**Nuclear Energy Research Initiative (NERI)
Quarterly Progress Report**

**Model Based Transient Control and Component
Degradation Monitoring in Generation IV
Nuclear Power Plants**

DE-FG07-02ID22612
(Formerly: DE-FG03-02SF22612/A000)

Quarter 2 Report
January – March 2003

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Collaborating Organizations: Westinghouse Electric Company
and Sandia National Laboratories

Submitted on: April 28, 2003

Technical Narrative:

Robust control methodology (Task 1.1)

A preliminary comparison of H_2 and H_∞ control of a traditional steam generator has just been made. These preliminary results, based on linear models, show different trade-offs between the two control methodologies. The simulation begins with a 50% ramp-reduction in steam demand and a 50% ramp-reduction in power. The H_2 controller is expected to maintain level control of the steam generator. The controller provides a smaller change in level, but leads to oscillations and a longer settling time than the H_∞ controller. The H_∞ controller shows no oscillations but provides a smooth monotonic change in level. These results are quite preliminary.

Standard linear control theory in the presence of unmodeled dynamics (disturbances) and sensor noise leads to the conflict between robustness—allowing for disturbances to the plant model—and noise rejection—avoiding having the controller respond to noise in the sensor signals. In linear H_∞ control theory this is addressed by postulating a separation in the frequency content between disturbances d and noise n , and introducing weight functions as design parameters. We have investigated how a general nonlinear system might or might not support this same separation of the effects of disturbances and noise.

Figure 1: Interconnections between plant, disturbances, controlled output, measurement noise, controller and control signal.

For the system interconnections shown in Figure 1, and assuming the required nonlinear inverse exists, the input-output relation mapping disturbances and noise to desired output is.

$$v = (I \square G \circ C)^{\square} (d + n) \square n$$

Note in this that all of the operators are nonlinear, and $G \circ C$ denotes composition of nonlinear maps. In the linear case this reduces to the standard result

$$v = (I - GC)^{-1}d + ((I - GC)^{-1} - I)n$$

in which the effects of disturbances and noise are separated and determined by the sensitivity operator $S = (I - GC)^{-1}$ and the complementary sensitivity operator $T = I - S = (I - GC)^{-1}GC$. But the nonlinear system *does not* clearly separate noise from disturbances, so it is not clear where to introduce a separation of the effects of noise and disturbances in an augmented plant model. An immediate task for this part of the project is to understand how to introduce design tools, analogous to the weight functions of the linear theory, that will allow the augmented system to be represented as a dynamical system that can be treated with the H theory. One approach to this may be to introduce high-pass and low-pass filters into the objective functional whose minimax property defines the optimal control strategy.

Plant Operation and Control for Integral Reactors – IRIS (Task 1.2)

The pressurized, light water cooled, medium power (1000 MWt) IRIS (International Reactor Innovative and Secure) reactor plant has been under development for three years by an international consortium of over 20 organizations from nine countries. The plant conceptual design was completed in 2001 and the preliminary design is currently underway. The pre-application licensing process with NRC started in October 2002 and IRIS is one of the designs considered by U.S. utilities as part of the ESP (Early Site Permit) process. Major characteristics of the IRIS design and supporting analyses are reported in several open literature publications as well as proprietary consortium documents and are not discussed here.

One of the objectives of this project is to develop advanced control systems for application to advanced reactors and to use IRIS as a test bed for these model based control systems. Integral reactors present several features that make the development of such control systems extremely important for optimal operation of these plants. During this quarter, Westinghouse has worked with other IRIS consortium partners to identify and evaluate which features of integral reactors will have an important effect on plant operations. This task was a fundamental step in defining an appropriate design of the control systems for IRIS. The features identified are:

Once-Through Steam Generators

IRIS employs Once-Through Steam Generators (OTSGs) rather than the recirculation SGs used in most PWRs. IRIS SGs also present a fundamental difference from the OTSGs used in B&W PWRs: secondary water flows inside the tubes and, therefore, no level measure and, thus, *no level based control system* can/need be implemented.

Power removed through the SGs directly depends on feedwater flow. This means that, following any large loss of main feedwater, the turbine must be rapidly tripped by closing the Fast Closure Admission Valves.

These characteristics of IRIS SGs make it impossible to implement classical PWR control logic.

IRIS SGs, with secondary flow inside the long tubes and exiting superheated, are prone to parallel channel instabilities. Based on Ansaldo experimental tests on Helical Coil Steam Generators (HCSGs), appropriate maps of stable operating conditions will be defined to provide input to the protection and control systems. The control system will have to monitor the steam system conditions against these stability maps.

Large RCS inventory

IRIS total reactor coolant system water inventory is over 16,000 ft³, which is significantly larger than any other PWRs, especially on a volume-per-MW basis. This is an important safety feature, since this large heat sink acts to mitigate several events and is a fundamental part of the LOCA response of the reactor. However, this characteristic leads to some differences from current PWRs that impact the design and requirements of the control systems:

Due to the large inventory, cooldown/heatup, startup and dilution procedures potentially require more time than in current PWRs. To optimize the plant operations, dedicated heating equipment will be implemented during startup procedures and the Chemical and Volume Control System (CVCS) will be sized to provide sufficient charging and letdown flow for effective management of cooldown/heatup and boron concentration change procedures;

The low flow velocity coupled with the large inventory leads to a characteristic residence time of about 40 seconds (vs. 10 seconds typical for PWRs). This leads to a system in which the core and steam generators are not as tightly coupled as in current PWRs. Having a control system that can anticipate transients (i.e., a model based control system) can have a significant impact on procedures and lead to better plant utilization;

The large thermal inertia allows for a relatively large delay between reactor trip and turbine trip to provide adequate initial cooling following a reactor trip.

Large Pressurizer Steam Volume

IRIS steam volume in the pressurizer is larger than in current PWRs. This is due to the fact that the large closure head of the pressure vessel defines the pressurizer boundary, and provides a large volume. IRIS steam volume at 100% power is about 50 m³ (>1700 ft³), significantly larger than any other PWRs, especially on a steam volume-per-MWt basis (steam volume-to-power ratio is ~4.5 times AP1000):

This improves the capability of the system to respond to Condition I and II events, without requiring any safety and relief valve actuation;

The improved pressurizer response allows for a design that does not feature sprays. This will lead to a slower recovery following transients that will rely on heat losses from the pressurizer. This characteristic needs to be evaluated to confirm whether sprays are required, and how to optimize the pressurizer heaters' control logic to optimize the plant operations;

Lacking sprays means that some other sort of coolant mixing must be provided to the pressurizer to maintain a water chemistry compatible with the RCS conditions.

Once the main IRIS characteristics were identified, a development plan was defined to provide an effective set of plant operation procedures and to optimize the design of the control systems. For each of the main operating modes of the reactor (startup, shutdown, hot standby, power operation mode) the requirements for the control system operation are being defined. The following main control systems are considered in this development:

1. Feedwater Control System
2. Steam Dump System
3. Rod Control System
4. Pressurizer Pressure Control System
5. Pressurizer Level Control System

Requirements and specifications for each system are being defined, with particular emphasis on the power operation range (20 to 100% power).

This definition of functional requirements and specifications for the control systems will constitute the background and will set the performance requirements for the development of robust algorithms that is one of the main objectives of this program.

Main Steam System RELAP model refinement and modifications for control simulation (Task 1.2.1)

The IRIS consortium had developed a detailed RELAP model for the safety analysis of the reactor. The model was developed for the specific purpose of evaluating abnormal events and design basis accidents, and includes a detailed reactor coolant system description, with specific models developed for each of the main components. However, only simplified models of the control systems and of the main steam systems were required for these applications. This is due to the fact that in most accident analysis, no credit is given for the operation of the control systems, and simplified, conservative assumptions on the steam system are sufficient.

The focus of this research program is, however, on the development of robust control systems. This requires the analysis of several operational transients to verify the effective operation of the control systems. Therefore, as part of this research program, Westinghouse has modified the original RELAP IRIS nodalization to include models of the control systems and main steam systems components in sufficient detail to allow analysis of different operating transients for the plant. This activity was identified in the original proposal as Task 1.2.1. With the support of other member organizations in the IRIS consortium (who cooperate on their own funding) the scope has been expanded to include a control system model based on standard Westinghouse methodologies to allow a benchmark platform for the robust algorithms that are being developed by the University of Michigan partner of the program.

During this quarter, models of the main feedwater system, the startup feedwater system, the main steam system (up to and including the common steam header), the four-stage steam dump system with modulated valves, and a simplified turbine and condenser model have been included in the plant model (represented in Figure 2).

Also, initial implementation of the plant control systems has been started, following the same approach used by Westinghouse in the model of control systems for

conventional PWRs. The following control systems are being modeled (percentage of the development that has been completed is reported in parentheses):

1. Pressurizer pressure control system: proportional heaters, backup heaters, Power Operated Relief Valves (PORVs), Safety and Relief Valves (80%)
2. Pressurizer level control system: charging and letdown flow, CVCS connections to the RCS (80%)
3. Rod Control System: RCS Tavg vs. Power program and implementation of rod insertion/withdrawal characteristic (25%)
4. Feedwater Control System: automatic feedwater control system – feedwater temperature and flow (25%)
5. Steam Dump System: steam dump valves model, steam dump pressure and temperature control programs (50%)
6. Startup Feedwater System: steam generator level measuring device and control of the startup feedwater system for startup, hot standby and shutdown operations (25%)

Figure 2 – IRIS Plant Model

Steam generator vibration model (Task 2.2.1)

Sandia staff started to conduct a survey on the performance, inspection and failure data on the tube assembly in conventional steam generators. A database on tube degradation mechanisms will be assembled from the survey results. An investigation is also underway to identify the state-of-the-art coupled physics codes to perform the hydrodynamic modeling of tube assembly. After an appropriate code has been selected, vibration models of the tube assembly will be developed to study their fluid-structure interaction in the operating environment inside the steam generator. There will be a parallel effort to perform vibration response analyses of tube assembly by using procedures and methodologies that have been adopted by practicing engineers in industry.

Sandia staff will interact closely with the project team members from Westinghouse to seek their support in providing the detailed design of the IRIS helical steam generator. Vibration models will be developed and analyzed based on this design details.

Stochastic degradation methodology (Task 2.3)

A Monte Carlo code to solve the differential Chapman-Kolmogorov equation has is being ported to the current Unix environment at the University of Michigan. This code was purpose created to study component degradation in the Big Rock nuclear power station, and is being examined to validate its solution algorithm for solving the equations that arise in the stochastic degradation methodology.

Cost

Performance

U of Michigan – Actual Costs / Anticipated Costs: \$29,925 / 104,000\$

Westinghouse – Actual Costs / Anticipated Costs: \$25,683 / 52,500\$

Sandia -- Actual Costs / Anticipated Costs: \$19,000/45,000 \$

Issues/Concerns

There are no budgetary concerns at present. As mentioned in the last quarterly report, the lack of graduate students has resulted in an under-expenditure of funds at the University of Michigan. The University of Michigan has appointed only one graduate student to work on this project, but has identified several new students who will begin work in the fall. A summer research student from KAIST may also work on this project in the summer of 2003. It is anticipated that starting in September 2003 we will appoint 3 graduate student researchers on this project. This is larger than originally planned, but the savings in this year's budget (which originally planned for two graduate students for the entire year) will allow this with no change in the overall personnel budget. Sandia's rate of expenditure is expected to increase significantly as work proceeds on steam generator vibration models.

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Status Summary of NERI Tasks:

Tasks starting year 1	Planned Completion	Actual Completion	Percent Complete
Robust control methodology	September 2003		10%
RELAP model for control	July 2003		50%
Assess Reliability Database	October 2003		25%
Steam generator vibration model	September 2004		10%
Stochastic degradation methodology	September 2003		10%
Low order modeling	September 2003		10%
Main steam system model	March 2003	April 2003	100%
Tasks starting year 2	Planned Completion	Actual Completion	Percent Complete
Extend control to MIMO	September 2004		
Develop control simulator	September 2004		
Sensor to state mapping techniques	February 2005		
Develop degradation simulator	January 2005		
Sensor state PDFs	January 2005		
Tasks starting year 3	Planned Completion	Actual Completion	Percent Complete
Control validation	September 2005		
Sensor placement optimization study	July 2005		
Degradation demo	September 2005		