APPLICATION OF THE CORE SURVEILLANCE SYSTEM SCORPIO AT SIZEWELL B

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Abstract

The on-line core surveillance system for Sizewell B is based on the SCORPIO system developed at the OECD Halden Reactor Project, and provides capabilities to evaluate the state of the reactor core with respect to operational margins and to predict the future state of the core in power manoeuvres.

Experience from physics tests during the commissioning phase of Sizewell B shows that the physics codes are capable of predicting the measured data with good accuracy. Recently, the system has been extended with two new major features: 1) on-line adaptation of the core simulator, and 2) an advanced strategy generator based on optimal core control.

Future versions of SCORPIO at Sizewell B will employ the PANTHER reference model, already in use at Sizewell B for off-line calculations. This delivers three advantages to the station:

- Reduces the costs associated with maintaining separate reactor physics models;
- Provides greater accuracy;
- Facilitates the exchange of core state information between on-line and off-line calculation routes.

Introduction

SCORPIO was developed at the OECD Halden Reactor Project (Norway), and is now installed on Ringhals Power Station in Sweden [1], several Duke Power plants in the USA, and at Sizewell B in the UK from first criticality.

The benefits of SCORPIO to the utility are the provision of a user friendly, automated core monitoring and prediction system which will:

- Assist the efficiency of reactor operation by continuously and accurately representing the current core state, assessed against the operational margins;
- Improved ability to plan power manoeuvres, avoiding infringements of operational restrictions;
- Improved ability to recover from trips;
- Improved ability to plan for shutdown.

SCORPIO is a flexible tool which can be adapted to the specific needs of a utility. At Sizewell B, it is coupled to the ECOS plant computer system which supplies the desired measurement data. The displays have been modified to comply with other control room systems and match the needs of the operators. It has now also been linked to Nuclear Electric’s 3D reference core model, PANTHER [2].

A brief system overview is given and the operational experience obtained so far at Sizewell B, including traces of operational transients.

A method for on-line adaptation of the core simulator is described as well as an advanced strategy generator based on optimal core control techniques.

System overview

SCORPIO provides capabilities to:

- Capture on-line plant signals from the station’s data logging system;
- Manage the automatic tracking of the evolution of the core through time using a 3D reactor model – both irradiation and xenon are followed;
- Evaluate the state of the reactor with respect to operational margins;
- Predict the future state of the core in power manoeuvres;
- Present all information to desk operators via a sophisticated graphical interface.

Two modes of operation are available, the core follow mode and the predictive mode.

In the core follow mode, the present core state is calculated based on a combination of instrument signals and a theoretical calculation of the core power distribution. An automatic limit check on the core state is performed and the information is then presented on colour CRTs in the form of trend curves and diagrams displaying margins to operational limits.

In predictive mode the operator may investigate the response of the reactor to proposed control strategies, using a high fidelity core model. Results at each future time point are checked against operational limits and the information presented to the user via dedicated graphic pictures designed for ease of comprehension.

Predictive analysis is usually iterative. The operator specifies the required power manoeuvre, uses the strategy generator to propose a control strategy which will keep the core within operation limits, then confirms the strategy by detailed calculation with the 3D core simulator. If it is found that safety limits cannot be satisfied, or the proposed control strategy has other undesirable features, the sequence is repeated with modified inputs until a feasible control strategy has been identified.

Much effort has been devoted to simplification of the man-machine interface for SCORPIO. The input to SCORPIO is entered through a combined use of a mouse or trackerball and an alphanumeric keyboard. The input to be specified by the operator is reduced to a minimum and the input procedure is made as simple as possible. In addition, the operator is guided through a dialogue procedure with context sensitive dialogue fields and functions to be selected from menus. The dialogue is made fault tolerant. This means that feedback is obtained in the form of messages if the operator tries to enter illegal data or for instance tries to start a simulation while the simulator is active, etc.

The pictures have been divided into three different classes according to their content:

- Measured data;
- Simulator results;
- Comparison between measured and calculated values.

Within each of these classes the pictures may be subdivided into trend- and present-data displays. The trend curves have dynamic vertical scales and time scales which the operator is free to modify. This type of “zooming” can be useful when focusing on details.

Operational experience

SCORPIO was installed at Sizewell B in January 1994 prior to the initial commissioning period. It is currently available for use to the “Nuclear Engineering Group”, who perform reactor physics calculations to support station operation. In the future, at a date yet to be decided, it may be made available in the control room.

During cycle 1 SCORPIO used the CYGNUS core simulator, which was configured with nuclear data generated by off-line PANTHER calculations, and iteratively adjusted to obtain a satisfactory measure of agreement with the reference calculation. It was possible to demonstrate that CYGNUS would predict assembly powers within 5% of the reference results, and axial offset within 2%. Performance in tracking the variation of core axial offset was entirely adequate during the first part of the cycle. It was also successful in predicting the variations of boron concentration required to compensate for rod movement, while operating at full power. Figure 1 shows a trace of predicted and measured axial flux difference during a rod calibration transient at 30% power. Note that there are two measured AFD's, from the primary and secondary protection systems respectively. Differences between these indications can be interpreted in terms of rod shadowing. The calculated value lies between the measurements. Figure 2 illustrates a comparison of predicted and measured boron concentration during the same transient, and demonstrates that the calculation follows the variations of boron successfully, subject to a systematic difference of 50 ppm. Note, however, that the model would not be able to provide satisfactory representation of reactivity variations through large power variations, and could not, for example, be relied upon to predict critical boron concentration during the start-up sequence.

Later in the cycle the Sizewell B core was predicted by PANTHER to become unstable to axial xenon oscillations, and the CYGNUS model also became unstable at approximately the same time. These effects were expected, but nevertheless, from this point it became impossible to follow the core xenon dynamics without an adaptive core model. The PANTHER model was therefore reconfigured to track the measured axial offsets, using standard features of the code. In the case of SCORPIO, work on an adaptive version of CYGNUS was already under way at the request of Ringhals, and was made available to Sizewell B in a major system upgrade in August 1996. It has, however, now been decided that from the start of cycle 2 the role of CYGNUS within SCORPIO will be replaced by PANTHER, simplifying the process of generating configuration data for the models and providing greater accuracy. The price of this additional accuracy is loss of speed: PANTHER runs approximately a factor of ten slower than CYGNUS. This has little impact on the core follow system, but impacts the user during predictive calculations. Overall response is, however, still considered acceptable.

During cycle 1, SCORPIO was a useful adjunct to the reactor physics capability at Sizewell B, but did not play a major role. This is likely to change, because the station will be required to operate in a mode which assists with the control of transmission grid frequency, involving changes in station power level. A reconsideration of the requirements therefore led to the decision to order an upgrade which was delivered in August 1996. Two extensions to the modelling capability were considered essential to support the foreseen role:

- The ability to look forward into the future seventy-two hours (rather than forty-eight as previously) and also use many more time points;

- The ability to control an adaptive core model (the same mechanism works for both CYGNUS and PANTHER).

A number of other functional changes were also made, such as the ability to accept and display a wider range of data from the logging system. It is also worth noting the improvements in system security, which now requires passwords to start, stop and change configurations. This is seen as most important for a software system that must run continuously to perform effectively in a role which may be valuable to station production, and be used by a number of engineers with different levels of knowledge.

New features and future work

On-line adaptation of the core simulator

Recent development has focused on a new method for on-line adaptation of the core simulator based on feedback from the ex-core detectors. During normal operation the behaviour of the core simulator is close to what is obtained from measurements. However, in certain situations the core may be axially unstable due to xenon oscillations and the delta-flux calculated by the simulator will then deviate from what is measured. Several methods may be applied to force the core simulator to follow measurements on-line. For instance the state variables, xenon/iodine distributions, can be estimated or the power distribution adjusted. However, if only ex-core detectors are available, it is difficult to estimate several thousands of state variables from just a few measurements.

The method adopted here is to estimate two correction parameters of the fast flux in the top (DCY2) and bottom reflector (DCY1) to minimise the deviation between the calculated delta-flux and the delta-flux measured by ex-core detectors. By continuously updating these two parameters one is able to track the measured delta-flux.

A Weighted Recursive Least-Square (WRLS) technique has been chosen [3-6]. The least-square criterion seeks an estimate of the unknown parameters in such a way that the sum of squares of the deviation between the actually observed and computed values, multiplied by numbers that measure the degree of precision, is a minimum. This method does not require any knowledge about noise statistics from the process. The method is not restricted to linear polynomials or to any specific functional form, but it is limited to model structures that are linear in the unknown parameters (or can be transformed to a structure like this).

The reactor core simulator CYGNUS is a complex non-linear model. One needs to transform the real estimation problem to a form which complies with the WRLS formalism.

The influence of non-linear effects is reduced by treating relative differences in delta flux rather than absolute values:

$$\hat{y} = \Delta DCY \cdot \varphi(P,C,B) \qquad \text{(Eq. 1)}$$

where

$\hat{y} = \hat{y}_{meas} - \hat{y}_{calc}$	estimate of the delta flux difference.
$\Delta DCY =$	the change in DCY values.
$\varphi(P,C,B) =$	a function of power(P), control bank(C) and burn-up(B).

The calculated delta flux y_{calc} in CYGNUS has been subtracted from the original measurement, creating the new delta flux difference variable. Our assumption is that these values are proportional to the changes in the DCY parameter. The $\varphi(P,C,B)$ function will be updated for changes in power, control bank positions and burn-up values. The deviation

$$\varepsilon = y - \hat{y} = y - \Delta DCY \cdot \varphi(P,C,B) \qquad \text{(Eq. 2)}$$

is the difference between the "measured" and estimated variable, where the modified measurement from the process is defined as

$$y = y_{meas} - y_{calc} \qquad \text{(Eq. 3)}$$

and y_{calc} is the calculated value from the non-linear model in the CYGNUS simulator. The recursive form of the WRLS algorithm is described as:

$$\Delta DCY_{(K+1)} = \Delta DCY_{(k)} + K_{(k+1)}\left[y_{(k+1)} - \varphi_{(k+1)}\Delta DCY_{(k)}\right] \qquad \text{(Eq. 4)}$$

To get a new updated value of the φ function for each sample, one can use information from the CYGNUS model at two different steps. The φ function can then be approximated as:

$$\varphi = \frac{y_{calc}(k+1) - y_{calc}(k)}{\Delta DCY(k)} \qquad \text{(Eq. 5)}$$

with the assumption that the changes in power, rod bank position, burnup and other variables, are rather constant from one step to another. This makes it possible to calculate φ on-line. φ is also used to calculate the gain factor K.

The estimated parameters DCY1 and DCY2 (from ΔDCY) are used to adjust the deviation in such a way that the calculated value becomes more equal to the ex-core delta flux value. Figure 3 shows the simulator CYGNUS adaptation to the measured delta-flux. First, there is a rather static deviation (CYGNUS is the lowest line to the left in the display). Then the adaptive algorithm is turned on and the simulator immediately adjusts to follow the ex-core line. A small overshoot is observed before the calculated delta-flux value approaches the measured one.

Advanced strategy generator based on optimal core control

Another new development of SCORPIO is a more advanced strategy generator based on the optimal core control method [7]. This facilitates a more flexible development of control strategies where different control objectives can be applied. Typical examples are optimisation of power changes and load cycle strategies, dampening of xenon oscillations, boron minimisation and temperature control at end of cycle.

The problem to be solved is that of finding the optimal control strategy over a future period of, typically, 24 hours. The control objectives include the total power, axial power distribution, and use of boron. The control variables are one rod bank, soluble boron in the coolant and the coolant temperature deviation.

A hierarchical optimisation method is used to solve the control problem, by iterating between two sub-systems: each with their own power densities and xenon concentrations. One sub-system is controlled by the real-world control variables (boron etc.) while in the other the power density itself is the controller. Convergence is achieved when both systems have the same power density.

Mathematically the problem is formulated in terms of an objective function to be minimised and the standard Lagrange coefficients.

A one dimensional model with 20 axial nodes is used, which is initialised from current state of the 3D core-follow simulation. In spite of the simplified model, the behaviour retains many features of a more detailed model, particularly with respect to xenon dynamics. However, if greater fidelity became important the method could readily be extended to deal with more complex models.

Usage of the optimisation module is similar to the original SCORPIO strategy generator, in that the user supplies a specification of a power manoeuvre, and proposed control strategy is checked using a full 3D simulation. However, the module allows the user to impose additional constraints on the calculation, including the typical asymmetric constraints on delta-flux as a function of power, and adjustments of the relative importance given to minimising boron changes against use of rods to control axial power distribution. It also handles the constraints on overlap of insertions when more than one rod bank is inserted in the core.

Implementation of the PANTHER code

From the start of cycle 2, SCORPIO will run using Nuclear Electrics' reference code PANTHER as the core model. The method of performing adaptive calculations within PANTHER differs from that in CYGNUS in the choice of the model parameters which are adjusted, but essentially the same control algorithms are employed; this means that PANTHER can be configured to present to SCORPIO exactly the same interface as that offered by CYGNUS, greatly simplifying the task of replacing one model with the other.

PANTHER is, however, capable of returning a range of additional calculated parameters, not available from CYGNUS, including:

- Moderator temperature coefficients;
- Decay heat calculations;
- Pin powers;
- Shut down margin estimates.

At present these are determined using an off-line PANTHER calculation, but it is anticipated that in the future the SCORPIO's core simulator interface and user interface may be adapted to offer these calculation facilities to the operator as interactive features.

Conclusions

Feedback from different applications and end-users has contributed to system enhancements in many areas:

The MMI has been made much more user-friendly, by allowing application of the mouse device as the input of predictive calculations and zooming/panning in history and predicted data. Allowing up to 72 hours prediction and 90 time-steps removes the practical limitation on the size of transients to be analysed. Flexibility to run several instances of SCORPIO in parallel has increased the availability of SCORPIO on-site and off-site. Security features have been implemented.

The new method to adapt the core simulator based on feedback from the ex-core detectors has been tested and works even if the core is axially unstable with respect to xenon/iodine dynamics. Further, the power profile is affected such that the axial power peak is preserved, and the influence of the parameter changes is highest in the top and bottom of the reactor. The adaptive CYGNUS version has proved to provide better agreement with the in-core detectors than the old un-adjusted version of the tracking simulator. The improved accuracy of the estimate of the core state will further improve the accuracy of the predictive simulations, since the initial model parameters and state variables will be more correct. The method is easy to apply by other core simulators as well, such as PANTHER.

Concerning the new advanced strategy generator based on optimal control, it has just been implemented and no operational experience from real plant installations has been obtained yet, but the test results are encouraging. It has been demonstrated that a relatively simple version of a hierarchical method can be applied to the optimal control problem of a PWR. However, the present method still contains some simplifications that should be improved. The advanced strategy generator offers a very flexible way of deriving control strategies based on different control criteria such as boron minimisation, temperature control and relaxed axial offset control. In particular the core model could be more detailed, and a full 3D model is envisaged in the future. The new advanced strategy generator has been integrated in the new version of SCORPIO, August 1996.

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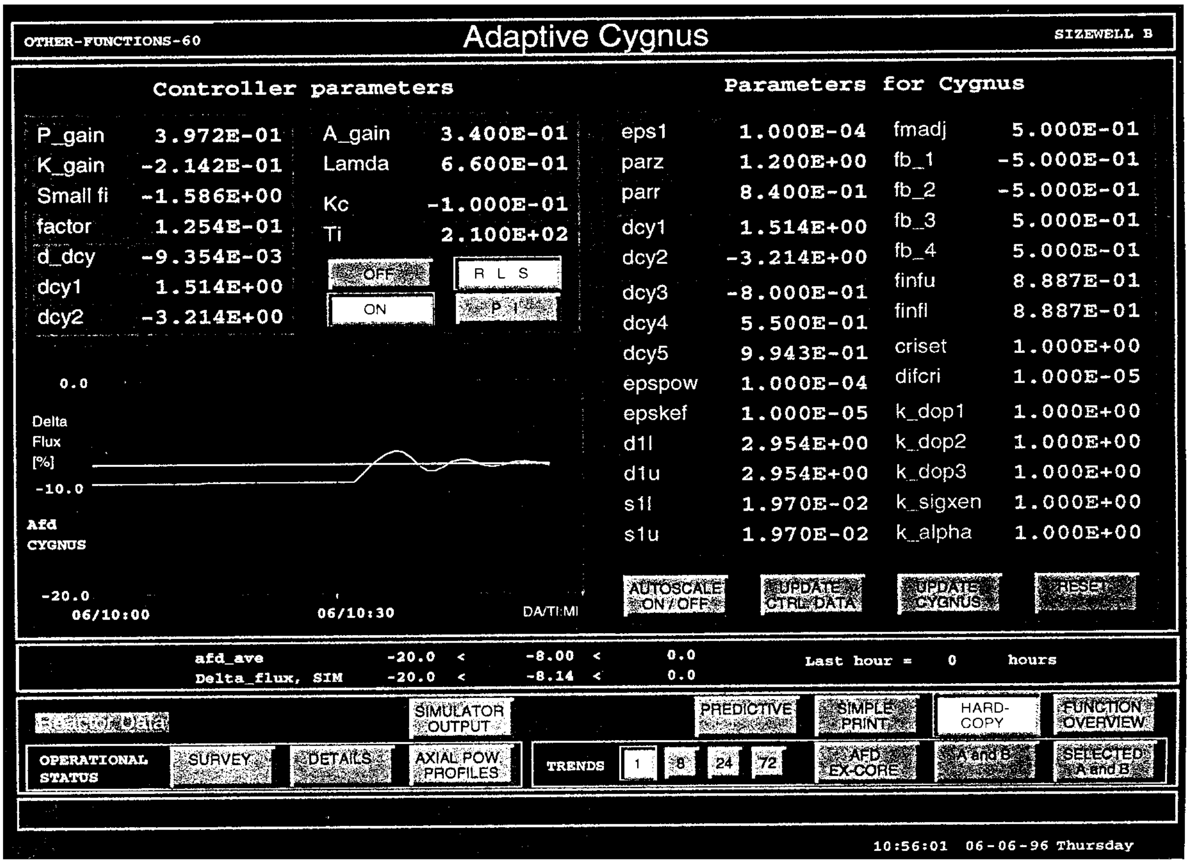
Figure 1. The simulator CYGNUS adaptation to the measured delta-flux



Controller parameters

P_gain	3.972E-01	A_gain	3.400E-01
K_gain	-2.142E-01	Lamda	6.600E-01
Small fi	-1.586E+00	Kc	-1.000E-01
factor	1.254E-01	Ti	2.100E+02
d_dcy	-9.354E-03		
dcy1	1.514E+00		
dcy2	-3.214E+00		

Parameters for Cygnus

eps1	1.000E-04	fmadj	5.000E-01
parz	1.200E+00	fb_1	-5.000E-01
parr	8.400E-01	fb_2	-5.000E-01
dcy1	1.514E+00	fb_3	5.000E-01
dcy2	-3.214E+00	fb_4	5.000E-01
dcy3	-8.000E-01	finfu	8.887E-01
dcy4	5.500E-01	finfl	8.887E-01
dcy5	9.943E-01	criset	1.000E+00
epspow	1.000E-04	difcri	1.000E-05
epskef	1.000E-05	k_dop1	1.000E+00
d1l	2.954E+00	k_dop2	1.000E+00
d1u	2.954E+00	k_dop3	1.000E+00
s1l	1.970E-02	k_sigxen	1.000E+00
s1u	1.970E-02	k_alpha	1.000E+00

afd_ave -20.0 < -8.00 < 0.0

Delta_flux, SIM -20.0 < -8.14 < 0.0

Last hour = 0 hours

10:56:01 06-06-96 Thursday

Figure 2. Predicted and measured axial flux difference during a rod calibration transient at 30% power

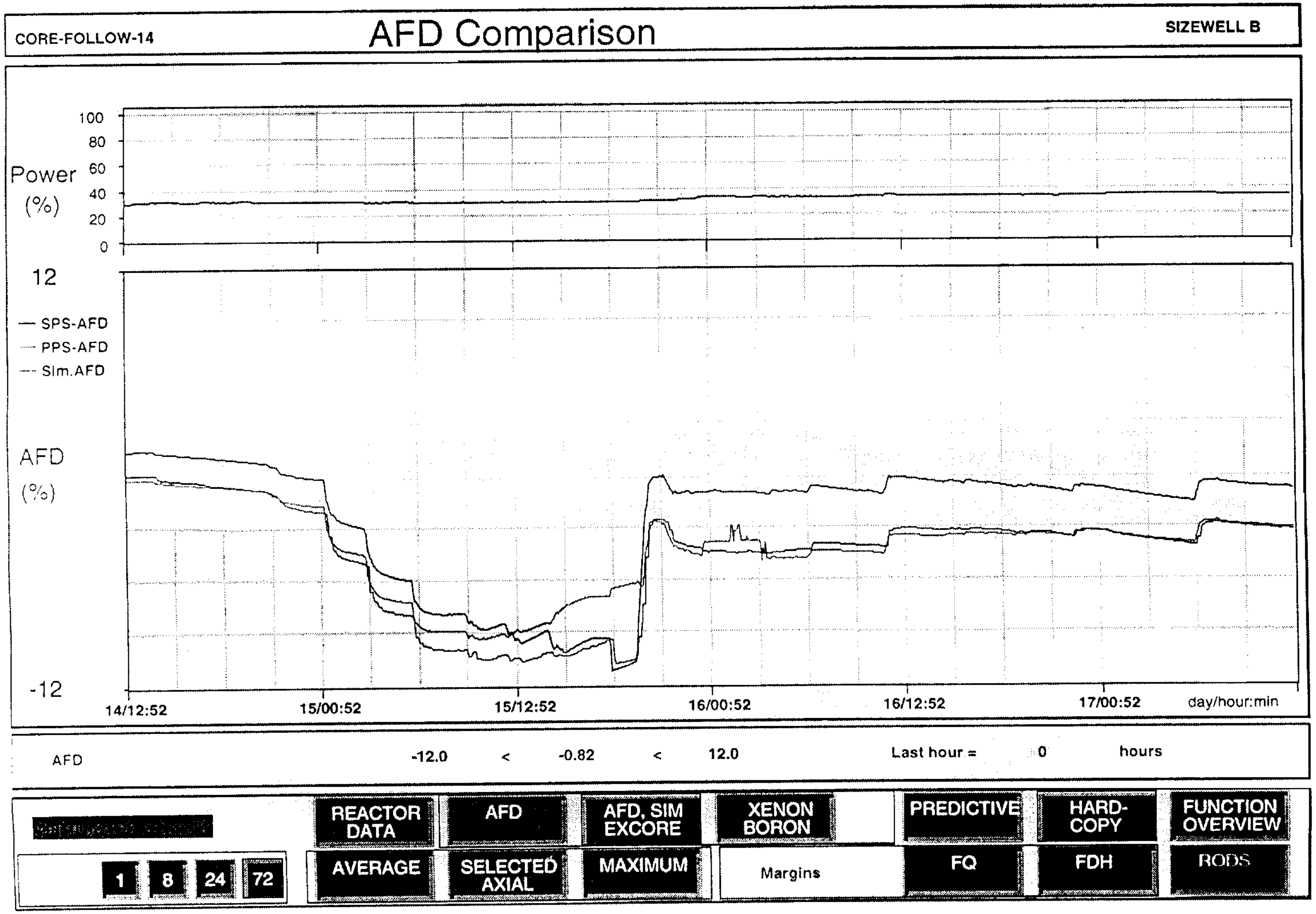
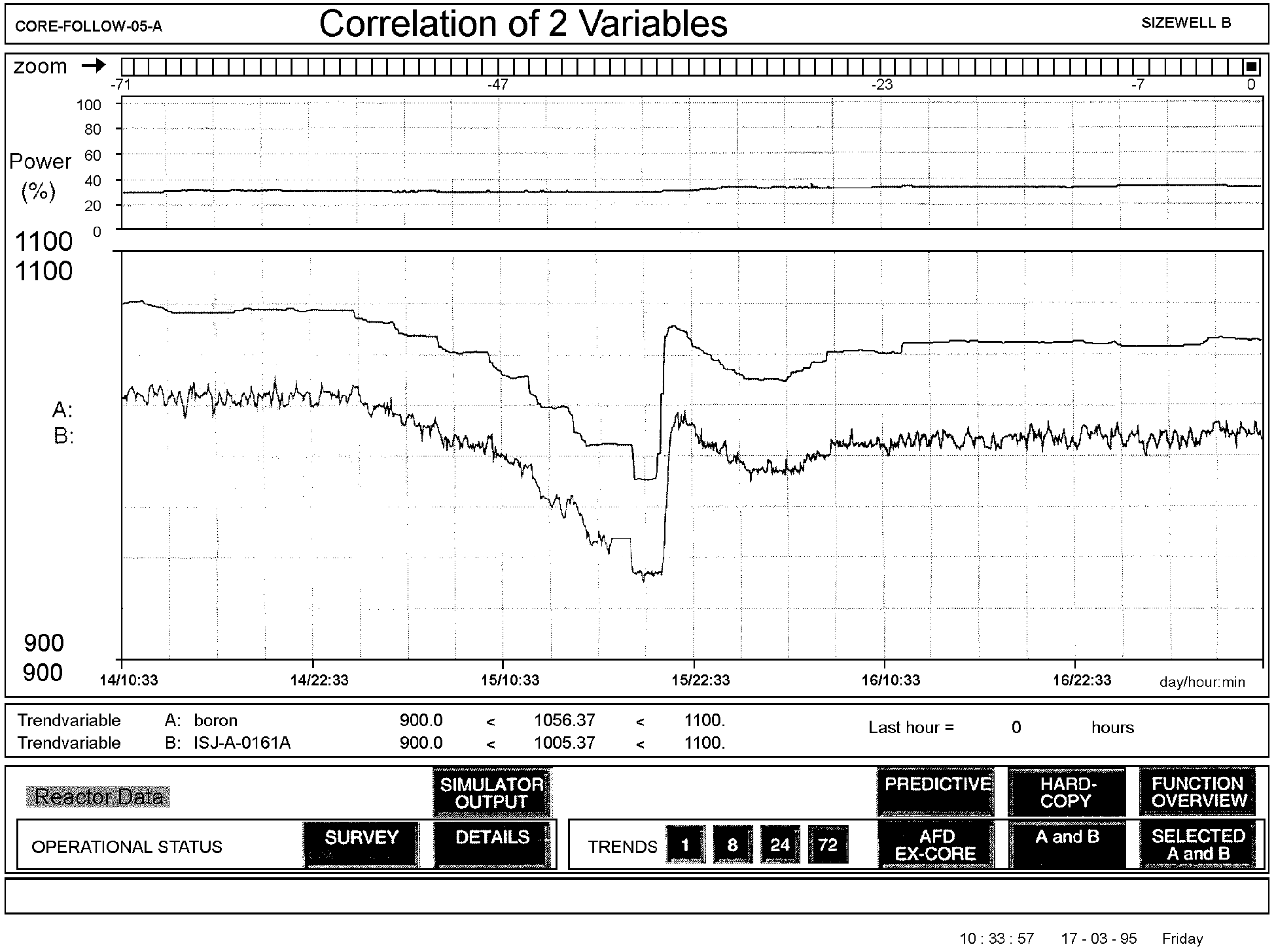


Figure 3. Predicted and measured boron concentration during a rod calibration transient at 30% power



Trendvariable A: boron 900.0 < 1056.37 < 1100.
Trendvariable B: ISJ-A-0161A 900.0 < 1005.37 < 1100.

Last hour = 0 hours

10 : 33 : 57 17 - 03 - 95 Friday