INVESTIGATION OF THE IMPACT OF IN-REACTOR SHORT-TERM DRY-OUT INCIDENTS ON FRESH AND PRE-IRRADIATED FUEL CLADDING

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Light water reactor cores may be subjected to thermal-hydraulic transients resulting in inadequate core cooling for short periods of time. In BWRs, the result is a short term dry-out at the fuel rod surface leading to a transitory temperature increase of the cladding. The transient is terminated when adequate cooling is resumed, which results in the overheated fuel rods being quenched. It is a safety requirement that after such an event reasonable fuel performance be maintained up to the subsequent shutdown. In order to assess post dry-out and quench fuel performance, it is necessary to know what effect such transients have on the microstructural and mechanical properties of irradiated Zircaloy cladding. To this end a series of dry-out experiments were carried out at the OECD Halden Reactor Project.

An instrumented fuel assembly (IFA), connected to a light water BWR loop within the Halden reactor, was designed for in-pile dry-out testing. The main feature of the rig was that it comprised three individual flow channels, each able to contain one instrumented test rod, allowing for individually controlled dry-outs to be performed. Two fresh fuel segments (Zry-2 and Zry-4) and six segments pre-irradiated to 22-40 MWd/kgU (Zry-2, Zyr-2 with liner and Zry-4) were fabricated into test rods. Each was fitted with 2 or 3 Cr/Alumel thermocouples to monitor clad surface temperature during the dry-out events together with elongation detectors. The test rods were exposed to reduced or no-flow conditions and once dry-out was achieved and the target temperature (650 or 750^{o}C) as indicated by the upper clad thermocouple was exceeded; the rod was quenched. If time at target temperature was not long enough, further dry-out events were initiated until sufficient accumulated time above the target temperature was reached.

Poor thermal contact between the thermocouple and clad outer surface for the first rods tested, led to these rods being more severely tested than planned, in terms of both accumulated time in dry-out and peak temperature reached. These rods developed maximum peak clad exposure temperatures (PCTs) estimated to be in the range 950-1200^{o}C. This was not the case for the final rods tested, for which the thermocouple attachment had been re-designed, which developed PCTs of 750 - 850^{o}C.

The surface condition and dimension of each fuel segment were assessed post dry-out, followed by destructive examination to investigate clad microstructure and mechanical properties. Thermal hydraulic calculations carried out prior to the in-pile testing had indicated that the dry-out transients induced in the test would result in an axial temperature profile in the cladding: a PCT plateau over the upper region with a steeply decreasing temperature gradient over a “transient zone” down to the loop saturation temperature (285^{o}C) over the bottom region of the test rod. Initial examination of the severely tested rods clearly suggested this to have been the case. Whilst the lower regions of the rods exhibited smooth, adherent grey/brown oxide the upper regions exhibited severe surface oxidation and spalling with clad collapse into pellet-pellet interfaces. Clad sections taken from the upper regions showed the clad had under-gone α to β phase transformation during the transient with the observed microstructure consisting entirely of quenched, former β-phase grains with an increased hydrogen content. The microstructure just below this “peak dry-out zone” was a mixture of large α-grains and former β-grains. Further down towards the bottom of each rod the microstructure was exclusively equi-axed α-phase grains with no grain growth.

The results from room temperature tensile testing varied in accordance with this observed axial variation in microstructure. The ”unaffected zone” at the bottom of the rods showed high UTS and intermediate ductility (see Figure 1(a)). Moving upwards the UTS showed a sharp drop in value accompanied with an increase in ductility. This trend continued until a maximum in the ductility coincided with a minimum in the UTS (see Figure 1(b)). Further up the rod, the ductility decreased to below the value for the non-affected zone, eventually being practically zero in the peak temperature dry-out zone at the top of the rods. However, despite the severe in-pile dry-out testing received by the first six rods, they did not fail in-pile, either during the quench or the subsequent month of normal reactor operating conditions.

Test rods, both pre-irradiated and fresh, that experienced less severe transients (PCTs of 750-850^{o}C) only exhibited a significant improvement in room temperature clad ductility in the dry-out zone, where a small α-phase grain structure was retained throughout the transient testing.

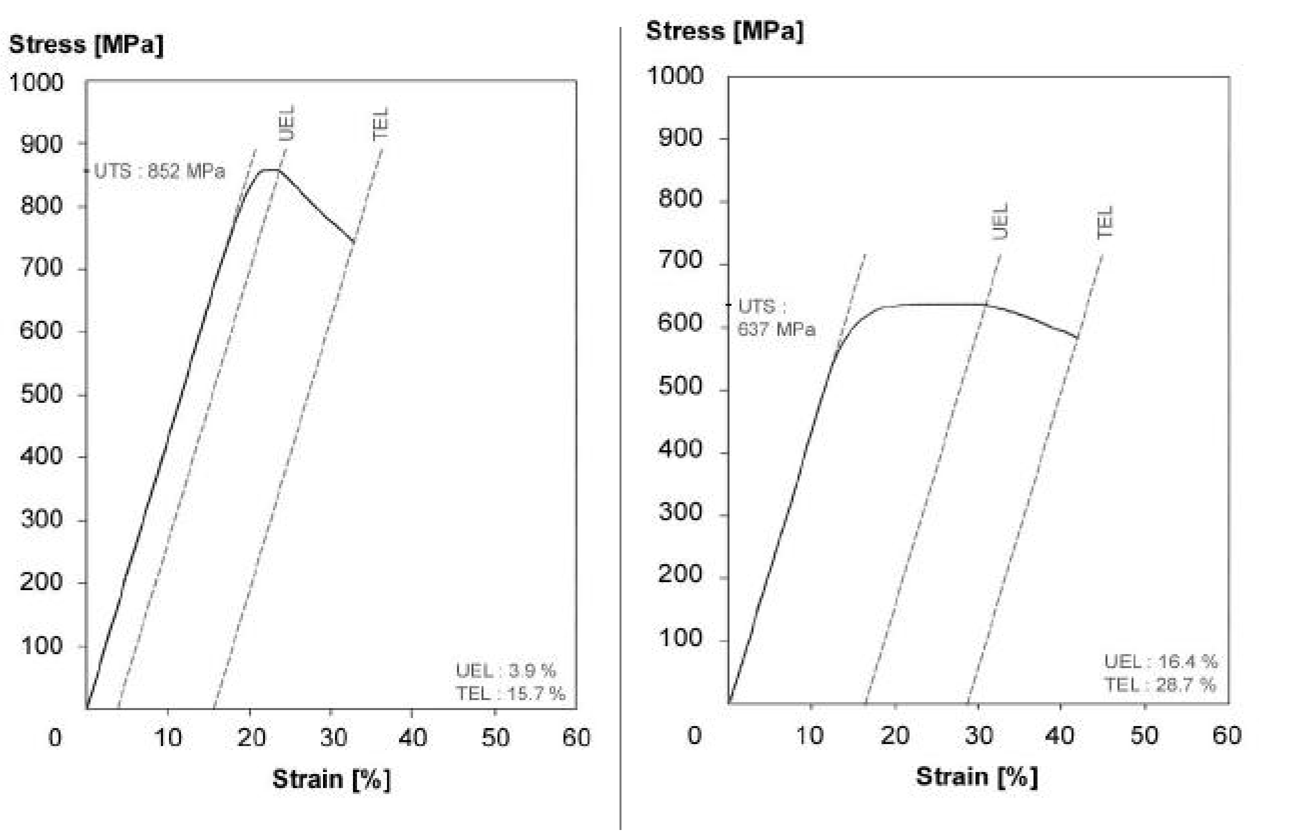

Figure 1. Stress strain curves generated from room temperature tensile testing of clad from a fuel rod exposed to in-pile dry-out from (a) unaffected zone and (b) dry-out zone (PCT<850^{o}C).

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