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GARDEL–PWR: Studsvik's Online Monitoring and Reactivity Management System

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ABSTRACT

The Studsvik Scandpower incore fuel management code system, CMS, is now extended to online core monitoring and reactivity management functions. This application, named GARDEL-PWR, is fuel vendor, reactor vendor, and incore instrumentation independent. GARDEL consists of the well established core design neutronics solution, SIMULATE-3, along with a highly automated core tracking system, database archive system, and user configurable graphical user interface which includes international language support. All plant measured signals and results from all neutronic calculations are automatically archived into the database facilitating rapid user access to important data. GARDEL is unique in modularity and flexibility, running on a variety of hardware systems (e.g., UNIX, Windows and Linux PCs), and accessible to multiple users simultaneously. No proprietary hardware is required. Due to binary file compatibility of CMS, GARDEL can be deployed on both homogeneous and heterogeneous (mixture of UNIX and PC workstations) computing networks. GARDEL is in use at a variety of operating PWR reactor sites, demonstrating exceptional results at both steady state and transient conditions. A system description, results from operating reactors and merits of the system are presented.

1. GARDEL OVERVIEW

Core monitoring and reactivity management calculations have traditionally employed approximate neutronic methods. Many of these approaches use pre-computed data libraries for signal/power conversion and pre-computed reactivity coefficients for reactivity management calculations. This approach, developed many years ago, is still predominantly used today. The disadvantages of these approximations are *accuracy,* compared to more robust methods typically used for core design and analysis, that they *do not always portray the actual state of the core* (i.e., do not reflect actual operating history), and that they are *susceptible to user error*.

GARDEL alleviates these potential shortfalls using a SIMULATE-3[1] neutronics model identical to that used in the core design along with actual plant operating data. This approach enhances accuracy of the calculations. In addition, GARDEL contains automated core support and reactivity management applications and a powerful and intuitive graphical user interface which protects against potential user error.

The SIMULATE-3 model in GARDEL is identical to that used for core design. SIMULATE-3 is used in 15 countries, has been licensed in six countries and is used by safety authorities in several countries. It has been applied to virtually all existing PWR fuel and core designs in use today[2]. These include ultra low leakage loading patterns, both UO_2 and MOX lattices, burnable poisons containing boron as well as integrated absorbers including erbium, gadolinia, and boron coating, and a variety of incore detector types; such as U_{235} fission chambers, gamma sensitive platinum emitters[3], gamma thermometers, fixed rhodium incore detectors[4], and vanadium aero balls.

Starting at the beginning of cycle, GARDEL updates the cycle specific SIMULATE-3 model, automatically, triggered by changes in core operating parameters and elapsed time (or manually by user demand). All neutronic calculations within GARDEL include the impact of the detailed operating history of the cycle.

GARDEL addresses potential user error during calculational applications (e.g., reactivity management) via an intuitive graphical user interface. Designed with the guidance of reactor engineers and operators, this interface, helps facilitate those unfamiliar with SIMULATE-3 to safely conduct accurate reactivity management calculations. An ECP (estimate critical position) calculation, for example, takes 2-3 minutes from case selection and specification until case completion and results are available.

Results from core follow, signal/power conversion, and reactivity management calculations are automatically stored along with measured data in GARDEL's own database. This database, specifically designed and written by Studsvik Scandpower, is an efficient, administratively controlled, centralized repository for all data associated with GARDEL. The database can be shared simultaneously among multiple authorized users.

Using GARDEL's highly efficient and intuitive graphical user interface all measured and calculated data from the database can be easily accessed, displayed, and exported. High resolution trend plots for scalar parameters and graphical representation of three-dimensional quantities are available. Other features include on-demand generation of periodic reports such as core follow or isotopic reports. These reports can be generated in either postscript or PDF format—expediting posting to the customers intranet web site for example. The user can customize and create additional site specific reports or procedures within GARDEL.

Since GARDEL is executing SIMULATE-3, additional benefits to other CMS applications can also be realized. The SIMULATE-3 history (restart) file based on actual plant operation and current core state can be exported on demand from GARDEL for direct use in other CMS codes. Typical applications are for use in:

- SIMULATE-3 core design or safety analysis calculations,
- Studsvik Scandpower's space kinetics code S3K,[5]
- the automated loading pattern design code, XIMAGE[6], e.g., assess the impact of actual EOC (end of cycle) conditions on the next cycle design,
- initializing the real-time simulator, S3R[7].

Access to features in GARDEL is administratively controlled. Users can be given different access rights to various features within GARDEL. For example, a user could be given access to the current core state and be able to view results but not authorized to perform calculations.

System reliability using GARDEL is enhanced by sophisticated event recovery logic. Communication between redundant GARDEL servers is continuously maintained. In the event one of the servers becomes inoperable, the remaining server continues to function independently. Once the failed server recovers, the functioning server feeds missing data to synchronize it to the current core state.

2. GARDEL CORE MONITORING FEATURES

Core monitoring includes continuous assessment of margin of power distribution related quantities to LCOs (limiting conditions of operation), plant process computer signal surveillance, and a summary display of the current core state.

The assessment of margin to power distribution limits is performed using a SIMULATE-3 core neutronics model that reflects the current state of the core. Optionally, calculated results used in the assessment can be modified by imposing a correction based on ratios of calculated to measured results.

Some plants use movable incore detectors to measure U_{235} fission rates. GARDEL directly converts these measured signals into relative reaction rates. These are defined as the measured U_{235} fission rates. Using the SIMULATE-3 core tracking model, GARDEL also generates calculated U_{235} fission rates. Correction factors are then defined as the ratio of measured to calculated U_{235} fission rates.

Similar corrections are also available in GARDEL for gamma sensitive devices and for fixed detector systems. GARDEL includes direct signal/power conversion of measured signals for all incore detectors in PWR use today, including movable fission chambers, vanadium aeroball systems, fixed rhodium detectors, fixed platinum detectors, and gamma thermometers. SIMULATE-3 also has the capability to calculate reaction rates for each of these devices.

Next, the correction factors are radially expanded to uninstrumented locations, and in the case of fixed detector systems, axially expanded to cover the span of the fuel column[8]. These factors can then be applied to calculated power distribution parameters in the assessment of margin to limits. The correction factors are assumed constant until the next measurement is available. In the case of the movable system this is typically once every 30 EFPDs (effective full power day). In the case of a fixed detector system the correction factors can be calculated continuously.

Additional corrections can be calculated using core exit thermocouples. These factors are calculated by assuming the enthalpy rise (calculated using the difference between measured inlet temperature and measured core exit temperature) is proportional to assembly power[9]. Correction factors are then formulated as the ratio of the measured to calculated assembly power.

An additional modification to these factors is made to compensate for resultant power distribution differences when a reference power distribution, e.g., based on incore detector measurements, is available[9]. This modification is equivalent to an electronic gain adjustment which provides a bias to be applied until the next reference is available. This approach has been used for many years in BWRs, for example, to adjust LPRM readings to agree with reference TIP results[8].

However, GARDEL experience to date indicates that application of thermocouple correction factors in margin to limits assessment is of marginal value. Due in part to the demonstrated accuracy of the uncorrected calculational results from SIMULATE-3, the uncertainty of the thermocouple signals exceeds the magnitude of the correction based on incore flux map measurements. In other words, the differences of the GARDEL calculated power distribution compared to the measured power distribution is smaller than the uncertainty of the thermocouple signals. Therefore, it is of questionable value to apply these correction factors to calculated results. A more important application of thermocouple data in GARDEL might be for use in signal surveillance. For example, these signals can be used as a "second opinion" to quickly identify unforeseen situations such as an individual control rod drop.

An important component to the core monitoring system is to continuously examine and validate plant measured signals being used in the core monitoring system. GARDEL contains automatic signal surveillance logic to flag anomalous signals. It also contains capabilities for the authorized user to override or substitute an invalid signal or to manually fail a signal. The extensive database archive, coupled with a robust intuitive graphical user interface, allows detailed examination of any of the signals available in the system (trend plots of correction factors as well as individual signals are available at all times) by an authorized user.

Signal surveillance is also useful in monitoring performance of the calculational model. Results from the core tracking model are continuously compared in GARDEL to analogous measurements to determine if the model is beginning to "drift" from the measured results. Reports are directly available from GARDEL summarizing calculations and comparison to data from various instruments. All data can be easily exported as simple text format from the GARDEL database for use in other software.

Beyond traditional monitoring functions, GARDEL also includes pin by pin PCI monitoring. Traditional models monitor change in power of only the hottest pin—disregarding whether the "hot pin" has changed locations. Since other pins in the assembly may still experience fairly large changes in power, conservative power ramp rates are used (e.g., 3% per hour), even though fuel vendor limits allow much faster ramp rates (e.g., 30% per hour). For PCI monitoring, GARDEL utilizes SIMULATE-3's three-dimensional power distribution for every pin in the core. Thus, using GARDEL, faster ramp rates are possible, resulting in significant cost benefit (for some PWRs the estimated cost savings is 1 EFPD per startup).

3. GARDEL SUPPORT AND REACTIVIY MANAGEMENT FEATURES

GARDEL includes highly automated operational support and reactivity management applications. Using efficient core design features of SIMULATE-3, coupled with detailed plant operational history, an intuitive graphical interface provides the GARDEL user the capability to easily perform sophisticated plant operational support and reactivity management calculations.

Among the automated calculations available in GARDEL are:

- **ASI / AFD (ΔI) Guidance During Power Maneuver** - with a user specified ramp rate, GARDEL determines control rod position and critical soluble boron concentration vs. power level and time to achieve a target ASI / AFD (ΔI). The calculation can be conducted prior to the actual maneuver and used as guidance by the reactor operator as to the expected control rod inventory and boron requirements during the maneuver. In addition, GARDEL includes a Recalculation feature which allows the user to modify the GARDEL projected scenario and investigate different power maneuver strategies.

- **Estimate Critical Condition** (ECC, sometimes referred to as ECPs) – following a scram, GARDEL can automatically determine critical control bank position at a fixed boron concentration or at a fixed control bank position determine critical boron as a function of time.

- **Shutdown Margin** – at either hot or cold conditions GARDEL can determine the amount of available shutdown margin. GARDEL automatically determines the high worth rod and excludes it from the calculation, or alternatively the user may manually select individual control rods to exclude.

- **Lifetime Depletion** – allows the user to project end of full power life or reactivity to reach a specific calendar date. The calculation can be repeated during the cycle to determine the impact the actual core operation has on projected end of cycle. It can also be used to estimate a calendar date for when the core will reach 300 ppm for EOC MTC testing.

- **Predictions** – users can manually specify their own operating scenarios. GARDEL includes all of SIMULATE-3's capabilities; e.g., to search automatically on control rod position to maintain criticality or a target axial shape index, or to search on critical boron, or critical eigenvalue at a fixed boron concentration. These calculations can be performed in GARDEL assuming either transient or equilibrium fission product treatment.

Since direct three-dimensional neutronic calculations are used for these reactivity management calculations, reactivity databook curves are no longer necessary. This results in improved accuracy, and resource cost savings (otherwise required to generate reactivity databook curves). Calculational integrity is assured through administrative controls that prevent the user from modifying results, software versions, libraries, input cards, etc.

4. GARDEL FOR TRAINING AND SIMULATORS

Licensing authorities in different countries are requesting fidelity between the full scope training simulator control room and the actual control room. This demand necessitates the need for having GARDEL available in the simulator control room. To accommodate this requirement, GARDEL can be configured to work with the simulator by simply replacing the plant signal data feed from the process computer with a feed from the simulator.

In addition, GARDEL can be used as a training system providing valuable core performance instruction using data from actual operating events. GARDEL files containing events of interest can be copied on demand from the online GARDEL server to a stand-alone training computer executing GARDEL. There they can be replayed and analyzed by students for training purposes.

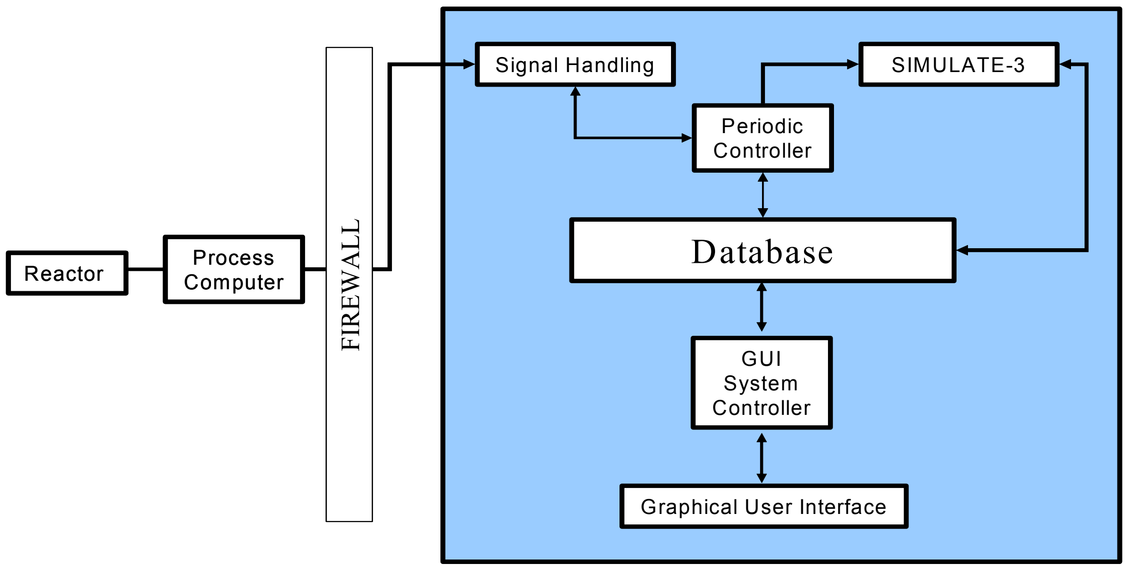
5. GARDEL SYSTEM DESCRIPTION

GARDEL is a modular system of several executables, each performing specific tasks. These programs are written in standard programming language of FORTRAN, C and Tcl/Tk making them highly portable to UNIX and PC computing systems. Files generated within the GARDEL system are written specifically to be binary compatible. This allows the system to be distributed on heterogeneous networks of PC and UNIX workstations.

A typical configuration is to have the GARDEL data collection processes and core tracking calculations executing on two redundant servers. GARDEL users sharing this network would run the GARDEL graphical user interface locally on their own desktop, to see the current core state, make trend plots, generate reports, perform support or reactivity management calculations, etc.

5.1 GARDEL System Configuration

Fig. 1 presents a simple diagram of the GARDEL system indicating the major components. 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 1-2 minutes) and data is passed to the GARDEL server. This data set is a small file containing relatively few parameters such as reactor power, flow, pressure, inlet and outlet conditions, control rod positions, excore and incore signals (when available), etc.



GARDEL

Fig. 1 GARDEL System Description

A brief description of these components is as follows:

- **Signal Handling** – controls receipt and storage of plant computer signals from the plant process computer. This data is then used in the neutronics model for core tracking. The frequency of the data transmission is dependent on the monitoring frequency desired, limited only by the neutronic simulator execution speed (typically less than 30 seconds for a full core 3-dimensional SIMULATE-3 calculation).

- **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.

- **SIMULATE-3** – GARDEL accesses the same CMS neutronics model developed by the core design group and used for core design calculations. Due to the modularity of GARDEL, several CMS calculations can be conducted simultaneously from different computers within a network.

- **Database** - archives all results (plant signals as well as calculational results). The database is specifically designed 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. Due to the modularity of GARDEL, the GUI module can be executed individually for each authorized user on their own desktop. This allows multiple users to simultaneously conduct and share calculations or access plant measured and computational results. Each user can configure the GARDEL display on their desktop independently of another user's configuration. User access to various features within the GARDEL system can be controlled by the GARDEL system administrator. Provided users have access to the network where GARDEL resides, they can use GARDEL remotely, e.g., telecommuter support.

Cycle initialization is a simple task involving import of the cycle specific SIMULATE-3 beginning of cycle restart file and the associated cross-section library (TABLES-3/CMSLINK). 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 simple graphical user interface panel.

6. GARDEL RESULTS

This section provides several specific examples illustrating the accuracy of the system and applicability in resolving operational issues. Since its inception several years ago, GARDEL has been installed at 5 PWRs and several engineering offices throughout the world. These installations comprise fixed and movable, neutron and gamma sensitive, incore instrumentation devices. GARDEL is used at these installations for a variety of applications from core monitoring to operational support and reactivity management with exceptional results[10].

6.1 PWR Steady State and ECC Results

Beznau NPP consists of two 2-loop Westinghouse PWRs. Beznau is currently performing online core monitoring with GARDEL for both units. About 20% of the fuel assemblies in both units are MOX fuel assemblies in the current cycle.

Beznau has performed an extensive benchmarking of the SIMULATE-3 model used within GARDEL covering more than 30 cycles of operation from both units[11]. This benchmark establishes the high degree of accuracy of the CMS code system to model cores containing MOX assemblies. The benchmark demonstrated the accuracy (RMS of calculated vs. measured reaction rates) of SIMULATE-3 for integrated (2D) U_{235} reaction rates to be better than 2%, and the three-dimensional accuracy better than 3%.

Fig. 2 presents an example of the GARDEL accuracy during several months of a representative cycle for margin to LCO for the calculated integrated radial peaking factor, $F\Delta h$. The figure shows the SIMULATE-3 calculated margin, FDHM0, compared to the margin based on correction factors from the latest fluxmap (FDHM1) and the margin calculated combining information from the latest flux map with the current thermocouple readings (FDHM2).

The difference between the FDHM0 and FDHM1 is on the order of 2%, which is approximately the accuracy of the calculated reaction rates, compared to measurement. Additional modification based on thermocouple data is negligible and therefore, Beznau does not use corrections based on thermocouple data for margin to limits assessment.

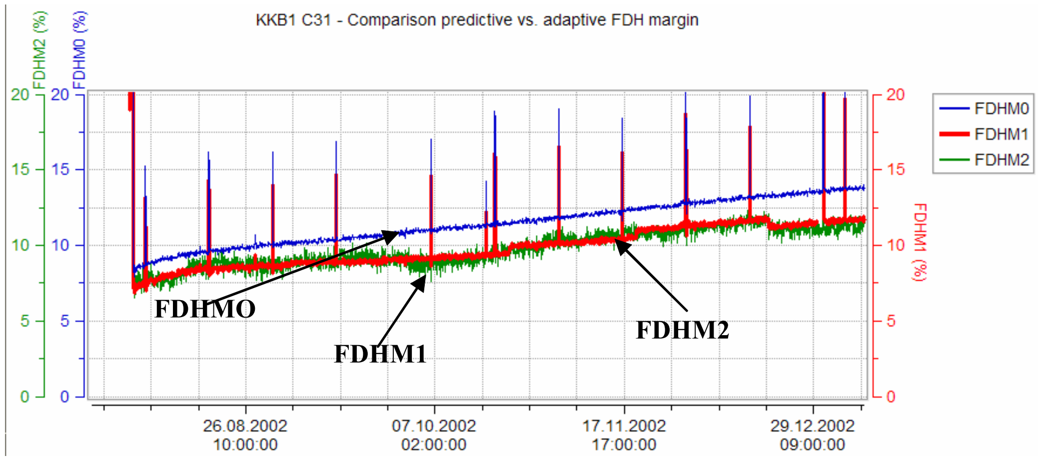


Fig. 2 Comparison of predicted and corrrected FΔh margins

Beznau also offers a series of criticals following plant scram within the cycle that illustrate the accuracy of SIMULATE-3 for reactivity management. Calculated to measured results are presented in **Table 1**.

Table 1 Beznau Estimated Critical Conditions Comparison

Cycle	Cycle Exposure (GWD/MTU)	Outage Duration (hours)	Accuracy meas.–calc. (pcm)
4	0.313	11.7	200
4	0.414	42.0	20
4	11.09	284.0	10
4	16.0	67	170
5	6.9	38.7	- 130
7	0.251	327	210
7	5.316	183	190
7	6.318	56	-220

Although the criticals occurred in past cycles, before GARDEL was implemented, they do provide an assessment of the expected accuracy since GARDEL utilizes the same SIMULATE-3 model. All calculated results are within the administrative acceptance criteria of 250 pcm and technical specification limit of 500 pcm.

6.2 PWR Near EOC Pump Trip Event

Operating at full power near end of cycle, the McGuire, Unit-1, 4-loop Westinghouse designed PWR, experienced a main coolant pump trip. This automatically triggered the reactor protection system to insert control rods and reduce reactor power. Once at the reduced power level, the plant was stabilized and a significant Xenon transient ensued. Shortly thereafter the plant was returned to full power. This event represents an integral test of the accuracy of GARDEL in calculating the axial flux imbalance, ΔI, an important parameter for core monitoring and operator guidance during a power maneuver. A graphical summary of power and lead bank position during the event taken directly from GARDEL is presented in **Fig. 3**.

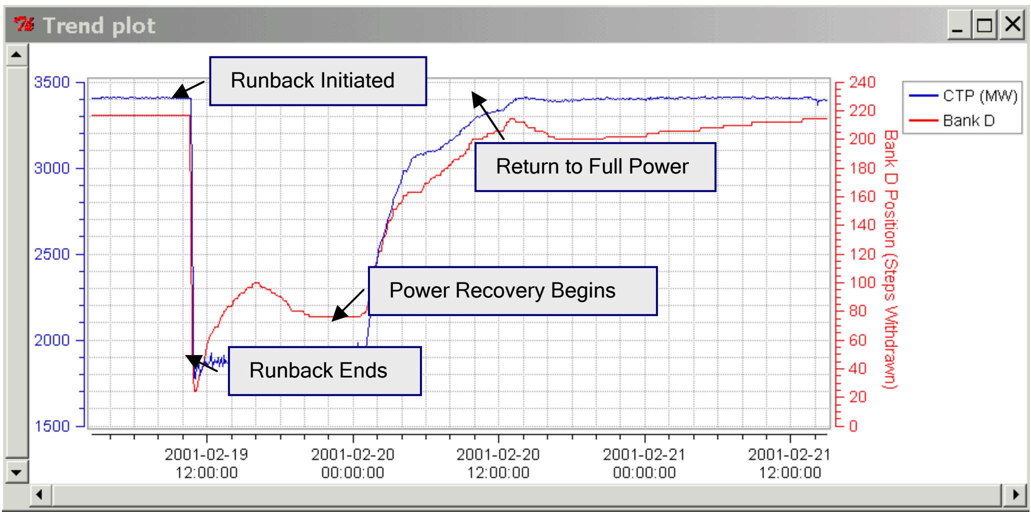


Fig. 3 GARDEL trend plot of key parameters during pump trip

Fig.4 presents a comparison of the actual measured ΔI vs. that calculated using GARDEL. The x-axis on this figure is identical to Fig. 3 which can be used as a cross reference for how reactor power and control bank position change during the event.

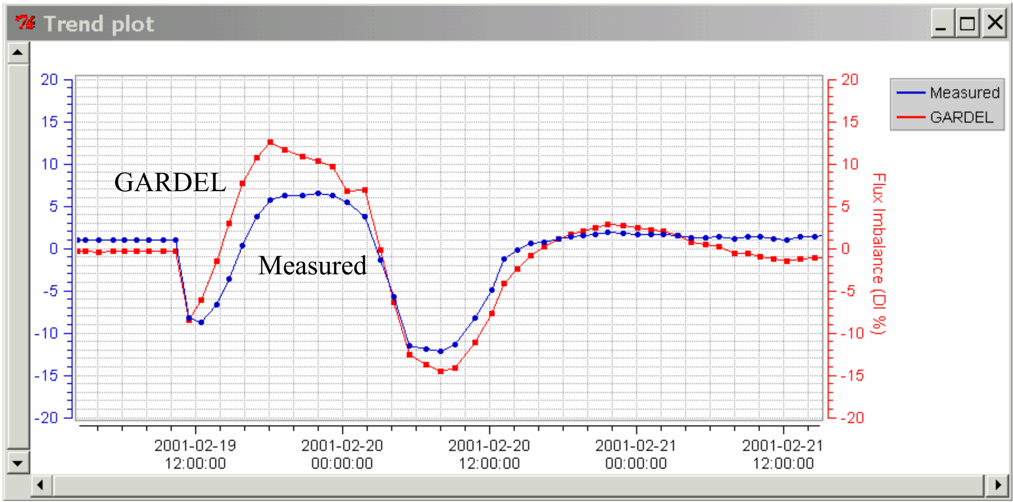


Fig.4 Measured vs. calculated ΔI during pump trip

In general, the agreement between measured data and GARDEL is very good. The largest differences occur shortly after the power runback, most likely due to incore/excore calibration deficiencies. (Typically the incore/excore calibration factors are calculated during testing with the lead bank inserted no deeper than 180 steps withdrawn. During this transient the lead bank was inserted to 28 steps withdrawn.)

6.3 GARDEL Experience with Fixed Detectors

This next example is for a CE implementation. Here GARDEL performs signal to power conversion directly for fixed detector signals. Since these detectors deplete, compensation is required within GARDEL to update charge accumulation and detector sensitivity for each individual detector. This feature alleviates the load on the process computer where the charge accumulation would normally be calculated. Also, as with movable detectors, the signal/power conversion factors are created on demand at plant conditions, eliminating approximations and reducing the resources traditionally required to generate the pre-computed library.

Fig. 5 shows a trend plot of the radial, axial and total (nodal) RMS between calculated and measured power distributions during the cycle. The overall RMS between the calculated and measured Rhodium reaction rates is 1.0% for the radial (2D integrated) and 2.7% for the total (3D). The results could provide a basis to decrease the current uncertainly factor used in the LCO monitoring of peaking factors. Since the current design has sufficient margin, uncertainty reduction is not currently needed. However, since power upgrade is anticipated in a future cycle, a reduced uncertainty could be beneficial.

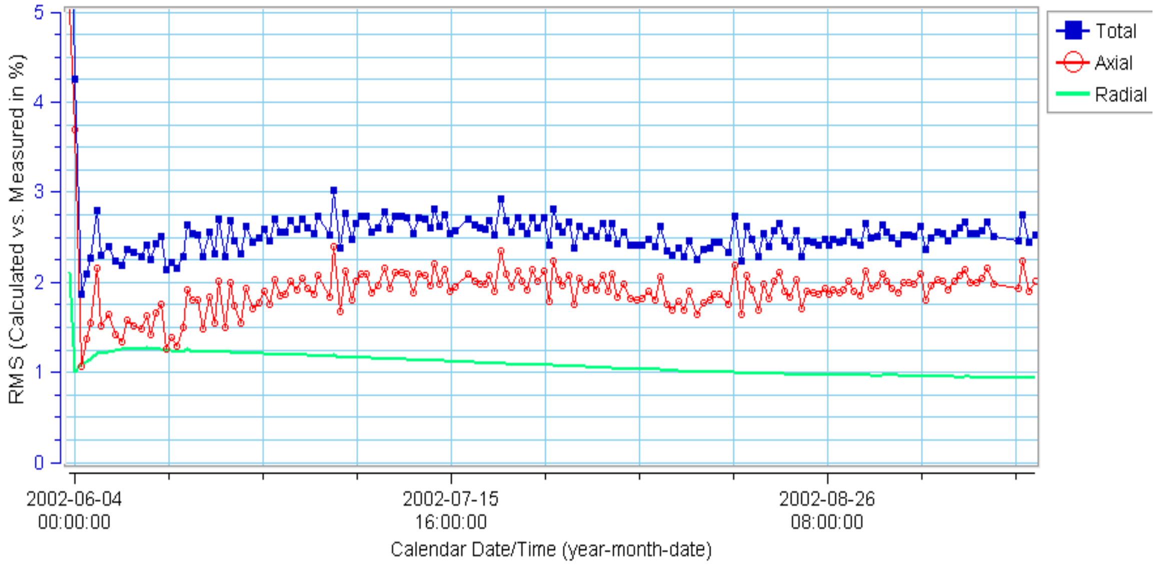


Fig. 5 GARDEL reaction rate accuracy for a fixed detector system

Additional benefits of GARDEL include automated report generation. **Fig. 6** presents a sample of some of the automatic reports available from GARDEL from the same plant. The figure includes excerpts from a core follow report, showing power distribution and related margin to limits results, as well as an excerpt from an isotopic report.

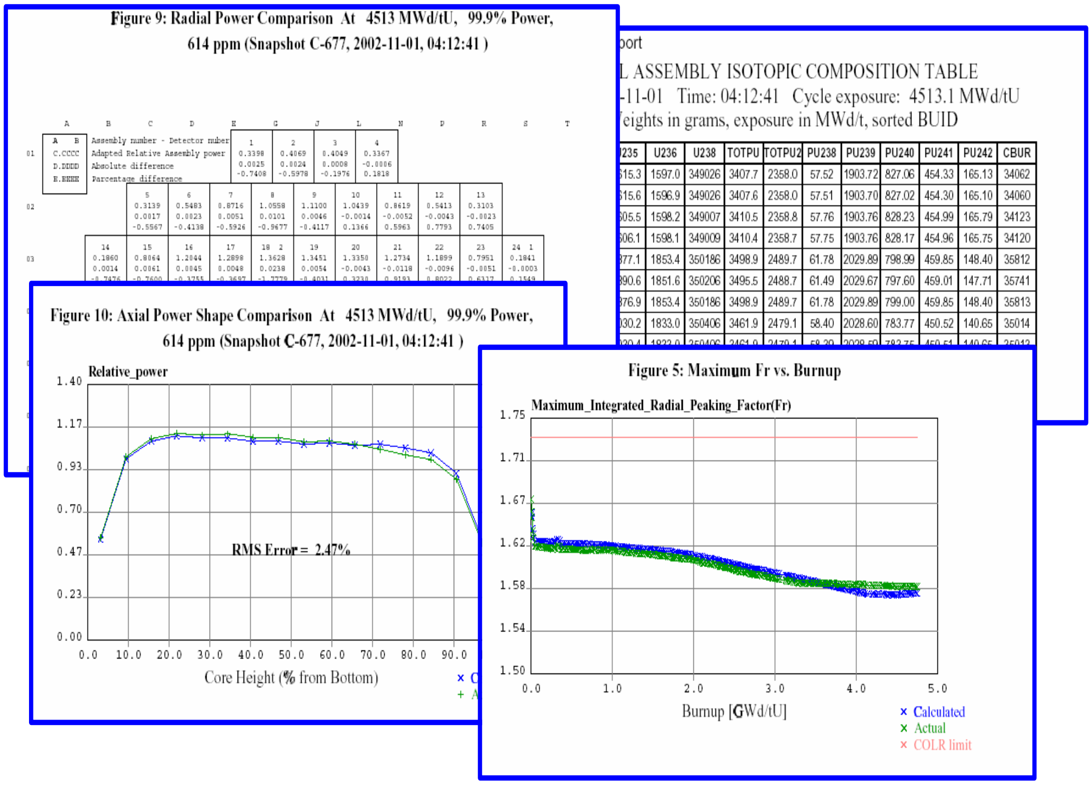


Fig. 6 Sample of GARDEL automatic reports

6.4 GARDEL Experience with Combined Fixed and Movable Detectors Systems

Another application of GARDEL comes from the Ringhals-2 unit, a 3-loop Westinghouse reactor. The Ringhals-2 incore detector system consists of both movable U_{235} fission chambers as well as fixed gamma thermometer detectors. Gamma thermometers have been introduced to replace movable detector instrumented locations that have been lost due to aging. The concern is to ensure that enough instrumented locations are available to meet the fluxmap surveillance requirement (i.e., at least 75% locations available). Other signal/power solutions have not successfully combined signals from these devices to produce useful power distributions.

Using the combined SIMULATE-3 calculations and calibration of gamma thermometers signals to movable detector data within GARDEL, acceptable power distributions were determined. **Fig. 7** presents a comparison of the calculated to measured power distribution RMS of the old system vs. GARDEL for the latest cycle.

Due to the age of the thermometers, frequent calibration is required making it doubtful they can be used as a stand-alone system. However, using GARDEL, a useful measured power distribution from the combined system has been demonstrated.

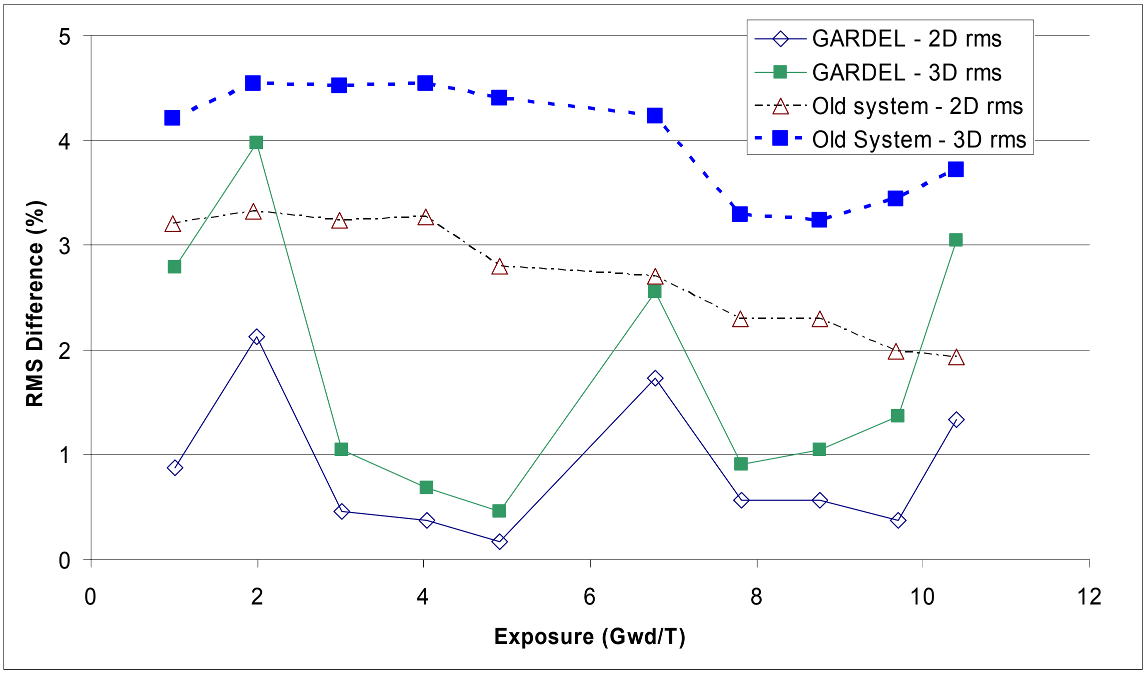


Fig. 7 Power distribution accuracy using a mixed detector system

7. SUMMARY

GARDEL is fully capable of providing a range of features from core monitoring, operational support and reactivity management. GARDEL is in use at several reactors throughout the world. GARDEL provides a vendor independent, reliable, accurate system that reduces, if not eliminates, user error in application. Set up and maintenance is minimal and the user is free to choose on which hardware GARDEL resides.

GARDEL features a core design grade neutronics model, an intuitive graphical user interface and an administratively controlled data archive system. Experience to date has demonstrated the efficiency and accuracy of the system. Resource expenditures traditionally required for such calculations are reduced. Using GARDEL increased ramp rates for power ascension are possible, resulting in significant cost savings.

Table 2 summarizes key features of GARDEL based on actual user applications. These features distinguish GARDEL in terms of capabilities and serves as a comparison to alternative core monitoring and reactivity management solutions.

Table 2 Summary of GARDEL features and merits

Feature	Merit
Vendor independent	Freedom to change fuel design without having to change monitoring system
Support multiple incore detector devices/mixed incore detector devices	Freedom to change detector system without having to change monitoring system
Pin by pin based PCI model	Cost - improve plant availability /faster ramp rates
Computer hardware independent	Cost – able to use best price/performance hardware
Work in heterogeneous computing network	Cost – able to use best price/performance hardware
Eliminate pre-computed signal/power libraries	Accuracy – signal/power at plant conditions Efficiency - save resource required to generate library
Eliminate "databook" approach to reactivity management	Accuracy – 3D neutronics model at plant conditions Efficiency - save resource required to generate databook
Automated GUI for reactivity management	Accuracy - Improve plant availability Quality Control - reduce/eliminate user error
Automated Core Tracking / Report Generation	Accuracy / resource savings otherwise required to generate documentation
Same neutronics model as core design group: Export core history model back to core design, safety analyses, LP code	Efficiency/Accuracy - CMS neutronics model Quality Control, resource savings (otherwise required for configuration management of multiple code systems, auxiliary linking codes, training, etc.)
JIT Training simulator support	Train at actual in-cycle plant conditions resource savings (otherwise required for setup)
Written in standard programming language	Efficiency - easily maintained, portable
Redundant server & recovery logic	Reliability
Does not run on plant process computer	Efficiency – no additional burden on plant computer department. No impact on safety related plant computer systems.
Support multiple users simultaneously	Efficiency – users can share results
Administer access levels for different users	Quality Control – keep unauthorized users from accessing sensitive features/data
User configurable	Efficiency – customizable to internal standards

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