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VERONA V6.22 – An enhanced reactor analysis tool applied for continuous core parameter monitoring at Paks NPP

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ABSTRACT

Between 2003 and 2007 the Hungarian Paks NPP performed a large modernization project to upgrade its VERONA core monitoring system. The modernization work resulted in a state-of-the-art system that was able to support the reactor thermal power increase to 108% by more accurate and more frequent core analysis. Details of the new system are given in Végh et al. (2008), the most important improvements were as follows: complete replacement of the hardware and the local area network; application of a new operating system and porting a large fraction of the original application software to the new environment; implementation of a new human-system interface; and last but not least, introduction of new reactor physics calculations. Basic novelty of the modernized core analysis was the introduction of an on-line core-follow module based on the standard Paks NPP core design code HELIOS/C-PORCA. New calculations also provided much finer spatial resolution, both in terms of axial node numbers and within the fuel assemblies. The new system was able to calculate the fuel applied during the first phase of power increase accurately, but it was not tailored to determine the effects of burnable absorbers as gadolinium. However, in the second phase of the power increase process the application of fuel assemblies containing three fuel rods with gadolinium content was intended (in order to optimize fuel economy), therefore off-line and on-line VERONA reactor physics models had to be further modified, to be able to handle the new fuel according to the accuracy requirements. In the present paper first a brief overview of the system version (V6.0) commissioned after the first modernization step is outlined; then details of the modified off-line and on-line reactor physics calculations are described. Validation results for new modules are treated extensively, in order to illustrate the extent and complexity of the V&V procedure associated with the development and licensing of the new calculations running in version V6.22 of VERONA. Some details on the experience collected during the operation of the new reactor physics calculations are also discussed. Finally conceptual plans for the next system modification phase are outlined briefly; these changes are induced by the forthcoming introduction of 15 month long fuel cycles (instead of the present 12 month long cycles).

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Abbreviations: 2D, two dimensional; 3D, three dimensional; AEKI, Atomic Energy Research Institute (Budapest, Hungary); BOC, beginning of cycle; CFD, computational fluid dynamics; CFX, widely used CFD code; C-PORCA, nodal diffusion code (used for core calculations at Paks NPP); COBRA, thermal-hydraulic code (used for fuel assembly subchannel calculations); CPU, central processing unit (in a computer); CUDA, compute unified device architecture; CULA, Compute Unified Linear Algebra; DBM, VERONA database manager; DVD, digital video disc; ECR, emergency control room; EOC, end of cycle; EXD, external data server; FIL, fine control rod position indication interface; FPD, full-power days; GE, general electric; GEPETTO, VERONA extrapolation method based on GPT; GPGPU, general purpose graphical processing unit; GPT, general perturbation theory; GW, gateway computer; HELIOS, lattice physics transport code for nuclear fuel analysis; HMI, human machine interface; HP, Hewlett–Packard; iFIX, HMI/SCADA system (GE Proficy); KFKI, Central Research Institute for Physics (Budapest, Hungary); LTA, lead test assembly; MCNP, Monte-Carlo N-particle transport code; MCR, main control room; NPP, nuclear power plant; OLE, object linking and embedding; O&M, operation and maintenance; OPC, OLE for process control; PC, personal computer; PDA, polyp data acquisition (in-core data acquisition system at Paks NPP); RAID, redundant array of independent disks; RAM, random accessible memory (in a computer); RAR, reactor physics archive; RPH, reactor physics server; RPhDB, VERONA reactor physics database; RPS, reactor protection system; TC, thermocouple; TCP/IP, transmission control protocol/internet protocol; SCADA, supervisory control and data acquisition; SPND, self-powered neutron detector; SQL, structured query language (relational database standard); VDB, VERONA database; VDP, VERONA data processing server; VERONA, VVER ON-line analysis; VM, virtual machine; VME, versa module Eurocard (industrial data acquisition standard); VVER, light water cooled and moderated nuclear power plant of Russian (Soviet) design; V&V, validation and verification.

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1. Introduction

1.1. Motivation of model developments

The basic aim of system development activities carried out between 2003 and 2007 was to establish a core monitoring system capable to support the reactor power increase process of the plant satisfactorily. This first modernization step resulted in the installation and commissioning of VERONA version V6.0, i.e. the system which was used at all Paks units during the power increase project to monitor core safety at elevated core power levels. This version fulfilled the expectations, since it was reliably working during its complete utilization period (until 2010). During this period the core thermal power of all Paks units was increased to 108% in such a manner, that safety requirements were continuously satisfied and limit violations were avoided (see Végh et al. (2008) for details).

When it was installed, however, version V6.0 was not ready to handle fuel assemblies with burnable poison. The reason for this deficiency was the time delay between the development of the new core analysis tools and the finalization of the fuel design to be used during the second phase of the power increase project. Final acceptance of this "optimal" fuel assembly design and the start of its licensing process happened about two years after the approval of the V6.0 system design document, therefore it was impossible to take into account requirements related to the "optimal" fuel during system development phase. Due to these circumstances the plant later initiated a second development step, aimed at developing new reactor physics modules for handling the "optimal" fuel containing three rods with gadolinium absorber. It has to be noted that the application of this fuel type was a strategic question for the plant, because this fuel ensured optimal fuel economy also at increased (108%) power level.

Design, development, testing, installation and commissioning activities related to the new V6.2 version took place between 2008 and 2010 (the preceding version V6.1 contained only minor modifications compared to V6.0 and none of these were related to core calculations).

Computational capabilities of version V6.2 surpass previous versions in several aspects:

- it is able to handle fuel assemblies with three gadolinium absorber rods accurately;
- it can handle mixed ("transitional") cores containing various fuel assembly types;
- it is able to run an advanced 2D extrapolation calculation with a 2 second cycle;
- it includes advanced neutron physics and thermal-hydraulics models;
- it uses an accurate model for assembly outlet temperature measurement interpretation.

Version V6.2 was installed successfully at all Paks units and it was operating satisfactorily during the introduction of the "optimal" fuel assemblies, including their "lead test" period (see Beliczai and Parkó, 2009).

Due to increased computational needs the computing resources demanded by the reactor physics analysis have increased significantly, and the load of the reactor physics server computers has been almost doubled, if compared to previous version. This problem was solved by replacing the processors of these machines with more powerful processing units.

It is natural that the operation of a power reactor unit continuously creates new operator's needs or suggestions, therefore the development of an on-line core monitoring system actually never stops, only from time to time it comes to a temporary halt. It is true for the VERONA system, as well, because shortly after the commissioning of version V6.2, a slightly amended version was installed upon the request of the plant (V6.21 contains a monitoring and reporting module to detect control rod misalignments or control rod drop). The presently operated V6.22 version also contains a new module with its associated human-system interface to monitor and report significant discrepancies between redundant primary loop and core temperature measurements.

1.2. Project organization and main development steps

As a result of a tendering process, KFKI AEKI was selected as main contractor to perform the modernization of on-line and off-line reactor physics codes. A detailed conceptual plan was prepared as a first step; after its approval the system design document was compiled, describing new algorithms and their programmed implementation. Special attention was paid to the verification and validation (V&V) of the new reactor physics codes, therefore a detailed V&V plan was prepared containing details of all tasks in the V&V process (results of the V&V procedure are outlined in Section 4). It has to be noted that the new reactor analysis modules were designed, coded, tested and documented in close co-operation with the Reactor Physics Department of the plant. This approach ensured direct feedback from an important end-users' group of the core monitoring system, and also created a framework to have frequent discussions and information exchanges with the plant's reactor physicists.

After programming activities were finished at module level (including individual module tests), system integration and integral V&V tests were carried out. Several Paks NPP experts participated in the specification, data delivery, testing and commissioning activities and their involvement resulted in a seamless acceptance of the new system. The location of integral tests with long duration (e.g. of tests lasting several weeks) was a special VERONA configuration assembled at Unit 3. This "test" configuration is devoted to carry out tests in a hardware and software environment as close to the unit configurations as possible. Measured plant data can be transferred to this system from any selected unit, then data processing, visualization etc. is carried out exactly the same way as at the unit VERONA. This feature gives the opportunity to compare the results given by the new calculation models with those produced by the "licensed" program version running at the unit and facilitates error detection to a great extent. Another unique "test field" is provided by the VERONA configuration installed at the Paks full-scope training simulator. In this case the simulator can be used as flexible test data source providing a wide variety of process transients and malfunctions that are obviously unavailable at the units.

After completing all prescribed off-line and on-line V&V tests, the new calculation system was run on-line for several weeks at the Unit 3 VERONA test configuration, receiving data from a selected unit in every two seconds. The basic aim of this long-term parallel operation was to reveal potential stability problems (e.g. memory leaks or oscillations) and to check calculations related to the determination of fuel isotope concentrations and time-integrals like fuel burn-up. All test results were handed over to the licensing authority and finally the Hungarian Atomic Energy Authority issued the license to perform software modifications at the units. Installations at the units were carried out in the following two years, according to the gradual introduction of the new fuel assemblies with burnable poison.

2. System architecture and main functions

The scheme of the presently operated unit VERONA systems is shown in Fig. 1.

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