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Rod insertion method analysis – A methodology update and comparison to boron dilution method

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ABSTRACT

The rod insertion method for control rod worth measurement is explained and past as well as recent developments are outlined. The original methodology is updated with a more consistent use of the flux redistribution correction, conversion from dynamic to static reactivity and a new procedure to account for the so-called reactivity overshoot. As an example, the procedure is applied to real measured data from Krško NPP. Resulting integral and differential worth curves are compared with reference measurements by the boron dilution method, where a previously unattainable match is observed. Additional research is presented in order to assess the remaining small deviations. Besides other advantages, the rod insertion method is demonstrated to produce results that are in excellent agreement with those of boron dilution method and can therefore be used as replacement.

1. Introduction to the rod insertion method

Among different ways to control the nuclear chain reaction in fission reactors the use of control rods can be regarded as the most intuitive. Although in pressurized water reactors (PWRs), control by soluble boron is preferred for slow reactivity changes (such as due to the burnup), control rods are used for short-term reactivity control (such as changes to the reactor power level), operating control over the axial power distribution needed to reduce Xenon oscillations in transients, and as the main safety mechanism for reactor shut-down. Control rod reactivity worth is a safety-related parameter. To determine it numerous methods exist (Keepin, 1965; Shaw, 1969). Among the classical methods, the distributed poison technique (*boron dilution method*) and the rod swap method can be used (also in combination with measurements of the stable period/doubling time or a direct solution of the inverse point kinetics equations with an on-line reactivity computer).

On the verge of 1990's, a new method, the so called "*rod insertion method for control rod worth measurements*" (named the **rod insertion method** for short) was developed at the Reactor Physics Department of the Jožef Stefan Institute (JSI) (Čopič, 1976; Glumac and Škraba, 1989; Trkov et al., 1995). It relies on the analysis of the reactor power signal, which is recorded during continuous insertion of a control rod bank. Thus, the major advantage over the other methods is indicated: its high execution speed (approximately 15 minutes per control rod bank), which is an important economic incentive for the operators of nuclear power plants (NPPs).

1.1. Work by other authors

After being validated at the JSI TRIGA research reactor (Trkov et al., 1995), the rod insertion method was used in low power physics tests (LPPT) at the Krško NPP. This power plant was the first in the world to apply the rod insertion method as the primary method of rod worth determination, followed by several other power plants throughout the world. Furthermore, the rod insertion method was later developed independently by the Westinghouse Electric Company and brought to market under the trademark DRWM™ (*Dynamic Rod Worth Measurement*) (Chao et al., 1992, 2000), which by itself is an evident fact on the efficiency of the method. Other authors adopted the rod insertion method as well: Kastanya and Turinsky, 1996 nearly simultaneously as Westinghouse, while some followed later (Petényi et al., 2005; Lee et al., 2005; Hong and Song, 2013; Wu et al., 2015; Kim et al., 2015). Applications of the rod insertion method to VVER-440 (Petényi et al., 2005) and modular reactors (Hong and Song, 2013) are also

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known. In general, these referenced works are very similar to each other from the theoretical point of view and mostly differ in details arising from various implementation constraints. Here however, we introduce a novel correction of the so-called reactivity overshoot.

Among the last authors writing about the rod insertion method, Lee et al. (2005) published an extensive report on their version of the method in 2005. However, a deficiency in their application of the rod insertion method exists, caused by a very slow control rod insertion speed (limited by the control rod drive mechanism). They have to initiate control rod bank withdrawal as soon as it reaches maximum insertion to avoid losing the flux signal. The signal background is then determined iteratively so that the differential worth at the maximum insertion is effectively zero. This procedure is less precise compared to a prolonged measurement with the control rod at fully inserted position, as we will see in the remainder of the text.

1.2. The principle

As already indicated, the experimental part of the rod insertion method is quite straightforward: start from a critical configuration, insert the control rod bank at its maximum but constant insertion speed and record the flux signal from a neutron detector. At fully inserted position wait for some 30–40 s and then withdraw the control rod bank. This experimental sequence and the corresponding power and reactivity signals are illustrated in Fig. 1. Obviously, the starting neutron signal level has an upper limit due to the onset of temperature feedbacks which would prevent us from distinguishing the contribution of the temperature and of the control rods. Moreover, no reactivity compensation is applied during the execution of the rod insertion method. Thus, the useful neutron flux signal in a deeply sub-critical core falls by several decades and diminishes to the level of the background signal. A way to properly determine this parasitic signal is therefore an integral part of the rod insertion method.

The time dependent reactivity is calculated from the measured signal using the inverse (point) kinetics equations (Henry, 1975; Trkov, 2004). For this purpose, the signal must therefore be proportional to the core-integrated neutron population, i.e. the neutron flux amplitude function, $T(t)$. During the insertion of the control rod bank, however, important spatial as well as temporal effects occur, which change the spatial distribution of the prompt and delayed neutron population. Since a detector measures the local flux at the detector location, the proportionality factor changes with time, because the neutron population density distribution also changes. Correction factors can be devised for this purpose (Trkov et al., 1995; Chao et al., 2000), namely the static correction due to the redistribution of the neutron flux and the dynamic correction due to a temporal delay (the delayed neutron distribution is trailing behind the distribution of the prompt neutrons). Dependence of the proportionality factor on the axial position of the control rod bank being inserted can either be tabulated or approximated by a simple function.

Spatial correction factors in general were also discussed by Rosselet (1999). He specifically addressed the need to reduce the dependence on the correction factors and the underlying computer simulations as these are subjected to uncertainties in nuclear data and geometrical models, as well as to errors arising from physical and numerical simplifications of the equations. The inherent dependency on correction factors obtained from calculations is one of the few downsides of the rod insertion method.

The effect of higher-than-fundamental flux modes is not accounted for in our application of the rod insertion method. The *dominance ratio* offers some indication on the error associated with this simplification, but the error is generally believed to be reasonably small (Chao et al., 2000). In our case, the dominance ratio is 0.992, which with the effective neutron lifetime of $\Lambda \doteq 10.454\,\mu\mathrm{s}$ means that after an excitation the first harmonic mode diminishes to 1% of the fundamental mode in just 6 ms (i.e. 3 ms per order of magnitude). Continuous insertion does provide continuous – but very small – excitations, so this approximation is well justified.

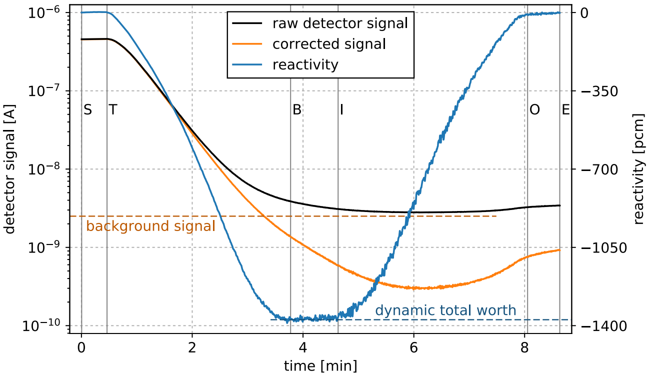

Fig. 1. Rod insertion method sequence with the corresponding power and reactivity signals – an example for the Krško NPP. The first and last of the "S, T, B, I, O, E" labels indicate the *start* and the *end* of the experimental procedure, while the other four correspond to the control rod bank position: *top*, *bottom*, *in* and *out*. Note how the usable (corrected) neutron signal is "drowned" in the background even before the control rod bank has reached its fully inserted state.

1.3. Computational model

The simulation tool used in our survey is the GNOMER computer program (Trkov and Merljak, 2015), which is a 3D neutron diffusion solver of the reactor core design system CORD-2 (Kromar and Trkov, 2009; Ravnik et al., 2008). Both have been available from the NEA Data Bank (Nuclear Energy Agency, 2016) for quite a while, and recently GNOMER has been thoroughly updated to support kinetic simulation (Merljak et al., 2017). Here, Green's function nodal method is used and the time-dependent neutron diffusion equation is solved directly at each time step.

The research was performed for a realistic test case: the Krško NPP, which has a Westinghouse-built PWR (Testa, 1984). For this reactor, there already exists a cyclic quadrant-symmetry core model for GNOMER (depicted in Fig. 2) that is more than appropriate for our purpose as it is regularly used to verify the core design provided by the fuel manufacturer. One node per fuel assembly is used, where its side-length is 19.89245 cm. In the axial direction, there are 24 layers of 15.24 cm thickness, enclosed at each end with a 30.48 cm thick axial reflector layer. Control rod bank positions are given in steps: 225 steps means fully withdrawn position and step 0 corresponds to fully inserted, bottom-most position.

In the simulation, at each time step the control rod bank was inserted a bit further into the core. At intermediate position within a node the cross-sections for the rodded and the unrodded fuel assembly were mixed by the volume-weighting method. Note that for simulation's simplicity the insertion was modelled as purely continuous while in Krško NPP the control rod drive mechanism is operating sequentially (Testa, 1984) (the movable and stationary gripper design results in a *move-wait* sequence with an approximate 0.9 s period). Influence of this simplification is examined in Section 3.1.