MANAGEMENT OF BWR CONTROL RODS

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Contents

1 Introduction

The main object of this handbook, is to cover the basis for management of the control rods. The handbook is to provide guidance for those needing an introduction to the topic as well as an up to date review and bibliography.

This information is of interest for people involved control rod management and water chemistry surveillance as well as those who are relative newcomers to this field, who may not be completely up-to-date on;

a) the phenomenology and mechanisms for cracking of the Stainless Steel (SS) cladding and various modes of degradation caused by ingress of water into the control rod,

b) surveillance of the integrity of the control rods,

c) management of control rods based on operation experience.

Such information is relevant to the development and implementation of effective mitigation actions, which impact integrity of the control rods and provide chemical surveillance methods for verification of control rode integrity. The main function of a control rod is controlled absorption of thermal neutrons. The control rods are replaced when they no longer has the required neutron absorption efficiency and thereby has reached its Nuclear End Of Life (NEOL). A control rod with cracks in the blade can fulfil its function of neutron absorption and can be inserted for shutdown. However, it is favourable to replace cracked control rods.

The report covers the range from basic information to current plant experience. The report is written and explained in such a way that those not familiar with the topic can easily follow and can find and grasp the appropriate information.

The report provides in depth understanding of the following topics:

- Section 3 describes the operation of the control rods and the obtained exposure.
- Section 4 describes design criteria and control rod efficiency caused by the depletion of the absorber material.
- The control rod designs of the vendors are presented in Section 5.
- Section 6 describes the absorber materials and neutron absorption properties.
- Section 7 describes cladding material. The factors, which have an influence of cracking in the cladding are also described.
- Section 8 describes produced inventory caused by the neutron capture reactions of the absorber materials.
- Section 9 describes the swelling of the boron carbide absorber. The neutron capture reactions in boron carbide produce helium. The helium is insoluble in the boron carbide lattice. Consequently, the helium retained in the boron carbide matrix resides in internal voids in dislocations or at grain boundaries. The swelling of the boron carbide is proportional to the retained helium in the matrix. The boron carbide swelling is the main the root cause for SS cladding cracking.

- Section 10 describes failure causes with emphasis on the first primary through wall defects allowing ingress of water into the sealed of absorber material. The typical occurrence of these defects are described in Sections 10.2 and 10.3. The main cause of mechanical failure of the control rods is Irradiation Assisted Stress Corrosion Cracking (IASCC). IASCC (Section 10.1) requires three simultaneous acting factors, namely: 1) tensile stresses in the SS material, 2) sensitization, mainly by irradiation of fast neutrons and 3) oxidising environment, reactor coolant. Thus, the stress induced by boron carbide swelling is an important factor.

- Section 11 describes the secondary degradation as a result of the through wall cracks in the absorber zone which allows ingress of water into the sealed off absorber material. Consequently, primary defects may result in secondary degradation in form of reaction between the irradiated absorber and reactor coolant. Ingress of water will also enable initiation of IASCC on prior sealed of inner surfaces.

- Section 12 describes release of neutron capture produced inventory caused by through wall cracks in the absorber section.

- Section 13 describes methods for off-gas and water chemistry surveillance and the experience of these techniques.

- Section 14 describes monitoring of control rod integrity based on off-gas and chemistry surveillance.

- Section 15 describes guidelines for operation of control rods based on operating experience.

- Section 16 describes neutron induced radioactivity of the control rods.

- Section 17 describes control rod management based on off-gas and water chemistry surveillance and the experience of these techniques, control rod operating experience and on understanding of control rod behaviour described in the other sections.

2 Background

The Boiling Water Reactor (BWR) is a light water reactor where water is utilized as a moderator and a coolant. The water in the reactor flows from the bottom of the reactor vessel up through the fuel in the core and thereby heated by the fuel to generate the steam for the turbines. The main circuit handles the generated steam from the core, which drives the turbines and then passes into the condenser where the steam condensates. After clean up, the condensate returns to the reactor. The reactor water is a highly pure water with extremely controlled chemistry. The coolant circuit is a flow of coolant used for cooling of the condenser. The coolant water can be water from the sea or a river.

BWR control rods are made of materials capable of absorbing thermal[1] neutrons without fissioning themselves. They are used to control the rate of fission of uranium and plutonium. The control rods are designed to go between the nuclear fuel assemblies in the reactor core. Four assemblies surround an inserted control rod in a so called super cell. In the BWR, the control rods are inserted from the bottom of the reactor pressure vessel by the control drive mechanism, which is located outside the vessel.

The control rods perform the function of *reactivity*[2] control both globally and locally and by the latter also control the power distribution of the core. Most control rods are completely withdrawn from the core during operation, but fully inserted for shutdown of the reactor.

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[1] A thermal neutron is a free neutron with a kinetic energy of about 0.025 eV.

[2] The fractional departure of a system from criticality is often expressed by the *reactivity*, ρ, and defined by: $\rho \equiv \frac{k_{eff}-1}{k_{eff}}$. In the steady state condition, just as many neutrons are produced by fission as are lost by absorption and leakage from the reactor in a given time. In such a system, the condition for *criticality*, i.e. for a self-sustaining fission chain to be possible, in the infinite system is that the effective multiplication factor, $k_{eff} = 1^2$. k_{eff} = Rate of neutron production/(Rate of neutron absorption + Rate of neutron leakage).

3 Operation of control rods

The control rods of BWR are used not only for shutdown of the reactor, but also to control the core reactivity and power distribution of the reactor. This is achieved by partially inserting control rods during the operation of the reactor.

The control rods are also used for SCRAM[3], which is an emergency shutdown of a nuclear reactor.

Depending on whether a rod is used for both core control and shutdown, or only shutdown, it is classified into two different groups, the control group or the shutdown group.

The control rods used to fulfil the following tasks and are labelled as follows:

- Shim rods used for power shaping and significant control of reactivity.
- Regulating rods used for fine adjustments and to maintain desired power or temperature.
- Safety rods, which are withdrawn during operation and available for very fast shutdown in the event of an unsafe condition.

3.1 Flux tilting

Flux tilting is a method used to detect which super cell contains failed fuel rods. Before the flux tilting is performed, the power of the reactor is considerably reduced. Insertion and with-drawl of the control rods are then used to alter the power ratio in the fuel rods of each super cell. This will influence the release of active isotopes, which are monitored during the flux tilt operation. The flux tilting operation results in a minor added exposure of the control rods.

Figure 3-1 shows how the power in a core cell is impacted at insertion of a control rod. At the insertion of the control rod, the fuel rod power surrounding the neutron absorbing material in the control rod will decrease. This results in an increase in the water fraction in the upper part of the fuel bundles (above the control rod). The increased water fraction (and less void fraction) will lead to more moderation and a power increase. This power increase in the fuel bundles above the control rod will cause an increase in activity release from the failed rod(-s) can be seen in Figure 3-2.

It is crucial that flux tilting is done correctly or otherwise a failed fuel rod may degrade (opening up of the failed rod) due to the flux tilt. Recommendations on how flux tilting should be done to minimise the risk of degradation of failed fuel can be found in [Rudling et al, 2003].

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[3] A legend has it that the control rods hung above the reactor, suspended by a rope. In an emergency a person would take a fire axe and cut the rope, allowing the rods to fall into the reactor and stop the fission. At some point the title of the person assigned this duty was given as SCRAM, or Safety Control Rod Axe Man. This term continues to be in use today for shutting down a reactor by inserting the control rods.

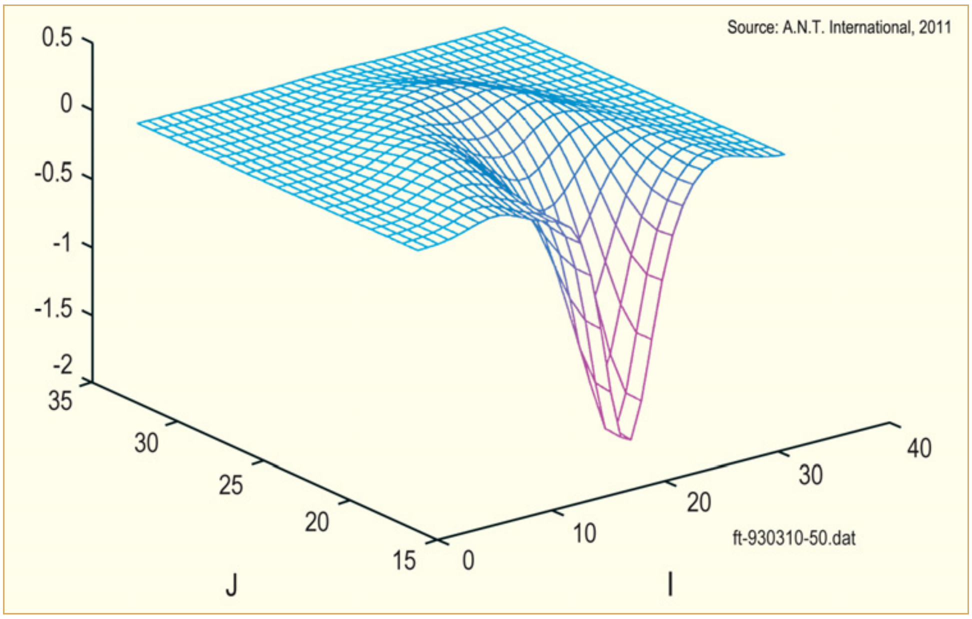

Figure 3-1: The global affect at 50 % reactor power at insertion of a control rod 50 % of in a core cell with high power. Modified figure accordning to [Rudling et al, 2003]

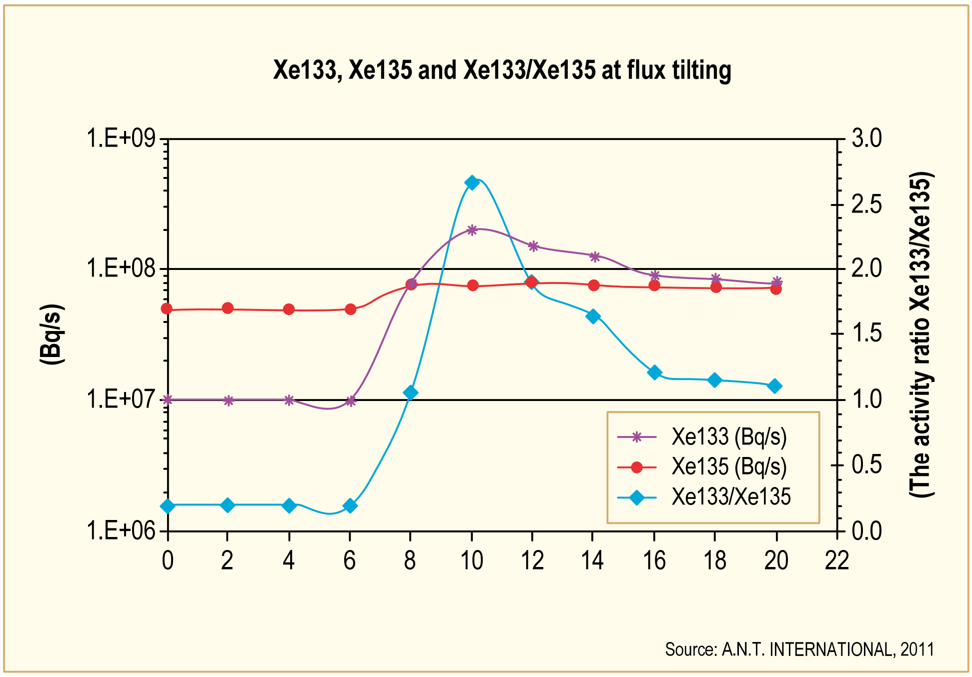

Figure 3-2: Variation of the release rates of Xe-133, Xe-135 and the activity ratio Xe-133/Xe-135 at flux tilting of a core cell containing a defect. Modified figure according to [Rudling et al, 2003].

3.2 Neutron exposure peaking

The uppermost absorber section (tip) of a fully withdrawn control rod is exposed to a neutron flux by leakage of neutrons from the bottom of the active core. This flux depletes the absorber in the tip of the control rod even when if it is fully withdrawn during the operation. The leakage of both fast and thermal neutrons are exponentially decreasing from the bottom of the core downwards. However, the moderation of neutrons immediately below the core results in a local increase of the thermal neutron flux and thereby a slight deviation in the exponential decrease.

Control rods inserted in the core during operation have peak exposures to neutrons close to the edge of the control rod blade wings. The edge of the blade wing will be subjected to an additional neutron flux from the assemblies facing the edge, while the other parts of the control rod are well shielded by the assemblies themselves and are exposed to a neutron flux only from the adjacent assemblies. This effect is further enhanced since the assembly is also somewhat wider than the absorber filled part of the blade wing.

3.3 Safety rods

Reactor shutdown is achieved by full insertion of all the control rods and thus halting the nuclear fission reaction by absorbing neutrons. Some control rods are used solely for this purpose. In a nuclear reactor, shutdown refers to the state of the reactor when it is subcritical by at least a margin (shutdown margin) defined in the reactor's technical specifications.

Shutdown margin is the instantaneous amount of reactivity by which a reactor is subcritical or would be subcritical from its present condition assuming all control rods are fully inserted except for the single rod with the highest integral worth, which is assumed to be fully withdrawn. Shutdown margin is required to exist at all times, even when the reactor is critical. It is important that there be enough negative reactivity capable of being inserted by the control rods to ensure complete shutdown at all times during the core lifetime. A shutdown margin in the range of one to five percent reactivity is typically required.

These control rods are withdrawn during operation and hence only the uppermost section (tip) of absorber section is exposed to the neutron flux. Consequently, over the years the neutron absorption capability of the tip is depleted. However, it takes many years to accumulate exposure to reach high tip ^{10}B depletion, see Section 8.

Figure 3-3 shows an example of a schematic typical obtained exposure profile for withdrawn control rods after 10 cycles in the core, example from a Nordic utility. The Figure 3-3 shows the accumulated thermal exposure in (snvt) versus the axial position in (m) from the top (uppermost absorber part) of control rod and downwards.

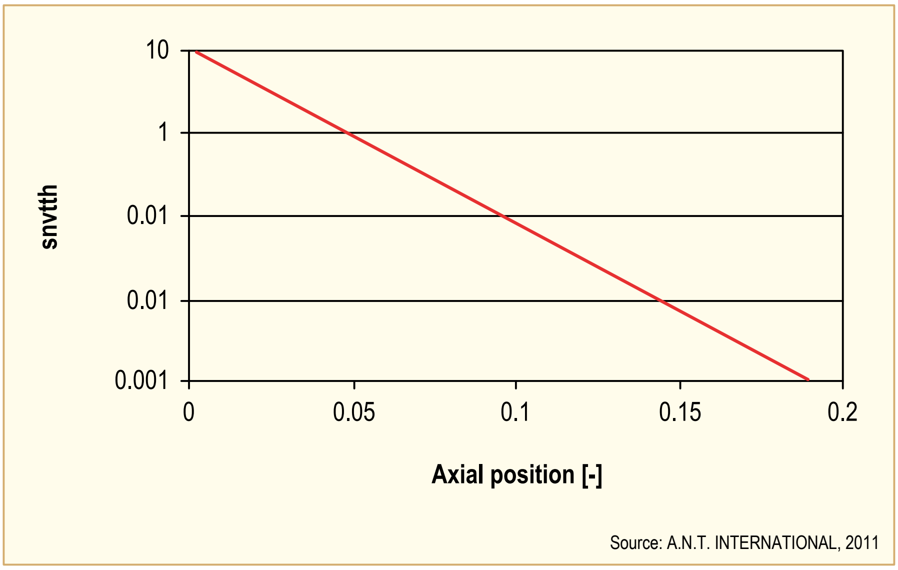

Figure 3-3: A schematic typical exposure profile of a control rod after 10 cycles of operation in withdrawn position. Accumulated thermal exposure in (snvt) versus the axial position in (m) from the top (uppermost absorber part) of control rod and downwards.

Control rods which are mainly used for shutdown operation may occasionally also be used as regulating rods operated partly inserted during some operation cycles. However, these control rods constitute a complement to the shim rods, and are thus generally operated shallowly inserted during power shaping. These control rods are then exposed over a larger section than the rods used solely for shutdown. They will also accumulate a higher exposure of the tip and thereby obtain higher tip depletion than operated in only withdrawn position.

Safety and regulating rods show a considerably larger accumulated neutron exposure in the upper most absorber section.

SCRAM is achieved by insertion of all control rods in the core as rapidly as possible. The BWR uses hydraulic control unit for rapid insertion of the control rods. A gas pressurized storage tank provides the force for rapid insertion of the control rods i.e. within four seconds. On a SCRAM for a reactor that held a constant power for a long period of time (greater than 100 hrs), about 7% of the steady-state power will initially remain after shutdown due to the decay of these fission products. As a result, once the reactor has been scrammed, the reactor power will drop significantly almost instantaneously. A small fraction (about 0.65%) of neutrons in a typical power reactor comes from the radioactive decay of a fission product.

3.4 CCC-operation and power suppression

A few shim rods are generally used for power regulation and are thus fully to partly inserted during a substantial part of an operation cycle, so called CCC-operation. The Control Cell Core (CCC) operation generally uses fixed control rod positions.

These control rods are the most exposed control rods, which accumulate a large neutron fluence during the operation cycle. This control rod group is generally used in combination with less inserted regulating control rods.

A common form of power regulation is based on a pattern of exchanging groups of power regulating control rods. These control rods are used in an exchange sequence where one group is inserted while the other groups of regulating control rods generally are fully with-drawn. Power regulation is performed by exchanging the groups by switch of insertion from one group to another group.