International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009)
Saratoga Springs, New York, May 3-7, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009)

THE WHITESTAR DEVELOPMENT PROJECT: WESTINGHOUSE'S NEXT GENERATION CORE DESIGN SIMULATOR AND CORE MONITORING SOFTWARE TO POWER THE NUCLEAR RENAISSANCE

William A. Boyd, Larry T. Mayhue, Vincent S. Penkrot and Baocheng Zhang
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, Pa 15230
boydwa@westinghouse.com; mayhuelt@westinghouse.com; penkrovs@westinghouse.com; zhangb@westinghouse.com

Abstract

The WhiteStar project has undertaken the development of the next generation core analysis and monitoring system for Westinghouse Electric Company. This on-going project focuses on the development of the ANC core simulator, BEACON™ core monitoring system and NEXUS nuclear data generation system. This system contains many functional upgrades to the ANC core simulator and BEACON core monitoring products as well as the release of the NEXUS family of codes. The NEXUS family of codes is an automated once-through cross section generation system designed for use in both PWR and BWR applications. ANC is a multi-dimensional nodal code for all nuclear core design calculations at a given condition. ANC predicts core reactivity, assembly power, rod power, detector thimble flux, and other relevant core characteristics. BEACON is an advanced core monitoring and support system which uses existing instrumentation data in conjunction with an analytical methodology for on-line generation and evaluation of 3D core power distributions. This new system is needed to design and monitor the Westinghouse AP1000 PWR. This paper describes provides an overview of the software system, software development methodologies used as well some initial results.

Key Words: ANC, NEXUS, BEACON, WhiteStar, AP1000

1. Introduction

A number of years ago, Westinghouse Electric Company engaged in a project to update its analysis and core monitoring methods to support existing PWRs as well as the next generation Westinghouse PWR – the AP1000. The goals of this project were to more tightly integrate the ANC core simulator and the BEACON™ core monitoring systems as well as develop a new system for nuclear data generation named NEXUS. The WhiteStar development project was chartered to design, develop and implement this system. This paper will describe the features of the NEXUS system, updates to ANC as well as the integration of ANC and BEACON. It will explore some of the unique features of the integrated BEACON and ANC systems needed to support the modeling and operation of the new Westinghouse AP1000 reactor design. In addition, it will describe some software development methodologies in use by the team integrating the ANC and BEACON methods.

2. NEXUS

NEXUS is an automated once-through cross section system designed to provide nuclear data to core simulators. The system has been designed for use in both PWRs and BWRs. The PWR version of NEXUS has been implemented, qualified, and licensed for use in the United States.

The discussion which follows will describe this PWR implementation of the NEXUS system. The PWR NEXUS system consists of five computer codes:

- NEXrun is the overall system controller. This program executes each of the following codes when needed and controls the data transfer between these codes. NEXrun is the only code with which the user has direct interaction. The user feeds NEXrun the NEXpre input file to begin NEXUS execution. There is no user involvement after NEXrun begins. At the conclusion of NEXrun execution, the cross section data file has been generated and is ready for use with the core simulator.
- NEXpre/ALPHA work together to provide the user input interface with the code system and generate all the input necessary for the lattice code. NEXpre is linked to a controlled database which supplies most of the data needed to develop the lattice code input including cycle specific fuel and plant data. NEXpre also reads the only user input required for NEXUS, a small, very simple input file. The only data in the user input file is data specific to the fuel assembly itself. NEXpre has been written in JAVA and has been designed to be easily modified to work with other lattice codes.
- PARAGON is the Westinghouse lattice transport code used to generate the lattice nuclear data. PARAGON was licensed in the U.S. in 2004 and is currently being used in PWR nuclear design as part of the Westinghouse APA nuclear code system.
- NEXlink is the implementation of the NEXUS cross section representation methodology, processing the nuclear data from the lattice codes and generating the fitted data and other nuclear data needed by the simulator. NEXlink has been written in a very general manner. The user does not have to input any details about the calculation matrix that NEXlink will fit. NEXlink determines the details of the calculations that it is being asked to fit at runtime. NEXlink generates backfitting statistics to keep the user informed as to the goodness of the fitting. NEXlink writes the final fitting data as well as pin data and other nuclear data needed by the simulator to a file in HDF5 format.

The NEXUS system is based on an improved methodology of cross section representation where both macroscopic and microscopic cross sections are fit as functions of three parameters: 1) spectrum index (SI), the ratio of fast to thermal group node-average fluxes, 2) fuel temperature (T_f), and 3) moderator temperature (T_m). The cross section data is generated using a predetermined matrix of calculations which include variations in boron, fuel temperature, moderator temperature, and the presence of spacer grids, control rods and discrete burnable absorbers if included in the assembly design.

The system has been designed to be completely automated. NEXUS reads most of the inputs needed to generate simulator nuclear data from a configured database in XML format which includes data for all current plant and assembly designs. Required user input has been minimized to only those data unique to a particular assembly design, i.e. enrichment pattern and burnable absorber loading and placement. Flexibility has been built into the system allowing the user to over ride any parameter from the database and also to run new designs that are not yet part of the database.

The cross section data file created by NEXUS consolidates all the fuel related data in one file. This includes the parameterized macroscopic and microscopic cross sections and the pin-wise data required for pin power reconstruction and pin-wise burnup and fluence tracking. These cross section data files are read directly by the ANC simulator without any additional processing.

The NEXUS data parameterization and the calculations performed by the predetermined calculation matrix have been designed to cover the range of calculations currently performed in PWR core design analyses. The range of the data covers the changes seen in moderator temperature and fuel temperature from cold zero power to greater than full power conditions. The current matrix of calculations covers assembly burnups up to 80 Gwd/MT. The calculation matrix has been designed to be easily modified and extended without making changes to the NEXUS codes.

NEXUS includes features that will be needed in the next generation of PWRs. For example, NEXUS provides the core simulator with the data necessary to deplete control rods. NEXUS also supports pin power methodology which captures the effects of prolonged control rod presence on pin powers.

The NEXUS system has been thoroughly tested and qualified. The accuracy of any data representation methodology is determined by how well the system reproduces the lattice code data over the range of conditions which will be seen by any node in the simulator. Single assembly, two dimensional calculations were run in ANC using the NEXUS methodology for a wide variety of assembly designs. These calculations were performed over a moderator temperature range of 68°F to over 600 °F and a fuel temperature range corresponding from zero power to 160% power, for assembly burnups up to 80 Gwd/MT. The results of these calculations were compared to 2D PARAGON calculations performed at the same conditions. These comparisons demonstrated the excellent performance of the NEXUS data representation methodology. Some results of these comparisons have been reported previously [1, 2]. Core calculations modeling previously operated cycles were also performed as part of the NEXUS qualification. These calculations used a version of the ANC core simulator described below. The results of these calculations were included in a topical report submitted to the NRC in 2005. The NEXUS/ANC methodology was licensed by the NRC in 2007. Results of some core calculations using the NEXUS/ANC system have been reported in earlier papers [2, 3, 4]. Startup measurements, HZP ARO critical boron and isothermal temperature coefficient, were, of course, included in the qualification. For 43 qualification cycles, the average difference between measured and predicted critical boron was 2.3 ppm with a standard deviation of about 20 ppm. Excellent results were also obtained for ITC with an average difference from measurement for the same 43 cycles of less than 0.1 pcm/°F and a standard deviation of about 0.5 pcm/°F. These results are representative of the quality of results for other qualification calculations that were performed with the NEXUS/ANC system.

3. ANC

ANC is a multi-dimensional nodal code for all nuclear core design calculations at a given condition. ANC predicts core reactivity, assembly power, rod power, detector thimble flux, and other relevant core characteristics. ANC was originally released in 1987 and has had numerous small and three large version updates since. The WhiteStar development project was tasked with developing the third large version update – Version 9.1 – to make use of the NEXUS methodologies in addition to a large number of other improvements. Many improvements have been made to ANC as part this development project. New input and output interfaces have been developed based on JAVA technologies to provide a more user-friendly experience. ANC has been updated to use a new data storage mechanism that is faster and easier to use. Also, in order to further improve the accuracy of ANC predictions and add flexibility in modeling complex fuel and core conditions, a number of major functionality changes have been made in ANC.

Previous versions of ANC (versions 7 and 8) made use of the FREAD input processing language developed at Westinghouse in the 1970s. This language was implemented in FORTRAN and had many limitations that made it difficult to use and extend. In particular, users were limited to six-character variable names and only floating-point numerical input. ANC version 9.1 makes use of the Primary Input Processor, known as PIP, developed at Westinghouse. This language is a hierarchical structured ASCII input language. This language supports what you see is what you get, a feature not previously available in FREAD. This language supports all data formats – strings, integers, real numbers, Boolean values, dates, lists, maps and structures. This new language reads structured ASCII input and translates it to an XML document that is read by ANC. ANC makes use of a FORTRAN-based XML library to validate and read the transformed user input. This new language has many advantages. The first is that input is now more human readable and easily verifiable, and thus, reduces the likelihood of human errors. Also, as new needs arise for input processing, user input can be easily translated into other formats using XSL transformations without recoding the input processor.

ANC 9.1 makes also makes use of JAVA technologies to produce its output. A number of years ago, Westinghouse developed a graphical output processor for ANC version 8 named DEPORT. DEPORT is built using JAVA technologies and allows users to graphically manipulate ANC version 8 data. ANC 9.1 currently uses DEPORT to generate all ASCII output. ANC 9.1 makes use of the JNI (JAVA Native Interface) to form a bridge for ANC (which is implemented in FORTRAN 95/2003) and JAVA to communicate. The integration with DEPORT allows for future enhancements to ANC output. These include generation of plots and tables in JPG format. The integration of DEPORT also serves the integration of ANC and BEACON. Since ANC is the processing engine for BEACON, BEACON will make use of the graphical user interface capabilities of DEPORT to augment the BEACON interface. In particular, future versions of BEACON will use DEPORT for all output generation – both graphical and textual – as well as the integration of a spreadsheet function into BEACON. Users of the BEACON 7 system will be able to post-process core monitoring data using a spreadsheet integrated into the BEACON interface.

It was recognized that as ANC becomes the processing engine for BEACON, the data storage mechanism cannot be a bottleneck. In particular, the data storage system must be capable of reading and writing multiple depletion-steps worth of data in a timeframe consistent on-line core monitoring needs (60 megabytes in less than two seconds). This performance is of critical importance to the AP1000. BEACON is required for AP1000 operation. ANC 9 makes use of a new data storage mechanism known as CoreStore developed at Westinghouse. This storage system was build using HDF5 and allows for platform independent storage of data and meets all performance requirements of an on-line core monitoring system.

In addition to the input and output processor changes, ANC has received a number of major functional improvements compared to version 8. These include the following:

3.1 Thermal-hydraulic Calculation

Instead of quadratic fitting, the new thermal-hydraulic module of ANC calculates the enthalpy of each node based on the core node-wise power distribution, channel (1/4 assembly as standard) inlet temperature, and the channel flow rate. From the enthalpy of each node, ANC thermal-hydraulic module obtains the moderator temperature and density distribution by directly looking-up the steam table based on the local enthalpy and core pressure.

3.2 Cross-section Representation

The new cross-section representation model constructs both microscopic and macroscopic cross-sections for each detailed material segment (so called sub-node) of the core according to the local neutron spectrum, temperatures, along with the fuel history data.

By taking advantage of using feedback-free cross-sections, the new cross-section model can precisely represent the neutron spectrum with the parameters mentioned in the above. Instead of creating multi-dimensional cross-section tables adopted by the most simulator codes, the new model uses the spectrum fitting coefficients, pre-generated by NEXUS and stored in CD file, to calculate the spectrum effect on the cross-sections based on the local conditions. In conjunction with other component and history effect, the cross-section is constructed from the new cross-section representation model as:

$$\begin{aligned}\Sigma_{x,g} &= \Sigma_{x,g}^{ref,free} \cdot F_{x,g}\left(\{p\}\right) + \\ &\Delta\Sigma_{x,g}^{Xe}\left(\{p\}\right) + \Delta\Sigma_{x,g}^{\mathrm{mod}}\left(\{p\}\right) + \Delta\Sigma_{x,g}^{Comp}\left(\{p\}\right) + \Delta\Sigma_{x,g}^{BA}\left(\{p\}\right) + \Delta\Sigma_{x,g}^{Hist}\end{aligned} \tag{1}$$

Here $\{p\}$ is the set of local state parameters, and

$\Delta\Sigma_{x,g}^{Xe}$ is the correction to get the xenon contribution

$\Delta\Sigma_{x,g}^{\mathrm{mod}}$ is the adjustment from moderator due to the water density change and present of boron

$\Delta\Sigma_{x,g}^{Comp}$ is to capture the impact of inserts (for instance, control rod, removable BA rod)

$\Delta\Sigma_{x,g}^{BA}$ is the explicit contribution from burnable absorbers (e.g. IFBA, Gadolinia, Erbia)

$\Delta\Sigma_{x,g}^{Hist}$ is the history correction caused by the deviation of number densities from both actinides and fission products. This correction is well-known as micro-depletion correction.

3.3 One-dimensional channel-wise calculation and homogenization

A one-dimensional calculation and axial homogenization has been implemented in ANC to obtain the axial flux distribution for each fuel channel (1/4 assembly as standard).

Incorporating 3D radial leakage data of each neutronic node, the 1D model derives the axial sub-node fluxes by solving one-dimensional diffusion equations for each channel. This 1D axial flux distribution describes the detailed impacts of the presence of different materials or components such as spacer grids, control rod, etc.

ANC uses this sub-node flux distribution to smear the sub-node macroscopic and microscopic cross-sections respectively to each axial neutronic mesh and exposure mesh. This function provides ANC with greater flexibility to separate axial neutronic mesh, exposure mesh and thermal-hydraulic mesh, and therefore to explicitly model the axial material structure and follow the control rod movement.

3.4 Exposure Node-wise Tracking

ANC allows user to define the axial exposure meshes structure for each fuel assembly type in the core.

For each exposure node of all fuel types, ANC tracks about 50 actinides and fission products using predictor/corrector technique by solving transmutation equations analytically. ANC also explicitly tracks burnable absorber chains for both integral BA (e.g. IFBA, Gadolinia, Erbia) and discrete BA (WABA, PYREX, etc.) for each applicable exposure node.

Moreover, ANC has the flexibility to add any new depletion chains without a coding change if the chain information is available.

3.5 Control Rod Depletion

In the latest Westinghouse PWR design – the AP1000, the core will be operated with control rod insertion. In order to follow the burnable absorber change during control rod depletion and take into account the impact on the reactivity, Westinghouse has developed a new control rod depletion methodology. The depletion model has been implemented in ANC.

If the control rod material is specified as burnable, ANC will deplete the burnable absorber chains. Based on the remaining absorption strength of the control rod, ANC makes the control rod depletion correction to the node average cross-sections where the control rod is present.

3.6 New Pin Power Reconstruction and Pin-Wise Tracking

The pseudo pin by pin calculation (P3C) methodology has been developed in Westinghouse, and adopted in the new pin-power reconstruction model. The new pin-power reconstruction model directly constructs the macroscopic cross-sections for each pin-cell based on the pin-cell history and the local condition. Since the new method follows the real history of each pin-cell, it significantly improves the prediction of the pin power distribution for the fuel node which can have a complicated history of control rod insertion and withdrawal.

4. BEACON

The BEACON (Best Estimate Analyzer for Core Operations – Nuclear) system is an advanced core monitoring and support system which uses existing instrumentation data in conjunction with an analytical methodology for on-line generation and evaluation of 3D core power distributions. The system provides the tools for core monitoring of the power limits delineated in the Technical Specification, core follow, core measurement reductions and core predictions. The system was initially developed in the early 1990's and approved by the USNRC for continuous on-line core monitoring in 1994.

Over the past 15 years the BEACON system has gone through several major upgrades and numerous smaller revisions with version 6.6.1 of the software being release in 2008. The development of BEACON version 7.0 as part of the WhiteStar project will be another major upgrade of the system that is designed to incorporate and support the following goals.

- Integrate the new and advanced nodal solution methods and data management being implemented in the Westinghouse core design codes
- Add features and functions to support the zero by ten (zero fuel failures by 2010) initiatives by utilities in the US.
- Support the new plant features and requirements for the Westinghouse AP1000 reactor design.
- Provide better and easier to use reactivity management and data interfacing tools to support the reactor operations staff.

The complete integration of the ANC 9.1 nodal methods and data storage/management methods in BEACON will not only keep BEACON consistent with the latest Westinghouse core design methods but will allow an ANC 9.1 model to be directly used in BEACON without the need to convert the model from an ANC data format to a formatted binary file set as is currently done. This is possibly now because the CoreStore data management system allows a model set to be stored and accessed as a single model file with minimal system overhead allowing models to be easily transportable between workstations. The ANC 9 model can be read and used in BEACON even if all of the parameters needed for on-line core monitoring and surveillance are not defined in the model. This eliminates the extra step of reformatting the ANC model into a set of transportable BEACON binary files and allows the BEACON GUI interface to become a tool easily used by both reactor operations and core designers.

To reduce fuel failures to their lowest possible level the US nuclear industry has been collectively working on a zero by ten fuel initiative. To support this initiative the BEACON 7 system will include the capability to monitor and predict local ramp rates, fuel conditioned powers and local fuel limits. A 3D core monitoring system is ideally suited to this task because of the detailed information it has on each assemblies pin power distribution. Predictive calculations can be used before startups or planned power maneuvers to predict local fuel ramp rates for different scenarios which can then be evaluated to determine which power maneuvers meet the operational goals with the most ramp rate margins. The improvements in system data management and storage capacity have made it easier and faster to save and track large amounts of data needed for this type of analysis over an operating core cycle.

The BEACON core monitoring system is a standard component of the Westinghouse AP1000 reactor design which has several advanced features. The major difference between the AP1000 design and the current generation of Westinghouse reactors is the use of MSHIM (Mechanical Shim) rods for reactivity control. MSHIM[5] eliminates the need for changing soluble boron concentration during all power maneuvers and daily core depletion letdown by using control rods of different worths for reactivity and axial offset control. The BEACON 7 system will be able to monitor and predict the positions of the MSHIM gray rod banks, axial offset control banks and the black rod control banks when doing startups and power maneuvers. Because the gray rod banks can be fully inserted into the core at any time, the ability to know and maintain a given shutdown margin at all times is not guaranteed unless support calculations are performed. The BEACON 7 system will have the capability to continuously monitor and evaluate the available shutdown margin against the plant limit.

The BEACON 7 system will have significantly improved data preparation and reporting tools to allow users to create customized plots and tables for use in presenting results. The integration with the DEPORT tool allows for the generation of customized plots and tables. Because of the total integration of ANC 9.1 and BEACON, the need to pre-generate many tables and plots of reactivity coefficients and parameter worths over wide temperature and power ranges for the entire cycle can be eliminated. Any needed tables and plots of coefficients and other reactivity parameters can be generated and customized by the reactor operations staff at the current conditions of the plant using the same core design methods that would be used by the Westinghouse core design staff. These generated plots and tables will typically be more accurate since the models used to generate the data will have actual operating history built into the model. New tools will allow users to perform basic manipulation of the data before displaying, such as taking ratios or differences of columns of data. This will allow quicker and easier evaluation of measured and predicted results while allowing them to be presented in a customized format.

5. Software Development Methodologies

The development of ANC and the integration with BEACON follow an iterative software development methodology and a phased development strategy. The project was broken into three distinct development phases, each of which with defined deliverables. The first phase of development of the project included the development of ANC 9.1, NEXUS and the integration of these components. The methodology updates to ANC described in this paper are also part of the first phase of development. The integration with PIP, DEPORT and CoreStore was also completed in the first phase of the project. The first phase of the project has completed. The second phase of the project included the feature development to support analysis needed for AP1000 core design. These features include limits and margin calculations, features to support the 3DFAC analysis as well as integration with the VIPRE-W code for DNB feedback. In addition, the MSHIM control strategy will be coded into ANC in the second phase of the project. The third phase of the project includes the integration of ANC and BEACON to support online core monitoring for both AP1000 and non-AP1000 cores.

In the first phase of development, every two weeks a new iteration is started where software developers selected a set of requirements to implement and demonstrate to be working. When the development goals had been completed, the code was released to internal users under a

BETA configuration to allow for evaluation. The development team followed this development methodology for 18 months to develop the first phase deliverables of the project.

The development of ANC followed a strict V-diagram (Fig. 1) for development. The development team is using the Telelogic DOORs application as a tool to faciliate requirements flow down through the development and testing phases. ANC has over 500 high-level requirements, 12000 detailed requirements, 8000 test cases and 2000 software designs. The regulatory environment in which ANC is developed requires the development team to show traceability of software requirements to software design and traceability of software requirements to test cases. The DOORS application allowed the development team to maintain this traceability to ensure that all requirements were implemented, had a software design and passed test cases.

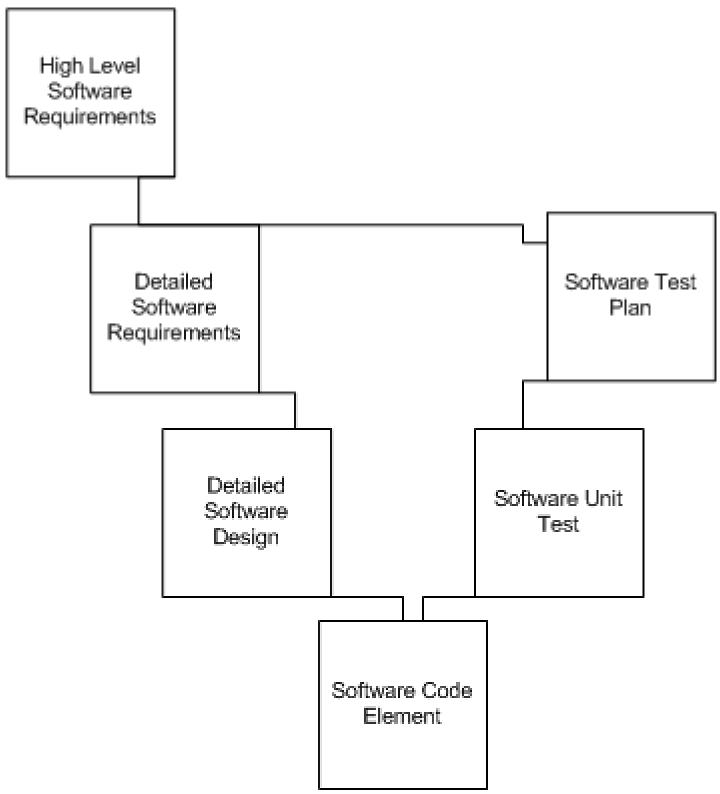

Figure 1 ANC Software Development V Diagram

6. CONCLUSIONS

The WhiteStar development project represents the next generation core design and monitoring methods and software from Westinghouse. The NEXUS system is the foundation of this system.

Many updates have been made to ANC that include methodology changes, a new input and output system and a new data storage mechanism. ANC will be the nodal engine underpinning the BEACON core monitoring system. The merging of ANC and BEACON is particularly important to the nuclear renaissance as the Westinghouse AP1000 reactor design will require the BEACON core monitoring system for normal operation.

This paper provides an architectural overview of the WhiteStar software system including computational modules, overall system architecture as well as software development methodologies used throughout the project.

ACKNOWLEDGMENTS

Special thanks to the WhiteStar development team for their continued contributions to the development of these codes powering the nuclear renaissance.

REFERENCES

1. Zhang, Baocheng; Müller, Erwin; Sato, Daisuke; Hah, Chang. J.; Mayhue, Larry; Casal, Juan "NEXUS – A New Nuclear Data System for Light Water Core Analysis", ICAPP'05, Seoul, Korea, 2005.
2. Mayhue, Larry; Zhang, Baocheng; Sato, Daisuke; and Jung, D. C. "PWR Core Modeling using the NEXUS Once-Through Cross Section Model", PHYSOR-2006, ANS Topical Meeting on Reactor Physics, Vancouver, Canada, September 10-14, 2006.
3. Jung, Dong Chul; Mayhue, Larry; Park, Sang Won; Jung, Yil Sup; and Lee, Chang Kue "The Qualification of the NEXUS Once-Through Cross-section System for OPR1000 Core", Transactions of the Korean Nuclear Society, Spring Meeting, Jeju, Korea, May 10-11, 2007.
4. Mayhue, Larry; Milanova, Radka;Huria, Harish;, Zhang, Baocheng; Müller, Erwin, Franceschini, Fausto, Ouisloumen, Mohamed, Forslund Guimaraes, Petri, "Qualification of the NEXUS/ANC Nuclear Design System for PWR Analyses", PHYSOR-2008, Interlaken, Switzerland, September, 2008
5. Morita, T., et al., "Application of MSHIM Core Control Strategy for Westinghouse AP1000 Nuclear Power Plant", GENES4/ANP2003, September 2003.