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MODERNIZATION OF KERNKRAFTWERK BEZNAU'S CORE MONITORING SYSTEM WITH STUDSVIK'S GARDEL SYSTEM

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Abstract – An analysis to select a new, modern core monitoring system replacement for twin Westinghouse Pressurized Water Reactors (PWR) is presented. The reactors, Kernkraftwerk Beznau (KKB), are located in Switzerland and operated by Nordostschweizerische Krafwerke AG (NOK). KKB was one of the first PWR reactor sites in the world to use a fuel vendor on-line core monitoring system starting in the early 1990's. Core monitoring for KKB is even more challenging than for most reactors due to over 25 years of operational experience using MOX fuel.

The objective of the investigation was to assess the merits of available core monitoring systems to determine if operational performance could be further improved. (KKB already demonstrated excellent operational performance, so this was no small task).

The investigation was motivated in part through the realization that the existing core monitoring solution used at KKB was built for an earlier era, constrained by the price/performance limitations of computational hardware of that time as well as the accuracy limitations of physics models developed for such hardware. Often, accuracy of the physics models employed was sacrificed for computational performance in the core monitoring system.

The selection of a new core monitoring system to replace the existing one was driven by the following criteria:

- *Improve operational performance by reducing uncertainties of calculated parameters associated with thermal margin (e.g., radial pin power peaking factors, LHGR, etc.)*
- *Improve operational performance by implementing a pin-based PCI model*
- *Improve operational performance by implementing on-line DNBR calculations based on plant-specific DNB correlations*
- *Provide the reactor operators and reactor engineers a reliable, intuitive tool to assist them in evaluating unexpected operational conditions*

- *Eliminate tedious and expensive cycle initialization procedures*

- *Reduce costs for hardware and software support for the core monitoring system*

- *Minimize impact on plant process computer*

After a one-year evaluation period, KKB chose Studsvik's GARDEL core monitoring system. GARDEL is based on Studsvik's well-established in-core fuel management code system, consisting primarily of the lattice code, CASMO, and the core physics model, SIMULATE. The Studsvik physics modeling software has been used in analysis of every commercially available light water reactors (PWR and BWR) fuel and core design in the world.

In addition to the Studsvik physics model, GARDEL includes a highly automated core physics model update throughout the cycle, triggered by monitoring changes of plant process computer signals. All data is archived in a flexible, highly efficient database system.

GARDEL also includes a flexible, configurable, graphical user interface as well as international language support. All data - both calculated parameters, as well as collected plants signals - are easily accessed via the user interface for analysis or via included automatic reporting functions. Multiple users can use the system simultaneously (e.g., an engineer can perform an operational maneuver forecast of control rod position vs. time to control axial flux imbalance, and an operator can access and view the projected results as the plant begins the maneuver).

GARDEL is unique in modularity and flexibility, as it runs on a variety of hardware systems (e.g., UNIX, Windows, and Linux PCs) with no proprietary hardware required. Furthermore, GARDEL's modular design allows for plant-specific network configurations, meeting strict data security requirements. Different levels of user access can be controlled administratively.

It is important to note that GARDEL does not run on the plant computer. No modifications to the plant computer are required for GARDEL. A simple query of the plant computer data archive is periodically conducted (typically every one minute) and data is passed to the GARDEL server.

During the evaluation period at KKB, considerable improvement to the accuracy of thermal margin related quantities, both at steady state and during transient conditions, were observed. This performance led to the decision to replace the existing core monitoring system with Studsvik's GARDEL as the official core monitoring system for KKB.

I. INTRODUCTION

Kernkraftwerk Beznau has an excellent operational record spanning over 66 fuel cycles of operation (34 cycles from unit 1, and 32 cycles from unit 2).

Among many other factors, KKB's constant vigilance in evaluating and implementing state-of-the-art technologies that improve performance has contributed to achieving and maintaining its impressive operational record.

For example, KKB was a pioneer among Westinghouse PWR's in the 1990's by introducing an on-line core monitoring system capable of providing continuous core monitoring and operational support. At that time, the conventional approach was to monitor the core by relying on data from periodic movable detector measurements and pre-computed power shapes.

Core monitoring solutions available at the time were highly limited by the computational power of the existing hardware. Thus even this earlier implementation of an on-line core-monitoring solution at KKB's was limited since approximate physics methods were required so as to achieve acceptable computational performance. Due to these limitations, achieving consistency of results from the on-line system vs. the more robust off-line calculations was difficult. One result of this accuracy issue was that these early on-line systems offered limited assistance in the operational support.

Another important fact about KKB is its vast experience in the use of a significant number of MOX fuel assemblies in the core since very early cycles. Since reactor physics codes at the time could not accurately model the strong spectral shifts and gradients in the boundaries between ordinary UO2 and MOX fuel assemblies, results were poor.

Since the first online implementation at KKB availability of more powerful computer hardware and improvements in the accuracy of reactor physics methods have occurred. Due to the earlier mentioned interest by KKB in applying state-of-the-art methods and technologies to modernize its core monitoring system, KKB decided to investigate the prospects of improving its on-line core monitoring system.

After an evaluation period of one year, KKB selected Studsvik's GARDEL system as its modern, on-line core monitoring system. This decision was based on the following factors in comparing GARDEL to alternative solutions:

- GARDEL's use of the CMS[1] code package, a well-established, licensing-grade, core design code system, with a large experience base of application throughout the world.
- CMS's demonstrated ability to accurately model the KKB cores, particularly with respect to calculated-to-measured accuracy for MOX fuel assemblies.
- GARDEL's straightforward initialization procedure, which eliminates resource expenditure required by other systems which require model "tuning" and ad-hoc manual intervention.
- GARDEL's powerful graphical user interface, designed in part with the assistance of Reactor Engineers at KKB, providing intuitive and prompt assistance to the control room operators.
- GARDEL's ability to extend monitoring beyond the standard margin-to-limit peaking factor calculations to include PCI, DNBR calculations and on-demand operational support.
- Since GARDEL is based on CMS, the formal licensing process was significantly diminished to licensing only CMS for KKB's cores.

I.A. Kernkraftwerk Beznau (KKB)

KKB consists of twin, two-loop Westinghouse-type PWR units, each containing 121 fuel assemblies, consisting of 14x14 arrays of fuel pins (even-pin lattice). Table I presents the general reactor design parameters describing each of the KKB cores.

Table I

General Reactor Specifications

Reactor characteristics	***Value***	***Units***
Core rated thermal power	1130	MWth
Core rated mass flow rate	6355	kg/s
Number of assemblies	121	
Reactor pressure	155.1	bar
Nominal core coolant inlet temperature at full power	280.7	C
Nominal core coolant outlet temperature at full power	315.1	C
Nominal core coolant average temperature at full power	297.8	C
Nominal core coolant inlet temperature at zero power	279.4	C
Heated flow fraction	0.955	
Core baffle material	SS	
Core baffle thickness	2.858	cm
Core barrel material	SS	
Core barrel thickness	4.45	cm
Distance from baffle to core barrel	6.74	cm

Fig. 1 shows the radial assembly layout, locations of control rod groups, and movable detector locations.

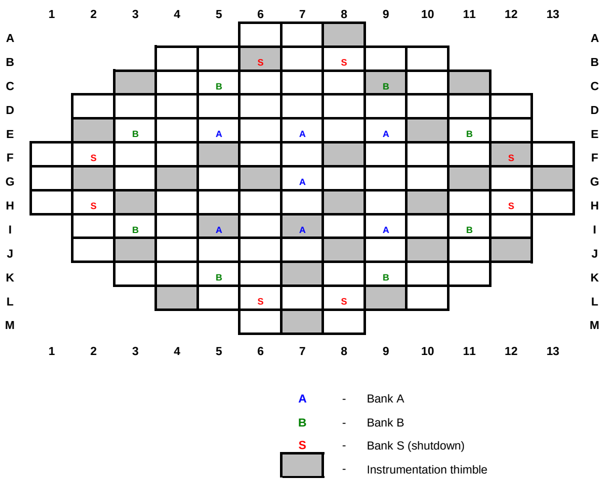
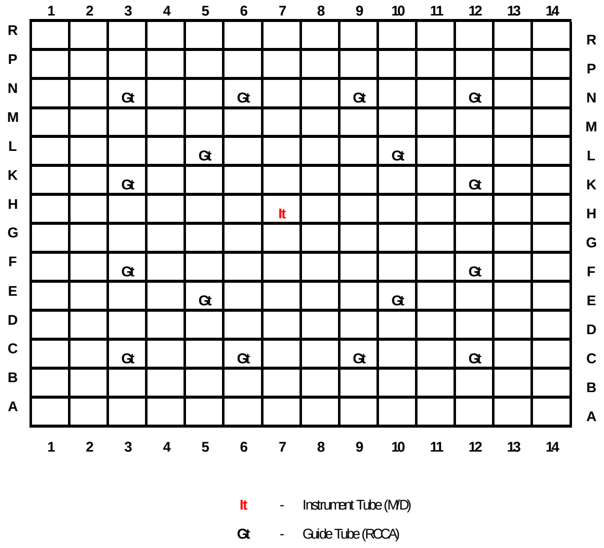


Fig. 1. KKB core layout

Fig. 2 presents the pin-by-pin lattice assembly configuration, showing location of fuel pins, control rods, and instrument guide tubes.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
R															R
P															P
N			Gt			Gt			Gt			Gt			N
M															M
L					Gt					Gt					L
K			Gt									Gt			K
H							It								H
G															G
F			Gt									Gt			F
E					Gt					Gt					E
D															D
C			Gt			Gt			Gt			Gt			C
B															B
A															A
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	

It - Instrument Tube (MD)
Gt - Guide Tube (RCCA)

Fig. 2. KKB lattice layout

II. THE GARDEL CORE MONITORING SYSTEM

GARDEL[2,3] is a modular system comprising several codes, each performing specific tasks. All GARDEL components are written in standard FORTRAN, C, and Tcl/Tk programming languages, making GARDEL highly portable to UNIX and PC computing systems. For example, files generated by GARDEL are specifically written to be binary-compatible between computing platforms. This allows GARDEL to be seamlessly deployed throughout a heterogeneous network of PC and UNIX workstations.

A high level of system availability is achieved at KKB by deploying simultaneously on two redundant servers. If one server should fail, GARDEL continues to function on the remaining server. Once the failed server is recovered the functioning server automatically feeds missing data back to the recovered server, synchronizing the two servers and re-establishing system redundancy.

GARDEL updates the cycle-specific core model automatically by monitoring changes in plant-measured signals. The plant data is transmitted to GARDEL in a small file, containing relatively few parameters such as reactor power, flow, pressure, inlet and outlet conditions, control rod positions, fixed and detector signals (both in-core and ex-core).

All measured signals and calculated results are stored for efficient access by the user. Each user can access the GARDEL graphical user interface locally on their own desktop, where they can access the current core state, make trend plots, generate reports, perform support or reactivity management calculations, etc.

It is important to note that GARDEL does not run on the plant computer. No modifications to the plant computer are required when using GARDEL. A simple query of the plant computer data archive is periodically conducted (typically once per minute) and passed to the GARDEL servers.

The main modules in the GARDEL system are:

- Signal handling – controls receipt and storage of plant computer signals from the plant process computer.
- Periodic controller – manages data flow from the plant computer to the GARDEL database. It automatically activates neutronic calculations based on changing reactor conditions or on-demand by an authorized user.
- CMS – GARDEL accesses and uses the same CMS neutronics model developed by the core design group used for core design calculations. In addition, CMS provides accurate modeling for a variety of in-core detector types found in NPPs throughout the world: movable fission chambers, vanadium aeroballs, fixed rhodium neutron detectors, and fixed and movable gamma detectors (TIPs, platinum, gamma thermometers, etc.).
- ADAPT – processes the available detector data, performs signal-to-power conversions and evaluates detector-biased alternative sets of power distributions.
- Database - archives all results (plant signals as well as calculational results). The database is specifically designed by Studsvik for GARDEL to maximize efficiency in archiving and retrieval of plant signals and CMS calculational results.
- Graphical user interface - displays current plant status and allows authorized users access to the database, and to conduct operational support and reactivity management calculations. Although GARDEL continuously evaluates alternative power and thermal quantities, only the adaptive level selected as the official core monitoring method will be available to the control room personnel. However, authorized users

(e.g., Reactor Engineers) may, at any time, access calculated results from the alternative adaptive methods in order to assess the accuracy of GARDEL's results.

Cycle initialization is a simple task involving import of the CMS beginning-of-cycle model. The graphical user interface panel within GARDEL guides the authorized system administrator to setup the new cycle for all users. Authorization rights for individual users are also controlled through a graphical user interface panel.

Since GARDEL utilizes CMS, additional benefits of the broad engineering application features of CMS are also available using GARDEL. The GARDEL-generated CMS core tracking history file, which reflects actual plant operation history and current core state, can be exported from GARDEL for direct application by other CMS products. One important example is for application in Studsvik's the real-time operator training simulator core model, S3R, for JIT (Just in time) training.

III. GARDEL AT KKB

At KKB, GARDEL is installed on two SUN Blade 1000 UNIX Workstations. These servers provide sufficient computing performance to accommodate simultaneous automatic core tracking, core monitoring, and on-demand reactivity management calculations available in GARDEL.

Data is automatically transferred from the process computer to GARDEL, which collects and applies the measured data for adaption and comparison with calculated three-dimensional axial power results using CMS.

Fig. 3 presents a schematic of the computer network configuration used at KKB for GARDEL. In the figure, ANIS refers to KKB's process computer system. The ANIS1 and ANIS2 nodes supply the redundant GARDEL servers, gardel-01 and gardel-02, all necessary process computer and measured detector data.

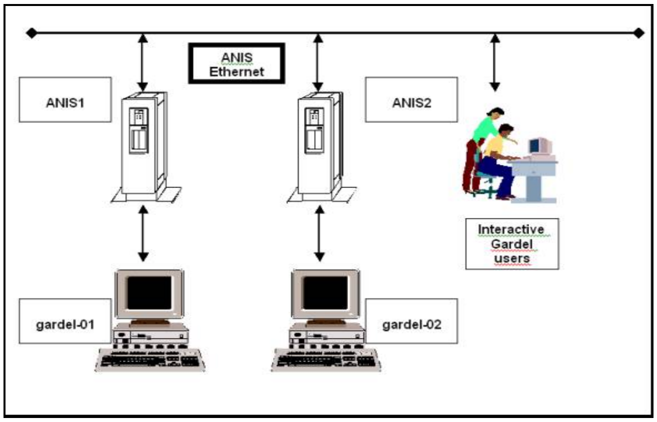


Fig. 3. GARDEL configuration at KKB

The GARDEL users access the GARDEL-GUI through the network, either from the control room or the engineering offices, exporting the GARDEL-GUI display to their own desktop. Access to the GARDEL servers is only permitted through the GARDEL-GUI, ensuring a high degree of data security. GARDEL supports multiple simultaneous users making it extremely powerful for KKB for efficient utilization of engineering resources.

Due to the quality of the data supplied by the ANIS system, which filters and flags for GARDEL unreliable values, GARDEL is capable of starting operation at cold, depressurized conditions, continuously following the reactor's approach to criticality.

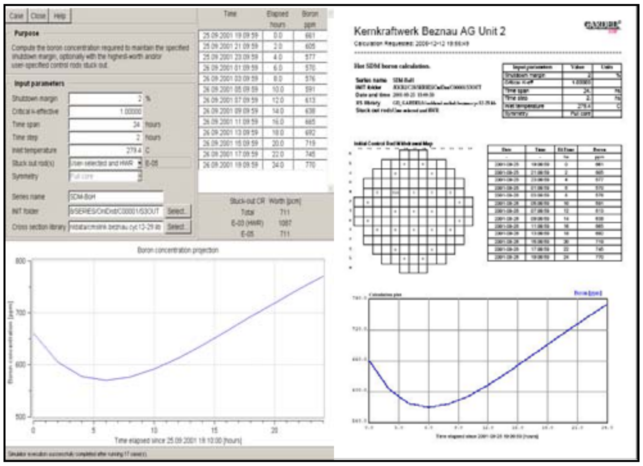
Once the reactor reaches HZP (hot zero power) conditions, GARDEL automatically analyzes and documents any movable detector flux map measurements conducted by the plant. Throughout the cycle, based on changes to plant measured signals, GARDEL automatically updates the CMS cycle-specific core model. CMS calculations are also available on-demand should the operator wish to override the automatic core updating.

All measured signals and calculated results are automatically stored in the system. This data is always available for viewing, for analyses, and for export by authorized users. In addition, important core monitoring-related results are continuously updated and available via an intuitive graphical user interface (GUI) for the reactor operators.

The key benefit of GARDEL for the reactor operators in the control room is simplicity. The GARDEL display panels for the reactor operator are designed with a prevent-events principle. This results in the ability of the reactor operator at KKB to perform high-fidelity neutronic calculations with a simple, highly automated interface, limiting the chance of user error.

Due to the modularity and flexibility of GARDEL, reactor engineers (or other authorized users) at KKB can have access to more in-depth functions within the system. Through a more detailed GUI available in GARDEL, reactor engineers can perform detailed analysis of past events and current conditions. They may also perform complex calculations for support and planning for future power maneuvers in order to achieve safe and efficient core operation.

Fig.4 below shows one example of a GARDEL calculation available to the reactor engineer for performing Estimation of Critical Condition (ECC) following a plant scram during the cycle. GARDEL automatically stores and documents the contents of the panel and all results from the calculation.



Purpose

Compute the boron concentration required to maintain the specified shutdown margin, optionally with the highest-worth and/or user-specified control rods stuck out.

Input parameters

Shutdown margin: 2 %
Critical k-effective: 1.00000
Time span: 24 hours
Time step: 2 hours
Inlet temperature: 279.4 C
Stuck out rod(s): User selected and HWR E-05
Symmetry: Full core
Series name: SDM-BoH
INIT folder: \SERIES\OnDist\C00001\S3OUT
Cross section library: [illegible]

Time	Elapsed hours	Boron ppm
25.09.2001 19:09:59	0.0	661
25.09.2001 21:09:59	2.0	605
25.09.2001 23:09:59	4.0	577
26.09.2001 01:09:59	6.0	570
26.09.2001 03:09:59	8.0	576
26.09.2001 05:09:59	10.0	591
26.09.2001 07:09:59	12.0	613
26.09.2001 09:09:59	14.0	638
26.09.2001 11:09:59	16.0	665
26.09.2001 13:09:59	18.0	692
26.09.2001 15:09:59	20.0	719
26.09.2001 17:09:59	22.0	745
26.09.2001 19:09:59	24.0	770

Stuck-out CR	Worth [pcm]
Total	711
E-03 (HWR)	1087
E-05	711

Simulator execution successfully completed after running 17 case(s).

Fig. 4. Example of Documented Reactor Engineer Calculation Panel Results

For core monitoring functions, GARDEL includes several levels of biasing calculated results to measured results, or adaption. This allows a higher confidence in the margin-to-limits calculations of key power distribution-related quantities. At KKB, there are four adaptive levels available in GARDEL:

- Level 0: Purely predictive results (CMS result directly), no biasing.
- Level 1: Constant bias based on the results of the active flux map measurement applied to level 0 results. The system administrator defines which flux map measurement is the active one (usually the latest one).
- Level 2: Radial bias, based on the current thermocouple readings, applied to level 1 results.
- Level 3: Axial bias, based on the current ex-core detector readings, applied to level 2 results.

In addition, the system administrator may decide to disable the thermocouple biasing. If the T/C biasing is "OFF," then level 3 adaption would be applied to level 1 results. The standard way of operating GARDEL at KKB is to select T/C adaption "ON", but use results those from level 1 as official core monitoring parameters.

IV. VALIDATION

As part of the validation of GARDEL, KKB and Studsvik extensively benchmarked[4] the CMS results against measured data for over 30 cycles of operation. The results demonstrated the accuracy of GARDEL's underlying methods and served as the basis for licensing GARDEL with the Swiss safety authorities.

Tables II and III below summarize the results of relevant parameters from the benchmark germane to on-line core monitoring: movable detector reaction rates and reactivity comparisons during startup and plant operation. It is important to note that the benchmark comparisons[4] demonstrate the same accuracy of CMS for the key parameters of interest for MOX cores and for UO2-only cores. As mentioned above, this was a key criterion of KKB's decision in selecting a new core monitoring system.

TABLE II
Summary of movable detector (flux map) comparisons

Parameter	(mean ± σ)	
	Unit-1	Unit-2
Number of Flux Maps	199	225
2-D Radial RMS[(A)](%)	1.36 ± 0.47	1.31 ± 0.37
Axial RMS1 (%)	1.69 ± 0.59	1.81 ± 1.05
3-D Nodal RMS[(A)] (%)	2.54 ± 0.60	2.69 ± 1.08
?A-O (%)	-0.89 ± 0.76	-0.65 ± 1.24
? Peak Reaction Rate[(B)](%)	-0.25 ± 1.59	-0.61 ± 2.20

(A) $$RMS = \sqrt{\sum_{i}^{N} \frac{(Meas - CMS)^2}{N}} \cdot 100\%$$

(B) $$Peak = \frac{Meas - CMS}{Meas.} \cdot 100\%$$

TABLE III
Summary of Startup Test Reactivity Parameter Comparisons

Parameter	Acceptance Criteria	CMS to Measured Difference (mean ± σ)

		Unit-1	Unit-2
ARO Critical Boron (Δ ppm)	< 50 ppm	1 ± 17 ppm	-25 ± 13 ppm
Control Rod Bank Worth	< 10 %	-2.1 ± 4.1 %	-3.5 ± 2.3 %
ITC (Δ pcm/°F)	< 2 pcm/°F	-0.3 ± 0.4 pcm/°F	-0.7 ± 0.4 pcm/°F

The accuracy of the calculating peak reaction rate is of note, since this effectively is the accuracy of GARDEL to reliably calculate margin to Fq limit (related to linear heat generation rate). This exceptional accuracy provides confidence in the system for on-line monitoring of future operation (predictive application).

V. OPERATIONAL EXPERIENCE AT KKB

GARDEL was officially licensed for core monitoring at KKB in July of 2003. Since that time, GARDEL has been used to continuously monitor operation of both units without interruption, providing 100% availability.

From this operational experience, GARDEL has demonstrated exceptional accuracy in calculating important core monitoring related functions and has shown potential for significant improvement in plant maneuvering by direct monitoring of PCI and minimum DNB. This section presents several examples of GARDEL's performance over the past few years.

<u>Start-up monitoring</u>: Fig.5 presents results from GARDEL's operation during the start-up of unit 2 at the beginning of Cycle 34. Following the refuelling outage, GARDEL was activated starting from cold, depressurised conditions and accurately followed the approach to criticality.

In the figure "TIN" represents the initial plant-measured inlet temperature, while "BORON" and "BORPRD" represent the plant-measured and GARDEL-calculated soluble boron. "BANK B" is the position of the lead regulating bank during approach to critical as a function of time. As the figure shows at the time of criticality (after 12 pm 13-07-2005) the accuracy of the predicted results compared to measured result was excellent. This is a clear indication that GARDEL can be used effectively for reactivity management.

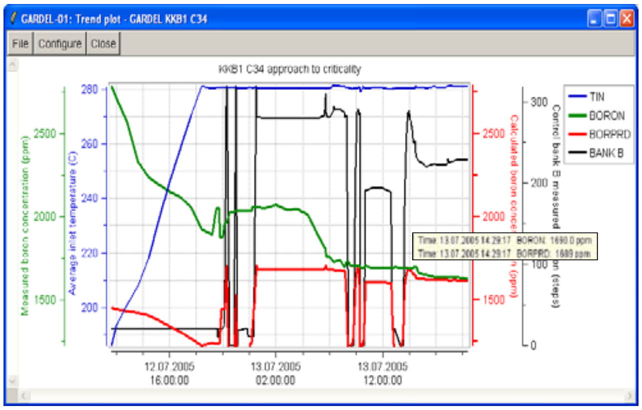


Fig. 5. Start-up monitoring with GARDEL

<u>At power conditions</u> – Fig. 6 presents the margin to limit results on radial peaking factor (FΔh) over the entire cycles for both KKB units respectively.

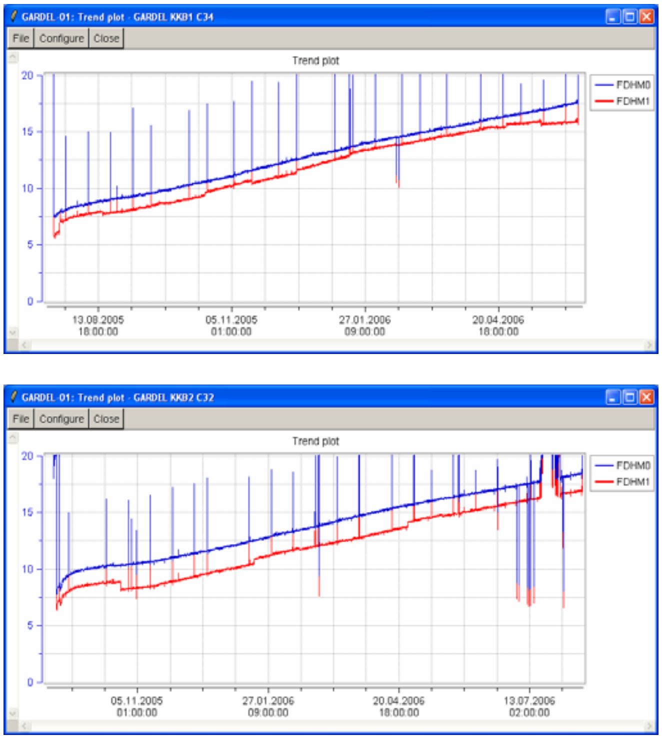
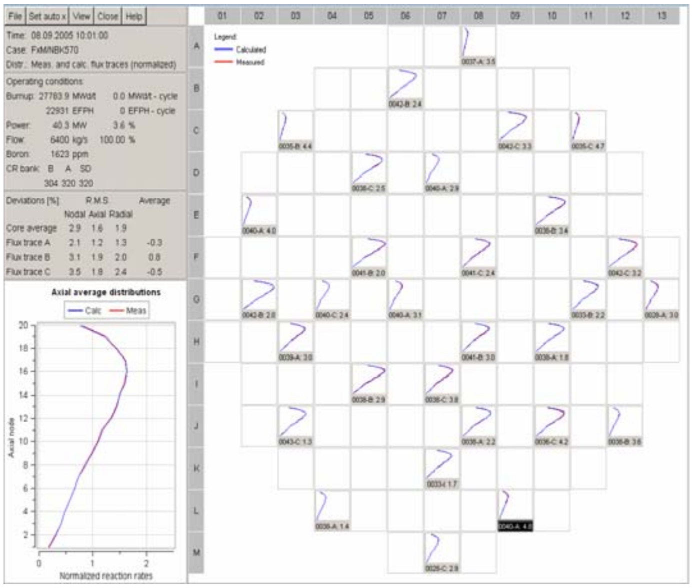


Fig. 6. FΔh whole cycle trends, KKB1 and KKB2

In the figure, "FDHM0" refers to the direct or un-adapted GARDEL-calculated FΔh margin. "FDHM1" is the GARDEL result, adapted using measured flux map results. As the figure illustrates, the difference is never larger than 3%. Thus the accuracy of GARDEL to predict margin–to-limits in terms of radial pin power peaking is 3%. This demonstrates GARDEL can be used effectively for projecting future operation with a high degree of confidence in the margin-to-limits results in radial pin power peaking factors.

Fig. 7 presents a typical flux map (the one in the figure is from HZP start-up conditions during the last cycle of KKB2). The figure shows the high degree of accuracy of GARDEL in calculating detector reaction rates (total 3D rms 2.9% and 2D rms of 1.9%), and, in part, why the difference in calculated and adapted results are so small.



Time: 08.09.2005 10:01:00
Case: FxM/NBK570
Distr.: Meas. and calc. flux traces (normalized)

Operating conditions:
Burnup: 27783.9 MWd/t 0.0 MWd/t - cycle
22931 EFPH 0 EFPH - cycle
Power: 40.3 MW 3.6 %
Flow: 6400 kg/s 100.00 %
Boron: 1623 ppm
CR bank: B A SD
304 320 320

Deviations [%]	R.M.S.			Average
	Nodal	Axial	Radial	
Core average	2.9	1.6	1.9	
Flux trace A	2.1	1.2	1.3	-0.3
Flux trace B	3.1	1.9	2.0	0.8
Flux trace C	3.5	1.8	2.4	-0.5

Fig. 7 – Typical GARDEL to Measured Flux Map Comparison

Based on this demonstrated accuracy, additional gains in operational flexibility (e.g., faster ramp rates in power manoeuvring) are potentially possible. In conventional operation of a Westinghouse plant, there is no monitoring of minimum DNB. In fact, the margin-to-minimum DNB monitoring is inferred by constraining power related peaking factors (e.g., FΔh).

However, GARDEL contains the ability, via CMS, to directly calculate minimum DNB. The accuracy of the GARDEL calculated FΔh just presented is an indication of the accuracy of this calculation.

Fig. 8 shows the minimum DNB trends for the latest cycle at both KKB units, with lowest values in the whole cycle at or above 3.0. This is an indication that additional margin-to-limits exist, meaning potential improvements in plant availability could be achieved if GARDEL were used to directly monitor minimum DNB.

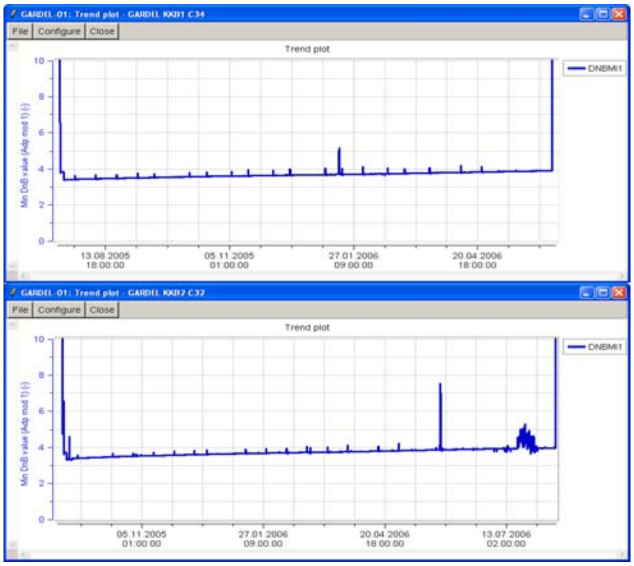


Fig. 8. DNBR whole cycle trends, KKB1 and KKB2

Additional Potential Benefits – In addition to potential benefits of directly monitoring minimum DNB, GARDEL is also capable of monitoring PCI directly. Conventional operation is to protect against PCI via conservative ramp rates when increasing reactor power. Therefore, any increase in ramp rate would be a direct benefit in terms of returning the reactor to power more quickly.

Fig. 9 shows a comparison between the maximum allowed reactor power level (top line) without violating PCI and the actual reactor power evolution during the latest start-ups for both KKB units.

The difference between these lines indicates the significant amount of power available if direct PCI supervision available in GARDEL were employed.

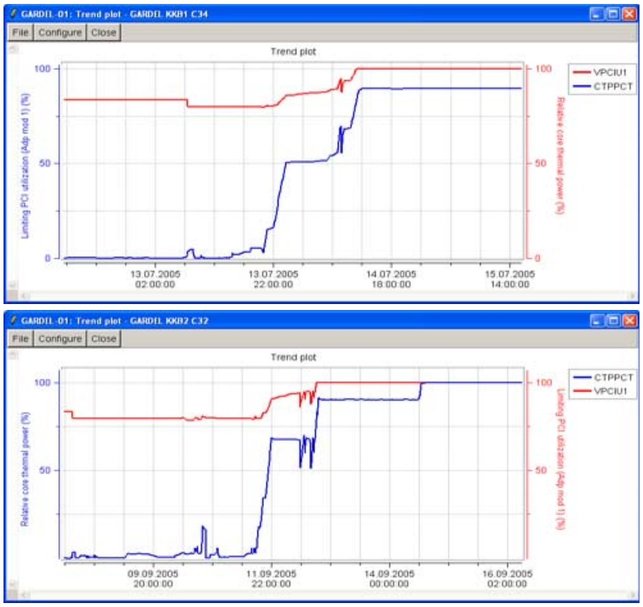


Fig. 9. PCI Limit vs. actual Reactor Power during start-up at KKB1 and KKB2

Transient Operation - Yet another important attribute of any core monitoring system is its effectiveness during transient or off-nominal operation. The ability for GARDEL to accurately predict axial imbalance during future operation is essential. A major component of the core monitoring system is the potential, for example, to mitigate large axial offset swings in core power that may occur during a power manoeuvre due to a Xenon transient.

Fig. 10 shows short periods of transient operation from both units close to the end of the cycle, when the core is most susceptible to unstable axial offset oscillations. In the plot, "AI1" refers to the GARDEL-calculated axial imbalance results adapted to the last flux map analysis, "AI3" indicates the measured axial imbalance from the ex-core detectors, and "BORON" is the measured boron concentration.

The "AI1" and "AI3" trends show the consistency of the GARDEL calculated-to-measured results for axial imbalance. The calculations are always in-phase with the measured axial imbalance. The accuracy here clearly demonstrates the effectiveness of GARDEL when used in analyzing future power manoeuvres and providing effective guidance to the operators during such manoeuvres.

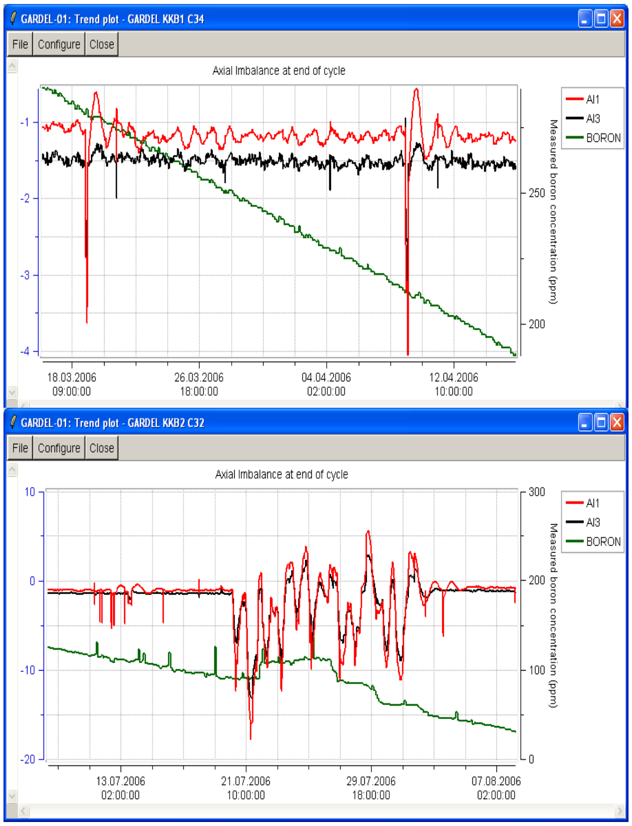


Fig. 10. Axial imbalance comparisons, KKB1 and KKB2

VI. OPERATIONAL EXPERIENCE AT OTHER SITES

Based on the success of the CMS reactor physics codes in modeling virtually all known light water reactor fuel and instrumentation, and, the remarkable success of GARDEL at Beznau, others organizations throughout the world have also noted and have moved forward in modernizing their on-line systems to GARDEL. This list is presented in TABLE IV.

Three key components of GARDEL - computational power and accuracy, modeling of reactor instrumentation, and standardization have resulted in rapid deployment of GARDEL worldwide.

TABLE IV

List of existing GARDEL users

Reactor name and country	Reactor Type and design	Operating system	Comment
Beznau 1 Switzerland	PWR Westinghouse	Solaris	MOX Fuel
Beznau 2 Switzerland	-"-	-"-	-"-
Brunsbüttel Germany	BWR Siemens	Linux SuSE	
Cooper USA	BWR General Electric	Windows 2000	
Fort Calhoun USA	PWR Combustion Engineering	Linux RedHat	Rhodium fixed in-core detectors
Monticello USA	BWR General Electric	Windows 2000	
Ringhals 2 Sweden	PWR Westinghouse	Linux RedHat	Fixed in-core gamma thermometer detectors
Ringhals 3 Sweden	PWR Westinghouse	Linux RedHat	
Ringhals 4 Sweden	PWR Westinghouse	Linux RedHat	

In addition, there are a number of plants in the process of implementing GARDEL. They are presented in TABLE V.

TABLE V

Plants currently implementing GARDEL

Reactor name and country	Reactor Type and design	Operating system	Comment
Gundremmingen B Germany	BWR Siemens	LINUX SuSE	30% fraction of MOX fuel assemblies
Gundremmingen C Germany	BWR Siemens	LINUX SuSE	-"-
Ohi-3 Japan	PWR Westinghouse	Windows 2000	
Tsuruga-2 Japan	PWR Westinghouse	Windows 2000	

As one can see from the various reactors listed in these tables, GARDEL has been implemented in several different countries. GARDEL's data and text dictionary supports translation into different languages. Via a simple switch, the GARDEL GUI automatically loads the translations available to fully support the customer's native language (e.g., English, German, or Japanese).

Note also, the wide variety of plant types that are being migrated to GARDEL. There are standard Westinghouse plants, there are Westinghouse plants with MOX or with combination fixed gamma thermometers and movable fission chambers. There are reactors with fixed rhodium in-core instrumentation. The table includes the only BWRs in the world with operational experience with MOX as well as BWRs with gamma and neutron in-core instrumentation.

In addition to on-line core monitoring, several other organizations apply GARDEL outside of core monitoring for operational support exclusively. This version of GARDEL, named CMSOps, is already in use at several additional plants listed in TABLE VI.

TABLE VI

List of Plants Implementing CMSOps

Reactor name and country	Reactor Type and design	Operating system	Comment
Forsmark 1 Sweden	BWR ASEA-Atom	LINUX SuSE	
Krümmel Germany	BWR Siemens	LINUX SuSE	
Philippsburg 1 Germany	BWR Siemens	LINUX SuSE	
Philippsburg 2 Germany	PWR Siemens	LINUX SuSE	
San Onofre 2 USA	PWR Combustion Engineering	IBM AIX	Currently migrating to Windows 2003
San Onofre 3 USA	-"-	-"-	-"-

The GARDEL software is applicable for use in full-scale training simulators. A simple data interface transfers the necessary simulator commands like LOAD/SAVE IC, RUN/FREEZE, etc. GARDEL responds to the instructor commands while still providing 100% fidelity to the reference system at the plant. Plants already using GARDEL in the full-scale training simulator are Beznau 1 and 2 and Monticello.

VII. CONCLUSIONS

The introduction of GARDEL at KKB resulted in a considerable improvement to the accuracy of thermal margin-related quantities, both at steady state and during transient conditions. Having achieved the desired accuracy, GARDEL is actively used as a reliable tool to support and plan the plant operation.

GARDEL's performance was later confirmed at many different sites in the world, monitoring and supporting the operations of PWR and BWR reactors of different designs, modelling a wide range of detector and fuel assembly types.

GARDEL's reduced variant, CMSOps, has also established itself as a reliable tool for operational support.

NOMENCLATURE

ANIS: KKB's process computer system
CASMO: Studsvik's lattice code. (Basic component of CMS.)
CMS: Studsvik's core management system
CMSOps: Studsvik's operational support system
GARDEL: Studsvik's core monitoring and operational support system
KKB: Kernkraftwerk Beznau AG
SIMULATE: Studsvik's core physics model. (Basic component of CMS.)

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