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GARDEL–BWR: Advanced BWR Online Monitoring

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1 Introduction

BWR Core monitoring has traditionally been limited to systems that are only provided by fuel vendors. These systems are normally non-graphical based, use older methods, run on proprietary hardware, and are not readily extendable by the utility.

A common limitation in existing systems is that there is a separation between on-line core supervision and off-line core calculations. This separation typically requires manual data transfers between the two systems and results in a large effort to maintain the quality assurance of the two different models. Also, in current systems there are difficulties to analyze past events and to plan future operation because operational data may be scarce or not available for core analysis purposes.

Studsvik Scandpower (SSP) has extended it strengths in in-core fuel management software to BWR online core monitoring in its GARDEL-BWR product, which removes all limitations listed above. GARDEL-BWR is a graphical based core monitoring system that is independent of fuel vendor, reactor type and uses non-proprietary and readily available modern computing hardware and operating systems. Furthermore, GARDEL-BWR shares a common platform with GARDEL-PWR, which has been implemented on different designs of PWRs extending SSP's commitment to model all western style LWRs.

This paper provides a description of the GARDEL-BWR system components and the calculational capabilities of the system.

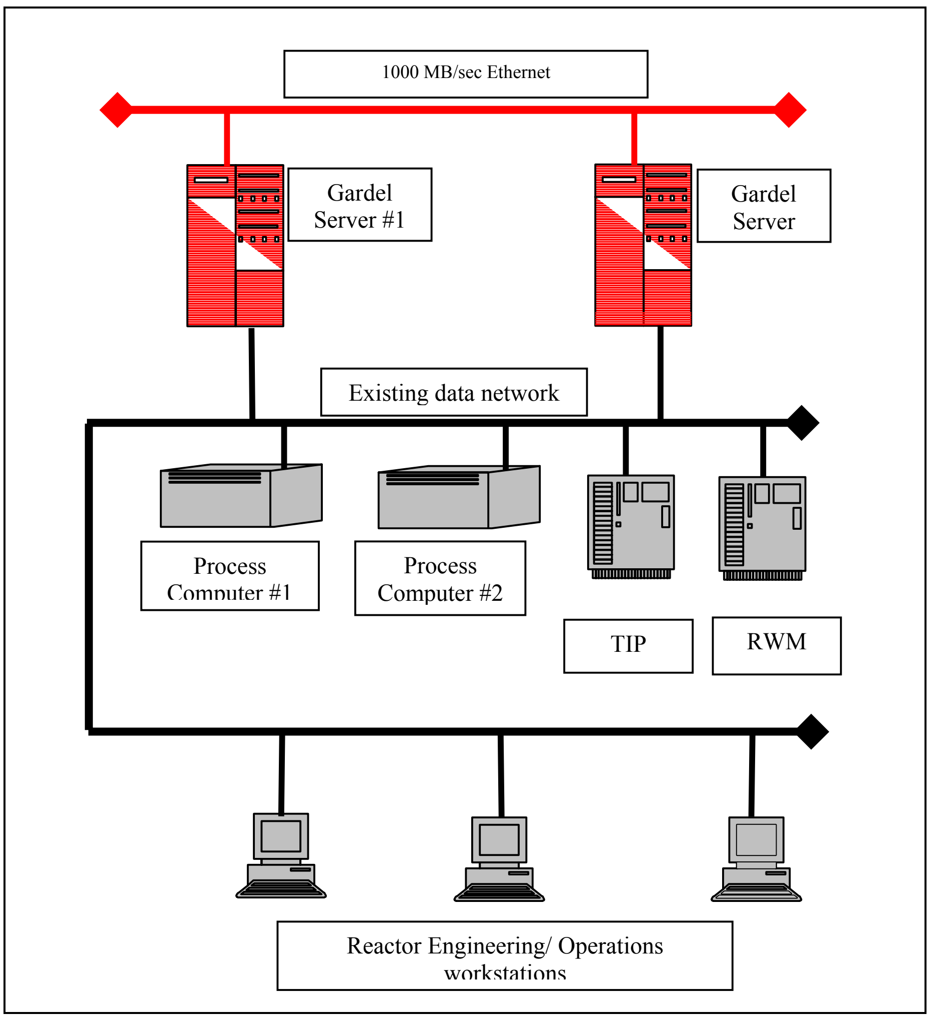
2 System Overview

A good core monitoring tool should provide the reactor engineer and reactor operator with an intuitive display of current reactor conditions and important calculational results needed to operate the reactor. The interface must provide a means to view and investigate trends in past operations, the ability to perform calculations to support current and future plant operations and a means of automated report generation.

Reliability is an important concept in GARDEL-BWR by using redundant hardware and process data feed paths to ensure uninterrupted operation. The system additionally performs results validation to monitor the quality of the results and provides comprehensive information in the event of unexpected conditions.

The GARDEL-BWR system consists of one or more server computers, which provide database storage and perform the automated online calculations. Data display can be performed directly on the server or by using remote Windows 2000/XP based PC workstation as client computers to graphically display results and to perform offline calculations. The general setup of the system of a Windows based implementation at the plant site is shown in Figure 1.

Figure 1 GARDEL-BWR system hardware configuration



The GARDEL-BWR system is designed to be independent of the underlying hardware and operating system by using standard FORTRAN programs for the calculationally intensive processes and uses the TCL/TK language for graphical interfaces that are used to display results and serve as the graphical user interface (GUI). The system has been ported to a variety of UNIX based (Sun, HP, Linux) systems and Windows 2000 Server platforms.

GARDEL-BWR server computers have various modules that perform the following automated functions; Process data signal handling, plant heat balance calculation, 3D SIMULATOR calculations including fission product and exposures updating and thermal margin evaluations, 3D Stability analysis calculations, database updating and automated report generation.

GARDEL-BWR workstation computers use preexisting Windows 2000/XP computers, as they are currently available on Reactor Engineering and Operators desktops. These computers provide the GUI capability that communicates with the server computers via the server database. The GUI consists of a number of interfaces that give the user the capability to display a variety of process data and calculational results in both radial displays; trend plots and PDF output reports. Reactor engineers can also run various offline calculations such as recalculation of past operation, future operation predictions, cold critical and shutdown margin analyses, and estimated critical rod pattern predictions. These calculations are input and results are displayed directly in the user interface.

3 Server Modules

This section details some of the main modules of the GARDEL-BWR Servers, which perform the automated data collection, engineering calculations, system documentation and system availability of the system.

3.1 Process computer communication and heat balance.

Interfacing to the plant process computer requires the establishment of a communications protocol based on the capabilities of the local plant process computer. This protocol typically consists of the process computer creating a text file, which contains the process signal values and status flags at the current reactor conditions, and then transferring that file to the GARDEL-BWR servers using a standard communications protocol such as FTP. This transfer of data happens about every few minutes.

A plant-specific data acquisition program in the GARDEL-BWR system processes this information, performing range and cross checking of the data values and using the process status to determine whether the signal should be passed into the calculation modules of the GARDEL-BWR system. When the data has been validated, the process data is used to perform a reactor heat balance calculation to determine reactor thermal power and inlet sub cooling.

An additional module in the GARDEL-BWR system, the periodic calculation controller, examines the heat balance and process data results to determine if there has been a sufficient change in reactor conditions (power, flow, control rod pattern, time) to trigger a new thermal limits calculation using the 3D core simulator.

3.2 3D SIMULATOR calculations

GARDEL-BWR is designed to use either of SSP's advanced nodal simulators, SIMULATE-3 or PRESTO-2 which have been extended for online specific applications and for data storage and retrieval via the GARDEL-BWR database. These simulators perform all basic functions of power shape calculation, fission product updating, thermal limits calculations, fuel exposure updating, pellet clad interaction (PCI), etc.

GARDEL-BWR uses the same executable, SIMULATE-3 or PRESTO-2, as is used in the core design analysis. This insures fidelity between the projected design grade thermal margins and those same results from the core monitoring.

An additional module in GARDEL-BWR performs the power shape adaption of the TIP and LPRM signals. Two adaptive methods are available: TIP-only and TIP+LPRM based. The adapt module calculates using each method a separate set of core distributions and thermal margins and stores them in the database. The system administrator can decide which thermal margins are GARDEL-BWRs official adaptive method: purely predictive, TIP-only or TIP+LPRM. To avoid confusion, the GUI main panels only show data from the selected method with an indication of which method is currently active. The results of the two other methods are however stored in the database and available for comparisons and analysis.

ADAPTs adaptive algorithms are based on the assumption that the ratios between predictive and measured power are the same as the ratios between predictive and measured detector readings. The program applies to the predictive power distribution the measured/predicted detector readings ratios to evaluate the adaptive power distributions and from those derive the adaptive thermal margin distributions.

3.3 Stability analysis calculations

Certain plants require that the stability of the core be determined by predicting both the global and regional decay ratios at the current core conditions. In GARDEL-BWR, this function is performed using explicit SIMULATE-3K stability calculations.

SIMULATE-3K is SSP's general full two-group, three-dimensional transient analysis code. S3K uses the same nodal solution method (QPANDA) used in the SIMULATE-3 steady state calculations but extended to include time dependence in the thermal hydraulic, pin thermal conduction and pin reconstruction models. S3K also contains peripheral systems to model in-vessel and out of vessel plant systems.

In the GARDEL-BWR system, four separate S3K cases are run to show the plant stability at current and worst case conditions:

- Case 1: current operating conditions, global stability evaluation
- Case 2: current operating conditions, regional stability evaluation
- Case 3: simulated pump trip starting at current conditions, global stability evaluation

- Case 4: simulated pump trip starting at current conditions, regional stability evaluation.

GARDEL-BWR tracks the decay ratio at each of these conditions and displays the results on the main interface window.

3.4 Database

GARDEL-BWR's database is based on SSP's own data management system HERMES. HERMES has some unique characteristics of special interest in reactor physics and simulation applications:

- Top performance. As compared to record-oriented databases, HERMES has high performance when processing large data arrays like nodal distributions in a BWR core.
- OS independence. HERMES is based on standard ANSII Fortran 90, which makes it portable to any operating system.
- Network configuration flexibility. HERMES supports network configurations with automatic binary format recognition. For instance, a user may run a Windows based graphical application accessing HERMES data distributed across the network and physically located on UNIX server.
- Automated data export/import. A powerful scripting language automates data exchange with other application, including GUIs.
- Protection of on-line core supervision data. Ordinary users have READONLY access to the on-line database. The system administrator and privileged users, however, may have full or partial control over the system.
- Traceability and/connectivity of on-line data. From current core conditions the user(s) may come back to any event during the cycle to get a complete representation of any past event.
- On-line and off-line consistency, same QA data. Any off-line calculation performed by a GARDEL-BWR users will be fully consistent with the data and programs used for on-line core monitoring.

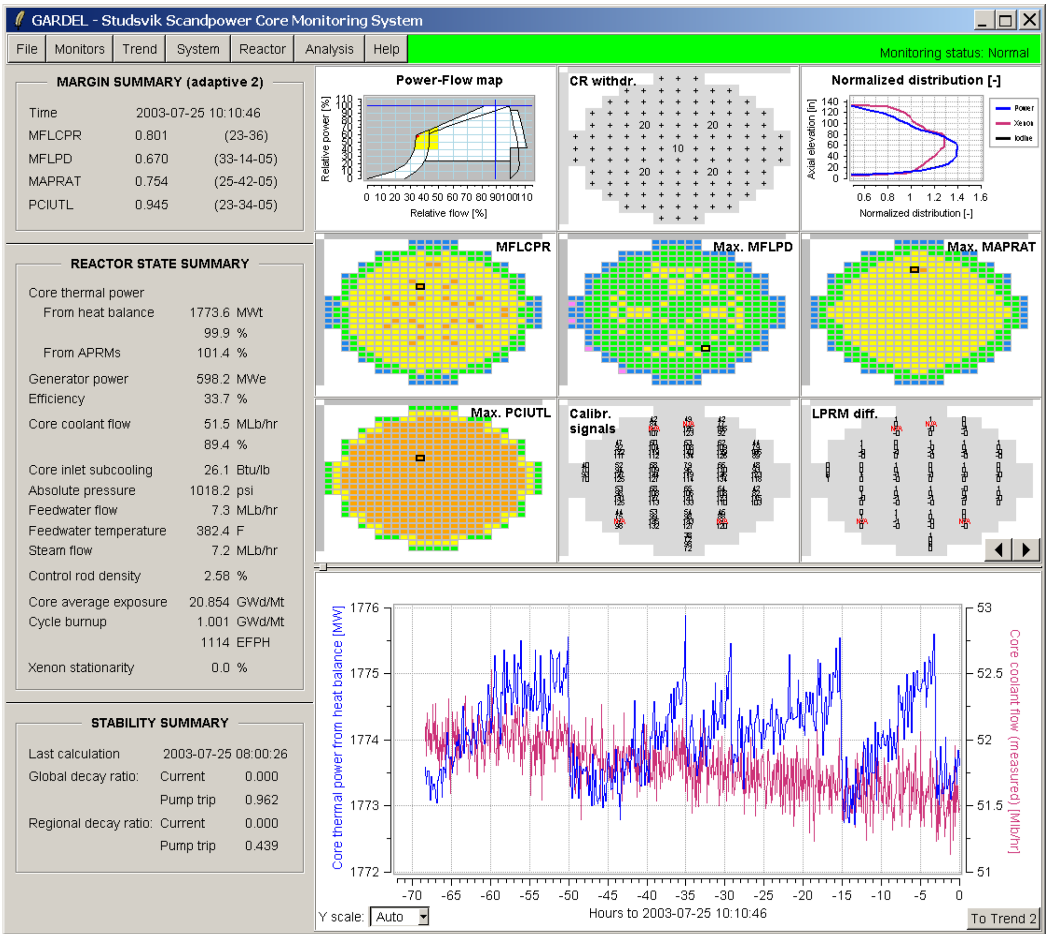
4 Online GUI Interfaces

The previous section describes many of the background processes that are the automated part of the GARDEL-BWR system. But as important as those processes are, it is also important how the user views and interacts with the system through a series of graphical user interfaces. The following sections provide more detail on these interfaces.

4.1 Main Data display

The main continuously updated graphical display as shown in Figure 2 provides the reactor engineer with the most important information needed to monitor the core.

Figure 2 Main GARDEL-BWR Graphical interface.



This information includes global reactor data with overall thermal margins core stability and reactor statepoint conditions, trend plots for core scalar values (both calculational results and process signal data, core radial maps of the most important current online distributions, measured and predicted LPRMs signals, the current power flow map with showing the last 72 hours of operation and core average power and fission product distributions.

From this main interface the engineer/operator can use the mouse to examine more in-depth information such as data on individual fuel assemblies such as nodal power or thermal margins and even down to individual pin powers.

Also authorized users can give commands to background processes to deactivate the system, run additional simulator or stability calculations and to select the adaption method for the official thermal margin results.

4.2 Process Signal handling

The process data that is feed into the GARDEL-BWR system can contain missing, out of range or even erroneous values. GARDEL-BWR provides a process signal substitution and/or acknowledgement interface which allows privileged users to override erroneous process signal and to acknowledge/validate process data that may have an unacceptable status flag.

4.3 Report generation

One of the powerful features of GARDEL-BWR is the automated and on demand report generation function. This feature provides for the viewing and printing of automatically generated reports in PDF or Postscript format for the following calculations: heat balance calculation, simulator calculation results, summary of daily and monthly operations, archive of all TIP calibration results in the current cycle and a core isotopic report.

5 Offline GUI Calculation interfaces

GARDEL-BWR provides a number of interfaces to perform the most frequently needed calculations. The interfaces are designed to only need minimal user input and display only the most important results from the simulator calculation for the targeted calculation type.

5.1 Recalculation and predictions

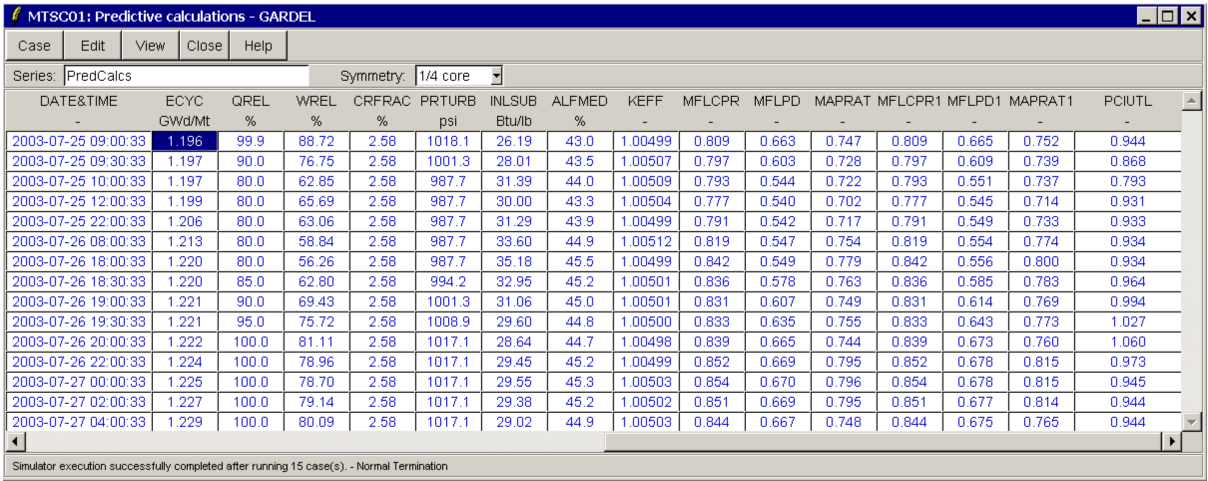
There are two general-purpose interfaces that allow the user to perform basic simulator calculations. These interfaces are in a spreadsheet format, which allow the user to input the most commonly needed core state point information – e.g., power, flow rod pattern, depletion interval, search type.

One interface allows the reanalysis of past operations using the core track series. The core track series is the automated core depletion calculations that GARDEL-BWR automatically generates during core monitoring operations. From this interface, a user can look back into past operation and replay the online monitoring calculations over a specific time period. The user and also adjust the operating conditions to create "what if" analysis scenarios

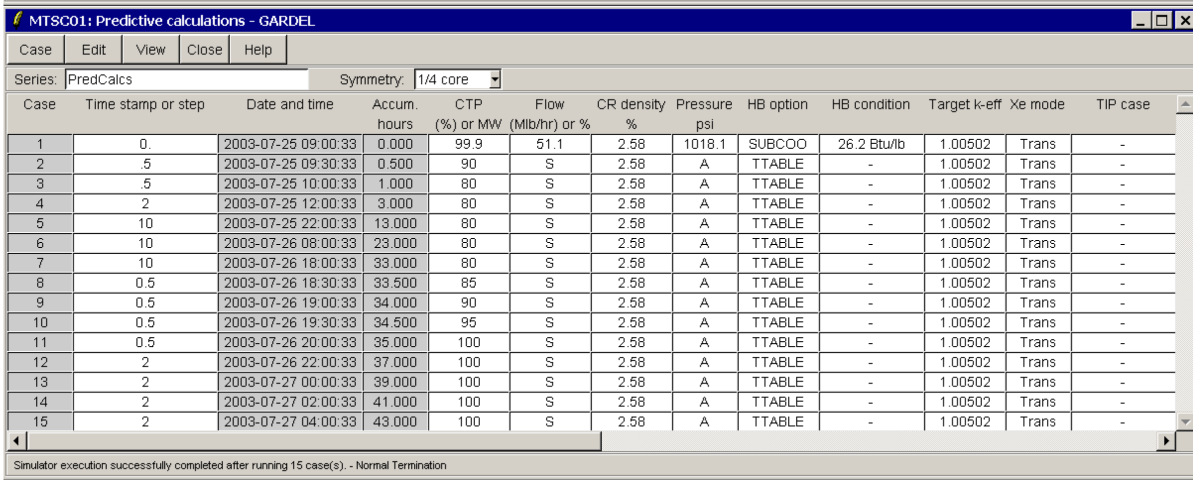
Another related interface is for general predictive calculations such as analysis of a control rod sequence exchanges, analyzing predicted rod patterns to end of cycle, and performing power, flow or control rod pattern searches, etc.

An example of these interfaces are shown in Figure 3.

Figure 3 Predictive calculation interfaces



DATE&TIME	ECYC	QREL	WREL	CRFRAC	PRTURB	INLSUB	ALFMED	KEFF	MFLCPR	MFLPD	MAPRAT	MFLCPR1	MFLPD1	MAPRAT1	PCIUTL
-	GWd/Mt	%	%	%	psi	Btu/lb	%	-	-	-	-	-	-	-	-
2003-07-25 09:00:33	1.196	99.9	88.72	2.58	1018.1	26.19	43.0	1.00499	0.809	0.663	0.747	0.809	0.665	0.752	0.944
2003-07-25 09:30:33	1.197	90.0	76.75	2.58	1001.3	28.01	43.5	1.00507	0.797	0.603	0.728	0.797	0.609	0.739	0.868
2003-07-25 10:00:33	1.197	80.0	62.85	2.58	987.7	31.39	44.0	1.00509	0.793	0.544	0.722	0.793	0.551	0.737	0.793
2003-07-25 12:00:33	1.199	80.0	65.69	2.58	987.7	30.00	43.3	1.00504	0.777	0.540	0.702	0.777	0.545	0.714	0.931
2003-07-25 22:00:33	1.206	80.0	63.06	2.58	987.7	31.29	43.9	1.00499	0.791	0.542	0.717	0.791	0.549	0.733	0.933
2003-07-26 08:00:33	1.213	80.0	58.84	2.58	987.7	33.60	44.9	1.00512	0.819	0.547	0.754	0.819	0.554	0.774	0.934
2003-07-26 18:00:33	1.220	80.0	56.26	2.58	987.7	35.18	45.5	1.00499	0.842	0.549	0.779	0.842	0.556	0.800	0.934
2003-07-26 18:30:33	1.220	85.0	62.80	2.58	994.2	32.95	45.2	1.00501	0.836	0.578	0.763	0.836	0.585	0.783	0.964
2003-07-26 19:00:33	1.221	90.0	69.43	2.58	1001.3	31.06	45.0	1.00501	0.831	0.607	0.749	0.831	0.614	0.769	0.994
2003-07-26 19:30:33	1.221	95.0	75.72	2.58	1008.9	29.60	44.8	1.00500	0.833	0.635	0.755	0.833	0.643	0.773	1.027
2003-07-26 20:00:33	1.222	100.0	81.11	2.58	1017.1	28.64	44.7	1.00498	0.839	0.665	0.744	0.839	0.673	0.760	1.060
2003-07-26 22:00:33	1.224	100.0	78.96	2.58	1017.1	29.45	45.2	1.00499	0.852	0.669	0.795	0.852	0.678	0.815	0.973
2003-07-27 00:00:33	1.225	100.0	78.70	2.58	1017.1	29.55	45.3	1.00503	0.854	0.670	0.796	0.854	0.678	0.815	0.945
2003-07-27 02:00:33	1.227	100.0	79.14	2.58	1017.1	29.38	45.2	1.00502	0.851	0.669	0.795	0.851	0.677	0.814	0.944
2003-07-27 04:00:33	1.229	100.0	80.09	2.58	1017.1	29.02	44.9	1.00503	0.844	0.667	0.748	0.844	0.675	0.765	0.944



Case	Time stamp or step	Date and time	Accum. hours	CTP (%) or MW	Flow (Mlb/hr) or %	CR density %	Pressure psi	HB option	HB condition	Target k-eff	Xe mode	TIP case
1	0.	2003-07-25 09:00:33	0.000	99.9	51.1	2.58	1018.1	SUBCOO	26.2 Btu/lb	1.00502	Trans	-
2	.5	2003-07-25 09:30:33	0.500	90	S	2.58	A	TTABLE	-	1.00502	Trans	-
3	.5	2003-07-25 10:00:33	1.000	80	S	2.58	A	TTABLE	-	1.00502	Trans	-
4	2	2003-07-25 12:00:33	3.000	80	S	2.58	A	TTABLE	-	1.00502	Trans	-
5	10	2003-07-25 22:00:33	13.000	80	S	2.58	A	TTABLE	-	1.00502	Trans	-
6	10	2003-07-26 08:00:33	23.000	80	S	2.58	A	TTABLE	-	1.00502	Trans	-
7	10	2003-07-26 18:00:33	33.000	80	S	2.58	A	TTABLE	-	1.00502	Trans	-
8	0.5	2003-07-26 18:30:33	33.500	85	S	2.58	A	TTABLE	-	1.00502	Trans	-
9	0.5	2003-07-26 19:00:33	34.000	90	S	2.58	A	TTABLE	-	1.00502	Trans	-
10	0.5	2003-07-26 19:30:33	34.500	95	S	2.58	A	TTABLE	-	1.00502	Trans	-
11	0.5	2003-07-26 20:00:33	35.000	100	S	2.58	A	TTABLE	-	1.00502	Trans	-
12	2	2003-07-26 22:00:33	37.000	100	S	2.58	A	TTABLE	-	1.00502	Trans	-
13	2	2003-07-27 00:00:33	39.000	100	S	2.58	A	TTABLE	-	1.00502	Trans	-
14	2	2003-07-27 02:00:33	41.000	100	S	2.58	A	TTABLE	-	1.00502	Trans	-
15	2	2003-07-27 04:00:33	43.000	100	S	2.58	A	TTABLE	-	1.00502	Trans	-

5.2 Cold critical and Shutdown margin calculations.

GARDEL-BWR provides interfaces to analysis both cold critical measurements and shutdown margin.

The cold critical interface allows the user to input the time after shutdown, the reactor temperature and rod pattern and also the measured reactor period. The interface then runs a simulator calculation using the precise fission products at the specified shutdown time and the displays both the raw and period corrected eigenvalues which are then used in subsequent, shutdown margin, ECP and notch worth calculations.

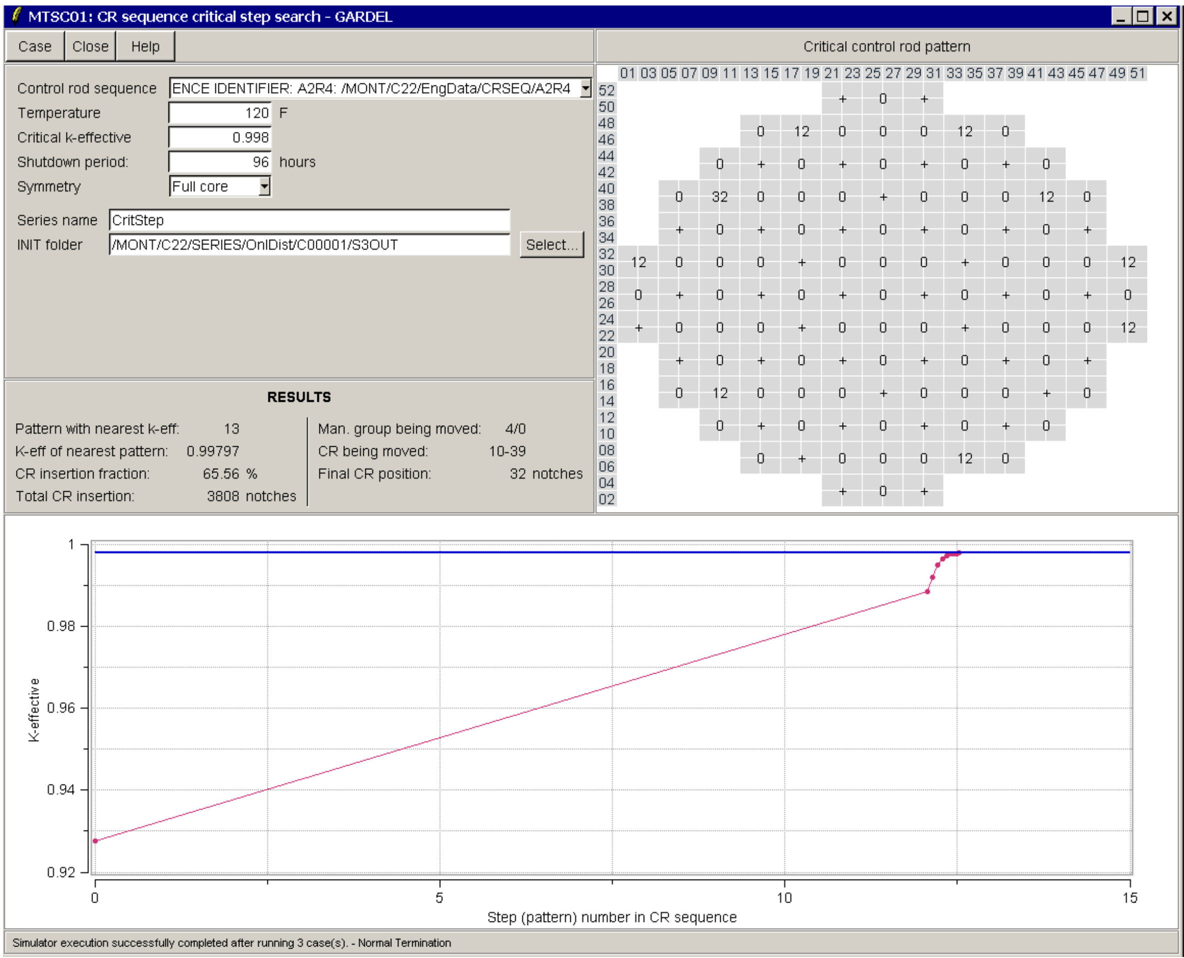
5.3 Estimated Critical positions (ECPs)

Estimating the critical rod position after a reactor shutdown is one the most common and more difficult to specify analyses performed by reactor engineers. During startup a number of core parameters (fission products, temperature) are continually changing which make predicting accurate ECP challenging.

GARDEL-BWR provides an interface to allow the user to easily perform ECP calculations. The interface allows the user to select different control rod withdrawal sequences, reactor temperature and time after shutdown. The ECP then runs a simulator calculation that accurately predicts the core Xenon and Samarium distributions as well as the shutdown cooling reactivity effects for the input time interval. The calculation then performs a rod pattern search at the specified temperature to precisely determine the rod pattern where criticality will occur.

An example of the ECP interface is shown in Figure 4

Figure 4 Estimated Critical Position interface



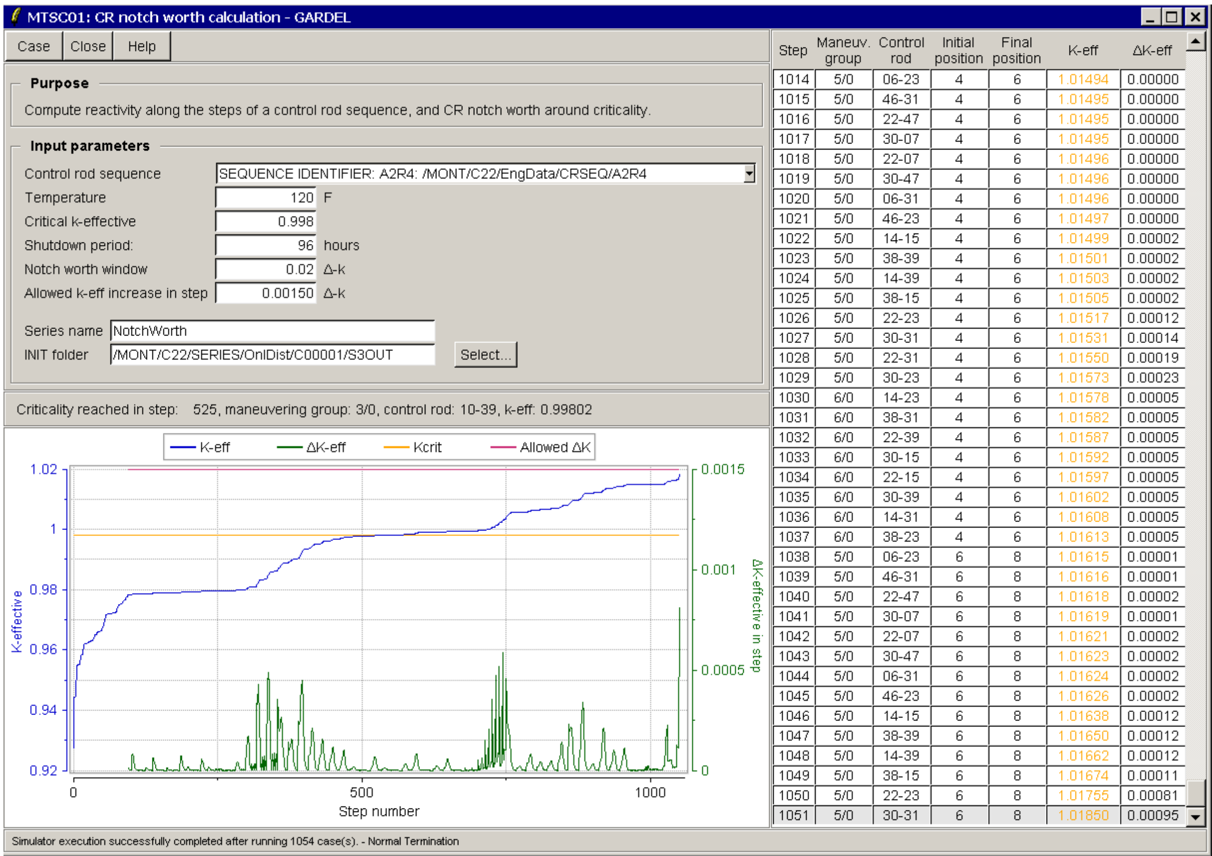
5.4 Notch worth

In GE BWRs, an important calculation is to determine the reactivity of each notch pull during the withdrawal of a control rod sequence. This reason for this is because the design of the GE control rod system results in relatively quick 6-inch withdrawals of a control rod. These 6-inch movements can result in relatively large reactivity insertions, which need to be minimized by adjusting the sequence in which the rods are withdrawn.

The reactivity analysis of a control rod withdrawal sequence is very computationally intensive, because as many as 1500 full core simulation calculations can be needed. Because of this complexity, it is very difficult for reactor engineers to perform this calculation based on the current core conditions. They would typically need to rely on pre-computed results, which are typically only done for BOC conditions at a fixed temperature.

GARDEL-BWR automates this calculation and allows it to be performed based on the current and/or projected reactor conditions with minimal user input. The user simply selects the sequence that is to be analyzed, the expected time after shutdown when the startup is to occur and the expected reactor temperature. GARDEL-BWR then graphically displays the results as shown in Figure 5.

Figure 5 Notch worth calculation interface



Step	Maneuv. group	Control rod	Initial position	Final position	K-eff	ΔK-eff
1014	5/0	06-23	4	6	1.01494	0.00000
1015	5/0	46-31	4	6	1.01495	0.00000
1016	5/0	22-47	4	6	1.01495	0.00000
1017	5/0	30-07	4	6	1.01495	0.00000
1018	5/0	22-07	4	6	1.01496	0.00000
1019	5/0	30-47	4	6	1.01496	0.00000
1020	5/0	06-31	4	6	1.01496	0.00000
1021	5/0	46-23	4	6	1.01497	0.00000
1022	5/0	14-15	4	6	1.01499	0.00002
1023	5/0	38-39	4	6	1.01501	0.00002
1024	5/0	14-39	4	6	1.01503	0.00002
1025	5/0	38-15	4	6	1.01505	0.00002
1026	5/0	22-23	4	6	1.01517	0.00012
1027	5/0	30-31	4	6	1.01531	0.00014
1028	5/0	22-31	4	6	1.01550	0.00019
1029	5/0	30-23	4	6	1.01573	0.00023
1030	6/0	14-23	4	6	1.01578	0.00005
1031	6/0	38-31	4	6	1.01582	0.00005
1032	6/0	22-39	4	6	1.01587	0.00005
1033	6/0	30-15	4	6	1.01592	0.00005
1034	6/0	22-15	4	6	1.01597	0.00005
1035	6/0	30-39	4	6	1.01602	0.00005
1036	6/0	14-31	4	6	1.01608	0.00005
1037	6/0	38-23	4	6	1.01613	0.00005
1038	5/0	06-23	6	8	1.01615	0.00001
1039	5/0	46-31	6	8	1.01616	0.00001
1040	5/0	22-47	6	8	1.01618	0.00002
1041	5/0	30-07	6	8	1.01619	0.00001
1042	5/0	22-07	6	8	1.01621	0.00002
1043	5/0	30-47	6	8	1.01623	0.00002
1044	5/0	06-31	6	8	1.01624	0.00002
1045	5/0	46-23	6	8	1.01626	0.00002
1046	5/0	14-15	6	8	1.01638	0.00012
1047	5/0	38-39	6	8	1.01650	0.00012
1048	5/0	14-39	6	8	1.01662	0.00012
1049	5/0	38-15	6	8	1.01674	0.00011
1050	5/0	22-23	6	8	1.01755	0.00081
1051	5/0	30-31	6	8	1.01850	0.00095

6 Summary

GARDEL-BWR is SSP's alternative to core monitoring systems from fuel suppliers. GARDEL-BWR completes SSP's product line of software products that include:

- Lattice codes
- 3D Core simulators
- Dynamic analysis codes
- Training simulator models
- On-line core monitoring and operational support systems

GARDEL-BWR is built with a number of technical features that differentiate it from other systems:

- A common database for on-line core monitoring and off-line core operation support and analysis
- Independence from operating system, proprietary hardware and network configuration
- And a powerful and intuitive graphical user interface

The use of GARDEL-BWR fits in a natural way into organizations already using SSP's codes for in-core fuel management. Implementation of the system requires no additional core design data and offers 100% compatibility with their existing off-line codes.

SSP's GARDEL-BWR and common platform GARDEL-PWR products are built using SSP's expertise in the core simulation fields. This expertise includes, extensive operational experience feedback, close interaction between developers of core simulation methods and GARDEL developers, and expert support.

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