# The Enhancement of VR-1 Reactor Utilization for Practical Education Using Portable Neutron Generator

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**Abstract**. The Czech Technical University in Prague, particularly the Faculty of Nuclear Sciences and Physical Engineering has long tradition in nuclear education in the Czech Republic. The faculty has been established nearly 60 years ago as a scientific support and human resource base for the beginning of nuclear programme in former Czechoslovakia. An important milestone in the nuclear education was the construction and commissioning of the Training reactor VR-1. This experimental educational facility has become an invaluable tool in nuclear education not only for students from Czech Technical University, but also for students from other universities throughout the Czech Republic. Although the VR-1 reactor provides enough opportunities for practical education in the field of nuclear engineering, reactor staff and lecturers permanently make efforts to expand and enhance the practical education at the reactor. The latest improvement is based on integration of a small compact neutron generator into the educational experiments at the VR-1 reactor. The neutron generator type P385 was purchased from Thermo Fisher Scientific. It is a portable neutron generator designed for laboratory or field applications. Neutrons are produced on the basis of the D-D reaction. The generator is capable of pulsed or continuous output and generates a maximum of $7 \times 10^6$ neutrons per second. The generator can be completely controlled using a standard RS-232 serial communications interface with a personal computer. Due to the small dimensions of the generator; it can be easily installed in the radial channel of the VR-1 reactor. The coupling of the reactor and the neutron generator significantly increase utilisation of the VR-1 reactor and enhance educational and training experiments. Particularly, the pulsed source methods will be implemented at the VR-1 reactor for determining the reactivity and kinetic parameters of the reactor. The new D-D neutron generator allows of studying the reactor response to the neutron pulses at various reactor states (i.e. subcritical, critical and supercritical).

## 1. Introduction

The Czech Technical University in Prague, particularly the Faculty of Nuclear Sciences and Physical Engineering has long tradition in nuclear education in the Czech Republic. The faculty has been established nearly 60 years ago as a scientific support and human resource base for the beginning of nuclear programme in former Czechoslovakia. An important milestone in the nuclear education was the construction and commissioning of the Training reactor VR-1. This experimental educational facility has become an invaluable tool in nuclear education not only for students from the Czech Technical University, but also for students from other universities throughout the Czech Republic.

The low-power research reactor VR-1 is a key facility in the Czech Republic in the field of nuclear educational and training [1], [2]. The reactor is a pool type reactor with light water moderator and low enriched uranium in form of $UO_2$. Its nominal thermal power is 1 kW and it allows maximum power of 5 kW for a short period. The reactor is operated by the Department of Nuclear Reactors of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. Four educational laboratories belong to the reactor - laboratory for neutron interaction studies, laboratory for neutron activation analysis, radiation protection & environmental studies laboratory, and I&C laboratory [1]. The reactor with several experimental devices specifically designed for education and training and four laboratories are the base for experimental education and training and hands-on experiences, which can get students and trainees in addition to theoretical knowledge gained at the Department of Nuclear Reactors. The VR-1 reactor layout is shown in FIG. 1 and the basic technical data of the VR-1 reactor are shown in TABLE 1.

TABLE 1. Basic Technical Data of Training Reactor VR-1 [1]

| | |
|---|---|
| Reactor type, nominal power | Pool type, 1 kW |
| Fuel (material, form, enrichment) | $UO_2$, tubes, 19.70 % |
| Moderator, reflector | $H_2O$ (standard moderator and reflector)<br>graphite, beryllium (optional reflector for certain experiments) |
| Maximum neutron flux density | ~ $2 \times 10^9$ n/cm$^2$.s (thermal)<br>~ $1 \times 10^9$ n/cm$^2$.s (fast) |
| Experimental facilities | 2 horizontal channels (radial and tangential)<br>Approximately 10 vertical channels<br>1 pneumatic transfer system<br>1 neutron generator (D-D type)<br>1 device for study of delayed neutron<br>1 device for study of reactor kinetics<br>1 device for study of void coefficients<br>1 device for study of temperature coefficients |

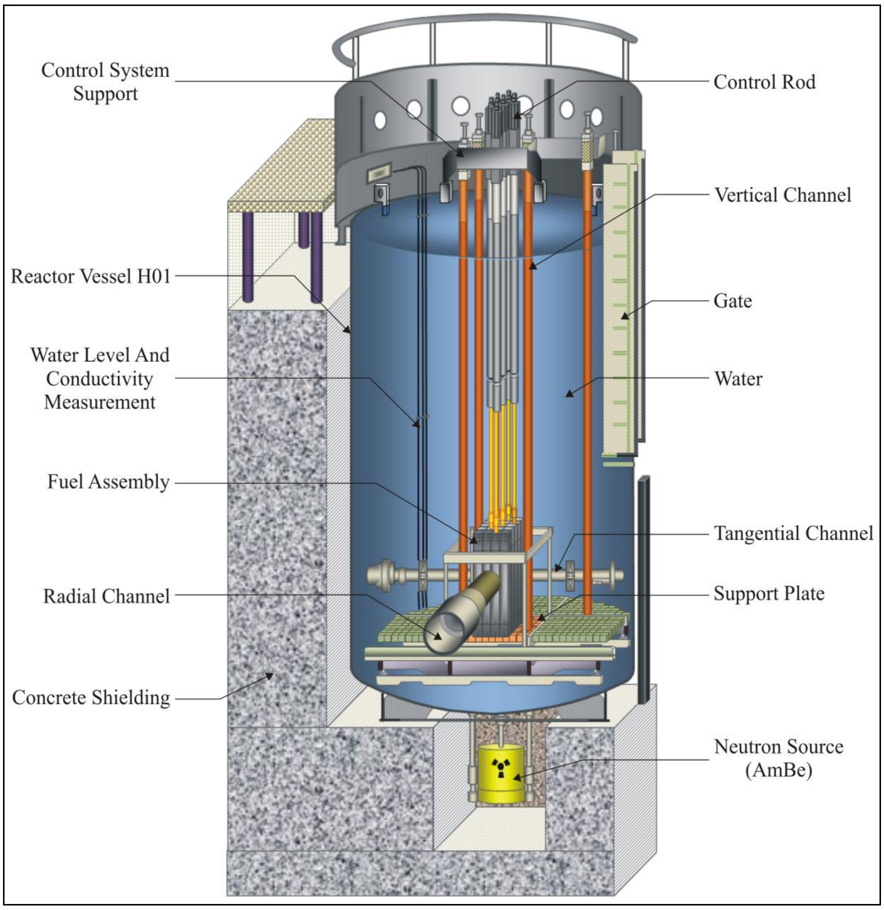


*FIG. 1. Cross section of Training Reactor VR-1 [3]*

## 2. The neutron generator P385

The neutron generator P385 is a portable generator designed for laboratory or field applications produced by US Thermo Fisher Scientific where neutrons are produced on the basis of the D-D reaction:

$$^{2}H + ^{2}H \rightarrow ^{3}He + n \quad Q = 3.27\ MeV$$

The D-D neutron generator produces fast neutrons with the kinetic energy 2.4 MeV. The P385 generator is capable of pulsed or continuous output of neutrons and it generates a maximum of $7 \times 10^{6}$ neutrons per second. The generator can be completely controlled using a standard RS-232 serial communications interface with a personal computer. Due to the small dimensions of the generator it can be easily installed in the radial channel of the VR-1 reactor. The basic technical data of the generator are shown in TABLE 2 and photo of the generator is shown in FIG. 2.

TABLE 2. Basic neutron generator P385

| Parameter | Value |
|---|---|
| Input voltage | 24 VDC ±10% @ 5 A or 100 to 240 VAC 50 to 60 Hz |
| Power | less than 75 W |
| Neutron yield | ~ $7 \times 10^{6}$ n/s |
| Neutron energy | 2,4 MeV |
| Max. accelerator voltage | 130 kV |
| Frequency | 250 Hz to 20 kHz or continuous |
| Duty cycle | 5% to 100%, 5 μs pulse width minimum |
| Weight | 13.6 kg |


*FIG. 2. The neutron generator P385*

### 3. Building up the D-D neutron generator capacity at the Training Reactor VR-1

The basic requirement for building up the neutron generator capacity at the Training Reactor VR-1 was to find a neutron generator with simple operation which can be easily used by students at all academic levels, i.e. Bachelor's, Master's and Doctoral degrees. The second requirement was coupling of the reactor core through the reactor radial channel (i.e. beam tube) and a small dimensional neutron. The third requirement was to use a generator based on D-D reaction, which doesn't bring tritium to the reactor hall, to the laboratories, and close to the students thus not requiring large changes in the current radiation protection system of the reactor. And finally, it should have been a standard neutron generator from the world market, which can be easily replaced by another piece of the same type for a reasonable price corresponding to available financial sources.

Over more than twenty years of the VR-1 reactor operation an effective procedure for implementing new experiments and new experimental devices in the reactor operation has been developed [1], [4]. Several new experimental devices successfully used at the VR-1 reactor for education and training are based on students' individual research or their master/doctoral thesis, for example the device for studying of void coefficients which allows to simulate boiling the VR-1 reactor core [4] or the device for studying temperature reactivity coefficients [5]. The same good practice was used in building up the neutron generator capacity at the VR-1 reactor.

The first idea of the coupling of the VR-1 reactor and the neutron generator came a few years ago from the academic staff working at the reactor. Later on, Jan Hrib, undergraduate student from the home Department of Nuclear Reactors, was selected to take part in this project and neutron generator became the main topic of his Bachelor's thesis. The first author of this paper was appointed as his supervisor. Later on, the student continued with this work in his annual research project in the first master study programme and finished it at the end of second master year in his Master's thesis [6]. An example of the MCNP model of a potential experimental setup with neutron generator in radial channel of the reactor performed by the student is shown in FIG. 3 and calculated relative reaction rate of $^{3}$He (n,p) reaction in three experimental channels during the last pulse of neutrons at kef=0.9797 is shown in FIG. 4.

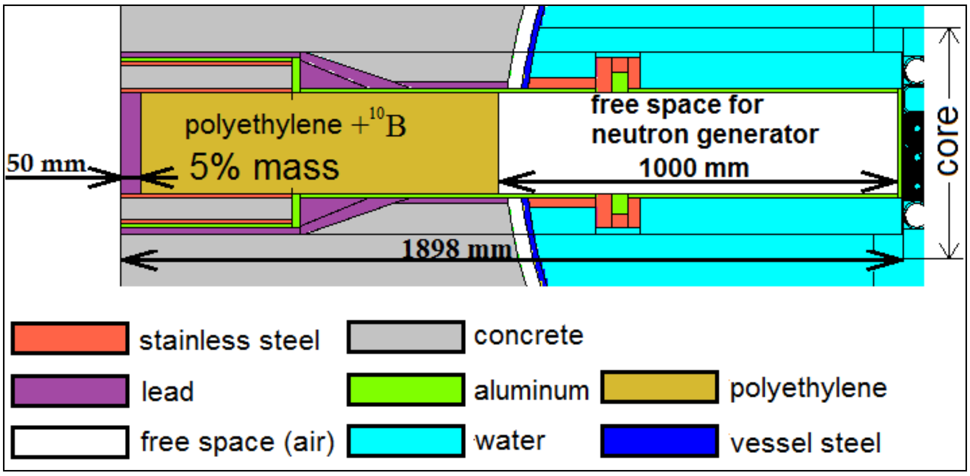


*FIG. 3. Experimental setup with neutron generator in radial channel [6]*

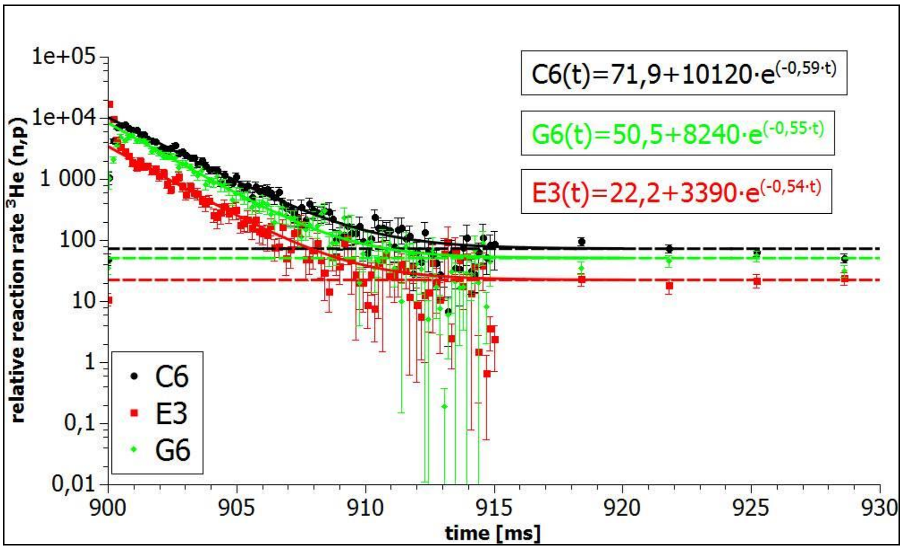


*FIG. 4. Relative reaction rate of $^{3}$He (n,p) reaction in three experimental channels during the last pulse of neutrons at kef=0.9797[6]*

Based on the research carried out within the Bachelor's thesis and on the reactor staff research, the neutron generator project was prepared in order to receive sufficient funding for building up the neutron generator capacity at the reactor. The project was submitted to the Development Research Foundation of the Ministry of Education, Youth and Sports of the Czech Republic and in 2013 the project received funding sufficient to cover 80 % of the further investment. Finally the D-D neutron generator P385 produced by US Thermo Fisher Scientific was selected as the best option among several other generators available in the world market. The generator was purchased and delivered to the reactor at the end of 2013.

In the beginning of 2014 the licensing process of the installation of neutron generator at the VR-1 reactor was carried out. It was expected that the licensing process can finished within a half of a year and the first preliminary experiments were expected in the autumn semester in 2014. Unfortunately the licensing process has been delayed for ca. 4-5 months and the license will be obtained by the end of 2014. The main reasons of delay apart from some minor administrative procedures were mainly radiation protection requirements from the national regulatory body. For example Czech legislative requires getting a special license for radiation protection supervisor of a neutron generator, which requires specific training and specific exams even for anybody who has radiation protection supervisor license in the field of research reactors.

It can be otherwise stated that as a result of high level of inherent nuclear safety of the VR-1 reactor there were found no obstacles neither problems from the point of view of nuclear safety during the licensing process of the installation of the neutron generator at the VR-1 reactor.

Several calculations must have been presented during the licensing process. MCNPX calculation of the dose rate in the measurement boxes attached to the VR-1 reactor with the neutron generator with maximum neutron yield is shown in FIG. 6 and the schematic drawing of the shutter of the radial channel of the VR-1 reactor and measurement boxes are shown in FIG. 5.

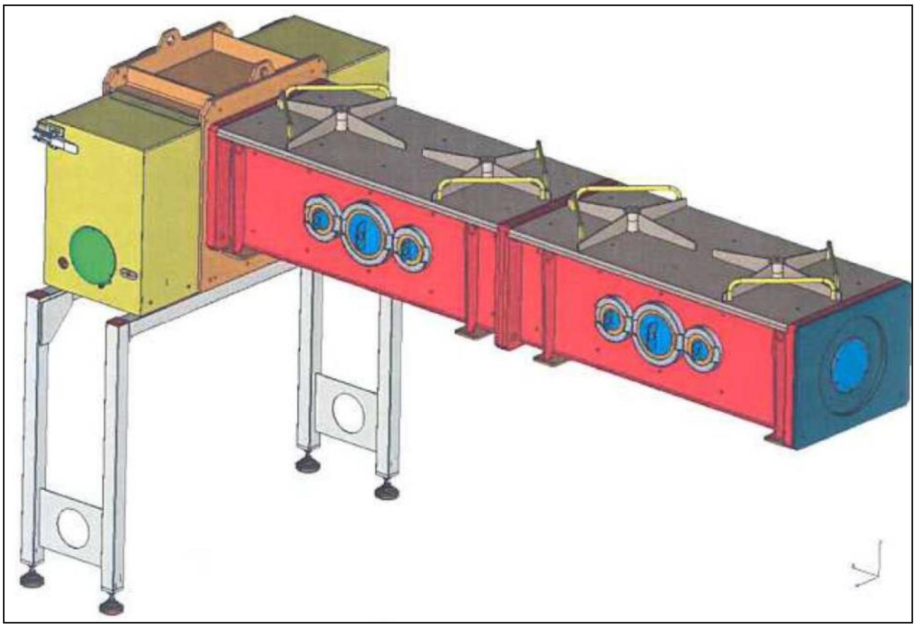

*FIG. 5. Shutter of the radial channel of the VR-1 reactor and measurement boxes*

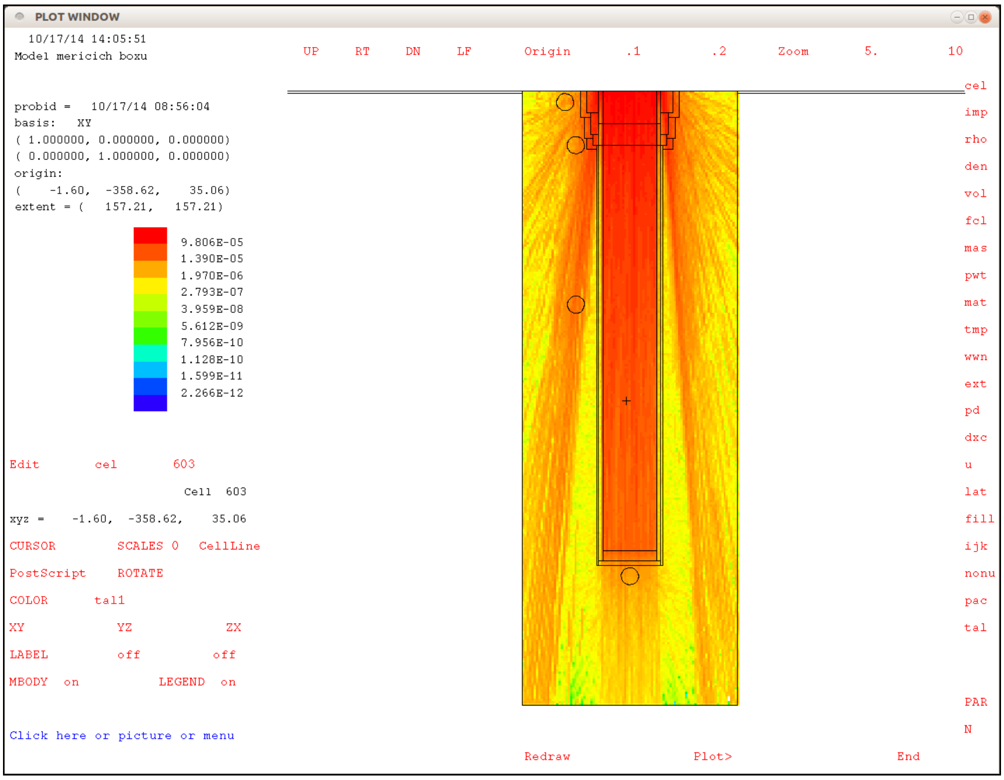


*FIG. 6. Calculation of the dose rate [μSv/h] in the measurement boxes with neutron generator attached to the VR-1 reactor for the licensing process*

## 4. The Enhancement of the VR-1 reactor utilization using portable neutron generator

The Training Reactor VR-1 belongs to the heaviest utilised low-power research reactors worldwide. Although very low nominal power of 1 kW [1] and day-shift operation basis on working days the reactor is in the operation for up to 1000 hours per year. The VR-1 reactor as a key educational and training facility in the Czech Republic with wide range of international users [1] usually reach utilisation factor up to 90-95 % in peak educational seasons (i.e. spring and autumn semester).

Although the VR-1 reactor provides enough opportunities for practical education in the field of nuclear engineering, reactor staff and lectures permanently make efforts to expand and enhance of the practical education at the reactor. The latest improvement is based on integration of a small compact neutron generator into the educational and training experiments at the VR-1 reactor. The coupling of the reactor and the neutron generator significantly increase utilisation of the VR-1 reactor and enhance educational experiments. Particularly, the pulsed source methods will be implemented at the VR-1 reactor for determining the reactivity and kinetic parameters of the reactor.

In the first phase of the use of the neutron generator in the reactor or as a stand-alone device following experiments are under development:

1. Study of the subcritical, critical and supercritical systems with external neutron source (i.e. neutron generator), where the VR-1 reactor will be in various states and various neutron pulses or continuous neutron beam from the generator will drive the reactor core. Using the standard I&C equipment and/or independent experimental detection systems reactor response will be studied.
2. Determination of kinetics parameters of the reactor core by various methods (e.g. Rossi-α, Feynman-α, Sjöstrand-Gozani method), where reactor is in deep subcriticality and the reactor core is driven by neutrons from the neutron generator. Using these methods several kinetics parameters such neutron lifetime or delayed neutrons parameters can be easily measured.
3. Study of a neutron transport through matter, where neutron generator as a stand-alone device produces neutron pulses or continuous neutron beam penetrating through moderator (e.g. water, graphite or polyethylene). This arrangement allows easily measure several basic diffusion parameters such diffusion length, diffusion coefficient, macroscopic absorption cross section etc.
4. Neutron activation analysis, where neutron generator as a stand-alone device produces neutron beam for neutron activation analysis similarly as in the reactor core which allows to increase capacity for neutron activation analysis at the reactor. Neutron generator also allows implementing prompt gamma neutron activation analysis for educational and training purposes.
5. Neutron imaging, where neutron generator as a stand-alone device produces neutron beam for neutron imaging. Low level of the neutron yield from neutron generator P385 doesn't allow development of a full scale neutron imaging but it is expected that as demonstration of this non-destructive neutron application for educational and training purposes should be feasible (e.g. image of strong absorber sample which has simple geometry).

## 5. Conclusions

Although the VR-1 reactor provides enough opportunities for practical education in the field of nuclear engineering, reactor staff and lectures permanently make efforts to expand and enhance of the practical education at the reactor. The latest improvement is based on integration of a small compact neutron generator into the educational and training experiments at the VR-1 reactor. The coupling of the reactor and the neutron generator significantly increase utilisation of the VR-1 reactor and enhance educational experiments. Particularly, the pulsed source methods will be implemented at the VR-1 reactor for determining the reactivity and kinetics parameters of the reactor. The new D-D neutron generator allows studying the reactor response to the neutron pulses at various reactor states (i.e. subcritical, critical and supercritical).

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