Commissioning Preparation of a Subcritical Experimental Facility For $^{99}$Mo Production

Syarip1*, P I Wahyono1, W Susilo1, K Donny2

1Centre for Accelerator Science & Technology, National Nuclear Energy Agency, JL. Babansari, POB 6101 ykbb, Yogyakarta
2Indonesian Nuclear Industry (PT-INUKI) Puspiptek Serpong.

*Email: syarip@batan.go.id

Abstract: A sub-critical reactor experimental facility for $^{99}$Mo isotope production (SAMOP) has been designed and constructed at the Centre for Accelerator Science and Technology (CAST), Nuclear Energy Agency (BATAN). The facility is fueled by uranyl nitrate and will be driven by an external neutron source from the radial beam-port of Kartini reactor. The aim of the paper is to report the status, progress and readiness for commissioning of the subcritical reactor experimental facility. The safety analysis results and integration of all components and systems are also discussed. The commissioning method is referring to the IAEA document on Safety of Research Reactors, Specific Safety Requirements No. SSR-3, 2016. All main components such as reactor core and reflector assembly, fuel tubes, and control rod have been constructed and tested. In overall the SAMOP experimental facility is ready for fuel loading/ commissioning and operation performance test.

1. Introduction
The most common radioisotope used in diagnosis is $^{99m}$Tc which is daughter isotope of $^{99}$Mo, accounting for 80% of all nuclear medicine procedures worldwide. Commonly, most $^{99}$Mo is produced using highly-enriched uranium placed in high-power nuclear research reactors [1,2]. Recently there are eight medical isotopes producing reactors that provide over 90% of the world's $^{99}$Mo needs. The unscheduled shutdown of two of these reactors in 2009 and 2010 (Canadian and Dutch reactors) caused worldwide shortages of $^{99}$Mo, leading to the delay or cancellation of many medical procedures [3,4]. The medical community has been plagued by $^{99}$Mo shortages due to aging reactors, such as the NRU (National Research Universal) reactor in Canada. There are currently no US producers of $^{99}$Mo, and NRU was being shut-down in 2016, which means that another $^{99}$Mo shortage is imminent unless a potential domestic $^{99}$Mo producer fills the void [5].

The $^{99}$Mo producing system without a critical nuclear reactor and without using highly-enriched uranium is being implemented at the Centre for Accelerator Science & Technology (CAST), National Nuclear Energy Agency (BATAN). The system is called a subcritical assembly for $^{99}$Mo production (SAMOP) experimental facility. In future, for its production process will use an external neutron source from neutron generator or a particle accelerator and target that generate neutron in the core of subcritical assembly [6]. Compact neutron generator (CNG) is a particle accelerator, as predicted that it will probably the best-known uses are for cancer therapy, medical isotope production, and food irradiation [7]. The similar method is being developed by SHINE which plans to produce at least one-half of the U.S. need for $^{99}$Mo by 2016 [1,8].
The SAMOP experimental facility as a test facility which use an external neutron source from the beam-port of Kartini TRIGA reactor, which has been identified suitable for this purpose [9,10]. It is expected that the SAMOP system will reduce much less waste than current $^{99}$Mo production methods. The use of subcritical aqueous homogenous reactors driven by accelerators presents an attractive alternative for producing $^{99}$Mo. In this method, the medical isotope production system itself is used to extract $^{99}$Mo or other radioisotopes so that there is no need to irradiate special targets. In addition, it can operate at much lower power compared to a traditional reactor to produce the same amount of $^{99}$Mo by irradiating targets [11,12]. Study to produce $^{99}$Mo with activation method by using TRIGA reactor have also been done to fulfill the need of $^{99}$Mo as $^{99m}$Tc generator for use in nuclear medicine [4,13,14].

The aim of the paper is to report the status and progress and commissioning preparation of the SAMOP reactor experimental facility. The safety analysis results and integration of all components and systems are also discussed.

2. Description of SAMOP experimental facility

The SAMOP experimental facility as a test facility which use an external neutron source emerge from the radial beam-port of Kartini reactor. The external neutron source has been identified as thermal neutron in order of $10^8$ n/cm$^2$s. The SAMOP core consists of annular cylindrical tube containing uranyl nitrate [UO$_2$(NO$_3$)$_2$] or UN as fuels and target, surrounded by ring of UO$_2$(NO$_3$)$_2$ tubes. The TRIGA fuel elements is loaded in the ring together with UO$_2$(NO$_3$)$_2$ tubes to increase neutron multiplication factor. The enrichment of all UN used in SAMOP is 19.75% $^{235}$U.

The SAMOP reactor core and reflector is a cylinder with 40.4 cm in diameter and 43 cm in height. The core and reflector is located in the cooling tank with diameter and height of 120 cm and 400 cm respectively. The SAMOP core, reflector, boral rod neutron absorber, and coolant tank is described in Figure 1. The SAMOP experimental facility is provided by an instrumentation and control system in such that if there is a criticality indication, the boral control rod neutron absorber will dropped automatically inserted to the SAMOP reactor core. Figure 2 shows the radiation shielding of SAMOP which is consisted of paraffin and barite concrete. The shielding at the front side is a combination of paraffin and concrete both with have the same thickness i.e. 55 cm. Figure 3 shows the location of SAMOP in the Kartini reactor.

![Figure 1. Core and reflector configuration and cooling tank of SAMOP experimental facility](image_url)
3. Materials and methods

3.1. Commissioning program

In general, the commissioning program is approaching the IAEA document on Safety of Research Reactors, Specific Safety Requirements No. SSR-3, 2016 [15]. Purpose of commissioning is to demonstrate that SAMOP systems and subsystems operate together in an integrated manner in accordance with the design objective and meet the performance criteria regarding operational requirements, occupational safety requirements and nuclear safety requirements. Pre-commissioning performed to demonstrate that systems operate as expected according to design objective, operational and safety requirements, interface with other systems or services, and appropriateness of operational and maintenance documentation.

Commissioning Plan: the responsibility of commissioning plan is a team under the Centre for Accelerator Science & Technology (CAST). The commissioning plan consisted of a description of the objective of commissioning, commissioning organization, management group, commissioning group
& teams, operations group, construction group, commissioning safety review committee, and commissioning quality assurance group.

Commissioning Stages: Stage A – Pre Fuel Loading Tests, to ensure that the plant systems properly function in an integrated manner. Stage B – Fuel Loading Steps, the fuel is loaded by following loading-unloading procedures. Fuel loading and first approach to lowest sub-criticality level i.e. UN at annular core ($k_{eff} \sim 0.8500$) and UN solution filing to UN-tube, this activity will be done at PT-INUKI (Indonesian Nuclear Industry Company) in Serpong near Jakarta. Then, the annular core and UN-tube containing UN solution is transported to CAST Yogyakarta, where fuel progressively loaded into the ring of annular core. The UN-tube and Triga fuel loading steps is done in accordance with procedure for optimum sub-criticality approach. The first step to achieve a higher sub-criticality level ($k_{eff} \sim 0.9000$), then continue loading fuel to approach the optimum $k_{eff} \sim 0.9800 – 0.9900$. The power and neutron flux tests conducted at the optimum sub-criticality level, and demonstrate core compliance with nuclear & thermal-hydraulic design.

The detailed commissioning program is submitted to the safety committee and the regulatory body and subjected to an appropriate review and assessment before being implemented.

3.2. Commissioning procedures and reports

Procedures is prepared, reviewed and made subject to approval for each commissioning test prior to the commencement of the tests. Commissioning activities are performed in accordance with approved written procedures. The commissioning program is including provisions and procedures for audits, reviews and verifications intended to ensure that the program has been conducted as planned and that its objectives have been fully achieved. Provisions is also including for resolving any deviation or deficiency that is discovered during the commissioning tests.

Commissioning procedures covering the scope, sequence and expected results of these tests are prepared in appropriate detail and in accordance with the quality assurance requirements. The commissioning reports are kept for the entire lifetime of the facility including the decommissioning stage. The reports cover the following: the purpose of the tests and the expected results; the safety provisions required to be in force during the tests; precautions and prerequisites; the test procedures; the test reports, including a summary of the data collected and their analysis, an evaluation of the results, the identification of deficiencies, if any, and any necessary corrective actions.

The results of all commissioning tests, whether conducted by a member of the operating organization or a supplier, are made available to the operating organization and maintained for the lifetime of the facility.

4. Result and discussion

SAMOP experimental facility is a part of Kartini research reactor utilization program, which is the utilization of neutron source from the radial beam-port of Kartini reactor. In accordance with Article 6 of regulation of Head of National Nuclear Regulatory Body (BAPETEN) No. 5 of 2012 on Safety in Utilization and Modification Non-power Reactors must obtain approval (license) from BAPETEN[16]. To implement utilization, Licensee must compile: document utilization program, and document utilization management system. The document of utilization program contains: preliminary; description of utilization; design, fabrication and installation; safety analysis; radiation protection; countermeasure of nuclear emergency; organization and responsibility; and description of the implementation schedule. The utilization management system is integrated with the system installation management.

The application letter for license request has been submitted to BAPETEN in November 2016 attached with 2 supporting documents. The titles of two documents are: “SAMOP radiation protection and safety program”, and “Kartini radial beam-port utilization program for SAMOP R&D”. Following the request, BAPETEN evaluates the document, and in the process it needs several revisions to the license application document. It is expected that the license can be issued by
BAPETEN at July 2018. These two documents representing the safety analysis report (SAR) document of SAMOP experimental facility. The license processing took time about one and half year.

The SAR result shows that for the required neutron multiplication factor of 0.98 to 0.99 (sub-criticality level) can be achieved by a combination of fuel (UN) height in the annular tube of 38 cm surrounded by 5 – 8 of UN tubes in the ring (see Figure 4). Whiles, the SAR result related to the radiation safety is shown in Figure 5, that the maximum effective radiation dose received by personnel in the working area of the SAMOP experimental facility is 2.76 μSv/h, this value is below the dose limit for radiation worker at the Kartini reactor, i.e. 7 μSv/h. The calculation of $^{99}$Mo isotope production in the UN-tube located in the center of core has also been done, the result shows that the mass, radioactivity, and effective dose of $^{99}$Mo per batch are $1.20 \times 10^{-6}$ g, 0.578 Ci, and 0.651 mSv/h respectively [17].

![Figure 4](image_url). The neutron multiplication factor $k_{eff}$ as function of UN-tubes inserted to the ring.  

![Figure 5](image_url). Calculated radiation exposure surrounding SAMOP reactor.

At the beginning of 2018, all the components of SAMOP have been made and ready for integration. The commissioning plan will begin with the pre-commissioning program that is to integrate all components and test their respective functions. The commissioning organization has been prepared according to regulations, the organization chart is shown in Figure 6. Whiles, the commissioning process has also been prepared which consisted of 6 steps such as shown in Figure 7. It is shown that there are 2 locations which needs a nuclear accounting and transport permit i.e. at PT-INUKI and CAST. UN fueling to UN-tube and to UN-annular-tube/core (conducted at PT-INUKI), then the UN-tube and core transported from PT-INUKI in Serpong to CAST in Yogyakarta to be irradiated in Kartini reactor beam-port.

The performance test is an irradiation process or operation of SAMOP experimental facility using neutron source from the radial beam-port of Kartini reactor. The operation time per batch is 100 h, then the reactor is shut-down and the UN-tube located in core center will be transported to PT-INUKI for $^{99}$Mo extraction. Post $^{99}$Mo extraction process, the UN will be reconditioned and reload to UN-tube, then the performance test will be repeated for reproducibility.
The preparation on installation works for mechanical components has been done such as reactor core and reflector, reactor coolant tank, and reactor control rod drive (Figure 8), and neutron beam collimator, radiation shielding (Figure 9). In general, all SAMOP components were ready for overall integration. The preliminary measurement of neutron source out from radial beam-port without collimator has been done and the result shows that the total neutron flux is $3.8 \times 10^8$ n cm$^{-2}$ s$^{-1}$ in average [18], this value is in accordance with the requirement for SAMOP. In the future, the SAMOP system will be developed using thorium nitrate as fuel and the preliminary study for this purpose has been done [19].

![Figure 6. SAMOP commissioning organization](image)

![Figure 7. The commissioning process](image)
5. Conclusion
The SAMOP reactor experimental facility system using uranyl nitrate to produce $^{99}$Mo isotope operate at subcritical condition with the neutron multiplication factor of 0.98 to 0.99 is ready to be commissioned. All main components such as reactor core and reflector assembly, fuel tubes, and control rod have been constructed and tested. The safety analysis result shows that all parameters meet the design requirements. The commissioning permit from BAPETEN is expected will be granted at July 2018. In overall, the SAMOP experimental facility is ready for fuel loading/ commissioning and operation for performance test.

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