ReDICS: 5 years’ operation experiences and its technology

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Abstract. PUSPATI TRIGA Reactor (RTP) is the one and only 1MW research reactor in Malaysia that has been operating since 1982. RTP is used for radioisotope production, various R&D activities and operator training. After more than 3 decades of operations with an analog system, the control console is upgraded into a digital system. Reactor Digital Instrumentation and Control System (ReDICS) is designed, fabricated, manufactured, installed, tested and eventually commissioned in 2014. ReDICS mainly consists of Reactor Protection System (RPS), Operator Work Station (OWS), Data Acquisition and Control System (DACS) and Control Rod Drive Mechanism (CRDM). This paper shares the experiences and performance status throughout the 5 years of ReDICS operation after its commissioning. Besides, technical and operational data of ReDICS are presented and then compared with the old analog I&C system. This paper also describes the instrumentation and measurement technologies in ReDICS as well as the work performed to ensure ReDICS is always functioning at its best and safely.

1. Introduction
The design of ReDICS is based on the safety standard NS-R-4, Safety of Research Reactors (now known as SSR-3), published by IAEA. The safety philosophy comprising of safety concepts and principles are described in NS-R-4 to meet safety objectives such as nuclear safety, radiation protection, and technical safety [1]. It encompasses the implementation of the defense in depth concept, the establishment of legislative and regulatory infrastructure, the adoption of measures for the management and verification of safety, and the application of technical principles during the design and over the lifetime of the installation.

The defense in depth concept was applied on the design of RTP with its physical barrier protecting the fuel matrix, the cladding, the reactor pool with primary heat transport system, and the reactor building. The effectiveness of these barriers are monitored via the measurements of fuel temperature, pool water temperature, pool water level, overpower, and period signal, and the radioactivity level at various localized point within the building. The single failure criterion is applied on the design of the Reactor Protection System which will SCRAM the reactor and maintain it in a safe shutdown state during Design Basis Accidents (DBA) such as Loss of Coolant Accident (LOCA) and Reactivity Initiated Accident (RIA) [2].

The inherent safety feature is achieved by the use of TRIGA fuel which has a negative prompt coefficient of reactivity. The cooling of the fuel is achieved by the natural circulation of pool water.

The Reactor Protection System (RPS) of ReDICS has a safety function which shuts down the reactor if any of the trip parameters values exceeds the trip set point. Thus the RPS is designed to meet the single failure criterion, high reliability and means for inspection, test, and maintenance.
2. Methodology

After commissioning of ReDICS in 2014, all operation and maintenance works are done by RTP personnel. There are some replacements and developments related to RTP I&C system made to enhance the performance of ReDICS and RTP operation. The technical comparison between the analog I&C system and ReDICS are presented with respect of design criteria for general and specific design. The ReDICS system which comprises of Reactor Protection System (RPS), Operator Work Station (OWS), Data Acquisition and Control System (DACS), Control Rod Drive Mechanism (CRDM) and Wide Range Neutron Measurement System (WR-NMS) is studied in this paper including its alarms system that will notify the reactor operators on any abnormal condition or if any one reactor parameter exceeds its limit. The alarm system is the principal source of information for the detection of any specific off-normal condition. The Area Radiation Monitoring System (ARMS) and the Seismic Monitoring System (SMS) are also part of the instrumentation systems at RTP. This paper also categorizes each measurement instrumentation within RTP into neutron detector, nuclear channel, radiation monitor and non-nuclear instrumentation. The operational data of RTP are presented from 2010 until 2018 which include reactor operation (hours), total energy released (MWhours), number of samples and number of experiments. The ReDICS was tested before commissioning to ensure its correct functionality. The tests performed were Site Acceptance Test (SAT), Construction Acceptance Test (CAT), System Performance Test (SPT), Integrated System Test (IST) and Reactor Performance Test (RPT). After commissioning and full operation, the annual and semi-annual maintenance work are performed which include inspection, periodic testing, calibration and maintenance.

3. Results and discussion

RTP as a nuclear research reactor is providing training and services to private enterprises and public institutions as well as being involved in several research projects carried out by the universities and other research groups. In order to grant a safe and continuous reactor operation for the future, improving reliability and extending the system life time, many activities were carried out and successfully completed throughout 5 years of ReDICS operation to ensure RTP preparedness for such training and services which include installation of Resistance Temperature Detector (RTD) for inlet & outlet in primary cooling system, replacement of Operator Work Station (OWS), replacement of fission chamber, replacement of Area Radiation Monitoring System (ARMS) at the reactor pool top and development of user authentication for security.

Table 1 shows the comparisons of general design between the analog I&C system and ReDICS. Some design criteria need to be achieved and met in developing reliable I&C system such as redundancy and single failure criterion, diversity, independence, fail safe and ease of testing and maintenance. Table 2 shows the comparisons of specific design between the analog I&C system and ReDICS. The design criteria for the specific design of I&C system are including Reactor Protection System, Data Acquisition and Control System and control room.
Table 1. Comparisons of general design between the analog I&C system and ReDICS.

| Design criteria                     | Analog I&C system                                                                 | ReDICS                                                                                 |
|------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Redundancy and single failure criterion | • Uses 2 redundant safety channels                                                | • Same as the analog I&C system                                                        |
|                                    | • Adopts 1 out of 2 (1oo2) coincidence logic                                        | • Redundant control computer enhances system reliability                               |
| Diversity                          | • Uses pneumatic and electrical control rods actuators                             | • Same as the analog I&C system                                                        |
| Independence                       | • Electrical isolation between safety and non-safety channels                       | • Functional and physical separation of RPS                                            |
| Fail safe                          | • Fail safe design in the event of loss of power                                    | • Isolation between RPS and DACS                                                       |
| Ease of testing and maintenance    | • Considered in the design                                                          | • Same as the analog I&C system                                                        |
|                                    | • Uses modern technology such as self-test and diagnostic capability                | • Considered in the design                                                            |

Table 2. Comparisons of specific design between the analog I&C system and ReDICS

| Design criteria                | Analog I&C system                                                                 | ReDICS                                                                                 |
|-------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Reactor Protection System     | • Trip parameters: i. Fuel temperature                                            | • Pool water level as new additional trip parameter                                      |
|                               | • i. Over power                                                                   | • Manual trip button (OWS, reactor pool top, emergency exit door)                        |
|                               | ii. Reactor period                                                                | • Diagnostic, display and trip event recording (using DACS and OWS)                     |
|                               | iii. Loss of HV supply                                                            | • Digitalized control system with dual-redundant structure                               |
|                               | iv. Manual trip                                                                   | • stepper motors for CRs control                                                       |
|                               | v. AC motors for CRs control                                                      | • Three (3) WR-NMS for better reliability                                               |
|                               |                                                                                   | • Robust control algorithm                                                            |
| Data Acquisition and Control System | • Analog hardwired circuit for control system                                      |                                                                                       |
|                               | • AC motors for CRs control                                                       |                                                                                       |
| Control room                  | • Accident analysis after event using limited pen recorders                       | • Accident analysis after event using plotting software                                 |
|                               | • Hard-wired switches                                                             | • Better situation awareness using Large Display Panel (LDP)                            |
|                               |                                                                                   | • Soft switches                                                                        |

By the comparisons between the analog I&C system and ReDICS in Table 1 and Table 2, it can be seen that the safety philosophy of the analog I&C system has been completely preserved. Furthermore, the ReDICS has better design from the safety, reliability, operational, and maintenance point of view.

ReDICS comprises of Reactor Protection System (RPS), Operator Work Station (OWS), Data Acquisition and Control System (DACS), Control Rod Drive Mechanism (CRDM) and Wide Range Neutron Measuring System (WR-NMS) as shown in simplified block diagram in Figure 1.
The Reactor Protection System (RPS) of ReDICS provides the same function as the safety channels of the analog I&C system, that is, to shut down the reactor when any trip parameter exceeds its specified set points. The RPS trip the reactor by causing control rods to be inserted into the core. The RPS consists of 2 independent safety channels, which adopts one (1)-out-of-two (2) coincidence logic for shutdown triggering. The functions of the RPS in ReDICS are equivalent to the functions of the corresponding analog I&C system. This is to ensure that the current safety features are not jeopardized by the new design. The RPS provides the defense mechanism to prevent fuel failure which could result in the release of radioactive materials from fuel matrix. Two major accidents are postulated to happen on RTP, that is, loss of regulation and loss of coolant. Loss of regulation is described as an uncontrolled increase of power and/or increase of fuel temperature. Loss of coolant may result from large leakage of water from reactor pool due to certain events such as beam port breakage. The following trip parameters are implemented for the RPS of RTP:

a) Fuel temperature: A high value of fuel temperature indicates loss of regulation. (500°C)
b) Neutron power: A high value of neutron power indicates loss of regulation. (110%FP)
c) Reactor period: A low value of reactor period indicates loss of regulation (3sec)
d) Neutron detector amplifier high voltage: A low value indicates inability to measure a neutron power due to loss of measurement. (0.75 x Nominal HV)
e) Pool water level: A low value of pool water level indicates loss of coolant (30 cm below reactor top)
f) Manual trip: The manual trip switches disconnects electrical power to all control rod magnets so that the control rods will fall freely by gravity in order to shut down the reactor. The locations of the manual trip switches are on OWS, on reactor pool top and near to reactor emergency exit door.
The RPS has displays and controls via two (2) safety panels in the control room. The displays are consisted of analog, digital or status indication as follows:

| Analog and digital indication | Status indication | Operator controls |
|------------------------------|-------------------|------------------|
| Neutron power and period     | Trip parameter status indicators | Manual trip switches |
| Fuel temperature             | Reactor trip status     | Trip Reset switches |
| Neutron detector amplifier high voltage | Channel trip status |                  |
| Pool water level             |                                 |                  |

The Operator Work Station (OWS) is the top level human machine interfacing equipment through which a reactor operator can understand the status of the reactor by monitoring the appropriate process parameters and may take appropriate action if required through control devices. The OWS desk is designed by applying ergonomic and human factor principles which consist of monitors for graphic display, keyboards, mouses, printers, and computers with the capability and capacity to implement functionalities specified on the specification. The graphic display on LCD monitor shows the current reactor condition and the operator can control the reactor power level by manipulation of the control rod up/down soft-switches or by adjustment of the demanded power. If the operating parameters exceeds the set point, alarms are displayed on a window on the monitor and audible alarms are initiated until the operator acknowledges the alarm by pressing the acknowledge button.

The Data Acquisition Control System (DACS) measures process parameters from instruments such as fission chamber, thermocouples, temperature probes, level sensors, control rods position sensors, area radiation monitors and other auxiliary systems. The signal from sensors are fed to I/O boards and processed in digital computers and transmitted to the OWS via a communication network. Interfacing between RPS and OWS is achieved through DACS. The reactor power is controlled from the source with range up to full power based on the control algorithm and operator input. The reactor operator adjusts the four control rods either manually or automatically in a stable and reliable manner. The startup of the reactor is done in manual mode and it is possible to operate in either automatic or manual operation if the reactor power is higher than 1W. During automatic operation, the four control rods are controlled by the control algorithm. The automatic reactor controller gets the reactor power level from the neutron flux monitoring system and compares with the demanded power level set by the operator and issues appropriate control rod movement signals while maintaining the reactor period longer than the trip set point. Besides the normal operation mode, square wave operation mode is also available. The square wave operation mode is used if required to raise the reactor power level quickly by firing the transient rod pneumatically. The DACS is designed not to share any hardware or software with the RPS. The DACS has no direct interface with the RPS. This is to ensure that the RPS is not prevented from performing safety function by the DACS. The DACS has two processors whose statuses are continuously and mutually monitored. If a processor fails, the failed component is disabled and excluded from the algorithm and while the working component performs all DACS functions. All of important hardware including main processor, I/O boards, and power supplies are dual redundant for system reliability and availability. The display provides accurate, complete, and timely information with appropriate engineering units and color coded designations for ease of understanding the reactor operation.
The old control rod drive mechanism of RTP consists of AC motors connected to a rack and pinion mechanism which has the function to drive the control rod up and down for power regulation. In ReDICS project, the AC motors of the old control rod drive mechanism are replaced by stepper motors.

### Table 4. Comparisons of control mode between NORMAL and SQUAREWAVE operation mode.

| Operation mode | NORMAL | SQUAREWAVE |
|----------------|--------|------------|
| Control mode   | Manual & Automatic: Safety, Shim, Regulating and Transient rods are movable in both modes. Reactor operation starts with Manual mode | Manual mode: Transient rod (quick mode) |
|                | Automatic mode: Safety, Shim, Regulating are movable |

### Table 5. Description of CRDM for all four control rods at RTP.

| Control rod drives | SHIM | SAFETY | REGULATING | TRANSIENT |
|--------------------|------|--------|------------|-----------|
| Re-used (as it is) | Gear shaft (Rack & Pinion) | Induction motor | Servo motor | Ball nut & Worm gear |
| Old design | | Stepper motor | | |
| New design | | | Worm gear box | Stepper motor |
| Change | Potentiometer | Limit switches | |

The stepper motor has simple and robust operation and maintenance. The stepper motor is able to drive the existing rack and pinion mechanism. As such, the end shaft of the stepper motor is coupled with the pinion in order to transform rotational motion into linear motion. The control rod which is attached to the rack therefore moves up and down according to the rotation of the motor. The stepper motor is mounted inside the existing motor housing. The end shaft of the stepper motor is also coupled to the existing potentiometer to be used as the position feedback encoder. The motor drive is a set of electronic circuit that converts the number of pulses calculated by the control algorithm into a driving current for the stepper motor. The motor drive receives the input pulse from the computer system and sends out the driving current to the stepper motor of the corresponding control rod. The CRDM is connected to the DACS. The control rod movement is calculated by the computer based on the current power, demanded power and reactor period signals. The computer commands the control rod by sending signal pulses from the I/O interface to the motor drive assembly to activate the control rod drive mechanism. The signal pulses are converted into motor driving current which rotates the shaft of the stepper motor according to the calculated control rod position. The potentiometer of the control rod drive mechanism gives feedback on the actual control rod position to the computer system. Appropriate actions are taken if the difference between the actual control rod position and the calculated control rod position exceeds certain set point.
The WR-NMS consists of neutron detector (fission chamber) and electronics for signal processing. The neutron flux is measured by the fission chamber and the signal is further manipulated to give the neutron flux level by the source, wide range log or linear flux channel. The output of the WR-NMS includes log power, linear power, and reactor period. Two (2) WR-NMS are provided for RPS. From each WR-NMS, the RPS receives three (3) contact signals related to log power, period, and malfunction. These contact signals indicate if the measured value exceeds its set-point as RPS trip parameters. Another one (1) WR-NMS is provided for DACS. However, the DACS receives signals from two (2) WR-NMS on the RPS to improve its reliability. Hence, the DACS uses all three (3) WR-NMS signals. The DACS receives analog signals (log power, linear power, and reactor period) from the WR-NMS that directly indicates the current neutron power level. These values are used in the DACS control algorithm to calculate the control rods movement speed. The WR-NMS measuring range is from 10% to 200% FP for log power range, 0% to 150% for linear power range, and -30 sec to +3 seconds for reactor period signals.

ReDICS is also equipped with alarm system which is used to notify reactor operators of abnormal operating conditions, or components malfunctions. Alarm systems are meant to help operators operate the reactor safely; under both normal and abnormal operating conditions. The water temperature monitoring channel, fuel temperature monitoring channel and pool water level have alarm system in the control room which are provided with visual and audible annunciators on the RPS cabinets as well as alarms of Information & Control Display on OWS. Audible alarms are provided by using OWS for notifying the status of RTP and components to operator. The OWS supports an alarm control function. The visual and audible alarms are ergonomically designed according to style guides for ReDICS. The Area Radiation Monitoring System, Stack Monitoring System and Seismic Monitoring System are stand-alone systems in control room and independently providing alarms to operator [3].

The Area Radiation Monitoring System is to monitor the radiation level inside the reactor hall. Four area radiation monitors are positioned on the wall at strategic locations facing each of the reactor beam port of the reactor. Another radiation monitor is placed on the reactor top. A radiation monitor is also located at reactor basement. It consists of a radiation detector of GM type, electronic circuitry for signal conditioning and signal processing, a large bright LED display and an alarm siren, if the set limit is reached.

The Seismic Monitoring System is to obtain seismic information such as historical data and data on peak ground acceleration level at the reactor building. It is not related to reactor operation but is available for display of information on any earthquake event. The seismic monitoring system consists of a seismic acceleration sensor and a seismometer.

In order to operate the reactor, many variables have to be measured and monitored. Some of them are considered vital for the safety of the reactor, and their measurements have to be fast and reliable. This paper categorizes the measurement instrumentations within RTP into neutron detectors, nuclear channels, radiation monitors and non-nuclear instrumentations [4]. All the measurement instrumentation in ReDICS are described in Table 6 below.
### Table 6. Instrumentation and measurement technologies in ReDICS

| Category               | Measurement instrumentation                                                                 |
|------------------------|---------------------------------------------------------------------------------------------|
| **Neutron detector**   | • Fission chambers (log percent power, linear percent power, cps for source power range, sec for wide range)  
• Self-powered neutron detectors (flux)  
• Pre-amplifier  
• Log and linear amplifier  
• Count rate meters (source range and wide range)  
• Current meters (signal conditioning unit for neutron detectors operating in DC current mode)  
• HV power supplies  
| **Nuclear channel**    | • Area radiation monitoring system  
  i. Low level gamma monitor (beamports; pre-alarm at 5 μSv/hr, alarm at 10 μSv/hr)  
  ii. High level gamma monitor (reactor pool top; pre-alarm at 5 mSv/hr, alarm at 10 mSv/hr)  
  iii. Area neutron monitor (Radiation Portal Monitor)  
• Air radiation monitoring system (Stack Monitoring System, Continuous Air Monitoring System)  
• Process radiation monitoring system - monitors radioactivity in the process systems (primary cooling system, heat exchanger, water purification system, effluent water monitoring)  
| **Radiation monitors** | • Temperature measurements  
  i. Thermocouple (fuel temperature)  
  ii. Resistance Temperature Detector (water temperature)  
  iii. Thermostat (ReDICS cabinets)  
• Flow measurements  
  i. Magnetic flow meter (Water flow)  
  ii. Differential Pressure Transmitter (Air flow)  
• Water level measurement  
  i. Float magnetic level transmitter  
• Pressure measurement  
  i. Pressure transmitter with capacitive cells  
• Seismic monitoring system  
  i. Seismic acceleration sensor  
  ii. Seismometer  
| **Non-nuclear instrumentation** | Non-nuclear instrumentation comprises process measurements that do not involve neutron or gamma parameters. It includes both safety signals and safety related signals. Research reactors have many process variables to be measured. The sensors used to measure process variables in RTP mainly on temperature, pressure, level and flow.  
• Temperature measurements  
  i. Thermocouple (fuel temperature)  
  ii. Resistance Temperature Detector (water temperature)  
  iii. Thermostat (ReDICS cabinets)  
• Flow measurements  
  i. Magnetic flow meter (Water flow)  
  ii. Differential Pressure Transmitter (Air flow)  
• Water level measurement  
  i. Float magnetic level transmitter  
• Pressure measurement  
  i. Pressure transmitter with capacitive cells  
• Seismic monitoring system  
  i. Seismic acceleration sensor  
  ii. Seismometer  

Table 7 shows the operational data of RTP from 2010 until 2018 [5]. In year 2014 which ReDICS was commissioned, there was quite significant amount of reactor operation (hours) while 2018 recorded the highest amount of reactor operation (hours). 2013 has less reactor operation (hours) due to reactor shut down for dismantling old analog console and installation of new ReDICS.

Table 7. Operational data of RTP (2010-2018).

| Year | Reactor operation (hours) | Total energy released (MWhours) | No. of samples | No. of experiments |
|------|---------------------------|--------------------------------|----------------|-------------------|
| 2010 | 522.03                    | 335.09                         | 3217           | 198               |
| 2011 | 348.63                    | 241.70                         | 2416           | 126               |
| 2012 | 413.53                    | 278.22                         | 3399           | 210               |
| 2013 | 291.95                    | 149.01                         | 3305           | 198               |
| 2014 | 544.60                    | 365.03                         | 5482           | 256               |
| 2015 | 453.45                    | 235.11                         | 3181           | 206               |
| 2016 | 414.62                    | 218.62                         | 1964           | 139               |
| 2017 | 497.65                    | 299.88                         | 2866           | 197               |
| 2018 | 675.38                    | 404.11                         | 1848           | 157               |

Figure 2. Graph of reactor operation time and total energy released by RTP in the year 2010-2018.
The I&C system of the RTP is very important as it connects the reactor operator and the plant. Therefore, ReDICS were tested before commissioning to verify that all components and systems in ReDICS are functioned correctly. It is also important to carry out well-planned maintenance of RTP in order to ensure the safe, efficient and reliable operation. Maintenance on I&C system of RTP is carried out twice a year to ensure the good performance of RTP operation as well as safety concern for effective monitoring and control of various process parameters [6]. Indirectly as a result, RTP shall remain as an active research reactor to continuously operate for research, training, education and training. Table 7 presented the work performed before and after commissioning of ReDICS to ensure ReDICS is always functioning at its best and safe.
Table 8. Work performed before and after commissioning of ReDICS.

| BEFORE COMMISSIONING | AFTER COMMISSIONING |
|----------------------|---------------------|
| **Site Acceptance Test (SAT)** | • This test verifies that RPS, DACS, OWS, and field instruments perform their intended functions correctly after installation<br>• The SAT includes all the required entities to ensure basic functional integrity of the systems and components. |
| **Construction Acceptance Test (CAT)** | • Differential Pressure Type Transmitter<br>• Resistance Temperature Detector (RTD)<br>• Level Transmitter<br>• Panel Indicators<br>• Area Radiation Monitoring System<br>• Control Rod Driving Test<br>• Rod Drop Test<br>• Seismic Monitoring System |
| **System Performance Test (SPT)** | • Reactor Protection System<br>• Data Acquisition and Control System<br>• Operator Workstation<br>• Under Normal Operating Condition<br>• Under Abnormal Operating Condition |
| **Integrated System Test (IST)** | • Loss of Control System<br>• Loss of Magnetic Power<br>• Loss of Instrument Air<br>• Response Time for RPS |
| **Reactor Performance Test (RPT)** | • Rod Worth Measurement<br>• Power Ascension<br>• Neutron Power Calibration<br>• Square-Wave Operation |
| **Inspection** | • Standard TRIGA fuel elements<br>• Control rods<br>• Ventilation system<br>• Cooling System<br>• Minimum safety interlock<br>• SCRAM period<br>• Reactivity insertion rate<br>• Measurement of high voltage supply to console<br>• Control rods, reactor power and measurement of shutdown margin<br>• Safety channel<br>• Monitoring system of reactor pool water temperature and level<br>• Area radiation monitoring system<br>• Stack monitor<br>• Control rods carrier<br>• Rotary rack system<br>• Water purification system |
4. Conclusion
Reactor safety is an important issue with respect to employees, public, operation and utilization of the reactor. There are some activities have been planned to maintain the adequate safety and operating conditions of RTP which include the replacement of magnetic float level transducer with ultrasonic water level sensor. Other than that, ReDICS database will be developed for convenient data management and analysis as well as the integration of I&C monitoring system data for RTP. The comparisons made between the analog I&C system and ReDICS shows that the safety philosophy of the analog I&C system has been preserved. Furthermore, ReDICS has improved design with higher reliability and stability to ensure safe operation of RTP for the rest of its remaining life.

5. References
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