Track 4 – Transient Fuel Behavior and Fuel Performance Methodologies and Test Facilities

Approach to analyze potentially limiting hot low power BWR control rod drop accident

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Introduction

Traditionally the BWR control rod drop accident (CRDA) for has been analyzed for cold zero power (CZP) and hot zero power (HZP), with focus on CZP. In this case the large sub cooling delays the effect of voiding and the only mechanism that in practice limits the power excursion is the fuel temperature feedback (Doppler). However, depending on the transient scenario, it has been shown that hot low power (HLP) might also be needed to consider.

The three BWR units in Forsmark (Sweden) plan for power up rates and are preparing a new final safety analysis report (FSAR). Westinghouse Electric Sweden (WSE) was given the task to support a rewrite of the parts considering reactivity insertion accidents (RIA) using current knowledge about the scenarios, and state of the art methods. Among the identified transients the CRDA analyses for HLP gave some unexpected results.

Description of the transient scenario

The whole startup domain, from cold reactor via nuclear heating to hot reactor operating at full power, must be covered by the analyses. The control rods are withdrawn in groups. Normally each control rod group consists of four control rods. Control rods belonging to a group are located in essentially symmetrical positions. The bayonet coupling between a control rod blade and a control rod drive is postulated not to be coupled correctly after an outage (i.e. human error) or it fails for some other reason (i.e. mechanical break). During control rod withdrawal the blade separates from the drive and the ratchet system, coupled to the drive, cannot prevent the blade from falling out. At the time when it gives the maximum control rod worth (CRW, highest reactivity insertion) it comes loose. This means that the blade can be stuck in its fully inserted position while the drive, together with the other drives (and blades) in the group, are fully withdrawn. The drop is modeled as a constant acceleration (gravity corrected for water buoyancy, 7.4 m/s^2 at cold conditions and 8.0 m/s^2 at hot conditions), which gives a movement from fully inserted to fully withdrawn in approximately 1 s.

If the reactor is critical at the time of the rod drop, a prompt criticality may occur; the course of events is dependent on the phase of startup, core loading and the CRW. This may lead to a substantial energy deposition in the fuel in a very short period of time, which in turn might cause a fuel failure. To avoid fuel failures during RIA transients, the Swedish nuclear power inspectorate (SKI) set limitations on the maximum allowed fuel enthalpy. It is however not practical to dynamically evaluate every core loading against the enthalpy limits. Instead, results of generic studies have correlated CRW (reactivity in pcm) and enthalpy. The CRW can be checked with static methods.

Current methodology

Core loadings and start-up-sequences are statically analyzed from CZP up to 5 % of nominal power. After each control rod group withdrawal, a CRW is calculated for each control rod not in its fully inserted position, i.e. every control rod that has been moved up to that point. The CRW is limited to 800 pcm.

Results from new evaluations

CZP analyses show that apart from a few central groups only the first withdrawn control rod in a group may contribute to a significant increase in reactivity, due to symmetry. To achieve a reactivity increase greater than the effective fraction of delayed neutrons (β_{eff}) one needs normally to consider an erroneous individual control rod maneuver. For a hot reactor the conditions are somewhat different. Even if the control rods are withdrawn in groups every single control rod in the group contributes with almost the same increase in reactivity. An example is given below.

Operating conditions are set to 2 % core power, 1 °C sub cooling, 7.0 MPa steam dome pressure and critical reactor consequently leading to about 1-2 % core average void. Withdrawal of one control rod group gives a reactivity increase of 1600 pcm and a CRW of about 400 pcm for each control rod in the group. This would meet the CRW limit of today but the calculations are done with thermal hydraulics, therefore the value corresponds to a CRW after the impact of void feedback, which reveals only partly the reactivity insertion by the control rod.

Dynamic calculations, with the help of the 3D code POLCA-T, show that the true CRW might exceed β_{eff} leading to a power excursion and potentially exceeding the enthalpy limits. Depending on the start-up-sequence, considerably high enthalpies may be obtained at HLP. An enthalpy maximum is achieved around 2-3 % core power. If the initial power is increased further a faster voiding limits the power excursion. The traditional HZP scenario does not have any initial void content.

Proposal of new methodology

In order to avoid unpractical and time-consuming dynamic cycle specific evaluations, a method of predicting the maximum enthalpy based on static evaluations has been developed.

For HLP conditions, the core loading and the start-up-sequence are important. The resulting enthalpy varies for almost the same static control rod worth, depending on core average void and axial power profile. The traditional methodology cannot be used, and therefore a modified methodology is suggested:

- Static calculations with minimum recirculation pump speed, 7.0 MPa steam dome pressure, 2 % reactor power and 1 °C sub cooling.
- The CRW is calculated with the same (‘frozen’) void distribution as calculated for the case with the rod fully inserted is utilized.
- The maximum local CRW:s for the limiting cases (highest CRW) are evaluated. Local CRW is expressed in pcm/% of control rod withdrawal.

The resultant value of the maximum local CRW is compared to the maximum allowed. The latter can be calculated generically by modifying a typical start-up-sequence and/or core loading in purpose to achieve enthalpies just below the limits.