

THE ADVANCED CANDU REACTOR ANNUNCIATION SYSTEM

COMPLIANCE WITH IEC STANDARD AND US NRC GUIDELINES

R. Leger, S. Malcolm
Atomic Energy of Canada Limited
2251 Speakman Drive,
Mississauga, Ontario,
Canada, L5K 1B2

E. Davey
Crew Systems Solutions
Deep River, Ontario
K0J 1P0

ABSTRACT

Annunciation is a key plant information system that alerts Operations staff to important changes in plant processes and systems. Operational experience at nuclear stations worldwide has shown that many annunciation implementations do not provide the support needed by Operations staff in all plant situations. To address utility needs for annunciation improvement in CANDU plants, AECL in partnership with Canadian CANDU utilities, undertook an annunciation improvement program in the early nineties. The outcome of the research and engineering development program was the development and simulator validation of alarm processing, display, and information presentation techniques that provide practical and effective solutions to key operational deficiencies with earlier annunciation implementations. The improved annunciation capabilities consist of a series of detection, information processing and presentation functions called the CANDU Annunciation Message List System (CAMLS). The CAMLS concepts embody alarm processing, presentation and interaction techniques, and strategies and methods for annunciation system configuration to ensure improved annunciation support for all plant situations, especially in upset situations where the alarm generation rate is high.

The Advanced CANDU Reactor (ACR) project will employ the CAMLS annunciation concepts as the basis for primary annunciation implementations. The primary annunciation systems will be implemented from CAMLS applications hosted on AECL Advanced Control Centre Information System (ACCIS) computing technology. The ACR project has also chosen to implement main control room annunciation aspects in conformance with the following international standard and regulatory review guide for control room annunciation practice:

- International Electrotechnical Commission (IEC) 62241 – Main Control Room, Alarm Function and Presentation (International standard), and

- US NRC NUREG-0700 – Human-System Interface Design Review Guidelines, Section 4 – Alarm System (Regulatory review guide).

In order for the ACR annunciation system to comply with IEC-62241 and NUREG-0700, the CAMLS concepts must satisfy their respective requirements and guidelines.

This paper will provide a summary of how CAMLS complies with IEC-62241 and NUREG-0700. Overall, the CAMLS-based annunciation requirements conform to the intent of the recommended annunciation practices included in both these documents. However, there are minor differences in requirements interpretation and annunciation practice between CAMLS implementation concepts and the recommended practice in each document. Generally the differences with IEC-62241 revolve around definitions, the display properties of new alarms, and video display unit (VDU) alarm display organization. The differences with NUREG-0700 revolve around segregation of status alarms, the use of spatially-dedicated, continuously visible displays, simultaneous display of high-priority alarms, audible signals for alarm states and reminder signals, blank lines in alarm message lists and manual silencing. These minor differences are discussed and rationales for the CAMLS implementation concepts are provided.

1. INTRODUCTION

In large, complex 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. More explicitly, annunciation is defined as a plant function that:

- Detects and may predict the occurrence of plant changes,
- Alerts users to changes important for the current operating situation,
- Presents information on plant changes detected, and
- Points users to additional plant information to understand and respond to the changes.

Over the past thirty years of nuclear plant operation, the understanding of the needs of operators within the system has improved and the available technology to support them has become more sophisticated. Even so, it is still common to find annunciation systems with deficiencies such as 'alarm flooding' during plant upsets, distracting alarms irrelevant to the operating situation, and alarms with cryptic messages.

The opportunity to improve nuclear plant annunciation has been well recognized worldwide for many years. In Canada, nuclear utilities and AECL have co-sponsored a research program to develop enhancements to the initial annunciation system designs. An improved system for CANDU annunciation, the CANDU Annunciation Message List System (CAMLS), has been developed incorporating concepts that significantly improve operations staff performance in developing and maintaining alarm state awareness. The ACR project will employ the CAMLS annunciation concepts as the basis for primary annunciation implementations. CAMLS can also

be retrofitted to current plants.

CAMLS was developed in the 1990's. Since the development of CAMLS, the IEC has developed a standard for control room annunciation practice, IEC-62241 [1]. The US NRC has also developed a regulatory review guide, NUREG-0700 [2]. In order for the ACR annunciation system to comply with the IEC standard and the US NRC review guide, the CAMLS concepts must satisfy their respective requirements and guidelines. The purpose of this paper is to provide a summary of how CAMLS complies with IEC-62241 and NUREG-0700. The remainder of this paper is divided into the following sections:

- Section 2 describes CAMLS, IEC-62241 and NUREG-0700,
- Section 3 describes how CAMLS meets IEC-62241,
- Section 4 describes how CAMLS meets NUREG-0700, and
- Section 5 discusses conclusions.

2. BACKGROUND

This section provides background information for CAMLS, IEC-62241, NUREG-0700 and the challenges of designing systems to meet these standards and client needs.

2.1 CAMLS

CAMLS is a computerized annunciation system for the control rooms of nuclear generating stations. CAMLS will alert operators to changes in plant conditions that may impact on safety and production and help staff to effectively respond. The design objectives of CAMLS are to:

- Provide a clear and concise overview of the current problems or faults in the plant,
- Provide an overview of the current state of the plant in terms of automatic process and equipment actions,
- Provide support for specific operational tasks, through either pre-configured or operator-configured annunciation displays, including:
 - Rapid and efficient upset response,
 - Plant stabilization,
 - Problem diagnosis,
 - Recovery action planning and implementation, and
 - Rapid recovery from trip and return to power operation.

To achieve these objectives, several information processing, presentation, and interaction concepts were used including:

- Alarm Processing Concepts/Features:
 - Definition of plant state (operating regions),
 - Prioritization based on plant state,
 - Alarm conditioning based on plant state,
 - Reduced message volume through improved utilization of information, and

- New types of alarms.
- Alarm Presentation Concepts/Features:
 - Separation of faults (problems) and status messages into separate displays,
 - Ordering faults by order of priority,Colouring messages by priority,
 - Retaining fault messages until fully acknowledged and returned-to-normal, and
 - Backshading unacknowledged alarms (new and return-to-normal).
- Alarm Interaction Concepts/Features:
 - Single key acknowledge/reset,
 - Single tone on initial alarm occurrence, and
 - Auto acknowledge for status messages.

The result is that CAMLS:

- Prioritizes relevant alarm data according to the consequence to the plant and the urgency for an operator response,
- Adjusts the alarm presentation and priority with variations in the operating state of the plant,
- Significantly reduces irrelevant alarm messages without losing key information,
- Improves operator accuracy, speed of diagnosis, and planning by providing organized information, and
- Minimises distraction from important operational activities through less intrusive and demanding operator interactions.

CAMLS has two distinct components--two central overview displays and a desktop inquiry system (Annunciation Interrogation Workstation, AIW).

CAMLS has been assessed for operational performance over several upset scenarios in full scope simulators at two different operating 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 CAMLS [3]. The evaluations clearly establish that CAMLS improves operator performance for most operationally significant tasks involving annunciation compared to existing CANDU annunciation systems. The implications of these improvements on safety margins, production costs, and human performance are significant.

2.2 IEC-62241

IEC-62241 is referenced directly by IEC-60964, Design for Control Rooms of Nuclear Power Plants [4]. IEC-60964 was developed to supply requirements relevant for the design of control rooms of nuclear power plants. Since it's first publication in 1989, it has been used extensively within the nuclear industry. The ACR project is using IEC-60964 as one of the design basis documents for the design on the main control room (MCR).

IEC-62241 provides the functional requirements for the alarm systems in the MCR of nuclear

power plants. The objective of the standard is to establish a common international understanding of the underlying functional design basis of alarm systems for control rooms, covering the corresponding functional requirements, the human factors requirements and design guidelines for the alarm functions and alarm presentation. The standard attempts to give guidance to reduce problems which have been experienced in the past, such as:

- Omission of important alarms,
- Delay in detecting important alarms,
- Increased workload that may affect the performance of other operational activities,
- Inattention to frequently activated alarms, and
- Confusion associated with the misunderstanding of the relationships among alarms and the importance of alarms.

2.3 NUREG-0700

NUREG-0700 provides the guidelines necessary to evaluate the conformance of interfaces between plant personnel and plant's systems and components with HFE criteria. The guidance provided in NUREG-0700 addresses the physical and functional characteristics of human-systems interfaces (HSIs). NUREG-0700 guidelines can also be used to evaluate documents which contain design-specific HFE guidelines or style guides. NUREG-0700 is organized into four basic parts, as follows:

- Guidelines for basic HSI elements,
- Guidelines for reviewing HSI systems, such as alarm systems,
- Guidelines for the review of workstations and workplaces, and
- Guidelines for the review of HSI support.

The guidelines contained in NUREG-0700 for alarm system review address the selection of alarm conditions, choice of setpoints, alarm processing, alarm availability (such as filtering and suppression of alarms), unique aspects of the display of alarm information (such as organization, coding, and alarm message content), and alarm controls. The alarm system section of NUREG-0700 is divided into the following sub-sections:

- Alarm System High-Level Function,
- Information Display,
- User-System Interaction and Controls,
- Reliability, Test, Maintenance, and Failure Indication Features,
- Alarms Response Procedures,
- Control-Display Integration and Layout, and
- Integration with Other HSI Elements.

The individual guidelines are presented in a standardized format, which includes:

- A unique guideline number,
- Guideline title,

- The review criterion,
- Additional information such as clarification, examples, exceptions and details regarding measurement, and
- Source document(s) from which the guideline was developed.

2.4 Designing to Comply With International Standards

In order to comply with international standards and guidelines such as IEC-62241 and NUREG-0700 and meet client needs, designers have to make some engineering judgements. Some generalized examples of these types of judgements are discussed below.

Rationalizing Competing Standards

Individual standards are seldom applied in isolation. The recommended practices for specifying design requirements for a specific project represent design interpretation and judgement. Ultimately, the design needs to achieve a balance between implementation choices. For example for the ACR project, a balance needs to be made between announcement audible alerting methods, current control room monitoring practices and the role of audible alerts, and the desire to minimize control room distractions and annoyances.

Rationalizing Local and International Practices

Typically, there will be some differences between local and international practices. For example, in order to meet client needs, CAMLS considers alarms as conveyors of changes in plant status. This definition of alarms is broader than the one used in international standards, which considers alarms as indications of problems alone.

Technology Dependence

Although every intent is made to write international standards independent of technology, they are derived from specific technology dependent experience. Therefore, interpretation and judgement is required where new technologies and approaches offer user improvements over former practices. For example, CAMLS display formats order fault alarm displays by priority as opposed to the IEC recommended chronology listing and tile formats.

Design Partitioning

A designer may partition and document a design differently than how the equivalent information is partitioned in standards. In such cases, requirements for specific functions may appear in different areas than expected. For example, for the ACR design, historical information recall capabilities is a common Plant Display System service rather than viewed as a specific announcement function.

The next two sections present a comparison of CAMLS with IEC-62241 and NUREG-0700. Minor differences, similar to the ones discussed above, are noted and rationales for the

differences are provided.

3. COMPARISON OF CAMLS TO IEC-62241

The CAMLS concepts were compared to the requirements contained in IEC-62241, Ed.1. Overall, the CAMLS concepts conform to the intent of IEC-62241. However, minor differences in requirements interpretation and annunciation practice between CAMLS and IEC-62241 were noted. They can be broadly characterized into three categories, as follows:

- Definitions,
- Display properties, and
- Display organization.

The differences in each of these three categories are discussed in detail below.

3.1 Definitions

Differences in definitions of three terms were noted. A rationale for applicability of the CAMLS concept to the ACR project is also provided.

Alarm Definition (Section 3.1 of IEC-62241)

- IEC - 'An item of diagnostic, prognostic, or guidance information, which is used to alert the operator and to draw his or her attention to a process or system deviation.'

'Note: Specific information provided by alarms includes the existence of an anomaly for which corrective action might be needed, the cause and potential consequences of the anomaly, the overall plant status, corrective action to the anomaly, and feedback of corrective actions.'

'Two types of deviation may be recognised:

- *Unplanned - undesirable process deviations and equipments faults;*
- *Planned - deviations in process conditions or equipment status that are the expected response to but could be indicative of undesirable plant conditions.'*
- CAMLS - An alarm is defined as a process or system change, either Fault (i.e. problem) or Status (i.e. non-problem) that Operations staff need to be alerted to.
- Rationale - The purpose of annunciation is to alert operators to changes in process conditions or systems configuration from a reference baseline condition to support overall alarm state awareness. Changes of operational significance include planned changes (i.e., Status information) as well as unplanned changes (i.e., problems).

Alarm Acknowledge Definition (Section 3.2 of IEC-62241)

- IEC - 'An action, which operators are required to carry out to show that they have recognized an alarm change of state presented to them.'
- CAMLS - An action, which operators voluntarily perform to inform the annunciation system to clear the visual highlighting of all alarms that have changed state since the previous acknowledgement action.
- Rationale - IEC and CAMLS are consistent as to acknowledgement behaviour but differ as to the purpose for acknowledgement. In the IEC case, the purpose of acknowledgement is to demonstrate that an operator has recognized an alarm change; whereby with CAMLS, acknowledgement is an action operators may choose to perform to assist them with display and alarm information management.

Visual highlighting newly occurring alarms and providing operator control of highlighting clearance, assists Operations staff in managing the information in alarm displays in relation to other duties. Visually highlighting newly occurring alarms assists Operations staff in identifying new plant changes that have occurred since the last alarm acknowledgement actions.

Alarm Coding Definition (Section 3.4 of IEC-62241)

- IEC - 'A method of highlighting an object of concern visually or audibly, with the intention of drawing the operator's attention to the object.'
- CAMLS - Visual and/or audible methods for conveying information about an alarm for the purposes of communication and alerting.
- Rationale - Coding properties are used for both alerting purposes (i.e., visual and audible highlighting) and conveying properties of an alarm (i.e., signal validity, alarm importance, channel and system affiliation).

3.2 Display Properties

Alarm Display Processing - General (Section 8.1 of IEC-62241)

- IEC - 'When an alarm is initially displayed, it shall have an associated flashing legend or flashing symbol until it is acknowledged (see 9.4), and should be accompanied with the initiation of an audible warning (see 9.2), which should sound until silenced.'
- CAMLS - The occurrence of new alarms shall be presented with the following properties:
 - Visual Highlighting - Backshading of the alarm texts for computer-based displays, and flashing of alarm fascia for conventional annunciator windows until the next alarm

acknowledgement operator action.

- Audible Alert - A brief, single-tone on alarm occurrence.
- Rationale - Backshading of alarm texts as a visual highlight for alarms in computer displays (e.g., list displays or window tiles) is visually salient without distraction, and doesn't impair alarm text recognition. Flashing is more distracting and reduces legibility, and may contribute to visual fatigue [5].

Use of a brief, single tone on new alarm occurrence has been shown to be an effective alert in all operational states, to substantially simplify operator need for annunciation system interaction, and reduce a longstanding source of control room distraction and annoyance [6].

Flash and Reflash (Section 9.3 of IEC-62241)

- IEC - 'A flashing visual signal should be included for all alarms, initiated when the alarm condition appears.'

'Reflash is an automatic alarm management function, which is used to generate an alarm message again if the alarm reappears after clearing or being acknowledged.'

- CAMLS - A salient visual highlighting characteristic should be initiated when a new alarm condition appears. The visual highlighting characteristic should be reapplied to an alarm if the alarm changes state after being acknowledged.
- Rationale - Visual highlighting should be used to identify the occurrence and re-occurrence of an alarm. Backshading of the alarm text is the preferred coding method for visual highlighting alarms. Flashing is a specific visual coding means for visual highlighting that is less suitable for alarm text applications [5].

3.3 Display Organization

Visual Display Unit (VDU) Alarm Display Organization (Section 10.3.3 of IEC-62241)

- IEC - 'The method of alarm display using VDUs should allow for display of the chronological record of alarms which have appeared. This may be done by a list of the more recent alarms divided into pages. The most recent page of alarms - called the top page - may be on display normally, with the alarms, which have just appeared shown with a flashing symbol adjacent to their alarm message.'
- CAMLS - The primary CAMLS alarm display does not display problem alarms in chronological sequence. The primary CAMLS alarm display consists of two lists, Faults organized by priority, and status alarms by sequence.

CAMLS does offer a chronological listing of alarm occurrences via a user selectable alarm history display capability. However, this view of the alarm stream is not expected to be used

by operators on a continuous basis for monitoring the plant alarm state due to the well-known limitations with chronological displays when the alarm state is changing.

- Rationale - The CAMLS Fault list is organized to mimic the manner in which operators mentally organize and prioritize their response to problem alarms. Organizing Fault alarms by priority is consistent with the way operators respond to problems in the plant, and has been proven in simulator trials to be a more supportive alarm state representation than former chronological alarm displays.

4. COMPARISON OF CAMLS TO NUREG-0700, SECTION 4

The CAMLS concepts were compared to the guidelines contained in NUREG-0700, Section 4, Rev.2. Overall, the CAMLS concepts conform to the intent of NUREG-0700, Section 4. However, minor differences in requirements interpretation and annunciation practice between CAMLS and NUREG-0700 were noted. They can be broadly characterized into three categories, as follows:

- High-level Function definitions,
- Information display, and
- User-System Interaction and Controls.

The differences in each of these three categories are discussed in detail below.

4.1 High-level Function Definition

Segregation of Status Indications (Section 4.1.2-5 of NUREG-0700)

- NUREG - 'Status indications, messages that indicate the status of plant systems but are not intended to alert the user to the need to take action, generally should not be presented via the alarm system display because they increase the demands on the users for reading and evaluating alarm system messages.'
- CAMLS - CAMLS incorporates non-problematic plant changes as Status alarms within annunciation. Status alarms are segregated from problem alarms called Faults, for presentation.
- Rationale -The purpose of annunciation is to alert operators to changes in process conditions or systems configuration from a reference baseline condition to support overall alarm state awareness. Changes of operational significance include planned changes (i.e., Status information) as well as unplanned changes (i.e., problems) [6]. Consistent with how operators mentally sort and manage both types of alarms, CAMLS displays Fault and Status alarms in two separate lists.

4.2 Information Display

Five differences were noted in the section covering information display. They are discussed below.

Use of Spatially Dedicated, Continuously Visible Displays (Section 4.2.1-4 of NUREG-0700)

- NUREG - 'Spatially dedicated, continuously visible (SDCV) alarm displays should be considered for:
 - The most important alarms used in diagnosing and responding to plant upsets, and
 - The most important alarms used to maintain an overview of plant and system status.

Additional Information: Spatial dedication means that the alarm messages always appear in the same position. Continuously visible means a parallel presentation method is used, i.e. the alarm information is always available to the operator, as opposed to serial presentation methods in which the operator must select the information to be seen.'

- CAMLS - The CAMLS Fault list organizes problem alarms by priority and this ensures that operators can always see the most important Fault alarms up to the alarm capacity of the display. While the location of individual alarms within the display is not spatially dedicated, the Fault alarm list within the Primary annunciation continuously visible alarm display provides a spatially dedicated and continuously visible view of the current most important problem alarms that comprise the plant alarm state.
- Rationale - The CAMLS Fault alarm display is considered to be consistent with the SDCV concept in that all the most important Fault alarms are continuously visible, and all Fault alarms will be continuously visible during the period when they are being responded to in multiple alarm situations.

Simultaneous Display of High-Priority Alarms (Section 4.2.2-2 of NUREG-0700)

- NUREG – 'For non-spatially dedicated alarm presentations such as VDU message lists, sufficient display area should be provided for the simultaneous viewing of all high-priority alarms.

Additional Information: Non-spatially dedicated alarm displays, such as message lists, should generally not be used as the primary method of presenting high-priority alarm messages. If non-spatially dedicated alarm displays are used, they should have sufficient display space available for simultaneous presentation of all high-priority alarms under the worst credible conditions. Operators should never have to page or scroll a display to view high-priority alarms.'

- CAMLS - CAMLS employs a message list organized by alarm importance (i.e., Fault alarm list) as the primary display for presenting high-priority alarm messages that represent

problem conditions. This display affords continuous presentation of the most important problems in the plant under all operational conditions

- Rationale - CAMLS overcomes the long-standing limitations with chronologically organized message lists for display of alarm state, by organizing plant Fault alarms by importance. This ensures that the most important problem alarms are always visible to operators and organized in a manner consistent with their response priorities under all operational conditions.

Audible Signals for Alarm States (Section 4.2.6.3-4 of NUREG-0700)

- NUREG - 'The tones used for incoming alarms should be separate and distinct from tones used to signify 'clearing' alarms.'
- CAMLS - Audible alerts for all changes of state of displayed Fault or Status alarms shall consist of a single, self-extinguishing tone.
- Rationale - Operator testing of various audible and visual alerting methods during CAMLS development demonstrated that a single audible tone on alarm occurrence and full message backshading were the most effective and compatible alerting methods for control room use.

Use of self-extinguishing alert features is effective in alerting operators to changes in plant alarm state, and substantially reduces the secondary tasks for operators associated with alarm management.

Reminder Audible Signals (Section 4.2.6.3-5 of NUREG-0700)

- NUREG - 'If the tone associated with an unacknowledged alarm automatically turns off after an interval of time, a reminder tone should be presented to alert the user to the continued presence of an unacknowledged alarm.'
- CAMLS - A single self-extinguishing audible tone is used for operator alert to all displayed changes in plant alarm state. Repeating audible alerts, as reminders for the continued presence of unacknowledged alarms are not used.
- Rationale - Operator testing with various audible alerting methods during CAMLS development demonstrated that reminder tones for unacknowledged displayed alarms were operationally unnecessary and a contributor to control room annoyance.

Blank Lines (Section 4.2.7.2-3 of NUREG-0700)

- NUREG - 'Alphanumeric alarm lists should have a separation (blank row) between every four or five alphanumeric messages.'

- CAMLS - Alarm message lists have no requirement for blank lines within the Fault, Status or history displays.
- Rationale - During CAMLS display development, the need for insertion of blank lines within list displays was found to be unnecessary. Current high-resolution graphic displays can provide adequate visual separation between adjacent alarm messages on displays to preclude the need for insertion of blank lines as an organizing or readability aid.

4.4 User-System Interaction and Controls

Manual Silencing (Section 4.3.2-2 of NUREG-0700)

- NUREG - 'Auditory signals should be silenced manually unless this interferes with other more critical actions.'
- CAMLS - A single self-extinguishing tone is used for audible alert to all changes in displayed plant alarm state.
- Rationale - The use of a single self-extinguishing tone as an audible alert has been proven to be effective and less distracting for operator use. The behaviour to manually silence alarms imposes an unnecessary distraction on operator control room activities and anchors operators unnecessarily to silence controls when the alarm generation rate is moderate or high.

5. SUMMARY AND CONCLUSIONS

The CAMLS concepts were compared to both IEC-62241 and NUREG-0700 in terms of requirements interpretation and annunciation practice. Overall, CAMLS conforms to the intent of the requirements and annunciation practice included in both of these documents. However, minor differences between CAMLS and IEC-62241/NUREG-0700 were noted. They are summarized in the table below.

Table 1 - Differences between CAMLS and IEC-62241/NUREG-0700.

IEC-62241		NUREG-0700	
Category	# of Diff.	Category	# of Diff.
Definitions	3	High-level Function Definition	1
Display Properties	2	Information Display	5
Display Organization	1	User-system Interaction	1
Total	6	Total	7

Common differences noted between CAMLS and both IEC-62241/NUREG-0700 include:

- CAMLS lists the faults by priority as opposed to chronologically. Organizing fault alarms by priority is consistent with the way operators respond to problems in the plant, and has been

proven in simulator trials to be a more supportive alarm state representation than former chronological alarm displays. This overcomes the long-standing limitations with chronologically organized message lists for display of alarm state.

- CAMLS uses a brief, single, self-extinguishing tone for audible alerts for all changes of state of displayed fault and status alarms. Both IEC-62241 and NUREG-0700 recommend manually silencing alarms. Use of a brief, single, self-extinguishing tone on new alarm occurrence has been shown to be an effective alert in all operational states, to substantially simplify operator need for annunciation system interaction, and reduce a longstanding source of control room distraction and annoyance.

6. REFERENCES

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