

Development of the SMART Plant Model using the Modular Modeling System (MMS)

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Abstract

A transient simulation model of an integral reactor plant, SMART, has been developed using a commercially available computer code package, Modular Modeling System (MMS). Several MMS modules are developed which represent the non-standard major components of the integral reactor, such as a once-through steam generator, self-pressurized pressurizer, core, preheater, etc. The MMS SMART model is then developed by combining the developed modules with the standard modules from the MMS Macro libraries. The whole plant system including the plant control logics are modeled as one integrated model. Benchmark calculations have been carried out in order to verify the developed MMS modules and the SMART model. These calculations cover steady-state conditions at various power levels, performance related events, a limited number of safety related events. The analysis results of the MMS SMART model were compared with those from design computer codes and showed good agreement. This MMS SMART model runs faster than real time in a Personal Computer in the MicroSoft Windows NT environment and it can be used for various purposes because of its fast, modular and flexible features.

1. Introduction

A SMART plant model is developed using the Modular Modeling System (MMS) code package. The SMART (System integrated Modular Advanced Reactor) is an integral-type pressurized water reactor which is under development by the Korea Atomic Energy Research Institute (KAERI)[1,2]. With the progress of design stages, various scoping analyses are required for decision-making on the system design, specifications of major components, control logic design and evaluations, etc. The Modular Modeling System (MMS) code package[3] is chosen for these scoping analyses. The MMS package is a commercial simulation package distributed by Framatome Technologies, Inc. (FTI). The fast running, modular and flexible features of the MMS package enable us to perform various scoping analyses and to design and test the control logics of the SMART plant.

Due to the many unique features of the integral-type SMART reactor, several MMS modules are developed in this study[4]. The developed MMS modules represent the specific physical models of the non-standard major components of the SMART, such as a once-through steam generator, self-pressurized pressurizer, core, heat exchanger for the residual

heat removal system, N₂ gas-filled pressurized tank, preheater, heat exchanging pipe, heat structure modules, etc. The MMS SMART model is then developed by combining the developed modules with standard modules from the MMS Macro libraries[5]. The primary system, secondary system, Residual Heat Removal System (RHRS), make-up system, component cooling system, and plant control logics are modeled as one integrated model. Benchmark calculations have been carried out in order to verify the developed MMS modules and the MMS SMART model[6,7]. These calculations cover steady-state conditions at various power levels, performance related events, and a limited number of safety related events. The analysis results of the MMS SMART model were compared with those from design computer codes and the two calculation results showed good agreement. This MMS SMART model runs faster than real time in a Personal Computer in the MicroSoft Windows NT environment. The MMS SMART model is being used for various design activities.

2. MMS module developments

For the MMS SMART model, as for any large simulation, custom coding is needed to model plant specific systems and features. Especially, the MMS standard macro library does not have the modules for the SMART unique components, e.g., the self-pressurized pressurizer, once-through steam generator, core, etc. Thus several new modules are developed in this study. Also a few existing modules are customized for the SAMRT model.

2.1 GPZR module

This module represents the self-pressurized pressurizer in the SMART system. It solves the mass and energy conservation equations for the End Cavity (EC), Intermediate Cavity (IC), Upper Annular Cavity (UAC) and the connected N₂-gas tank. The gas tank isolation valve and the mass and energy exchange through the isolation valve are also modeled. This module determines the system pressure, water temperature in each cavity, gas and vapor temperature inside the cavity gas-vapor space and inside the connected N₂-gas tank. It also tracks the pressurizer water level during all kinds of reactor operating modes. Condensation and evaporation models are included for the modeling the mass and energy exchange across the gas-vapor and water interface. A rainout model is also incorporated for modeling the raining droplets by bulk condensation. All the heat transfer rates are modeled between cavities, pressurizer cooler, reactor riser, steam and feedwater lines passing the UAC. When the heat transfer is modeled between many different parts, the water level inside the cavities are carefully taken into account.

2.2 FUEL module

This module represents multiple fuel nodes in a reactor core. It has the 6 delayed neutron group model, 3 decay heat group model, iodine-xenon chain model, Moderator Temperature Coefficient (MTC) and Doppler Coefficient models. The control rod reactivity is modeled outside of this model as a Fortran subroutine. The calculated thermal power will be distributed into the fuel nodes and connected coolant nodes according to the user-provided fraction of energy deposition. A user can divide the core into n control volumes axially and radially. Each fuel node represents the nuclear fuel contained in each control volume. The nuclear fuel cladding and coolant channel contained in each control volume is simulated outside this module by separate QMETAL and PIPEHX modules, respectively.

2.3 PIPEHX module

This module represents a section of piping. Multiple instances of this module may be connected in series to model piping with shorter sections and thereby reduce spatial discretization errors. This module works with other modules to calculate the heat transfer from the fluid to other fluids, to the ambient, or to metal walls.

The PIPEHX module is a modified version of the existing MMS RTC (Real Time Capable) module[3], PIPEM. The PIPEHX module was extended with an emphasis on the capability to model thermal (heat transfer) networks. Major additional features of PIPEHX compared with the existing PIPEM are as follows;

- PIPEHX can be connected with the QMETAL module which represents the heat structure like tube metal, immersed metallic structures, etc. For this purpose, PIPEHX has four heat transfer ports in addition to the normal fluid flow in and out ports.
- A user can specify a specific set of empirical heat transfer correlations for each PIPEHX module by providing FORTRAN codes in the HTCUSR.FOR subroutine.

The PIPEHX modules are used for heat transfer modeling such as in the SMART core, a once-through steam generator and residual heat removal heat exchanger sub-models.

2.4 QMETAL module

This QMETAL module represents the heat structures like the tube metal in a heat exchanger or nuclear fuel cladding. The QMETAL module has two heat transfer ports where the PIPEHX or FUEL modules can be connected. Thus the QMETAL behaves like a bridge connecting heat transferring modules like PIPEHX, FUEL, etc. With the combination of the PIPEHX modules, a very complicated heat transfer network can be modeled. A user can specify how the metal thermal inertia is to be modeled. The user can specify the fraction of metal mass to be added to the connected modules as equivalent mass, or can choose to solve a transient conduction equation to model as a separate thermal inertia.

2.5 RHRTANK module

This module represents a tank in which a string of pipe sections (modeled by PIPEHX modules) are to be immersed. The fluid in the tank is heated and evaporated by the pipes. In the SMART model, it is used for modeling the Emergency Cooldown Tank of the Passive Residual Heat Removal System (PRHRS). This module calculates the level and the temperature of the bulk liquid. The PIPEHX modules calculate the heat flux for each pipe section according to the level and temperature of the bulk liquid. This module is designed to work with multiple QMETAL and PIPEHX modules.

2.6 GTANK module

This module represents a closed tank partially filled with water with negligible evaporation and covered with a non-condensable gas. It solves the water mass conservation equation and tracks the water level. The tank gas pressure is determined by using the ideal gas law. The gravity head of the tank water is taken into account for the tank exit pressure.

2.7 PREHEATER module

This module represents a feedwater preheater, consisting of a shell and tubes. The steam enters, condenses, and drains out as liquid in the shell-side and the feedwater is heated by the condensing steam.

3. MMS SMART model development

The MMS SMART model consists of several subsystem models, such as the core, once-through steam generator, reactor coolant system, main steam and feedwater system, residual heat removal system, makeup system, component cooling system, secondary system, and the plant control logics. Each subsystem model consists of many MMS modules which represent specific physical models, such as the nuclear fuel, pressurizer, pipe, valve, pump, turbine, condenser, heat exchanger, valve actuator, tank, heat structures, control logics, etc. MMS users can combine the necessary component modules in a Graphical User Interface (GUI) - the MMS model builder[3]. The basic idea of the Modular Modeling System (MMS) is that, as a hardware machine is produced by assembling components like pumps, valves, bolts and nuts, a system is modeled by combining the MMS component modules. After a system model is built within the MMS model builder, the component design data can be input by double clicking the corresponding component modules. The MMS system model can be translated into the ACSL (Advanced Continuous Simulation Language) language[8] using the MMS model builder. The ACSL code is translated into a FORTRAN source code by the ACSL builder[8], and then the executable file can be generated by a FORTRAN compiler and linker. As can be seen in Fig. 1, a user can interact with the MMS model in several ways. This feature makes the MMS package difficult to understand, but provides a lot of flexibilities for developing, debugging and utilizing the MMS models.

The seven Man-Machine Interface (MMI) screens are also developed in this study[9]. The MMI screens are running with the MMS SMART model in a synchronized way. The MMS SMART model and the SMART MMI constitutes the engineering plant analyzer[9] for the SMART plant. Anytime during running the SMART plant analyzer, a user can snapshot the instant status of the SAMRT plant and simulate the transient forward and backward to the snapshotted status easily. The detailed descriptions of the MMS Simulation Tools[10] and the SMART MMI will be presented as a separate paper.

The plant control and protection logics are coded in a code block, but the component control logics are written in the code block attached to them. The code block is a special module with universal port types that can be connected to any module. If the system being modeled has features that are not modeled by the MMS modules, the user can use the code block and provide ACSL coding that models the missing features. The MMS SMART model is shown in Fig. 2.

The developed SMART model can simulate a whole range of plant operation modes including normal heatup, scheduled shutdown, power maneuvering and emergency shutdown operations, etc. The SMART plant analyzer runs much faster than real time in a PC environment. The SMART system analysis results using the MMS SMART model were compared with those from design computer codes and are presented in the next section.

4. Test calculations

Benchmark calculations are carried out for the following nine test cases in order to verify the developed MMS modules and the SMART model.

1. Simulation of the steady-state operations at partial loads,

2. Simulation of the nuclear heatup process,
3. Simulation of the scheduled shutdown,
4. NSSS steam output change from 20 to 100% and vice versa at the rate of 5%/min,
5. Step changes of feedwater flow rate by $\pm 10\%$ /sec,
6. Unauthorized increase of feedwater flow rate from 20 to 100% at the rate of 10%/sec,
7. Loss of power to all four MCPs,
8. Unauthorized trip of one MCP,
9. Stop of steam bleed to TGU.

The analysis results with the MMS SMART model are compared with those from some design computer codes. The results of the three test cases, i.e., 1, 3 and 4 in the above list, are presented in this paper.

4.1 Simulation of the steady-state operations at partial loads

After initializing the MMS SMART model at the rated plant condition, the steady-state conditions at partial loads are obtained by decreasing and stabilizing the reactor power to the specific power levels. The calculated major thermal hydraulic parameters are compared with available design data. The comparison results are summarized in Table 1. As can be seen in Table 1, the overall consistency is obtained between the design data and the simulation results using the MMS SMART model.

4.2 Simulation of the scheduled shutdown of the SAMRT system

A scheduled shutdown is simulated with the complete MMS SMART model that includes primary and secondary systems. The simulation begins from the 100% rated power level. At first the reactor power is reduced to 20% of the rated power level by decreasing the feedwater flow rate at a specified decreasing rate. When the power reaches 20% of the rated power level, a series of control actions are taken with some time intervals. For example, the main turbine and main feedwater pumps are turned off, and the startup pump is turned on and the seawater pump is changed to low speed. The reactor power is reduced further to 10% of the rated power level and the auxiliary turbine is turned off. Until the reactor power decreases to 5% of the rated power, the control rod movements are controlled by the deviation of the core outlet temperature and the reactor power level from the control set values. The reactor cooldown process continues with a specified cooldown rate until the coolant temperature reaches about 200°C where the reactor tripped. The MMS SMART simulation results are shown in Fig. 3 for the initial 30000 secs. Figure 3 shows the variations of the core inlet and outlet temperatures, feedwater flow rate and the normalized reactor power. For this simulation, there was no appropriate design calculation result for comparison for the whole range of the cooldown process.

4.3 NSSS steam output change from 20 to 100% at the rate of 5%/min.

Figures 4 and 5 show the trends of the important parameters for the case of steam output increase from 20 to 100% rated power. Figure 4 shows the MMS SMART simulation results and Figure 5 shows the design calculation results. As can be seen in Figs. 4 and 5, the steam temperature of the design calculation is lower than that of the MMS simulation result. It can be explained as follows. In the design calculation, the secondary system pressure was assumed to be constant within the once-through steam generator for simplification. It is

known that this model underpredicts the steam temperature about 3°C. Another difference we can observe is the control rod movements. This came from the different control rod worth between the core designs of the conceptual design and the current design. As the design stages proceed, the specific design features of the SMART are changing, and thus we have these discrepancies. When the new design calculations are available, the MMS SMART model will be reevaluated. However, even now the two calculation results show overall agreement.

5. Conclusion

A transient SMART model has been developed using the Modular Modeling System (MMS) code package. For the benchmark purpose of the developed MMS modules and the MMS SMART model, the MMS SMART model simulation results are compared with the design calculation results for the nine test cases. The overall trends of the major parameters showed good agreement.

The developed MMS SMART model can be used for various purposes because of its fast, modular and flexible features. The MMS SMART model simulates the whole plant including the primary, secondary and auxiliary systems, simultaneously. This feature is especially useful for the analyses of an integral reactor utilizing a once-through steam generator where the thermal-hydraulic interactions between the primary and secondary systems are fast and closely related. Another merit of using the MMS SMART model is that it simulates a whole range of plant operation modes including the nuclear heating and scheduled shutdown operations. It also runs about five times faster than real time in a PC environment including the SMART MMI. The developed engineering plant analyzer has a very flexible expandability such as attaching various hardware and extending to a simulator. Currently, it is being used to perform quick turnaround performance analyses, and to design, evaluate and optimize the plant control logics and operational procedures.

Acknowledgments

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References

1. D.J. Lee, et al., "Design and Safety of a Small Integral Reactor (SMART)", Proceedings of International Workshop on Utilization of Nuclear Power in Oceans; N' ocean 2000, Feb. (2000).
2. M.H. Chang, et al., "SMART – An Advanced Small Integral PWR for Nuclear Desalination and Power Generation," Proc. of Global 99, International Conference on Future Nuclear Systems, Jackson Hole, USA, Aug. 29 - Sept. 3, (1999).
3. Framatome Technologies, Inc., "MMS (Modular Modeling System) Basic Manual", (1998).
4. KAERI-FTI, "Description of the Developed or Modified MMS Modules for the SMART Model", SMART -MMS-005, (2000).
5. KAERI-FTI, "Documentation for the SMART MMS Model", SMART -MMS-006, (2000).
6. KAERI-FTI, "Test Specification for the SMART Model", SMART -MMS-008, (2000).

7. KAERI-FTI, "Test Results of the MMS SMART Model", SMART -MMS-009, (2000).
8. MGA software, "Advanced Continuous Simulation Language (ACSL) reference manual", version 11, (1995).
9. KAERI-FTI, "SMART NPA User' s Manual", SMART -MMS-010, (2000).
10. KAERI-FTI, "Simulation Tools Integration", SMART -MMS-007, (2000).

Table 1. NSSS major parameters at partial loads.

Parameters \ Steam output [%]	20	40	60	80	100
Power [MWt]	68.0 67.6	136.2 135.6	204.7 203.8	273.0 272.3	338.9 339.0
Primary coolant temperature at SG inlet [°C]	298 298	301 300.9	304 303.8	307 306.5	310 310
Primary coolant temperature at SG outlet [°C]	289.9 290.2	284.8 284.9	279.4 279.5	273.8 273.8	268.5 268.9
pressurizer volume of steam-gas medium [m ³]	5.25 5.33	5.27 5.33	5.28 5.33	5.30 5.34	5.33 5.30
pressurizer temperature of steam-gas medium [°C]	68.6 70.99	69.1 70.86	69.6 70.64	70.2 70.35	70.6 71.57
Primary pressure [MPa]	15.13 14.99	15.07 14.99	15.08 14.98	15.06 14.95	15 15.05
Feedwater heating [°C]	5.4 7.35	3.1 3.85	2.3 2.66	1.9 2.08	1.7 1.8
Steam temperature at NSSS outlet [°C]	297.6 297.8	300.0 300.2	301.7 302.1	302.5 303.4	296.3 299.6

Design data	MMS SMART
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: Legend

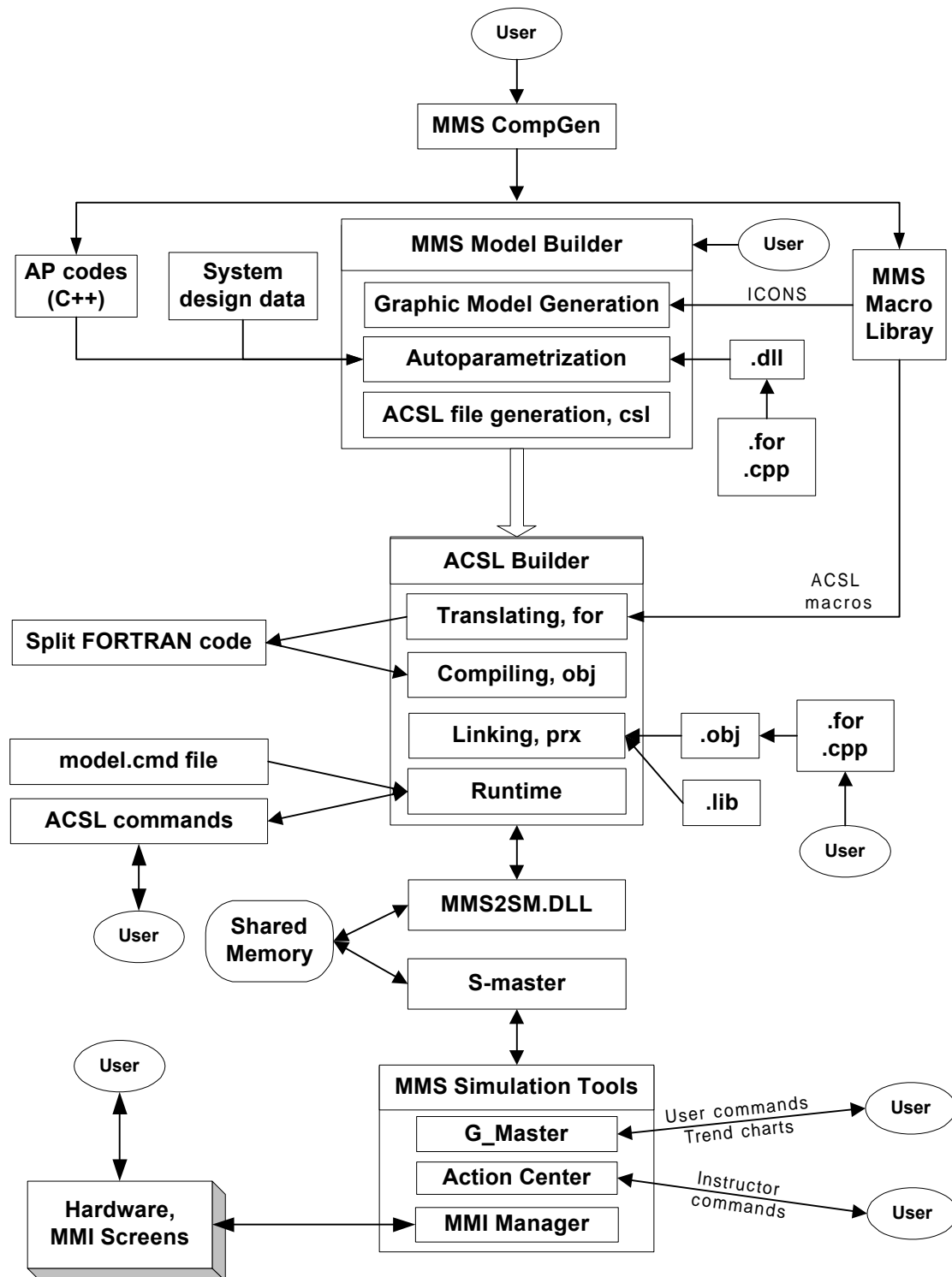


Fig. 1 Overall structure of the MMS code package

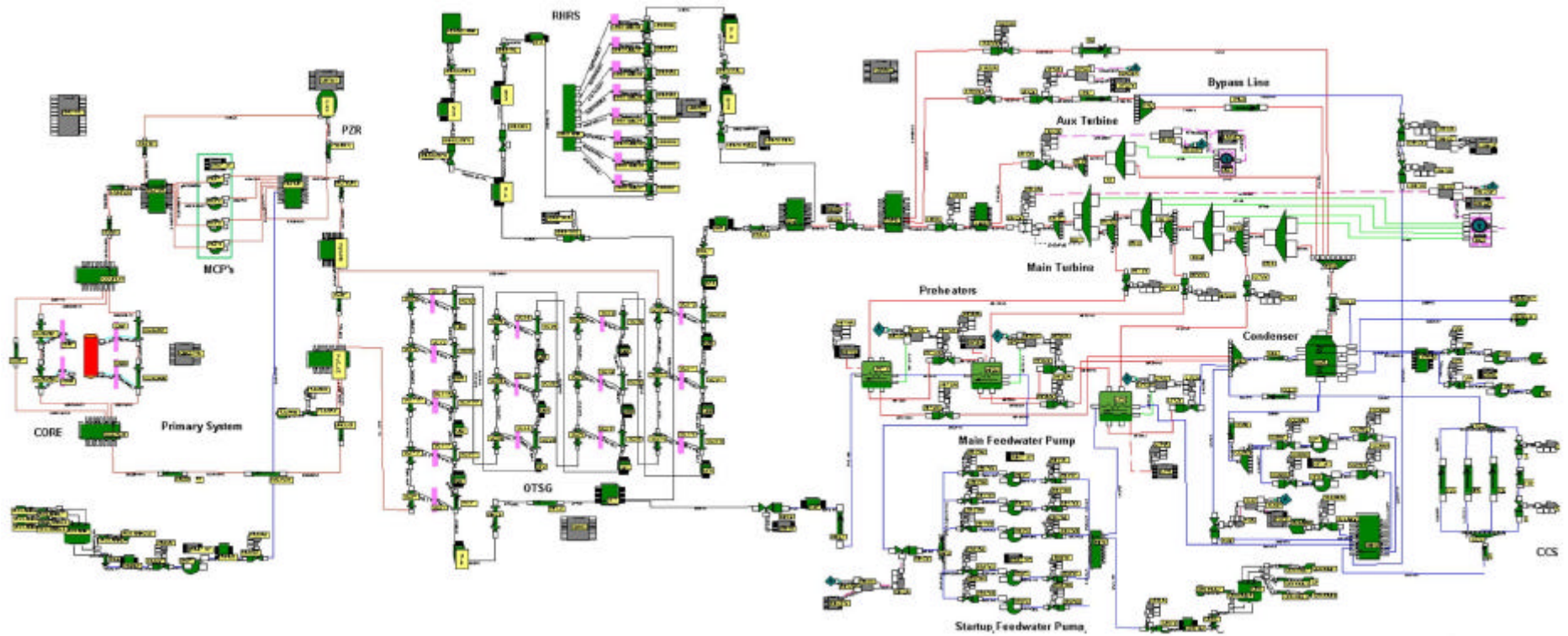


Fig. 2 MMS SMART model

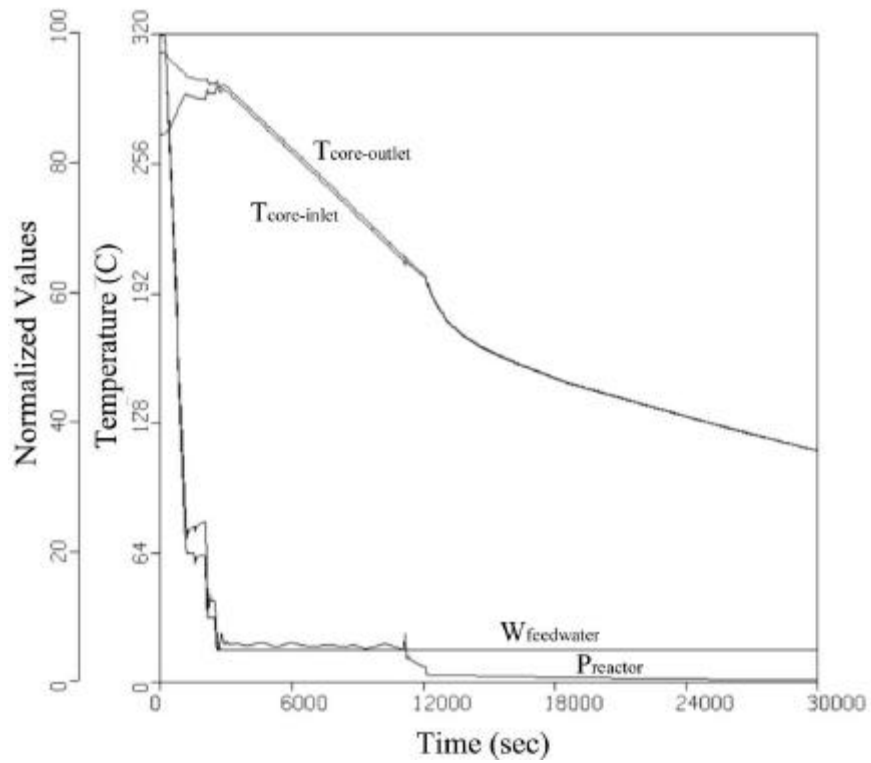


Fig. 3 Simulation of the scheduled shutdown

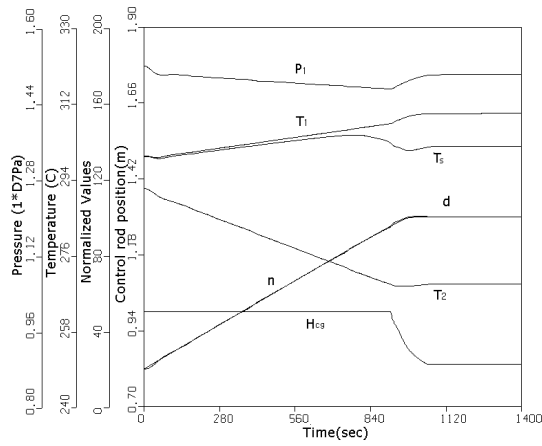


Fig. 4 MMS SMART simulation results for power maneuvering (20 to 100%)

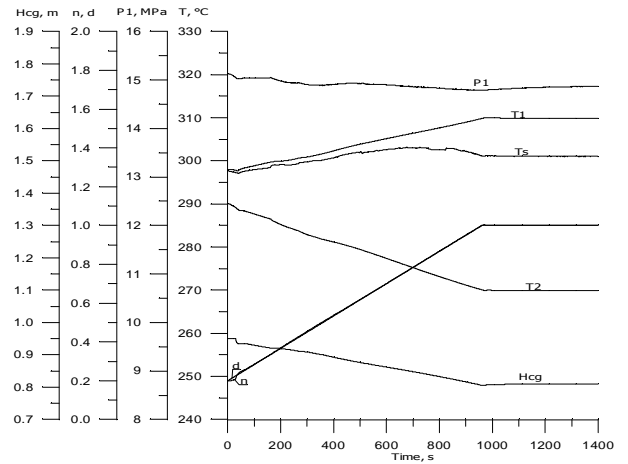


Fig. 5 Design calculation results for power maneuvering (20 to 100%)

P_1 =primary coolant pressure, T_1 =primary coolant temperature at SG inlet, T_2 =primary coolant temperature at SG outlet, T_s =steam temp. at NSSS outlet, d =relative feedwater flow rate, n =relative core power