which made it possible to rotate the bundle. All four sides of the bundle were inspected and recorded on a video film. The fuel rod positions and side numbering convention is shown in Figure 4..

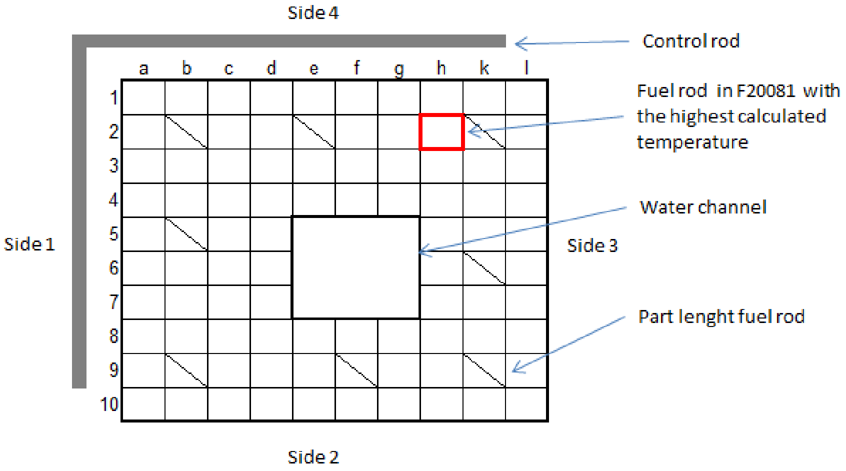

Figure 4. Fuel bundle overview; fuel rod coordinates and side numbering during the inspection.

5 Results of the end of life inspection

5.1 Fuel rod lengths

Very little differential fuel rod growth was observed between the peripheral rods along each side of the fuel bundle, see examples in Figure 5.1 (side 3 away from control blade) and Figure 5.4 (side 4 adjacent to control blade). Since the fuel rods are all in contact with the lower tie plate (see Figure 5.2 and Figure 5.3) the difference seen in the top shoulder of the rods also reflect differences in the total rod length.

Since the camera pan was set to zero (angle of view directly normal to the side of the bundle), it could also be checked that none of the fuel rods in the row interior to the peripheral row stuck up above the shoulders of the peripheral rods. The rod identified as that experiencing the peak cladding temperature in the transient dryout was rod h2, in a semi-peripheral row. As can be seen in Figure 5.4 this rod was essentially the same length as its neighbours and thus did not display any unusual growth compared to other fuel rods less affected (or not at all affected) by the transient dryout event. The small differences in length of the peripheral rods essentially followed their differences in burnup (or lifetime averaged power).

Figure 5.1 Side 3 top of bundle.

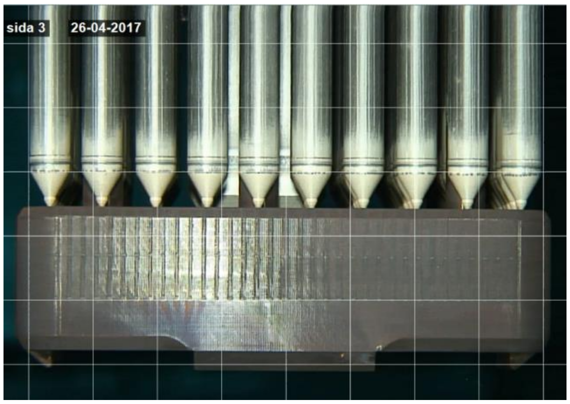

Figure 5.2 Side 3 bottom of bundle (all rods resting on lower tie plate)

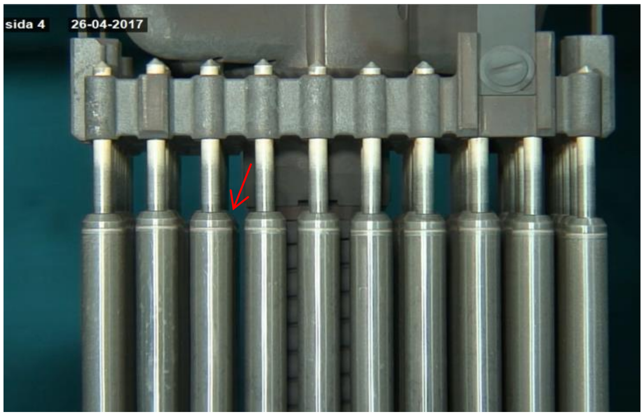

Figure 5.4 Side 4 top of bundle. The limiting rod h2 is in the second row as shown by the arrow.

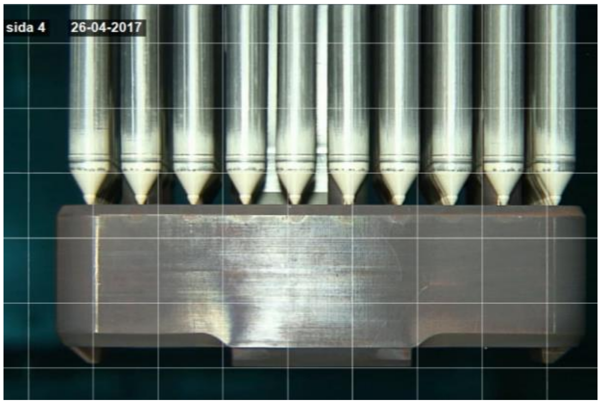

Figure 5.3 Side 4 bottom of bundle (all rods resting on lower tie plate

5.2 Cladding oxide

Since the fuel rod expected to have experienced the highest peak cladding temperature in the transient (h2 rod) is located in an interior row, it was not possible to directly observe its cladding surface by inspecting the bundle without disassembling and removing fuel rods. The dryout was expected to have initiated and had the longest duration just below the uppermost spacers, while the surface of all the rods would have been fully wetted (i.e. not experienced a temperature transient) above the spacer. As can be seen in Figure 5.5, there was no indication of spalling oxide or other unusual oxide appearance at this elevation, which could have been caused by the transient early in life.

The patchy oxide appearance on the fuel rods near the corners of the bundle (rods a1, b1 and l1 in Figure 5.5) is due to the non-uniform transition from a thin darker oxide layer to a slightly thicker, lighter coloured oxide layer. In the other fuel rods with more uniform colouring most or all of the cladding has an oxide covering that is thicker than the transition thickness where the colour change occurs. These differences in visual appearance are not related to the transient dryout early in life.

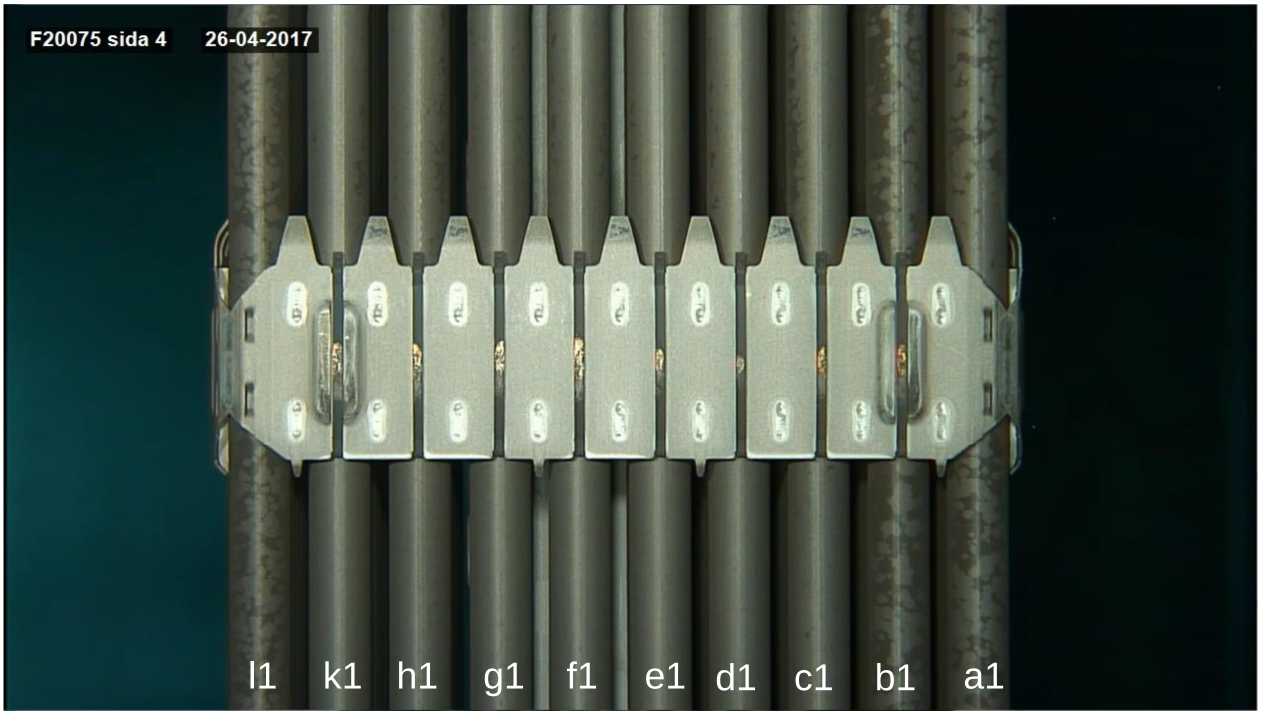

Figure 5.5 Bundle F20075, spacer 7, side 4.

5.3 Fuel rod bowing

Visual inspection of the fuel bundle from all sides enabled examination of the rod-rod gaps along the entire length of the bundle, both for the peripheral rods but also to some extent for the interior rods (since it was possible to see into the bundle along the equally spaced gaps). There were no indications of any apparent fuel rod bowing.

6 Conclusion

18 fuel assemblies in Forsmark 2 experienced a short transient dryout in connection with a recirculation pump trip event in 2008. Detailed analyses and post-irradiation examinations verified that there was no apparent impact on the fuel assembly and fuel rod that had been calculated to have experienced the highest peak cladding temperature during the transient. Following the verification of the fitness for continued operation, all the affected fuel assemblies were reloaded in the core for operation to their normal end of life discharge burnup, without any special operating restrictions. One of the fuel assemblies was visually inspected at EOL focusing on the elevation where the brief dryout would have occurred. There were no signs of abnormal oxide appearance or any other adverse behaviour due to the dryout and the fuel appeared to be in good condition. This demonstrates that such a transient dryout event, of short duration and leading to a limited peak cladding temperature, has no adverse impact on the continued operation of the fuel to its planned discharge burnup, without the need for any special operating restrictions or other considerations.

7 References

[1] E. Ramenblad et al., “Transient dryout in Forsmark 2 during a fast pump runback – course of events, fuel investigations and measures taken”. Proc. TopFuel 2009 Paris, September 6-10, 2009, Paper 2105.

[2] Kwadwo Kese and Pia Tejland, "Recovery of irradiation hardening in recrystallized Zircaloy-2 in short-duration annealing tests with and without electrical current" Poster presented at 18th Int. Symposium on Zirconium in the Nuclear Industry, 15-19 May, 2016, Hilton Head SC, USA.