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SCORPIO-VVER CORE SURVEILLANCE SYSTEM

by

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ABSTRACT

The Halden Project 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. So far the system has only 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 initiated in co-operation with the Nuclear Research Institute Rez, and industry partners in the Czech Republic. The first system will be installed at Dukovany NPP. The goal is to adapt the functionality of SCORPIO to address the particular needs in VVERs. An enhanced PCI model and a new module for on-line primary coolant gamma spectrometry monitoring will be included.

1. INTRODUCTION

The SCORPIO system, ref [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 Duke Power Co. in USA, ref [2].

The SCORPIO system was designed to be modular which is particularly important if other plant models (for instance the core simulator) are desired or one wants to connect to a specific type of core instrumentation. This is mostly the case with the core follow system because the instrumentation may vary from plant to plant. The predictive system is the most generic part.

The development of the VVER version of SCORPIO is 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 is to adapt the functionality of SCORPIO to address the particular needs in VVERs. The project has been initiated and is partly funded by the Science and Technology Agency (STA), Japan through the OECD NEA assistance program.

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

2. FUNCTIONAL DESCRIPTION

The main software framework of the PWR SCORPIO system is used as a basis for the development of the VVER version. The operator interface will also build on the existing, user interface management system Picasso-3, ref [3].

The core physics simulator in the VVER version of the SCORPIO system will, however, be changed to one appropriate for VVER core calculations. The simulator must be capable of handling hexagonal fuel assemblies. The VVER-440 reactors have shrouds surrounding the fuel assemblies and the height of the active core is only 2.42 meter. This means that axial xenon oscillations do not play the same important role as in larger Western

PWRs. The VVER 1000 reactors have no shrouds surrounding the fuel assemblies, and the active core height is increased (~3.5 m). This means that axial power distribution variations are more important, and the core dynamics are more similar to the Western reactors.

Special characteristics which have been emphasised 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. Further, it might be desirable, in certain operating regimes, 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 will increase 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.
- Another type of sensors which needs validation is feedwater flow sensors which are used for calculating the thermal power. A number of flow sensors are used for calculation of thermal power, and drift in these flow sensors may be hard to detect.

In addition to the change in the core physics simulator in the VVER version of SCORPIO, new modules will be developed to support VVER operation. The major new features of the proposed 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
- Improved man-machine interface for operators and reactor physicists
- Improved HW/SW reliability, by introduction of a new computer system.

3. SYSTEM DESIGN

The SCORPIO-VVER version will use the core simulator MOBY-DICK, ref [4] and the user interface management system Picasso-3 ref [3]] which simplifies the interfacing to other systems. In addition two new modules, a new PCI model PES, see ref [5], and a primary coolant monitoring system PEPA, see ref [6], will be integrated with the basic SCORPIO system.

The SCORPIO-VVER system will be implemented on workstations running in UNIX environment with the X Window System and duplicated Ethernet communication based on the TCP/IP protocol. The type of platform considered in the first version will be Hewlett Packard. For implementation the programming languages will be C, C++ and FORTRAN. As far as possible the system should be made configurable to allow easy extensions/modifications of system parameters. Adding new instruments, for instance, should not require any reprogramming.

The SCORPIO-VVER system will be able to run in parallel with the present VK-3 system at the Dukovany NPP.

The main modules in SCORPIO are identified in the block diagram shown in Figure 1. Two basically different modes of operation are available, namely the core follow mode and the predictive mode. A short description of each module is given in the following sections.

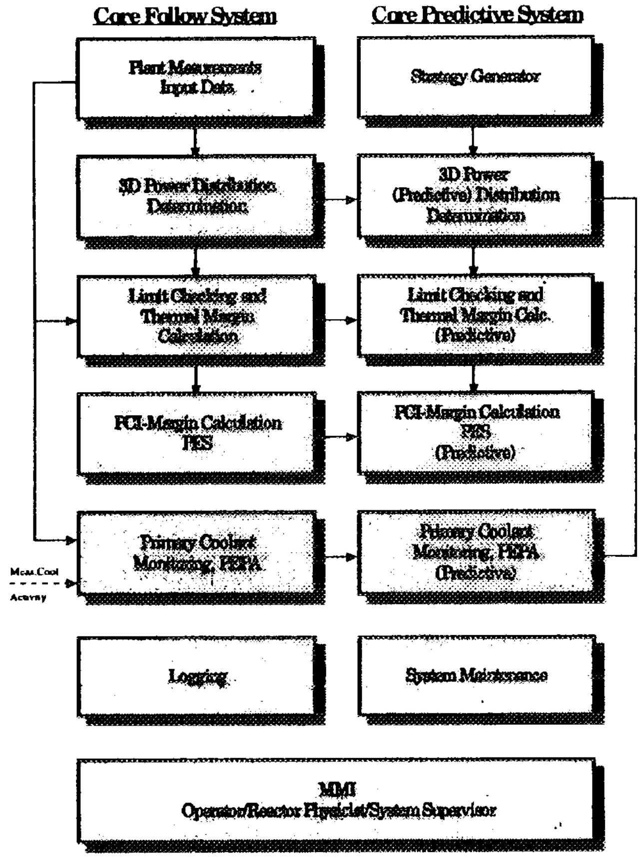

Figure 1 Main Modules of the SCORPIO-VVER System

3.1 The 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. These data are passed to the data base and an automatic limit check on the core state is performed. The operator obtains relevant information on core status through the Man-Machine Interface. This information is presented on colour CRTs in the form of trend curves and diagrams displaying margins to operational limits. The primary coolant monitoring is an extension of the core follow mode functionality.

3.1.1 Plant Measurements Input Data

This subsystem will pre-process all measured signals and carry out an extensive signal validation. The basic primary and secondary circuit parameters will be calculated and mode of plant operation will be identified. The transformation coefficients of SPND signals to linear power will be determined. A special module will be devoted to calculation of outlet thermocouple corrections from isothermal reactor state measurements.

This module will have the following functions:

- Identification of Operational Regime (operational states with different number of loops in operation, shutdown states, stuck rods, etc.)
- Signal conditioning, stabilisation and signal quality checking
- Signal validation
- Signal transformation to physical units
- Calculation of primary/secondary circuit parameters including reactor power
- Calculation of transformation coefficients for SPND detectors either
    1. Existing method
    2. Advanced method using explicit simulator calculation of detector material depletion and pin-wise power distribution
- Determination of thermocouple corrections from isothermal reactor states, including supervision of temperature stabilisation process
- Correction of coolant outlet thermocouple measurements on radiation heat-up

3.1.2 3D Power Distribution Determination

The main task is to supervise calculations of 3D power distribution and critical boron concentration performed by the core simulator MOBY-DICK on the nodal level. The representative distributions will be determined based on the validated outlet temperature thermocouples, SPND measurements and theoretical results mentioned above; the two alternative methods (traditional and advanced one) will be provided for this purpose. A special module will carry out adaptation of diffusion data used by the simulator to minimise the deviations between its results and measurements. The data needed for validation of SPND and outlet thermocouple signals (based on calculated distribution) will be produced.

This module will have the following functions:

- Triggering of the 3D power distribution calculation
- 3D power distribution and critical boron calculation with all necessary feedback including burnup, xenon and samarium
- Measurement based 3D-power distribution reconstruction
- Best estimate 3D-power distribution determination based on measurements and calculation
- Adaptation of 3D power distribution calculation based on the best estimate 3D power distribution
- Processing of data needed for sensor signal validation
- Generation of data for the predictive system

3.1.3 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 calculated and checked on the basis of the 3D coarse mesh core follow power distribution, see ref [7].

Detailed 3D pin-wise power distribution will be 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 will be processed to provide information for PCI-margin calculation (PES) and off-line reactor vessel fluence calculation.

This module will have 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 determination of 3D pin-wisc power distribution and pin-wise F_Q and $F_{\Delta H}$
- New function for assessment of the margins to the safety limits (DNBR, LOCA and saturation temperature)
- Calculation of integral data for assessment of fluence at the reactor vessel wall
- Automatic selection of limit values depending on operational mode

3.1.4 PCI -margin calculation, PES

The PES module will evaluate local fuel damage probabilities due to mechanisms of pellet cladding interaction. The model will determine the maximum allowable local and global power changes.

This module will have the following functions:

- Calculation of the conditioned power distribution
- Determination of limit for permitted reactor power change

3.1.5 Primary Coolant Monitoring, PEPA

The package, based on measurements of radioactive nuclides activities in primary coolant, will estimate the number of damaged fuel elements. Moreover, it will enable the plant personnel to obtain information about the character of damaged fuel elements and the type of their damage.

This module will determine 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)

3.1.6 Logging of data

This system will provide short time (< 72 hours) logging of data important for core monitoring: measured data, calculated data, limits and margins, calibration factors, etc. Also the interface for the long term archiving (Operational States Database) and for off-line analyses will be provided.

3.2 The Predictive Mode

The predictive mode of SCORPIO may be a new unique feature of core surveillance systems in VVERs, because to our knowledge there are no such systems available in VVERs. Use of predictions has proven to be very valuable in core surveillance systems for Western PWRs and we think predictive capabilities will be relevant for VVER systems as well. In this respect the benefit gained in operator training by providing a predictive simulator of core behaviour should not be forgotten.

In the predictive mode of operation, the operator can precalculate 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. Also in the predictive mode, results from the simulator are stored in the database. 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.

Predictive analysis is carried out in a sequence as illustrated in Figure 2. The operator first has to specify the desired power to be produced. Then the strategy generator is activated and a proposal for how to use the controllers is produced. Simulation is started with initial data from the core follow system and results are examined as the simulation goes on. If safety limits are exceeded or undesired control settings are detected, the operator modifies input at critical timepoints. A new simulation is then initiated and examined. This interactive adjustment of a transient is carried out until the operator is satisfied.

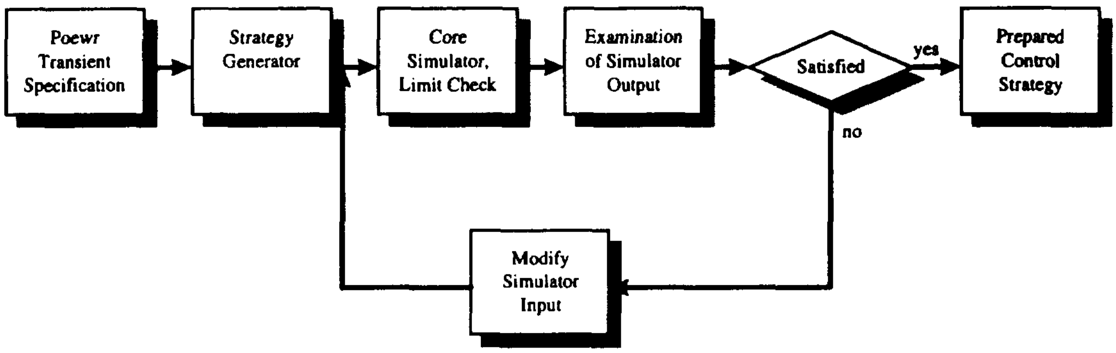

Figure 2 Procedure for predictive simulation with SCORPIO

3.2.1 Predictive simulator

The predictive core simulator will be used for calculation of 3D power distribution and critical parameters several hours (<48h) ahead. The initial conditions will be provided by the 3D Power Distribution Determination Module (Core Follow System).

The Strategy Generator module and/or the user himself will prepare the necessary input data for various types of predictive tasks.

The predictive simulator will provide information to the PEPA (Predictive) module and the module for limit checking and thermal margin calculation (Predictive).

3.2.2 Strategy Generator

The main task of the Strategy Generator is to assist the operators and reactor physicists to derive various operational strategies which can be verified by the predictive simulator before the actions are implemented on the reactor.

The Strategy Generator will also make possible core control optimisation during power transients on the basis of analyses by a simplified core model.

The calculated control strategies will be verified by the predictive simulator, i.e. 3D power distribution and critical parameters such as critical boron concentration, rod positions, inlet temperature in various transients like SCRAM, start-up, end of cycle, load changes, etc.)

3.2.3 Limit checking and thermal margin calculation in predictive mode

Detailed 3D pin-wise power distribution will be 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 will be processed to provide information for PCI-margin calculation (PES).

3.2.4 PCI margin prediction (PES)

Based on results of the on-line PES module, the predictive part will evaluate local fuel damage probabilities due to mechanisms of pellet cladding interaction and check the acceptability of the planned load-follow manoeuvres etc. from this point of view.
This module will have the following functions

- Interface to the PES in the Core Follow System
- Interface to the limit checking and thermal margin calculation, predictive system
- Calculation of the conditioned power distribution
- Determination of limit for permitted reactor power change

3.2.5 Primary Coolant Activity Prediction (PEPA)

The predictive part of the PEPA software system will allow, based on results of the on-line module, calculation of radioactive nuclides activities in the primary coolant in transient states of the reactor.

This module will have the following functions

- Interface to the PEPA in the Core Follow System
- Interface to the predictive simulator (total power, boron, flow, etc.)
- Prediction of activity levels in the primary coolant assuming different operational strategies

4. System Maintenance

The core surveillance system comprises a number of plant specific and fuel specific data which must be maintained. Partly data will be changed as new signal calibrations are done or the burnup changes. When new fuel is loaded, the parameters for the physics codes are updated. Further, the MMI may be changed as feedback from users is obtained.

An adequate set of tools and procedures will be required to facilitate system maintenance. The system supervisor functions are:

- Operational limit values and calibration factor modifications
- Test facilities, diagnostics, self-testing
- Means for database corrections and maintenance (fuel reloading, etc...)
- Tools for modifications of the MMI
- System start-up and shutdown by simple procedures

5. THE MAN-MACHINE INTERFACE

5.1 MMI principles

Traditionally, simulator codes require several input files and produce a huge amount of calculated data. However, operators usually should not need to specify or change more than a few input parameters like total power demand and the controller settings for a predictive simulation. Likewise, analysis of simulation results can often be limited to some key parameters like the axial offset or the most critical spots in the entire core. The details should be hidden but could be presented if requested.

Much effort has been devoted to simplification of the Man-Machine Interface of SCORPIO. No special keyboard is required for the new UNIX based version as was required for the old version of SCORPIO, Ref. (1). All pictures can be selected from a "keyboard" picture.

The input to SCORPIO is entered through a combined use of a mouse or trackerball and an alphanumeric keyboard. The input to be specified by the operator is reduced to a minimum and the input procedure is made as simple as possible.

In addition, the operator is guided through a dialogue procedure with context sensitive dialogue fields and functions to be selected from menus. The dialogue is made fault tolerant. This means that feedback is obtained in form of messages if the operator tries to enter illegal data or for instance tries to start a simulation while the simulator is active etc.

The dialogue system of SCORPIO is made flexible such that the operator himself can choose if he will specify all input to a predictive run or if he wants the strategy generator to supply the controller settings. In the latter case only the total power as function of time is specified. Both a graphical and numerical representation of the input are shown in the picture. This makes it easy to check the input because errors will show up immediately in the picture and they can be corrected at once.

The strategy generator is activated by a function key in the lower field of the picture. The desired power trajectory is read and after a few seconds (<5 seconds), values for inlet temperature, boron and control bank positions are proposed. The operator can also here investigate the proposed control strategy carefully in pictures with both graphical and numerical representation. If the operator wants to modify this proposed strategy, he is free to type in new values in the dialogue field.

When simulator input is prepared, the simulation is activated with a function key. The simulation output is presented in colour coded self-explanatory pictures. The operator can observe the calculations by looking on a picture which displays trends of key core parameters such as axial offset and most critical margins to LOCA, DNB and PCI. For instance channel power distributions can be investigated.

Strategy improvements are carried out by modifying previous strategy input. To modify the strategy is fast if modifications are done in the last part of the strategy only. This means that the first unchanged part of the strategy is copied from the previous calculations, only the last new part of the strategy is calculated.

5.2 User Groups

The SCORPIO-VVER system will have three groups of users. These are:

- Reactor Operators
- Reactor Physicist
- System Supervisor.

Relevant pictures covering functions and informations needed for the different users will be provided.

5.2.1 Operator's MMI

For the operator, there will exist Overview displays covering the following informations:

- Summary of key parameters related to core monitoring
- Summary of information from primary circuit
- Distinguish between validated data and bad values, measured values, calculated values
- Diagnostic information on sensors and data acquisition system (Hindukus)
- Margin to limits
- Radial power distributions
- 2D distribution of temperature rises, margins to limits
- All new calculated limits associated with 2D distribution presentation
- Trends of key variables
- Specific display of axial power distribution
- Summary of information from PES and PEPA
- Standard output display for key results of power transients and critical parameters, margins to limits, e.g. critical boron concentration during start-up

In addition, special displays will be provided to support specification and organisation of various predictive analyses, including:

- Selection of predictive tasks such as load follow, start-up boron concentration calculation, etc.
- Specification of predictive tasks (e.g. power transient).
- Specification of Strategy generator objectives
- Specification of conditions for limit checking, thermal hydraulic calculations, PCI (PES) and PEPA, etc.

5.2.2 Reactor Physicist's MMI

All the screens used by the operator will also be available for the reactor physicist. In addition the following information (detailed calculation results etc.) will be provided.

- Power distributions including information on pin-wise level
- Comparisons between calculated and measured data
- Detailed information on validation of measured data (why some data was disregarded)
- Adaptation parameters changes, etc.
- PES detailed distribution of conditioned power, stresses, etc...
- PEPA activity in primary coolant, trends for different isotopes

5.2.3 System Supervisor's MMI

Specific screens for accessing data files and procedures will be provided:

- Calibration factor modification
- Test facilities, diagnostics, self-testing
- Means for database corrections and maintenance (fuel reloading, etc...)
- Tools for modifications of the MMI
- System start-up and shutdown by simple procedures

The functions included in the system supervisor's MMI should be protected against unauthorised use.

6. CONCLUSIONS

The development of the SCORPIO-VVER system has been going on since the middle of January 1996. The specification phase is completed and the design phase is nearly finished. The implementation phase has already started, and the system is expected to be in operation at Dukovany from the beginning of 1998.

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