Breaking the Digital Ceiling: Research Reactors Driving Innovation

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INTRODUCTION

Test, Research and Teaching Reactors (TRTRs) are a valuable driver in the innovation of design and implementation of new technologies, breaking the glass ceiling for new products which may have significant challenges at the industrial level. They continue to perform an important role in the United States' national energy security through nuclear scientific advancement and human capital development. The Purdue University Reactor Number One, a 10 kW thermal light water reactor, is providing support to the national TRTR mission through the design, licensing, and implementation of an all-digital safety and control system. This innovative and first-of-its-kind Instrumentation and Control (I&C) framework, currently under licensure review by the US NRC, will provide unique pedagogical opportunities and rebaseline methods used to appeal to the iGeneration. At its core, the facility serves as a teaching behemoth through its execution of high fidelity, easily accessible data which enables the students to process and analyze experimental results and affirm theories presented in the lecture space. In the age of big data, future nuclear engineers will be expected to be fluent in digital data processing techniques, coupling measurement results to fundamental models, and thereby make sound engineering decisions which promote economic competitiveness while maintaining the health and safety of the public. Through this all-digital I&C system, Purdue University students will be prepared to immediately and effectively impact their employer's financial bottom line.

The U.S. DOE has provided infrastructure support for university research reactors through NEUP funding. This financial boost has stemmed the tide of decommissioning TRTRs across the country. With over 80 similar facilities at one point, the number of nonpower utilization facilities has now fallen to under 30. Infrastructure support was used at the Purdue University Reactor (PUR-1) to replace a noise plagued control system with a fully digital RCS and RPS in 2016. The LAR is currently undergoing review by the U.S. NRC [1]. When the LAR is granted, the PUR-1 will become the first NRC licensed reactor with an all-digital RCS and RPS.

Historical Design Concept

The PUR-1 first went critical in 1962. Designed and installed by Lockheed Nuclear, it uses flat-plate MTR-type fuel assemblies in a square matrix, surrounded by a graphite reflector on four sides. Originally supplied with HEU, the fuel loading was converted to LEU in 2007 under the NNSA GTRI program. The RCS consists of three neutron flux detector channels which inform the operator of the reactor power level and rate of change (period). The RPS takes input feeds from each of the three channels and has a fourth, independent, neutron flux channel that outputs only to the RPS. The two borated stainless steel safety control rods are electromagnetically coupled to drive motors. As the reactor power or rate of change approach the license limits, the current to the electromagnets is suppressed, causing the safety rods to drop into the core under gravity if the condition is not corrected by the operator. When any limit settings are reached, relays will cut the magnet current entirely. In the event of any scram, the reactor may be completely shut down by either of the shim-safety rods. Additionally, other RPS actions such as a RAM alarm, manual scram, etc. will cut the magnet power.

The principle design of many research reactors such as the PUR-1 is to promote flexibility while maintaining a negligible risk profile. Success in this space is realized through a diverse safety system and a large factor of safety. Many of the significant accident scenarios analyzed in the Safety Analysis Report do not involve operations at all. Because of this fact, the PUR-1 is a prime candidate for bleeding edge digital control and safety technology.

Digital Design Concept

The design philosophy employed at the PUR-1 for the digital systems was to imitate, as far as was practical, the analog system level design. Channels and operational functions of the original analog RCS and RPS were maintained or very nearly replicated. This decision was deliberately taken to simplify the design and was anticipated to significantly shorten the licensing processes. For all major RCS and RPS operations a parallel can be drawn between the original analog equipment and its function in the new digital systems. The digital system was designed and fabricated by Mirion Technologies and Scientech Corporation. New RAMs and a new CAM were purchased from Thermofisher and have been tied in to allow alarm conditions to trip the RPS scram relays. The new RCS also consists of three neutron flux monitoring channels and the RPS has a fourth neutron flux detector channel. The original control rods and electromagnet couplings are being used, and any scram condition will open a relay that cuts the magnet current. The possible pathways to a scram condition are also reflections of

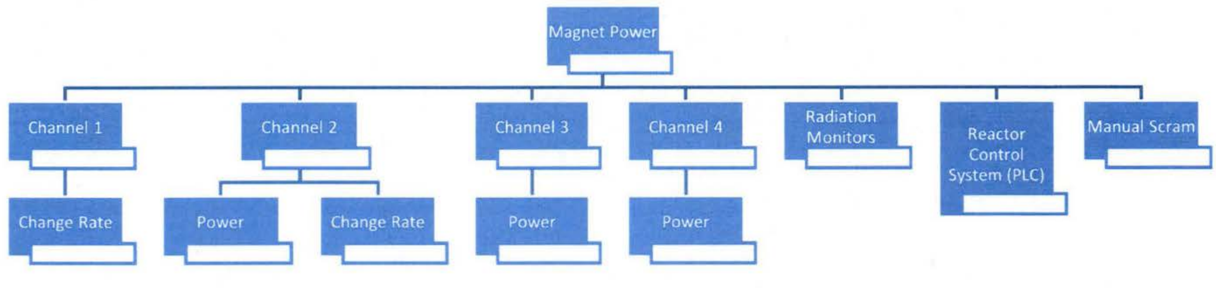

Figure 1. Magnet Circuit Interrupts for the RPS [1]

the historical design. For example, Channel 1 (Log Count Rate) has a scram trip for excessive change rate (short period) in the analog design. Likewise, there is a Channel 1 scram trip for change rate in the digital design. This design decision allowed a nearly one-to-one mapping between previously acceptable system functionality and the redesigned digital system. Figure 1 shows the resulting magnet circuit interrupt connections for the digital design, and Figure 2 shows the operator's screen. Additionally, this design basis simplified the explanations needed in the LAR and in conversations with NRC personnel to communicate the system construction strategy such that they could perform the analysis needed for regulatory assessment.

Notably, additional pathways to a scram condition to allow a simplified design gave rise to an expected increase in the probability of regulatory acceptance. For example, a known potential issue with digital systems is "bad" data (via packet loss in Ethernet transmission). As a consequence, digital systems perform a check on the information to ensure the entire message was sent and received giving a final fidelity grade of acceptability. Allowing the system to ignore bad data packets necessitates determination of the number which can be ignored, the duration of poor data, and regular verification of this operability. Alternatively, PUR-1 elected to have a "bad" data grade open a scram relay and cut the magnet power. Simple and straightforward, this design concept has been important to resolving issues quickly and allowing the design and LAR processes to proceed.

New Capabilities

The digital RCS offers significant new capabilities for teaching and research. Specifically, the parameters that the RCS monitors (four detector outputs, change rates, power level, rod positions, etc.) are recorded to a database on the RCS workstation. The data is expected to be accurate to the tenth of a percentile and is recorded every 10 milliseconds. An example of this output is shown in Figure 3. With this temporal resolution, students will be able to see short-time effects such as the decay of the delayed neutron precursors. With improved neutron flux resolution, students will more readily observe parameters like temperature feedback effects within the core.

Space comes at a premium inside the reactor bays of most nuclear facilities. While attempting to convey reactor physics data and operation principles, congestion around the operator console significantly limits class size. The new digital I&C exports data through a commercial grade data diode to a secondary workstation. This secondary workstation is accessible throughout Purdue's campus and provides a mechanism to access live reactor data for a variety of different undergraduate and graduate courses. With a clone of the workstation software on a laptop and log in credentials, a presenter can show the reactor parameters in real time in any global classroom. The class can see the results of historical operation or can participate in an interactive session in which they communicate with the operator and watch the changes to power and change rate remotely. Data can be provided in a variety of formats (CSV, Excel, etc.) for post processing by students.

Figure 2. The Main Operator Screen, which was designed to look much like the original operator control panel. [1]

The researcher in need of high accuracy, time dependent data has access to new important tools as well. When coupled with the facility produced Monte Carlo models, researchers will be capable of knowing the exact flux to which an experiment has been exposed as well as the time dependence of the flux.

Figure 3. Example flux monitor output visible to operator or available to researchers. [1]

Industry Impact

As the PUR-1 staff continue to pursue an all-digital I&C system, recognition is given to the ultimate source of financial assistance: industry and the American tax payer. In recognition of this fact, the authors note several important outcomes from the Purdue work. First, as the nation's reactor fleet ages and the industry works to "Deliver the Nuclear Promise ®,[2] an important consideration is the phased replacement of analog components with their more economic digital counterparts. As facilities begin to require replacements in the digital I&C space, being able to point to a partner in technology who has successfully implemented a similar system will be incredibly valuable. Additionally, the regulator will be more prepared, through the review framework and technology familiarity, to license equipment.

The public also benefits from the digital I&C work being completed. As noted in the introduction, the next generation of scientists and engineers will have been born in the age of the smart phone. Their ability to relate to the science is significantly enhanced when viewed through a digital lens versus the hand soldered vacuum tubes and resistors of the past. These future nuclear engineers are responsible for the production of nearly 20% of the nation's energy supply and maintaining the diverse electricity portfolio the United States currently employs. Their interest in nuclear topics will deliver elite engineers of the future.

RESULTS

The DOE infrastructure support for university research reactors allowed the PUR-1 to upgrade the RPS and RCS to an all-digital system, replacing the 1962 installed analog console. This infrastructure support for university research reactors with a digital system will allow new capabilities, specifically high fidelity data acquisition of detector outputs and rod positions for research experiments and the opportunity for real time interactive operations with remote classrooms. This major upgrade has improved the capabilities of the PUR-1 facility and has extended the expected lifetime by many years.

Continuing work at the facility involves the finalization of the license amendment request to the U.S. NRC. With final approval expected in the spring of 2018, the PUR-1 is poised to quickly and effectively implement these new capabilities. Final evaluation of the licensing and design process is underway to determine the effectiveness of the system framework. Timeline from project initiation to completion is expected to be approximately 30 months.

NOMENCLATURE

CAM = Continuous Air Monitor
DOE = U.S. Department of Energy
GTRI = Global Threat Reduction Initiative
HEU = Highly Enriched Uranium
LAR = License Amendment Request
LEU = Low Enriched Uranium
MTR = Materials Test Reactor
NEUP = Nuclear Energy University Program
NNSA = National Nuclear Security Administration
NRC = U.S. Nuclear Regulatory Commission
PUR-1 = Purdue University Reactor 1
RAM = Radiation Area Monitor
RCS = Reactor Control System
RPS = Reactor Protection System

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