USING THE MODULAR MODELING SYSTEM FOR FAILURE-MODE ANALYSIS OF PWRs WITH RECIRCULATING STEAM GENERATORS

by

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ABSTRACT

This paper describes the results of the first phase of an application of the Modular Modeling System (MMS) for failure-mode analysis of a three-loop Pressurized Water Reactor (PWR). Such analysis contributes to minimize reactor trips and the cost of electricity. For the first phase, an MMS model was developed to simulate a single plant loop and seven failure modes that may cause a reactor trip due to low pressurizer pressure. These failure modes can be simulated while the plant is either at steady state or undergoing a normal power ramp. The model runs on IBM-compatible personal computers within the DOS environment.

The MMS model includes:

- MMS modules for a single-node reactor, non-equilibrium pressurizer, and U-tube steam generator
- Control logic, reactor trip logic, and some plant alarms
- Graphical user interface for:
  - -- Interactively selecting the failure mode and associated interlocks, the variables to be trended, and the plant transient to be run
  - -- Monitoring the trends, a plant schematic with updated values of key parameters, and the sequence of events.

The model was generated using the automated MMS-EASE+ graphic preprocessor to interconnect the MMS modules and to automatically calculate model parameters to represent the simulated plant. The command file included macros to run each failure mode transient and to plot the results after the transient.

By taking advantage of the automation in MMS and MMS-EASE+ and by utilizing prior experience with MMS and nuclear power plant modeling, the model was developed in only five man-months. Planning for subsequent phases is under way.

MMS incorporates modules for modeling PWRs, BWRs, and fossil power plants. A company can build the model for its own application by licensing the MMS software, or by contracting B&W Nuclear Service Co. to have a model built to its specification.

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INTRODUCTION

The Modular Modeling System (MMS) is a user-friendly automated software system used worldwide for modeling the dynamics of nuclear and fossil power plants (1, 2). The Electrical Power Research Institute (EPRI) was a sponsor during the original development of MMS. MMS has been used for many applications such as those in power plant design, operation, and training with a recent application being for digital feedwater control system development (3, 4).

Recently the B&W Nuclear Service Co. (BWNS) completed the first phase of the application of the MMS for failure-mode analysis of a three-loop Pressurized Water Reactor (PWR). For this phase, a single-loop MMS model of a three-loop PWR was developed to demonstrate the feasibility of MMS for failure-mode analysis. In this application, the MMS model complements the conventional fault-tree analysis of failure-related transients by generating data on the relative timing of the onset of plant alarms and the actuation of system interlocks. This model can also be used to train the operator to infer the failure mode and necessary remedial actions based upon the plant response as it unfolds on the model display screen. Plant procedures may be modified based on the simulation analysis to minimize reactor trips and the cost of electricity.

MMS models use Advanced Continuous Simulation Language (ACSL) (5). The demonstration model, like other MMS models, benefits from the powerful features of ACSL, such as:

- Statement sorting during translation
- Runtime selection of integration algorithm
- Save and restore initial conditions
- Plotting after running a transient
- Linear analysis.

In addition, the model has a graphical user interface for 1) selecting from a menu the failure mode to be simulated and the model variables to be trended during the transient, and 2) monitoring the selected trends, a dynamically updated plant schematic, and a sequence-of-events log.

This paper describes the demonstration model in the following sections:

- Demonstration model specification
- Dynamic model
- Graphical interface
- Demonstration model
- Conclusions.

DEMONSTRATION MODEL SPECIFICATION

Since the model was to be used by the plant engineering and operations staff, a graphical user interface was appropriate to enhance user convenience and effectiveness. The demo model was therefore to be made up of two parts:

1. Dynamic model with differential equations representing conservation of mass, energy, momentum, etc.
2. Graphical user interface.

The failure modes to be included in this model were those that may cause a reactor trip due to low pressurizer pressure. There were 18 failure modes in this category, many of which were functionally redundant in terms of their effect on pressurizer pressure and level. Thus only the following seven basic failure modes are included in the model scope:

- Failure of the proportional heater of the pressurizer to turn on
- Inadvertent opening of the pressurizer spray valve
- Inadvertent closing of the charging flow control valve
- Inadvertent drop of control rod
- Inadvertent opening of the boron feed control valve
- Inadvertent opening of one out of three pressurizer safety valves
- Total loss of main feedwater.

The model was to be capable of conveniently initiating the selected failure. For the failure modes to be analyzed, it was sufficient for the dynamic model to include the reactor, pressurizer, one of the three steam generators with the other loops represented by boundary conditions, letdown and charging flows, boron addition, and control logic for controlling reactor power and average reactor coolant temperature, pressurizer pressure and level, and steam generator downcomer level.

To perform failure-mode analysis, the user was to first select the failure mode and associated parameters, and then run the model. Accordingly, the graphical user interface had to include two screens:

- Selection Screen with menus to select the failure mode to be simulated and associated interlocks and timings, and the model variables to be trended.

- Run Screen to display the selected trends, a dynamically updated plant schematic, and a summary of sequence of events.

DYNAMIC MODEL

The dynamic model was developed using the MMS-EASE+ graphic preprocessor (6), an automated preprocessing system available for IBM-compatible personal computers (PCs). The MMS modules used in this model include a single-node reactor (RX1), non-equilibrium pressurizer (PZRB), and U-tube steam generator (UTSGA). Also included in the model are control logic, reactor trip logic, and some plant alarms. The control logic includes logic for controlling reactor power and average reactor coolant temperature, pressurizer pressure and level, and steam generator level. An interconnection diagram (Figure 1) showing the interrelationship of the modules used in the model was first prepared using a mouse to select, place, and interconnect the "icons" on the screen. The icons are graphical elements that represent MMS modules.

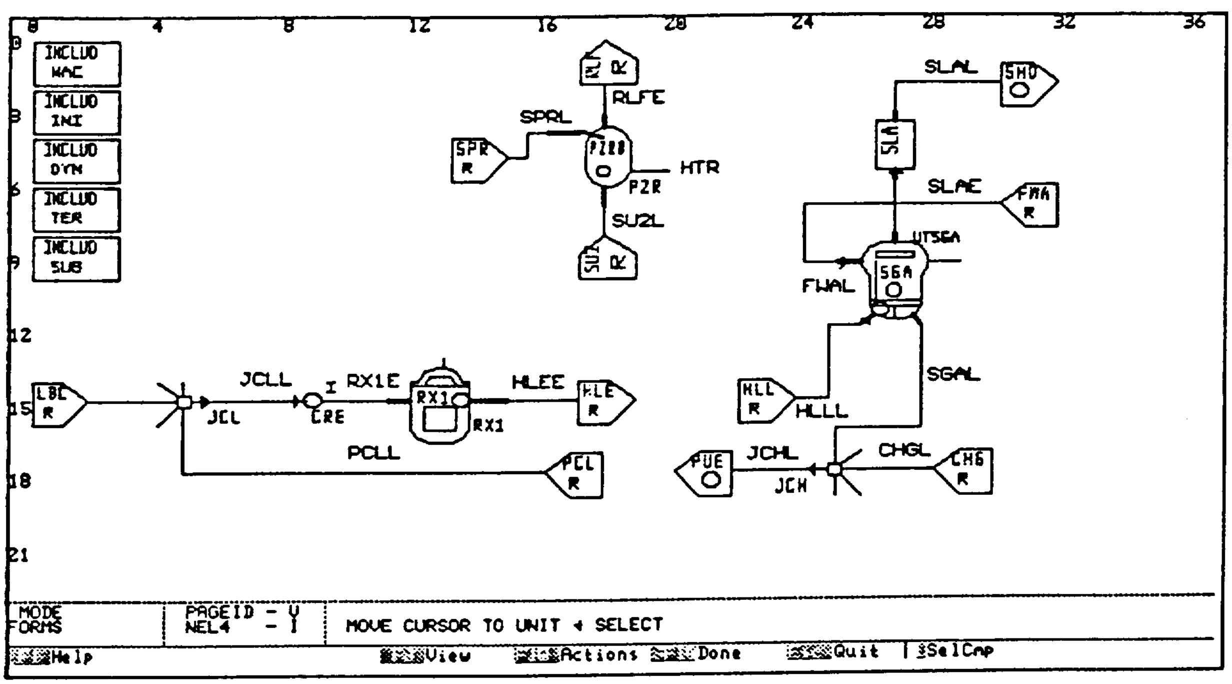

Figure 1 MMS Interconnection Diagram

Each icon has one or more forms for entering physical and operating data (Figure 2) for the represented module (and therefore the component that the module represents) and one or more forms for parameter output (Figure 3). The forms include a description of each data entry and a space for entering a value. To automatically determine the values of model parameters ("auto-parameterization"), values were entered in the input forms of the selected icons. To accommodate input data in metric units, an MMS utility called SIEASE was used.

```
MMS:9  FORM:RX1_0                                              03/01/91 10 08

                RX1   —   Operating Point Data Input Sheet

Component ID:     RX1

Cold leg pressure     [illegible]        Hot leg pressure      (psia)  2250.55
Cold leg enthalpy     527.67             Hot leg enthalpy      (Btu/lb)  617.5
Primary flowrate                                               (lbm/hr)  1.0076e+8
Fraction of delayed neutrons in i-th group (i=1-6)                      2.5000001e-4
0.0015        0.0014        0.0028        0.3600002e-4    3.14e-4
Decay constant of i-th group of delayed neutrons               (1/sec)  0.0124
0.0305        0.111         0.301         1.1             2.
Fraction of decay heat in i-th group (i=1-3)
0.357                 0.241                 0.402
Decay constant of i-th decay heat group                        (1/sec)
0.0555                0.0043                6.6599990e-5
Fraction of energy released promptly in fuel                            0.913
Fraction of energy released via decay heat                              0.061
Fraction of energy released in moderator/coolant                        0.026
Control rod position (fraction withdrawn)                               0.9620

Help  Range                    Skp-Frm  Prv-Frm  Nxt-Frm
```

Figure 2 MMS-EASE+ Auto-Parameterization Input Form

```
EASE+: FORM:RX1_1                                              03/01/91 10 19

                      MACRO RX1 ("ID", "VE", "WL",1)
                        AUTO-PARAMETERIZATION SHEET

Component ID:   RX1              Description:    reactor

   Constant Parameters
Fraction of delayed neutrons in      : KBP_ID(1)  2.5000001e-4
   i-th group (3 groups)                     (2)  0.0057
                                             (3)  0.00115
Boron worth                          : KBR_ID     1.10e-4        (1/ppm)
Fuel heat capacity                   : KCM_ID     14497.17       (Btu/F)  (J/C)
Diffusion length                     : KDL_ID     4.10           (cm)     (cm)
Primary flow conductance             : KFC_ID     2.52257e+6
Doppler coefficient                  : KDP_ID     -1.36e-5       (1/F)    (1/C)
Fraction of neutrons delayed         : KFD_ID     0.0071
Fraction of heat deposited in fuel   : KF1_ID     [illegible]
Fraction of heat deposited in coolnt : KF2_ID     0.026
Elev. diff. from cold leg to core    : KHC_ID     16.0660        (ft)     (m)
Elev. diff. from hot leg to core     : KHH_ID     16.0660        (ft)     (m)
Moderator coefficient                : KMD_ID     -5.55555e-5    (1/F)    (1/C)

Help  Range                    Skp-Frm  Done     Nxt-Frm
```

Figure 3 MMS-EASE+ Auto-Parameterization Output Form

SIEASE permits the user to key-in the data in metric units, converts the data to U.S. units, the default units at present, and inserts the converted data in the forms. The output forms then displayed the automatically calculated parameters. To automatically generate the model source code in ACSL, the "Generation of MMS ACSL File" option in the MMS-EASE+ menu was selected. The resulting code includes calls to module macros and the calculated parameters, custom ACSL coding, and custom Fortran subroutine coding included in model definition. The model code was then translated to Fortran using the ACSL translator, compiled, and linked to produce the executable model. The model was debugged and fine tuned.

GRAPHICAL INTERFACE

The graphical interface was developed in parallel with the dynamic model. The graphics were generated using computer-aided graphics (CAD) software and graphical subroutines featuring EGA/VGA support and keyboard/mouse interaction. The graphical user interface has two screens: Selection Screen and Run Screen.

Selection Screen

As shown in Figure 4, the Selection Screen has six windows.

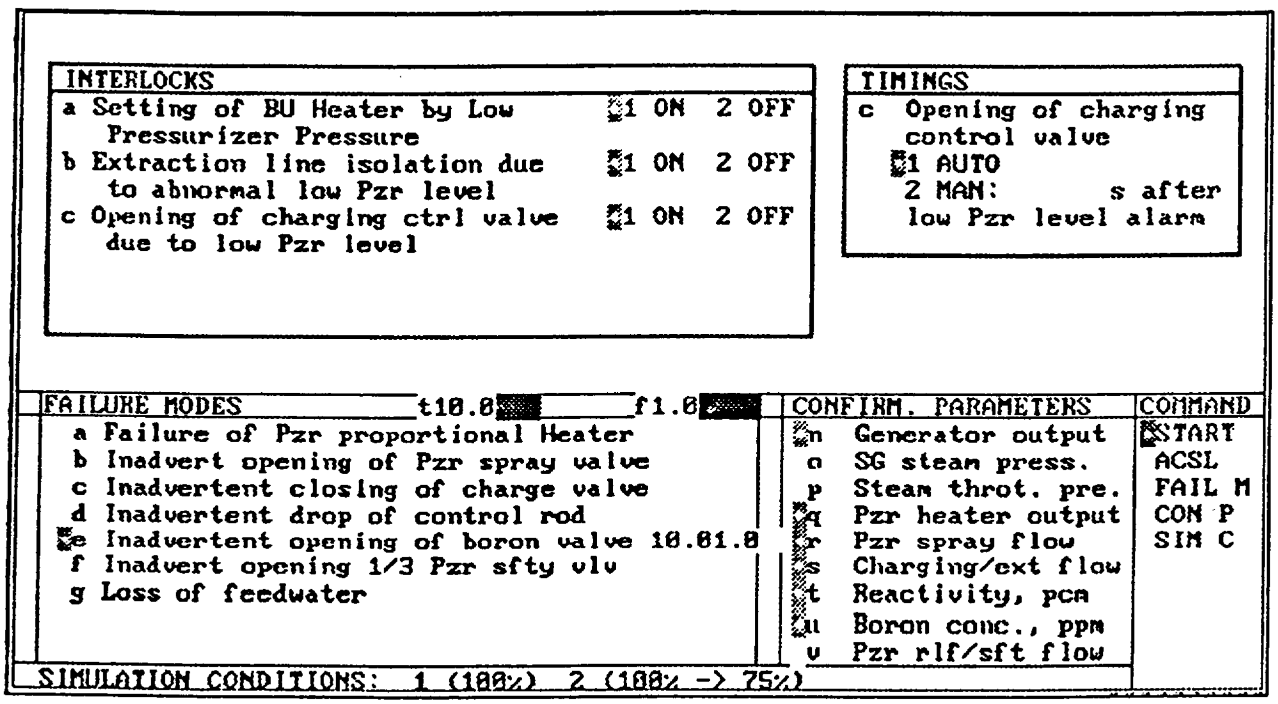

Figure 4 Selection Screen

The COMMAND window at the lower right has the top level commands. Commands FAIL M, CON P, and SIM C are expanded in the windows captioned FAILURE MODES, CONFIRM(ation) PARAMETERS, and SIMULATION CONDITIONS, respectively. The FAILURE MODES window is further expanded in the INTERLOCKS window for selection of interlocks. The INTERLOCKS window is further expanded in the TIMINGS window to select the timing of interlocks. To make a selection, the cursor is moved to the desired item with the cursor up, down, left, and right keys and the "Enter" key is pressed. To return to the previous window, "Esc" key is pressed. After the selections are made, the user selects START to start the transient and monitor it on the RUN screen. Selecting ACSL or pressing the Esc key causes control to be transferred to the ACSL executive and the ACSL> prompt to be displayed. A mouse can be used for making selections.

Selecting the FAIL M command activates the FAILURE MODES window. After selecting the desired failure mode, the user is prompted to enter the time of failure in seconds by the letter "t" and the degree of failure (DOF) (0.0 to 1.0) by the letter "f". The DOF input is used to specify partial failures. For example, for the pressurizer safety valve, a degree of failure of 0.5 will cause the valve to fail-open halfway, while a DOF of 1.0 will fail the valve fully open. After the DOF input, the INTERLOCKS window associated with the selected failure mode automatically pops up. If the user selects an interlock to be ON, the TIMINGS window associated with the selected interlock automatically pops up for the user to select AUTOmatic or MANual. For MANual selection, the user also has to enter the time elapsed in seconds between an alarm and the activation of the interlock.

Selecting the CON P command activates the CONFIRM PARAMETERS window. The user can select the variables he wants to see trended on the RUN screen. There are more parameters than the window can hold. So the window is automatically scrolled to provide access to variables not seen in the window if the user tries to go beyond the limits of the window.

Selecting the SIM C command activates the SIMULATION CONDITIONS window. The user can select the failure to occur while the plant is in steady state at 100% power or while the plant is undergoing a power ramp from 100% to 75% power.

Run Screen

The Run Screen (Figure 5) displays the selected failure modes, trends, dynamically updated plant schematic, and sequence of events. The selected trends are displayed along with the current values and are updated every cycle. The trends are scrolled to show the most recent information. Values of selected variables are updated every cycle on the schematic. The time of occurrence and a short description of events appear in the EVENT LIST window, and are also written to the disc file, EVENT, when a predefined event occurs. A red spike appears in the TREND window at the time an event occurs. The EVENT LIST window is scrolled to show the most recent events. Selecting ACSL or pressing the Esc key causes control to be transferred to the ACSL executive and the ACSL> prompt to be displayed.

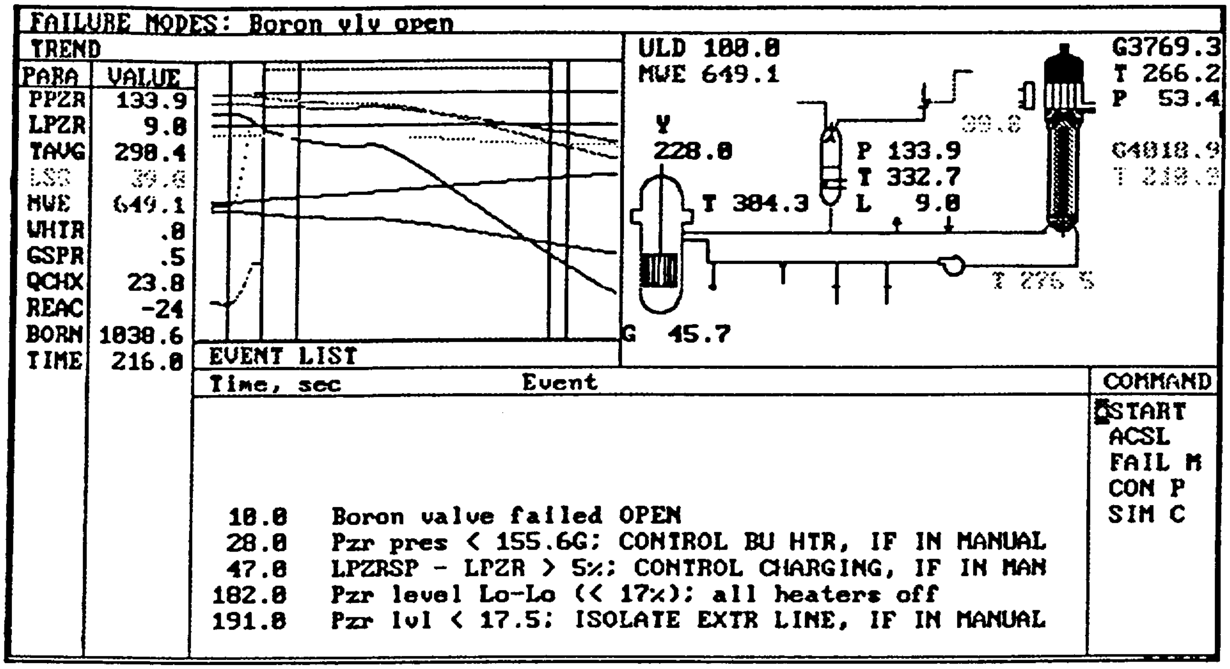

Figure 5 Run Screen

DEMONSTRATION MODEL

The demonstration model was generated by integrating the dynamic model and graphical user interface. The demo model runs on IBM-compatible PCs within the DOS environment. To facilitate running this model, a command file incorporating a macro for each failure mode and a macro for plotting the results after running the transient was created. The model runs approximately twice as fast as real time on a 486/25 PC.

CONCLUSIONS

The demonstration model has proved the feasibility of the MMS for failure-mode analysis. By taking advantage of the automation in MMS and MMS-EASE+, and by utilizing prior experience with MMS and nuclear power plant modeling, the model was developed in only five man-months. The dynamic model and the graphical user interface were developed in parallel to shorten the schedule. Planning for subsequent phases is under way.

The MMS includes modules for modeling PWRs, BWRs, and fossil power plants. Modules for advanced reactors will be added in the near future. A company can build a model for its own application by licensing the MMS software, or by contracting BWNS to have a model built to its specification.

REFERENCES

1. Norm S. Yee. "A Modular Approach to Modeling Power Plant Systems." In Proceedings of the American Power Conference, Chicago, Illinois, USA, April 23-25, 1990.

2. B&W Nuclear Service Co. MMS Manuals. P. O. Box 10935, Lynchburg, VA, USA 24506-0935, 1988.

3. S. S. Godbole. "MMS Simulation of RSG/FW Train of a Nuclear Power Plant for Developing a RSG Level Control System." In Proceedings of the Eastern MultiConference, Nashville, TN, USA, April 23-26, 1990.

4. S. S. Godbole. "A Nuclear Simulator Concept for Hardware-in-the-Loop Development of Digital Feedwater Control System." In Proceedings of the American Power Conference, Chicago, Illinois, USA, April 23-25, 1990.

5. Mitchell & Gauthier Associates. ACSL Reference Manual. 73 Junction Square Drive, Concord, Mass., USA 01742-3096, 1987.

6. B&W Nuclear Service Co. MMS-EASE+ User Manual. P. O. Box 10935, Lynchburg, VA, USA 24506-0935, 1991.