LEIBSTADT NUCLEAR POWER PLANT

Leibstadt NPP is powered by a General Electric boiling water reactor (BWR) of 1,220MWe power output, commissioned in 1984.

PRESENT EXTENDED OUTAGE AT LEIBSTADT NPP

At Leibstadt, the planned 2 August 2016 partial refuelling outage was originally scheduled to end on 27 August, was first extended by a further 8 weeks until 29 October, but is now projected to last through to February 2017.

Apparently, at that time in its routine reporting to the Swiss federal nuclear safety regulator (ENSI), the Leibstadt operator Axpo failed to fully disclose its understanding as to why eight or so fuel pins had sustained surface damage whilst in core – the damage was subsequently acknowledged to be due to an in-core phenomenon referred to as 'dryout' dating back to the 2012-2013 fuel core cycle. It is now reported that similar levels of fuel pin surface scarring arose in subsequent fuel core cycles.

For the 2015-16 fuel cycle Axpo put in place specific measures to eliminate what it believed to be the root cause triggering dryout and the accompanying fuel pin scarring but examination of the 2015-16 fuel core fuel removed in mid-August revealed the problem persisting with similar area of fuel pin dryout surface scarring developing during the fuel cycle. In other words, the root cause solution implemented by Axpo did not address and rectify the dryout phenomenon.

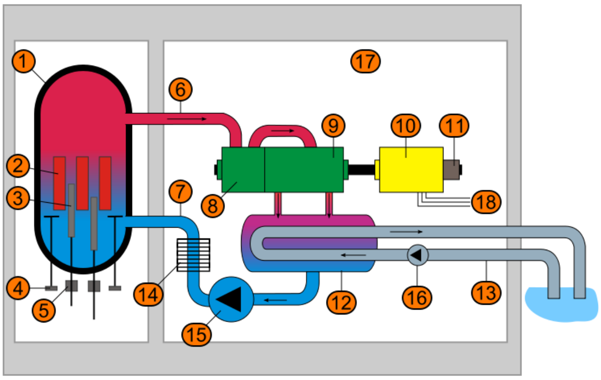
In order for Leibstadt NPP to be allowed to start up again, ENSI has stated (20 December 2016) that

> *". . .the fuel core loading and reactor operation must be such as to exclude dryout during normal operation, in the event of operational malfunctions and in accident categories 1 and 2 of the design basis accidents".*

Preparations towards satisfying this ENSI requirement seems to have been the reason why a normally 3 to 4 week refuelling outage of 2016 has now been extended indefinitely until at least February 2017 (24 weeks+).

DRYOUT PHENOMENON

To better understand the dryout phenomenon, consider the general operation of a BWR shown by the following schematic:-

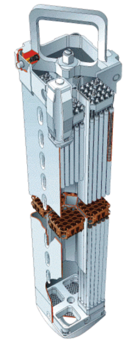


In the BWR the reactor water coolant circuit passes through the reactor fuel core (2) emerging as saturated steam in the reactor pressure vessel (1) header plenum, thence directly to the turbo-alternators (9-10), condensed in the separate condenser (12) to be pump (15) returned via the cold leg (7) to the RPV.

As the cooler water passes up through the fuel core (2-3), receiving 'sensible' heat from the nuclear fuel, the boiling point is reached at which the temperature ceases to rise further. Thereafter, the water undergoes the (physical) state change from water to vapour, receiving heat input from the fuel in the form of 'latent heat of vaporisation'.

Thus the higher section of the BWR coolant circuit is in a quasi equilibrium condition of 'saturation', existing in the state of a liquid (water), or vapour (saturated steam), and/or a combination of both. Ideally, the boiling phase is 'nucleate' being the formation of miniscule bubbles of steam forming on the surfaces of the fuel pins to rise through the water to the liquid-vapour surface interface – much the same as the boiling process than can be observed on the heating element of a domestic electric kettle as it comes to the boil.

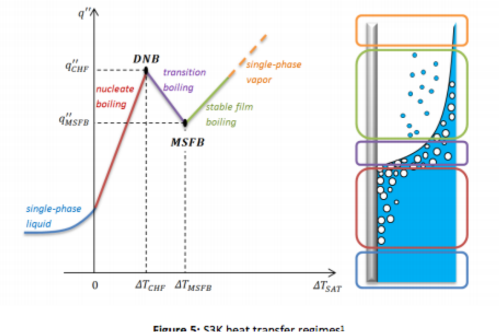
In the case of Leibstadt NPP the equivalent of the kettle heating element surface is the fuel core containing (648) fuel assemblies each of which is made up of a lattice of (91 or 96) slender fuel pins, each about 4m long and of ~20mm diameter – a typical BWR fuel assembly is shown right. Each fuel pin is sheathed within a sealed cladding tube of thin gauge (~1mm) zirconium alloy containing a stack of ceramic, uranium oxide pellets. At the completion of each fuel cycle about 130 or so fuel assemblies are withdrawn from the core and replaced afresh - this is an equivalent burn-up rate of about 25 tonnes of low enriched uranium per reactor year of operation.



Water boiling under saturated conditions occurs over the height of the fuel core. Ideally, the saturated steam gathered at the top of the RPV (1) to be fed to the turbine (9) should be 'dry', that is free of water droplets which will erode the turbine blades – for this condition all of the 'sensible' heating phase should have been completed in the lower to mid section of the fuel core, with the 'vaporisation latent' heating completing as the steam emerges at the top of the fuel core.

If, however, the fuel core 'sensible' heating is too low then the steam collecting in the upper dome cavity of the RPV (1) will be too 'wet' and unsuitable to pass to the turbine (9) - this condition can be rectified by reducing the coolant mass flow rate through the fuel core and/or by increasing the nuclear reactivity (fission heat generation) of the fuel by appropriately retracting the control rods (5).

On the other hand, if the 'sensible' heating is excessive in the lower regions of the fuel core, the state change to a vapour may be premature with steam completely displacing the liquid state in the mid and higher sections of the fuel core – this is the condition of 'dryout'. Dryout is accompanied by two further processes that of, first, 'transition' followed by 'stable film' boiling (shown right) – avoiding occurrence of the first of these boiling regimes, ie 'boiling transition' is essential for the safe and economic operation of light water moderated reactors, particularly the BWR design such as Leibstadt NPP.



DEVELOPMENT OF DRYOUT

To some extent dryout can be controlled by jiggling around with the hydro-thermodynamics of the situation, for example increasing the liquid phase mass flow by deploying the jet recirculation pumps (4), and/or by inserting the control rods (5) further into the fuel core, thereby suppressing both reactivity and heat output of the fuel.

However, the dryout phenomenon is accompanied by several detrimental effects being, first, a significant reduction in the efficacy of heat transfer from the fuel pin to the vapour phase resulting in a rapid internal temperature rise within the fuel pin itself, leading to accelerated cracking and granulation of the ceramic oxide fuel pellets within the zirconium alloy sheathing. At dry, elevated temperature the pin sheathing is vulnerable to exothermic and violent reaction (ie oxidation liberating free hydrogen - $Zr + 2 H_2O \rightarrow ZrO_2 + 2 H_2$) with the remaining high temperature steam fraction in the void.

The unstable initiation of the oxidation process of the zirconium alloy (Zircaloy) sheathing that results in tell-tale surface scarring of the fuel pins subject to localised dryout - it is this scarring present on 8 or so fuel pins from the 2015-16 fuel cycle at Leibstadt NPP that have justified the present extended outage (over all of the recent fuel cycles about 47 pins have been surface damaged by dryout).

Dryout is usually associated with short periods of time when the plant is adjusting to a change in demand but in circumstances where the dryout phenomenon lasts for longer time periods the continuing integrity of the fuel cladding might be challenged. In this case, a failed fuel pin sheathing will permit radioactive fission product material being released into the coolant stream and heavy radioactive contamination of the turbines and condenser equipment. Avoiding 'transition' boiling during both normal operation and, particularly, anticipated operational occurrences (AOOs), is key to the safe and economic operation of BWR nuclear plant.

The second detrimental effect relates to the nucleonic response to the presence of steam void in the reactor fuel core, the formation of a steam void (the void fraction) results in an immediate reduction in neutron moderation (ie steam is a very much less effective moderator of neutrons than water, so less slowed or moderated neutrons and a lessening chain reaction). The automatic response to a bout of negative reactivity is a withdrawal of the control rods (5) to maintain steady power output. At first consideration management of this void fraction phenomenon might seem relatively straightforward, being within the neutron and reactivity control systems of the nuclear plant. However, the dryout (and steam voidage) at Leibstadt NPP seems to have occurred asymmetrically which could lead to oscillatory instability in the core.

Applied to BWR plants, like Leibstadt NPP, the thermal margin against dryout and the absence of boiling transition is referred to as the transient critical power ratio (CPR). The CPR is the threshold at which the surface temperature of the cladding starts to rapidly increase, indicating the onset of dryout so, factored into this, is setting the minimum critical power ratio (MCPR) that should not violate the defined safety limits in order to prevent boiling crisis conditions taking hold. Obviously, if fuel clad surface scarring has occurred (as at Leibstadt NPP) then the immediate response would be to reduce the MCPR but this will be accompanied by a reduction in thermal efficiency of the plant overall.

In recent years cross cooperation between the Swedes and Axpo has resulted in development steady-state and transient analysis for both fuel and operating conditions at the Leibstadt NPP. For transient calculations and modelling Axpo uses the transient nodal code developed by the Swedish company Studsvik Scandpower (SSP). This approach has enabled Axpo to simulate fuel core behaviour under limiting AOO transients and for calculating the ΔCPR thermal margins under those transient conditions – this has led to a further refinement which takes into account the developing approach that models the peak fuel pin cladding temperature (PCT) for relative short-term AOO transients. The benefit of greater reliance upon the PCT, against the MCPR, results in greater thermal efficiency of the NPP.

Greater dependence on PCT-related criteria requires a fuller understanding of the downstream steamline feeding the turbines. This is because in the BWR design the steamline is directly connected to and influences the conditions and transients occurring in the nuclear reactor, this applying for even for the most minor of AOOs. For example, the sudden closure/opening of a steamline valve will transmit a pressure wave that could collapse a steam void in the fuel core leading to a decrease of the void fraction and a sharp spike of positive reactivity, with the accompanying increase in fuel clad temperature leading to a dryout transient.

If the downstream steamline conditions are incorrectly modelled then an actual AOO could have resulted in the fuel pin surface scarring discovered at Leibstadt NPP.

The Axpo PCT programme must have been approved by the Swiss regulator ENSI and, if so, it is somewhat surprising that the occurrence of surface damaged fuel was not foreseen or, indeed, avoided in subsequent fuel cycles. In 2009 ENSI introduced further requirements for AOOs that, most probably, related to application of the Swedish transient nodal code - *Anforderungen an die deterministische Störfallanalyse für Kernanlagen: Umfang, Methodik und Randbedingungen der technischen Störfallanalyse, ENSI-A01, Switzerland, Eidgenössisches Nuklearsicherheitsinspektorat.* ENSI is also reported to have issued a confidential guideline limit for minimum critical power ratio (MCPR) that is complemented by time-dependent criteria using the peak cladding temperature (PCT) – if so, this follows several Nordic countries have already implemented safety criteria drawn from PCT modelling.

The potential for dryout also relates to the fuel pin and fuel assembly design – it is known that the Westinghouse fuel supplier to Leibstadt NPP has used a test loop facility for transient dryout tests on the resilience and integrity of the fuel but, like Axpo simulation work, nothing much of value is publicly available. Typically, fuel pins have a power limit imposed of around 43 kW/m of fuel rod length (about 170kW for each Leibstadt NPP fuel pin). This limit ensures that the axial centreline temperature to below the fuel pellet melting temperature in the event of the worst case plant transient/scram.

In a credible worst case event scenario, the main steam line is instantly shut to isolate the turbines triggering an immediate rise in BWR RPV pressure. This rise in pressure effectively subcools the reactor coolant instantaneously; and the saturated steam voids collapse into the liquid state (solid water). With steam void collapse, the fission reaction increases (more moderated neutrons) and core power surges drastically (~120% and greater) until it is terminated by the automatic insertion of the control rods – during this highly unstable phase the boiling regime on and nearby the fuel pin surface passes through 'transition boiling', enters 'stable film' boiling and is likely to enter the superheated gas phase of 'single phase vapour heating' – entering this final single phase heating mode is accompanied by a high risk of fuel pin sheathing failure. It is this risk that has (most likely) justified the present extended outage of the Leibstadt NPP.

ASSESSING THE PRESENT OUTAGE DURATION

First, because of the repetitive occurrence of fuel pin surface scarring in successive fuel cycles, from at least 2012 through to 2016, Axpo's analysis and understanding of the dryout phenomenon has failed to identify the root cause.

The fuel pin surface scarring, essentially the engagement and development of oxidation of the zirconium alloy sheathing, is a process that if allowed to continue, would result in sheathing failure and release of fission product particles and gases into the steamlines feeding to the turbines. A near simultaneous or simultaneous failure of the sheathing of several pins would lead to an unacceptable level of fission product contamination of the turbine circuit and, potentially, a significant uncontrolled release into the atmosphere with corresponding radiological consequences to members of the public beyond the perimeter of the Leibstadt NPP.

Accordingly, until the root cause of the Leibstadt NPP dryout has been identified and demonstrated it is unlikely that ENSI will permit restart to any level of power operation. Essentially, this is because intrinsic to the BWR design is that the reactor hydro-thermodynamics are matched to the saturated steam conditions of the turbine so it is not practicable to derate one without seriously affecting the performance and stability of the other – these same hydro-thermodynamics drive the onset and persistence of the dryout phenomenon.

Although Axpo submitted a report on its then understanding of the Leibstadt NPP dryout in mid-December 2016, at this time there is insufficient information in the public domain to assess the present position and proposed remedial measures.

However, it is possible to postulate possible topics of root causes and some very rudimentary gauges of the timescales involved at Leibstadt NPP:-

1) Fuel

   Changes in the fuel pellet/pin design and/or material composition could also contribute to the dryout root cause and, no doubt, the fuel suppliers have underway investigations and proving trials relating to any changes in the fuel. That said, it would be a relatively straightforward action simply to revert to any previous fuel system in use prior to the known onset of dryout in or about 2012. Although, that said, dryout may have been present in earlier fuel cycles but overlooked during post irradiation examination (PIE) of spent fuel removed from the RPV core.

   PIE is challenging because the spent fuel is intensely radioactive and heat emitting (by virtue of its radioactive decay alone) and so has to be handled and examine remotely in a shielded hot cell. Fuel pins located in the inner parts of the fuel assembly grillage have to be extracted for examination which may not be practicably possible without first damaging the pin itself.

   > **Timescale:** If exclusively fuel design related, then complete refuelling of core required, so Westinghouse production lag time and, possibly, some time required for transfers of spent fuel from the Leibstadt NPP fuel ponds to accommodate additional fuel core.

2) Dryout Location

   Determining the number and location of pins that have been subject to dryout damage requires the entire core (of 648) fuel modules being extracted from the RPV and temporarily moved into the fuel storage pond for subsequent PIE.

   Typically, an operational nuclear power plant would not have the specialised PIE hot cell facilities to expediently sift through the entire fuel core contents and, if so, at some considerable time penalty the fuel would have to be transported off-site for examination (usually to the fuel supplier Westinghouse – either Springfields UK or Västerås, Sweden). Moving freshly irradiated (spent) fuel requires a special nuclear safety case because of the presence and risk of release of the highly volatile radioiodine (I-131) during a transportation incident/accident.

Examining the fuel pin surfaces whilst in the pond by robotic underwater endoscope working in the close confines of the pin racking within the assembly grillage has practical limitations and would require some time to develop the equipment and procedures. This may have been the methodology adopted for the total of ~20,000 fuel pins that have been PIE at Leibstadt NPP to date, representing about one-third of the in core fuel, or less than one-fifth of the total fuel throughout to from 2012 to date.

If and when a pattern of the dryout damage is established then modification to that component(s) would have to be undertaken within the design-basis and subject to physical trials – the RPV candidate components include the flow vanes within the RPV; individual fuel assemblies and/or the interlocked clusters of fuel assemblies that form the fuel core overall; asymmetry of the jet pumps; and so on.

Any modification to these components is likely to require approval of a comprehensive safety case review.

> **Timescale:** Depends on complexity of components involved; rate and number of fuel pin PIE; and depth of safety case reviews – at least months.

3) Downstream/Upstream Acoustic Perturbations, etc

More remote from the RPV are sources of downstream/upstream sources of perturbations that could trigger an AOO creating in fuel core conditions conducive to a localise area of dryout.

Modelling the downstream/upstream hydro-thermodynamic conditions would be a challenging exercise, particularly in identifying the appropriate range of AOOs. If it can be shown that the dryout damage experienced to date is linked to a specific or sub-group of AOOs, then modification and in situ testing of the steamline hydro-thermodynamics would be required.

> **Timescale:** Depends on complexity of components involved and availability of in situ modelling which may require full scale physical modelling – at least months.

4) Modified Future Outage Periods

A practicable but somewhat expedient approach might be to limit time period that Leibstadt NPP is permitted to operate at power – the end point of the powered-up period would be whilst the extent of dryout damage to the fuel pins remained within a margin set below which failure was anticipated (ie tipped into probable).

For this scheme of things the initiating AOO(s) would need to be identified and understood; it would require greater reliance upon monitoring the circuit for fuel fission products and improved resilience of 'leak-before-break' margins; there would be electricity production losses because the outage time would need to be extended for fuel pin PIE; and, over the interim term, the overall outage time would be greater because of the increased frequency of outage and lost electricity production.

> **Timescale:** Most likely expedient and holding option for the interim-term until dryout is fully resolved – this is the most likely option to have been forwarded in the Axpo mid-December 2016 report submitted to ENSI – might be achievable by February-March 2017 but heavily dependent upon the discretion of ENSI.