SCORPIO-VVER Core Monitoring and Surveillance System with Advanced Capabilities

Jozef Molnár, Radim Vočka

Nuclear Research Institute Řež plc, Czech Republic

19th AER Symposium
21 – 25 September 2009
Varna, Bulgaria

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER
The Developers

The first version of SCORPIO-VVER Core Monitoring System for Dukovany (CZ) was developed in 1998 in co-operation between:

- IFE Halden, Norway,
- Nuclear Research Institute Řež plc (CZ),
- Škoda JS a.s. (CZ),
- Chemcomex Praha a.s. (CZ).

For SCORPIO-VVER implementation at Bohunice NPP in Slovakia (2001) the system was enhanced with startup module KRITEX in co-operation with:

- VUJE a.s. (SK).

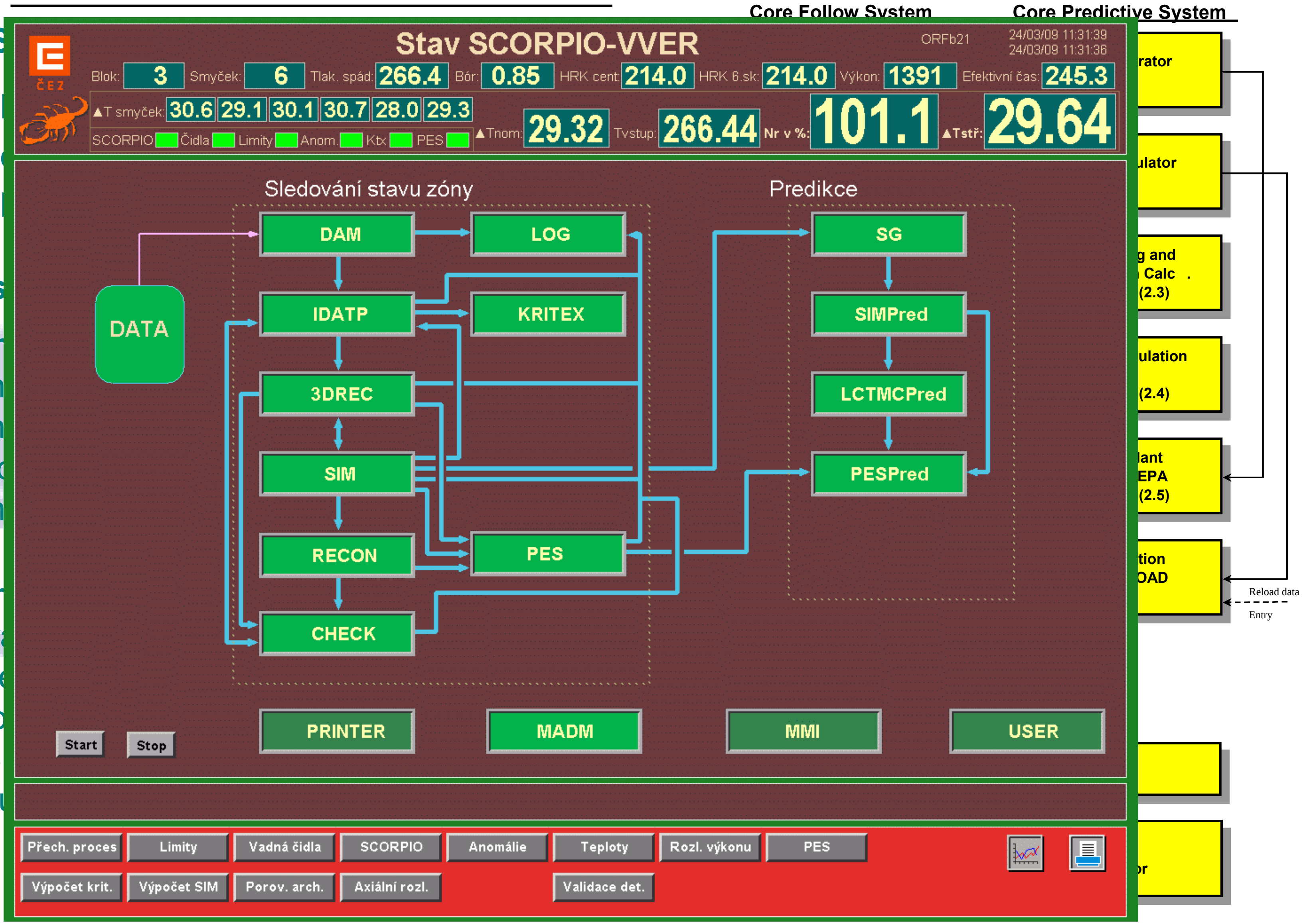
SCORPIO-VVER basis
Surveillance of reactor CORe by PIcture On-line display

The S

- Th
- F
- Th

The s

- th
  in
  in
  co
  in
- th
  tr
  ge
  fo
  S
  nu



SCORPIO-VVER basis
Surveillance of reactor COREe by PIcture On-line display

The SCORPIO-VVER system includes following features:

- Validation of plant measurements and identification of sensor failures.
- Optimum combination of measurements and calculations to obtain precise values of important parameters.
- On-line 3D power distribution calculation with pin power reconstruction.
- Limit checking and thermal margin calculation allowing for surveillance of VVER core limits such as DNBR, Sub-cooling margin, FdH and FQ peeking factors.
- Integrated modules for monitoring fuel performance and coolant activity for identification of fuel failures.
- Predictive capabilities and strategy planning, offering the possibility to check the consequences of operational manoeuvres in advance, prediction of critical parameters, etc.
- Convenient monitoring of approach to criticality during reactor start-up.
- Automated transition between cycles (fuel reload).

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER
Implementation and upgrade history

First implementation at Dukovany NPP in Czech Republic:

- completed in 1998, migrated to all 4 units.

Dukovany's short upgrade history:

- **2000, Upgrade-1**, system maintenance and system tuning.
- **2003, Upgrade-2**, adjusting the physical modules to EDU's requirements.
- **2004, Upgrade-3**, adaptation to use the Gd2 fuel type, moving to 42 axial layers.
- **2005, Upgarde-4**, system adaptation to work with the upgraded I&C system.
- **2007-2009, Upgrade-5**, improvements in operation support tools, implementation of SPNDs to the 3D Power Reconstruction, support of new GD2+ and Gd2M fuel, support the up-rated reactor thermal power, upgrade of the system HW.

First implementation at Bohunice NPP V2 in Slovak Republic:

- completed in 2001, migrated to 3. and 4. unit.

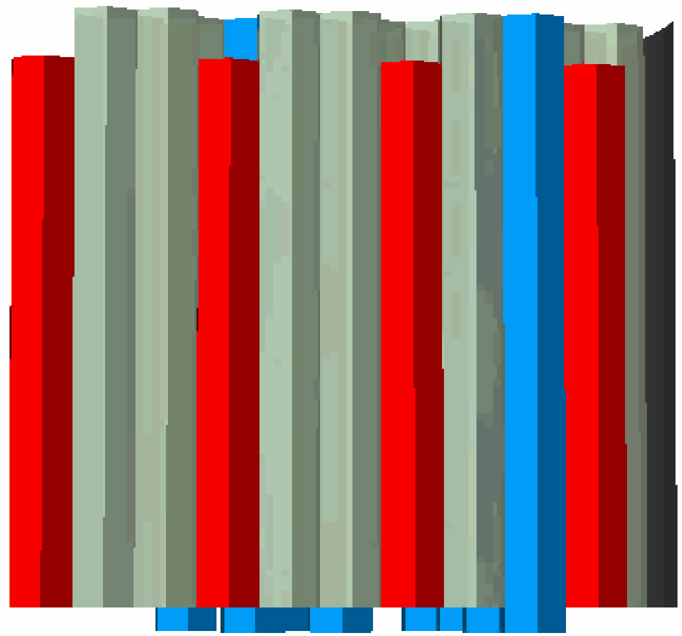
Bohunice's short upgrade history:

- **2006, Upgrade-1**, adaptation to use the Gd2 fuel type, moving to 42 axial layers, improvements in SG, implementation of online shape function generation.
- **2008-2009, Upgrade-2**, adaptation to the newly implemented I&C, improvements in limit checking (online shutdown margin calculation) and 3D Power Reconstruction method, improvements of Strategy Generator, support the up-rated reactor thermal power, upgrade of the system HW.

SCORPIO-VVER upgrades:
The most important upgrade features

The most important improvements in the area of neutron physics, core thermal analysis and operation support are:

- 42 axial nodes across the whole system (2004).
- New cross section library to support mixed core with differences in axial geometry of the Profiled and Gd2 fuel and enhanced Core Simulator boundary conditions model, to properly address the “wild” geometry in axial direction (2004).
- Extended form functions for pin-wise reconstruction to improve pin-power prediction in control rod coupler region (2004).
- System adaptation to the new upgraded digital I&C unit system (2005).
- Implementation of new On-Line form function generation to module RECON (2006).
- New Strategy generator with advanced predictions (2007)
- Up-Rated reactor thermal power support (2008)
- Extended “full core” limit checking and online SDM calculation (2008)
- New 3D power reconstruction with SPND interpretation (2009)



Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER latest development:
Operator Support tools - The Strategy Generator

Requirements:

- Based on the function of the “Strategy Generator” from the old TOPRE/X core monitoring system at Bohunice NPP V-1 Unit 1&2.
- Based on operation requirements of Bohunice NPP V-2 Unit 3&4.

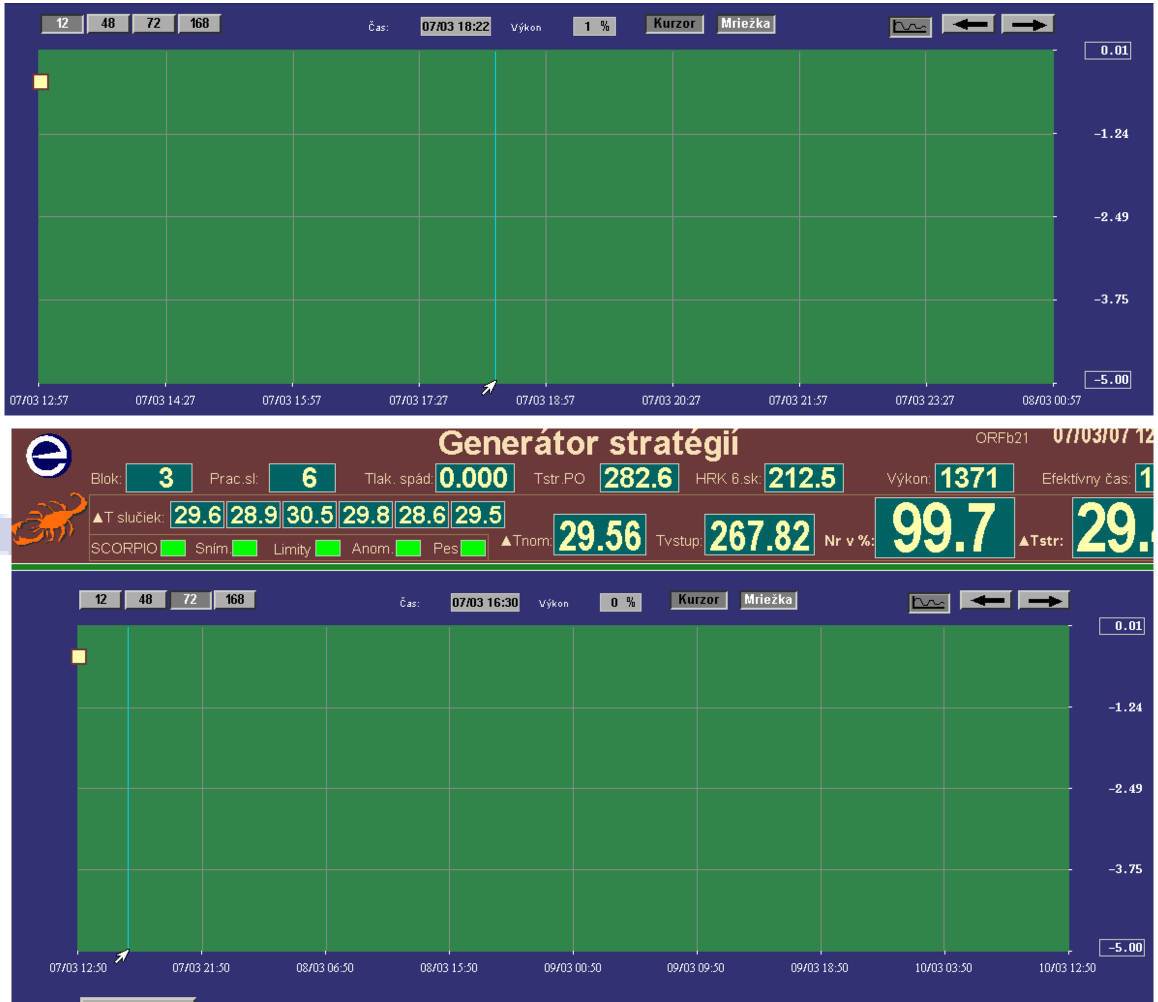
New physical model:

- New fuel-cycle end detection algorithm was developed. Automatic steam header pressure control were implemented to SG.
- New model of CA efficiency was implemented. Now the CA efficiency depends on the position of CA and on the Tef.
- In correspondence with Tech Spec new strategy rules were implemented.
- Special boron acid vs. control rods pre-compensation function was added.
- New, off-line prediction mode (start from past and start from future) was developed and integrated to the SG.
- Adjustable flow rates for pure water and boron acid were implemented.

SCORPIO-VVER latest development:
Operator Support tools - The Strategy Generator (cont.)

New user interface:

- Strategy definition was improved – manual data input – free input by mouse.
- Increased the number of power changes in one trend (Subsequent Breakpoints).
- Advanced Breakpoints properties. (exact values, priorities, technical specification rules, MSHP control, changing the boron acid concentration, etc.)



SCORPIO-VVER
EDU's Limit Checking MMI Interface

Leaving the old limit checking interfaces with selected groups of "old" and "new" fuel

SCORPIO-VVER
EDU's Limit Checking MMI Interface

The control of margins to the technical specifications:

- Extended to full core – all FA is controlled individually in core
- The limits are definable up to 59 FA (1/6 symmetry)
- 4 limited parameters are controlled – Kr, qlin, Toutfa, dTfa
- 2 additional parameters are monitored – dTsat, DNBR

- 3 new MMI interfaces is developed to present the limited and controlled parameters in core

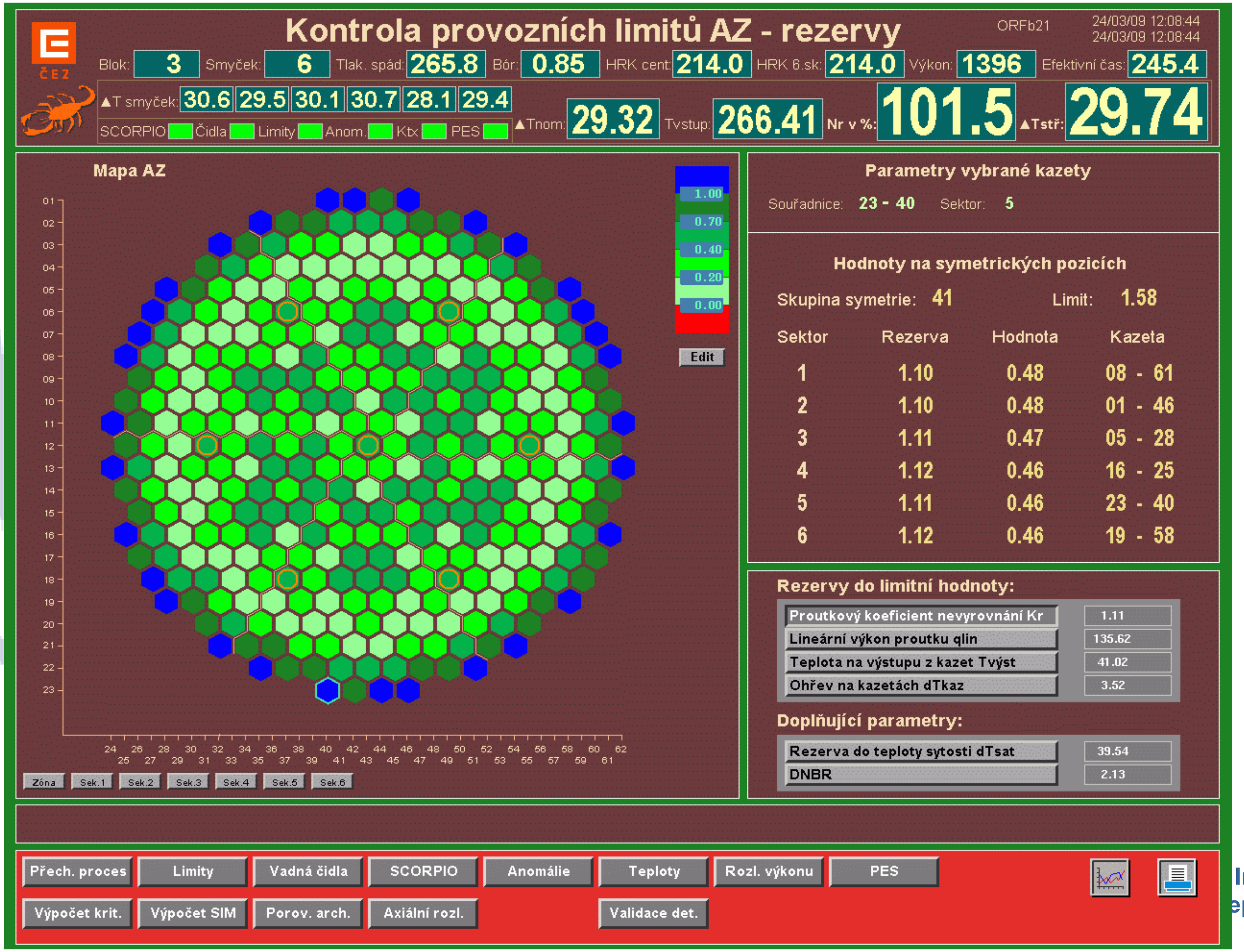
Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER
EDU's Limit Checking MMI Interface

And moving to the full scope core monitoring

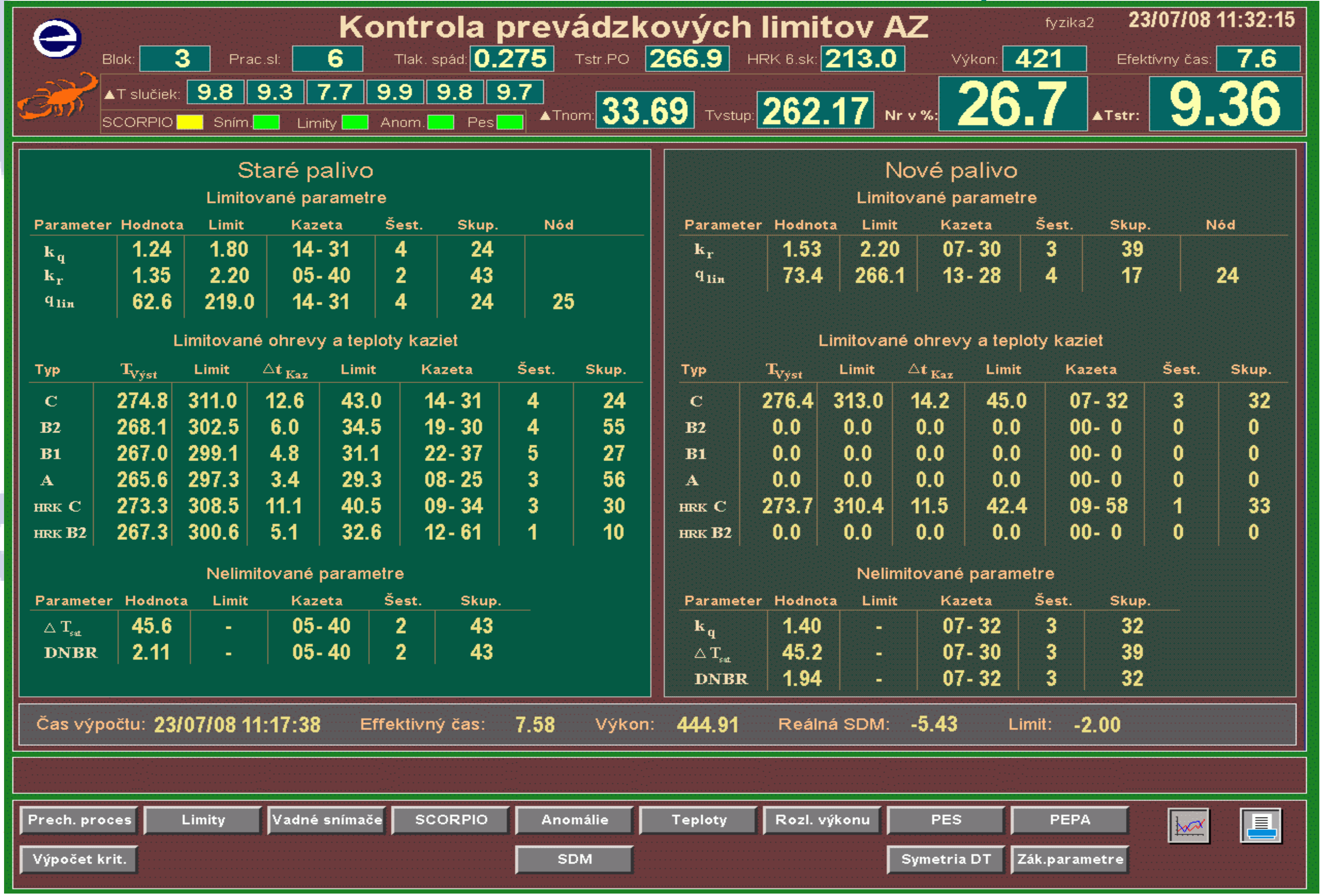
SCORPIO-VVER
EDU's Limit Checking MMI Interface

And moving to the full scope core monitoring



SCORPIO-VVER
EBO's Limit Checking MMI Interface

At Bohunice NPP the existent interface was extended with new parameter – with SDM



SCORPIO-VVER latest development: Limit Checking – The On-Line calculation of SDM

The basis of implementation:

- Based on the results of detailed study.
- Calculated by core follow simulator (SIM) running in 1/6th core symmetry.
- 24 nodes per assembly section are needed to obtain accurate results for core reactivity with inserted control assemblies.
- The worth of the stuck control assembly is pre-calculated offline during the reload process.

The results:

The SDM calculation is done in two steps:

- In the 1st step the simulator module calculates the reactivity with all control assemblies in core. The result of this calculation presents the “Ideal SDM” not considering the stuck control assembly.
- In the 2nd step the “Ideal SDM” is corrected to the SDM by the worth of the stuck control assembly, which is parameterized on the average core burnup.

SCORPIO-VVER latest development: Limit Checking – The On-Line calculation of SDM

The corrections:

- The corrections for “Ideal SDM” to “Real SDM” are prepared in off-line mode automatically by RELOAD module at the beginning of the fuel cycle and stored in special input file for SIM module.

Controlling of calculations:

- Automatic calculation, with definable period, the default period is 8hours.
- Automatic calculation triggered by core parameters changes:
  - reactor thermal power changes (user defined, default value 100 MWt),
  - control assembly position changes (user defined, default value 50 cm).
- Calculation triggered by user – should be invoked any time.

The presentation of the calculation results:

- The actual and valid results of SDM calculation are presented in operator’s MMI screens (Operation Limits and SDM Calculation) of the SCORPIO-VVER system completed by short history of SDM and characteristic core parameters.

SCORPIO-VVER
EBO's Limit Checking MMI Interface

And the list of interfaces was extended with new one – with SDM details.

Čas výpočtu	Tef prevádzky reaktora od začiatku kampane [FPD]	Tepelný výkon reaktora [MW/t]	Stredná teplota chladiva v studených vetvách slučiek [°C]	Hmotnostný prietok chladiva v PO [kg/s]	Polohy jednotlivých skupín kaziet HRK: 1.sk. HRK [cm]	2.sk. HRK [cm]	3.sk. HRK [cm]	4.sk. HRK [cm]	5.sk. HRK [cm]	6.sk. HRK [cm]	Výsledky výpočtu bezpečnostnej zásoby podkritičnosti SDM: Stav reaktoru pri výpočtu	Ideálná SDM [%]	Reálná SDM [%]	Teplota chladiva [°C]	Koncentr. H_3BO_3 [g/kg]
23/07/08 11:17:38	7.6	444.9	260.8	9110.5	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 11:17:22	7.6	445.0	260.8	9111.2	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 11:13:56	7.6	444.4	260.9	9110.3	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 11:13:40	7.6	444.4	260.9	9110.5	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 10:35:31	7.6	445.1	260.8	9110.8	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 10:33:55	7.6	444.7	260.9	9109.2	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
23/07/08 10:33:39	7.6	444.0	260.9	9109.0	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.4	240.0	5.6
26/06/08 14:58:55	0.0	560.0	265.3	5446.5	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-7.9	-4.4	240.0	6.2
26/06/08 14:58:39	0.0	561.2	265.5	5445.5	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-7.9	-4.4	240.0	6.2
26/06/08 14:53:45	0.0	541.0	267.9	5423.8	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-7.8	-4.4	240.0	6.1
26/06/08 14:47:40	0.0	794.5	268.9	6890.0	250.0	250.0	250.0	250.0	250.0	161.0	kritický	-7.7	-4.3	240.0	6.1
26/06/08 14:25:01	0.0	1339.5	267.7	9021.2	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.8	-4.3	240.0	6.1
26/06/08 14:24:45	0.0	1340.9	267.6	9021.1	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.7	-4.3	240.0	6.1
26/06/08 14:19:11	1.7	1340.8	267.7	9019.4	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.1	240.0	4.2
26/06/08 14:18:54	1.7	1342.1	267.7	9019.9	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.1	240.0	4.2
25/06/08 14:06:57	0.7	541.5	267.7	5425.4	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 13:36:57	0.7	1339.8	267.7	9020.8	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 13:36:41	0.7	1339.4	267.7	9019.0	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 13:32:18	0.7	1342.3	267.7	9019.7	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 13:32:02	0.7	1342.7	267.7	9019.1	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 11:52:09	0.6	554.3	267.1	4500.0	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-7.5	-4.1	240.0	4.5
25/06/08 11:21:59	0.6	1342.2	267.7	9019.8	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 11:21:43	0.6	1342.7	267.7	9019.1	250.0	250.0	250.0	250.0	250.0	238.0	kritický	-7.6	-4.2	240.0	4.6
25/06/08 10:58:36	0.6	225.3	263.1	9079.6	250.0	250.0	250.0	250.0	250.0	191.0	kritický	-8.9	-5.5	240.0	5.5
25/06/08 10:28:35	0.6	433.7	261.3	9104.8	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.9	-5.5	240.0	5.5
25/06/08 09:58:34	0.6	786.9	266.8	6000.0	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.0	-4.6	240.0	4.9
25/06/08 07:40:10	0.5	684.0	265.2	6000.0	250.0	250.0	250.0	250.0	250.0	215.0	kritický	-8.3	-4.8	240.0	5.2
25/06/08 06:49:03	0.5	583.4	263.8	6000.0	250.0	250.0	250.0	250.0	250.0	180.7	kritický	-8.2	-4.8	240.0	5.1
25/06/08 06:07:26	0.5	482.4	262.4	6000.0	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-8.0	-4.6	240.0	5.1
25/06/08 05:30:49	0.5	372.9	264.7	6000.0	250.0	250.0	250.0	250.0	250.0	137.0	kritický	-8.1	-4.7	240.0	5.2

SCORPIO-VVER in development: Improved 3D Power Distribution Reconstruction

The main task of 3D Power Distribution Reconstruction (3DREC):

- to provide representative 3D nodal power distributions in the core, using information from validated fuel assembly (FA) outlet thermocouple measurements, validated SPND measurements and results of Simulator calculation.

Until now there were two alternative methods of the power reconstruction implemented in 3DREC module:

- **1st**: „Traditional“ method, corresponding to the one applied in former Russian VK3 monitoring system, i.e. using relatively simple „local“ interpretation of large number of in-core measurements, with limited support from calculation (but in SCORPIO-VVER the calculation role is amplified by extensive input signal validation).

- **2nd**: „Advanced“ method with increased weight of results from the Simulator (based on the Moby-Dick code) if compared to the traditional method.

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER latest development:
Improved 3D Power Distribution Reconstruction

Limits found during the operation:

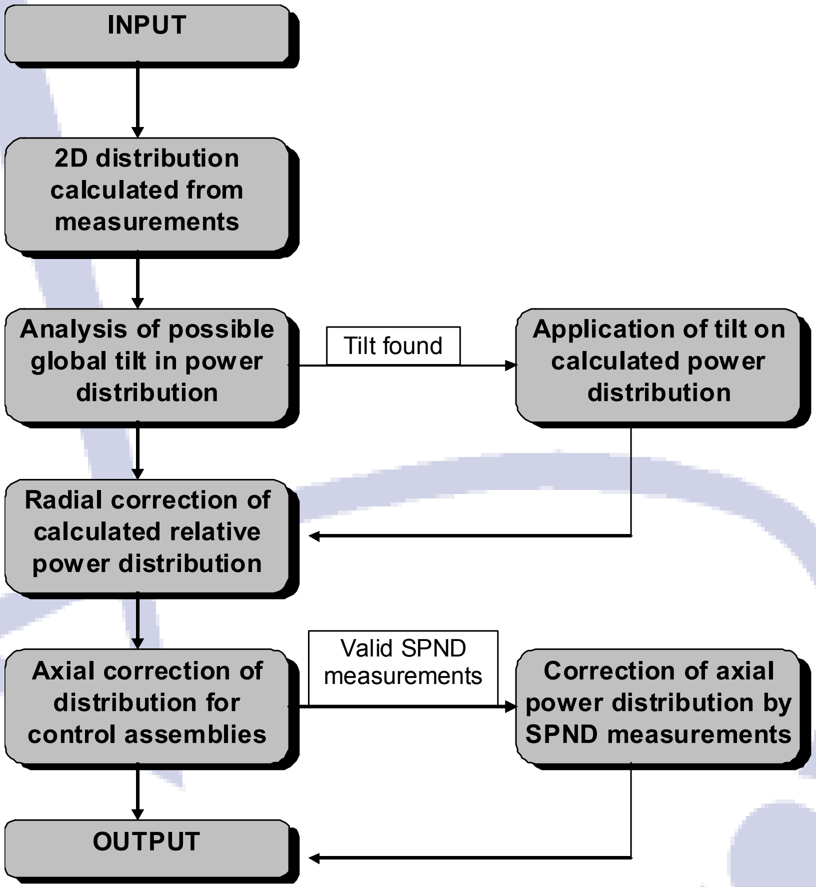
- the precision of the power distribution evaluation by Traditional and Advanced method is limited by the accuracy of FA outlet temperature measurements,
- the measured temperatures do not correspond exactly to the average FA outlet temperatures (imperfect mixing of the coolant above the FA, difficult interpretation of the measurements in the modern profiled Gd bearing fuel assemblies where the measured and average outlet temperatures depends on the fuel burnup too).

Even if the imprecision of FA outlet temperatures is relatively small and it does not cause a safety concern, it limits the accuracy of the 3D power reconstruction.

Two ways of the solution:

- to improve the interpretation of measured temperatures (already are studied by analytical (sub-channel and CFD calculations) and statistical (based on measured temperatures) methods,
- Development of the new methodology of 3D power reconstruction, which does not rely heavily on the thermocouple measurements (improving the 2D radial power distribution).

SCORPIO-VVER latest development: Improved radial power reconstruction in 3DREC module



Data flow:

- Validated input of measurement.
- 2D power distribution calculation based on:
    - coolant temperature measurements,
    - SPND linear power measurement.
- Analyzing the results from the measurements and the Simulator.
- Application of radial correction of 2D power distribution (based on found tilt and weight factors).
- Application of axial shaping / correction of the 3D relative power distribution.
- Output of the results.

SCORPIO-VVER latest development:
Improved radial power reconstruction in 3DREC module

Two types of measurements may be used for the 2D radial power distribution reconstruction:

- **Coolant temperature measurements:** Coolant inlet temperatures at assemblies are calculated using temperature measurements at cold legs of the primary circuit loops and coolant distribution table. Coolant specific enthalpy is calculated at inlet and outlet of assemblies with temperature measurements specified in the configuration file. Specific enthalpy rise for each assembly is used as the value proportional to the power of the assembly.

- **SPND linear power measurements:** individual linear power values calculated from SPND measurements are integrated for each SPND channel and the result is used as the value proportional to the power of the corresponding fuel assembly. Individual missing linear power density values (at positions with faulty measurements) are replaced by values interpolated from other values in channel using the axial power distribution of the assembly calculated by the Simulator Module. Channel with more than 2 faulty measurements are not used in the reconstruction process (zero weight).

Changes:

- Several classes of measurements is defined,
- Separation of measurements to groups allows different weights to be specified for subsequent procedures of the 2D power distribution reconstruction.

Weight of each relative value of assembly power is calculated from credibility factors of corresponding measurements.

In a standard configuration of the module two groups of measurements are defined: first with all temperature measurements at outlet of assemblies (210 values) and s measurements (36 channels).

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER latest development:
Improved radial power reconstruction in 3DREC module

Radial correction of calculated relative distribution:

1st correction - Tilt application:

The differences of the relative radial (2D) power distribution calculated by the Simulator and values obtained from measurements are analyzed and if the significant global tilt (in the whole core) is found it is applied on calculated array**.**

- **The tilt is analyzed** for each group of measurements separately. Symmetrical pairs of assemblies with measured relative power values are selected in pairs of opposite sectors and power values are compared.

- **Weight of asymmetry coefficients** obtained from comparison of symmetrical assemblies in sectors is calculated using the weight of measurements and the weight factor for each group of measurements specified in configuration file.

- **Application of the tilt** to the power distribution array calculated by Simulator depends on the level of the systematical deviation found and on the weight of coefficients described above.

SCORPIO-VVER latest development: Improved radial power reconstruction in 3DREC module

Radial correction of calculated relative distribution:

2nd correction - Correction factors for the calculated relative power of assemblies are based on:

- **Difference of calculated and measured relative assembly power**. This factor is applied only at assemblies with measurements. Weight of the factor depends on the credibility of the measurement, method of reconstruction (traditional or advanced) and the overall weight of the group of measurements specified in the configuration file.

- **Differences of calculated relative power and mean value of measured relative power at symmetrical positions in other 60 deg. sectors**. Only assemblies with measurements are taken into account. Weights for the mean values calculations are dependent on the credibility factors of measurements, method of reconstruction and the overall weight of the group of measurements specified in the configuration file.

- **Differences of calculated relative power and measured values at symmetrical positions in other 30 deg. sectors.** This factor is used only in advanced method of reconstruction and only in cases when the core is really symmetrical in 30 deg. sectors - the Simulator results are analyzed to verify the symmetry. Calculation and application of this factor is similar to the previous one (60 deg. symmetry) and the same weighting factors are used.

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER latest development: Improved 3D Power Distribution Reconstruction

Axial correction of 3D relative distribution:

- Axial power distribution at control assemblies is corrected according to actual C.A. positions to minimize the influence of the mesh size in the Simulator calculation (42 axial nodes per 6 cm).

- SPND measurements are used for axial power distribution corrections in standard assemblies. For assemblies without SPND strings corresponding measurements are attached according to the core symmetry (both 60 deg. and 30 deg.) and a similarity of the calculated axial power distribution at assemblies.

All radial and axial power distribution corrections are applied on the Simulator results for both methods of reconstruction.

Summary:

- The new method of 3D power reconstruction benefit from the precise interpretation of SPND measurements and their conversion to linear power.

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER
Conclusions

- Since the first installation the SCORPIO-VVER system has a remarkable operating history and experience.
- The SCORPIO-VVER core monitoring system with its flexible and modular framework successfully responses to the plant operating needs and advances in nuclear fuel cycle strategies and fuel design.
- Modular framework allows for easy modifications of the system and implementation of new methods in physical modules.
- Even if the system is installed only on VVER-440 reactors, it could be adapted for VVER-1000 needs.

SCORPIO VVER Project

molnar@ujv.cz

Nuclear Research Institute Řež plc
Czech Republic

SCORPIO-VVER IN ACTION

Nuclear Research Institute Řež plc
Czech Republic