Improvements of the Training Reactor VR-1 - Only Way how to be Attractive for Students and Scientists

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Abstract.
The paper describes important improvements of the Training reactor VR-1 which has been achieved during last four years. Reactor has been successfully converted from the HEU IRT-3M fuel to the LEU IRT-4M fuel in 2005. This task was completed within the scope of the RERTR programme, that was initiated by the US DOE, consistent with the global non-proliferation policy goal of minimizing the use of HEU in civil programmes worldwide. The I&C upgrades started in 2001 with the human-machine interface, continued in 2002 with the control rod motors, drives and safety circuits upgrade. The control system upgrade followed in 2003. The next upgrade stage was the independent power protection system upgrade in 2004/05. Actually on progress is the upgrade of the operational power measuring system which is expected to finish in autumn 2007. The original radiation monitoring system was developed in the mid-80s. The new system was implemented at the reactor in 2004. The new comfort and more reliable physical protection system was installed at the reactor in 2006.

1. Introduction

The operation of the reactor started in 1990 by the Department of Nuclear Reactors of the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague. The reactor is a pool-type light-water reactor based on enriched uranium with maximum thermal power of 1kW. The moderator of neutrons is light demineralised water, which is also used as a reflector, a biological shielding and a coolant. Heat is removed from the core by natural convection. The reactor core contains 17 to 21 low enriched fuel assemblies IRT-4M, depending on the geometric arrangement and kind of experiments to be performed within the reactor. The reactor is used in education of technical university students, in R&D, in the education and training of specialists in the power industry, and finally in promotional activities in the field of nuclear power. The education and training is oriented to the reactor and neutron physics, dosimetry, nuclear safety, and control of nuclear installations. R&D has to respect reactor parameters and requirements of the so-called clean reactor core (free from a major effect of the fission products). Research at the reactor is mainly aimed at the preparation and testing of new educational methodologies, investigation of reactor lattice parameters, reactor dynamics studies, research in the field of control equipment, neutron detector calibration, etc.

During last four years a large number of improvements in operation has been achieved. Four of them are the most important: conversion of the reactor and operation with LEU fuel and upgrade of the control and safety system, the radiation monitoring system and the physical protection system.

2. Conversion of the reactor and operation with LEU fuel

During the autumn of 2005 Czech Technical University successfully converted the reactor from the Russian made IRT-3M fuel containing highly enriched uranium (HEU, enrichment: 36 % ^{235}U) to the Russian IRT-4M fuel containing low enriched uranium (LEU, enrichment: 19.7 % ^{235}U) [4]. This task was completed within the scope of the Reduced Enrichment for Research and Test Reactors (RERTR) programme, that was initiated by the United States Department of Energy (DOE), consistent with the global non-proliferation policy goal of minimizing the use of highly-enriched uranium in civil programmes worldwide [4]. Until the fuel swap, the reactor was operating with the fuel IRT-3M, enrichment 36 % ^{235}U. After the fuel swap, with the new fuel IRT-4M (Fig. 1) with enrichment of 19.7 % ^{235}U, the limit for LEU of 20 % is fulfilled. The fuel swap involved a direct cooperation of DOE and National Nuclear Security Administration from the RERTR programme, a Russian fuel supplier NZCHK, the Czech regulatorory body, Euratom, International Atomic Energy Agency, and a Russian company SOSNY, which was repatriating the HEU fuel IRT-3M. Since Czech Technical University expertise is in education and not transport or logistic, several other subcontractors were also involved [4].

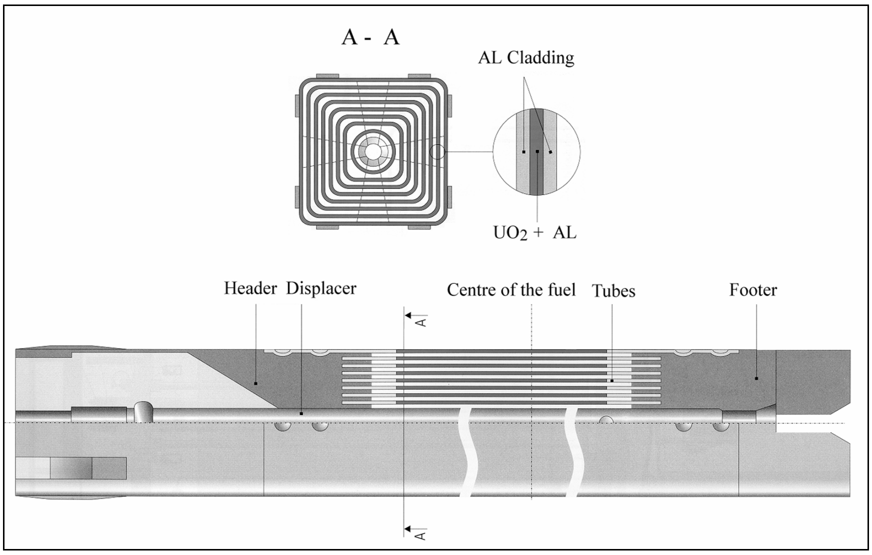

FIG. 1.Eight-tube fuel element IRT-4M

Preparation of the reactor for the new LEU fuel is well described in [1][2][3][4], and was done in the following ten stages:

(1) Agree the legal contract framework for the entire fuel swap.
(2) Create a new computational model of the reactor core to calculate and validate the C1 and C2 core configurations.
(3) Conduct thermo-hydraulic, safety and transient analysis for the new core configurations.
(4) Adjust the reactor's control system.
(5) Update operational and safety documentation, obtain necessary licenses.
(6) Inspect the fuel manufacturer; check the new fuel properties, new fuel delivery.
(7) Conduct a basic criticality experiment with the new C1 core configuration following the Czech regulatory body approved programme.
(8) Measure the neutronics properties of the C1 core and completion the core license.
(9) Operate the reactor in a testing regime; preparation for education.
(10) Evaluate the testing regime's results; switch to the standard operation.

The calculations were based on the data provided by the producer of the fuel and on the experience of the reactor staff [3][5]. All this takes into account that neither the criticality nor the thermo-hydraulic parameters of the IRT-4M fuel are significantly different from those of the IRT-3M. Criticality calculations provided by reactor physicists were based on MCNP calculations [3] and independently verified by experts from Argonne National Laboratories in USA. The thermo-hydraulic calculations and safety analyses were provided by experts from Argonne National Laboratories and Nuclear Research Institute Rez in the Czech Republic. Their results were in compliance with the procedure used in the Safety analysis report and were carefully analysed by VR-1 reactor physicists. The results of the calculations confirm the assumption that the new IRT-4M fuel is fully suitable for operation in the reactor and no consequences affected nuclear safety of the VR-1 Reactor were found [3].

The preparation of the reactor for the operation with IRT-4M fuel included criticality calculations [3], safety analyses and modifications of the reactor technology and tools [2]. Both types of the fuel IRT-3M and IRT-4M have practically the same geometry, they are mutually interchangeable, the same handling equipment is used. Minor modifications of the technology and tools were provided. Only one larger change was needed - the replacement of the instrumentation for bubbly boiling simulation (void coefficient studies) [2].

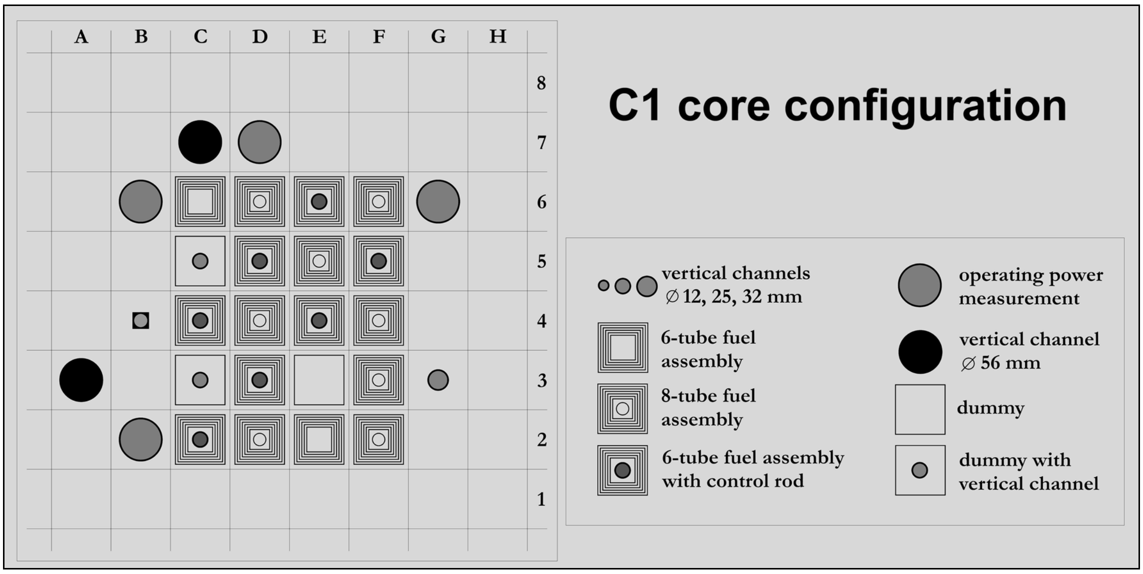

FIG. 2. Core configuration C1 with IRT-4M fuel [2]

The first critical state with the C1 configuration (Fig. 2) was attained on October 18, 2005. Approaching the critical state with the C1 core (Fig. 3) was prepared in the usual arrangement, which is typical for the reactor based on the Czech law and the relevant international recommendations [2].

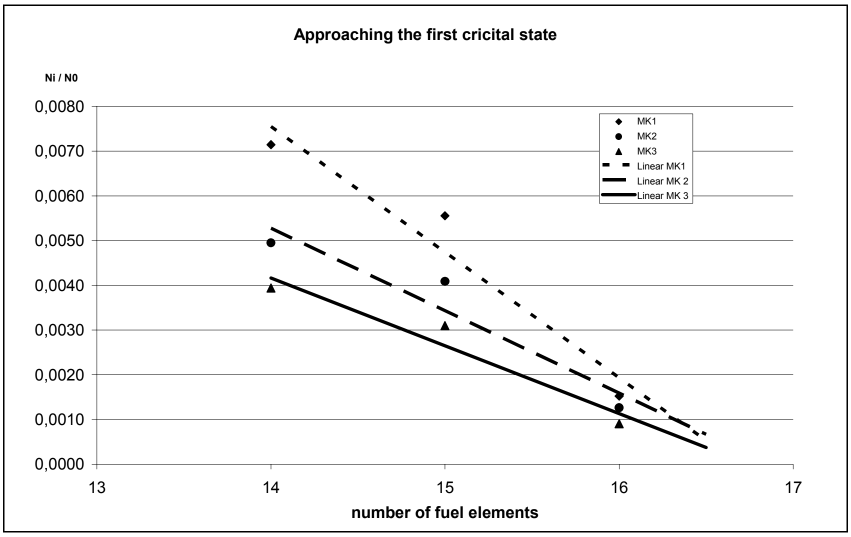

FIG. 3. Approaching the first critical state with IRT-4M fuel [2]

During the first critical experiment with LEU fuel (Fig. 3) and the testing regime all criticality and neutronics characteristics of the LEU core were measured; hence the necessary conditions to license the core were fulfilled. The results of the calculations of the selected critical states, worth of the control rods and the experimental equipment and the calibration curves of the control rods are in a good fit with the experimental measurements [2]. All the results confirm theoretical calculations when was expected that the reactor would behave equally with the new LEU fuel practically in a the same way as with the HEU fuel [5]. The measurements confirmed the difference, that was expected in the calculations, of a lower neutron flux density with the LEU fuel compared with the HEU fuel.

The testing regime of the reactor was conducted between October 24, 2005 and January 15, 2006. All remaining neutronics characteristics of the C1 core were measured; hence the necessary conditions to license the core were fulfilled [1]. Then the other reactor's operational characteristics were measured, such as thermal neutron flux at different positions in the core or reflector. All standards experiments were implemented and the effects of the new LEU fuel were closely watched [1].

For the safety operation of the reactor it is necessary to have a good knowledge about its dynamics in various operating modes. Among others experiments reactor dynamics with LEU fuel and its comparison with HEU fuel was studied very closely [1]. The VR-1 reactor is a low power reactor (or zero power) without measurable feedback in standard operational regimes, negative feedback is important in potential emergency states of the reactor only during power excursion. Dynamic behaviour of the reactor in subcritical, critical, and supercritical states were studied. Reactor responses to the negative, positive, and periodic reactivity changes with and without external neutron source in all reactor states were measured and compared with theoretical calculations. Measurements were performed by reactor physicists and staff only and later as a part of educational and training courses with students [1]. The following results of dynamics studies were performed during Eugene Wigner course on reactor physics experiments 2006 which was held in September 2006 [7].

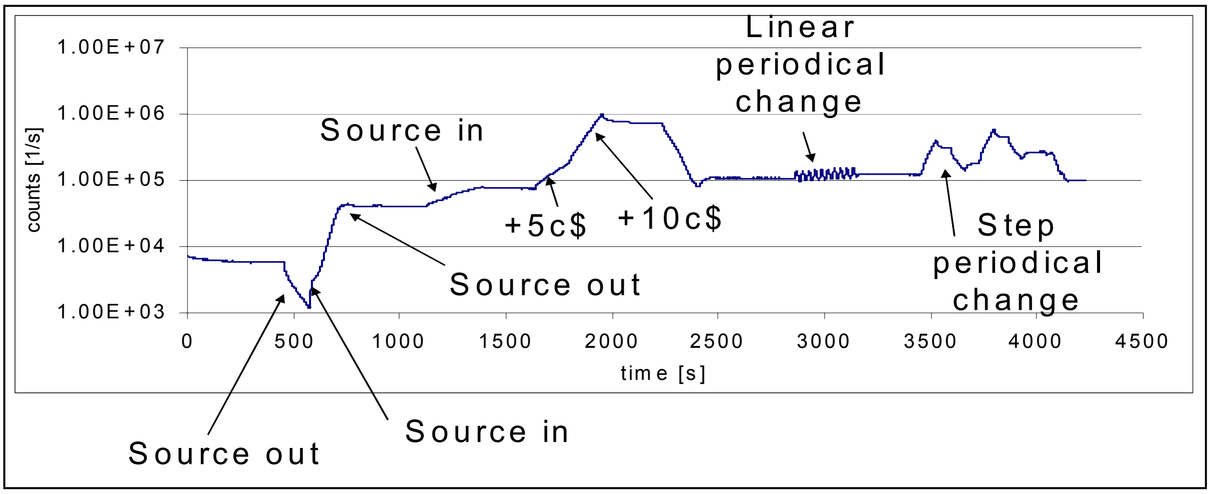

FIG. 4. Study of reactor dynamics with LEU fuel IRT-4M fuel [7]

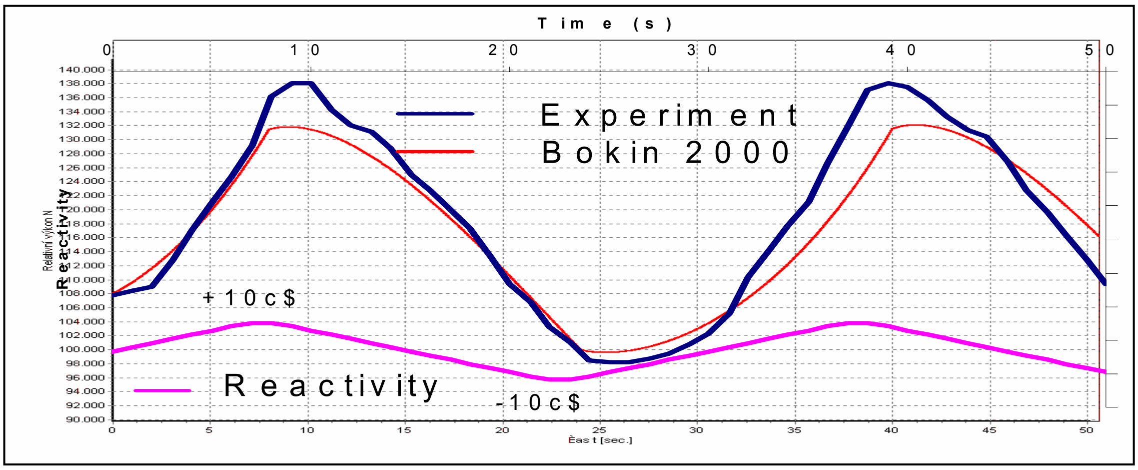

FIG. 5. Study of linear periodical change of reactivity with LEU fuel IRT-4M fuel [7]

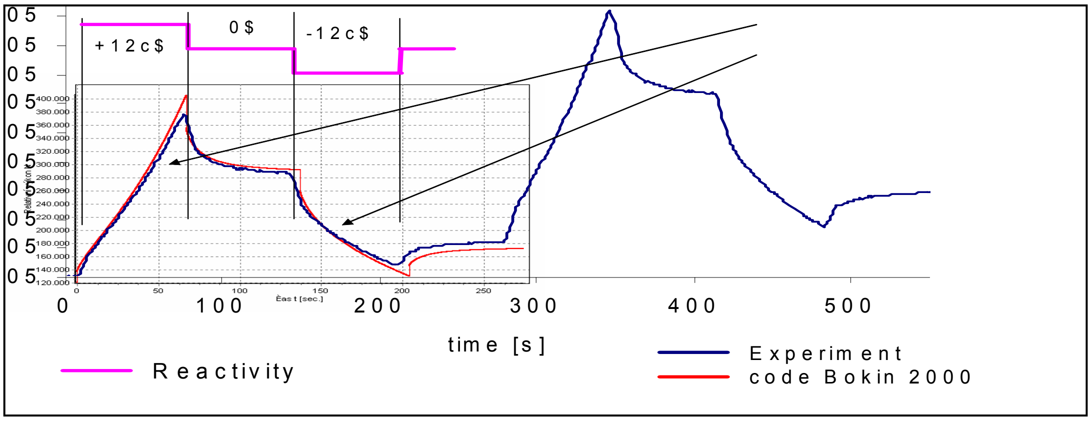

FIG. 6. Study of step periodical changes of reactivity with LEU fuel IRT-4M fuel [7]

Response of the reactor to the various reactivity changes is shown in (Fig. 4) and detailed comparison with theory for linear periodical change of reactivity is shown in (Fig. 5) and for step periodical changes of reactivity is shown in (Fig. 6). The results of the dynamics studies were compared with the same experiments using the HEU IRT-3M fuel and do not show any important changes in the dynamic behaviour of the reactor.

3. Upgrade of the control and safety system

The reactor was put into operation in the 1990. The original reactor I&C seemed to be obsolete and their replacement (upgrade) was carried out. The upgrade is done gradually in five stages during holidays in order not to disturb the reactor utilization during education and training [6]. The new I&C substantially improves the reactor safety, the comfort of the reactor operation, and facilitates the maintenance. The upgrades bring the reactor I&C to the top conditions and enable a prolongation of its functionality and maintainability for at least next 10 years [8], [10].

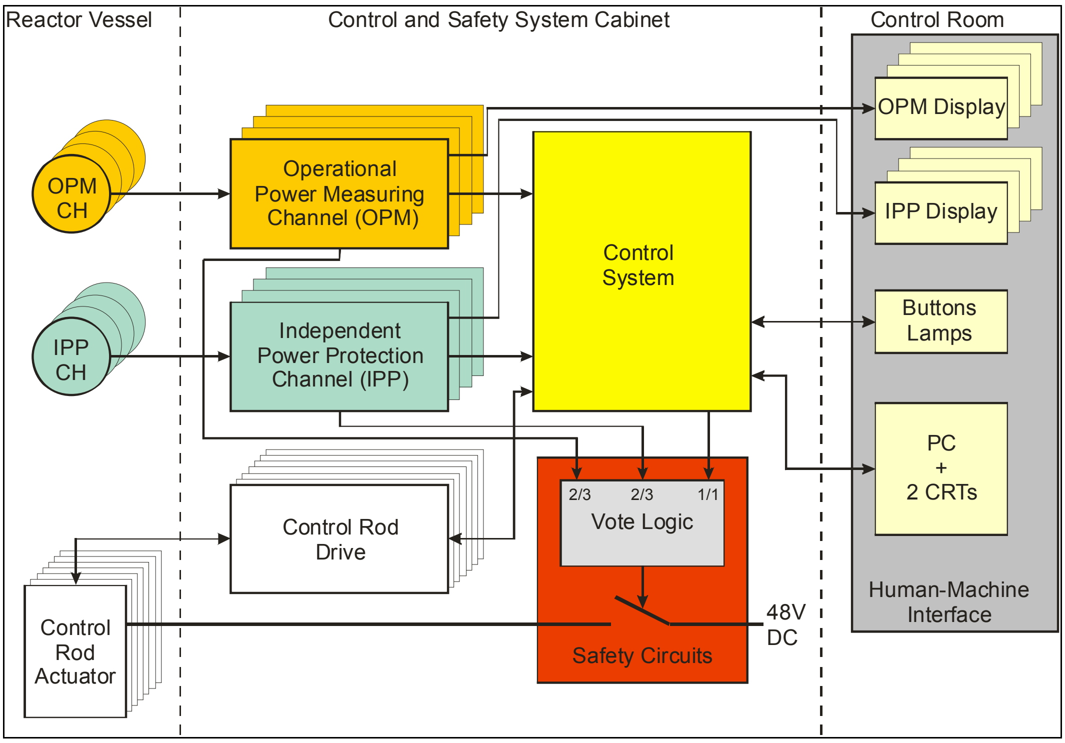

FIG. 7. Block diagram of I&C [8]

The first stage of the control and safety system upgrade (Fig. 7) was the human machine interface (HMI) and the control room upgrade in 2001 [9]. A significant upgrade of the control room and operator's desk (Fig. 9) with strong improvement of the data acquisition and visualization capacity was carried out. The operator's desk of the reactor was completely changed. A new desk with substantially better ergonomic and aesthetic properties was installed. The PC based system provides two large scale screens (19‘‘), one for alphanumeric communication and the other for graphical data representation. A large LED information panel was installed in the reactor hall. Software for the new information system was prepared with utilization of the InTouch development tool. This development tool, produced by WonderWare Company and working in the Microsoft Windows 2000 environment, is intended for data acquisition and visualization. The software recognizes commands from the keyboard and sends them to the control and safety system of the reactor, receives messages and data from the control system, and displays them on the monitors. The software is also responsible for the graphic presentation of the reactor status. It is also possible to display the core configuration, pictures stored in the PC, to calculate the reactivity and rod calibration, and to set parameters [9].

FIG. 8. New operator's desk of the reactor

The control rod drives, motors, and safety circuits were upgraded in the year 2002 [9]. The rod motors were replaced with new ones that provide appropriate qualities and dimensions. Necessary mechanical changes on the control rod mechanism, induced by the utilization of the new motor, were done. High quality connectors were used for connection of cables to the motors. The PLCs (Programmable Logic Controllers) Simatic S7 200 equipped with proper power electronic boards serve as motor drives. Appropriate software for the PLC control was developed. Before the control system upgrade, the PLC had been connected to the interface of the original control system that consisted of digital outputs for the rod up and down movement, and an analogue output signal to define the speed of the rod movement. After the control system upgrade, the PLCs communicate with the control system via a ProfiBus (RS485) line. The original safety circuits suffered relays ageing. Problems with the quality of contacts also arose. The new safety circuits use high quality relays with forced contacts to guarantee high reliability of operation. The safety circuits are installed in a 19’’ crate for easy installation in new cabinets of the upgraded control and safety system [9].

The control system upgrade as the third stage of the whole I&C upgrade was carried out in 2003 [9]. The upgraded control system is based on a high quality industrial PC mounted in a 19" crate. The operating system of the PC is Microsoft Windows XP with the real time support RTX of the VentureCom. The software for the control system was developed according to requirements in

MS Visual C. A large amount of work has been devoted to the software requirements to specify all dependencies, modes and permitted actions, safety measures, etc. The control system receives data from the power measuring and power protection channels and compares them with safety limits. It also controls the safety circuits. Furthermore, it calculates the average values of the important variables (power, velocity), and sends data and system status to the human-machine interface. Next, it receives commands and button inputs from the operator's desk and carries them out according to the reactor operation mode. Finally, it serves as an automatic power regulating system. The information about the control system and the reactor operational status were enlarged substantially in comparison with the old system. Furthermore, complex tests and control rods diagnostics were added [9].

The independent power protection system (IPP) upgrade started in 2004 and finished in 2005 [9]. The IPP is a component of the reactor safety (protection) system with high quality and reliability requirements. The system is redundant (4 channels; 3 of them active, 1 in a stand by mode; 2 out of 3 logic); each channel evaluates the reactor power and the velocity of power changes and provides safety functions. The IPP channel hardware consists of an analog and a digital section. The analog section processes the signal from the boron neutron chamber, amplifies it, and provides proper discrimination of neutrons. The digital section counts pulses from the neutron chamber, evaluates the reactor power and the power rate. Next, it compares gained data with the safety limits and sends the safety signal. It also communicates with the reactor control system via fiber optics lines, controls the individual display on the operator's desk and provides testing of the channel. The digital section consists of 5 microcomputer units. The reason for the utilization of more microcomputers was to divide single functions into separate microcomputers to guarantee easier structure of the system hardware and, in particular, of system software.

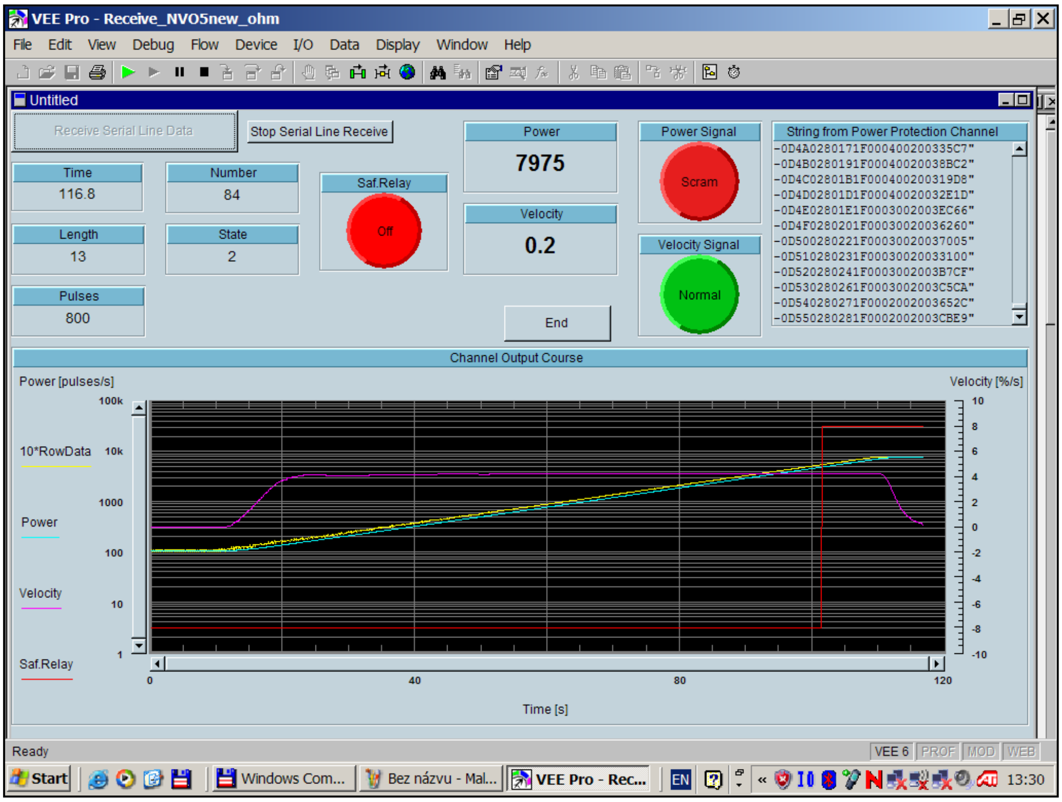

FIG. 9. Validation test of the independent power protection system [8]

The software for IPP was developed in accordance with nuclear standards. The software design was coded in C language. The reputable μVision 2 software development system of Keil Software was used. The system was carefully tested during non active and active tests. Configuration management, verification and validation (Fig. 9) accompanied the software development [9].

Currently on progress is the last stage - the upgrade of the operational power measuring system (OPM) which is expected to finish in late autumn 2007 [8], [9]. The OPM channels receive signal from the wide range fission chambers RJ1300, evaluate it according to the reactor power in pulse or current range, calculate the reactor power and the power rate, and send the values to the reactor control system and to the relevant individual display on the operator's desk in the reactor control room. The channels also compare values of the power and the power rate with the safety limits, and if the limits are exceeded, the request for a safety action is sent to the vote logic. Next, the OPM channels send the calculated reactor power and power rate together with the system status, etc. to the control system. The OPM channel consists of an analog and a digital section. The analog section processes the chamber signal and transforms it to be suitable for the digital section. This section processes the neutron chamber signal either in pulse, Campbell or DC current ranges and provides signals proportional to the neutron flux density (reactor power). The digital section of the OPM channel is based on a high quality industrial PC with an appropriate additional hardware – an input unit for reading data from analog section; a supervisory unit for the supervision of the OPM hardware and software; communication unit for communication with the control system, the control desk individual display and service computer; local display for the OPM status presentation and a safety relay to control the safety circuits. The OPM channel software has to fulfil quality requirements for the safety (protection) systems of nuclear facilities; quality assurance, configuration management, verification and validation activities must fulfil respected standards and guides. The computer operating system is going to be the reputable system Phar Lap, the software is going to be coded in the C Language. After the hardware/software integration, thorough validation tests are being accomplished now. The validation tests are being carried out with simulated input signals instead of neutron chambers. After the successful validation tests, the new OPM channel is going to be installed parallel with the original reactor I&C to thoroughly test the channel and to acquire enough operational experience.

4. Upgrade of the radiation monitoring system

The original radiation monitoring system STADOS was developed in the mid-80s. The new radiation monitoring system RMS has been installed at the reactor in 2004. New RMS system is fully computerised (Fig. 10) state-of-art system connected with reactor information system.

FIG. 10. LCD touch screen of the RMS

RMS system consists of:

(1) two neutron detectors, each consists of scintilator detector ^{6}LiJ(Eu), polyethylene sphere and three channel analyzer JKA300N, and measures 10 keV – 10 MeV neutrons and dose rate from 0.01 to 100 mSv/h,

(2) ten GM gamma detectors GMS3 in the reactor hall with measuring range of the dose rate 0.01 to 100 mSv/h,

(3) two alpha-beta aerosol detectors, each consists of ZnS scintilator detector for alpha and beta detection and GM gamma detectors for gamma correction,

(4) an external gamma detector GMS3 located at the roof of the reactor hall,
(5) on-line computer control unit,
(6) computer archive system which allows archive all important data with the periodicity 1 hour in normal operation conditions (Fig. 11) and with the periodicity 6 sec. in abnormal and emergency conditions,
(7) user friendly LCD touch screen for control with all necessary information and connection with reactor console.

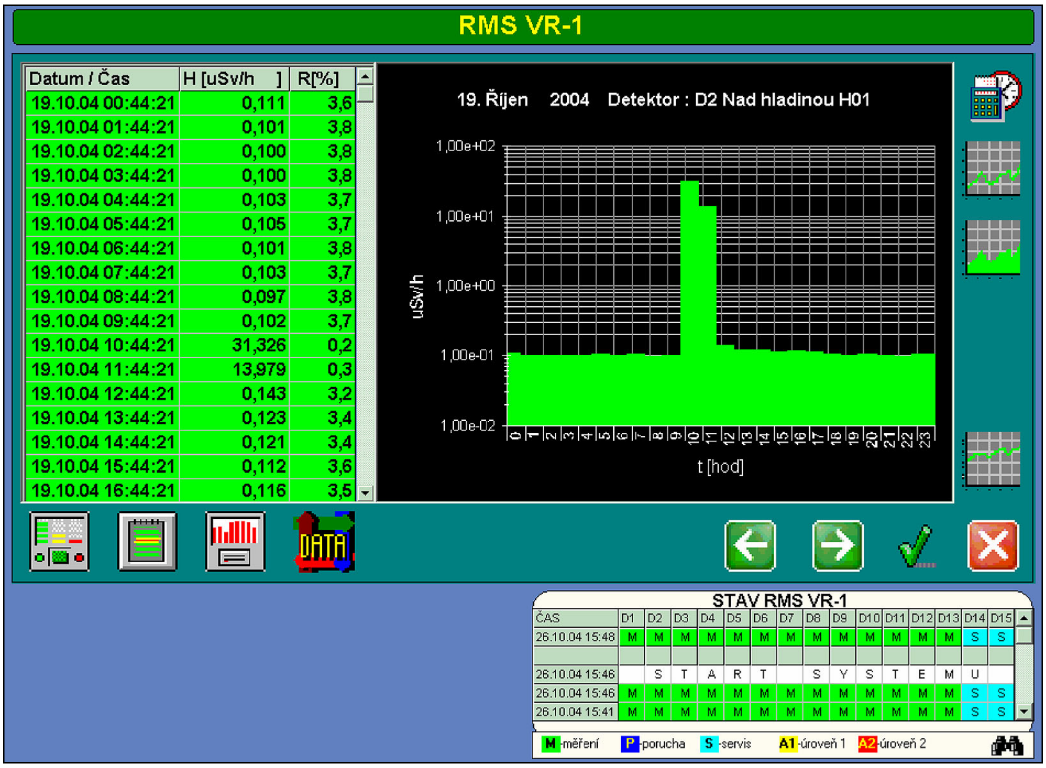

FIG. 11. Archive system of the RMS (loading fuel, increasing background at the measurement point)

5. Upgrade of the physical protection system

After the reactor conversion from HEU to LEU fuel the nuclear materials category was decreased to the Category 3, but the physical protection system corresponding to the higher Category 2 has not been changed. The new comfort and more reliable physical protection system has been installed at the reactor in 2006. The new fully electronic system respects all changes at the reactor hall during all five stages of the I&C upgrades. System allows to protect the reactor hall at higher level using new technologies in the alarm communication and display between the physical protection system, reactor staff, doorkeeper and respond forces.

6. Conclusions

The training reactor VR-1 is a key facility for nuclear education in the Czech Republic. Its reliable and safe operation is essential because the reactor is very intensively used for education of students and training of NPP staff. During last four years a large number of improvements in operation of the reactor has been achieved. Conversion of the reactor from HEU to LEU fuel and operation with new fuel, upgrade of the control and safety system, the radiation monitoring system and the physical protection system described in this paper are the most important. Incessant improvements and upgrades of each training reactor, its experimental equipment and educational training methodologies to state-of-art level is only way how to be attractive for students and scientists.

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