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Review Article

Design and development of enhanced criticality alarm system for nuclear applications

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A B S T R A C T

Criticality alarm systems (CASs) are mandatory in nuclear plants for prompt alarm in the event of any criticality incident. False criticality alarms are not desirable as they create a panic environment for radiation workers. The present article describes the design enhancement of the CAS at each stage and provides maximum availability, preventing false criticality alarms. The failure mode and effect analysis are carried out on each element of a CAS. Based on the analysis, additional hardware circuits are developed for early fault detection. Two different methods are developed, one method for channel loop functionality test and another method for dose alarm test using electronic transient pulse. The design enhancement made for the external systems that are integrated with a CAS includes the power supply, criticality evacuation hooter circuit, radiation data acquisition system along with selection of different soft alarm set points, and centralized electronic test facility. The CAS incorporating all improvements are assembled, installed, tested, and validated along with rigorous surveillance procedures in a nuclear plant for a period of 18,000 h.

1. Introduction

Significant quantities of special nuclear fissile materials such as ^{233}U, ^{235}U, and ^{239}Pu are handled in nuclear plants. These plants adopt ever-safe geometry, safe mass, safe concentration, and administrative controls. Still, there exists an extremely small probability of occurrence of criticality. Nevertheless, in view of the radiological consequences of such events in terms of large exposures to radiation workers, a criticality alarm system (CAS) [1–7] is used for prompt detection and alarm against such criticality events. The event could be a single excursion (10^{14}–10^{19} fission) or could be multiple events followed by self-sustaining chain reactions of various amplitudes in duration from 1 second to several hours [8]. The gamma and neutron doses from such events could be significantly higher, necessitating the immediate evacuation of the area by the occupants. Design of the CAS is meant for continuous operation such that it neither failed to detect even a single criticality event nor triggered a false criticality alarm due to system failure. However, failures associated with low voltage power supply, high voltage, system on battery, battery-charging/isolation diode, and single-channel alarm are found as a primary cause of system unavailability that can generate false criticality alarms. False criticality alarms not only create panic among radiation workers but also erode the credibility of the system, resulting in failure to promptly react to criticality alarms. The CAS suffers design deficiencies on diagnosis of dangerous detectable and undetectable failures. This work aims to enhance CAS design at each stage by means of early fault alarm announcement in the control room, *in situ* and *ex-situ* surveillance techniques for maximum availability, and prevention of false criticality alarms.

Presently, failure mode and effect analysis (FMEA) [9,10] is carried out on each element of the CAS to detect inherent dangerous faults and to develop early fault detection circuits for alarm announcement in the control room. In addition, a detailed review of our recent developments on design enhancement of the CAS is also presented. Two different methods are developed to ensure the functionality, one method for channel loop functionality test [11] and another method for dose alarm test using transient electronic pulse [12]. The design enhancements of the external systems that are integrated in the CAS include the power supply, criticality evacuation hooter circuit, radiation data acquisition system (RADAS) along with a selection of different soft alarm set points, and centralized electronic test facility [13]. The soft alarm is a user-defined level or a condition specified in the RADAS that enables visual indication without audio.

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2. Conventional CAS design

The CAS consists of three independent channels. Each channel contains an ionization chamber, preamplifier, and electronic module. The ionization chamber is a gamma-based detector, qualified for radiation tolerance of 10^3 Gy/h; it has a sensitivity of 3×10^{-8}A/Gy/h [7] for an operating voltage of 200–1000 V. The current signal from the detector is connected to the resistor-capacitor (RC) network for the equivalent output voltage. The output voltage is applied to the preamplifier for further amplification from 1 V to 5 V for the dose rate display of 0.01–100 mGy/h. The preamplifier is an integrated field-effect transistor based amplifier, and its output is connected to the electronic module. The electronic module consists of low and high voltage power supplies, processing electronics, display, and channel alarm relay contacts. Each channel is provided with class I (battery) power supply in case of mains failure. During the normal operation, the channel works on the low voltage power supply and provides a float charge on battery through a battery-charging/isolation diode. The front panel of each electronic module provides light emitting diode (LED) indications for normal operation, channel alarm with a beep sound, mains, and high voltage. An electronic test/reset facility is provided within each electronic module. A test voltage of 1 V is applied to the input stage of the preamplifier during the test. This provides an equivalent dose rate of 40 mGy/h on the display and a testing of the channel alarm. Fig. 1 is a block diagram of the CAS in which the alarm relay contacts from three electronic modules are connected to the alarm module. The alarm module generates a criticality alarm based on 2 out of 3 (2oo3) voting logic using a relay that operates in a fail-safe mode [10], i.e., the alarm relay deenergizes on criticality alarm condition. Maintaining this system with maximum availability and minimum false criticality alarm probability is a challenging task. CAS design is capable of detecting a minimum accident of concern of the accident mechanism. This is the one that will result in a dose of 0.2 Gy in the first minute at a distance of 2 m from the reacting material, assuming only nominal shielding [14–16]. The CAS initiates a channel alarm if the steady dose rate exceeds 40 mGy/h or if the integrated dose is delivered at 30 μGy due to criticality spike of duration within 500 ms.

Fail-safe behavior is the capability of any system or component to proceed to a predefined safe state in the event of a malfunction. In the CAS, triple modular redundancy with 2oo3 voting logic is used. It offers a balance between safety and reliability actions. To reduce the probability of failure on demand [17] of the CAS, there is a scope to reduce the failure rates associated with dangerous detected and undetected failures. The dangerous detected component is improved by selecting an appropriate configuration (fail-safe design) and by providing fault diagnostics of the system in case of a dangerous failure. The dangerous undetected component is reduced by improving the diagnostic coverage, periodic surveillance, and testability of the system.

3. Design enhancements in the CAS

3.1. FMEA of CAS

The FMEA [10] of existing CAS is carried out for potential failures of components/modules that may cause channel alarm at the system level considered. Based on FMEA, the elements that cause system unreliability and generate false criticality alarms are identified. Table 1 shows the FMEA of crucial elements in the CAS. The failures associated with the low voltage power supply in both electronic and alarm modules are dangerous but detectable. In case of low power supply failure to these modules, owing to the failure of the DC regulator, the battery-charging/isolation diode opens. If this is not noticed within 40 hours, the battery of the electronic module will be completely drained; the fail-safe channel relay, deenergized, will trigger the false channel alarm, and the channel will not be available.

Similarly, the high voltage power supply to the ionization chamber fails, and if it is not noticed immediately, the channel will subsequently not be available. If the channel battery fails, then channel availability is dependent on the uninterruptable power supply (UPS) backup. Similarly, failures in either ionization chamber or preamplifier cause unavailability of the channel. Channel loop functionality failure occurs because loss of integrity between the preamplifier, high voltage, detector, cables, and connectors. These dangerous undetectable failures cause channel unavailability. Failures of criticality evacuation hooter circuit will be detected immediately as this circuit is operated in a fail-safe condition. The communication bus, along with the RADAS, is used for data acquisition and logging. Failures of such systems will not affect the prime functionality of the system and trigger the criticality alarm. Based on the FMEA, two additional hardware circuits are developed, one for early detection of failures and another circuit for channel loop functionality test.

3.1.1. Development of early fault detection circuit

Based on the FMEA, an early fault detection circuit is developed for failures associated with low voltage, high voltage, system on battery, battery-charging/isolation diode, and single-channel alarm to alarm annunciation. The circuit contains two comparators, two driving transistors, and a two-pole relay. The circuit is designed based on fail-safe condition as any inherent faults require an announcement. The sampled high voltage is compared with the respective battery reference voltage using a level comparator (U1), as shown in Fig. 2. Similarly, the battery voltage is compared with the low voltage power supply reference using a level comparator (U2). The output of each comparator drives two independent transistors, and the circuit requires fine-tuning of reference voltages for the intended function. The output of the transistors is connected to the AND gate logic to drive a two-pole relay in fail-safe mode. This circuit is installed in each electronic module. A similar circuit is also used in the alarm module to detect failures of the low voltage power supply, the system on the battery, and the battery-charging/isolation diode. The NO contacts of each relay in all the electronic modules are connected in series and connected to the early fault detection circuit for alarm annunciation.

3.2. Method developed for channel loop functionality test

The ionization chamber, preamplifier, and high voltage/electronic module of the CAS channel are located geometrically at different places in the plant. The channel loop functionality [11,18] of the CAS channel is to be tested at periodic intervals to ensure its availability. The channel loop functional test method is developed based on creating a known perturbation in the high voltage applied to the ionization chamber during the

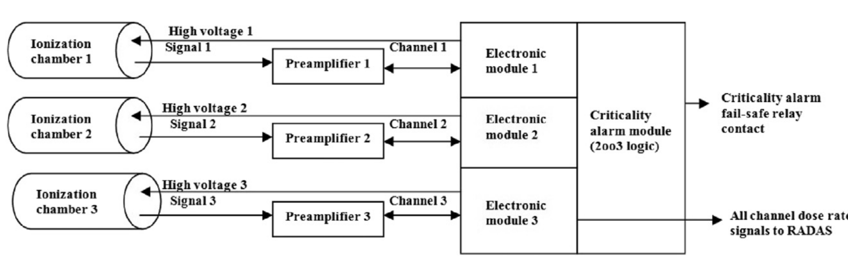

Fig. 1. Block diagram of the CAS.
CAS, criticality alarm system; RADAS, radiation data acquisition system.

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