RECENT I&C IMPROVEMENTS AT THE MISSOURI S&T REACTOR

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Instrumentation and control system upgrades conducted at the Missouri University of Science and Technology Reactor within the last five years are presented. These modifications include: a revised pulse-counting preamplifier, installation of digital data recorders in place of original strip-chart units, installation of a "new old/original stock" nuclear instrument channel as vendor was terminating operations, and revised reactor control system logic and wiring. Screening and evaluation under 10 CFR 50.59 and other frameworks are discussed, as well as challenges and lessons learned.

1. Introduction

The Missouri University of Science and Technology (Missouri S&T) Reactor facility (MSTR) consists of a 200-kW light water pool-type reactor, with High-Assay Low-Enriched Uranium (HALEU), Materials Testing Reactor (MTR)-type silicide fuel. MSTR serves as a research, training, and education facility both for Missouri S&T's Department of Nuclear Engineering and Radiation Science (NERS) and for the greater campus, with approximately 150-200 students annually utilizing the facility for classes and 20-40 students participating in the operator training program. MSTR also performs a significant public-outreach and education mission, with approximately 1,000 persons touring the facility on an annual basis.

To continue supporting the facility's education, outreach, research, and training missions, substantive, active modernization as well as preventative maintenance must be employed. The modifications and system repairs discussed herein are a substantive subset of those performed in the last five years of the facility.

1.1. Historical Instrumentation and Controls Summary

MSTR (or as it was originally called, the Missouri School of Mines Reactor) began operation in 1961 with instrumentation and controls (I&C) that were typical of the period, as the facility was effectively a downsized clone of the Curtiss-Wright Research Reactor [1][2]. Five discrete vacuum-tube-based nuclear instrumentation (NI) channels, four strip-chart NI recorders, analog mechanical gauges, an annunciator panel, a plethora of process monitoring equipment, and an electromechanical relay-based safety and control system served as the initial mainstay, although solid-state NI channels were installed as part of an aborted Training, Research, Isotopes, General Atomics (TRIGA) conversion in the late 1960s.

In 1992, a suite of Gamma-Metrics instrumentation (Log and Linear system, Wide Range Linear system, and Wide Range Log system) and newer strip-chart recorders were purchased. From this set, only a Log and Linear Channel was fully installed in August 1996, in combination with a two-pen replacement strip chart recorder to track reactor period and power (Log N). The remaining systems were tested sporadically (and in one case, used as temporary replacement ion chamber power supply) but never permanently installed.

By the start of the period of discussion (2018), almost every I&C system of the MSTR had been replaced at least once. Only two strip-chart recorders, the annunciator panel, and an ion chamber power supply remained plant original, with a Programmable Logic Controller (PLC)-based control and digital servo rod drives installed in 2013. The NI channels, as implemented at the start of the period of discussion, are summarized in Table I. The following abbreviations apply: FC – Fission Chamber, CIC – Compensated Ion Chamber, UIC – Uncompensated Ion Chamber, NIM – Nuclear Instrumentation Module.

Table I: Nuclear Instrumentation Channel Summary

Channel	Detector	Signal Processor/ Amplifier	Power Supply	Recorder
Log Count Rate	WL-6376A (FC)	General Atomics B001-0163C	Discrete NIM	Leeds&Northrup Speedomax H*
Linear	WL-6377 (CIC)	Keithley 485	Discrete Drawer*	Leeds&Northrup Speedomax H*
Log N and Period	RS-C1-2514-115 (CIC)	Gamma-Metrics 900309-101	Integrated	Leeds&Northrup Speedomax 250
Safety 1	RS-C2-2510-104 (UIC)	IST NPA-2011	Discrete NIM	-
Safety 2	WL-6937 (UIC)	IST NPA-2011	Discrete NIM	-

* Indicates original equipment

It is noted that four digital recorders (a Yokogawa DX1000 and three Yokogawa DX2000 units) had also been procured, but only a set of non-NI channels (temperature and continuous air monitor) were converted.

1.2. MSTR Procedural Requirements and Guidance

Chapter 10 of the United States Code of Federal Regulations (CFR), Part 50, forms the licensing basis of the MSTR, with 10 CFR 50.59 providing a process for determining the review threshold for facility modifications. MSTR procedures regarding facility modifications were revised in 2017 following staff training by an external company on 10 CFR 50.59 Screenings and Evaluations. As part of these revisions, a requirement was enacted that all changes to digital systems (control or safety-related) would screen-in under 10 CFR 50.59 and require an explicit evaluation.

Nuclear Energy Institute (NEI) report 21-06 was utilized where applicable, which provides guidance on the performance of 10 CFR 50.59 Screenings and Evaluations for Non-power Production or Utilization facilities (NPUF), such as the MSTR [3]. However, several of the discussed modifications pre-date the issuance of NEI 21-06.

2. Facility I&C Modifications

2.1. Startup Channel Preamplifier

To attempt to minimize noise and signal loss, the MSTR Log Count Rate (Startup) Channel utilizes a preamplifier mounted on the reactor bridge, bisecting the approximately 60 feet of coaxial cable between the NI drawer and the in-pool detector. The original preamplifier (as supplied by General Atomics with the NI drawer) was rebuilt numerous times, prior to being redesigned in 2014. The new design (see Figure 1) was more easily maintained with commodity/hobbyist components, and performance/noise tolerance was improved. However, the new design was not without faults. Exposed wiring risked shorting out transistors, and the non-soldered contacts underwent significant corrosion in the humid reactor bay. Further, no spare assemblies were available, complicating troubleshooting and repair efforts.

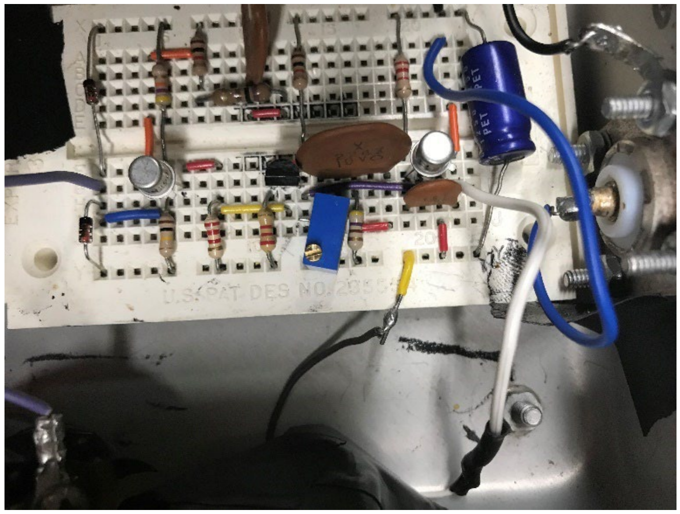

Figure 1: As-discovered Preamplifier

Following several transistor failures (and in combination with a failing fission chamber) in July 2020, long-term solutions were investigated, including the potential installation of the Gamma-Metrics Wide Range Log system from the 1992 instrument acquisition. However, that system's preamplifier had also failed during the sporadic interim testing, leading to the decision to reuse the existing preamplifier design, but with a dedicated printed circuit board (PCB).

The proposed modification screened-out under 10 CFR 50.59 and was directly implemented. Board schematics and design were generated in Electrical Computer Aided Design (ECAD) software, such that Gerber files could be provided to an acceptable U.S. PCB fabricator. Several boards (including spares) were acquired, as were new passives and transistors. MSTR staff assembled and tested a new unit (spare board in Figure 2) prior to installation, which completed December 2020.

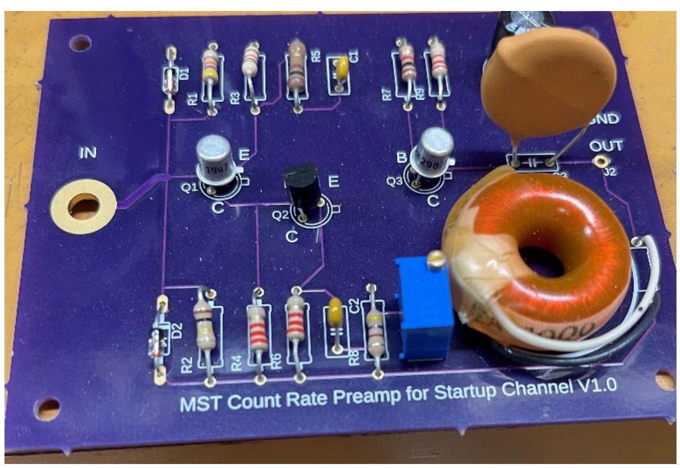

Figure 2: Assembled Preamplifier Board (Spare)

Post-implementation, noise-related faults of the Startup Channel are much less frequent, and every fault significant enough to impact operations has been traced to errant ground loops and coaxial connector issues.

2.2. Startup Channel Recorder

Continued use of the facility-original strip chart recorder for the Startup Channel posed several challenges and limitations. The plant-original Startup NI channel (signal processing drawer and recorder) was designed with an effective upper limit of 10^4 counts per second (cps), while both the current signal processing drawer and corresponding fission chamber (WL-6376A) are capable of over 10^5 cps. Operations are not known to have been halted from this limitation, but restart scenarios (i.e., startup promptly following a shutdown or scram at a significant fraction of licensed power) can feasibly become complex if proper intermediate range instrument response is not achieved by end-of-scale of startup range instrumentation (especially due to a likely undercompensation of fission product decay gammas). Recorder paper was becoming exceedingly difficult to source, due to few vendors still offering production, significant and increasing costs (which, when evaluated for replacement was over $50 per roll of 33 hours runtime and as of writing has exceeded $110 per roll), and very long production timelines (over three months).

With the aforementioned challenges in acquiring recorder paper, MSTR exhausted its supply of recorder paper for the Startup Channel in February 2022, and resupply timelines extended well into April (including during operations in support of the first commercial customer of the facility in over a decade). Installation of the replacement Yokogawa DX2000 had been targeted for Summer 2022 but was rapidly accelerated. The pre-modification component layout is provided in Figure 3.

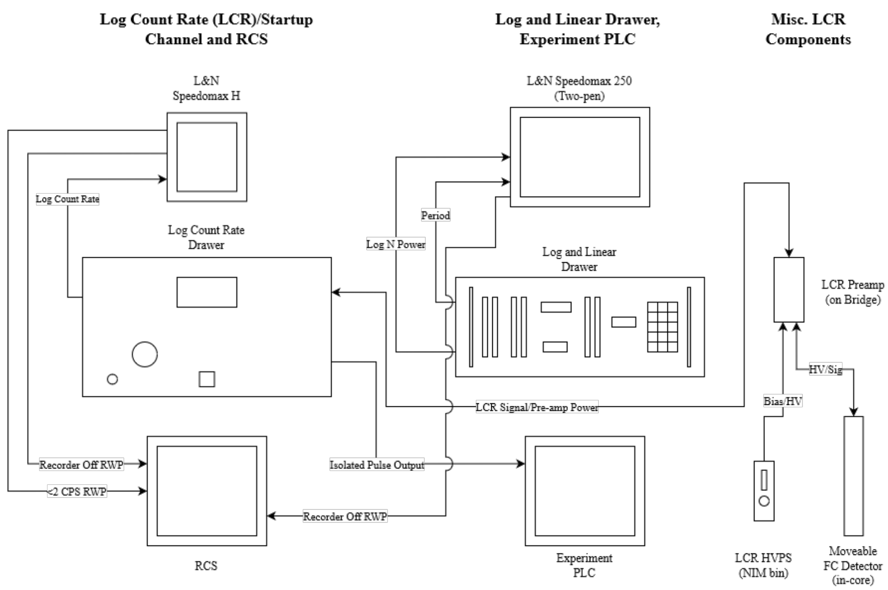

Figure 3: Previous Startup Channel and Log and Linear Channel Configuration

As a digital replacement for a control system component, the proposed modification screened-in under 10 CFR 50.59 (per facility procedures), and no significant concerns were noted in the following evaluation as the system is not safety-related. The facility oversight committee reviewed and approved the evaluation, testing and installation plan, and operator training plan for the modification [4].

The original recorder utilized a 0-10 mVDC signal for the log count rate, which while compatible with the replacement unit, was very noise sensitive and offered no isolation between the drawer and recorder. As part of the recorder installation, a 0-10 VDC signal conditioner was installed into the instrument drawer, and a spare drawer connector was utilized for the output signal to support reversing the modification if needed (that is, the original 0-10 mVDC signal path was undisturbed).

As can be seen in Figure 4 (which presents the modified systems), when installing the replacement recorder, the Log N Power signal was duplicated from the Log and Linear Channel (albeit in a non-credited manner) to support future recorder replacements.

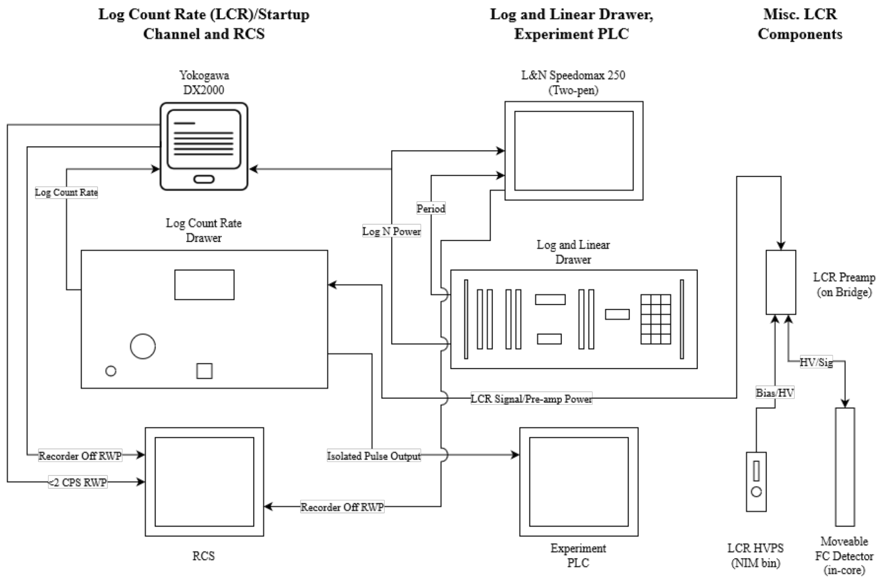

Figure 4: Recorder, Startup Channel, and Log and Linear Channel Post-Modification

Implementation began on February 16, 2022, and normal operations were restored by February 22, 2022.

2.3. Linear Channel and Recorders Installation, Control System Modifications

Similar issues were encountered regarding the cost and supply of paper for the remaining strip chart recorders (scaled linear power and a combination log power and period unit). Upon feedback from other research reactor facilities, some expanded use of the recorder media was gained in reversing the paper. However, repeated issues were encountered in excess paper tension overloading the recorder drive motor and feed jamming. Several potential solutions were investigated, with initial efforts focused on a smaller scale modification, such as replacing just the recorders. Another consideration was simultaneously replacing the picoammeter with a newer system (e.g., a Keithley 6485). These options were effectively ruled out by the manner in which the linear channel and recorder are coupled to the Reactor Control System (RCS) and other NI components.

The recorder, in addition to plotting the linear demand signal, was utilized for automatic servo control in calculating the error signal (i.e., deviation of reading from setpoint) for Proportional-Integral-Derivative (PID) loop control. As a 0-10 mVDC signal, generated by artificially truncating the picoammeter output (nominally within ±2 VDC), noise sensitivity remained a concern. Severe noise (represented as up to 200% of scale) was frequently encountered on scaling the picoammeter, but the moderate traversal rate of the linear channel recorder (i.e., the cams controlling the marking pen in relation to limit switches) prevented nearly all such events from causing unplanned shutdowns. With the digital replacement recorder, such behavior would effectively always cause a shutdown. Irrespective of which option was selected, significant control system modifications and potentially NI signal processing mechanisms were going to be necessary.

The existing system is depicted in Figure 5. Note that the ion chambers and cabling for the linear as well as the log and linear systems are not represented.

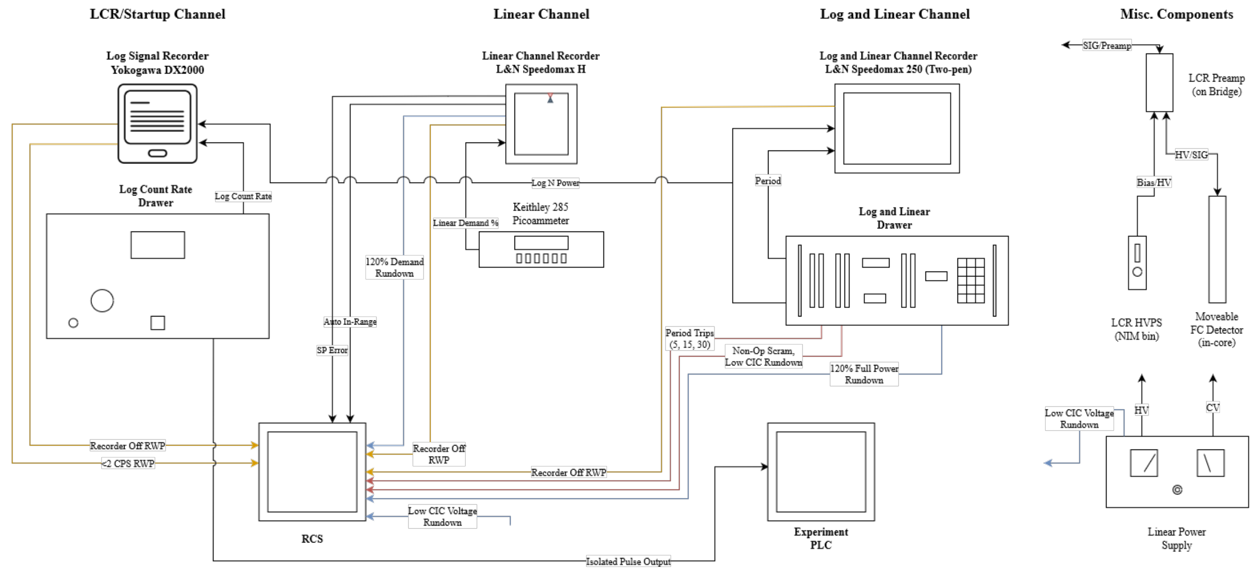

Figure 5: Previous MSTR NI Configuration

Preliminary testing indicated acceptable performance of the 1992-procured Gamma-Metrics Wide Range Linear system and Yokogawa DX2000. On this system, scaling noise is suppressed by design, and trip functions can be performed without auxiliary relays. Several other factors also encouraged a complete Linear Channel replacement: ability to replace a plant-original vacuum tube-based ion chamber power supply, capability to inject test signals without auxiliary equipment, direct gain adjustment (previously performed by physically moving the detector), internal watchdog functions, isolated 0-10 VDC outputs, and improved power resolution via a split scaling mechanism (i.e., magnified 0-40% of scale). With the large-scale modification of replacing the Linear Channel signal processor, linear recorder, period recorder, and any necessary supporting RCS modifications selected, scope creep of the project became a concern.

As the design progressed, changes to the RCS and system wiring were determined to be necessary. Even though the PLC-based RCS was installed in 2013, much of the wiring still corresponded to the original relay-based system, and wiring that had been modified failed to meet any standard of organization (e.g., by color indicating signal type or voltage, labeling, or other means). Circuit protection (e.g., fuses and circuit breakers) was also underutilized. PLC input/output (I/O) blocks were saturated and would not be able to handle the additional I/O points from the replacement NI channel. The PID and servo control logic would need to be centralized and reworked, as would the ladder logic forming the RCS control program.

Upon completion of the design, the proposed modification was screened against 10 CFR 50.59 in concert with the recently released NEI 21-06 methodology. Just as for the Startup Channel recorder modification, this project screened-in and underwent an explicit safety evaluation by facility staff with no significant concerns noted (all impacted systems are not safety-related). The facility oversight committee reviewed and approved the evaluation and modification [5].

Implementation began on August 23, 2022, but problems were almost immediately encountered. Undocumented wiring changes, unobserved in the previous, smaller scale modifications, presented a significant challenge to trace, resolve, and document. The last issue, which prevented successful operation of the annunciator panel, was unresolved until October. Dynamic testing completed on October 20, 2022, returning the facility to normal operations. A schematic of the impacted NI and more apparent RCS changes is depicted in Figure 6.

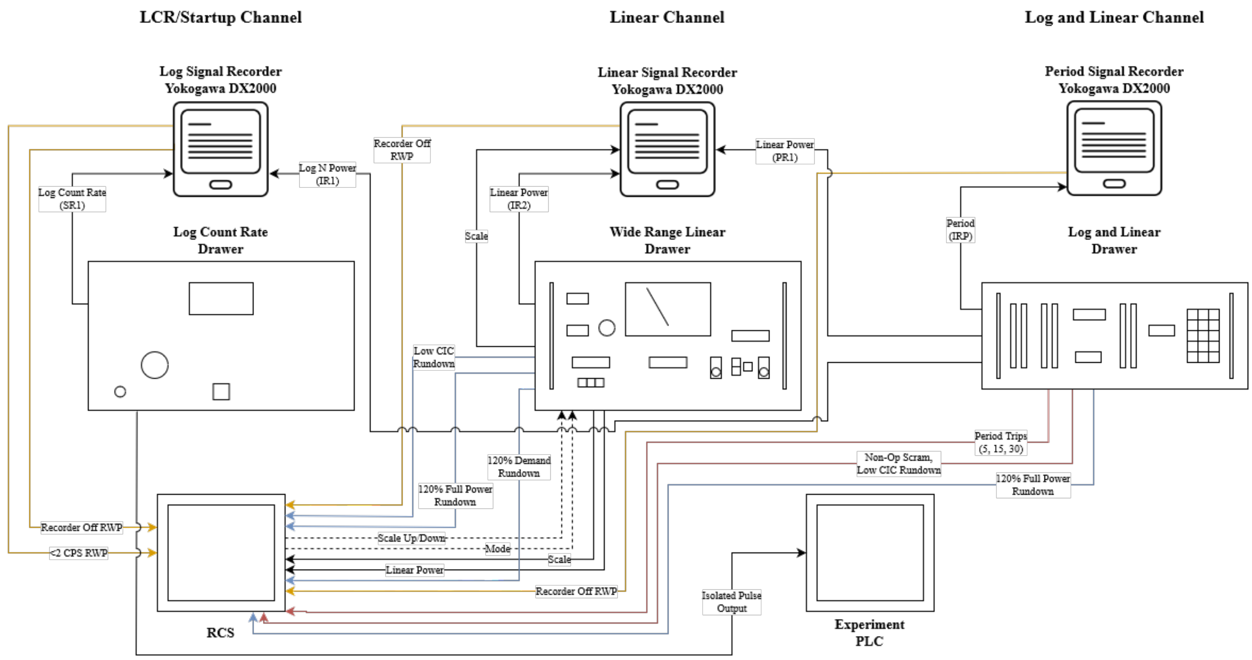

Figure 6: Reactor Control Console Post-Linear Modifications

Autocontrol servo functions are non-ideal following the modifications; however, the system is in an operable state and readily supported the operations of the last six months. Further testing and development to improve the autocontroller response is tentatively scheduled for June 2023. One hardware failure has been observed post-installation: the switched-mode power supply for the linear channel detector high voltage required replacement, with the failure suspected to be age-related. An exact replacement for the failed component was acquired (although new-old stock), and the power supply was repaired and returned to service.

3. Compounding Factors

3.1. Surveillance Requirements and Requalification

Startup channel inoperability due to preamp and detector caused the facility to exceed the surveillance interval for control rod visual inspections (all three inspected annually). An exigent license amendment was sought prior to a violation, and a one-year extension to the surveillance was granted in-line with regulatory guidance per NUREG-1537 [6][7].

Startup channel inoperability also provided a challenge by way of impeding operator requalification activities. Per the MSTR Operator Requalification Program, on-the-job training, including an assessment of control manipulations while operating, is required on a calendar year basis [8]. Operability was restored December 28, 2020, and the operating assessment was completed promptly. As a contingency, efforts were also started to seek relief from the Requalification Program from the Nuclear Regulatory Commission, with December 28 functioning as a go/no-go date on an exigent request submittal.

3.2. Staffing, Budget, and COVID-19

In 2019, full staff turnover at the MSTR was observed, with only a single full-time employee on staff (the author) as of June 2019. An agreement was reached with the previous Senior Reactor Operator (SRO) to maintain licensure and facility surveillances until the author was able to undergo licensing, which was accomplished December 2019. Staffing levels to date have consisted of the author, student operators, and student assistants. It is noted that another full-time employee has been hired as of October 2022, with start pending completion of visa and export control reviews.

The MSTR is primarily funded through State of Missouri allocations through the University of Missouri System. Even with a very conservative budget, state appropriations cover approximately half of the annual facility operating costs (excluding the salary and wages of two full-time employee billets). As such, modifications and repairs are nearly always postponed until critical, either by way of safety or regulatory concerns. This has also led to the use of very low cost means of repair in several areas of the facility (i.e., the as-found startup channel preamplifier), requiring further engineering time and materials to restore degraded performance when hindering operations.

COVID-19 impacts began to take effect just as the facility resumed more normal operations following the 2019 staffing issues. Budget and staffing cuts were made throughout Missouri S&T. The MSTR, having already undergone significant staffing cuts, avoided a further reduction of resources, although it was made clear that no restoration of needed support would be available. However, the facility was still directly impacted by the cuts, as the campus health physicist, who was responsible for the radiation protection activities at MSTR, was terminated. The health physicist role was combined with the campus Radiation Safety Officer (RSO), who also serves as the Director of Environmental Health and Physics. While all regulatory and license requirements continue to be met despite this change, the facility does consider the combination to result in an unreasonable workload for the RSO.

3.3. Termination of Vendor Support

ThermoFisher Scientific (corporate owner of Gamma-Metrics) had previously announced their intention to cease production and support of the Gamma-Metrics neutron flux monitoring systems. Troubleshooting, testing, and ensuring operability of the replacement Linear Channel signal processing drawer was challenged as contact between MSTR and ThermoFisher technicians was effectively terminated mid-modification.

It is noted that Paragon Energy Systems has announced support for these systems, but this development occurred after the completion of the discussed modifications.

4. Future I&C Plans

4.1. Timing and Synchronization Systems

All digital systems of the MSTR control system use separate real-time clocks (RTC). While this does not hinder operations, it does impede data analysis using the digital recorder data (e.g., for rod worth measurements), as all data must be manually synchronized. Additionally, with discrepancies in RTC throughout the control room, focus is placed on only using the console clock as the time of record for all events. An aging, residential alarm clock from the 1980s serves as this system, leading to a goal of near-term replacement.

A Masterclock GMR5000 synchronization system is targeted for installation in Summer 2023. This system, in combination with an air-gapped network, will synchronize all RTC systems and allow for the future implementation of a data historian system. The GMR5000 can also be used to supply precision timing signals for instrument calibration and the performance of experiments.

4.2. Startup Channel Replacement

The existing Startup Channel signal processor is nearly 60 years old. While significant upgrades have been made for the preamplifier and signal processing drawer (new circuit breakers, power supplies, signal conditioners and pulse isolators), much of the signal processing components, including operational amplifiers (op-amps) and transistors, are original. Replacement of this system is a significant I&C focus for the facility in the next five years.

As previously discussed, a Gamma-Metrics Wide Range Log unit was purchased with other hardware as part of the 1992 procurement. The manufacturer has ceased supporting this system, but a secondary vendor has offered future support. Prior to installation of the Wide Range Log drawer, aging and outdated hardware (including plasma bar graph displays) would need repair and/or replacement, as would the failed preamplifier. With the projected cost of the repairs and parts nearing 20% of a new NI system of similar capabilities, the facility may need to consider abandoning this approach and seek procurement of a more modern replacement.

4.3. Pool Height Measurement and Bridge Accelerometer

Other than limit switch-connected floats to verify that Limiting Conditions of Operation are met for pool height, no active measurement is performed. As part of startup procedures, the pool height is measured and recorded by an operator via a ruler mounted to an in-pool skimmer. While most operations are not significantly impeded by this process, the MSTR thermal power calibration methodology relies upon routine and precise manual sampling.

As a natural convection-cooled facility, system heat balance methods are not available, and foil activations have been historically avoided. Thermal power is therefore calibrated by measuring expansion of the pool under a 40-kW-hr target load using a series of dial indicators on float assemblies. This measurement setup is erected and disassembled for every calibration (surveillance required annually), and the overall process usually requires several runs to address run-to-run inconsistencies and environmental factors. For one week or more each year, successful completion of the thermal power calibration becomes the prime focus of the facility. It is also noted that if the MSTR pursues forced convection cooling (e.g., as part of a power uprate), this process is likely to be superseded by standard heat balance methods.

To measure pool height at a precision and accuracy sufficient for thermal calibration, as well as online monitoring by the operator, a high-precision ultrasonic distance (tank-level) sensor is targeted for procurement and installation in Fall 2023. Data from this system will feed into the existing digital data recorders. The overall design goal is to improve consistency in performing the power calibration and automate the data collection, leading to better staff and facility availability to support other efforts.

Per facility Technical Specifications, control rod drop times (i.e., the time taken to fully insert a fully withdrawn shim rod during a scram) are to be measured semi-annually and whenever the rod drives are disassembled. This process is currently performed using a microphone to measure rod impact (i.e., when fully inserted) compared to the scram signal observed on an oscilloscope.

Installation and implementation of an accelerometer sensitive enough to detect the rod impact is targeted for Spring 2024. A more automated method of performing the rod drop measurement using the reactor control system will be implemented concurrently. While the improvement in consistency and reduction in staff effort in performing surveillance is not expected to reach the degree projected for the thermal power calibration, this system should aid in overall maintenance of the facility. Additionally, with appropriate qualifications, the accelerometer may be sufficient for assessing seismic loads exacted on the core.

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References

[1] D.S. Epplesheimer, D.R. Edwards, A.R. Schade, et al, "Hazards Summary Report for the University of Missouri at Rolla Nuclear Reactor", 200 kW revised operation, University of Missouri at Rolla and Curtiss-Wright Corporation Nuclear Radiation Department, Rolla, MO, April 1959.

[2] G.A. Anderson, "Hazards Evaluation Report, Curtiss-Wright Research Reactor", CWR-4062, Curtiss-Wright Corporation Research Division, Quehanna, PA, April 1959.

[3] H.M. Lane, "Guidelines for 10 CFR 50.59 Implementation at Non-Power Production or Utilization Facilities," NEI 21-06, Rev. 1, Nuclear Engineering Institute, Washington, DC, December 2021.

[4] E.C. Taber, J.T. Graham, "Modification Package: Startup Channel Recorder", Mod. 2021-03, Missouri University of Science and Technology Reactor, Rolla, MO, February 2022.

[5] E.C. Taber, J.T. Graham, "Modification Package: Linear Channel, Linear Recorder, Period Recorder, and RCS Modifications", Mod. 2022-01, Missouri University of Science and Technology Reactor, Rolla, MO, October 2022.

[6] Letter from W.B. Kennedy to E.C. Taber, "Board of Curators of the University of Missouri– Issuance of Amendment No. 22 to Renewed Facility Operating License No. R-79, for the Missouri University of Science and Technology Research Reactor to Extend the Period to Perform Visual Inspections of the Shim/Safety Rods," EPID No. L-2020-NFA-0011, Nuclear Regulatory Commission, Washington, D.C., November 2020.

[7] "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactor: Format and Content," NUREG-1537, Part 1, Nuclear Regulatory Commission, Washington, D.C., February 1996.

[8] C.T. Reisner, A.A. Alchin, "Operator Requalification Program for the Missouri University of Science and Technology Reactor," Revision 4, Missouri University of Science and Technology Reactor, Rolla, MO, August 2018.