CORE MONITORING AND ASSISTANCE TO OPERATION IN BELGIAN PWRs

Roger Fraikin
Tractebel Energy Engineering
Avenue Ariane, 7, B-1200 Brussels, Belgium
roger.fraikin@tractebel.be

ABSTRACT

The paper presents the situation of the Nuclear Power Plants in Belgium. A private company, Electrabel, owns and operates seven Westinghouse or Framatome type PWRs, with a total capacity of 6000 MWe, producing more than 50% of the country electricity. This high percentage is likely to result in load variation transients, creating a need for core operation assistance. A core monitoring system has been developed and used in Tihange 1 unit for 13 years.

Using the experience gained with this system, Tractebel developed a new core monitoring, covering the 3 units of the site. The main enhancements are a new hardware, fully integrated to the plant computer system and to the site network, and a redesigned man-machine interface, adapted to "Y2K users" knowledge and habits, and providing more flexibility in the core operating strategy. The xenon monitoring has been enhanced by evaluation of the amplitude of axial power oscillations, based on source importance function related to axial imbalance.

This paper focuses on the experience feedback from both the developer and the user, and on the main issues for core monitoring & operation assistance : signal validation, man-machine interface and human factors. The support of a training program is of major importance, because the capabilities as well as the limits of the system should be recognized.

1. INTRODUCTION : BELGIAN NPP's

1.1 CORE OPERATION

The fuel strategies vary from annual cycles to long cycles (18 month), with extensive use of Gd burnable poisons in the latter case (up to 16 pins/assembly, with 10% Gd_2O_3). In addition, two units are partially loaded with MOX fuel. The availability rate of the Belgian PWRs is very good (95 % in 1999).

The protection of the core is based on ex-core detectors (source, intermediate and power level). During the cycle, the power level and the axial imbalance are monitored using long chamber ex-core detectors. These are calibrated on the basis of in-core flux measurement at cycle startup. In-core flux maps (with mobile detectors) are performed monthly to check the power distribution and safety parameters (FQ, FNDH). The in-core axial imbalance is compared to the ex-core measurement; if the discrepancy exceeds 3%, a new calibration is performed by inducing an axial oscillation of power.

The on-line core follow provides axial power distribution, operating margins, and xenon poisoning, as shown on figure 1. The status of the system is informative and the system is not licensed to take benefit of possible margins beyond technical specifications: the aim is to facilitate core operation.

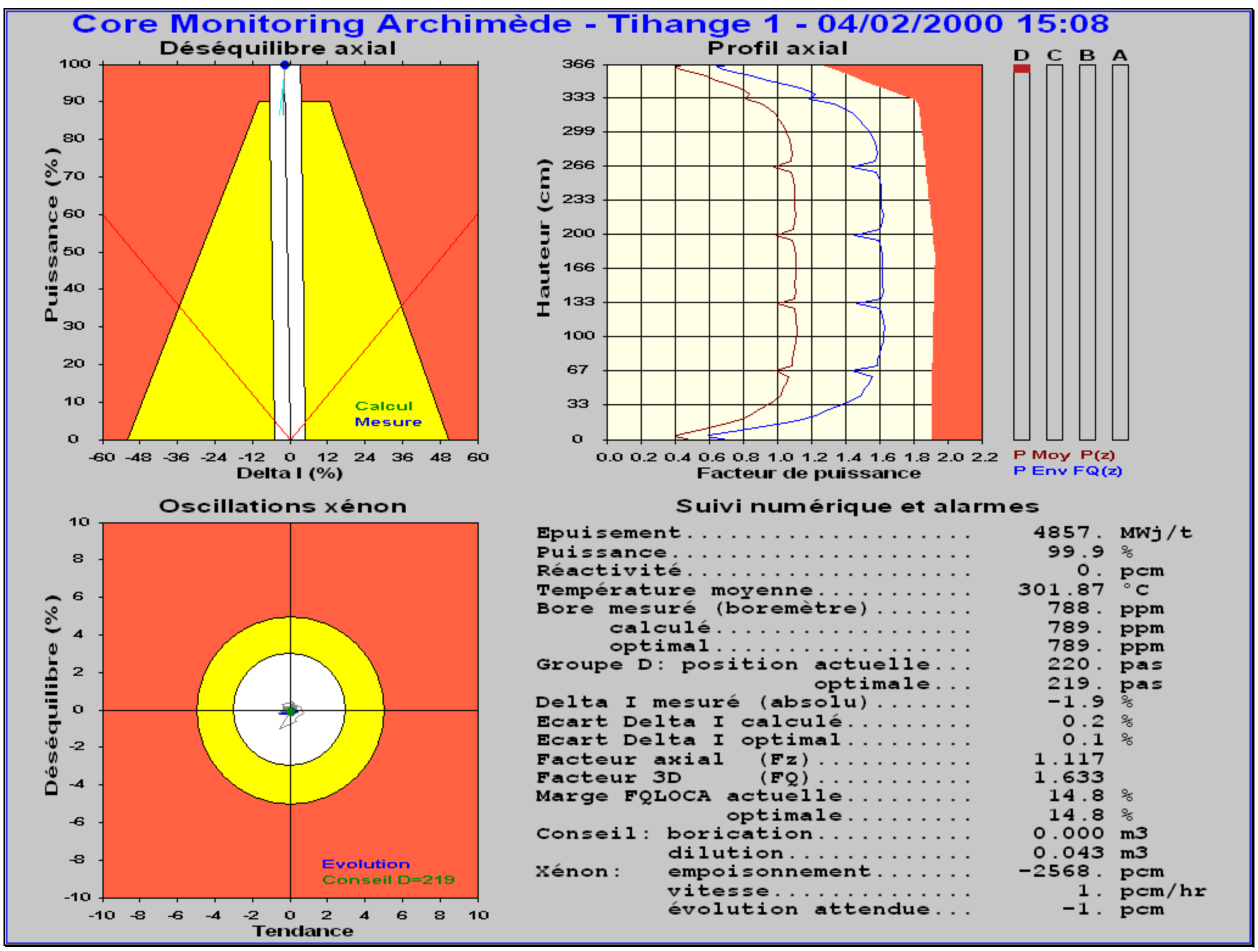


Figure 1 : On-line core follow display

During start-up physics tests, at the beginning of each cycle, reactivity measurements are performed using a data acquisition system, including a digital reactivity meter and analysis tools[7].

1.2 HISTORY OF THE CORE MONITORING PROJECT

Three PWR units are in operation at the site of Tihange. Recent replacement of steam generators was combined with power upgrading, so that each unit produces now more than 1000 MWe. In the 1980's, the "nuclear" electricity reached 67% of the total Belgian production. Power reductions were therefore necessary during weekends or summer, so that a need for predictive capability was felt [3]. Tractebel developed the system in 1985, starting with an off-line version, first installed in Tihange 1, and later extended to units 2 and 3. The on-line coupling to the process computer of Tihange 1 was activated in 1989 [4-5].

The neutron calculation method is based on 1D-2D synthesis, also used by Tractebel Energy Engineering (TEE) for safety analyses [1,2]. Casmo-3 (Studsvik) and Mercator-Mca (TEE) provide the neutron data. For predictive calculations, the strategy generator takes benefit of adjoint fluxes and source importance function [3] related to axial imbalance to determine the optimal rods position and boron concentration.

After 13 years of operation, the old (MicroVAX 2) hardware has been replaced by an Alpha Workstation, connected to the site network. The interactive tasks are now distributed onto the PC desktops, available to both operators and engineers. This new system was officially put into operation end October 1999 in Tihange 1, while units 2 and 3 followed after their next outage, in the spring of 2000.

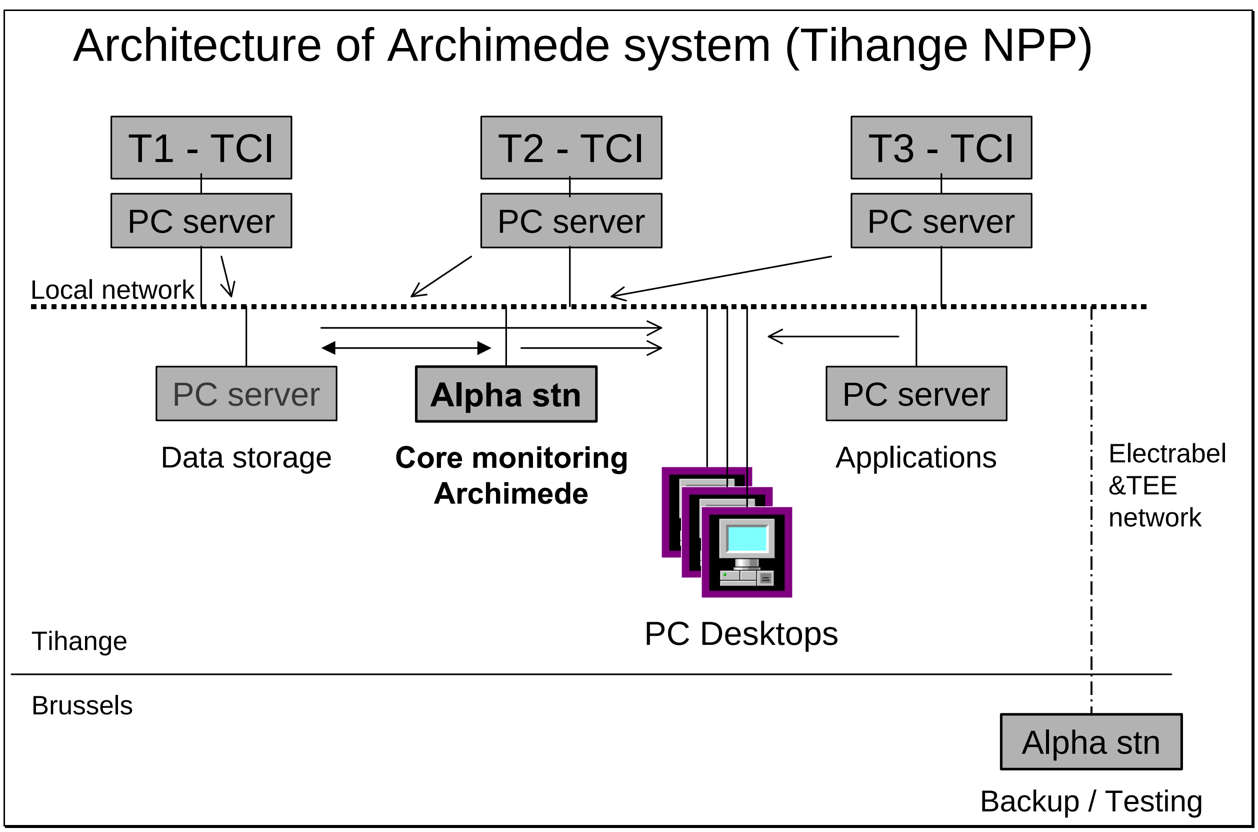


Figure 2 : Architecture of the site core monitoring system in Tihange NPP

1.3 OPERATION ASSISTANCE

TEE provides operation assistance to the Belgian plants, from the start-up physics tests to the end of the cycle. The operator receives from TEE the core/cycle characteristics interactive documentation as a basic tool for power operation. This documentation, called "curves book", is automatically generated from TEE calculations. A new module, called CUBA (CUrves Book Archimede) was recently developed for this purpose; the plot collection is accessed through a MS-Excel workbook, including multi-curves interpolation functions, as shown on figure 3.

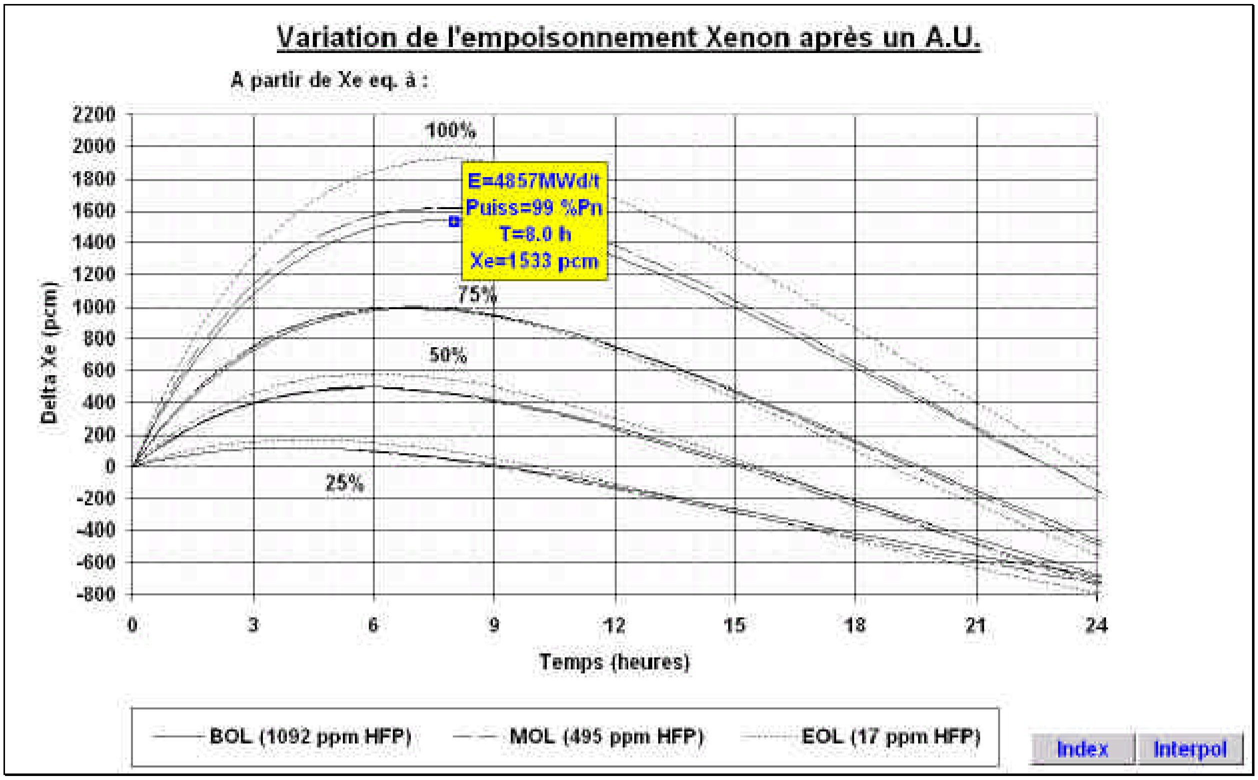


Figure 3 : Interactive core/cycle documentation (CUBA), including curves interpolation

A predictive calculation module allows to prepare power load transients and to determine start-up conditions after a shutdown. The initial state is loaded from the on-line core follow system. During the power variation, this system provides on-line advice, aiming to optimize axial imbalance.

A specific module evaluates Xenon poison and axial power oscillations; it calculates the contribution of xenon in each node, weighting cross-sections with source importance function related to axial imbalance. Time derivative is calculated from xenon and iodine concentration, so that the imbalance is determined in both phase and amplitude. Because the first order perturbation neglects flux distribution change, this model needs to be calibrated by simulating an oscillation. The xenon production is numerically amplified to eliminate damping so that the calibration factors are easily obtained. For a given reactor, these depend mainly on burn-up state.

An example is given on figure 4; the xenon module suggests an optimal position of regulation banks to correct the power imbalance, and displays the effect of this correction on the amplitude of the oscillation. This correction may be mandatory to maintain the power imbalance in the allowed range, but the operator should be aware that subsequent actions could be necessary if the first action increased the amplitude of the oscillation.

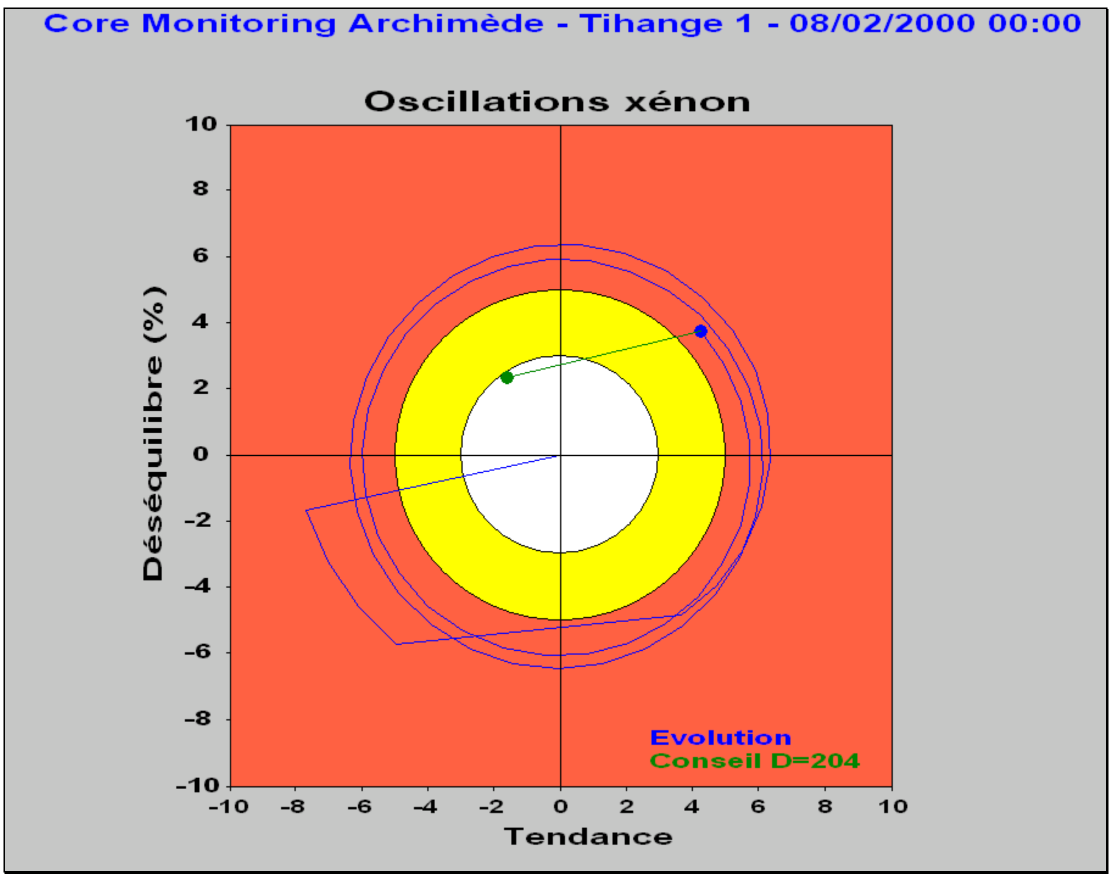


Figure 4 : Xenon oscillation monitoring
A corrective action is suggested (Bank D insertion to 204 steps)

2. EXPERIENCE FEED-BACK

Tihange 1 was the first Belgian plant equipped with Archimede; we collected the experience feedback (13 years) from reactor engineers, supervisors and operators; this feedback was used to build the new Man-Machine Interface (MMI) of Archimede.

2.1 PREPARING POWER TRANSIENTS AND RESTARTING AFTER SHUTDOWN

In Tihange 1, the reactor engineers do always base the preparation of planned transients on a predictive calculation. Most of the control room supervisors are also experienced in using the system, and do it to calculate restart conditions or to adapt a prediction to actual schedule and core conditions. Several operators have also developed a skill with the tool. The predictive calculation module is also available for training in the full scope simulator room, to palliate the lack of opportunities to maintain their skill during long periods of operation at nominal conditions.

In some cases, a deeper analysis is requested. For example, during stretch-out, Tihange 1 had to stop one of the two turbine groups for two weeks; after that, returning to the maximum achievable power could have been very slow, because the dilution capability was extremely reduced. We used instead Archimede to determine the optimal timing, taking benefit of the xenon temporary positive reactivity feedback to increase power with minimal production of effluents. However, such detailed analysis are judged out of the scope of production teams, and delegated to the engineering office (TEE).

2.2 MANAGING POWER TRANSIENTS

The results from the core monitoring are included in the process computer database. A text display, called "operation assistance", is available, and graphic follow-up is possible. These functions are found "very useful" by the operators.

The system also provides on-line advice:
- Optimal control banks position, with respect to axial imbalance,
- Borication or dilution volume necessary to reach this position,
- Xenon reactivity, variation rate, and axial oscillations control.

While an on-line core monitoring can provide a comprehensive set of information, reactor engineers claim that it is important to keep the information simple and manageable. During an unplanned transient, the operator cannot indeed afford looking to details, because he is busy with actions related to the problem that has caused the transient.

2.3 HUMAN FACTORS AND TRAINING

The training program is of vital importance to give the operators trust in the core monitoring system, while at the same time making them aware of its limits. If the first goal is not met, situations may arise where an operator who distrusts the system uses his own intuition until he meets with axial imbalance limits. At which point it is usually too late to use the prediction, because the axial imbalance history has deviated from the computed one. Then, xenon (iodine) feedback is likely to increase the discrepancies with the core monitoring system.

The second goal of training is to avoid excessive trust in the system, and to underline the limits of the model. For example, the borication and dilution volumes are calculated using a simple model, which does not take into account the delays due to make-up circuitry.

It is therefore important that the training courses focus on this point: the system provides guidelines, while fine-tuning is left to the operator. He has experience with the plant, and may "cut the corners" and cope with schedule changes.

2.4 THE NEW SYSTEM

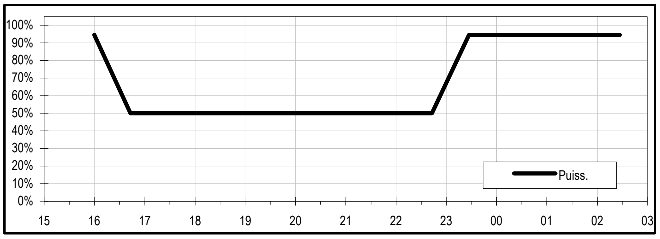
The targets of the last developments where:

- **Extension to Tihange 2 and 3**: the old system was developed for Tihange 1, and the process computer are not the same in the three units.

- **On desk availability**: the old system ran on a single computer located in the control room, while the new system distributes the information to engineer's offices, through the site network.

- **Calculation speed improvement**: the old system took 20 minutes for a predictive calculation, while the job is now achieved in a few seconds.

- **Enhanced user interface**: today's people have more experience with computers than 15 years ago. With PC's invading both working and private domains, users are familiar with widely spread interfaces, such as MS-Windows, Excel or Internet Explorer. It was therefore judged interesting to take benefit of this experience in the new MMI. For example, the predictive calculation interface is now based on MS-Excel, as shown on figure 5. With respect to the old "output listing", the new system offer more possibilities to highlight problems as shown on figure 6.



Archimede A10 - R2.10 - Calcul prévisionnel
Tihange 2

Puiss. nomin.		Température		Débit maximum		Acide
Electr.	Therm.	HZP	HFP	Dilution	Boric.	Bor.
975	2895	286.0	299.0	27	13.5	7000
MWe	MWT	ºC	ºC	m3/h	m3/h	ppm

Date	Puiss.	#	Commentaires	Puissance		Durée ou Taux		Temp.	Gr. D	Bore	Rech.	Limit.	Bande
	%							ºC	pas	ppm	criticité	débit	Delta I
08/02 16:00	94.6	1	Charger l'état initial	94.6	%		hr	297.9	225	16.6			
08/02 16:43	50.0	5	power reduction	50.0	%	10	MWe/min	Réf.	DDI	Crit	Bore	Oui	5.0
08/02 22:43	50.0	6	stabilization	50.0	%	6	hr	Réf.	DDI	Crit	Bore	Oui	1.0
08/02 23:27	94.6	5	power increase	94.6	%	10	MWe/min	Réf.	DDI	Crit	Bore	Oui	5.0
09/02 02:27	94.6	3	stabilization	94.6	%	3	hr	Réf.	DDI	Crit	Bore	Oui	0.0

Lancer le calcul | Nettoyer | Compléter | Insérer ligne | Supprimer ligne

Figure 5 : Data for predictive calculations are defined through MS-Excel.

Prévision Archimède Tihange 2 Début : 08/02/00 16:00 Fin : 09/02/00 02:27

Eau de dilution : 184.78 m3 à 0 ppm
Acide borique : 1.288 m3 à 7000 ppm

Problèmes éventuels : sous-criticité, lim. grappes atteinte, viol bande DI,
Conclusion : manque de réactivité - réduire la puissance, contrôler la durée de sortie de bande Delta I.

Date	Puiss.	Gr. D	Gr. C	Delta I		Conc. bore	React ivité	Volume dilution	Débit appoint	Volume boric.	Bilan Bore/eau	Temp. prim.	Effet Xénon
	%	pas	pas	abs. %	écart %	ppm	pcm	litres	m3/hr	litres	litres	Deg.C	pcm
08/02/2000 16:00	94.6	225	225	3.7	1.	17			0.0			297.9	-2650
08/02/2000 16:08	85.6	220	225	7.3	4.9	41			5.1	730		297.1	-2655
08/02/2000 16:17	76.7	194	225	2.5	.3	41			0.0			296.0	-2665
08/02/2000 16:25	67.8	171	225	-2.3	-4.2	42			0.3	36		294.8	-2679
08/02/2000 16:34	58.9	156	225	-2.6	-4.2	52			2.2	310		293.7	-2699
08/02/2000 16:43	50.	133	225	-2.9	-4.3	57			1.0	151		292.5	-2725
08/02/2000 17:43	50.	160	225	1.5	.1	57			0.0			292.5	-2887
08/02/2000 18:43	50.	168	225	3.2	1.8	50		27000	27.0			292.5	-2992
08/02/2000 19:43	50.	169	225	4.0	2.6	44		27000	27.0			292.5	-3053
08/02/2000 20:43	50.	167	225	3.9	2.5	39		27000	27.0			292.5	-3080
08/02/2000 21:43	50.	162	225	2.7	1.3	34		27000	27.0			292.5	-3085
08/02/2000 22:43	50.	160	225	2.5	1.1	34		2989	3.0			292.5	-3072
08/02/2000 22:51	58.9	186	225	6.7	5.1	33		3942	27.0			293.7	-3069
08/02/2000 23:00	67.8	208	225	11.6	9.7	32		3969	27.0			294.8	-3060
08/02/2000 23:09	76.7	225	225	13.7	11.6	32	-81	3969	27.0			296.0	-3034
08/02/2000 23:18	85.6	225	225	10.7	8.3	31	-263	3942	27.0			297.1	-3004
08/02/2000 23:27	94.6	225	225	6.5	3.9	31	-448	3969	27.0			298.3	-2971
09/02/2000 00:27	94.6	225	225	5.9	3.3	27	-213	27000	27.0			298.3	-2765
09/02/2000 01:27	94.6	225	225	5.3	2.7	24	-49	27000	27.0			298.3	-2625
09/02/2000 02:27	94.6	218	225	2.8	.2	26			0.1	61		298.3	-2533

Figure 6 : Results obtained from a predictive calculation.
The feasibility of the transient is evaluated, and corrective actions are suggested.

3. IMPORTANT ASPECTS AND ISSUES

3.1 VALIDATION OF MEASUREMENTS

Validation of measurements is of major importance, since the simulation is based on a few parameters only [10]. Measurements can be affected not only by signal inaccuracy, but also by periodic tests and calibrations. Because of the time-integration, it is necessary to make the model robust, in order to take into account temporary unavailability of the process computer.

3.2 ADAPTIVE OR BEST-ESTIMATE CALCULATION ?

The results of the on-line core simulator calculations can be treated in two principally different ways: the adaptive and the best estimate method, respectively. In the adaptive method the calculated power distribution is adapted to the local power measurements [8]. In the case of the Belgian PWRs, only ex-core measurements are permanently available.

While best-estimate calculation allows for continuous validation by comparing calculation to measurements, adaptive calculation has the advantage to provide more consistent information to the operator, and to avoid dephasing during persistent xenon oscillations. Of course, measurement validation is of major importance when switching to adaptive calculation.

3.3 SOFTWARE AND HARDWARE INTEGRATION

Archimede is designed for smooth integration to the existing hardware, software, network, and interfaces. The on-line core follow runs on a dedicated workstation, located in the site computer room, the database resides on a site server, while all interactive functions run directly on local PC's. In this way, there is a clear separation between core follow, databases and MMI.

The modular structure of the application allows for easy maintenance and flexibility. Data security is handled through specific access rights for each category of users: display only, calculation, data modification, and maintenance.

3.4 MAN-MACHINE INTERFACE

The Archimede MMI follows today's trend, using existing building blocks [9] and well-known interfaces (MS-Windows, -Excel, -Internet Explorer), as shown on figures 2-6.
Beyond the MMI, human factors have to be considered to improve user manual design, and perform efficient training of the operators and supervisors.

CONCLUSIONS

The experience gained with the core monitoring system installed in Tihange 1 unit was used to build a site core monitoring, covering the 3 units of the site.
The success of this project is based on smooth integration with the plant computer system and network, with existing user interfaces, and with support of a training program, so that the capabilities of the system are known and its limits are recognized.
The main issues for core monitoring & operation assistance are signal validation, man-machine interface and human factors.

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