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RADIATION MONITORING SYSTEM UPGRADE FOR THE NBSR

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1. ABSTRACT

The Radiation Monitoring System (RMS) at the NIST Center for Neutron Research (NCNR) Reactor (National Bureau of Standards Reactor – NBSR) has demonstrated reliability issues due to outdated hardware and lack of vendor support. The existing radiation monitors communicate to a controller in the control room, which then displays an LCD segmented display to operators. If the value is over its pre-defined threshold, the machine actuates an annunciator to indicate an unsafe condition.

Over time, multiple RMS devices have gone out of commission, being unable to communicate with the centralized controller, and localized monitors had to be used to monitor area radiation safety. The original manufacturer of the system has since gone out of business and attempts to repair and replace broken components have been fruitless. It is due to these reasons that a new system has been engineered using modern control and communication systems integrated into the NBSR Control Console Upgrade.

Keywords: Radiation Monitoring; Ethernet communication; Modbus; Fault Mode; Effects; and Analysis; Analog to Digital Upgrade

2. NOMENCLATURE

ARM	Area Radiation Monitor
DAQ	Data Acquisition
DCS	Distributed Control System
ECR	Engineering Change Request
ECN	Engineering Change Notice
FMEA	Fault Mode, Effects, and Analysis
FSAR	Final Safety Analysis Report
HMI	Human Machine Interface
IAEA	International Atomic Energy Agency
I/O	Input/output
MHA	Maximum Hypothetical Accident
MTBF	Mean Time Between Failure
NBSR	National Bureau of Standards Reactor
NCNR	NIST Center for Neutron Research
NIST	National Institute of Standards and Technology
PLC	Programmable Logic Controller
RMS	Radiation Monitoring System
RSS	Reactor Safety System
SCADA	Supervisory Control and Data Acquisition
TID	Total Ionizing Dose
UDR	Universal Digital Ratemeter

3. INTRODUCTION

The maintenance and modernization of the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) reactor, known as the NBSR reactor, is an ongoing process to endure until the eventual decommissioning of the reactor. Within the operation of the NBSR, the Reactor Safety System (RSS) is tightly connected to reactor control and operation. One of the most important safety instruments is the Radiation Monitoring System (RMS), which is an integral part of reactor control and the RSS.

The purpose of the RMS at the NCNR is to detect high gamma and beta radiation levels within specific areas of the building and different reactor process systems. The RMS is crucial to the safety of NIST employees and the public because it provides safety actions and alarms when hazardous levels of radiation are detected. For instance, the ARMs may give the first indication of a radioactive release resulting from an experiment or a reactor malfunction.

Existing radiation monitors and their respective human-machine interfaces on the console are difficult to maintain.

A new acquisition was completed from 2019 through 2021 to acquire 12 new ARMs with a new DAQ HMI and calibration equipment. Consequently, the RMS as a whole is being upgraded, including all associated monitors and their control room display and alarm systems.

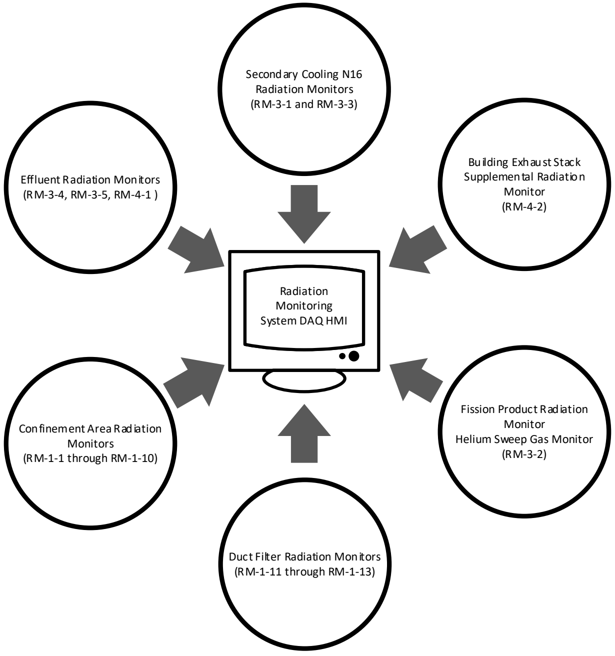

FIGURE 1: RMS SUBSYSTEM FLOW DIAGRAM

4. SYSTEM DESIGN CONSIDERATIONS

In this section, we will discuss the system parameters that informed our choices for the RMS upgrade components and design. By staying true to these guidelines for parts and design, our overall system will similarly hold to these values. The designers decided on these parameters to ensure long-term and effective engineering controls.

4.1 Digital Infrastructure

As the market advances, there has been a trend to upgrade from analog devices to digital versions. While the primary justification for upgrading the radiation monitoring system is to ensure that replacement components and devices are commercially available, the upgrade to digital infrastructure offers further advantages over analog, making this upgrade an even more attractive option.

4.1.1 Fidelity

Digital signals are more resistant to noise and other electromagnetic interferences (EMI) when compared to analog signals. While EMI can potentially cause false or missed messages, the capability of this type of interference on digital signals is significantly less likely than on a similar analog signal. This is due to the mechanism by which digital signals are created, as the ability for EMI to “impersonate” or “mask” a bit in a message is incredibly unlikely. In an analog signal, EMI can change the measured value proportionally to the amplitude or intensity of the EMI applied.

4.1.2 Distance

Digital signals are the preferred methods for signal propagation over long distances due to their nature of discrete values. Analog signals are prone to voltage drops across very long cable runs, making use complicated at best.

4.1.3 Fault Detection

Using digital signal processing, the probability of error occurrence can be reduced by employing error detection and correction codes. The most prevalent example in this project is Modbus TCP/IP communication, which employs multiple levels of message structure sequencing to ensure that the entire message is correctly transmitted and received.

4.1.4 Security

Digital signals can be routed through network firewalls and software data diodes to ensure that only preapproved messages are transmitted in the direction specified.

4.1.5 Maintainability

Digital controllers offer greater flexibility for modifications to be made compared to analog systems. A digital controller can be programmed, either as a PLC or DCS, whereas an analog system would require circuit redesigns or other adjustable components.

4.1.6 Cost and Market Justification

Due to the reasons stated above, the overall market is trending towards replacing analog devices with digital ones. The density of transistors on a single chip has increased dramatically, making even the most complicated analog processors simple and cheap to implement on a digital device.

4.2 Robustness and Reliability

The hardware used for all upgraded devices have been chosen for their excellent Mean Time Between Failure (MTBF). Digital recorders have a MTBF of 30.7 years. The IO modules and extensions for the recorders have more than 50 years of MTBF. The WESCHLER digital meters are built as nuclear grade and use firmware qualified to 10CFR50 APP. B & 10CFR21 and carry a lifetime warranty.

4.3 Redundancy

The primary display for measured sensor values and historical trendlines is on a screen developed on a trending recorder. The measured area radiation levels are displayed on a mimic screen developed by Fluke Biomedical. Three Weschler nuclear-grade digital meters display the levels and scram parameters of the effluent monitors. The loop signal is provided in series to each piece of equipment. Trending recorder and mimic displays employ separate, isolated I/O units to acquire readings. Digital meters use internal I/O circuitry to gather readings.

4.4 Diversity

Digital components with different firmware and make are interchangeably used in the system. Hardware used in the RMS provides functional, software, and equipment diversity for displaying sensor information and actuating associated alarms.

4.5 Defense-in-depth

Process parameters are displayed on a mimic screen and a trend screen both provided by two independent systems. The Confinement Area Radiation Monitoring HMI, digital meters, and digital recorder are isolated from each other preventing single-point common cause failures. Any of these devices failing does not affect the others for signal, power, or relay actuation.

4.6 Modularity

Configuration files for the digital trend recorder, industrial Fluke® HMI, and digital meters, are saved on a subversion system. The components can be easily hot-swapped with minimal impact and testing. Connections to the process are made by plug-and-play type terminals, like DB9, RS485, or RJ45 connections.

While in normal operation, the monitoring system will display current readings of instrumentation within the NBSR Radiation Monitoring System. Trending data will be available for the operators to scan back up to a week with data points stored at 0.5-second intervals. The system does not have any control functionality, and therefore does not involve any automatic or manual switch. The system provides protective actions by redundant relays actuating scram and annunciators depending on the device being monitored.

4.7 Configuration Management

The RMS components are configured, calibrated, tuned, and modified through several levels of security and physical access requirements. Only visual and computational changes are allowed for the digital recorders through the network, or via physical access along with username-password combinations. Three levels of user privileges limit the ability to make changes in the system. Recorder firmware changes require administrative user access along with the physical intrusion of a memory disk into the hardware. The digital meters are isolated, meaning they are not connected to any other system through a network or other means. These digital meters can only be configured using a PC by physically connecting an RS-232 cable. Hence, in normal operation, it is not possible to make configuration changes to the digital meters. Digital recorders and a Unix data collection computer are within a protected network inside an isolated subnet. To ensure cyber-security, the RMS is connected to the outside research network over a physical one-way data diode system.

4.8 System Sizing

Spare parts for the radiation monitors, digital recorders, HMI, digital meters, and I/O modules are kept on-site. The latest configuration settings are stored in a protected subversion system. Technicians would replace broken parts with minimal testing and work by disconnecting broken hardware. All hardware is modular and connected via quick disconnects to the terminal strips. No cable replacement is necessary when replacing hardware.

4.9 Software

The RMS system utilizes commercial off-the-shelf digital meters and digital recorders to perform data display, acquisition, and alarming functionality. These units come with firmware installed, tested, and verified by the manufacturer. Configuration changes made by the NBSR engineers and technicians are recorded on a subversion system for version control. Configuration changes on the HMI require the individual to log in as an administrator, upload the updated version of the SCADA program onto the local PC drive, then start the development application to build and run the new program. These changes are likewise to be recorded on a subversion system for version control.

Digital recorders and digital meters are then tested for accurate display, alarm, and failures following the standard NBSR digital system test procedure. Unauthorized changes to the configurations and/or firmware are prevented by multiple mechanisms, including physical and air-gap barriers, and all changes are logged. It is not possible to make firmware or configuration changes on digital meters without the installation of a physical cable and a laptop. Digital recorders require administrative authentication and physical installation of an SD card to change the firmware.

4.10 Cybersecurity Considerations

The system connects some control console devices that were previously un-networked. If one device on that network is compromised, the concern is that the device would then have the capability to compromise other devices on the network.

To prevent an outside malicious programmer from having any means to directly access the RMS system, the Reactor Network is a private network with no connection to the internet. Also, there is no means to accidentally connect the reactor network to the internet as all of the devices on the network are configured to static private network IP addresses. To enforce further protection, the reactor network is configured such that all traffic must pass through a Modbus Read-only firewall. This firewall only allows properly formatted Modbus read requests and Network Time messages to pass through it. All other network traffic is stopped by the firewall.

Physical security is one of the lowest-hanging fruit when evaluating a plant's cybersecurity program. To further avoid unauthorized access to the SCADA PC, users are advised to:

1. Perform a hazard and risk analysis that considers all hazards resulting from access to (and operation on) the network/Fieldbus and develop a cyber security plan so.
2. Verify that the hardware and software infrastructure that the Box is integrated into (along with all organizational measures and rules covering access to the infrastructure) consider the results of the hazard and risk analysis and are implemented according to best practices and standards such as ISA/IEC 62443.
3. Verify the effectiveness of the IT security and cyber security systems using appropriate, proven methods.
4. Keep your system up to date (security patches).
5. Keep your antivirus up to date.
6. Define properly the security of the Box: access rights, and user's accounts. Ensure that the minimum access rights are given to users to avoid illegal access or too much privilege given to the user.
7. Limit access to only needed information and users.
8. Utilize anti-virus protection software.

Cyber security features available on the SCADA PC:

1. The SCADA architecture is based on the operating system.
2. BitLocker in collaboration with the TPM module is used to secure the hard disk and provide full encryption of the disk.
3. The integrity of the operating system is also checked by UEFI (Extensible Firmware Interface) mechanism that ensures that the OS is the official one.

5. RESULTS AND DISCUSSION

5.1 Area Radiation Monitor Components

Below is a discussion of the choices that were ultimately decided on for the RMS upgrade design.

5.1.1 Fluke Detector

This is a mid-range GM detector capable of measuring the radiation within the range of 0.1 mR/h to 10 R/hr. The detector electronics are rated for a Total Ionizing Dose (TID) of 10000 Rad. The cable is rated for a TID of 1E+07 rad. The GM Detector is factory calibrated on a Cs-137 range. A ± 20%, 8-point, NIST-traceable factory calibration, procedure, CAL-GM6, is performed to obtain a calibration factor and dead time correction factor (Tau) for the detector.

The detector contains an internal check source, which is one of the deciding factors for the NCNR. The device can be commanded to perform a source check test, which verifies that the detector reads expected radiation values and alarms as expected. This is a function that is required as part of NBSR operating procedures.

5.1.2 Fluke Ratemeter

The Universal Digital Ratemeter, or UDR, monitors several equipment failures conditions, such as Detector failure, Detector over-range, and microprocessor failure, that can produce a FAIL alarm and, in some cases, an error message. The "failed" condition is true whenever any equipment failure is detected and false when no equipment failures are detected. When a failure condition occurs, other than power failure, the green light tower LED turns off, and the failed relay coil de-energizes. To return the channel to normal operation after a FAIL alarm, the condition that caused the alarm must be located and corrected. Upon correction of the failure condition, the FAIL alarm will automatically clear and the green light tower LED illuminates. UDR is rated for a TID of 3000 to 4000 rad, based on the most limiting component, which is N-type low-power MOSFETs.

5.2 Data Acquisition and Display Components

5.2.1 SCADA HMI

The SCADA HMI device is made up of two main components, a touchscreen display module, and a Windows-based industrial computer. The MTBF of the main board of the PC, the component of the device that is quickest to fail, is about 28.9 years according to the manufacturer.

The display module also complies with the following standards:

- Underwriters Laboratories Inc., UL 62368-1, and CSA 62368-1 (Audio/Video, Information and Communication Technology Equipment).
- RCM and EAC. Refer to product markings.
- Federal Communications Commission, FCC Part 15, Class A
- WEEE, Directive 2012/19/EU
- RoHS, Directive 2011/65/EU, and 2015/863/EU
- RoHS China, Standard GB/T 26572
- REACH regulation EC 1907/2006

In the case of an application crash or freeze, the software is designed to be immediately recoverable via a power cycle of the Supervisory PC. In the case of a hardware failure, the device is designed to be quickly replaced with a spare and sent to the manufacturer for a diagnosis and, if applicable, a Return Merchandise Authorization (RMA).

In the case of computer and screen hardware failures, the Supervisory PC also comes equipped with an application named System Monitor 3.0, which provides remote monitoring. Remote monitoring also supports function logs and sends notifications and creates entries in the Windows Event log.

5.2.2 Digital Trend Recorder

Selected process parameters are displayed on a trending digital recorder. Operators can analyze current, as well as past trends for all or selected parameters. The trending recorder uses individual I/O modules to gather parameter readings and displays as shown in FIGURE 2. Each point to be trended displays its tag name and its value in engineering units. Other than the default display, operators can perform analysis of historical trends, and review alarms only after authentication by entering a username and password.

The alarm list provides a detailed description of the event or the tag name if applicable, low/high details, and a timestamp. By default, the trend screen provides historical data spanning the last 30 minutes. Operators are not authorized to make any permanent changes to the recorder. It would display these parameters when needed on a different view accessible through recorder buttons.

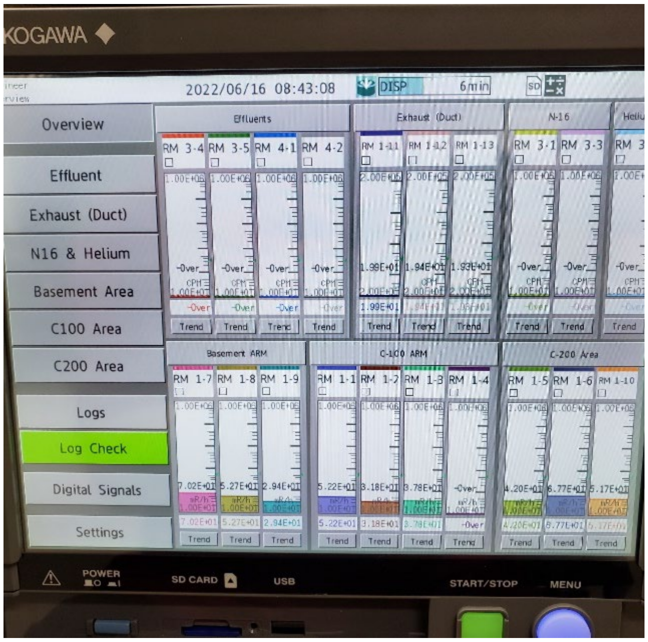

FIGURE 2: TRENDING DATA RECORDER MAIN DISPLAY

The MTBF for digital recorders is 30.7 years. Digital recorders also have a separate relay for failed output, actuated whenever a CPU failure has happened. “The relay is energized when the CPU is normal and is de-energized when a CPU error occurs. Therefore, a relay output is carried out also when the power is off (including a power failure).” (Yokogawa Electric Corporation, 2014).

The digital recorders employ advanced security functionality, and as configured within the RMS system, none of the possible threats are to be considered practically possible to cause any damage or prevent normal operation. The recorders support SA US 172608, UL61010-1, and UL61010-2-030.

5.2.3 Bar Graph Meters, Nuclear Safety Related (Service 1E) Indicator

The bar graph meters were chosen specifically for their use in commercial nuclear power plants. Power plants have different regulatory requirements than research reactors such as the NBSR, and the devices that are employed at power reactors meet and exceed requirements for devices to be employed at research reactors. The bar graph meters are used only for the effluent monitors which initiate a major scram, the only automatic safety action of the entire RMS upgrade. As such, this system and its components must have as much reliability as reasonably achievable. To improve the reliability, diversity, and defense-in-depth of this subsystem, the alarm output of the bar graph meter has been connected in series to the alarm output of the digital recorder as described above, meaning if either device detects an over-threshold reading, a major scram will initiate. This prevents a common-cause failure to propagate into a failure to scram in the case of an accident.

5.3 Duct Filter Monitor Components

5.3.1 Thin wall beta-gamma detector

The thin-wall beta-gamma detectors are replacing the NRC MD 12-I Geiger-Mueller tubes used for duct filter monitoring, which have reached end-of-life. These tubes match the existing NRC GM tubes closely in terms of geometry and response characteristics. These devices are set to alarm when detecting a 10x increase in background radiation, which means that the replacement tubes do not need to exactly match all response characteristics. The new tubes have an MTBF of 5 x 10^{11} counts. Using an average count per minute of 13617 counts per minute, calculated over a year (between June 2020 to May 2021) from the recorded readings from the prior GM tubes, the tubes have an expected lifespan of 1,676 years, which indicates that these devices are unlikely to fail when operating in a standard environment.

5.3.2 Counter Module

The counter module interfaces with the duct filter monitor detector tubes (Thin wall beta-gamma detector explained in 5.1.6). The module provides high voltage to each of the detectors via a BNC connector and then transmits the counts' value via RS-232 serial communications to a PLC for further transmission.

5.3.3 Communications PLC

The communications PLC is used to read the RS-232 signal generated by the 3-Channel Counter Module and convert that signal into counts per minute that are transmitted via Modbus ethernet to the digital recorder in the control room. The digital recorder in the control room handles the display and annunciator activation. The PLC's MTBF is estimated at 101,000 hours, which translates to about 11.53 years.

5.4 Alarm System

Process alarms are assigned for every device in the Radiation Monitoring System save for the supplemental stack monitor. Further, scram actions are actuated by two relay outputs, the digital recorder, and the bar graph meter. The recorder and the HMI maintains an alarm summary providing a time of occurrence, tag name (if applicable), and type of alarm (high-low, etc.).

5.5 Implementation Challenges

Designing the system to the same minimum specifications as the original system, to reduce the need for a time-consuming license amendment, also proved to be a difficult challenge. There are many standards and specifications that are simply not applicable to modern-day components, and as such the designers had to uncover the underlying mechanics and system needs that informed those choices. As to be expected from a well-aged system such as the one at the NBSR, documentation on these mechanics and needs is sparse and difficult to come by. Particularly with the system response timing, as discussed in section 5.4 System Response Timing, the underlying mechanic to balance is dose to employees and dose to the public. As long as our design meets or reduces the expected dose to employees and the public as defined in the MHA of the FSAR, the designers can state that the upgraded design is apt for the replacement of the existing analog system.

5.6 System Response Timing

The RMS replaces systems in the control console which actuate alarms and scram signals. To ensure that the RMS maintains a safe response profile, the individual detector circuits have been analyzed below. The start point of the circuits is measured by the detectors themselves picking up a response, and the endpoint is the annunciator (or scram signal where appropriate) actuating. Track A is the current functional path of the detector, while track B is the proposed functional path.

The input to all tracks is a step increase from baseline radiation to the threshold radiation which would trigger an alarm. In most cases, this means that it would take a minimum of 60 seconds to detect the unsafe change in the radioactive environment and start the annunciator or scram process, as the CPM is an average taken over a minute window.

To evaluate the sensors more fairly, a second track has been analyzed with arbitrary input. This input is such that the CPM average is immediately high enough to trigger an alarm on its next cycle. This track is noted in the bottom rows of the tables below, separated by a double line.

The raw time delta is noted as the time of track B minus track A. This value has been used to calculate the percent change from track A going to B as Delta divided by track A.

5.6.1 Manual Action

Most of the detectors in the RMS do not have any automatic actions (i.e. Scram) associated with them. It can be assumed that the time between a sudden radiologically unsafe environment and an operator performing the steps in their associated annunciator procedure is most greatly affected by the time it takes for an operator to notice and act on the signal, which is on the order of seconds. This is downstream in the timeline of events and dwarfs the response time of the individual sensors, which is on the order of milliseconds usually. As such, the system response timing of these items is less important than the sensors with Automatic Actions, laid out below in section 5.4.2.

5.6.1.1 Area Radiation Monitors

The Confinement Area Radiation Monitors actuate in two distinct ways: a local alarm and a remote alarm. The local alarm informs individuals in the immediate area of an unsafe radioactive environment and is outlined in **TABLE** 1. The remote alarm signals to the Reactor Control Room that an area has been declared an unsafe radioactive environment, which then begins the requisite annunciator procedure, a procedure that operators use in response to an annunciator and is outlined in **TABLE** 2.

Both functions are performed by different devices in the current configuration of the reactor. The proposed system would perform both functions simultaneously.

TABLE 1: AREA RADIATION MONITOR LOCAL BREAKDOWN

Device Track	**Total Time to Action**	**Δ time (msec)**	**Δ time (%)**
A – Dora Ratemeter and detector	72 – 75	---	---
B – Fluke Ratemeter and Detector	72	0 to -3	-4.0%
A – Dora Ratemeter and detector	12 – 15	---	---
B – Fluke Ratemeter and Detector	12	0 to -3	-25.0%

TABLE 2: AREA RADIATION MONITOR REMOTE BREAKDOWN

Device Track	Total Time to Action	Δ time (msec)	Δ time (%)
A – NRC Detector and Ratemeter	67 – 70	---	---
B – Fluke Ratemeter and Detector	66.2	-0.8 to -3.8	-5.3%
A – NRC Detector and Ratemeter	7 – 10	---	---
B – Fluke Ratemeter and Detector	6.2	-0.8 to -3.8	-11.4% to -38%

5.6.1.2 Duct Filter Monitors

The existing exhaust monitors communicate to the control console via an RS485 circuit to the TA-3 (V30) NRC ratemeter housed on the console. These monitors have no local alarms.

TABLE 3: EXHAUST MONITOR ALARM ACTION BREAKDOWN

Device Track	Total Time to Action	Δ time (msec)	Δ time (%)
A – GM Tube and Ratemeter	65	---	---
B – Counter Module, Omron PLC, Recorder	65.6	+0.6	+ 0.9%
A – GM Tube and Ratemeter	5	---	---
B – Counter Module, Omron PLC, Recorder	5.6	+0.6	+ 12%

5.6.1.3 Helium Sweep Gas Radiation Monitor and Secondary Cooling N16 Radiation Monitor

These devices are connected directly to an annunciator via the DRM 200A ratemeter's digital output. The proposed design reroutes the digital output from a GX-20 recorder instead.

TABLE 4: FISSION PRODUCT AND N16 MONITOR TIMING TABLE

Device Track	Total Time to Action	Δ time (msec)	Δ time (%)
A – Direct Output	65	---	---
B – GX-20 Recorder	65.6	+0.6	+ 0.9%
A – Direct Output	5	---	---
B – GX-20 Recorder	5.6	+0.6	+ 12%

5.6.2 Automatic Actions

Automatic actions in this case refer to Scram/Major scram actions. The only sensors in the RMS system that actuate a major scram are the Effluent Monitors. As such, their timing will more readily affect the protective systems of the reactor, and their design is to reduce the response time of these sensors to around or below the system response time of the existing devices.

5.6.2.1 Effluent Monitors

The existing effluent monitors connect to both the annunciator and scram circuits directly from their respective ratemeter's alarm relay output. The proposed system will utilize the alarm relays from the GX-20 recorder (track B.1) and a nuclear-grade digital bar graph meter (track B.2) in parallel. If either of these devices are tripped, both the annunciator and scram circuits will activate.

The delay in the circuitry of the proposed system is negligible when compared to the latency of the existing effluent monitoring systems, as analyzed below. The time delta shows a considerable decrease in the time to action for the effluent monitors. As such, there is no increased risk of significant release of radioactive contaminants.

TABLE 5: EFFLUENT MONITOR TIMING TABLE

Device Track	Total Time to Action	Δ time (msec)	Δ time (%)
A – Existing Design	71	---	---
B.1 – GX-20 Recorder output	63.7	-7.3	-10.3%
B.2 – BG2 Relay output	64.3	-6.7	-9.4%
A – Existing Design	11	---	---
B.1 – GX-20 Recorder output	3.7	-7.3	-66.4 %
B.2 – BG2 Relay output	4.3	-6.7	-60.9%

5.7 Reliability Analysis

To ensure that the design meets reliability expectations for the NCNR, a systems analysis was created. The system was broken down into subsystems, the control panel, area radiation monitors, duct filter monitors, and effluent monitors, and those subsystems were broken down into their components. A chart is then created to break down how a component failure propagates through the system, and the equations below are used to calculate a reliability index per component. Equation (1) demonstrates the relationship between Mean Time Between Failure, MTBF, which is a standard value reported on data sheets, and the lambda constant that is used in our equation (2). This is assuming a constant failure rate and an exponential distribution.

$$MTBF = \frac{1}{\lambda} \tag{1}$$

$$R_i = e^{-\lambda_i t} \tag{2}$$

Systems can be modeled as a network of two types of component relationships, serial and parallel. In a serial network, devices are fed sequentially from outputs to inputs. In this system, if any device fails, the result is a failure of the system. The reliability index of the system can be calculated through a product of the individual reliability indices, or e raised to the sum of the λ calculated in expression (1) multiplied by time, as shown in equation (3).

$$R_{serial} = \prod_{i}^{n} R_i = e^{-(\sum_i^n \lambda_i)t} \tag{3}$$

In a parallel network, with active redundancy assuming independence, the functional pathway of data transmission is split among multiple branching devices. In industry, this is commonly referred to as “adding redundancies”, whereby if a single device fails, the plant still has another path by which the entire system does not enter a failed state. Each of these paths has its reliability indices, and the total system reliability index can be calculated through equation (4).

$$R_{Parallel} = 1 - \prod_{i}^{n} (1 - R_i) \tag{4}$$

An entire system is rarely a purely serial or parallel network. However, components can be grouped to create a subsystem that acts as a stand-in for the devices in another equation. The strategy is identical to the one employed by electrical engineers to find circuit impedances through various serial and parallel relationships.

5.7.1 System Design and Analysis

By using these equations, we can plot the reliability curves for the listed subsystems of the Radiation Monitoring System over months. Of the 10 radiation monitors, they can be grouped by the area in which they operate: C100, C200, and Basement. Further, the duct filter and effluent monitors have been evaluated to ensure their change in system configuration is as reliable as the current design. Their reliability diagrams have been depicted in the figures below.

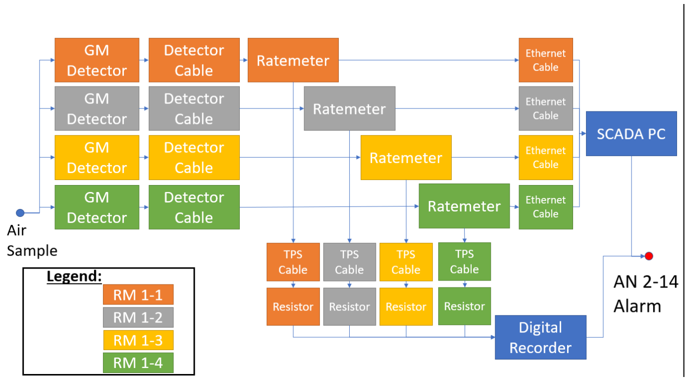

FIGURE 3: C100 ARMS

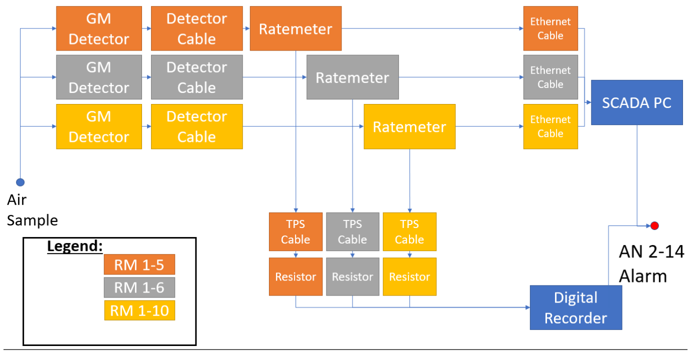

FIGURE 4: C200 ARMS

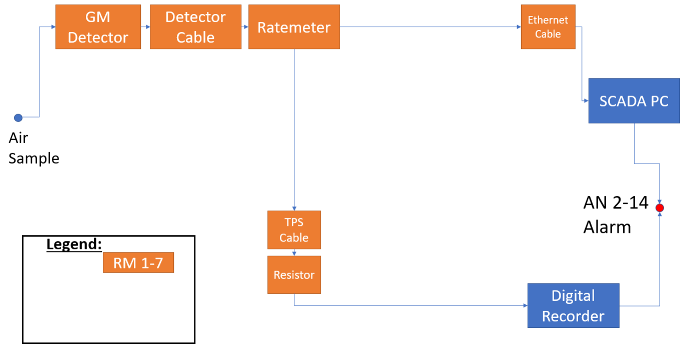

FIGURE 5: BASEMENT ARMS

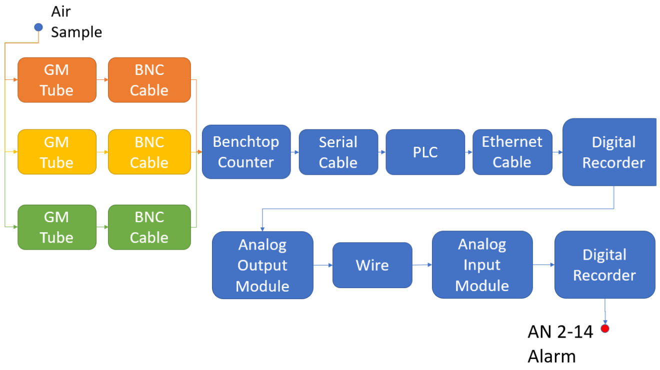

FIGURE 6: DUCT FILTER MONITORS

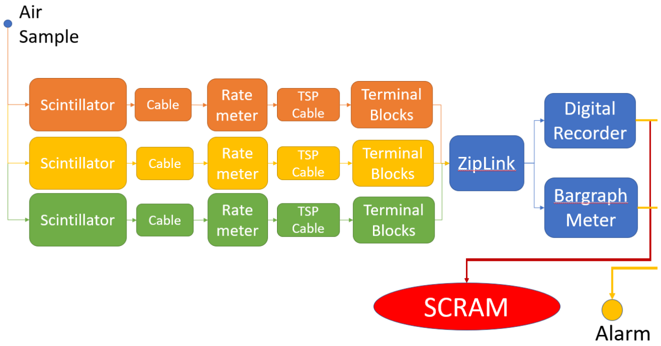

FIGURE 7: EFFLUENT MONITORS

The Area Radiation Monitor groups are depicted in the below graph in blue, yellow, and green respectively in **FIGURE 6**. You can see that the number of parallel devices has a positive effect on the reliability graph of the overall system. The C100 subsystem drops below our threshold (99% reliability index) later than the C200 subsystem, which drops off considerably later than the basement subsystem. Due to supply chain issues caused by the COVID-19 pandemic, there is only 1 ratemeter present in the basement, causing this precipitous drop.

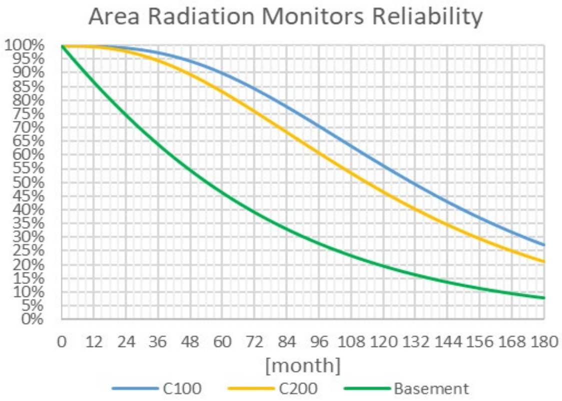

FIGURE 8: RELIABILITY CURVE FOR AREA RADIATION MONITORS

5.7.2 Maintenance and Reliability

Regular maintenance is an important aspect of all plant operations. Of note is that the graph in **FIGURE 6** assume *no maintenance*, meaning the devices are effectively installed and ignored for the rest of their life. To accurately determine the reliability of a system, we need to determine the effects of maintenance on the reliability plots.

We can model maintenance's effect on reliability as returning the device to 100% reliability, effectively replenishing the diminished reliability of the system. If we zoom in on the top of the graph and add in regular maintenance once per year, we can see the effects on the systems. Let us evaluate the effect of maintenance on our problem system, the basement ARMs. You can see in **FIGURE 7** that the reliability of the basement ARM drops to approximately 87.5% just before maintenance, at which point it is returned to 100%, and the cycle repeats.

As we can see, one method to ensure the continued reliability of a system is to schedule regular maintenance, and the maintenance intervals can be directly calculated from the expected level of reliability the system needs to design. If our reliability needs to stay above 95%, we can schedule maintenance every 4-5 months. If we need to maintain 99% reliability, our maintenance schedule increases every month. This is a considerable burden to the maintenance team, and as such it is preferable to enhance reliability through the methods discussed in section 5.5.1 System Design and Analysis, specifically to increase the number of parallel systems to 3 detectors and perform annual maintenance.

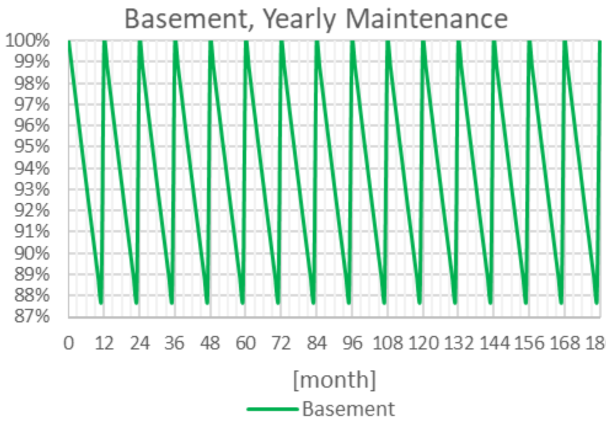

FIGURE 9: YEARLY MAINTENANCE EFFECT ON RELIABILITY OF BASEMENT ARMS

This analysis was performed for the ARMs, the Duct Filter Monitoring subsystem, and the Effluent monitor subsystem, and their results are tabulated in **TABLE 6**. Particularly important is the effluent monitor subsystem, as these devices control major scram and need to maintain above 99% reliability. However, as these devices are safety-critical, they have a regular maintenance schedule that ensures continued functionality of the major scram action.

TABLE 6: RELIABILITY CALCULATIONS WITH MAINTENANCE

Maint Freq. [months]	C100 [%]	C200 [%]	Basement [%]	Duct [%]	Eff. [%]
None	27.1	21.3	7.8	6.9	11.9
24	99.2	98.2	75.6	71.2	91.7
12	99.8	99.7	87.7	84.9	96.7
9	99.9	99.8	90.9	88.8	97.6
6	99.9	99.9	94.3	92.8	98.6
3	99.9	99.9	97.6	97.0	99.4

5.8 Failure Mode, Effects, and Analysis

An FMEA table was created to ensure the RMS upgrade as designed is robust and reliable for the foreseeable future. While the entirety of the FMEA table is outside of the scope of this technical paper, the results indicate that the reliability and redundancy of component selection have made the system safer than it would be without those choices. The most notable of the subsystems that demonstrates the value of the design considerations from section 4 is the effluent monitor subsystem. The effluent monitors control a major scram, which is the only automatic action controlled by the RMS. As such, it must be designed such that the system shall effectively never fail to actuate a major scram action in the case of raised radiation levels. The first iteration of the design had the major scram only actuated by the nuclear bar graph meters, due to their nuclear grade and commercial offering. However, this would reduce the diversity, redundancy, and defense in depth of the overall system. With minimal design change, the system was instead designed to have both the bar graph meters and the digital recorder actuate the major scram at the same time, meaning even in the unlikely event that one of the devices fails, the other device will pick up the slack and still actuate the expected action.

6. CONCLUSION

The RMS upgrade as designed in this document is robust and can support the NBSR for the foreseeable future. This is a necessary upgrade to the aging reactor control console and is only one part of the greater reactor control console upgrade planned at the NCNR. The system was designed with reliability and safety at the front of our minds and accomplishes the goals set forth by the NCNR.

7. ACKNOWLEDGEMENTS

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DISCLAIMER

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