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The Development of Neutron Imaging Instrument at PUSPATI TRIGA MARK II Nuclear Research Reactor

Muhammad R. M. Zin[1,⋆], *Rafhayudi Jamro*[1], *Azraf Azman*[1], *Mohd Haire Rabir*[1], *Khairiah Yazid*[1], *Zaifol Samsu*[1], *Hishamuddin Husain*[1], *Faridah Idris*[1], *Muhammad S. Sarkawi* [2], *Muhammad F. Azizan*[3] *and Nirmala Sharipudin*[3]

[1]Malaysian Nuclear Agency, 43000, Bangi, Selangor, Malaysia
[2]University Technology of Malaysia, Skudai, Johor Baharu, Malaysia
[3]Department of Museum Malaysia, Jalan Damansara,50480 Kuala Lumpur, Malaysia

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Abstract: This article describes about the newly developed neutron radiography and imaging (NURI) instrument at 1 MW PUSPATI TRIGA MARK II (RTP) Nuclear Reactor in Malaysian Nuclear Agency, Malaysia. The NURI has been utilizing neutron beam from the reactor core through the collimator in radial beamport #3. Operating power for the NURI instrument is 750 KW. The thermal neutron flux at 4.7 meter away from the collimator inlet is around 10^5 ncm^{-2}s^{-1}. The flat neutron beam area at the sample location is governed by 24 inches diameter of neutron beam with the maximum L/D ratio of 130. NURI can be utilized based on conventional film or using digital imaging system. Currently, NURI is using the CCD based neutron camera. The new collimator improves exposure period 4 times faster than the previous one. NURI instrument has capability for obtaining radiographic projections for tomography reconstruction for various applications.

Keywords: Neutron imaging, Radiography, Tomography, PUSPATI.

1 Introduction

The PUSPATI TRIGA MARK II (RTP) is the only one nuclear research reactor in Malaysia. The first criticallity for this reactor was achieved on 28 July 1982, from there on this nuclear reactor has been utilized for neutron irradiations for many applications and also in neutron radiography and imaging. Incore irradiation mainly in the applications of neutron activationas analysis, radioisotope production and also small angle neutron scattering [1]. Design power of the reactor is at maximum capacity of 1 MW, however, utilization for irradiation is at 750 kW, depending on the user requirement. Total neutron fluxes of reactor core irradiation facility is about 8.5x10^{13} ncm^{-2}s^{-1} at central timble, 8.50x10^{12} ncm^{-2}s^{-1} at pneumatic transfer system and 2.0x10^{12} ncm^{-2}s^{-1} at rotary rack [1]. These facilities are located inside the reactor core. The radiography facility is located outside the reactor core utilizing neutrons through the radial beamport #3. The beamport is inserted inside the graphite reflector and facing the reactor core in radial direction. For imaging instrument, neutron reaches the object in the exposure room are extracted by the collimator which is inserted in this beamport. The layout of beamport for PUSPATI TRIGA MARK II reactor is shown in Fig. 1.

Neutron Radiography and Imaging (NURI) instrument at PUSPATI TRIGA MARK II nuclear research reactor is completed after following the three phase of development stages. Where, first radiography station known as Nur-I had been installed at radial beamport #1, the step divergence collimator was used where the inlet of collimator facing the graphite directly [4]. This resulting in low neutron and high gamma radiation [1]. The issue of low thermal neutron flux made the exposure time longer and not economical for radiography application. Therefore, Nur-I had been relocated to beamport #3. Second development phase involve the installation of old collimator into the beamport #3 [4]. The profile of neutron beam produced from this instrument was not in the flat shape, but the half-oval instead. This give effect to the radiograph resolution in the radial direction of the image. This instrument usage radiographic film for capturing and recording the image. The exposure time using film method was optimized at 20 minute considering the best

* Corresponding author e-mail: muhammad_rawi@nm.gov.my

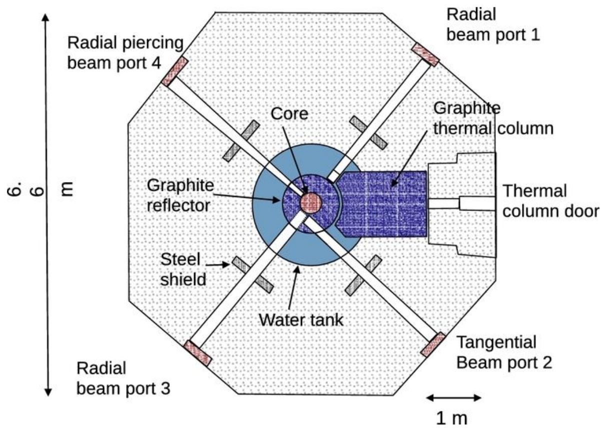

Fig. 1: Cutting view of PUSPATI TRIGA MARK II Nuclear Research Reactor located in Malaysian Nuclear Agency [6].

resolution at L/D ratio of 75. This facility had been utilized by academia and research institutions in Malaysia. In addition to many industrial applications, it also utilized to image the cultural heritage object in collaboration with the National Museum.

In the third development phase, it was to replace film usage for recording the radiographic image to the applications of charge couple device coupling with digital camera. However, the exposure for digital radiography was not achieved even at L/D ratio 75 which was the largest or smaller. Following this development, recent results is achieved for digital radiography by utilizing new collimator [2] [3]. The enhancement of radiography and imaging capability utilizing this small reactor is mainly to increase reactor utilizations. The capability in digital radiography will diversify the applications, particularly for neutron tomography. With this current development, many improvement have been made. The flat beam profile is achieved though out the beam axial direction while much shorter exposure time is obtained. Therefore, this article will describe some important characteristic of newly developed radiography and imaging (NURI) at 1 MW PUSPATI TRIGA MARK II in Nuclear Malaysia.

2 Description of the Instrument

NURI instrument is comprised of four main components including the neutron source which is the reactor core, the collimator for neutron optics, the detection and recording system and the exposure compartment. The nuclear fuel elements in the reactor core of RTP are configured in such that the thermal neutron flux at the core neighboring to the collimator inlet at beamport #3 is about with the order of magnitude 10^{12} $ncm^{-2}s^{-1}$. The collimator inlet is inserted into the graphite reflector of radial beamport #3 where neutrons entering the collimator directly. The shielding part of collimator is made sandwiches of solid lead and ferro-boron concrete. The aperture is made from cadmium sheet with 1.0 mm thick. The opening of aperture is 3.0 cm, it is located at 27.62 cm from collimator inlet and several centimeters away from the outer ring of reactor core. The shielding of collimator was made by ferro-boron concrete and aperture is made by cadmium sheet with opening of 4.3 cm diameter. Gamma radiation in the collimator is suppressed by applying the filter made of 15.0 cm length of bismuth rod. The 6.0 cm single crystal of sapphire was applied to homogenize direction of fast and thermal neutron where it is installed sequentially with the bismuth in relative to the incoming neutrons beam.

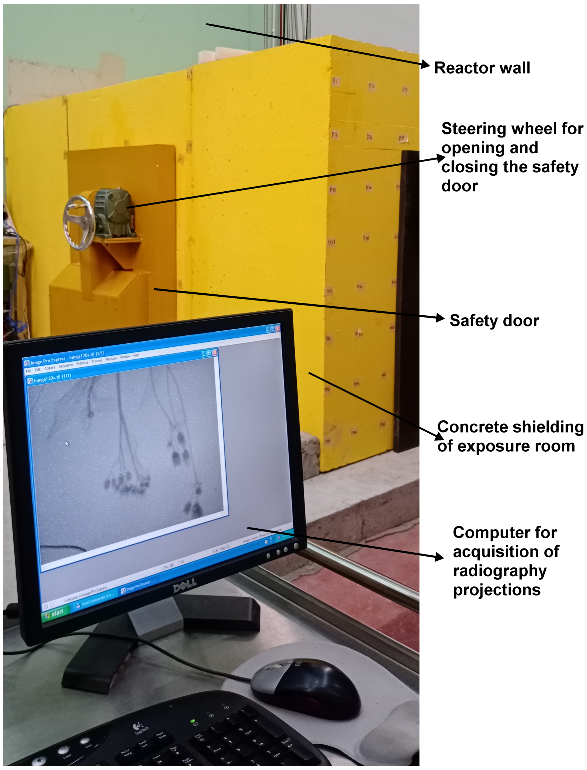

Fig. 2: The exposure room of NURI consists of heavy concrete shielding with the sliding safety door which is controlled manually by steel wheel handle.[6]

Thermal neutron flux at the inlet is with the order of magnitude 10^{11} $ncm^{-2}s^{-1}$. There are three pieces of single crystal sapphire rod are assembled after the cadmium aperture. The total thickness of these crystals are 7.62 cm. On the other side from aperture, there is the bismuth rod with 15.0 cm length is coupled to the sapphire. The simulations have shown that this thick of bismuth is sufficient to suppressed gamma radiation in the neutron beam. While the sapphire also sufficient to optimize beam homogenization along the neutron beam collimation. The effect from uncollimated beam is obtained by making the collimator shielding by ferro-boronated concrete with also solid lead materials. Details design of the collimator and simulation involved in the design is reported in [2],[3].

The instrument also consist of beam catcher made by lead and ferro-boronated concrete. It is located in front of collimator opening. Total thickness of the beam catcher is around 48.0 cm. Direct neutron beam will cause large activation when interacts with the shielding materials. Therefore, it is suppressed by applying the beam stop which is embedded in the high density concrete wall of exposure room where it is made by ferro-boronated concrete. This is quite unique because the beam stopped is build-in in the high density concrete wall. The total thickness of beam stopper is 40.0 cm, which is the whole thickness of exposure room shielding. This approach makes the space in parallel direction with the incoming neutron beam can be maximized, it is quite crucial to optimize thermal neutron flux at the sample position. This is an advantage for neutron radiography instrument in small research reactor without tolerate the safety aspect. The layout of exposure room is shown in Fig. 2.

The scanning of object located at the system centeric position for imaging experiment is obtained by implementing the linear (XYZ directions) and rotating stages. The linear stages are used for axial, normal and vertical directions relative to the incoming neutron beam from the collimator. For each radiography projection, the object is placed on the rotational stage with the center of rotation is the centeric point of the imaging system. The height of sample normal to incoming neutron beam is controlled by moving the laboratory jack in up and down. The L/D ratio from 100 to 130 can be achieved by moving the sample forward and backward in parallel to the incoming neutron beam. However, most of the time L/D ratio of 130 is maintained for imaging work.

Detection system for radiography projection images are obtained by conventional film or digital camera. The NURI configuration has been tested using film method as well as digital neutron camera. The cool charge couple device (CCD) camera of Photonic Science is used. The imaging part consists of scintillation screen and super mirror are contained in the black box as shown in Fig. 3. The scintillation screen is made by the composites of $Li_6F/ZnS:Ag$ materials. The effective area is given by a square area of scintillation screen around 100.0 cm^2. The super mirror used for reflecting light in the black box is made by highly polished titanium, it is placed at 45° from the reflected light emitted from the scintillation screen. The cooled CCD is coupled with the optic camera and the radiography image acquisition software, ImagePro via FireWire USB interface. Additional in house software based on Visual Basic is developed to couple the angular scanning device with the image acquisition software. This is crucial for recording the radiography projection in tomography application. The neutron camera or the black box is placed on the linear table which is aligned and standing on the steel rails.

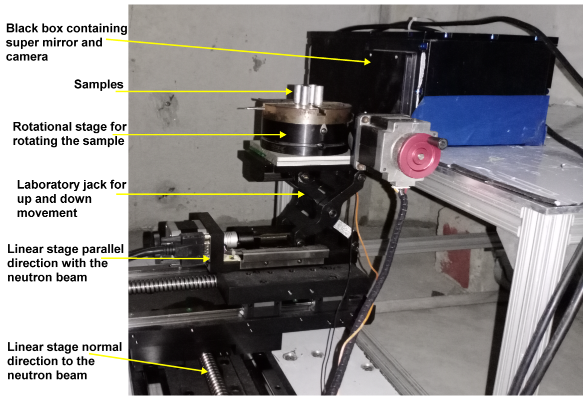

Fig. 3: Object positioning and detection system comprised of XYZ linear stages and rotational stage which is coupled to the sample table and the black box containing optics with the digital camera.

The neutron camera used to capture radiography projections is placed in the exposure room. The exposure room shielding is made by high density concrete with the wall thickness is 40.0 cm. This thick of concrete shielding is sufficient to obtain total dose rate outside the exposure room about 0.5 μ Sv hr^{-1}. The section where it is exposed directly to neutron beam is made by concrete wall but the internal shape is similar with the typical beam catcher. This part is made by ferro-boronated concrete. The roof has 24.0 cm x 24.0 cm square hole, it is for window to bring the sample inside the exposure room when using the over head crane if the sample is heavy. The door for exposure room is made adjacent to the reactor wall. The door itself has an interlocking with the adjacent wall of concrete shielding. It is made from the heavy concrete composited with the lead shots. The door can be moved forward and backward using the steel wheel standing one the steel rails. The opening and closing of the exposure room door is obtained using the steering coupled to the rotating gear system.

3 Results and Discussion

NURI has been utilized for demonstration to the academia and industries just after the commissioning. Furthermore, demonstration to industries and government agencies have been made using various sample types, for example, plants, ceramic, metals and etc. The collaboration with the muzium has firstly implemented using the ceramic objects as given in Fig. 4. The radiographic projections in axial and radial directions from these objects are shown in Fig. 5 and Fig. 6 respectively. The bowls are the ancient ceramics were obtained from Nassau ship wrack which has been submerged in Malacca straits in 1606 during the trade in the South East Asia. This Dutch vessel had been collapsed due to a fleet battle between the Dutch and Portuguese known as the battle of Cape Rachado that took place on August 16, 1606. At that time the Straits of Malacca were under Portuguese control started from the year 1511 after the Malay kingdom of Malacca and the Strait of Malacca region were conquered by the Portuguese.

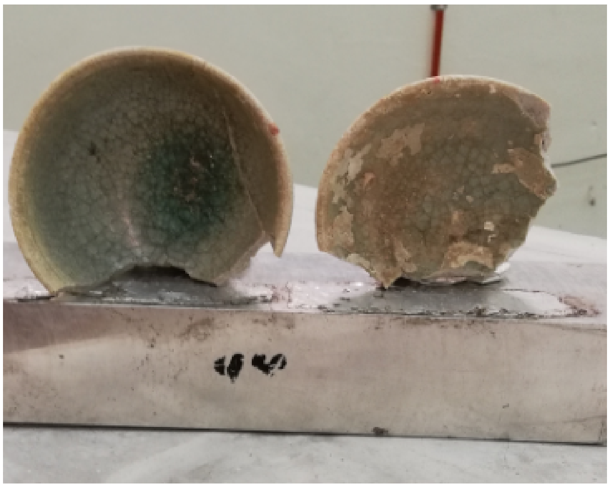

Fig. 4: Two ceramic bowls collected from Nassau ship wreck in Malacca straits

The contrast through the thickness of ceramic as shown in Fig. 5 indicates that there is no water stayed in the ceramic materials as it is bright throughout the ceramic thickness. This is an evident of that the ceramic

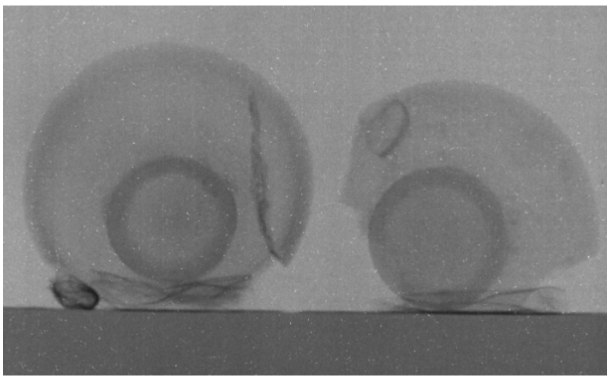

Fig. 5: Neutron Radiograph of two ceramic bowls collected from Nassau ship wreck in Malacca straits recorded in axial direction at NURI PUSPATI TRIGA MARK II Research Reactor

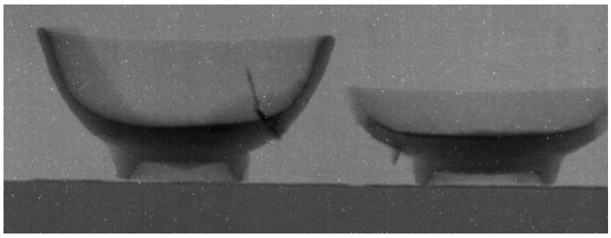

Fig. 6: Neutron Radiograph of two ceramic bowls collected from Nassau ship wreck in Malacca straits recorded in radial direction at NURI PUSPATI TRIGA MARK II Research Reactor

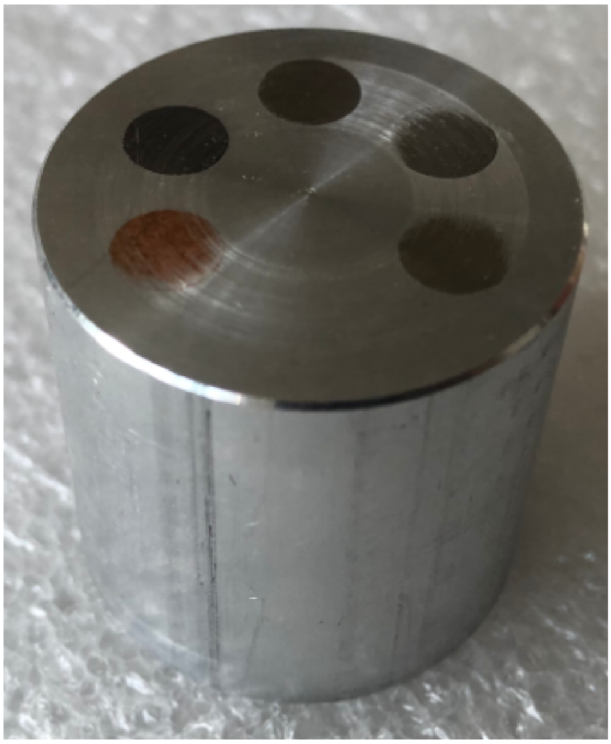

Fig. 7: Aluminum cyclinder consist of iron, titanium, lead, copper, nickel and aluminium rods.[6] [7]

is composed with the materials with less water adsorption characteristic, it is also shows that the ceramic was well fabricated during the manufacturing process. The exposure time to obtain these radiographs was 30 second. The ceramic objects was made by clay where it is mainly comprised of silicon element. Where the thermal neutron cross section of silicon element is small, therefore, the radiograph image with low contrast is obtained. Where as the thicker part in relative to the neutron aabsorption this absorbed larger amount of thermal neutron which resulting in high contrast radiographic image as indicated by dark color.

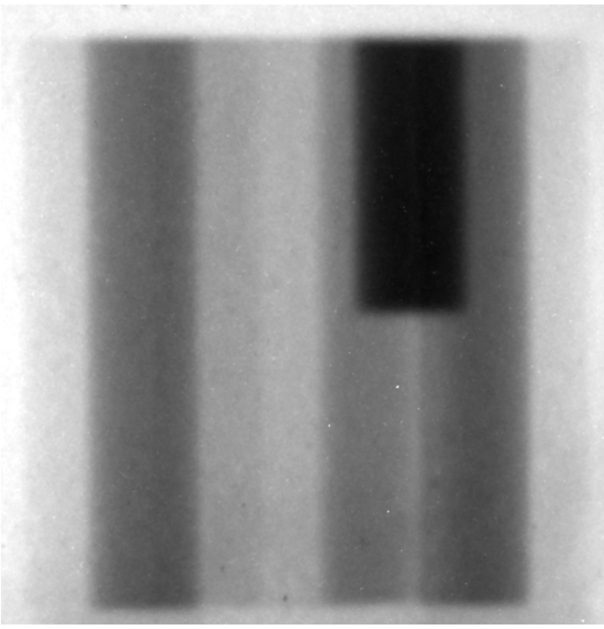

Fig. 8: Neutron radiograph of aluminum rod embedded with several rods made of different materials.

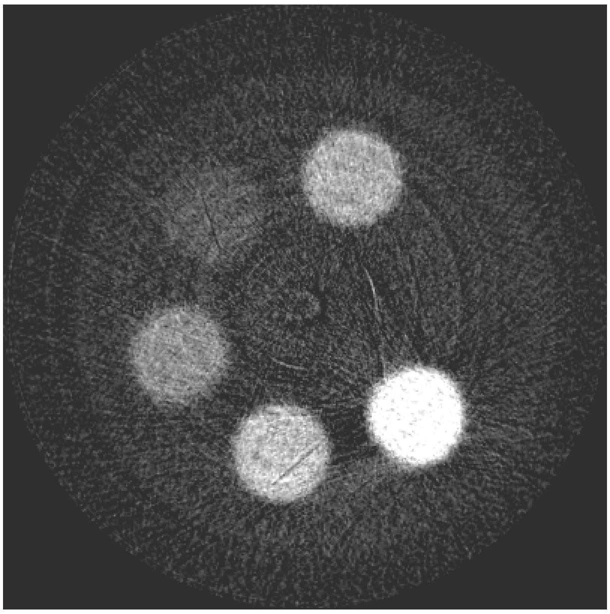

Fig. 9: Tomography image of aluminum rod embedded with several rods made of different materials.

Another objects used for demonstration were the grass flower and leaves and the Paul Sherer Institute (PSI) specimen for computed tomography contrast measurement. The grass was tested using radiography only, while the PSI specimen was tested using neutron radiography and also tomography. The image shown in

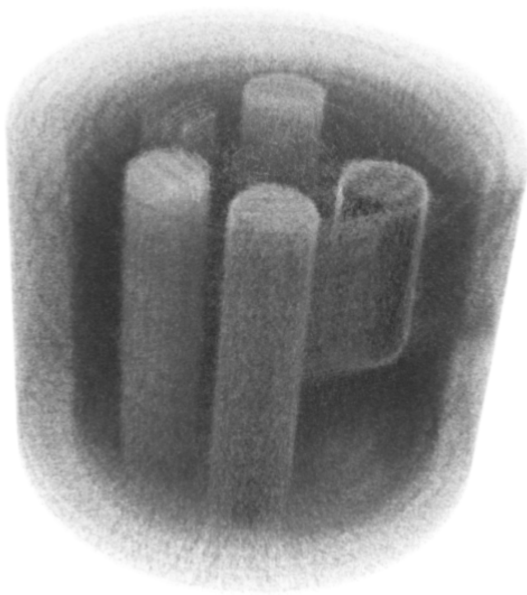

Fig. 10: Neutron tomographic image of aluminum rod embedded with several rods made of different materials. This 3D image is obtained using InVesalius 3.1 free software.

Fig. 7 is one of the radiographic projection of PSI sample for contrast measurement. The sample is made by aluminum cyclinder, it is embedded with the small rods made of iron, copper, nickel, lead and titanium. The sample for this testing has been exposed to the neutron beam around 30 seconds for each projection. There were 185 radiographic projections have been recorded for tomography reconstruction. This figure shows that, the contrast for each radiograph is acceptable even though the materials makes each object are significantly different.

The 3D reconstruction of PSI contrast sample is shown in Fig. 10. The embedded rod could be revealed significantly except the aluminum rod. It is expected because its has similar contrast with the big cylinder since it is made by aluminium materials. In this case, neutron would sees the big and small aluminum rod as one single peace. The absorption of neutron from aluminium also small since its has much less neutron absorption compared with copper, iron, nickel, lead and titanium. This effect clearly exhibit from the empty hole with the half hole contained the rod made of nickel material. Where, there is almost no materials absorbed neutron therefore, telling that part has an empty hole.However, the hole contained nickel is the darkest part, indicates absorption of neutron is large. This is because neutron cross section and neutron mass absorption of nickel is larger compared with copper, iron, lead and titanium. Currently, 3D rendering is achieved using freeware

InVesalius 3.1, which is designed for imaging in medical applications [7].

Fig. 11: Neutron radiograph of wild plant consists of flowers and leaves.

The image of wild grass in Fig. 11 shows that the contrast within the leaves is low compared with the image of flower. This is due to the content of water in the flower that is absorbed water is larger than in the leave. The trunk and leave can be seen clearly in the radiograph. This is an indication that the NURI facility is suitable to investigate the simple plant as used in this testing experiment.

4 Conclusion

This article has briefly presented the newly developed neutron radiography and imaging instrument based on charge couple device camera installed in 1 MW TRIGA MARK II PUSPATI Research reactor in Malaysia. The results shown in this article demostrated that this instrument has capability for and intended to be used in neutron imaging applications for industry, agriculture, cultural heritage objects and forensic sciences.

5 Acknowledgement

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