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SCORPIO - VVER Core Surveillance System

by

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ABSTRACT

The Institutt for energiteknikk has developed the core surveillance system SCORPIO, which has two parallel modes of operation: the Core Follow Mode and the Predictive Mode. The main motivation behind the development of SCORPIO is to make a practical tool for reactor operators, which can increase the quality and quantity of information presented on core status and dynamic behaviour. This can first of all improve plant safety, as undesired core conditions are detected and prevented. Secondly, more flexible and efficient plant operation is made possible. The system has been implemented on western PWRs, but the basic concept is applicable to a wide range of reactors including VVERs. The main differences between VVERs and typical western PWRs with respect to core surveillance requirements are outlined. The development of a VVER version of SCORPIO has been done in co-operation with the Nuclear Research Institute Rez, and industry partners in the Czech Republic. The first system is installed at Dukovany NPP, where the Site Acceptance Test was completed 6. March 1998.

1. INTRODUCTION

The SCORPIO system [1] has been in operation at the Ringhals PWR unit 2 in Sweden since the end of 1987. In addition, the system has been installed at Nuclear Electric's Sizewell B PWR in UK and all the 7 NPPs of Duke Power Co. in USA [2].

The development of the VVER version of SCORPIO has been carried out in co-operation with the Czech partners Nuclear Research Institute (NRI), Skoda and Chemcomex, with the NPP Dukovany as the target plant. The goal has been to adapt the functionality of SCORPIO to address the particular needs in VVERs. The project has been initiated and partly funded by the Science and Technology Agency (STA), Japan through the OECD NEA assistance program.

The system specification is general covering all VVER type reactors, and the target system has been prepared such that adaptation to other VVERs, including VVER-1000, can be easily achieved.

Special characteristics, which have been emphasised for VVERs, are:

- Control of radial power distribution to minimise fluence at the vessel wall may be important in VVERs due to the small diameter of the pressure vessel. In certain operating regimes, it might be desirable, to reduce the load on certain identified leaking fuel rods.
- In VVERs there are a number of fixed in-core neutron detectors and core exit thermocouples, which are used for core surveillance. One problem is to validate the correctness of these measurements. In Western plants one has reported problems with effective validation of the exit thermocouples. With a detailed simulator one can use the simulator to calculate the measurements thus providing analytical redundancy. This increases the possibility of detecting sensor failures at an early stage. This has been demonstrated in PWRs and BWRs where the simulator is used to check the status of fixed in-core sensors and other measurements.
- Thermocouple measurements are more credible in a VVER reactor than in standard western plants due to the shrouds surroundings of the fuel assemblies.

The major new features of the SCORPIO-VVER core surveillance system compared to existing VVER core monitor systems can be summarised as follows

- Improved limit checking and thermal margin calculation
- On-line 3D power distribution calculation based on the same physics model as used for core design and safety analysis
- Improved validation of plant measurements and identification of sensor failures by utilising the core simulator as an independent means for calculation of 3D power distribution
- Optimum combination of measurements and calculations to obtain more precise values of critical parameters
- Predictive capabilities and strategy planning, offering the possibility to check the consequences of operational manoeuvres in advance, prediction of critical parameters, etc.
- Provide interfaces to off-line analysis codes for core loading pattern design, neutron fluence calculations at the reactor vessel wall, etc.
- Integration of modules for monitoring fuel performance and coolant activity as a means for detection and identification of fuel failures

As a consequence of these requirements it was decided that the SCORPIO-VVER version should use the core simulator MOBY-DICK. It was also decided to continue using the PICASSO system as the MMI part of SCORPIO-VVER. The old Picasso-2 system was replaced by Picasso-3 [3] which includes much more functionalities than Picasso-2. In addition two new modules, a new PCI model PES [6] and a primary coolant monitoring system PEPA [7] were to be integrated with the basic SCORPIO system.

2. IMPLEMENTATION

The SCORPIO-VVER system consists of autonomous modules, which communicate through the communication package Software Bus [4]. The main modules in SCORPIO are identified in the block diagram shown in Fig. 1. A short description of each module follows.

2.1 Core Follow Mode

In the core follow mode, the present core state is calculated based on a combination of instrument signals and a theoretical calculation of the core power distribution. An automatic limit check against the core state is performed on these data. The operator obtains relevant information on core status through the Man-Machine Interface (MMI) in the form of trend curves, core map pictures and diagrams displaying margins to operational limits.

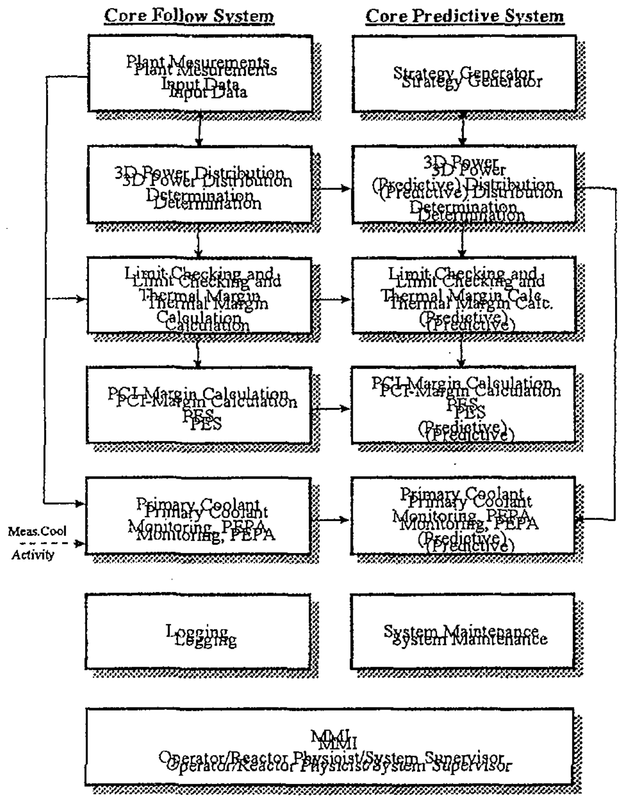

Fig. 1. Main Modules of the SCORPIO-VVER system

2.1.1 Plant Measurements Input Data

Two modules take care of this task:

The Data Acquisition Module (DAM) is implemented with communication facilities to handle two types of data acquisition units (Hindukus and Temperature Measurements Backup System) connected by LAN as TCP/IP clients and provides input data for other modules.

Basic functions

- Accepting of multiple client connections
- Preparation of data structures with Hindukus and TMBS signals
- Confirmation of data transfer by special messages
- Periodic updates of communication status information

- Software Bus interface to other modules for transfer of data and status information

Technical features

- Non-blocking communication with clients, safe in the case of client or LAN malfunction
- Immediate processing of the client message not blocked by other processing (e.g. output)
- A complete message with the Hindukus data processed in less than 100 milliseconds

Following characteristics are checked in a data set received from any client:

- Size of data structure corresponds with predefined data format for this type of client.
- Signal identifiers are in appropriate positions according to predefined data format.
- Data are readable; numbers and arrays are in an appropriate format.

The Input Data Processing Module (IDATP) processes all signals from measurements collected by the DAM.

Basic functions

- Identification of Operational Regime (number of loops in operation etc.)
- Signal conditioning, stabilization, quality checking and validation
- Signal transformation to physical units
- Calculation of primary and secondary circuit parameters including the reactor power
- Calibration of temperature sensors in isothermal reactor states

Both discrete and analogue signals from Hindukus and TMBS are processed. Most important outputs are temperature and pressure values in all measured locations, linear powers, state of primary circuit loops, control assemblies positions, boron acid concentration, mean reactor inlet and outlet temperatures, temperature rises, coolant flow rate and reactor thermal power. Input data validation is performed in two steps. Primary signal checking is based on comparison of values from signal interpretation and maximum reasonable limits. Faulty sensors are excluded in this step. Advanced method of signal validation is applied to thermocouple and Self Powered Neutron Detector (SPND) measurements. Credibility factor is assigned to each measurement using statistical evaluation of measured and calculated values. For thermocouples and resistance thermometers calibration before the reactor start-up, a special procedure monitors the temperature stabilization process and calculates individual correction coefficients for sensors.

2.1.2 3D Power Distribution Determination

The main task of this functionality is to supervise calculations of 3D power distribution and critical boron concentration performed by the core simulator MOBY-DICK on the nodal level.

The 3D Power Reconstruction module (3DREC), activated each basic system cycle (15 sec), provides representative 3D nodal power distribution using validated FA outlet temperature and SPND linear power measurements obtained from IDATP and the Simulator results.

Basic functions

- Calculation of the reconstructed 3D power distribution by two different methods
- Triggering of Simulator calculation according to changes in the reactor state.
- Triggering of Simulator adaptation according to reactor state and user requests.

Two alternative methods of power reconstruction are implemented in 3DREC. "Traditional" method is similar to that applied in the VK3 monitoring system, using "local" interpretation of validated in-core measurements, with limited support from Simulator calculation. "Advanced" method, oriented more on "global" interpretation of both measurement types, uses the Simulator results with higher priority. This method is able to reach acceptable results with significantly less number of valid in-core sensors.

The Simulator module (SIM), activated on request from the 3DREC module (usually each 15 min), has been designed in accordance with the following principal requirements:

- The module is based on universal finite-difference few-group program MOBY-DICK [5]. A simple adaptation procedure has been added to "fit" radial and axial power shapes calculated by SIM to the actual "reconstructed" power distribution. A standard 2-group diffusion data library of off-line MOBY-DICK is utilised.
- SIM performs coarse mesh (nodal) 3D analysis of actual core states. It solves either a 60° core symmetry segment (standard mode) or the full core (360°) if an explicit perturbation of core symmetry exists, i.e. if there is a significant asymmetry of core loading or individual CFAs are dropped or misaligned. Switching between symmetries is automatic, and return to the 60° calculation is carried out when symmetrical power distribution is restored and stabilised. Full core solution is performed with a little simplified core model (with 6 mesh points per FA cross section, instead of 24 points used at SIM symmetrical solution).
- SIM uses standard off-line MOBY-DICK archive files as its initialisation files.
- SIM provides calculated power, neutron flux and burn-up distributions for: 1) "reconstruction" of the representative 3D nodal power distribution (performed in 3DREC); 2) power distribution "de-homogenisation" (i.e. determination of pin power peaking factors F_q and $F_{\Delta H}$, carried out in RECON); 3) signal validation (carried out in IDATP); 4) evaluation of probability of fuel defects caused by PCI (performed in PES module). In addition, critical boron concentration calculated by SIM is used to determine the boron concentration in primary circuit, and special input data are prepared for Strategy Generator (SG).

2.1.3 Limit checking and thermal margin calculation

The present NPP Dukovany Specification for operation, such as nodal power peaking limits and fuel assembly (FA) temperature rise are checked on the basis of the 3D coarse mesh core follow power distribution [8]. Detailed 3D pin-wise power distribution is produced for determination of F_q and $F_{\Delta H}$ power peaking factors and assessment of all margins to the safety limits (DNBR, LOCA and saturation temperature) on the basis of subchannel analysis. Detailed pin-wise power distribution is processed to provide information for PCI-margin calculation (PES). Two modules are taking care of this functionality:

The Reconstruction Module (RECON) has the following functions:

- Determination of 3D pin-wise power distribution and pin-wise F_q and $F_{\Delta H}$
- Transformation from 20 mesh to 7 points for FAs including SPND detectors.

The Check Module (CHECK) has the following functions:

- Traditional checking of nodal power peaking factors (k_q and k_v)
- Traditional checking of coolant temperature rise in the fuel assemblies
- New function for assessment of the margins to the safety limits (DNBR, LOCA and saturation temperature)
- Automatic selection of limit values depending on operational mode
- Calculation of transform coefficients for SPND detectors

2.1.4 PCI -margin calculation, PES

The PES module is evaluating local fuel damage probabilities due to pellet cladding interaction. This module has the following functions:

- Calculation of the conditioned power distribution
- Determination of limits for permitted reactor local and global power change

2.1.5 Primary Coolant Monitoring

The **PEPA Module** determines the number and type of fuel defects based on the coolant activity analyses (i.e. identification of noble gases and fission products in the coolant).

2.1.6 Logging of data

The **LOG Module** collects output data from other modules, maintains an archive of outputs and provides output to the LAN for other systems and printed text output of selected arrays.

Basic functions

- Asynchronous data capturing from DAM, IDATPD, 3DREC, SIM, CHECK and PES modules.
- Data sorting (synchronization) in accordance with time stamps in data sets.
- Temporary storage of multiple data sets in memory.
- Short-term (up to 3 days) disk archivation of selected data from sets stored in memory.
- TCP/IP interface for other computers of Unit LAN performing output of selected data.
- Automatic calculations of main reactor state parameters mean values per hour and per day.
- Automatic recovery after the shutdown - reuse of backups and archive after new start-up.
- Configurable print service for printing of selected arrays in specified time intervals.

Technical features

- Non-blocking communication with clients, safe in the case of client or connection malfunction.
- Input calls are processed with a higher priority than output tasks to eliminate data loss.
- Memory and disk space requirements are controlled by configurable parameters.

When output structures from other modules are received, LOG checks time stamps included in structures and assembles the archive data sets. Selected data are stored in memory approx. 30 minutes to enable a fast output and then a subset of data is transferred to a disk archive.

Print service of the Logging Unit is able to print or save on the disk selected arrays in periodical intervals or after user request from MMI. Arrays may be printed in various formats and organized in predefined forms according to a specification in the configuration file.

2.2 Predictive Mode

In the predictive mode of operation, the operator can forecast the reactor behaviour during the coming hours. As no detector signals are available in this case, the accuracy of the predicted core state depends heavily on the quality of the physics model in the predictive core simulator. The state is checked against limits, and the predicted behaviour of the core may be analysed by the operator through a number of dedicated pictures.

2.2.1 Strategy Generator

The main task of the **Strategy Generator (SG)** is to assist the operators and reactor physicists to derive various operational strategies that can be verified by the predictive simulator.

The strategy generator employs an extremely simplified core model to suggest control strategies for achieving a given power manoeuvre [9]. Power and xenon-iodine densities are calculated for the upper and lower core halves without solving the neutronics and hydraulic equations. The calculations are based on precalculated coefficients for the reactor's response to changes in the inlet temperatures, control-rod movements, and boron and xenon concentrations. These coefficients are found by running the off-line MOBY-DICK for various reactor conditions, and correspond to multidimensional numerical expansion of reactor reactivity.

2.2.2 Predictive simulator

The **Predictive Simulator Module (PREDSIM)** is based on the MOBY-DICK [5]. It is used for calculation of 3D power distribution and critical parameters up to 72 hours ahead of current time. The initial conditions are provided by the 3DREC module. The Strategy Generator module and/or the user himself prepare the necessary input data.

The predictive simulator can be used to solve 5 different sorts of tasks. These are:

- Solution of load-follow transient without recalculation of critical parameters.
- Solution of a load-follow transient with recalculation of critical parameters
- Calculation of start-up critical boron concentration and concentrations providing selected subcriticality margins for specified three coolant temperatures and one Bank 6 insertion.
- Calculation of start-up critical Bank 6 positions and positions of Banks 4 to 6 selected subcriticality margins for specified 3 coolant temperatures and one boron concentration.
- Calculation of shutdown boron concentration at one specified coolant temperature with all rods out of core.

Tasks 3 and 4 can only be performed at zero power. The predictive tasks can be started in 60° core symmetry only. To accelerate calculation, 6 mesh points per FA cross section are used.

2.2.3 Limit checking and thermal margin calculation in predictive mode

The **Predictive Limit Checking Module** is triggered by the PREDSIM. It produces detailed 3D pin-wise power distribution for determination of F_q and $F_{\Delta H}$ power peaking factors and assessment of all margins to the safety limits (DNBR, LOCA and saturation temperature) on the basis of subchannel analysis.

2.2.4 PCI margin prediction

The **Predictive PES module** is used to find the minimum difference between limit and linear power on the detailed pin-wise level. The result is based on initial condition from the PES Core Follow Module and inputs coming from PREDSIM, the Predictive Limit Checking Module.

2.2.5 Primary Coolant Activity Prediction

The **Predictive PEPA module** allows, based on results of the on-line module, calculation of radioactive nuclide activities in the primary coolant in transient states of the reactor. The transient is defined by using the Strategy Generator.

2.3 Man Machine Interface

The man machine interface has been designed to be used by three different user groups:

❶ Reactor Operator ❷ Reactor Physicist ❸ System Supervisor

and to be used in the two operation modes:

❶ Core Follow ❷ Predictive

The system was designed such that is easy to use and presentation of information is easy to understand and read. An example of a SCORPIO-VVER screen is shown in Fig. 2. This picture shows the reconstructed outlet temperatures. The colour of assembly cells has in this case been selected to indicate the difference between measured and reconstructed temperature rise.

3. CONCLUSIONS

The development of the SCORPIO-VVER system has been going on since the middle of January 1996. The development process has followed a well-defined Quality Assurance Plane. Dukovany NPP staff has taken part in the requirement specification, reviews, testing and in coupling of the system to the plant instrumentation. Factory Acceptance Test (FAT) was taking place in the first part of November 1997 and Site Acceptance Test (SAT) was successfully performed during the first week of March 1998. The system is now implemented on two of the four units at the Dukovany NPP.

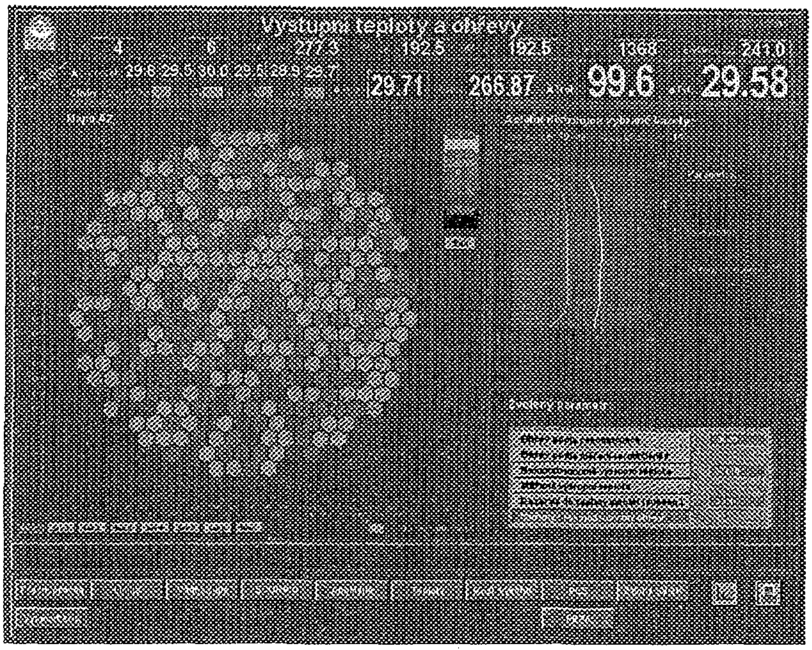

Fig. 2. The "RPD, Outlet Temperatures" picture

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