# SMART CANDU™ - PREDICTING TO IMPROVE PLANT PERFORMANCE

by

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## ABSTRACT

Nuclear power plants are designed for safety and performance, but as systems and components age performance inevitably declines. Operations and maintenance staff are called upon on a daily basis to make operational decisions and take mitigative action to reverse the affects of plant aging and achieve optimal plant performance. This paper describes selected applications of SMART CANDU™ Operations and Maintenance support software to illustrate how diagnostic tools and predictive models imbedded in the software enable engineers and operators to make proactive and informed decisions to manage and improve plant performance.

## 1. INTRODUCTION

The chief requirement for nuclear power plants is to provide safe, reliable and economical performance. Although initial performance is determined during design and construction, ongoing good performance as the plant progressively ages requires effective monitoring, inspection and maintenance programs to allow the plant engineers to identify degradation and take appropriate action to restore performance. Taking appropriate action, however, requires the operations staff to make proactive and informed decisions and to be able to predict the impact of these decisions on plant performance.

The situation is illustrated in Figure 1. Systems and components are designed and built to have an acceptable safety margin to account for approximations and assumptions made during design and to account for the effects of aging. Operating margins inevitably decline during operation, however, and so remedial measures must be taken to restore performance. The challenge is in knowing where the system or component is on the performance curve, and in particular, in knowing the impact of certain events, such as missed maintenance or a chemistry excursion, on performance degradation.

This paper describes selected applications of SMART CANDU™ Operations and Maintenance support software to illustrate how diagnostic tools and predictive models imbedded in the software enable engineers and operators to make proactive and informed decisions to manage and improve plant performance.

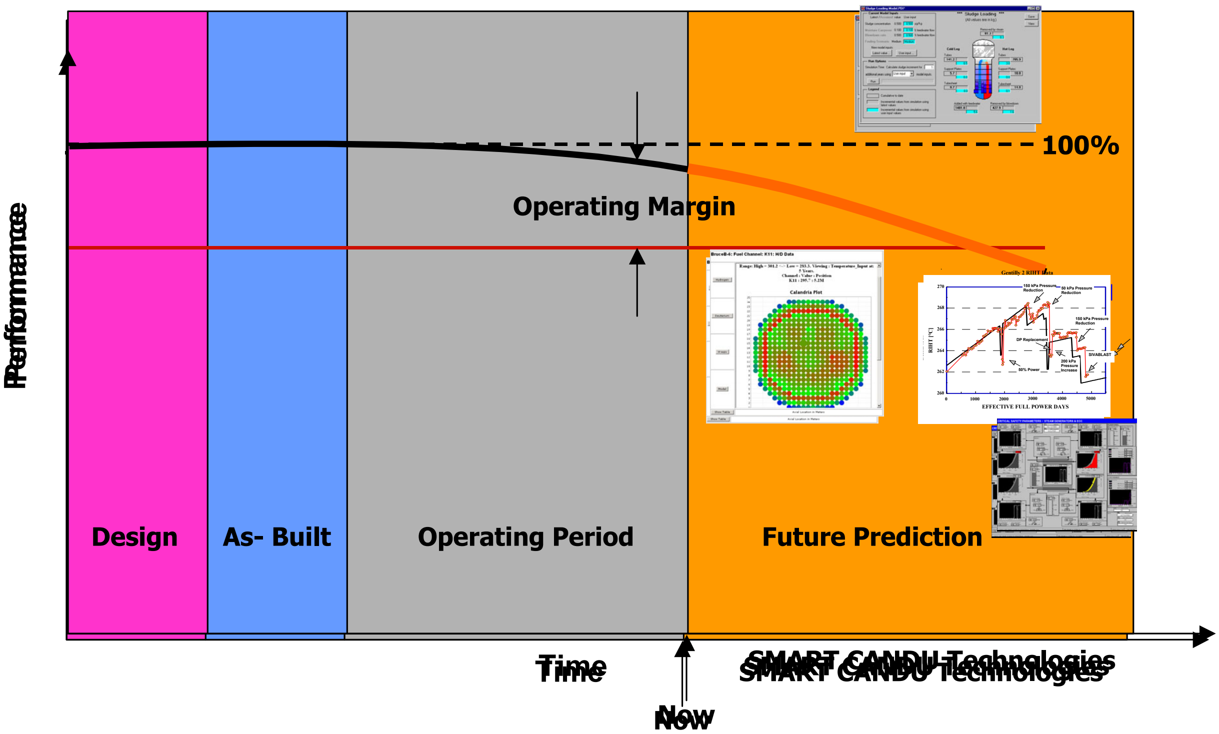


**Figure 1: Schematic of typical performance curve for systems and components.**

## 2. MAKING THE RIGHT DECISION

O&M staff are called upon daily to make and act upon decisions that ultimately affect the future performance of the plant. For example, decisions regarding where to inspect, when to clean, what maintenance to perform, whether to refurbish or replace aging equipment and whether or not to make a particular design and/or process change will all have a bearing on how the plant performs in the future. These decisions are based upon knowledge of the current condition of a particular system or component in the plant, and how that condition may evolve with time. To make these decisions, staff must first gather and organize data to identify trends and/or relationships that provide information about the current condition of a particular component or system. Additional analysis is then required to assess the impact of the current condition on future performance. The knowledge that results from this additional analysis provides the basis for making O&M decisions to manage and improve plant performance. The process of gathering data, organizing it into information and performing additional analyses to generate knowledge to support O&M decisions is illustrated in **Figure 2**. The final step of the process, learning, takes place when the results of past decisions are used to make operational changes to improve performance in the future.

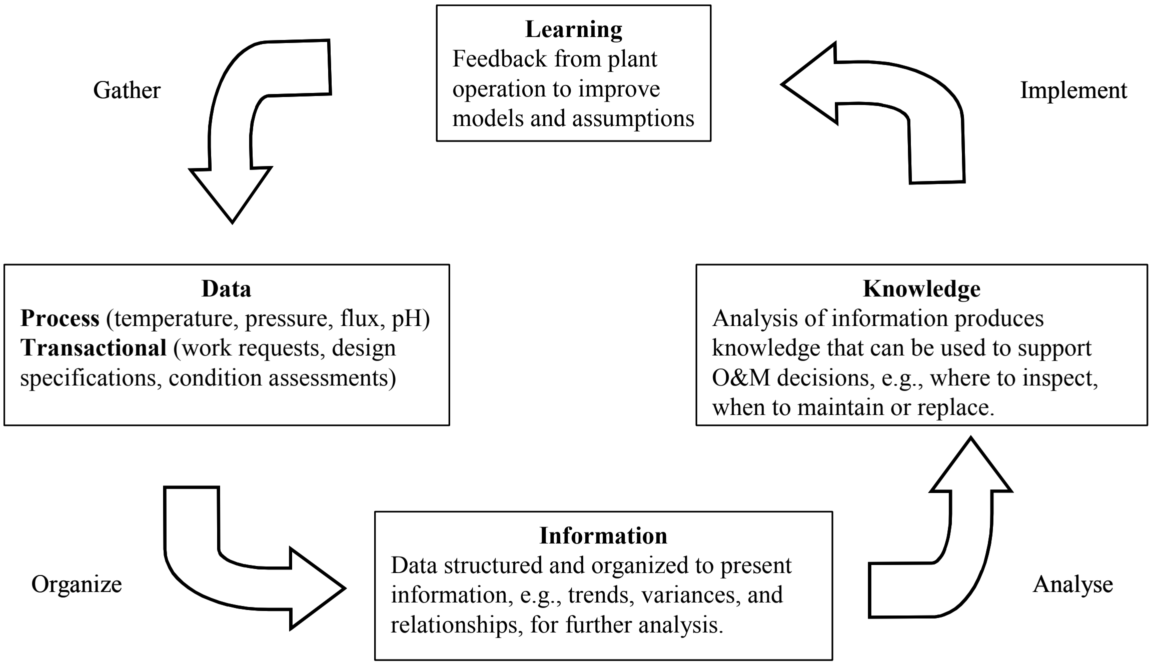


**Figure 2: O&M decisions require gathering, organizing and analysing plant process and transactional data.**

Plant staff face two significant challenges when trying to follow the decision-making process outlined in **Figure 2**. The first challenge is that plant data come from many disparate and isolated sources, and the collection and organization of these data into information can be time consuming and labour intensive. The amount of time and effort required is often the limiting factor that determines how much information is derived from the data and how frequently this information is updated. The second challenge is that operations staff generally do not have ready access to the analytical tools, models and supporting technical basis to fully analyse plant data and quantitatively assess the impact of specific O&M decisions on plant performance.

To help maintain world-class plant performance throughout the life cycle, Atomic Energy of Canada Ltd. (AECL) has been developing SMART CANDU™ Operations and Maintenance (O&M) support software to enable plant engineers to manage plant performance with the aid of diagnostic tools and predictive models that are directly interfaced with plant transactional and process data. Within the suite of O&M software products are applications that support each of the five core processes identified in the Nuclear Energy Institute standard process model: Operate Plant, Configuration Control, Equipment Reliability, Materials and Services and Work Management[1]. The diagnostic tools and predictive models imbedded in the SMART CANDU software incorporate knowledge gained from research and development programs funded by AECL and the CANDU Owners Group (COG), and enable plant engineering staff to make O&M decisions based on the most current understanding of the behaviour of systems, materials and components under CANDU operating conditions. Individual SMART CANDU products are

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[1] Nuclear Energy Institute / Electric Utility Cost Group Task Force Report, A Standard Nuclear Performance Model, Nuclear Energy Institute, Washington, D.C., October 1998.

being developed in close collaboration with utility staff and field tested during development to ensure that they are fully compatible with utility work practices.

SMART CANDU software facilitates all aspects of the decision-making process by gathering data from various sources, organizing and presenting the data in a way that makes interpretation easy, and interfacing it with diagnostic tools and predictive models to support making proactive, informed decisions to manage and improve plant performance. Selected applications of SMART CANDU software to the management and prediction of plant performance are discussed below.

## 3. MANAGING AND PREDICTING PERFORMANCE

### 3.1 Operate Plant

Providing control room operators with the information they need to make good decisions is key to maximizing plant performance and meeting safety goals. As part of an on-going program to advance the CANDU product, AECL has developed the Advanced Control Centre Information System (ACCIS).

ACCIS is an IEC SIL-2 capable, real-time plant display, monitoring and supervisory control system that was developed to meet the functional performance, maintainability and quality assurance requirements of CANDU plant applications. It includes a flexible display system capability that can be configured to meet the applicable human factors standards for display design (e.g., system, function and task displays), an enhanced computerized alarm message system (CAMLS) that meets the requirements of IEC-62241, and an on-line, high-performance real-time database and historian.

In Qinshan, ACCIS was used to implement enhanced display, annunciation and calculation capabilities designed to complement traditional CANDU digital control functionality. For example, ACCIS was used to:

- implement a critical safety parameter monitor (Figure 3) that provides operators with a comprehensive overview of key safety-related parameters (e.g., reactor power, sub-cooling margin and steam generator level),
- add a CAMLS-based alarm management interrogation capability, (Figure 4) that allows operators to search alarm history and retrieve alarm related information, and
- introduce interfaces to the emergency response centre and a ‘life of plant’ data historian.

For future CANDU plants and retrofits, AECL expects to separate display and control, and plans to use ACCIS to implement the display system. This system with include features that will facilitate the introduction of other SMART CANDU enhancements, e.g., transmitter anomaly detection, on-line procedures, and safety system testing automation.

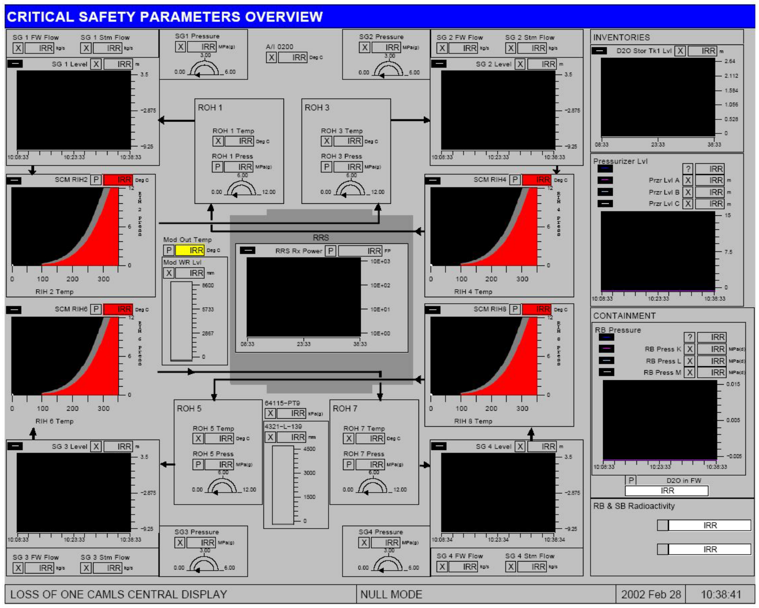


**Figure 3: Critical Safety Parameter Monitoring Display**

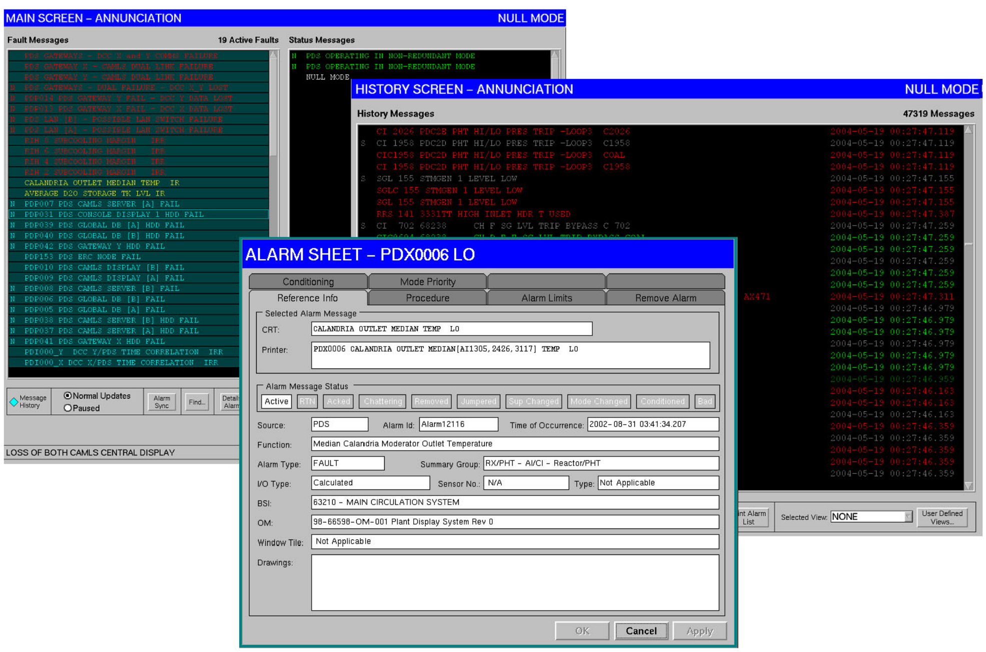


**Figure 4: Alarm Interrogation Display**

Good chemistry control has long been recognized as key to minimizing the degradation of systems and components, so AECL has developed ChemAND[2] to perform monitoring,

[2] "ChemAND – A System Health Monitor for Plant Chemistry", C.W. Turner et. al, Can. Nucl. Soc. Bull. **22**, No. 2 (2001).

diagnostics and analysis of chemistry in all systems in the plant requiring chemistry control. ChemAND automatically extracts data from various sources throughout the plant (on-line data from the digital control computer, chemistry data historian, and plant data loggers), compares it to control limits and alerts staff to parameters that are out of specification using the status panel display shown in Figure 5. The coloured tiles help to prioritize work by directing attention to those systems where various warning or control limits have been exceeded. Navigation aids quickly direct the user to a list of parameters that are out of specification, and provide function-based displays to help diagnose the cause of the problem.

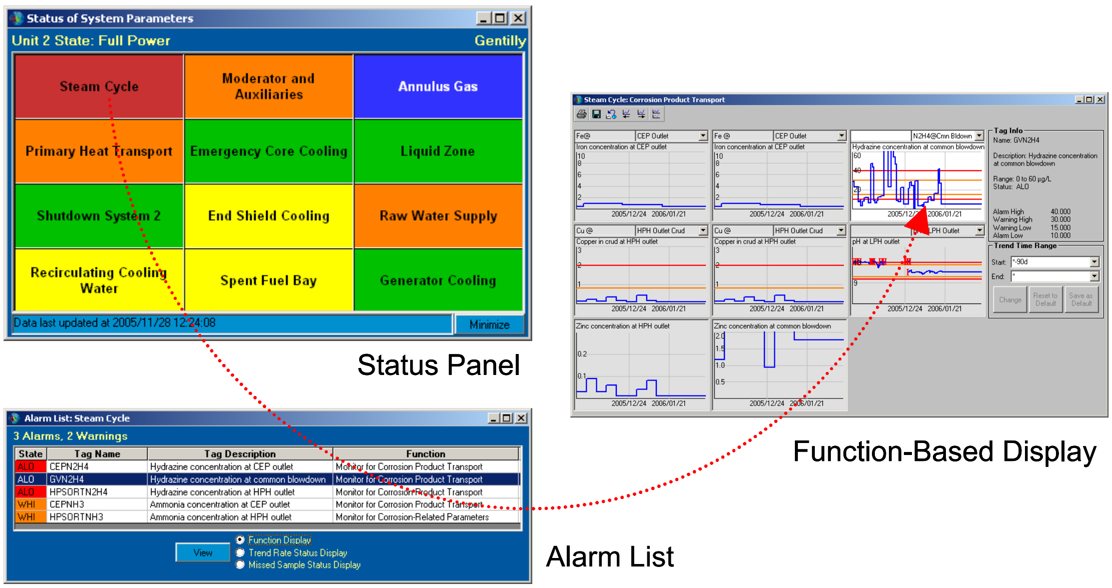


**Figure 5: Status panel display, including a list of parameters out of specification and a function-based diagnostic display.**

To aid the management of steam generator (SG) performance, ChemAND has models to predict SG fouling and crevice chemistry as a function of SG operating conditions. For example, the impact of chemistry, including transient conditions, on SG tube integrity is assessed by calculating the local chemistry environment within a SG crevice region (i.e., between the tube and tube support structure) and determining whether the tube lies within a "recommended operating zone"[3], as illustrated in Figure 6. This methodology can be used to assess the impact of condenser leaks, upsets in the water treatment plant and startup conditions on SG tube integrity by determining whether the chemistry transient has taken the SG tubes outside of the recommended zone.

[3] Y.C. Lu, "Electrochemical Aspects of Defining the Safe Potential/pH Zone for Corrosion Prevention of Alloy 800 Steam Generator tubing", in Proc. of the 4th CNS International Steam Generator Conference, Paper #3-18, (2002).

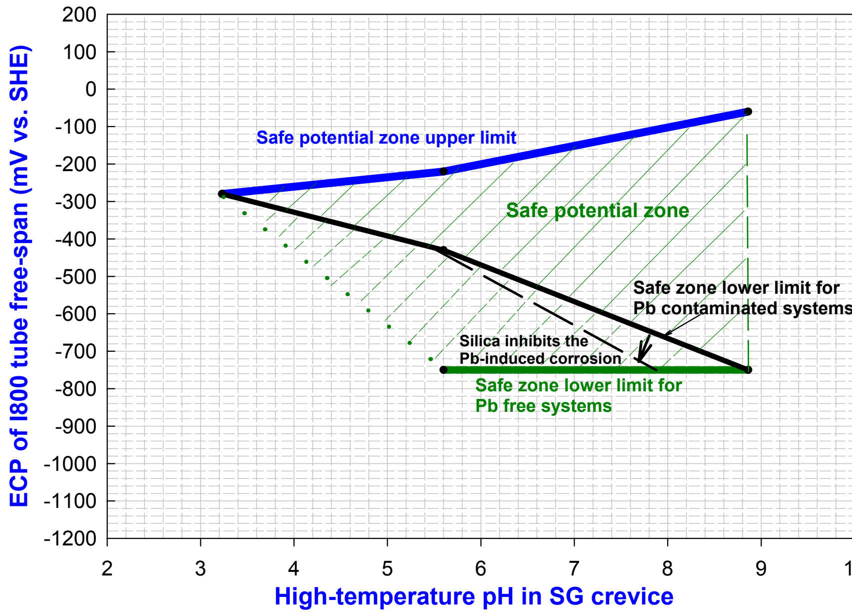


**Figure 6: Recommended operating zone for Alloy 800 at 300°C.**

Other models are included in ChemAND to analyse chemistry conditions (i.e., local pH, hydrazine concentration) throughout the steam cycle, activity transport in the primary heat transport and main moderator circuits, and the emission of radionuclides from the moderator cover gas. Output from each model can be used directly by plant engineering staff to make decisions pertaining to the optimization and prediction of plant performance.

## 3.2 Equipment and Component Reliability

Fuel channels are one of the most critical components in the CANDU reactor, so significant effort is devoted towards ensuring that they are operating within approved safety and design margins. AECL has developed, therefore, FCMAT (Fuel Channel Monitoring and Assessment Tool), a web-based software product to aid with the rapid monitoring and assessment of fuel channels. FCMAT links ingot and material property databases with in-service inspection data and engineering design limits to allows station engineers to handle more data in a more efficient manner, thereby enhancing fuel channel performance through targeted inspection plans and maintenance campaigns. FCMAT also employs models for deformation, corrosion and deuterium uptake to compare end-of-life predictions with current fuel channel condition and engineering design limits. The user interface for FCMAT facilitates comparison of the performance of different fuel channels within a given unit or between units at a multi-unit plant. FCMAT thus allows users to concentrate their efforts on value-added activities, such as data analysis and assessments.

Figure 7 shows the user interface for accessing inspection data and model predictions for specific fuel channels in the prototype currently on field trial. Password-protected login restricts access so that users can only view data from their organization, unless authorized otherwise. The left-hand side of the Figure shows an end-view of the reactor core. Colour-coding indicates what data are currently available for display. The right-hand side of the Figure shows a comparison between measured and predicted deuterium uptake as a function of axial location and time for a selected fuel channel. Such a critical review of information allows stations to target inspections to the most critical areas of the reactor, while at the same time developing mitigating strategies well before reaching the limits of the safety and design margins.

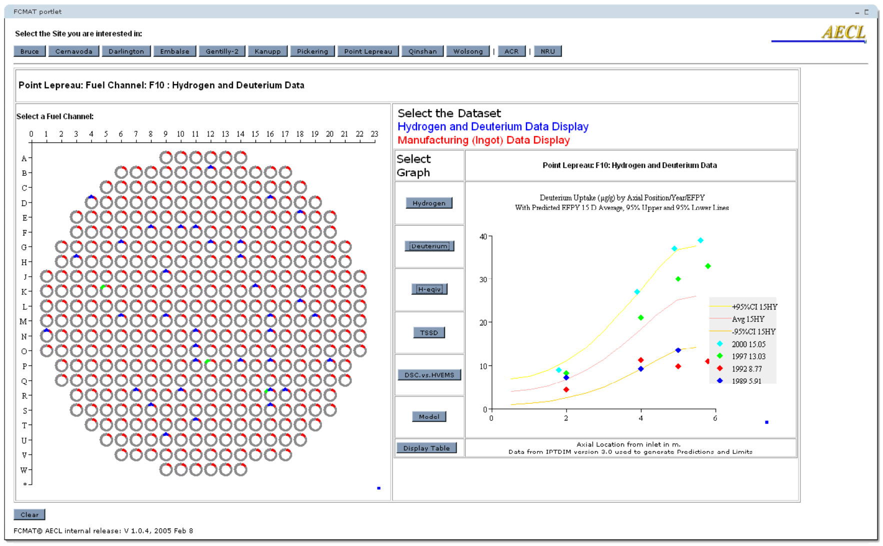


**Figure 7: FCMAT display showing a comparison between measured and predicted deuterium uptake as a function of axial location and time for a selected fuel channel.**

Similar tools for monitoring and assessment of feeder performance (FDMAT) and fuel performance (FPMAT) are under development and will undergo field trial within one and two years, respectively.

Monitoring and maintaining the health of numerous heat transport and auxiliary circuits throughout the Nuclear Steam Supply and Balance of Plant is an important responsibility of the plant system and equipment engineers. To facilitate these activities, AECL has developed ThermAND to provide monitoring, diagnostics and analyses of process and mechanical systems and components. ThermAND was developed along the same lines as ChemAND, and has recently completed field trial at Point Lepreau Generating Station[4]. Like ChemAND, ThermAND has a status panel display to direct attention towards those systems with parameters trending past warning or control limits, function-based displays to help diagnose problems and tools to perform more detailed analyses of plant data. By tracking temperature, pressure and flow, for example, ThermAND captures the essential input data for a more detailed analysis of thermal performance and thermal fatigue for all major heat transport and auxiliary systems in the plant.

Figure 8 shows a display of the average SG fouling factor (lower left) plotted along side graphs showing trends in related parameters, such as reactor inlet header temperature, feedwater and primary side flow rates, SG pressure and reactor power. This display facilitates tracking of SG

[4] "Field Trial of ThermAND at PLGS", by G.R. Burton, G. McKay, M. Thompson, C.W. Turner and S. Robertson, Proc. of the 7th CNS International CANDU Maintenance Conference, Toronto ON, 2005 Nov 21 – 23.

thermal performance as a function of effective full-power years of operation as well as the comparison of the performance of one SG to another within the same unit. ThermAND can also be interfaced with 3rd party software to optimize the steam cycle for thermal performance (so-called 'megawatt hunting'). Finally, ThermAND has a facility for tracking the number of thermal cycles and calculating temperature ramp rates for each cycle for comparison to the design basis to provide an initial assessment of fatigue usage, and could be interfaced with a more sophisticated tool if a more detailed analysis of fatigue usage is warranted.

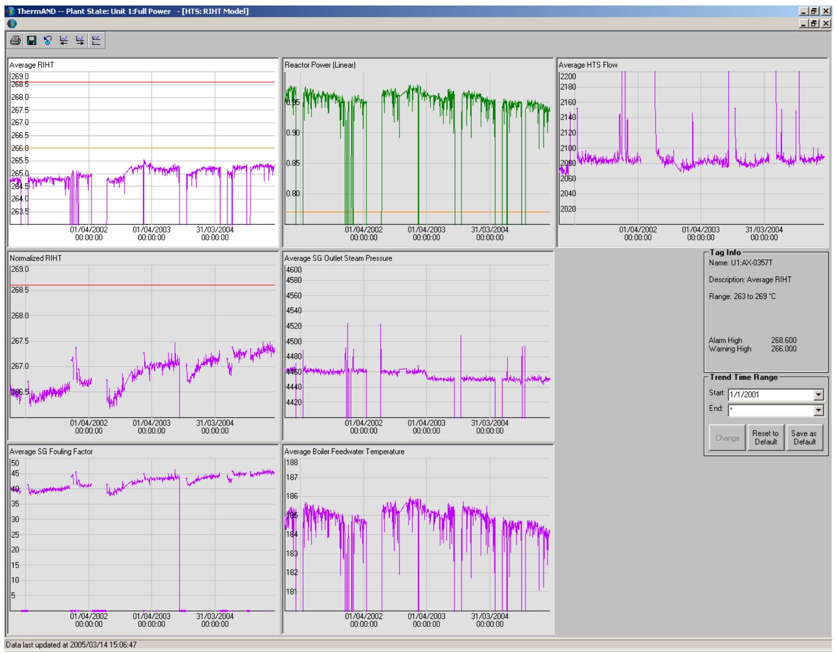

**Figure 8: ThermAND display for SG thermal performance (fouling factor – lower left) plotted alongside trends of related parameters.**

### 3.3 Configuration Management

Information and information management is key to both the successful delivery and the successful operation of a nuclear power plant. During the project implementation phase, large amounts of information and documentation must be produced in a correct and consistent form and delivered in a format that is widely accessible on a secure, controlled and convenient platform and readily available to end users. To address the need for information management from plant design through procurement to plant operation, AECL has developed a fully integrated and proven set of design and engineering tools to:

- facilitate capturing and updating the design information electronically,
- make associated information available throughout construction, and
- deliver 'as-designed', 'as-analyzed' and 'as-built' documentation to the end user in electronic form throughout the operational phase of the plant lifecycle.

AECL's plant configuration management capability is based on five key applications:

- a plant design system (PDS) supplied by Integraph that provides 2- (PDS 2D) and 3-D (PDS 3D) design capability,
- an equipment, wiring and cable management application (IntEC),
- a materials management and procurement system (CMMS), and
- a plant information management repository (TRAK).

As illustrated in Figure 9, TRAK is the heart of AECL's plant configuration management capability. The TRAK information repository is central to management, control and delivery of all documents, drawings, analysis results and software associated with a CANDU project.

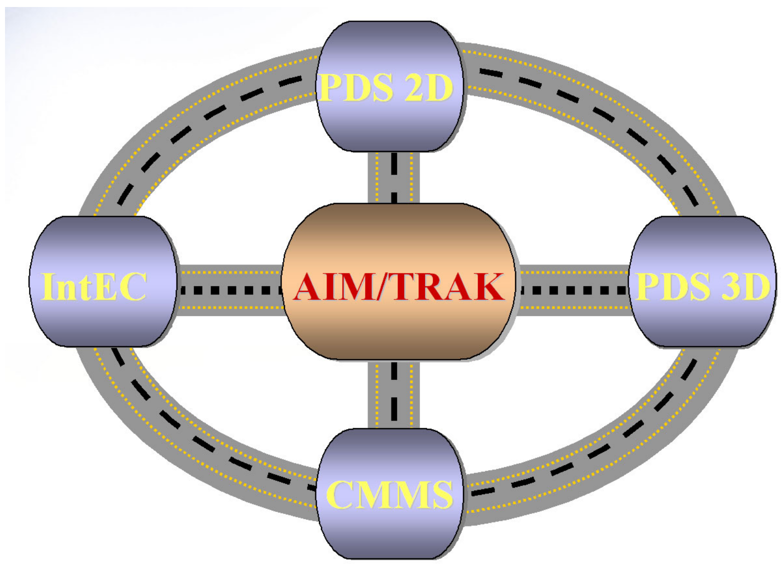


**Figure 9: The AECL Suite of Plant Configuration Management Tools**

A key aspect of this configuration management capability is the fact that data rather than documents become the focus. The PDS models, drawings and other documents are rendered from design data. The tools work with data structures so that actual changes (e.g., wiring changes) are controlled at an elementary level. The safety rules and design codes are built into the tools to ensure compliance with CANDU design philosophies and regulatory requirements. In addition, due to the integration between the tools, the design and subsequent design changes are guaranteed to be consistent with the design requirements, safety analysis and equipment specifications. Change control and the propagation of changes throughout the plant lifecycle become manageable.

## 4. FUTURE DEVELOPMENTS

AECL is working on other initiatives to improve the safety, reliability and economic performance of CANDU reactors through its SMART CANDU Operations and Maintenance support tools. One such initiative is the development of an on-line Regional Overpower Protection (ROP) system to calculate 'instantaneous' trip set points and trip probability. The on-line system would calculate 'instantaneous' flux maps from in-core flux detector readings and use an integrated suite of analysis tools to calculate the time-averaged channel power and critical channel power distributions. Preliminary analysis suggests that the on-line trip set points calculated from the 'instantaneous' flux shapes have a larger margin to trip than those calculated off-line using the conventional methodology. Implementation of such a system, therefore, would enable the reactor to operate at a higher power level than allowed by the conventional off-line methodology.

Another initiative that is showing good promise is the development of an information exchange portal that serves to link plant management, operations and technical unit staff with the data (both process and transactional) and the applications (e.g., health monitoring, work management) they use to manage plant operation and performance. The principal is that "data should be entered once and used many times". The information exchange portal, My Information Management Centre (MIMC), will permit each user to have a home page that can be customized to meet their specific needs with access to the station databases and software tools (e.g., SMART CANDU Operations and Maintenance support software as well as in-house applications and the work management system) they require to simplify and manage their work flow, as illustrated in Figure 10. One of the specific applications under development for MIMC to simply work flow is the automatic generation of system health monitoring reports. MIMC will start field trial before the end of 2006.

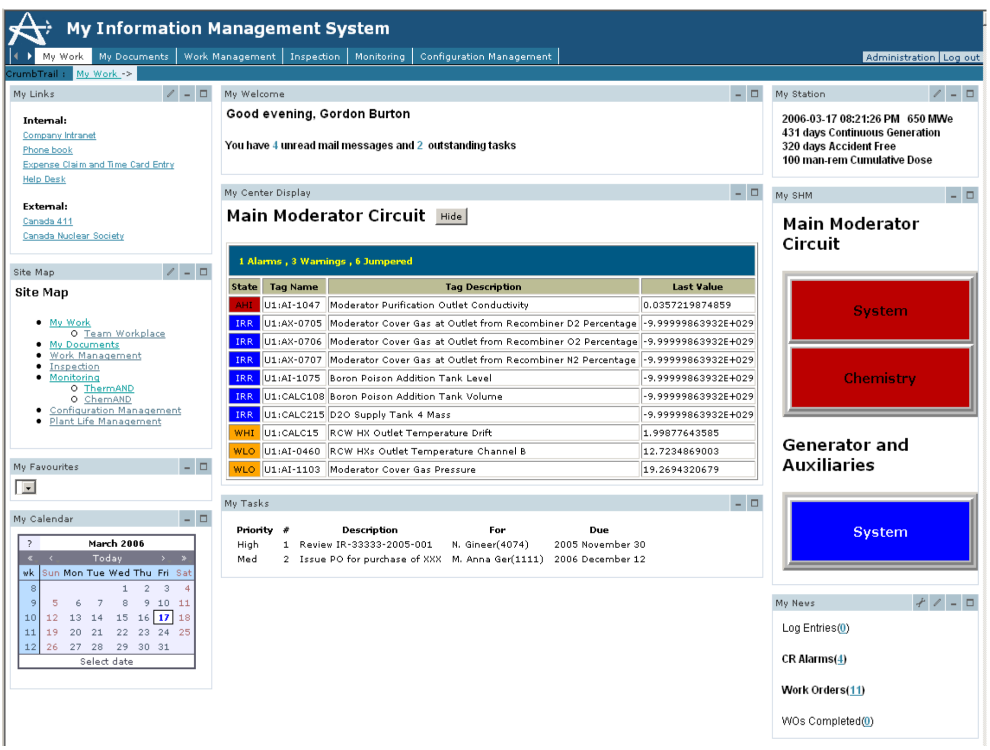


**Figure 10: Customized MIMC home-page for the moderator system engineer.**

Reliability analysis techniques in Reliability Centered Maintenance are readily available to predict the probability of component failure and the resulting system and, ultimately, plant reliability. To relate component reliability to plant performance, however, (i.e. electricity output, production cost) one must consider the consequences of failure (e.g., repair cost, outage duration) in addition to the failure probability. AECL is currently investigating the feasibility of developing a methodology to integrate the consequences and probability of failure in order to predict overall plant performance and identify the optimum balance between operational targets and maintenance expenditures. Such a methodology would provide a useful tool for optimizing operations and maintenance costs for a given performance level.

## 5. SUMMARY

SMART CANDU Operations and Maintenance support software is being developed to enable plant operations and maintenance staff to achieve predictable plant performance. The software supports the decision making process by gathering data from disparate sources, organizing and presenting it in a way that makes interpretation easy, and interfacing it with diagnostic tools and predictive models to support making proactive and informed decisions to manage and improve plant performance.

SMART CANDU software supports the five core processes identified in the NEI standard process model: operate plant, equipment and component reliability, configuration management, materials management and work management. The implementation of the SMART CANDU tools discussed in this paper in build projects and operating CANDU plants is summarized in Table 1.

SMART CANDU software is being included in the new Enhanced CANDU 6 (EC6) and Advanced CANDU Reactor (ACR) designs, and can be implemented incrementally to complement information management systems at existing plants.

| | |
|---|---|
| **OPERATE PLANT** | |
| CAMLS | Qinshan project |
| ChemAND | Gentilly-2, Point Lepreau Generating Station, Wolsong Unit 3 |
| **EQUIPMENT AND COMPONENT RELIABILITY** | |
| FCMAT | Field trial launched Dec 2005 with Ontario Power Generation and Bruce Power |
| ThermAND | Field trial at Point Lepreau Generating Station Nov 2004 to March 2006 |
| **CONFIGURATION AND MATERIALS MANAGEMENT** | |
| IntEC | Wolsong, Qinshan and Cernavoda projects, Gentilly 2, Bruce B, Wolsong. |
| TRAK | Qinshan and Cernavoda projects, OPG, Bruce Power and CANDU 6 clients |
| CMMS | Qinshan project |
| **WORK MANAGEMENT** | |
| MIMC | Field trial launch before end of 2006 |

**Table 1: Implementations of SMART CANDU Operations and Maintenance support software discussed in this paper at CANDU utilities.**

## 6. ACKNOWLEDGEMENTS

The authors acknowledge and thank the many experts at CANDU plants who have provided valuable feedback on the challenges of operating and maintaining a nuclear power plant. We also acknowledge the many technical experts at AECL who have worked on the development and field trial of SMART CANDU technology. In particular, the authors acknowledge the contributions by Mr. R. Olmstead, Mr. R. Didsbury and Dr. R.L. Tapping, Dr. G.R. Mitchell and Dr. G. R. Burton.