Development of Improvements to CANDU Computerized Annunciation

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Abstract: Canadian nuclear utilities and AECL have successfully completed a multi-year development program to improve the computerized control centre annunciation in CANDU nuclear power plants. The outcome of this program has been the definition and validation of an improved strategy for CANDU annunciation. The alarm processing, presentation and interaction concepts comprising the strategy have the potential to significantly improve station economic performance, are retrofitable to current plants, and are being incorporated into new CANDU plant designs.

This paper outlines the key program activities, the specific improvements developed, and the significant operational benefits realized by theses annunciation improvements. The paper also summarizes the lessons learned in developing these annunciation improvements and describes the progress underway to apply these improvements to current CANDU plants on a retrofit basis and to new CANDU plant designs.

Keywords: Nuclear power plant, CANDU, control centre, annunciation.

I. INTRODUCTION

In large process systems such as nuclear power plants, annunciation is intended to alert operations staff to important changes in plant conditions that may impact on operational goals. Annunciation, along with the routine monitoring of control room displays and field communication, should enable operations staff to keep up-to-date with the current plant conditions and predict future plant states for all phases of plant operation.

In response to operator needs for improved annunciation support, Canadian nuclear utilities and AECL have recently undertaken a multi-year development program to improve the control centre annunciation in CANDU nuclear power plants. This development program involved extensive prototyping and refinement of proposed annunciation improvements with operations staff at all three Canadian nuclear utilities. The last two years of the program, was devoted to full-scope simulator evaluation of the support provided to operations staff by the new annunciation improvements in comparison with current plant annunciation systems. These evaluations demonstrated that the new annunciation improvements offered utilities substantial operational benefits in terms of both plant production and safety.

With the development program completed, work has now turned to applying the annunciation improvements in near-term retrofit projects and in new plant designs.

II. BACKGROUND

A. The Need for Annunciation in Supervisory Control

In CANDU plants, the control room operators are assigned full responsibility and authority to control all aspects of unit operation within administrative limits. To carry out this responsibility, meet production and safety goals, and work effectively with automated systems; operators must be supported by information and control systems that allow them to actively supervise a highly automated process system and be responsively informed of off-normal conditions and changes in automation control behaviour [1].

In addition to direct supervision of unit operation, operators are expected to perform additional duties (e.g., planning, supervision of work protection, approval of maintenance work, logging). Current experience demonstrates that more than 80% of an operator's time can be occupied by tasks other than those involved with direct process supervision. Even during instances when the unit is directly monitored, it is only practical for operators to maintain an awareness of a very small subset of the available plant parameters. Consequently, operators depend on the plant annunciation systems to alert them to plant changes requiring intervention and to assist them in maintaining an up-to-date awareness of all important changes in plant conditions.

B. The Role of Annunciation

The role of annunciation is to ensure that control room staff are promptly alerted to and supported in their response to important changes in plant conditions that may impact on operational goals. In fulfilling this role, annunciation must perform three functions:

- detect and may predict the occurrence of plant changes,
- alert users to plant changes important for the current operating situation, and
- points users to additional plant information to understand and respond to the changes [2,3].

There are two kinds of changes in plant conditions that the annunciation should alert operators to:

- *Fault alarms* - challenges to current operational goals that represent potential or current problems in the plant (e.g., process disturbances or equipment faults), and

- *Status alarms* - changes in equipment, system or plant conditions that do not represent a challenge to current operational goals (e.g., confirmation of the completion of an automatic action).

Operators require timely information on both types of plant changes. Information on impending and current problems is required so operators can interpret what operational goals are challenged, and plan and prioritize compensatory actions. Information on other changes in plant conditions (i.e., not problems) is required to maintain an up-to-date awareness of the plant configuration. Such an understanding is essential for planning and prioritizing the response to impending or current problems (i.e. faults).

C. Current CANDU Annunciation

CANDU control rooms contain two main annunciation systems:

- *Primary* - a computer-based system with alarms presented as individual messages on central CRT displays, and
- *Backup* - a logic-based system with alarms presented on panel window annunciators.

The computer-based system enables changes in the status of several thousand analog, contact input and calculated variables across all plant systems to be individually annunciated. Alarms are presented on one or more central alarm monitors based on their order of occurrence. When the displays become full, new alarms begin to overwrite the oldest previously displayed alarms. The importance (i.e., priority) of each alarm is applicable to the full power operating state and is thus less relevant to other operating situations. Two means of alarm suppression are provided. A capability to suppress some alarms based on specific plant signals is available but is not extensively used due to a lack of supporting analysis. A second capability provides suppression of lower priority alarms for a few minutes following significant plant upsets (i.e., stepback, reactor trip or turbine trip).

The window annunciator system provides basic alarm functionality for a limited number (i.e., ~200) of key safety-related and production-related alarms. The primary intent of this system is to provide independent indication of a minimum set of key alarms in the event of loss or unavailability of the computer-based alarm system. With this system, the states of alarms are indicated by individually illuminated annunciator tiles. As with the computer-based alarm system, the indicated importance of window alarms are applicable only for the full power operations state. There is no capability to condition or suppress window alarms on plant conditions or events.

D. Areas Requiring Improved Annunciation Support

Overall the computer-based annunciation system supports operations staff well in understanding the alarm state of the unit during conditions when only a few alarms are present and the alarm generation rate is low (e.g., normal stable operation and minor disturbances).

During conditions when many alarms are active and/or the alarm generation rate is high (e.g., controlled manoeuvres, upsets and outages), the computer-based annunciation displays are less useful, for example:

- irrelevant alarms routinely overwrite displayed operationally relevant alarms as result of minimal relevance conditioning,
- the chronological listing of alarms shows only the most recent alarms rather than the most important to the operating situation, and
- the indicated and fixed priority of alarms based on the full power operating state may not be appropriate for the various other non-full power operating situations.

In such circumstances, operators employ increased monitoring of plant indications and the alarm status of key window annunciators to allow them to keep abreast of important plant changes. To provide an awareness of the full alarm state of the plant, printed alarm summaries are periodically reviewed. Once the pace of activities and alarm receipt rate allow, operators transition back to exclusive usage of the computer-based alarm displays.

III. DEVELOPMENT PROGRAM

A. Objectives

The objectives of the development program were to:

- establish an improved annunciation strategy for CANDU plants based on an understanding of CANDU operational principles and needs, models of supervisory control and human decision-making, and human perceptual and cognitive performance capabilities.
- develop specific enhancements to CANDU computer-based annunciation so that it could fulfill the primary annunciation role and provide the necessary annunciation support to operations staff in all plant operating situations,
- confirm and quantify the operational benefits of improved annunciation support in simulator trials with station operations crews,
- assess the relative operational effectiveness and financial benefit of specific annunciation configurations of interest to stations for retrofit and AECL for new plant designs, and
- assist CANDU stations and AECL projects in selecting practical annunciation improvements for application to retrofits and new projects.

In working to achieve these objectives, the project team took into account the successful aspects of current CANDU annunciation design and operations experience, plus the experience and lessons learned from international annunciation projects. Thus, the new annunciation strategy and improvements developed and assessment approaches applied represent a blend of the 'ideal' tempered with the

realities of variations in utility operation philosophies, human performance capabilities and limitations, and practical technology innovations and choices.

B. Activity Timeline

The development program was structured into four phases and comprised the following activities [4]:

· Information Needs and Requirements Analysis - 1991/92

- *Operations Review* - Operating experience with current CANDU annunciation systems was reviewed with station operations and AECL design staff to characterize aspects of good performance to be retained and areas for performance improvement.

- *Survey of International Developments* - Relevant international work to improve annunciation was reviewed to establish development team awareness of innovations offering promise of meeting CANDU needs [5].

- *Definition of Annunciation* - The generic functions and information to be supported by plant control centre annunciation were characterized through extensive discussions with station and design staff [2].

- *Benchmarking the Current Design* - The performance and usage of an existing annunciation system was assessed based on international guidelines and specific usability evaluations [6].

· Concept Generation and Refinement - 1993/94

- *Function and Task Analyses* - Detailed function and task analyses of annunciation use in support of plant upset management and restoration of power were developed to further characterize the information needs of operations staff, match information needs with specific alarm generation, processing and display innovations, and identify relevant performance criteria for assessing annunciation system performance [7].

- *Strategy Definition* - Building on earlier work, this activity documented the operational role for plant annunciation, the types of information to be alarmed, the principles to be followed, and the recommended annunciation facilities and features to be provided [3].

- *Prototype Development and Demonstration* - To support demonstration and refinement of specific strategy elements, several prototype annunciation systems were developed. Subjective evaluation of the prototypes by operators, trainers, station managers, licensing staff, and design engineers was used to focus improvement emphasis.

· Concept Validation - 1995/96

- *Assessment Approach and Criteria* - The development team employed a range of assessment techniques of increasing fidelity and formality to assess the operational impact of specific improvements. For the final simulator-based tests, formal experimental methods involving hypotheses definition, assessment methods and performance measures selection, control of and testing for experimental confounds, and statistical analysis of collected data were employed [8].

- *Single Operator Upset Response Trials* - Simulator trials were conducted with eight Point Lepreau operations staff using two upset scenarios to assess the improvement in support provided by the new annunciation concepts in comparison to the current station annunciation [9].

- *Crew Startup and Outage Trials* - Simulator trials were conducted with ten Darlington control room crews using startup and outage scenarios to assess the improvement in support provided by the new annunciation concepts [9].

· Infrastructure and Engineering Implementation - 1994/96

- *Regulatory Dialogue* - Beginning with the concept generation and refinement phase, a dialogue was established with Atomic Energy Control Board staff to keep them abreast of program developments and directions. This provided a forum for identification and discussion of potential issues that might hinder future regulatory acceptance.

- *Analysis Tool Development* - To support station or project application of the new annunciation concepts a software tool was developed to assist designers with the initial specification and maintenance of alarm information and configuration decisions [10].

- *Software Engineering* - In preparation for AECL project use, AECL designers have engineered annunciation software applications incorporating the CAMLS improvements for the plant display system of the CANDU 9 control centre.

IV. IMPROVEMENTS DEVELOPED

A. Features

The elements of the improved annunciation strategy comprise a set of alarm generation, processing, display and interaction features, and application principles. This combination of features and application principles comprise the CANDU Annunciation Message List System (CAMLS). Full or partial application of the features and principles are embodied by two control room annunciation facilities:

- *Real-time Annunciation Displays* - Alarm message list displays that alert operations staff to plant changes as they occur and provide continuous presentation of the most important fault conditions and most recent changes in plant configuration, and
- *Interrogation Workstation* - A console-based interactive workstation that provides electronic access to both real-time and historical annunciation message logs, annunciation message detail, and links to related information (i.e., procedures, parameter displays, and flowsheets), and the capability to group and sort annunciation messages to support control room staff in responding to annunciated conditions.

Key features comprising the CAMLS suite of annunciation improvements include [3]:

- *Separation of Fault and Status Alarms* - Provision of separate displays for these two message streams removes the need for operations staff to mentally sort messages in real-time.
- *Display of Fault Alarms by Priority* - This form of alarm display ensures that the most important fault conditions are always visible and supports operator goal-based decision-making.
- *Determination of Operating Context* - Determination of the current plant state and enables alarms to be presented consistent with their relevance and importance to the operating situation. Three dimensions (i.e., reactor power level, heat sink state, and turbine/generator state) are used in determining operating context.
- *Relevance Conditioning* - Selective suppression of alarms irrelevant to the current operating goals, plant operating situation and equipment configurations can substantially simplify operator alarm state interpretation and diagnosis. Conditioning factors can include plant operating contexts, events, or local process and equipment states.
- *Dynamic Prioritization* - This feature enables the displayed alarm priorities to vary as a function of plant operating context to better reflect the true importance of alarm information with changing operating conditions.
- *Similar Message Coalescing* - Replacement of several similar alarms with a single summary message effectively conveys the same alarm state information while reducing the alarm presentation rate.
- *Functional Alarm Generation* - New alarms to support higher-level interpretation of plant alarm state can be created based on the logical combination of process conditions, alarms and calculated variables.
- *Simplified New Alarm Acknowledgment* - Operators are audibly alerted to new alarms with a single tone and only fault alarms require manual acknowledgment. This approach provides a better match on operator demands between alarm management and other control room tasks.
- *One-step Access to Supporting Information* - Electronically linking displayed alarms with support information such as annunciation response procedures substantially improves support material access and use in executing alarm response tasks.

B. Operational Benefits Realized

The operational benefits of the CAMLS annunciation improvements have been demonstrated and confirmed in full-scope simulator trials at two CANDU stations. A formal validation process was used to arrive at statistically valid statements of comparative system performance between the current CANDU annunciation systems and the CAMLS improvements [9]. These evaluations clearly established that the CAMLS features improve operator performance for most operationally significant tasks involving annunciation compared to existing CANDU annunciation systems. Specific operational benefits include:

- *Improved production potential* - Increased production capability as a result of the improved view of the plant alarm state in all operating conditions. This improved understanding shortens startups and outages since work can progress faster, reduces the probability of major upsets and trips, and improves overall response and recovery when upsets occur.
- *Reduced operations, maintenance and administrative costs* - Reduced costs as a result of lower demands on unit staffing in support of specific operations, improved equipment protection, and more timely detection and response to equipment problems.
- *Enhanced Safety* - Improved plant safety through a better ability to monitor and understand the overall plant alarm state, and more timely detection and response to challenges to plant operating margins.

V. LESSONS LEARNED

Key lessons learned during the conduct of this development program were:

- *Display Form* - the form of alarm display has a large impact on operator understanding of overall alarm state and can compensate or accentuate other alarm system generation or processing deficiencies,
- *Selective Conditioning* - substantial improvement in the relevance of displayed alarm information can be achieved through selective application of conditioning to specific operating situations - requiring definition of only a limited number of conditioning relationships rather than a complete alarm database analysis,
- *Alarm Information Definition* - with an analysis framework and suitable guidance, engineering staff with an operations perspective can accurately and reliably perform the bulk of the analysis needed to define context specific alarm priorities and conditioning relationships,
- *Operational Impact and Financial Benefits* - the financial benefits of improved annunciation support to plant operation can be directly linked to objective measures of operator understanding, decision-making and response behaviour to supplement traditional subjective assessment measures.
- *Simulator Testing* - full-scope simulator testing can be undertaken in a cost effective manner by integrating assessment needs with on-going station refresher training programs,

- *Functional Displays* - operations staff supervise the plant from an integrated functional perspective and are appreciative of information systems that support this perspective as a supplement to the existing system-based organization of panel indications and process displays.

Overall, four factors were essential to the success of this development program:

- the development of a highly motivated and focused multiple-disciplinary project team,
- the enthusiastic participation of operations staff from several plants in all aspects of the work,
- the use of successive rapid prototype and evaluation cycles to evolve and refine the concepts developed,
- the use of full-scope simulator validation trials to demonstrate the significant operational benefits of using the new annunciation concepts in comparison with current plant annunciation systems, and
- the continuing support and encouragement of utility and AECL management.

VI. APPLICATION INITIATIVES

The CAMLS annunciation improvements have been considered for application in several station and project applications. Recent initiatives include:

A. Hydro Quebec - Gentilly 2

As part of a station initiative to revise the strategy for upset response, Gentilly 2 has undertaken a number of annunciation improvements. As a means to reduce the number of relevant alarms in upsets and startups, they have successfully applied a form of CAMLS event-based conditioning and channelized alarm coalescing [11].

B. Ontario Hydro - Bruce A

The Bruce A plant has been undertaking a major control room retrofit that included an upgrade to the control room display technology. As part of this effort, AECL and Ontario Hydro staff applied CAMLS alarm prioritization concepts to develop an alarm prioritization strategy for retrofit to Bruce A alarm displays. This strategy was successfully pilot tested with Bruce operations, training, licensing and engineering staff in the summer of 1996. Following the pilot test, two operations staff completed the prioritization analysis of all plant alarms over a two month period.

C. Ontario Hydro - Darlington

In conjunction, with station support of the simulator evaluation of CAMLS annunciation concepts, Darlington asked AECL to undertake a study to investigate the technical feasibility and cost/benefit of applying the new annunciation concepts for retrofit to the Darlington control room. This study involved three components:

- definition of a Darlington annunciation retrofit strategy based on CAMLS concepts,
- specification of the hardware and software options for implementation, and
- estimation of the financial benefits to be realized from the annunciation improvements and the expected costs of implementation.

The findings from this study indicated a payback period of 3 years for a proposed retrofit implementation [12].

Darlington engineering staff have recently begun formulating a plan to undertake a series of annunciation improvements over the next few years and are considering the incorporation of specific CAMLS annunciation improvements as retrofit options.

D. Ontario Hydro - Pickering B

We are currently working with Pickering B staff to assist them with characterizing control room annunciation deficiencies and recommending options for improvement. A survey of station annunciation deficiencies has been completed and operations-based requirements for the information and behaviours, that improved control room annunciation should exhibit, have been defined. Work is progressing on characterizing the financial benefits and costs of implementation for specific annunciation improvements, including those drawn from the CAMLS feature suite.

E. AECL - CANDU 9

The full CAMLS suite of annunciation improvements have been adopted for incorporation into the CANDU 9 control centre. Software engineering of the annunciation application to support all aspects of the CAMLS functionality is nearing completion as one of the first plant display system applications.

VII. CONCLUSIONS

This paper has summarized recent work to develop, validate and apply new improvements to CANDU control room annunciation. The improved annunciation strategy and concepts developed were an outcome of a multi-year project between CANDU utility operations, training and engineering staff, and AECL product development staff. Simulator trials at two plants have demonstrated that the new annunciation concepts offer substantial improvements in annunciation support to operations staff across all plant operating situations. AECL and CANDU utilities are applying these improvements to current projects and are continuing to refine these concepts through station and project application experience.

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X. BIOGRAPHIES

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