Neutron imaging on the VR-1 reactor

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Abstract. Training reactor VR-1 is a low power research reactor with maximal thermal power of 1 kW. The reactor is operated by the Faculty of Nuclear Science and Physical Engineering of the Czech Technical University in Prague. Due to its low power it suits as a tool for education of university students and training of professionals. In 2015, as part of student research project, neutron imaging was introduced as another type of reactor utilization. The low available neutron flux and the limiting spatial and construction capabilities of the reactor’s radial channel led to the development of a special filter/collimator insertion inside the channel and choosing a non-standard approach by placing a neutron imaging plate inside the channel. The paper describes preliminary experiments carried out on the VR-1 reactor which led to first radiographic images. It seems, that due to the reactor construction and low reactor power, the neutron imaging technique on the VR-1 reactor is feasible mainly for demonstration or educational and training purposes.

1. Introduction
Neutron radiography (also known as neutron imaging) is a non-destructive analytical method based on two-dimensional detection of neutrons that penetrate an object being imaged. Any material that forms an object has its own unique attenuation properties that are also incident neutron energy dependent. The decrease of neutron beam intensity caused by an object can be expressed in a simple form of the exponential attenuation law as follows

\[ I(x) = I_0 e^{-\Sigma_{tot} x}, \]  

where \( I(x) \) is the neutron beam intensity in the detector plane, \( I_0 \) is the initial neutron beam intensity, \( \Sigma_{tot} \) is the macroscopic cross section summed over all isotopes occurring in the object and \( x \) is the thickness of an object.

Neutron radiography is in its principle same as X-ray radiography well known from medical diagnostics. As X-rays interact by electromagnetic interaction with electrons in the electron cloud, the probability of interaction (microscopic cross section) increases with increasing atomic number. This does not apply for neutrons. The probability of neutron interaction with matter does not exhibit regular dependence on the atomic number. Neutrons, which are not electrically charged, interact mostly by strong interaction with the atomic nucleus, furthermore neutron interaction probability with a nucleus depends on the incident neutron energy.[2] Neutron radiography and X-ray radiography are imaging methods that are complementary due to different ways of interaction of thermal and cold neutrons (which are used for neutron imaging) and X-rays with matter.[4]
Nowadays, for reactors above 250 kW, neutron radiography is a well-established imaging method ([1], [3]). The main purpose of this work was to analyze the possibility of performing neutron radiography on very low power reactors, such as the VR-1 reactor.

2. Experimental setup

A basic setup of every neutron imaging facility consists of a neutron source, a collimator, an object being imaged and a neutron detector. The VR-1 reactor is low power pool-type light water training reactor with maximal power level of 1 kW. The fuel type is IRT-4M enriched to 19.7% with negligible burnup. Light water is used as coolant, moderator, reflector and biological shielding. Due to its low power, heat removal is provided by natural convection. Its experimental equipment includes specific educational and experimental instrumentation (such as instrumentation for fast reactivity changes, instrumentation for study of void coefficients) as well as standard R&D instrumentation (such as rabbit, vertical and horizontal beam tubes). Its maximum neutron flux is at the level of $10^9$ cm$^{-2}$s$^{-1}$.[5]

As a reference for neutron imaging the LVR-15 reactor was used. The LVR-15 reactor is tank-type light water research reactor operated by the Research Centre Rez Ltd with maximum power of 10 MW. It uses the same type of fuel as the VR-1 reactor (IRT-4M). Its maximum neutron flux is at the level of $10^{14}$ cm$^{-2}$s$^{-1}$. The LVR-15 reactor is a multipurpose reactor mainly used for radioisotope production, silicon doping and beam experiments.[8]

Neutron imaging on the VR-1 reactor was carried out in its only radial channel. The channel is a tool for extracting neutrons from the core through the reactor vessel and biological shielding to the irradiation position. The reactor instrumentation does not include a large irradiation box neither a thermal column, therefore samples were irradiated inside the radial beam port (channel). The beam port was partially closed with a plug and sealed with polyethylene bricks. For better moderation, a plastic bottle filled with water was added to the part of channel adjacent to the core. Simple neutron beam collimation was supposed to be provided by a cadmium plate rolled in cylindrical shape. As a neutron detection system, a Fujifilm neutron imaging plate BAS-ND 2025 [7] was used. Besides neutrons the imaging plate utilized for measurements is sensitive to electrons, X-rays, gamma radiation, alpha radiation. The imaging plate consist of two main parts, a phosphor material whose crystalline lattice stores the energy of incident radiation and of a neutron converter (Gd$_2$O$_3$ - Gd producing gammas that are internally converted into electrons).[2] The basic scheme of the experimental setup is shown in Figure 1. Figure 2 shows the samples being placed on the imaging plate. The samples were subsequently

![Figure 1](image_url). Experimental setup in the radial channel of the VR-1 reactor.
inserted inside the radial channel. The beam port exit was sealed by the plug and polyethylene bricks. (see Figure 3).

**Figure 2.** Fixing the samples on the imaging plate before irradiation.

**Figure 3.** Beam port exit sealed by the plug and polyethylene bricks.

### 3. Results

Three preliminary experiments (on the VR-1 reactor) and one reference experiment (on the LVR-15 reactor) were carried out. All radiographs from the VR-1 reactor were taken with the same exact power level. Only irradiation times were different (30 mins, 60 mins, 90 mins). During the 60 minute irradiation, a 10 cm neutron filter made of mono-crystalline silicon was added into the channel for epithermal and fast neutron beam content suppression. This filter also reduces the gamma radiation content originating from fission reactions in the core.

Radiographs of specific objects were taken during experiments on the VR-1 reactor. The set of samples for neutron imaging consisted of roller skates bearings, a computer fan, polyethylene plugs and a cadmium plate. Bearings are mostly made of stainless steel (balls and two rings). Balls, which enable revolving motion, are held by plastic in between the two rings. Inside inner diameter of two bearings out of three, a small polyethylene cylinders with a central hole (one borated polyethylene, one non-borated) were placed.

On the radiographs from the VR-1 reactor, stainless steel exhibits better attenuation than plastic parts (plastic holding balls, plastic in computer fan and polyethylene plugs) which is in contradiction with expectations and with the radiograph obtained on the LVR-15 where the neutron beam characteristics are well-know (fast neutrons and gamma is suppressed over thermal neutrons). It seems that the neutron beam from the VR-1 is probably not enough thermalized and due to the proximity to the core neutron beam is contaminated with a significant portion of gamma which also affects the images (see Figures 4, 5, 6 and 7). Also epithermal neutrons which are another possible contaminant of the beam could be thermalized in polyethylene parts of samples resulting in what could appear as a higher intensity detected. Therefore neutron spectrum in the radial channel is yet to be determined. Since this paper was focused on the feasibility of neutron imaging on a low power reactor, the spatial resolution is not yet available. The L/D ratio of the setup used on the VR-1 reactor is approximately 8.
4. Conclusion and future works

Preliminary information about the neutron beam intensity at the sample position were obtained by a Monte Carlo code Serpent [6]. Although future calculations are planned to be performed with the MCNP code as it comprises a designated neutron radiography tally and also up-to-date model of the VR-1 reactor is available. Experiments carried out on the VR-1 reactor clearly showed that it is possible to perform neutron radiography on a low power reactor, at least for demonstrational and educational purposes. Future works should continue with neutron radiography investigations and with development of suitable instrumentation such as neutron filters, neutron collimators and neutron detectors and with setting the most suitable irradiation times.
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