ENHANCEMENTS TO THE SLOWPOKE-2 NUCLEAR RESEARCH REACTOR AT THE ROYAL MILITARY COLLEGE OF CANADA

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Abstract

In 1985 a Safe Low Power C(K)ritical Experiment (SLOWPOKE) nuclear research reactor was installed at the Royal Military College of Canada (RMCC). The reactor at nominally 20 kW thermal was named SLOWPOKE-2 and the core was designed to have a total of 198 fuel pins with Low Enriched Uranium (LEU) fuel (19.89% U-235). Installation of the reactor was intended to provide an education tool for members of the Canadian Armed Forces (CAF) and an affordable neutron source for the application of neutron activation analysis (NAA) and radioisotope production. Today, the SLOWPOKE-2 at RMCC continues to be a key education tool for undergraduate and post-graduate students and successfully conducts NAA and isotope production as per its original design intent. RMCC has significantly upgraded the facility and instruments to develop capabilities such as delayed neutron and gamma counting (DNGC) and neutron imaging, including 2D thermal neutron radiography and 3D thermal neutron tomography. These unique nuclear capabilities have been applied to relevant issues in the CAF. The analog control system originally installed in 1985 has been removed and replaced in 2001 by the SLOWPOKE Integrated Reactor Control and Instrumentation System (SIRCIS) which is a digital controller. This control system continues to evolve with SIRCIS V2 currently in operation. The continual enhancement of the facility, instruments and systems at the SLOWPOKE-2 at RMCC will be discussed, including an update on RMCC's refueling plan.

1. Introduction

Safe Low Power C(K)ritical Experiment (SLOWPOKE) nuclear research reactors were designed at Atomic Energy of Canada Limited (AECL) as a simple, safe, and affordable neutron source for universities and hospitals for application of neutron activation analysis (NAA) and radioisotope production. In 1985, the Royal Military College of Canada (RMCC) commissioned a 20 kW SLOWPOKE-2 reactor into its new engineering building in support of the proposed Canadian nuclear submarine program. The nuclear submarine program never materialized but the SLOWPOKE-2 has proven to be an extremely versatile and valuable asset for RMCC and the Canadian Armed Forces (CAF). Since its installation, RMCC has continued to upgrade and reinvest in the facility to develop new instrumentation and nuclear capabilities required by the CAF. Two such systems are the DNGC system which is capable of non-destructive analysis of fissile materials and the neutron imaging system which provides 2D and 3D thermal neutron images of aircraft flight control surfaces. Reinvestment in the hardware and operating system that regulate SLOWPOKE-2 at RMCC has also continued to develop over the years. A digital control system called the SLOWPOKE Integrated Reactor Control and Instrumentation System (SIRCIS) was designed and installed by an RMCC graduate student and a member of the CAF. Subsequently, SIRCIS has been upgraded into a later version. This digital controller provides a variety of “real time” data and measurements vital to the safe and efficient operation of the reactor. The digital controller provides valuable data that can be used to analyze how the regulating system interacts with the flux detector and thereafter to help correct “bugs” in the regulating system. Because the SLOWPOKE-2 continues to be a very vital asset to the CAF and the current reactor core is reaching it’s end of life, the process of obtaining authorization and funding to refuel the reactor core has begun.

2. Design and Construction

The aluminum container for the SLOWPOKE 2 reactor core is suspended in a water- filled pool, which has an inner diameter of 2.46 m and a depth of 5.87 m. Both the reactor container and the pool are filled with light de-ionized water. This water provides cooling, radiation protection and acts as a moderator for the critical assembly. The core has a total of 198 fuel pins with Low Enriched Uranium (LEU) fuel (19.89% U-235). The fuel pins are arranged vertically inside a beryllium assembly. The beryllium acts as a neutron reflector. The annulus contains five inner radiation sites, one of which now contains a neutron flux detector. Any of the four inner irradiation sites or the three appropriate outer sites may be used for sample irradiation.

In order to provide a higher neutron flux for neutron imaging, an outer irradiation site was replaced (before reactor commissioning) by a thermal column containing heavy water between the beryllium annulus and the reactor container as shown in Figure 1. At half power, the thermal neutron flux measured at the location adjacent to the heavy water column is 2.7 times greater, [1] $1.4\times10^{11} n\,cm^{-2}s^{-1}$ compared to $5.1\times10^{10} n\,cm^{-2}s^{-1}$ measured at the reactor container wall at a different radial location [2].

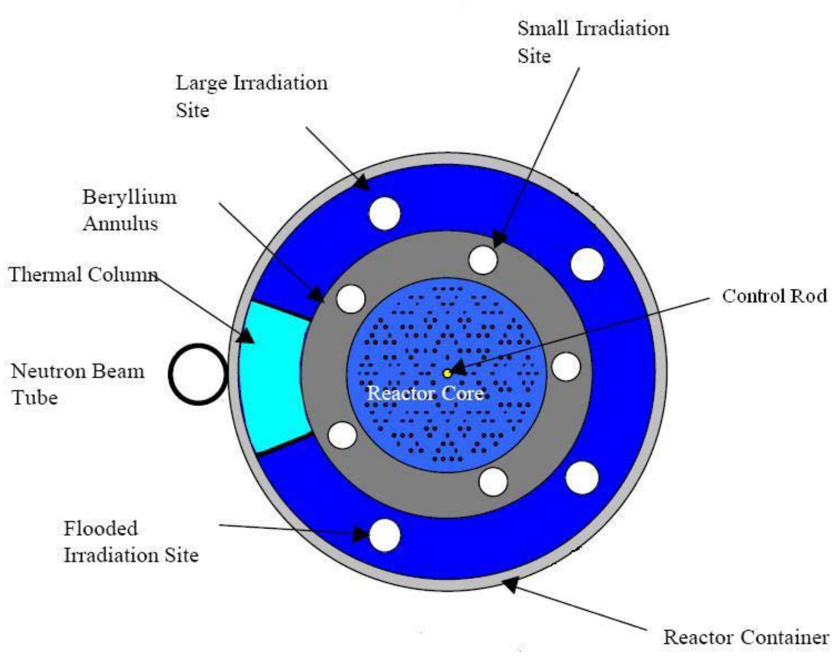

Figure 1: Cross Section View of RMCCs SLOWPOKE-2 Reactor Core

A Neutron Beam Tube (NBT) was installed in the reactor pool to permit thermal neutron imaging. When neutron imaging is not being conducted, the NBT is positioned vertically in the reactor pool away from the core. To initiate imaging, the NBT is moved towards the reactor core by a hydraulic jack until the bottom of the NBT contacts the reactor container and forms an 8.5^o angle from vertical. The bottom of the NBT is called the illuminator and is made from a graphite block. When the NBT is coupled to the reactor container, neutrons travel through the beryllium reflector and the heavy water thermal column to the graphite block. The graphite block redirects the neutron beam upwards through the divergent beam tube. The beam tube and peripheral equipment required for neutron imaging are shown in Figure 2.

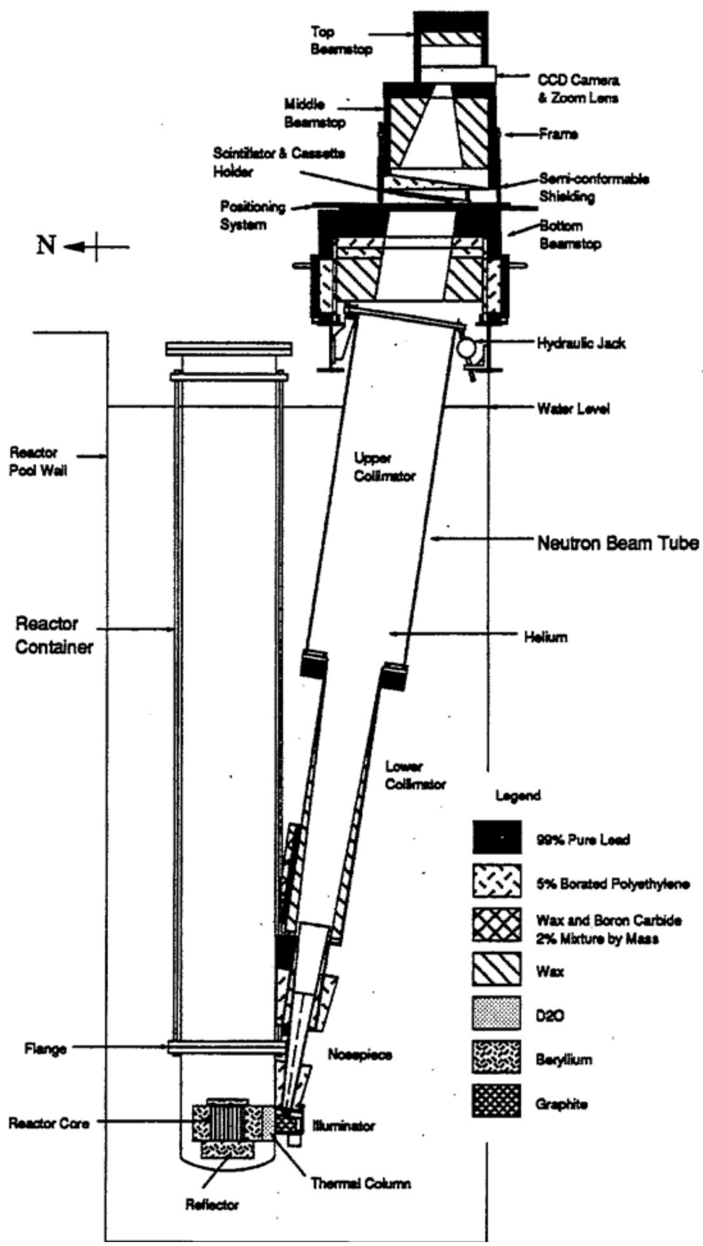

Figure 2 : Side View of RMCC Neutron Imaging System

3. Enhancements

Enhancements to SLOWPOKE-2 at RMCC including DNGC and neutron imaging and SIRCIS all will be briefly examined.

3.1 Delayed Neutron and Gamma Counting (DNGC)

A prototype DNGC system had been developed within the SLOWPOKE-2 facility to enhance special nuclear material detection instrumentation available to the CAF [3]. An array of ^{3}He detectors recorded the temporal behaviour of delayed neutrons produced after the irradiation of special nuclear material (SNM) (^{233}U, ^{235}U and ^{239}Pu) in an inner irradiation site of the SLOWPOKE-2 reactor. The DNGC allowed for the rapid and non-destructive analysis of fissile mixtures via the assay of temporal and cumulative delayed neutron measurements. Figure 3 shows the differences in delayed neutron temporal behavior recorded at RMCC for ^{233}U and ^{235}U emissions, which have been initialized to the same count rate.

The DNGC system has recently been upgraded to simultaneously record delayed neutrons (He-3 detectors) and delayed gammas via the inclusion of a high purity germanium detector, and is now known as the Delayed Neutron and Gamma Counting (DNGC) system [4]. Delayed particle measurements from this system are compared to MCNP6 simulations in collaboration with the Monte Carlo Codes group at Los Alamos National Laboratory [5] [6]. Additionally, the DNGC system will contribute to Canada's participation in an upcoming nuclear forensics exercise.

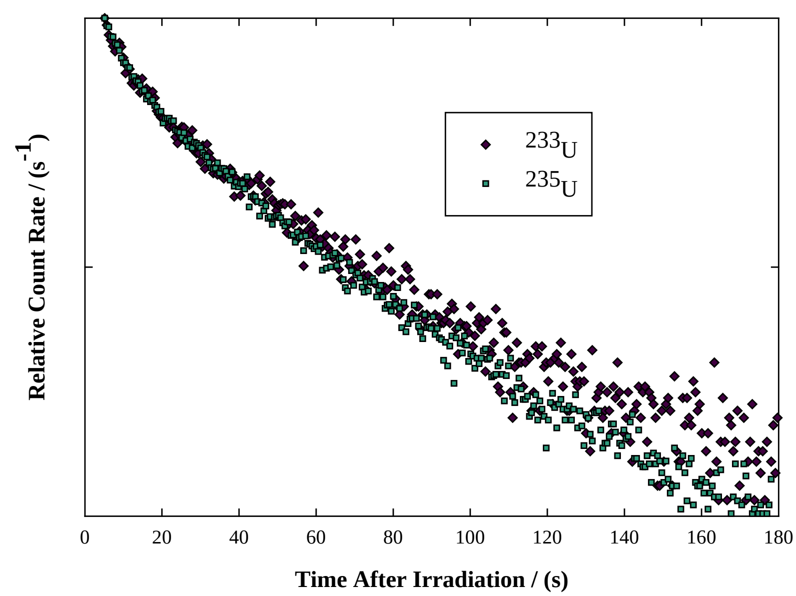

Figure 3: Differences in recorded temporal behavior of delayed neutrons emitted from ^{233}U and ^{235}U in RMCC's delayed neutron counting system.

3.2 Neutron Imaging

The honeycomb composite flight control surfaces (FCS) on CF-188 aircraft are susceptible to water ingress. Water enters these components and can cause structural degradation to the interior honeycomb structure. The degradation can become so severe that numerous rudders have departed the aircraft during flight. The CAF conducted an evaluation of various non-destructive evaluation (NDE) techniques capable of locating water within honeycomb composites. Several NDE techniques proved effective at locating the water, but neutron imaging was determined to be the most sensitive [7]. A thermal neutron radiograph of water inside the honeycomb core of a CF-188 rudder is shown in Figure 4.

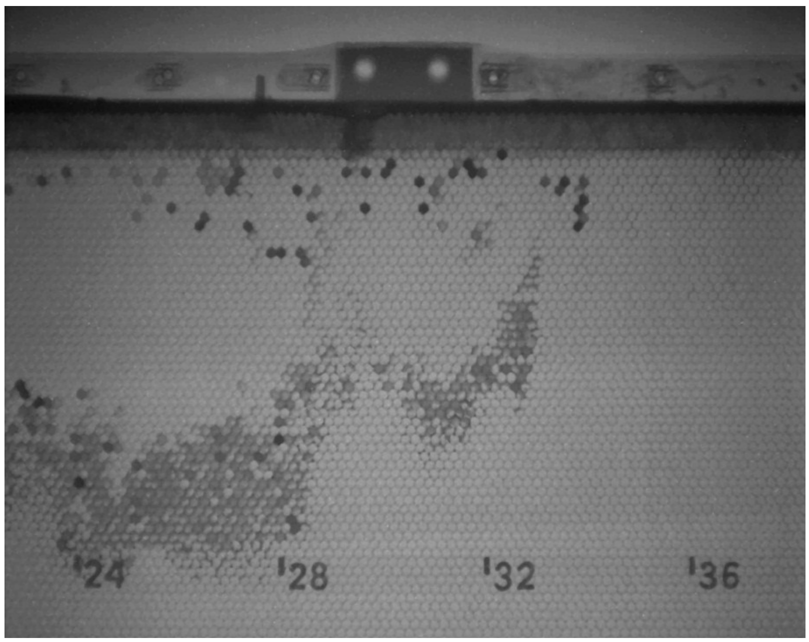

Figure 4: Water Ingress in CF-188 Rudder

Neutron imaging was used as the primary NDE technique in the development of an effective and non-invasive water removal technique for CF-188 flight surfaces. The successful drying method utilizes vacuum pressure and heat to allow water to be removed from the FCS [6]. This process is now performed at CAF fighter bases and has been instrumental in the reintroduction of numerous rudders previously compromised by water ingress. However, not all rudders can be returned to service following the drying procedure. The original designer of the rudders, Northrup Grumman, has developed water ingress limits which restrict the location and degree of water exposure, due to fears of structural degradation [7] [8].

In order to characterize degradation in honeycomb composites and assist in the quantification of degradation, a neutron tomography system was designed and built at RMCC [9]. The tomography system is capable of determining the exact location of water ingress inside honeycomb composites and to identify which structural adhesive bonds potentially are degraded.

Figure 5 is a neutron tomographic reconstruction of water ingress in a section of the honeycomb composite core of a CF188 rudder (full and side view).

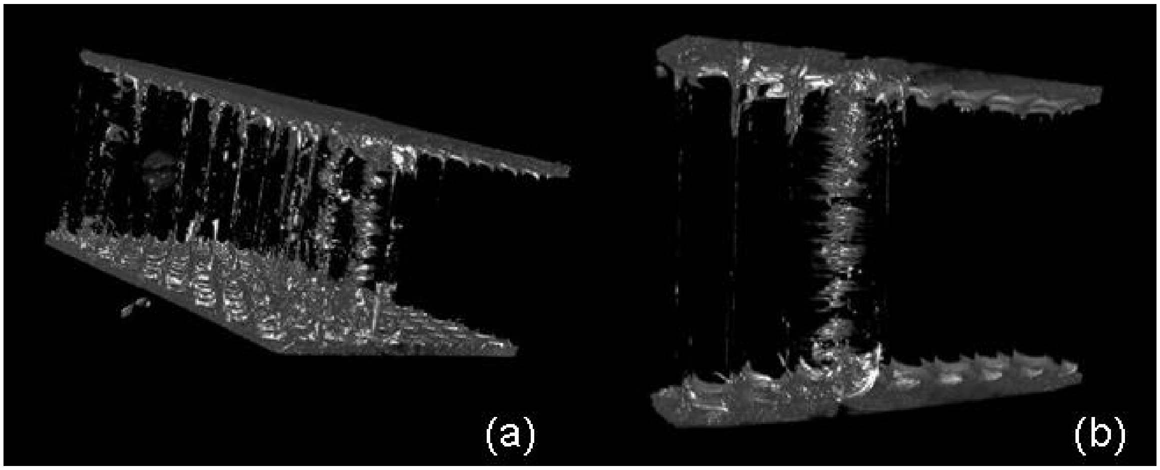

Figure 5: Water Ingress in Honeycomb Core; Full View (a), Section View (b)

During the initial licensing of the Neutron Beam Tube and imaging system at RMCC, the regulator limited usage to half power or a flux of $5.0\text{x}10^{11} n \cdot cm^{-2} \cdot s^{-1}$ at an inner site in the Be annulus . In February 2013, the Canadian Nuclear Safety Commission (CNSC) approved a license amendment, which permits neutron imaging to be conducted with the inner site thermal flux set point set to full power or $1.0\text{x}10^{12} n \cdot cm^{-2} \cdot s^{-1}$. This resulted in an increase in the neutron flux at the image plane as shown in Figure 6.The increase in flux has improved the spatial resolution and signal to noise ratio of the neutron imaging system at RMCC and enhances the instruments capability to investigate a wider variety of objects.

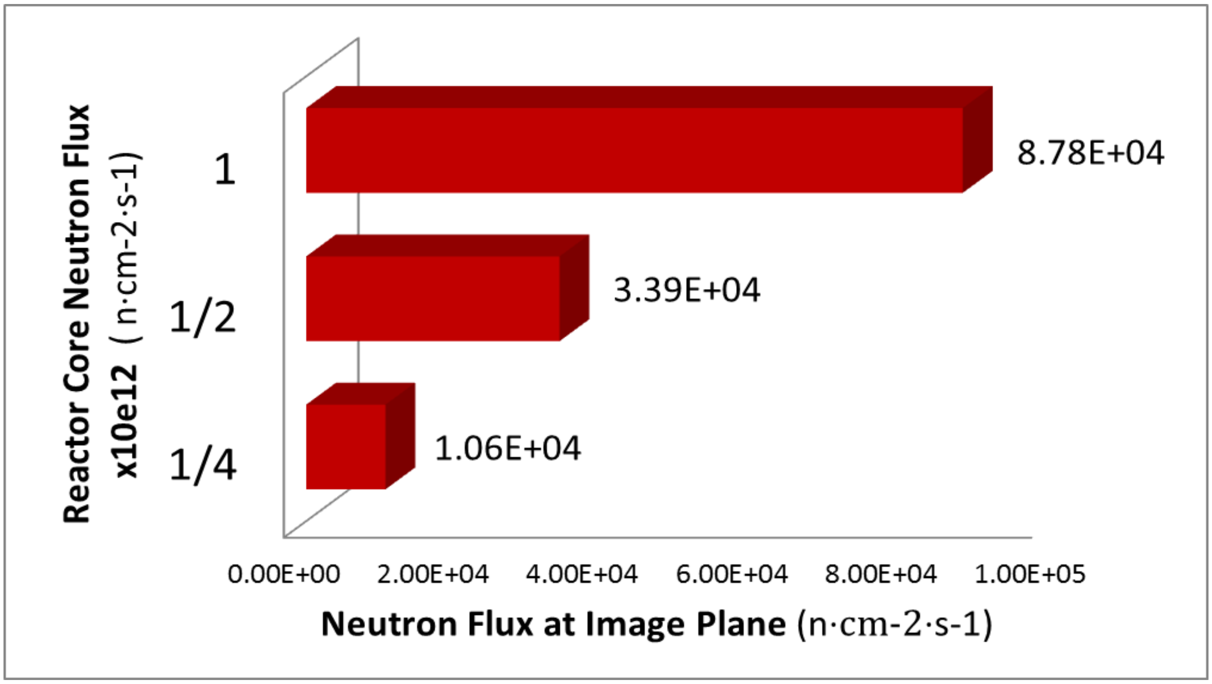

Figure 6: Neutron Flux at the Image Plane

3.3 SLOWPOKE-2 Integrated Reactor Control and Instrumentation System (SIRCIS)

RMCC's SLOWPOKE-2 reactor was installed in 1985 with an analog control system, MK-2, supplied by AECL. In 2001, the analog system was replaced with a digital system, designated SIRCIS. Version 1 of this digital system was in use from 2000 to 2012, when it was updated to V2. SIRCIS V2 uses LabVIEW and a National Instruments signal conditioning and switching interface (SCXI) to regulate the reactor thermal flux through the positioning of the control rod. The main input signals come from a Keithley 6485 Picoammeter which measures the neutron flux detector current. Thermocouples measure the pool temperature and the reactor core inlet and outlet temperatures. The optical encoder on the control rod assembly adjusts the control rod position based on the input signals and desired operating conditions [12].

The various information and functions provided to the operator by SIRCIS can be best examined by looking the graphical user interface (GUI) shown in Figure 7. All reactor operator interactions are performed through the GUI, which is divided into several areas by function.

1. Central Area (light grey): This rectangle contains the Neutron Flux and Power Scales along with all major reactor controls. The bottom area contains the Alarms & Events window, which displays all recent alarm and event messages, which are programmed to be displayed.
2. Left Area: This area contains the reactor core mimics. The top displays the Control Rod position with associated temperatures. The bottom is used for displaying and controlling the status of the Irradiation Site Controllers, and for displaying the Neutron Beam Tube position.
3. Right Area:

a. The top area, light grey rectangles, is used for alarm/warning indicators and also the status of water levels. Underneath these rectangles are the various status indicators.
b. Chart Area: This area contains charts for Neutron Flux and Control Rod Position, and the Reactor Core and Pool temperatures, and Reactor Power.

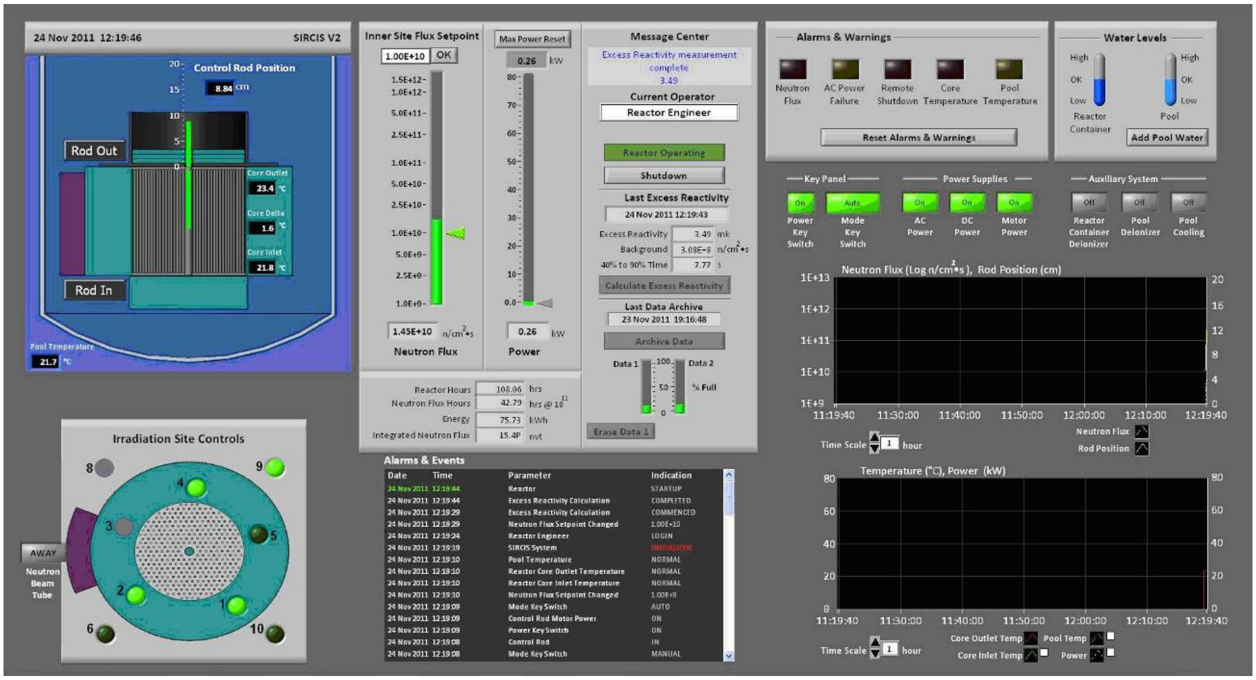

Figure7: SIRCIS GUI IN AUTOMATIC Mode

4. Conclusions

The SLOWPOKE-2 nuclear research reactor is a powerful and important scientific resource for the CAF. Nuclear capabilities provided by the reactor such as DNGC and neutron imaging are used to measure and evaluate a wide range of issues significant to the CAF. Due to its continued relevance, the CAF is committed to reinvesting and upgrading the facility and instrumentation. Examples of continued commitment are the recent upgrade and commissioning of SIRCIS V2 and the initiation of the documentation required for refueling. The current intention is to replace the original SLOWPOKE-2 fuel assembly at RMCC by 2017.

5. References

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