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Original Article

Design and development of enhanced criticality alarm system for nuclear applications

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ABSTRACT

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

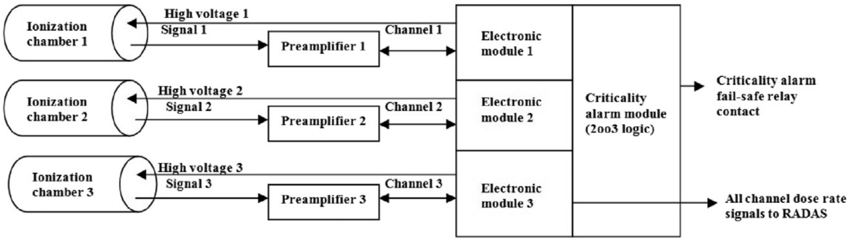


Fig. 1. Block diagram of the CAS.
CAS, criticality alarm system; RADAS, radiation data acquisition system.

Table 1
Failure mode and effects analysis of crucial elements in the CAS.

S. NO	FMEA Component	Potential failure mode	Potential cause(s)/ mechanism	Effects of failure	Probability (P) (estimate)	Severity (S)	Detection (Indications to operator and maintainer)	Detection dormancy period (D)	Risk level (P*S)+D	Mitigation/ Requirement
1. Detector	Ionization chamber	Detector fail	Gas leak/guard ring/ electrode fault	Channel fails to detect criticality	Remote (B)	Minor (III)	Detectable in quarterly surveillance	Quarterly surveillance	Low	
2. Preamplifier	Integrated FET amplifier	FET/Transistor/Zener diode fail	FET/Transistor/Zener diode Open/short	Channel fails to detect criticality/Channel alarm	Remote (B)	Minor (III)	No response in channel during test	Weekly (surveillance)/ alarm in CR immediately	Low	
3. Electronic module	Low voltage power supply	DC regulator fail/battery-charging/isolation diode open	Overheating/ component fail	No immediate effect, after class I battery drain (40 h), higher chance for channel not available and false channel alarm	Remote (B)	Minor (III)	After class I battery drain, higher chance of channel not available and false channel alarm	Within a shift/ weekly (surveillance)	Low	
	Class I	Battery failure	Battery open/No charging/fails to drive load	No immediate effect, after class II fails higher chance for channel not available and false channel alarm	Remote (B)	Moderate (IV)	After class II fails higher chance for channel not available and false channel alarm	Weekly (surveillance)	Low	
	High voltage	High voltage failure	High voltage transformer/ oscillator fail	CAS channel is not available to detect criticality event	Extremely unlikely (A)	Moderate (IV)	Indication in CAS	Within a shift (surveillance)	Low	The failures of low voltage, high voltage, system on battery, battery-charging/ isolation diode, and single-channel alarm shall be provided with an alarm annunciation in control room for immediate attention and action to prevent false criticality alarm. & A method is to be developed to test the channel loop functionality test for each channel.
	Channel loop	Detector/Preamplifier/ electronic module/cables and connectors	Loose contact/wrong connections/ component failures	CAS channel is not available to detect criticality event	Extremely unlikely (A)	Moderate (IV)	Indication in CAS	Weekly (surveillance) or during maintenance	Low	
	Single-channel alarm relay	Driving transistor open/ relay failure	Overheating, output transistor open/relay coil open	False channel alarm	Remote (B)	Minor (III)	Indication in CAS	Within a shift (surveillance)	Low	
4. Alarm module	Low voltage power supply	DC regulator fail/battery-charging/isolation diode open	Overheating/ component fail	No immediate effect, after class I battery drain, higher chance for false criticality alarm	Remote (B)	Moderate (IV)	After class I battery drain, higher chance for false criticality alarm	Within a shift/ weekly (surveillance)	Low	
	Class I	Battery failure	Battery open/no charging/fails to drive load	No immediate effect, after class II fails chance for false criticality alarm	Remote (B)	Moderate (IV)	After class II fails chance for false criticality alarm	Weekly (surveillance)	Low	
	Criticality alarm relay	Driving transistor open/ relay failure	Overheating, output transistor open/relay coil open	False criticality alarm	Remote (B)	Minor (III)	Indication in CAS	Immediately	Low	
5. RADAS	Communication bus	CAS channel connectivity fail	Cable fault/loose contact/digital I/O module	Alarm indication in the RADAS	Occasional (C)	Very minor (II)	Alarm in the RADAS	Immediately	Low	
	Server/software	RADAS server/ connectivity fault	Server/cable/ software problem	RADAS display is not available	Occasional (C)	Very minor (II)	RADAS display is not available/hanging	Immediately	Low	
6. Criticality evacuation hooter circuit	External hooters	Redundant hooter power supply	One power supply fail	No immediate effect	Remote (B)	Moderate (IV)	Indication on alarm annunciation	Immediately	Low	
		Individual hooter fail	Fuse fail/hooter fail	No immediate effect	Remote (B)	Minor (III)	Faulty hooter detected in weekly test, hooter LED fails to glow	Weekly (surveillance)	Low	
		Hooter relay failure	Relay coil open	False criticality alarm	Remote (B)	Minor (III)	Immediately	Immediately	Low	
7. Centralized electronic test facility	Electronic test	Channel failed to test/ reset	Mechanical problem/ human error	Channel test not possible/channel alarm	Remote (B)	Minor (III)	Immediately	Immediately	Low	
		CAS hooter bypass switch on	Mechanical problem/ human error	Hooters are not available during particular criticality alarm	Remote (B)	Minor (III)	Alarm in CR	Immediately	Low	

CAS, criticality alarm system; CR, control room; FMEA, failure mode and effect analysis; RADAS, radiation data acquisition system.

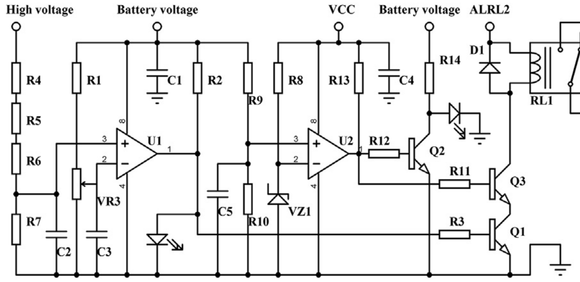


Fig. 2. Early fault detection circuit.

test. The dose rate response is compared with the predefined response of each channel. Based on the equivalent circuit of the ionization chamber, as shown in Fig. 3, it offers a current source I_1 in series with a capacitance (C_i) at zero background radiation. As soon as the high voltage is applied to the ionization chamber, voltage across the capacitance of the chamber gradually increases and fully charges within 5 time constants. Similarly, the charging current through C_i is at its maximum and gradually decreases to zero within 5 time constants. The current from the ionization chamber contributes a maximum dose rate of 100 mGy/h to the channel display for a period of 5–6 seconds. The current from the ionization chamber depends on the amplitude of the high voltage applied. This concept is used to test the channel loop functionality of the ionization chamber, the high voltage, the electronic module, the cables, and the connectors in each channel. The experiments are conducted for optimum test perturbation in the high voltage supply.

3.2.1. Development of channel loop and functional test circuit

Based on the experiments, channel loop and functional test circuits are developed. The circuit, containing a monostable multivibrator, two-pole relay, and driving transistor, is shown in Fig. 4. The output of the monostable multivibrator is a single-shot pulse with pulse width of 6 s; it is connected through a driving transistor to a two-pole relay. The relay pulls the primary winding of the high voltage blocking oscillator to lower the voltage from its normal value. The high voltage (typical 700 V) is instantly reduced to 620 V, subsequently reducing the electric field in the ionization chamber, which causes a reduction in output current due to the internal capacitance. As a result, the preamplifier output voltage is reduced from its normal value. The high voltage output automatically increases to its typical value up to 6 s. The charging current in the ionization chamber is increased instantly. The preamplifier output voltage increases more than the normal value and is restored after 10 s. Fig. 5 shows the test profile of the high voltage applied to the ionization chamber during the channel loop functional test. The channel loop functional test can be triggered manually using a spring-loaded key-operated switch mounted on the three electronic modules of the CAS. This is a more comprehensive system test to ensure the reliability of the CAS.

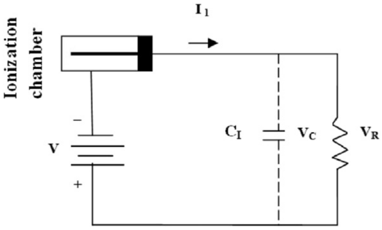


Fig. 3. Equivalent circuit for ionization chamber.

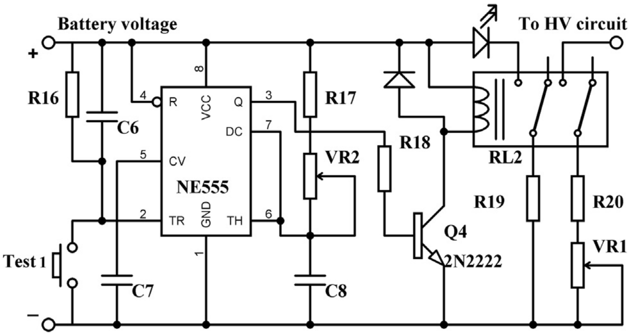


Fig. 4. Channel loop functional test circuit.

3.3. Method developed for dose alarm test

The CAS initiates a channel alarm if dose rate exceeds 40 mGy/h or if the dose exceeds 30 μGy within 500 ms. Dose rate alarm is tested using the standard ^{137}Cs or ^{60}Co radioactive source at the installed location of the ionization chamber. However, the dose alarm is tested using X-ray dose or similar radioactive source motion setup, which is practically difficult for installed detectors. The dose alarm test method is developed using an electronic transient pulse [7,12,19]; the sensitivity of the ionization chamber, the dose rate alarm set point, and the input one-Giga ohm resistance are considered. Location of test input is applied during the electronic and transient test as shown in Fig. 6.

The voltage developed across the one-Giga ohm resistance due to the sensitivity of the ionization chamber is 0.3 V per 10 mGy/h. The corresponding voltage at dose rate alarm (40 mGy/h) is 1.2 V. The dose alarm set point is 30 μGy/500 ms, and the equivalent dose rate is 216 mGy/h. The voltage for the dose alarm at 216 mGy/h is 6.48 V. The time (t) required to trigger the dose rate alarm at 1.2 V is calculated based on the transient response of the RC network, having a time constant (τ) of 2.2 s during charging.

$$t = -\tau * \ln\left[1 - \frac{\mathrm{Vin}(t)}{\mathrm{V0}(t)}\right] \tag{1}$$

Based on Eq. (1), the value of t is calculated and found to be 450 ms. Using a programmed pulse generator, the dose alarm of each channel is practically tested with the transient pulse of pulse amplitude 6.48 V and with pulse width varied from 300 ms to 600 ms. The status of the channel alarm corresponding to the preamplifier output voltage is captured in the oscilloscope. Similarly, the response of the dose rate at different pulse widths is also recorded in the RADAS.

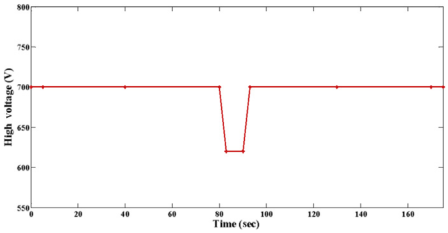


Fig. 5. The test profile of the high voltage applied to the ionization chamber during the channel loop functional test.

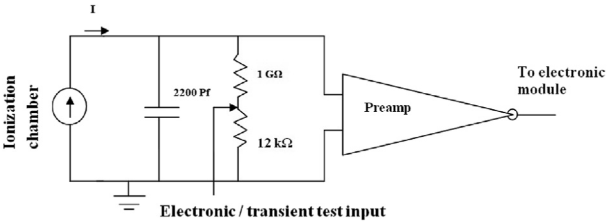


Fig. 6. Ionization chamber, RC network, and preamplifier circuit. Location of test input applied during the electronic and transient test.

4. Design enhancement of external systems for the CAS

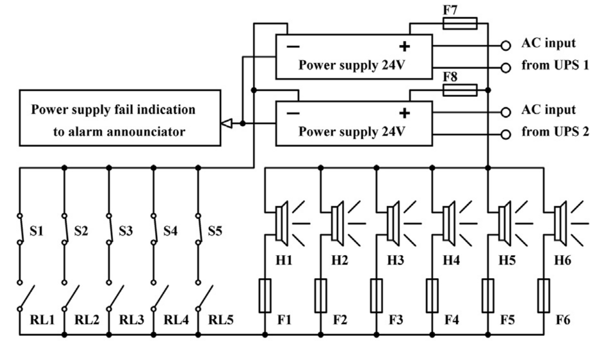
4.1. Reliable power supply to the CAS

Four different classes of power supplies are connected such that one acts as the backup to another power supply. To ensure reliable power supply to the CAS [13], each electronic module is provided with a class I (battery) power supply, which is connected from sealed maintenance free type lead–acid batteries. Class II (UPS) backs up the class I power supply. Similarly, class II is backed up by class III (diesel generator), and class III is backed up by the class IV (off-site) power supply. Each electronic module operates on DC power obtained from AC 230 V, 50 Hz through an AC transformer, rectifier, DC filter, and DC regulator output voltage. A dedicated double conversion–based online UPS is recommended for CAS loads; this device provides electrical isolation against surges. The DC voltage at the filter capacitor output is used to provide the float charge on class I batteries. This voltage is connected to class I batteries through a battery-charging/isolation diode; at this point, both power supplies are connected in parallel. Class I power supply is provided to three electronic modules and to the alarm module using independent batteries. For immediate attention, the fail-safe–based relay contacts are provided for both UPS input and output AC mains failure alarm announcement on the control panel.

4.2. Design of criticality evacuation hooter circuit

The criticality alarm fail-safe relay contacts from each alarm module of the CAS (considering five CASs in the plant, CAS1, CAS2…and CAS5) are multiplied using interposing relays. One pair of relay contacts are used to connect the alarm annunciation in the control room, and another set of relay contacts is used to activate the criticality evacuation hooter circuit in case of criticality alarm. This circuit is provided with redundant 24 V DC power supplies [13]. The inputs to the power supplies are connected from two different AC sources (UPS). The healthy status relay contacts (NO) of both 24 V DC power supplies are connected in series and routed to the alarm announcement in the control room in case of any fault in the 24 V DC power supplies. Fig. 7 shows that the output of the evacuation hooter circuit is connected to the distributed low powered high sound DC piezoelectric hooters with individual fuses for failure indication. Each piezoelectric hooter provides 120 dB sound at a one-meter distance. The advantage of distributed piezoelectric hooters is low power consumption and the provision of audio redundancy.

The series combinations of the fail-safe criticality alarm relay contact and the criticality evacuation hooter bypass switch of each CAS are connected in parallel with similar series combinations of other CASs. Similarly, the series combination of electronic hooter along with fuse failure indication is connected in parallel. These combinations are connected in series with redundant power supply. In case of a criticality alarm from any of the CAS, the criticality alarm relay deenergizes, NO contact becomes NC contact, and the criticality evacuation hooter circuit is triggered. In this design, it is ensured that the current rating of the criticality alarm relay contact provides sufficient current for number of electronic hooters in the loop. The criticality alarm relays in the CAS, the piezoelectric hooters, the criticality evacuation hooter bypass switch, the 24 V DC power supplies/fuse failure indications, and the alarm announcement are placed geometrically at different locations in the nuclear plant. The internal cabling between these components becomes very complex. The cable route will be diverse and must be properly labeled for easy identification.



CAS hooter bypass switches S1 to S5, CAS alarm relays RL1 to RL5 & Electronic hooters H1 to H5.

Fig. 7. Criticality evacuation hooter circuit.
CAS, criticality alarm system; UPS, uninterruptable power supply.

4.2.1. Criticality evacuation hooter bypass facility

The criticality evacuation hooter circuit [13] provides a bypass facility for any one of the CAS using a criticality hooter bypass switch (S1–S5) during preventive maintenance; other CASs will continue to be operated normally. Each hooter bypass switch is a two-pole key-operated switch installed on the control panel. One set of NC contacts are used to bypass the CAS from the evacuation alarm circuit, as shown in Fig. 7. Another set of NC contacts are connected in series and routed for alarm annunciation on the control panel. This is done to ensure that the bypass is restored after every preventive maintenance in the CAS.

4.3. Configuration of CAS with the RADAS

Fig. 8 shows the architecture of the RADAS along with one CAS. The voltage output signal (1–5 V) from each CAS, the preamplifier output, is connected to a digital I/O module to display the dose rate in the RADAS [20]. The digital I/O module is provided with galvanic isolation and no loading effect on the input signal. The digital I/O module converts analog voltage signals (dose rate) to corresponding digital RS-485 signals. The RS-485 signals are converted to transmission control protocol/internet protocol (TCP/IP) signals using an RS-485-TCP/IP converter. The

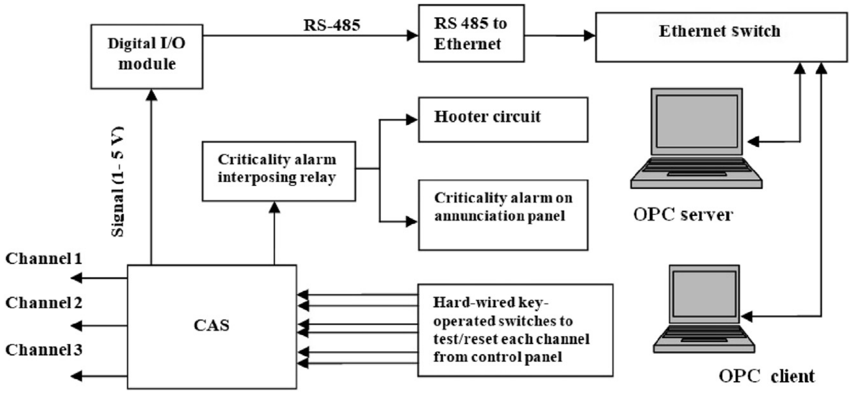


Fig. 8. Centralized electronic test facility, alarm annunciation, and RADAS architecture of CAS.
CAS, criticality alarm system; OPC, open platform communication; RADAS, radiation data acquisition system.

RADAS server communicates with the field devices through the Modbus protocol in TCP/IP. Table 2 shows the Modbus tags used for data communication to the RADAS in the control room. An open platform communication server and supervisory control and data acquisition (SCADA) software are installed in the RADAS server. The graphical user interface screens are developed in SCADA for each CAS channel dose rate, as well as in the bar graphs, soft alarms for each channel alarm, real-time graphs, historical trend graphs, and soft alert alarms for each channel. The channel soft alert alarms enable blue indication in the RADAS without audio. A soft criticality alarm indication is developed for each CAS in SCADA. All the CAS information is available on graphical user interface screens in real time, and these data are logged in the RADAS server for historical trend graphs.

4.4. *Validation of the RADAS for dose alarm*

The practical scan time of the RADAS is 0.5–1.5 s; in this case, some of the dose alarms are not recorded during the electronic transient test due to high scan time [21] if the dose rate of the soft alarm has its set point at 40 mGy/h for each channel in the RADAS. The RADAS must detect each criticality event without failure. An experiment is conducted with a transient pulse of 6.48 V amplitude and pulse width of 500 ms using a programmed pulse generator, which is applied to the preamplifier input and to the digital storage oscilloscope.

$$V0 = e^{-t/RC} \tag{2}$$

Based on the discharging characteristics of the RC network, as per Eq. (2), the total time taken to discharge the capacitor up to the equivalent voltage from the preamplifier output (1.5 V) of 10 mGy/h is found suitable for the dose alarm set point in the RADAS. The preamplifier output during capacitor discharge and channel alarm are reordered in the oscilloscope.

4.5. *Centralized electronic test and alarm annunciation*

Using key-operated switches from the control panel, three channels of each CAS are provided with independent hard-wired remote electronic test/reset for testing of the dose rate and the channel alarm, as shown in Fig. 8. During the test, 1 V test voltage is applied to the input of the preamplifier, and the corresponding channel dose rate is shown on the electronic module and open platform communication client personal computer in the RADAS. This test ensures the functionality of the preamplifier, electronic module, visual and audio alarms in each channel, real-time trend graph, and all soft alarms in the RADAS. Electronic test is also carried out periodically to test the 1 out of 3 (1oo3), 2oo3, and 3 out of 3 (3oo3) logics, the audiovisual criticality alarm, and the corresponding dose rate values recorded in the RADAS.

Table 2
Modbus tags used for data communication to the RADAS in control room.

Digital I/O Module				
Name	Modbus tag address	Data type	Client access	Scan rate (ms)
Channel 1	400001	Word	Read-only	100
Channel 2	400002	Word	Read-only	100
Channel 3	400003	Word	Read-only	100
Criticality alarm	400005	Word	Read/Write	100

RADAS, radiation data acquisition system.

5. Results and discussion

5.1. *FMEA of the CAS*

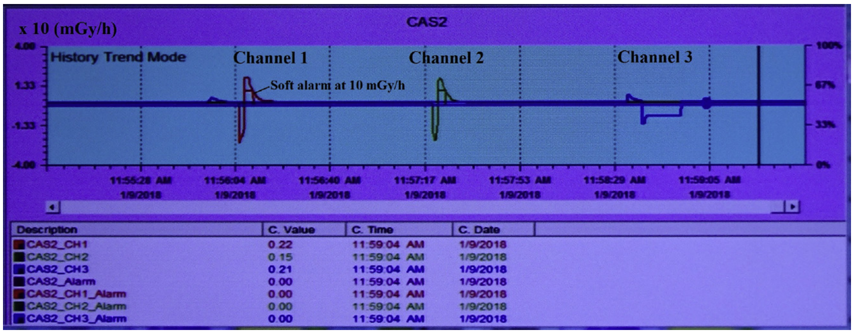
Based on FMEA, the critical elements that cause system unreliability and trigger false CAS alarms are identified. Failures associated with low- and high voltage power supplies, system on battery, battery-charging/isolation diode, and single-channel alarm are considered to develop on printed circuit boards. These printed circuit boards are tested, validated, and installed in the CAS for a common alert alarm annunciation in control room for immediate attention to prevent false criticality alarm.

5.2. *Channel loop functional test circuit output*

Fig. 9 shows the RADAS historical trend graph during the channel loop functional test for three channels of CAS. The responses of channels 1 and 2 show high voltage test profiles applied to the ionization chamber. As the high voltage is changed from 700 V to 620 V, reduced current flows from the ionization chamber due to its internal capacitance. The preamplifier output voltage becomes less than its normal voltage. Subsequently, the dose rate reaches a negative peak and then returns to zero. After 6 s, the high voltage is increased back to 700 V, the current from the ionization chamber is increased, and then the preamplifier output voltage becomes greater than normal voltage. The dose rate output generates a positive peak and then returns to zero. Similarly, the response of channel 3 is improper in shape concerning the pulse amplitude, pulse width, and timing. This is due to the inappropriate sensitivity and high voltage adjustments. The proper shapes of channels 1 and 2 indicate that the integrity of the ionization chamber, high voltage, preamplifier, cables, and connectors is intact and that the functionality of the channels is healthy. The soft alarm in each channel is also observed at 10 mGy/h. The channel loop functional test is *in situ* and is recommended as a final test during every maintenance work in the CAS because, to avoid human-related errors, it consists of three sets of similar cables and connectors.

5.3. *Dose alarm test using electronic transient pulse*

The transient pulse amplitude of 6.48 V with pulse width 500 ms is applied to the input of the preamplifier, and the channel alarm status



Description	C. Value	C. Time	C. Date
CAS2_CH1	0.22	11:59:04 AM	1/9/2018
CAS2_CH2	0.15	11:59:04 AM	1/9/2018
CAS2_CH3	0.21	11:59:04 AM	1/9/2018
CAS2_Alarm	0.00	11:59:04 AM	1/9/2018
CAS2_CH1_Alarm	0.00	11:59:04 AM	1/9/2018
CAS2_CH2_Alarm	0.00	11:59:04 AM	1/9/2018
CAS2_CH3_Alarm	0.00	11:59:04 AM	1/9/2018

Fig. 9. The RADAS historical trend graph during the channel loop functional test for three channels of the CAS. The responses of the channel 1 and 2 show high voltage test profiles applied to the ionization chamber. As the high voltage is changed from 700 V to 620 V, the dose rate reaches a negative peak and then returns to zero. After 6 s, the high voltage is increased back to 700 V, then dose rate output generates a positive peak and then returns to zero. Similarly, the response of channel 3 is improper in shape concerning the pulse amplitude, pulse width, and timing. This is due to the inappropriate sensitivity and high voltage adjustments.
CAS, criticality alarm system; RADAS, radiation data acquisition system.

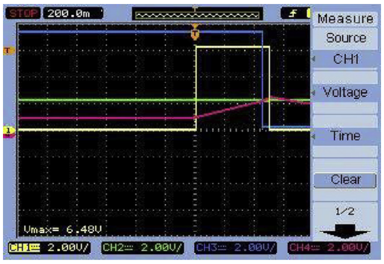


Fig. 10. Dose alarm test using transient pulse captured in the oscilloscope. The yellow color represents transient input test pulse with a pulse amplitude of 6.48 V and pulse width of 500 ms. The green color shows the equivalent voltage level of channel alarm at 40 mSv/h. The pink color represents the corresponding preamplifier output due to transient test pulse, and the blue color shows the channel alarm generation within 500 ms from the high logic level to the low logic level.

along with the dose rate is noted. Fig. 10 shows dose alarm test results obtained using transient pulse captured in the oscilloscope. The yellow color represents transient input test pulse with a pulse amplitude of 6.48 V and pulse width of 500 ms. The green color shows the equivalent voltage level of channel alarm at 40 mSv/h. The pink color represents the corresponding preamplifier output due to transient test pulse, and the blue color shows the channel alarm generation within 500 ms from the high logic level to the low logic level. As soon as the preamplifier output voltage reaches the alarm set point, the channel alarm is triggered within 450 ms; this is also equal to the theoretically calculated value as per Eq. (2). Fig. 11 shows the historical trend graph generated in the RADAS during the dose alarm test using a transient pulse. The pulse width of the test pulse varied from 300 ms to 600 ms, and as a result, there was a gradual increase in the dose rate. The dose rate alarm is initiated at 40 mGy/h in the CAS channel for pulse widths of 500 ms and above.

5.4. Centralized electronic test and alarm annunciation facility

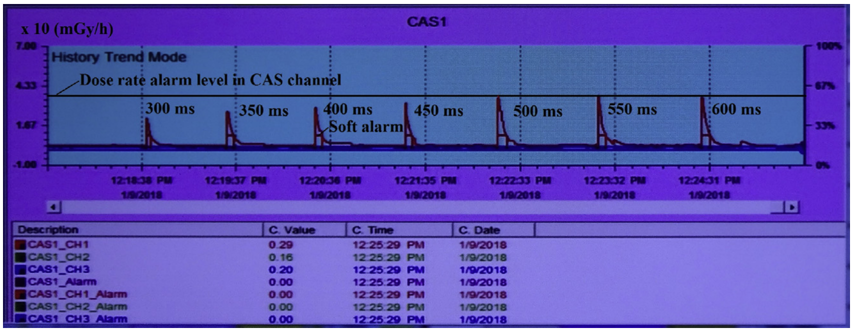
The electronic test was enabled on each channel of the CAS using the key-operated switch from the control panel. Fig. 12 shows the historical trend graph generated during the electronic test for the three channels as red, green, and blue colors. The test voltage of 1 V is applied to the input stage of the preamplifier to the three 1oo3 logic, independently, to test each channel dose rate and channel alarm. Similarly, testing is performed of all the combinations, including three 2oo3 and one 3oo3 logics, to generate the criticality alarm in the CAS and RADAS. The soft alarm in the RADAS for each channel is also observed at 10 mGy/h.

5.5. Selection of dose alarm in the RADAS

Dose alarm was initiated using transient input test pulse with an amplitude of 6.48 V and pulse width of 500 ms. Fig. 13 shows the discharge characteristics of the RC network captured in the oscilloscope to select the dose alarm set point in the RADAS. CH2 (blue) shows that the preamplifier output voltage during the discharge cycle up to 3.04 s is 0.5 V. This is equal to 10 mGy/h, which is selected as the dose alarm set point in the RADAS. CH3 (pink) shows channel alarm generation from high logic level to low logic level. In this case, no dose alarm is missed in the RADAS. A soft alert alarm set point is also provided at +4 mGy/h for each channel in the RADAS. These additional alarms alert the control room operator in case of any fluctuations in the dose rate beyond this level due to background radiation or drift associated with low voltage power supply, high voltage, etc.

5.6. Enhanced CAS design along with rigorous surveillance procedures

The CAS incorporated with all improvements are assembled, installed, tested, and validated in a nuclear plant for a period of



Description	C. Value	C. Time	C. Date
CAS1_CH1	0.29	12:25:29 PM	1/9/2018
CAS1_CH2	0.16	12:25:29 PM	1/9/2018
CAS1_CH3	0.20	12:25:29 PM	1/9/2018
CAS1_Alarm	0.00	12:25:29 PM	1/9/2018
CAS1_CH1_Alarm	0.00	12:25:29 PM	1/9/2018
CAS1_CH2_Alarm	0.00	12:25:29 PM	1/9/2018
CAS1_CH3_Alarm	0.00	12:25:29 PM	1/9/2018

Fig. 11. The historical trend graph generated in the RADAS during the dose alarm test using a transient pulse. The pulse width of the test pulse varied from 300 ms to 600 ms, and as a result, there was a gradual increase in the dose rate. The dose rate alarm is initiated at 40 mGy/h in the CAS channel for pulse widths of 500 ms and above.
CAS, criticality alarm system; RADAS, radiation data acquisition system.

Description	C. Value	C. Time	C. Date
CAS1_CH1	0.17	10:36:48 AM	1/9/2018
CAS1_CH2	0.19	10:36:48 AM	1/9/2018
CAS1_CH3	0.21	10:36:48 AM	1/9/2018
CAS1_Alarm	0.00	10:36:48 AM	1/9/2018
CAS1_CH1_Alarm	0.00	10:36:48 AM	1/9/2018
CAS1_CH2_Alarm	0.00	10:36:48 AM	1/9/2018
CAS1_CH3_Alarm	0.00	10:36:48 AM	1/9/2018

Fig. 12. The historical trend graph generated during the electronic test for the three channels as red, green, and blue colors. The test voltage of 1 V is applied to the input stage of the preamplifier to the three 1oo3 logic, independently, to test each channel dose rate and channel alarm. Similarly, testing, of all the combinations, is performed, including three 2oo3 and one 3oo3 logics, to generate the criticality alarm in the CAS and RADAS. The soft alarm in the RADAS for each channel is also observed at 10 mGy/h.
CAS, Criticality alarm system; RADAS, radiation data acquisition system.

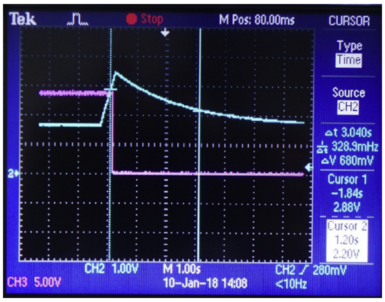


Fig. 13. Discharge characteristics of the RC network captured in the oscilloscope to select dose alarm set point in the RADAS. CH2 (blue) shows that the preamplifier output voltage during the discharge cycle up to 3.04 s is 0.5 V. This is equal to 10 mGy/h, which is selected as the dose alarm set point in the RADAS. CH3 (pink) shows channel alarm generation from high logic level to low logic level.
RADAS, radiation data acquisition system.

18,000 h. Rigorous periodic surveillance procedures are carried out on each channel of the CAS and on the class I batteries, class II power, RADAS, and other developed circuits, daily, weekly, quarterly, and yearly for maximum availability. Therefore, the system is found to operate consistently with no false criticality alarm. The design enhancements are compatible with the intended application.

6. Conclusion

In this work, development of enhanced CAS design for maximum availability and to prevent false criticality alarms is presented. The early fault detection circuit is developed for immediate attention to prevent false criticality alarm. Methods for channel loop functional test and dose alarm using transient electronic pulse are developed to ensure the functional availability of the CAS. Design enhancement is also performed for the external systems that are integrated with the CAS. Based on studies on the discharging characteristics of the RC network, the total time taken to discharge the capacitor up to 10 mGy/h is found to be 3.04 s. The voltage equivalent of 10 mGy/h dose rate output is selected for the dose alarm set point in the RADAS. A soft alert alarm set point is also provided at +4 mGy/h for detection of fluctuations in each channel. Rigorous periodic surveillance procedures are carried out for maximum availability of the system. The CAS incorporated with all improvements are assembled, installed, tested, and validated in a nuclear plant for a period of 18,000 h. Therefore, the system is found to operate consistently with no false criticality alarm. The enhanced CAS designs are compatible with the intended application. For higher reliability and stability, advanced electronics such as field programmable gate arrays are to be used in place of discrete electronic components.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.01.022.

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