AN ON-LINE ADAPTIVE CORE MONITORING SYSTEM

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Abstract

An on-line core monitoring system has been in operation for three years in the Dodewaard Nuclear Power Plant. The core monitor uses the on-line measured reactor data as an input for a power distribution calculation. The measurements are frequently performed, the power distribution is recalculated every two hours and whenever a significant change in certain measured parameters occurs.

The system is used for monitoring as well as for predicting purposes. The limiting thermal hydraulic parameters are monitored as well as the pellet-clad interaction limits. The data are added to a history file used for cycle burn-up calculations and trending of parameters. The reactor states are presented through a convenient graphical user interface.

At the Dodewaard NPP the assessment of the power distribution is entirely based on the neutron Traversing In-core Probe (TIP) measurements and calculations. The core monitor calculation of the power distribution is calibrated with the TIP traces measured at least once a week. This is done by adapting the calculated TIP traces to the measured TIP traces in an iterative process. Corrections are added to the nodal $k_\propto$ values in such a way that at the end of the process the calculated TIP traces match exactly the measurements. These corrections of $k_\propto$ have an impact on the power distribution which is slightly changed in accordance with the TIP-measurements. The $\Delta k_\propto$'s are stored and used for calculation of the power distribution until the next calibration with the measurements is performed. When no $\Delta k_\propto$'s are used, the RMS-value of the difference between measured and calculated nodal TIP traces is typically 4%. Using the old $\Delta k_\propto$'s in forecasting the future TIP traces gives a RMS of 2%.

Introduction

The Dodewaard NPP has a BWR (183 MWth) which is cooled by natural circulation. This first Dutch nuclear power plant was started up in 1968. At the moment a plant upgrade project is in progress. As a part of this project a core monitoring system is being installed for continuous observation of operation limiting parameters. This system has been developed since 1992 and will be implemented in the control room in the future.

Description of the core monitoring system

A core monitoring system has been developed by the Dodewaard Physics Group. The core monitor calculation of the power distribution is based on the nodal code LWRSIM [1] (a code developed for this purpose) which uses a one group kernel method. The CASMO code [2] provides the k_∞, M^2 and detector response functions for LWRSIM. CASMO is a 2D assembly burn-up code making use of the transport theory.

The core monitor can run in several modes depending on the purpose necessary.

The system is continuously running in the MONITOR mode to watch the thermal hydraulic parameters and create a history file with all the interesting measured and calculated quantities. In this mode no human interaction is necessary. The measured reactor data are collected by a data logging computer and then retrieved by a separate workstation for use in the core monitoring system. The 3D power distribution inside the core is calculated on-line with the measured reactor data as input. From the power distribution thermal hydraulic parameters like Maximum Linear Heat Generation rate (MLHGR) or Minimum Critical Power Ratio (MCPR) are derived and monitored. The parameters related to pellet clad interaction limits are monitored as well.

Because there are no local power range monitors in the Dodewaard reactor there is no possibility of a continuous measurement of the power distribution. The neutron TIP recordings provide the only way to monitor the power distribution and the thermal hydraulic quantities. Therefore the TIP measurements are done on a weekly basis. The TIP traces are recorded on paper and electronically on a hard disk. A calibration of the calculated 3D power distribution by the core monitor is started automatically as soon as the TIP measurements are finished. The physicist only has to check that the measurements and calibration have been done correctly and that all the parameters have remained within operating limits.

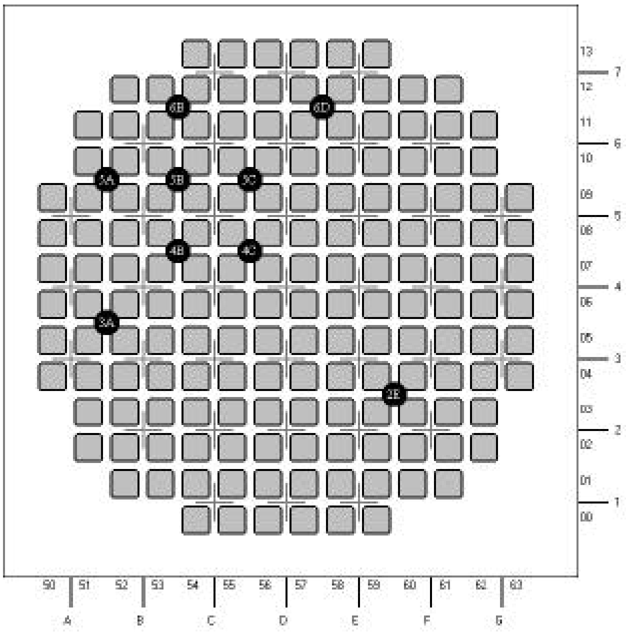
All the other modes are started manually. They do not interfere with the on-line MONITOR mode, although the reactor states saved by the MONITOR mode, can be read in and used. The REPORTER mode is used to view and print the reactor core states. The CALIBRA mode is used to manually start a calibration of the core monitor with the measured TIP curves. Predictive capabilities of the system are used in the WIZARD mode to help the physicist or operator in finding the best operating strategy and keeping the reactor state within Technical Specification limits. The WIZARD mode includes search options for control rod pattern, thermal power and k_{eff}. This mode is used to make predictions starting with the actual reactor state as calculated by the core monitoring system in the MONITOR mode.

A back-end graphical user interface is developed for convenient data presentation of reactor states, trending of parameters and forecasting calculations. The user interface is running on all PCs which are connected to the core monitoring system through a local computer network. The user interface gives full access to all the parameters on a nodal level (36 axial nodes for 164 assemblies). Elementary condensing operations like averaging over all axial nodes, or taking the maximum nodal value of a specific assembly can be performed through a control panel on screen. Parameters can be plotted versus time after having read the saved reactor states from the past or predicted future reactor states.

Description of the adaptive method

An adaptive method based on an idea by Congdon *et al*. [3] is used to match the calculated TIP traces to the measured TIP traces. In an iterative process corrections are added to the nodal k_∞ values in such a way that at the end of the process the calculated TIP traces exactly match the measurements.

Figure 1. Geometry and TIP positions of the Dodewaard core



TIP measurements are performed at a limited number of positions in the core (see Figure 1). At places where no measurement is done a TIP trace is constructed by using the quadrant symmetry of the core and by inter- and extrapolating the measured TIP traces. The TIP readings are translated to a flux Φ_m at the position of the assemblies using bilinear interpolation from the four nearest TIP traces. The k_∞ values are calculated in the first quadrant of the core where most of the TIP measurements are done. For this purpose TIP curves *3A* and *6D* are copied to their imaginary mirror positions *4A* and *6C* in the first quadrant (not indicated). TIP curve *2E* in the third quadrant is not used for the adaptive process but to check the symmetry of the core power distribution. The same Δk_∞ values used in the first quadrant, are applied to the mirror positions in the other three quadrants.

The diffusion equation applies to both the flux derived from the measured TIP curves Φ_m and the flux derived from the simulated TIP curves Φ_s, where in the equation for Φ_m an extra correction term Δk_∞ is added to the k_∞ value:

$$\nabla^2 \Phi_s + B^2{}_s \Phi_s = 0, \quad B^2{}_s = \frac{\left(\frac{k_\infty}{k_{eff}} - 1\right)}{M^2}$$
$$\nabla^2 \Phi_m + B^2{}_m \Phi_m = 0, \quad B^2{}_m = \frac{\left(\frac{k_\infty + \Delta k_\infty}{k_{eff}} - 1\right)}{M^2} \tag{1}$$

Here B^2 stands for buckling and M^2 stands for migration area. After subtracting these equations an expression is obtained for the difference in flux $\Psi = \Delta\Phi = \Phi_s - \Phi_m$:

$$\nabla^2 \Psi + \Delta B^2 \Psi = 0, \quad \Delta B^2 = B^2{}_s - B^2{}_m = -\frac{\Delta k_\infty}{k_{eff} M^2} \tag{2}$$

Solving this expression for Δk_∞ yields:

$$\Delta k_\infty = -k_{eff} M^2 \Delta B^2 = k_{eff} M^2 \frac{1}{\Psi} \nabla^2 \Psi \tag{3}$$

The term $\nabla^2\Psi/\Psi$ in the last expression is estimated with a finite difference approximation for the second derivative. Finally the estimation of the correction term Δk_∞ is used in an iteration loop. When the iterative process is converged the simulated TIP curves are equal to the measured TIP curves. The 3D power distribution and derived quantities are slightly changed by this process and are now in accordance with the measured TIP values. The Δk_∞'s are stored and used for future on-line power distribution calculations until the next calibration is performed.

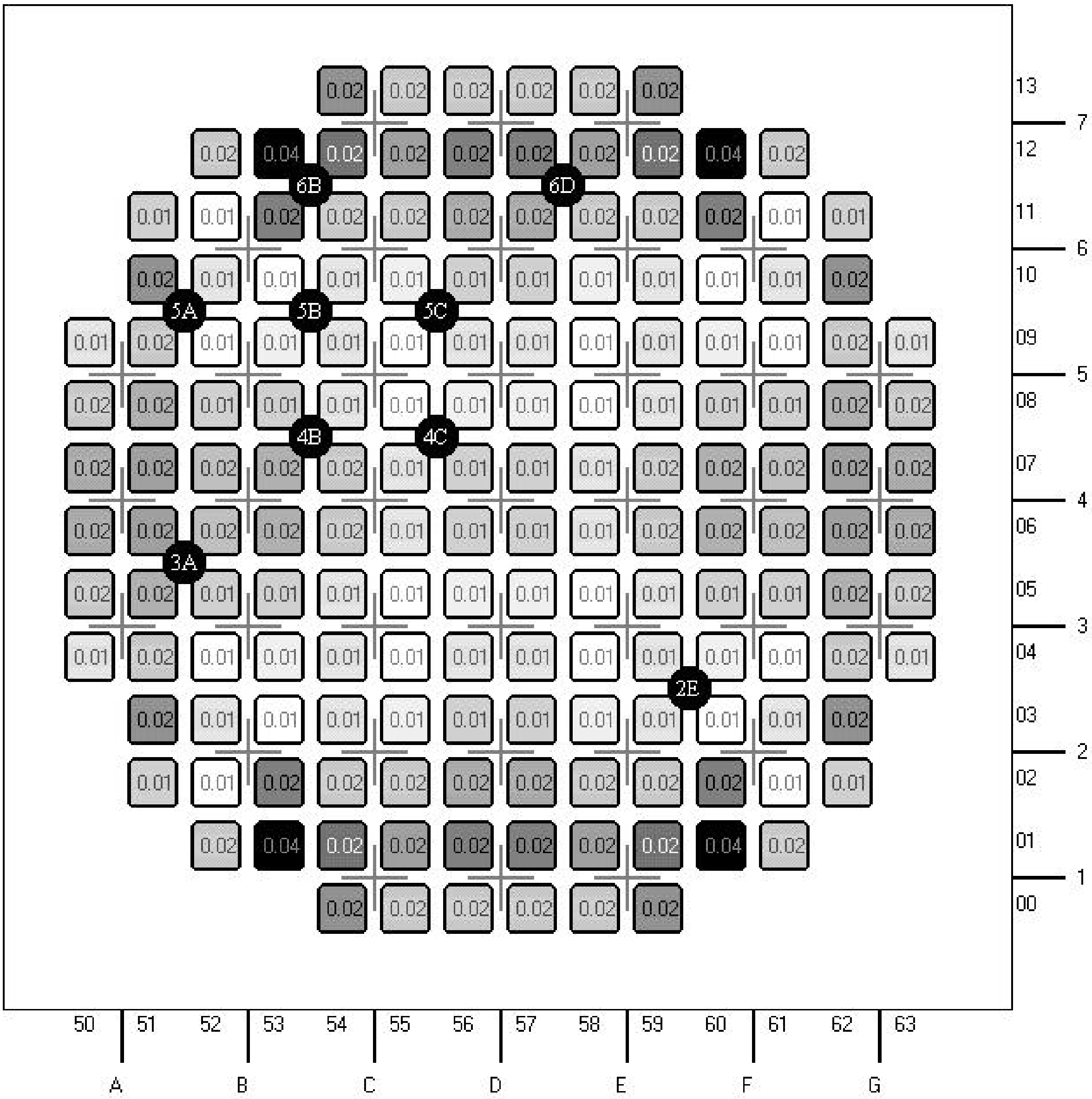
The adaptive process is a mathematical way to substitute the differences in TIP values with differences in k_∞ values. It is done to make the calculation of the power distribution in complete agreement with the measurements. The price that has to be paid for this is a set of k_∞ correction values the most of which are small. Since the adaptive process works with almost any set of TIP curves, the Root Mean Square (RMS) value of the TIP differences before adaptation or the RMS value of the k_∞ differences after adaptation should be considered to assure that no obvious mistake in either the measurement or the calculation has been made.

Results

In an earlier study the correlation between the nodal Δk_∞ and other nodal parameters was examined [4]. No correlation was found for any of the examined parameters (relative power, control rod fraction, void fraction, burn-up, flow) except axial and radial positions. These last two dependencies will be discussed below.

Figure 2 shows the radial distribution of the average absolute Δk_{∞} values from the calibration with a typical set of TIP curves in cycle 27. The value of the Δk_{∞} of an assembly is indicated by a degree of darkness. As shown, in this case the largest corrections are needed in the assemblies around the TIP tube *6B*. This indicates that the differences between predicted and measured TIP values are the largest for TIP curve *6B*. A possible explanation is that one or more of the assemblies next to this TIP tube has a bowed channel. Channel bowing has a large impact on the detector response function and results in deviations between measurement and calculation of TIP curves. Because the amount and directing of channel bowing is not known beforehand it can not be modelled.

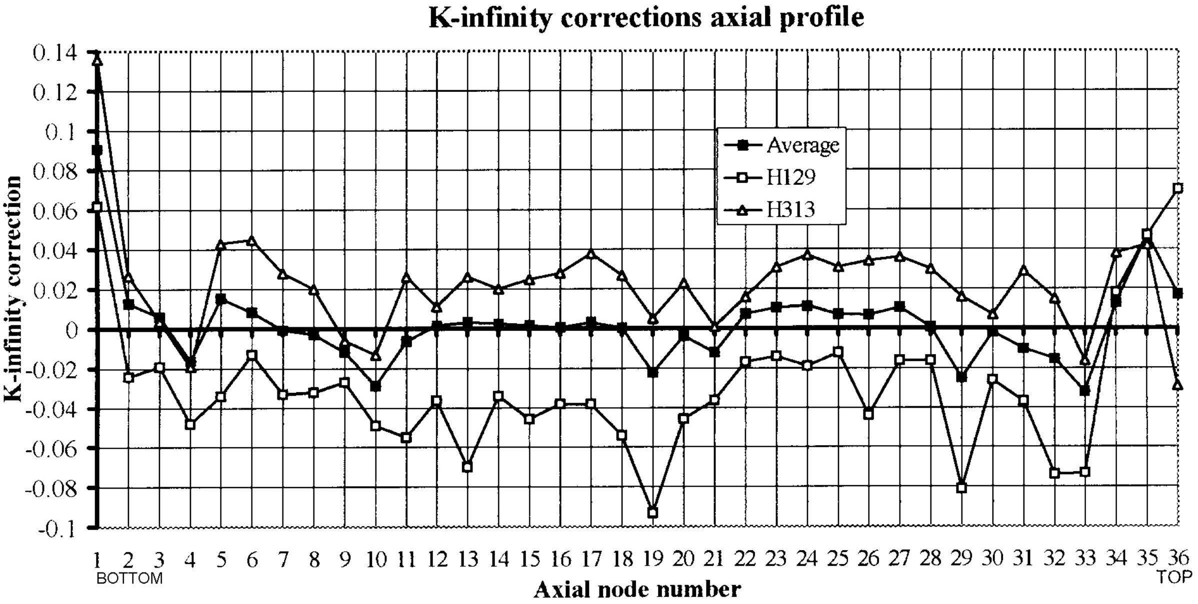
Figure 2. Radial distribution of average absolute Δk_{∞} from TIP measurements on July 22, 1996



It turns out that the radial distribution of Δk_∞ changes gradually during a cycle and stepwise from one cycle to the other. This strokes with the fact that assembly properties like burn-up or channel bowing vary gradually during a cycle. In a next cycle the properties of an assembly at a specific location in the core can change stepwise when the original assembly was replaced by another one. In order to examine a possible correlation of Δk_∞ with channel bowing, at the end of cycle 24 the four channels around the TIP tube where the largest corrections were needed were measured for bowing. The bowing of these channels was not as large as to have to be rejected, whereas by other channels this was the case. Because the measurement of the channel bowing is quite inaccurate no correlation was shown between channel bowing and the radial distribution of Δk_∞ as well.

Figure 3 shows the axial profile of Δk_∞ from a calibration with a typical TIP measurement in this cycle.

Figure 3. Axial distribution of Δk_∞ from TIP measurements on July 22, 1996



The core average Δk_∞ is shown, as well as the axial distribution for the assemblies H313 and H129 which have the highest and the lowest average Δk_∞ respectively. The local minimums at node 10, 19 and 29 can be explained by the fact that there are extra materials at these positions that have an influence on the detector response function. This influence is difficult to model and give rise to systematic errors in the simulated TIP traces. There are spacers at positions 9.8, 19.5 and 29.1 in the core. Furthermore at positions 9.7, and 21.0 there are placeholders between the inner and outer TIP tubes and at node 32 and higher there is a spring and other material located.

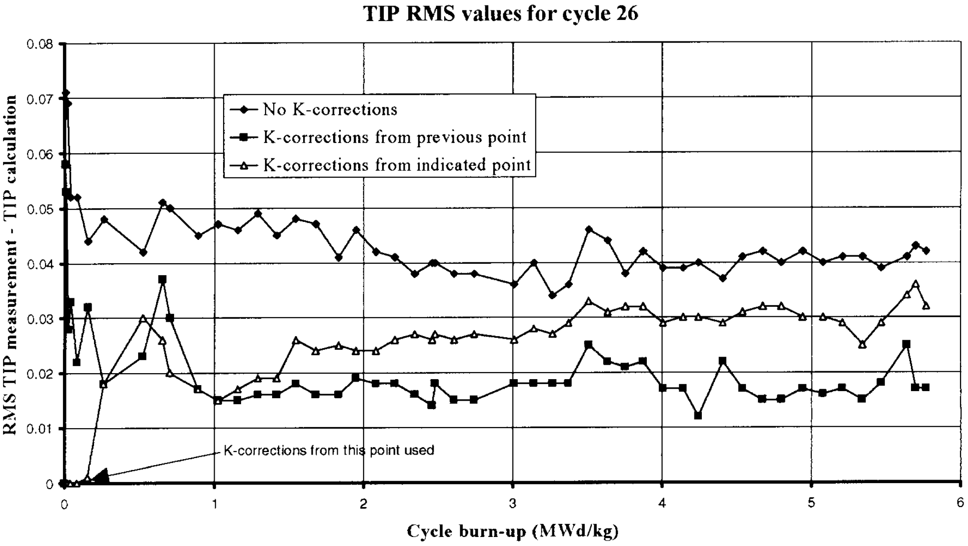
The high value of Δk_∞ at node 1 is caused by an incorrect axial bottom albedo coefficient that is used in the 3D nodal power distribution calculation code LWRSIM. This coefficient can be changed in such a way to minimise the difference in Δk_∞ for node 1.

The axial and radial deviations discussed here can also be seen in a direct comparison of the measured and calculated TIP values.

The information obtained in previous calibrations and stored in the Δk_∞ values, can be used to improve the prediction of TIP curves. A part of the errors is space-dependent but time-independent. This holds true for the errors caused by the influence of extra materials in the core on the detector response function. These errors can be filtered out by storing the Δk_∞ values obtained during a calibration and reusing them in future calculations.

To show this in Figure 4 the RMS values for the difference between the measured and calculated TIP values is plotted versus cycle burn-up in cycle 26.

Figure 4. RMS of ΔTIP values in cycle 26 for different prediction modes



Three different prediction modes are shown for the calculated TIP values. The first is a straightforward calculation without doing any calibrations. This yields a RMS value of about 4 %. The second one uses the Δk_∞ values from the previous calibration normally one week old. This gives a RMS of about 2%. The last one uses the Δk_∞ values of a calibration in the beginning of the cycle which is representative for the rest of the cycle. The first few calibrations are not representative because they are done at startup conditions with low power or no control rods inserted. At the beginning the prediction is as good as in the case that the k-correction from the previous point is used, but gradually the information stored in the correction factors Δk_∞ for the time dependent part of the errors is lost and the RMS value increases. A gradual increase in the RMS value from 2% to 3% towards the end of the cycle can be noted. Nevertheless, at the end of the cycle a prediction with the corrections from the beginning of the cycle is better than the prediction without using Δk_∞ values.

Objectives for the future

At the moment the core monitor is in a verification phase. During this cycle it has been operating successfully. It has been used by the Physics Group as a working tool and for reporting to the Dutch licensing authorities. In the near future it will also be available to the operators in the control room. For this purpose some additional developments have to be accomplished:

- A front-end graphical user interface

  A front-end graphical user interface will be developed in order to simplify the use of the core monitoring system. Especially in the WIZARD mode this will be a useful tool. An operating strategy can be entered in terms of control rod pattern versus time, in which case a corresponding thermal power is calculated, or in terms of thermal power versus time, in which case corresponding control rod patterns are calculated.

- Read measured reactor data directly into the core monitoring computer

  At the moment the core monitor is running on a workstation and is getting the measured reactor data from a separate data logging computer, and measured TIP curves from a third computer. The three dependent computers used by the core monitor make the system vulnerable with respect to possible computer or network malfunctions. In the near future the whole system will run on a single computer collecting and processing all the data. The computer network will not be used for transferring measured data but only to access the system using the PC graphical user interface.

- Implementation in the control room

  A special version of the back-end graphical user interface will be developed which provide the operator only the parameters which are of interest to him; normally operation limiting parameters and some measured reactor data. For instance, instead of all 3D information regarding the linear heat generation rate only the core maximum of this parameter will be presented.

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