TRIGA KARTINI REACTOR FOR EDUCATION AND TRAINING
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Introduction

The Kartini reactor is the second Training, Research, Isotopes, General Atomics (TRIGA) reactor built by the company in Indonesia. As a TRIGA reactor Kartini has become a regular practice laboratory collaborating with Gadjah Mada University (UGM). Practice started in 1979 after the initial criticality to support the establishment of UGM nuclear engineering in the same year.

The Kartini reactor is located in the Yogyakarta Special District. As a special region Yogyakarta is also an educational city centre in Indonesia. UGM is an icon of education, and dozens of universities are located within a 30 km radius outside Kartini reactor. This location is very supportive for training or physical experiments.

In accordance with the roadmap for the development of nuclear power in Indonesia, the National Nuclear Energy Agency (BATAN) will build an experimental nuclear power plant. This reactor is a bridge to the Nuclear Power Plan. To support the reactor, Kartini supports the preparation of human resources by training personnel in engineering and safety, operations and other related aspects.

Increasing collaboration with universities has been important to support nuclear human resources development by education, training and research. As a part of this effort, access must be made available for students coming from universities far from the reactor facility, and programmes must be developed for research and development in the medical field and nuclear analytical techniques for environmental and mining element analysis.

The Safety Analysis Report prepared for relicensing was submitted in 2010, with review by the regulatory body approved in 2012. The ageing management programme; maintenance programme; assessment of the safety classification of structures, systems and components; and modification and aging assessment reports were included in the report as a part of the relicensing documents. Manpower additions for staff and reactor operators were conducted to prepare for staffing replacement of retirees. Implementation of the programme has resulted in a decrease of regulatory funding, increase in the operation hours for utilization, and opportunities to become an internet reactor laboratory and centre for nuclear training and medical research.

Characteristic of TRIGA Kartini

The Kartini reactor is located in the Yogyakarta Special District of Indonesia. This reactor is a TRIGA type using uranium zirconium hydride (UZrH) fuel with 19.75% enrichment. The reactor has a nominal power of 100 kW, and it is cooled by light water. The cooling water is demineralized and circulated by the primary cooling system. The reactor hall is equipped with a ventilation system in order to maintain a negative air pressure in the reactor hall above 0.1 cm H₂O. The inherent safety of the TRIGA fuel is robust to handle changes in reactor power operations due to
the large temperature coefficient of reactivity. The reactor is equipped with three control rods: a safety rod, a shim (compensating) rod and a regulating rod, which is used to regulate reactor operation. Any abnormal operation will cause the reactor to scram, i.e., all control rods fall to the bottom of the core. With the rods in their bottom position, the reactor is in a shutdown state.

The applications of the Kartini reactor are education and training, research and neutron activation analysis (NAA).

The three safety basic principles for the Kartini reactor are:

- The control of neutron production due to fission reactions in the reactor core using the control rods as well as the neutron detection systems,
- The confinement of fission products from reactions in the fuel using the fuel cladding, and
- The cooling of the core by the removal of the energy produced by fission and gamma heating in the fuel elements using the primary and secondary cooling systems.

Kartini reactor is typically operated at levels of power ranging from 10 W to 100 kW. One of the safety parameter of the reactor is the reactor period. The period of the reactor must be kept above 7 seconds when increasing the power of the reactor. A period below 7 seconds leads to a reactor scram by the reactor protection system. Another safety parameter is the maximum power of the reactor. If power reaches 110% of the nominal power the reactor is scrammed by the reactor protection system. In both cases, the reactor is shut down. These two parameters, the period and maximum power, are safety settings of the reactor safety system at the Kartini reactor.

In the reactor hall, for radiation protection purposes radiation monitoring systems and gamma area monitoring (GAM) are installed. The personnel working on the Kartini reactor, including researchers, must wear personal film badge dosimeters. As for guests and students pocket dosimeter are used. Air circulation in the reactor hall uses the ventilation system, which is equipped with a high efficiency filter in order to filter potentially activated particulate before air is released to the environment.

Environment monitoring is done regularly every month in order to characterize the environmental radioactivity conditions related to the impact of reactor operation. The concentrate activities and exposure are measured using a survey meter and environment material sampling such as air, sand, grass, surface water and ground water.

In order to perform reactor operation safely, all reactor systems must be operational, with their routine calibration and maintenance schedules accomplished, and used according to their operating procedures and guidelines.

**Experience for Education and Training**

Reactor operation and maintenance is conducted under the Kartini TRIGA Reactor Maintenance and Operation Quality Assurance Programme. A number of the staff have licenses, including:

- Operators and supervisor of reactor operations of the Group of Operation
- Technicians and supervisor of reactor maintenance of the Group of Maintenance
- Administrator and supervisor of the Group of Safeguards
The reactor staffing plan is shown in Table 1.

Table 1. Kartini TRIGA reactor staff

<table>
<thead>
<tr>
<th>Group of Maintenance</th>
<th>Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 supervisor and 10 technicians</td>
<td>Mechanics</td>
</tr>
<tr>
<td>1 supervisor and 3 technicians</td>
<td>Electric</td>
</tr>
<tr>
<td>2 supervisors and 4 technicians</td>
<td>I&amp;C</td>
</tr>
<tr>
<td>1 technician</td>
<td>Water chemistry</td>
</tr>
</tbody>
</table>

**Group of Safeguards**

| 1 supervisor and 5 responsible | Nuclear material inventory management (KMP) and physical inventory taking (PIT): KMP (A, B, C, D-0), AP |

**Group of Management**

| 1 technical manager | Reactor safety |
| 2 deputies to the technical manager | Nuclear Material Accountancy and Decommissioning Plan Reactor operating and maintenance |

**Group of Operation**

| 1 supervisor and 12 operators | Reactor operation and instrumentation and control (I&C) systems, primary cooling system, secondary cooling system, ventilation system/blower, water pH, pneumatic system, emergency diesel generator |

**Reactor Operations**

The objectives of Kartini reactor operation are research; irradiation for activation analysis; and education and training, including safety, security and safeguard inspections. The research and development activities of reactor operation include the fields of physics, I&C, substance analysis, process technology and neutron radiography using the irradiation facility. In order to enhance expertise in the field of nuclear reactor I&C, Kartini reactor is used for I&C testing and calibration, power and control rod calibrations and simulations based on the reactor. In addition, the Kartini reactor is used for student exercises and implementation of research for theses of students from several universities around the Yogyakarta region, which is called Joglosemartogo (Yogyakarta, Solo, Semarang, Purwokerto, Solotigo). During the years of 2010–2015, several activities utilizing the Kartini reactor were carried out, including Asia-Pacific regional activities such as the Nuclear School Experiments of Reactor Physics and Neutron Applications for Asia Pacific. This nuclear school was a collaboration among the International Atomic Energy Agency (IAEA), BATAN and Nuklear Malaysia that offered one week of lectures and exercises at the Kartini TRIGA reactor.
and a second week at the TRIGA Puspati of Malaysia. The IAEA supported the nuclear school by sending experts to assist in the preparation and practice of experiments at each reactor.

Table 2. Human resources in reactor technology

<table>
<thead>
<tr>
<th>Position</th>
<th>Field</th>
<th>Number of Personnel</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research professor</td>
<td>Reactor physics</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Researchers</td>
<td>Neutronics</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermohydraulics</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Nuclear device management staff</td>
<td>I&amp;C</td>
<td>2</td>
<td>1 research professor</td>
</tr>
<tr>
<td></td>
<td>Mechanics</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The use of the Kartini reactor for education of students from universities around Yogyakarta implemented under the guidance of the human resources in Table 2 can be seen in Table 3.

Table 3. Student guidance example around Joglosemartogo in 2013

<table>
<thead>
<tr>
<th>University</th>
<th>Number of Assistant Students and Experimenters</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGM</td>
<td>11, plus an experiment group</td>
</tr>
<tr>
<td>UNSOED</td>
<td>8</td>
</tr>
<tr>
<td>UNS</td>
<td>2</td>
</tr>
<tr>
<td>UNY</td>
<td>8</td>
</tr>
<tr>
<td>UNY</td>
<td>8</td>
</tr>
<tr>
<td>UIN</td>
<td>3</td>
</tr>
<tr>
<td>UNES</td>
<td>7</td>
</tr>
<tr>
<td>STTN</td>
<td>1, plus an experiment group</td>
</tr>
</tbody>
</table>

In addition to operating the Kartini reactor for various applications, the reactor directly provides information and views on nuclear technology and its application in the field of reactor technology to the community through visits to the facility. The data on visits of students and non-students can be seen in Figure 1.
As a part of the use of the Kartini reactor as a facility for training, various events have been held such as training for reactor operators and supervisors, maintenance technicians, on-the-job training (OJT) in reactor safety and IAEA fellowships as well as education and training for managers and supervisors in nuclear materials and safeguards. The activities related to education and training using the Kartini reactor can be seen in Table 4.

Table 4. Types of education and training at the Kartini reactor

<table>
<thead>
<tr>
<th>Number</th>
<th>Year</th>
<th>Number of participants</th>
<th>Date</th>
<th>Title</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2009</td>
<td>4</td>
<td>12–28 October 2009</td>
<td>OJT on Reactor Safety</td>
<td>BAPETEN</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>23</td>
<td>6–23 April 2009</td>
<td>Maintenance of Kartini Reactor</td>
<td>PTAPB-BATAN</td>
</tr>
<tr>
<td>3</td>
<td>2010</td>
<td>10</td>
<td>26 July–6 August 2010</td>
<td>OJT on Reactor Safety</td>
<td>BAPETEN</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>22</td>
<td>12–23 April 2010</td>
<td>Reactor Operator and Supervisor</td>
<td>PTAPB-BATAN</td>
</tr>
<tr>
<td>5</td>
<td>2012</td>
<td>27</td>
<td>17–28 September 2012</td>
<td>Safeguards</td>
<td>PTAPB-BATAN</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>24</td>
<td>5–16 March 2012</td>
<td>Kartini Reactor Maintenance</td>
<td>PTAPB-BATAN</td>
</tr>
<tr>
<td>7</td>
<td>2013</td>
<td>2</td>
<td>14 Jan.–1 February 2013</td>
<td>OJT on Reactor Maintenance</td>
<td>Bangladesh, IAEA</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>23</td>
<td>18 Feb.–7 March 2013</td>
<td>Reactor Operator and Supervisor</td>
<td>PTAPB-BATAN</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>14</td>
<td>31 Jan.–1 Feb. 2013</td>
<td>Reactor Operator and Supervisor</td>
<td>PTNBR-BATAN</td>
</tr>
</tbody>
</table>
---|---|---|---|---|---|
11 | 12 | 1 April–1 May 2014 | I&C System Coaching | BATAN |
12 | 142 | 22 November 2014 | Soft launching IRL in NYS-Jakarta 2014 | Young nuclear of 7 countries |
14 | 25 | 3–4 March 2015 | Nuclear Material Workshop | BATAN |
15 | 9–20 March 2015 | Retraining of Technicians and Supervisors, Maintenance of Kartini Reactor | PSTA-BATAN |
17 | 10 | 14 April 2015 | Nuclear School of Reactor Experiments | University of Sebelas Maret |

**Nuclear School Experiments**

The programme is aimed at young technical professionals with basic nuclear experience. Candidates should have technical degrees in engineering or science, with some nuclear background and current or future assignments linked to research reactor activities. The school is provided for young professionals seeking hands-on experience at a nuclear reactor facility to support the development of a nuclear power programme. The nuclear school programme involves theoretical classes and hands-on experimental activities.

The target participants come from the countries in the Asia-Pacific region that operate or are considering building a research reactor and those that wish to develop nuclear competence and infrastructure as a first step to develop a nuclear power programme. The programme was organized by Nuklear Malaysia and BATAN in cooperation with the IAEA. The program was implemented in the first week at the Kartini TRIGA reactor in Yogyakarta, Indonesia and the second week at TRIGA Puspati reactor in Bangi, Selangor, Malaysia.

Participants arrived from Thailand (2), Cambodia (1), Bangladesh (1), Indonesia (2), Malaysia (2), Vietnam (2), and Iraq (1). The schedule of experiments is provided in the Appendix.
The programme for the nuclear school carried out during the first week at the Kartini reactor related to:

- Theoretical lectures on safety and security instructions, principles of nuclear reactors, overview of research reactors, reactor kinetics and dynamics, neutron and gamma detection and introduction of kinetics and dynamics experiments
- Hands-on experimental activities by a visit to the Kartini reactor, reactor criticality and approach to criticality (protocol 1), reactor startup (protocol 2), reactor kinetics and dynamics (protocol 3), rod and core measurements (protocol 4), fuel temperature reactivity measurement (protocol 5), reactivity measurement of the fuel, graphite or aluminium (protocol 6) and power calibration (protocol 7).
Internet-Based Reactor Learning

Reactor physics education for students is easier so far at the reactor facility using the information facility as well as information technology application such as internet. The Kartini reactor has undertaken an effort to develop internet-based reactor learning with preparations to host an internet reactor laboratory (IRL) system. The concept was tried at the Nuclear Young Summit (NYS) 2014 forum (See Fig. 5). In that forum involving 142 young nuclear professionals from 7 countries, Australia, Vietnam, Thailand, Philippines, Malaysia, Bangladesh and Indonesia, reactor operation as well as a protocol was implemented by providing explanations and impressions on the website in the forum room and a videoconference link between the Kartini reactor main control room and NYS forum. Due to the several necessary inputs the IRL is still under development by assessment of the internet, software and I&C fields. Therefore, the application of the Kartini reactor for an IRL needs more reliability in its availability and establishment of contractual obligations among customers.

![Fig. 5. Soft launching IRL at the Nuclear Youth Summit (NYS)](image)

Conclusion

The Kartini TRIGA reactor is a research reactor of 100 kW power that has performed well in operations over the last 5 years. Located in a region where several universities are close, the reactor has numerous opportunities to utilize the reactor for the purpose of education and training. The types and numbers of students could enhance the general knowledge in reactor physics. The Kartini reactor’s operating experience for education and training has highlighted its benefits in reactor physics experiments and neutron applications. The Kartini reactor also has potential for utilization in more advanced fields of education and training such as the use of internet-based learning. More advanced utilization requires facilities that are more reliable, but the staff aim to fulfill the obligations required of an IRL.
Reactor Physics and Nuclear Engineering

Protocol – Kartini Reactor

Reactor criticality

I. Purpose

The purpose of this training course is twofold.

Part 1: At first, by the loading of fuel assemblies into the core, we will determine the critical mass of fissile material for the reactor.

Part 2: Once the fuel loading sequence is finalized, we will determine a critical configuration of the rods by the approach to criticality technique.

II. Theoretical Background

Reactor criticality is a condition in which the population of neutrons in the reactor core is in steady state. The minimum mass of fissile material that allows the reactor to reach the critical state is called the critical mass.

Criticality of a reactor is measured by defining a quantity called the $k_{\text{eff}}$ which is the ratio of neutrons in one generation to the number of neutrons in the previous generation (without external source of neutrons). For $k_{\text{eff}}>1$ the reactor is in supercritical conditions, in this case the population of neutrons in the reactor core continuously increases with time. Conversely, if $k_{\text{eff}}<1$, the reactor is subcritical and the number of neutrons decreases with time. The reactor is in a critical condition when $k_{\text{eff}}=1$.

In this experiment, the determination of the critical mass is done by recording the neutron detector signal (proportional to the neutron density) against the number of additional fuel into the core, searching for $k_{\text{eff}}=1$ conditions.

For that purpose the neutron source (Am–Be) has to be inserted into the reactor core. The number of neutrons ($S$) that enter the core at the beginning produce a number ($k_{\text{eff}}S$) of neutrons at the end of the first generation and a number ($k_{\text{eff}}^2S$) at the end of the second generation and so on.

The total multiplicity of neutrons in the core becomes

$$X = S \left( \frac{1 + K_{\text{eff}} + K_{\text{eff}}^2 + \ldots}{S} \right) = \frac{1}{1 - K_{\text{eff}}}$$

For $k_{\text{eff}}<1$ the total number of neutrons in the core becomes
\[ X \cdot S = \frac{S}{1 - K_{\text{eff}}} \]

When a detector is placed around the core, the count rate (C) is a portion of the number of neutrons in the core.

\[ C = F \cdot X \cdot S = \frac{F \cdot S}{1 - K_{\text{eff}}} \]

with F equal to the fraction of neutrons that is detected.

\[ \frac{1}{C} = \frac{1 - K_{\text{eff}}}{F \cdot S} \]

\(K_{\text{eff}}\) increases by increments of fuel, and if the condition has reached critical (\(K_{\text{eff}}=1\)) parameters, \(1/C\) is zero. By knowing the weight fraction of fissile material in each fuel element that has been inserted, the reactor’s critical mass can be determined.

The same technique can be applied for the determination of the critical configuration of the rods by moving the regulating rod up step by step and recording the count rate. By plotting \(1/C\) versus the position of the rod, the critical position of the rod can be found by extrapolation.

III. Equipment

1. Counting system
2. Binoculars
3. Flashlight
4. Calculator
5. Graph paper

Part 1 – Experimental procedures for the determination of the critical mass

1. In order to proceed with the critical mass determination, the reactor should be in the following state: 7 fuel elements in the ring F are removed and placed on a shelf in the tank. The reactor is in a subcritical condition.
2. The neutron source is inserted into the core. The three control rods are raised to their top position (fully withdrawn). In this condition, the neutron counting rate C of the fission chamber detectors is recorded.
3. Then adjust the position of the control rods as follows
   - Safety rod at the top position,
   - Compensation rod at 50% withdrawn
   - Regulating rod at the bottom
4. A fuel element is inserted into its original position in the core, and then all control rods are raised to their top position. The counting rate C of the fission chamber detectors is recorded.
5. Plot the graph $1/C$ versus mass of fissile material (U-235), and check if the next fuel assembly can be loaded.

The sequence for the fuel loading, the fuel assembly number, its position in the core and its mass of U-235 are given in the following table. Report in this table the values of $C$ and $1/C$.

<table>
<thead>
<tr>
<th>Fuel loading sequence</th>
<th>Assembly reference</th>
<th>Position in the core</th>
<th>Mass of U-235 (g)</th>
<th>Count rate $C$ (c/s)</th>
<th>$1/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial state</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>No. 2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>No. 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>No. 4</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>No. 5</td>
<td></td>
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<td>No. 6</td>
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<tr>
<td>No. 7</td>
<td></td>
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</tbody>
</table>

6. Repeat steps (3)–(5) until all the fuel elements are loaded in the core, checking that the reactor does not become supercritical through the increase of fissile material and the control rods are in the positions indicated in step (3).

7. When the core is loaded insert all control rods.

8. Using the graph $1/C$ versus the mass of fissile material (U-235), determine the critical mass of fissile material.

Notes:

One can notice that the graphical form to the critical conditions can vary, as shown in Figure 1. A linear-shaped graph is the most ideal for extrapolating the addition of fuel, and during phase 1 has been able to provide good estimates of the critical mass of the reactor. Estimates obtained from the stage 1 concave curve gives the number of the critical mass that is too small, while the convex curve provides estimates that are too large. The concave shape of the curve is generally obtained when the detector position is too far away from the neutron source, while the convex curve is obtained when the detector position is too close to the neutron source.
Part 2 – Experimental procedure for the determination of the critical configuration

1. In order to proceed with a determination of the critical configuration of the rods, the reactor is brought to the following state: All fuel elements are loaded, the neutron source is inserted into the core and the reactor is in a subcritical condition with the rods in the following positions:
   - Safety rod at the top position
   - Compensation rod at 70% withdrawn
   - Regulating at the bottom

2. The regulating rod is extracted step by step to a position close to the critical position. For each position of the rod, we wait for the count rate to stabilize. Then we record the counting rate C and calculate 1/C (Use the following table).

3.

<table>
<thead>
<tr>
<th>Rod Position (%)</th>
<th>Counting Rate C (s⁻¹)</th>
<th>1/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
4. Using the recorded count rate, plot the graph \( 1/C \) versus the position of the rod (in % of the upper position).
5. From the curve, decide to move further the rod until the critical position is approached: \( 1/C \) going to zero.
6. Using the three last values (linear part of the curve for better estimate) determine the critical position of the regulating rod.

V. Reference

1. A.E. PROFIO. Experimental Reactor Physics, John Wiley & Sons, New York, USA.

Reactors Physics and Nuclear Engineering

Protocol – Kartini Reactor

Reactor Power Calibration

I. Purpose

Perform calibration power reactor, which determines the actual power generated in the reactor core compared to the indicated power meter.

II. Theoretical Background

Reactor power is generated by the energy released from fission reactions that occur in the reactor. The number of fission reactions that occur per second per unit reactor volume is determined by \( N\phi\sigma_f \).

If the number of fission reactions per second needed to generate a power of 1 watt is \( 3.2\times10^{10} \) fissions, then the total power \( P \) of the reactor is given by the equation:

\[
P = \frac{S_f}{3.2 \times 10^{10}} \int_0^{r_c} f(v)dv \quad \text{(watt)}
\]

\( S_f = \) macroscopic fission cross-section
\( V_c = \) volume of the reactor

So by measuring the neutron flux in the core, reactor power can be determined. Another method is using the calorimeter method, which can be done in two ways:

Method 1: Reactor operated with the cooling system not in operation – cooling system off.
Method 2: Reactor operated with the cooling system is operation – cooling system on.

In Method 1, when the cooling system is off, i.e., non-stationary method, the heat generated by the reactor core accumulates in the tank, so the water temperature in the reactor rises. The maximum
limit of the temperature allowed for the water tank at the Kartini reactor is 40°C. The rate of temperature rise in the water tank at a fixed power level can be used to determine the actual power of the reactor. The power of the reactor is expressed by the following equation:

\[ P = \frac{\text{d}Q}{\text{d}t} = \frac{\text{d}T}{\text{d}t} \quad \text{Equation (1)} \]

with

- \( P \) = real reactor power in kW,
- \( Q \) = heat that is formed in the reactor,
- \( H \) = water value of KARTINI reactor = 19.0476 kWh/°C,
- \( T \) = temperature of the water tank reactor in °C,
- \( t \) = observation time interval, in hours.

In Method 2, when the cooling system is on, i.e., stationary method, the heat produced in the reactor tank is taken by the primary cooling system. Then, through a heat exchanger, heat is transferred to a secondary coolant system. The coolant flow rate being constant, we obtain stationary conditions. In the stationary condition, the heat transferred from the reactor core depends on water discharge (G) and different inlet and outlet temperature of the primary coolant system. Reactor power is determined mathematically by the following equation:

\[ P = 0.06G \cdot c \cdot \Delta T \quad \text{Equation (2)} \]

With

- \( G \) = primary cooling water discharge system, in litre/min,
- \( c \) = specific heat of water, 4.187 Ws/g°C,
- \( \Delta T \) = the difference in temperature between the exchanger inlet and outlet, in °C.

At reactor console, the reactor power can be read using either:

- The linear power channel (% power) associated with the Compensated Ionisation Chamber (CIC) detector in reactor
- The logarithmic power channel (power) associated with the fission chamber detector in the reactor.

If the linear power channel (% power) meter indicates a value different from the one given by the power calibration by Method 1, it is necessary to calibrate the linear channel (% power) as well as the logarithmic channel.

III. Equipment

1. Thermometer 20–100°C
2. Stopwatch
3. Small bucket to fetch water from reactor tank.
IV. Experiment Procedures

Method 1 – Cooling system off

1. Reactor is operated in critical without reactor coolant system running.
2. Raise the reactor power to a constant level of power of 100 kW.
3. Observe during one hour the water temperature increase in the reactor tank. Record the temperature value every 5 minutes in the following table.

<table>
<thead>
<tr>
<th>Time (mn)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
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4. Plot the graph of the temperatures versus time.
5. Calculate the slope of the curve.
6. From the value of the slope determine the actual power of the reactor using Equation (1).
7. Compare the value obtained to the power indicated by the linear power meter.

Method 2 – Cooling system on

1. The primary and secondary cooling systems are turned on.
2. Record and write in the following table the temperature of the water tank, of the heat exchanger inlet and outlet of the primary cooling system, every 10 minutes until the tank water temperature remains constant (stationary).
<table>
<thead>
<tr>
<th>Time (mn)</th>
<th>Tank Temperature (°C)</th>
<th>HE Inlet Temperature (°C)</th>
<th>HE Outlet Temperature(°C)</th>
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3. Once the stationary state is obtained, use Equation (2) to calculate the actual power reactor.
4. Compare the value obtained to the value obtained by Method 1 and to the power indicated by the linear power meter. Comment the results.

**Reactor Physics and Nuclear Engineering**

**Protocol – Kartini Reactor**

Rods and Core Reactivity measurements
(Control Rods Calibration)

I. Purpose

a. To establish the calibration curve of the regulating rod by the positive period technique,
b. To deduce the differential reactivity curve of the regulating rod (\(\Delta \rho/\Delta H\) versus the height \(H\) of the rod),
c. To establish the calibration curve of the shim rod by the swap technique using the calibration curve of the regulation rod, and to extrapolate the total worth of the shim rod,
d. To establish the total worth of the safety rod by comparison with the worth of the shim rod,
e. Calculate three control rod reactivities in the reactor,
f. To calculate the reactor excess reactivity,
g. To calculate the shutdown margin of the reactor.

II. Theoretical Background

Kartini reactor has three control rods:

- One safety rod,
- One compensating or shim rod
- One regulating rod.
The height of the rod is given in % of the maximum height, i.e., when the rod is fully extracted. When moving up the rod into the core the reactivity of the core is increased by the efficiency of the rod corresponding to $\Delta \rho$.

The calibration curve of a rod gives the $\Delta \rho$ of the core as a function of the height of the rod $H$ as shown in Figure 1. This curve is used to predict the change in the core reactivity related to the change in the position of the rod.

![Figure 1: Calibration curve, $\Delta \rho$ versus $H$](image1)

The differential curve $\Delta \rho/\Delta H$ versus $H$ can be also established (See figure 2).

![Figure 2: Differential curve, $\Delta \rho/\Delta H$ versus $H$.](image2)

The region in which the reactivity of the core varies almost linearly with the position of control rod is found in the central part of the core height, typically in the region $20% < H < 80%$.

Due to shadowing effect (the decrease of the neutron density induced by one road will decrease the effectiveness of the other rod), the total worth (maximum $\Delta \rho$) of the three control rods is generally less than the sum of the worth of each of the three control rods taken independently. Nevertheless, assuming that the shadowing effect is negligible for rods that are far away one from other in the core, it is possible to assume that the total worth of the rod is the sum of the worth of each rod.
Core excess reactivity will be then calculate taking the difference between the total worth of the rod and the worth brought into the core by the three rods when they are placed in a critical configuration at low power (10 W for example).

The shutdown margin of the reactor is defined as the total worth of the rods minus the core excess reactivity. It is an important parameter for the safety of the reactor. This shutdown margin has to be also calculated with a rod stuck in its upper position, taking the assumption that the rod with the larger worth is stuck.

In order to plot the calibration curve of the regulating rod by the positive period method, in fact the measurement of the doubling time for the training course, we need to relate the doubling time and the reactivity of the core when it is supercritical.

When the reactor is supercritical, the neutron density increases exponentially (after the prompt jump and a transitory state). According to the reactivity of the core, the speed at which the neutron density is increased can be characterized by the reactor period, i.e. the time taken to increase the power by “e”, e=2.718.

Experimentally, it is easier to measure the time taken to multiply the power by a factor 1.5 or 2.0. We will measure the doubling time in this training course.

Using the equation of kinetics it is possible to establish a curve called the In-hour curve which relates the reactivity of the core and the doubling time. This curve and a table giving the doubling time for particular values of reactivity are given in the Appendix.

III. Equipment
   a) Picoammeter Keithley
   b) Stopwatch
   c) Reactivity graph versus time with factor 1.5 or 2.0

IV. Experiment Procedure

Part 1 – Plotting the calibration curve of the regulating rod – doubling time measurement

1. The reactor is stabilised at low power (10 W) with the safety rod in position up and regulating rod in position down. The Shim rod is used for the control of the reactivity.
2. The compensation ionisation chamber (CIC) is connected to the picoammeter to record the current.
3. The regulating control is moved up by a small step. The reactor becomes supercritical. The picoammeter is used to measure the doubling time.
4. Once the measurement is done, the shim rod is lowered to reduce the power back to its initial value (10 W), and later on it is moved to find a new critical state with the regulation rod at its previous position.
5. From the doubling time measured in step 3, the reactivity increase due to the extraction of the regulation rod is determined. This value is reported on a graph as a function of the height of the rod.
6. The steps 3 and 4 up are repeated until the regulating rod is fully extracted in its upper position.
7. The total worth of the Regulation rod is established.

Part 2 – Plotting the calibration curve of the shim rod – swap method:

1. The reactor is stabilised at low power (10 W) with the safety rod in position up and shim rod in position down. The regulation rod is used for the control of the reactivity.
2. The CIC is connected to the picoammeter to record the current.
3. The Shim rod is extracted by a small step maintaining the reactor critical by moving the Regulating rod down to compensate for the change in the core reactivity.
4. The change in the reactivity related to the insertion of the Regulation rod is used to find the change in the reactivity related to the withdrawing of the Shim rod using the calibration curve of the regulation rod.
5. The value is reported on a graph as a function of the height of the rod.
6. Steps 3–5 are repeated until the shim rod is fully extracted. The critical configuration for the shim rod at the height 50% will be searched during this experiment in order to use the results in part 3.
7. Assuming that the core is symmetrical on the vertical axis, established the total worth of the shim rod.

Part 3 – Establishment of the total worth of the safety rod – related to the worth of the shim rod

1. The reactor is started up with the shim rod fully extracted (used as the safety rod), the safety rod being place at the height 50%. The regulation rod is used to increase and stabilize the power at 10 W.
2. By comparing the critical configuration obtained in this condition to the one established in Part 2 with the shim rod at 50% and the safety rod fully extracted, the total worth of the safety rod will be estimated (making the assumption that the core is symmetric on the vertical axis).

Part 4 – Determination of the core reactivity

From the previous results calculate:

1. The total reactivity of the three control rods (Assuming there is no shadow effect)
2. The excess reactivity of the core
3. The shutdown margin of the core
4. The shutdown margin of the core with one rod stuck (with the largest worth)