

## A Plant Control System Development Approach for IRIS

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The plant control system concept for the International Reactor Innovative and Secure (IRIS) will make use of integrated control, diagnostic, and decision modules to provide a highly automated intelligent control capability. The plant control system development approach established for IRIS involves determination and verification of control strategies based on whole-plant simulation; identification of measurement, control, and diagnostic needs; development of an architectural framework in which to integrate an intelligent plant control system; and design of the necessary control and diagnostic elements for implementation and validation. This paper describes key elements of the plant control system development approach established for IRIS and presents some of the strategies and methods investigated to support the desired control capabilities.

**KEYWORDS:** *Integral pressurized water reactor, helical coil steam generator, control system, diagnostics, supervisory control, plant operation*

### I. Introduction

Integration of distributed control loops and utilization of diagnostic information for autonomous operational decisions can not only support increased automation and greater availability within future nuclear power plants, but these approaches can contribute to optimizing plant and component design margins. Use of intelligent control can reduce operational stress on plant systems and extend the range of conditions that can be accommodated without overburdening the plant operators or challenging the safety systems. The plant control system needs to provide features and characteristic to address not only plant operation at full power but also reactor and plant start-up, power ascension, load-follow, and shutdown operations. In addition, the plant control system should provide the capability for self-validation and adaptation throughout extended operational periods over the plant lifetime. The development of a plant control system for the International Reactor Innovative and Secure (IRIS) will address these issues to enhance the economy, efficiency, and reliability of the plant. To accomplish this goal, the IRIS plant control system will make use of integrated control and diagnostic modules to achieve a highly automated intelligent control capability.

The plant control system development approach established for IRIS involves determination and verification of control strategies based on whole-plant simulation; identification of measurement, control, and diagnostic needs; development of an architectural framework in which to integrate an intelligent plant control system; and design of the necessary control and diagnostic elements for implementation and validation. A key aspect of this development effort is to identify an operational strategy that optimizes plant control while addressing any unique dynamic behavior characteristics resulting from the integral primary system and the once-through helical-coil steam generators (HCSGs). The candidate strategies address coordination of control for pressurizer level, reactor power, and primary coolant average temperature while accounting for the strong coupling between the HCSGs and the primary coolant system in the maintenance of sufficient secondary coolant inventory. The specification of control, measurement, and diagnostic needs is based on an evaluation of the required command and sensing capabilities, derived from the selected control strategy, to support intelligent control over the full range of operational conditions. To facilitate intelligent control, a supervisory control architectural framework supports the integration of

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control, diagnostic, and decision elements into a comprehensive, hierarchical command and decision system that can adapt to altered goals or degraded conditions.

## II. International Reactor Innovative and Secure

The pressurized light water cooled, medium power (1000 MWt) IRIS nuclear 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 under way. The pre-application licensing process with U.S. Nuclear Regulatory Commission (NRC) started in October 2002, and IRIS is one of the designs considered by US utilities as part of the Early Site Permit (ESP) process.

pressure vessel, but the size of the IRIS containment is a fraction of the size of corresponding loop reactors, resulting in a significant reduction in the overall size of the reactor plant.

IRIS features a design with innovative safety characteristics.<sup>1,6)</sup> The first line of defense in IRIS is to eliminate event initiators that could conceivably lead to core damage. In IRIS, this concept is implemented through the “safety by design” approach. The key difference in the IRIS “safety by design” approach from previous practice is that the integral reactor design is conducive to eliminating

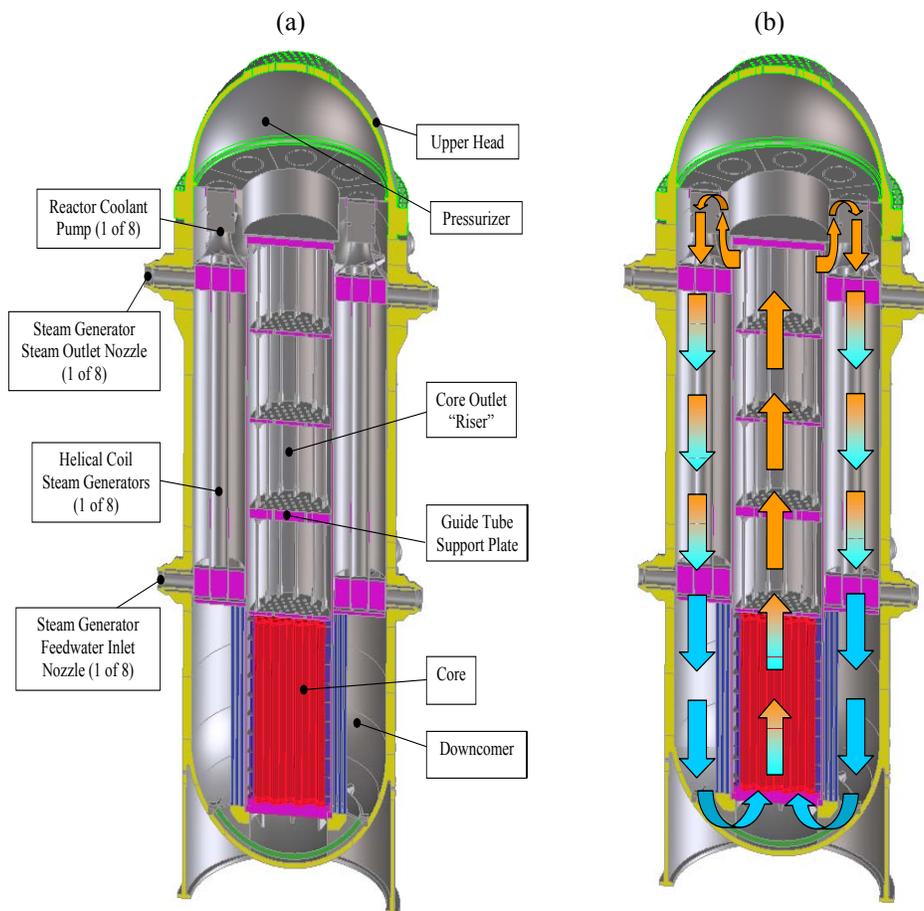


Fig. 1: IRIS integral layout: (a) main components; (b) main flow path.

IRIS is a pressurized water reactor that utilizes an integral reactor coolant system layout,<sup>1,2)</sup> as shown in Fig. 1. The IRIS reactor vessel houses not only the nuclear fuel and control rods, but also all the major reactor coolant system components including pumps,<sup>3)</sup> steam generators,<sup>4)</sup> pressurizer<sup>5)</sup> and a neutron reflector. The IRIS integral vessel is larger than a traditional pressurized-water reactor (PWR)

accidents to a degree impossible in conventional loop-type reactors. The IRIS design builds on the proven technology provided by over 40 years of operating PWR experience, and on the established use of passive safety features pioneered by Westinghouse in the NRC certified AP600 plant design. The use of passive safety systems provides improvements in plant simplification, safety, reliability, and

investment protection over conventional plant designs. Because of the safety by design approach, the number and complexity of these passive safety systems and required operator actions are further minimized in IRIS. The net result is a design with significantly reduced complexity and improved operability, and extensive plant simplifications to enhance construction.

### III. Integral Reactor Operation and Control Overview

The IRIS design, while presenting an innovative engineering of the reactor coolant system, presents several similarities with loop-type PWRs from the point of view of operation and control. However, some features of the design have an important effect on the plant characteristic response to several operation maneuvers. The design of an intelligent control system for IRIS starts with the identification of IRIS specific features that influence the operational response in various operating modes of the reactor. The most important of these features are identified as follows.

#### 1. Once-Through Steam Generators

IRIS employs once-through steam generators (OTSGs) with helical coils rather than the recirculation SGs used in most PWRs. IRIS steam generators also present a fundamental difference from the OTSGs used in Babcock and Wilcox (B&W) PWRs: secondary water flows inside the tubes and, therefore, no level measure (and, thus, no level based control loop) can/need be implemented. Power removed through the OTSGs 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.

Also, IRIS steam generators, with secondary flow inside the long tubes and with a 40°C superheating at the steam generator exit, are prone to parallel channel instabilities. Based on experimental tests on HCSGs, appropriate maps of stable operating conditions (in terms of power, feedwater flow, and steam pressure) will be defined to provide input to the protection and control systems. The control function will have to monitor the steam system conditions and provide automatic operational limitations based on these stability maps.

#### 2. Large RCS inventory

IRIS total reactor coolant system water inventory is over 16,000 ft<sup>3</sup>, which is significantly larger than any that of other PWRs, especially on a volume-per-MWt basis. This is an important safety feature, since this large heat sink acts to mitigate several events and is a fundamental part of the loss-of-coolant accident (LOCA) response of the reactor. However, this characteristic leads to some differences from current PWRs that impact the design and requirements of the control loop.

- Due to the large inventory, cooldown/heatup, startup, and dilution procedures potentially require more

time than in current PWRs. During startup operations, dedicated heating equipment will be utilized to bring the primary system up to temperature 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 an integrated plant 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.

#### 3. 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 pressurizer volume. IRIS steam volume at 100% power is about 50 m<sup>3</sup> (>1700 ft<sup>3</sup>), significantly larger than any other PWR, especially on a steam volume-per-MWt basis (IRIS steam volume-to-power ratio is ~4.5 times larger than AP1000).

- This improves the capability of the system to respond to normal and abnormal occurrences (Condition I and II events), without requiring any safety and relief valve actuation.
- The improved pressurizer response allows for a design that possibly 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 define the pressurizer heaters' control logic to optimize the plant operations.

### IV. Functional Requirements for IRIS Plant Control System

The function of the IRIS plant control system is to establish and maintain the plant operating conditions within prescribed limits. The plant control system improves plant safety by minimizing the number of situations for which some protective response is initiated and relieves the operator from routine tasks.

The functional requirements of the IRIS plant control and instrumentation systems are not significantly different from a loop-type PWR. The plant control system includes the following functions.

- 1) **Reactor Power Control Loop** – The reactor power control loop coordinates the response of the various reactivity control mechanisms; enables daily load follow operation with minimal manual control requirements and is also responsible for axial nuclear power distribution control.
- 2) **Rod Control Loop** – The rod control loop, in conjunction with the reactor power control system, maintains plant parameters (nuclear power, temperatures, etc.), without challenges to the protection system, during normal operational transients.
- 3) **Pressurizer Pressure Control Loop** – The pressurizer pressure control loop maintains or restores the pressure to the nominal pressure (i.e., within the acceptable deadband) following normal operating transients and avoids challenges to the protection system during normal operational transients.
- 4) **Pressurizer Water Level Control Loop** – The pressurizer water level control loop establishes, maintains, or restores the pressurizer level to its programmed value. The required level is programmed as a function of reactor coolant temperature and nuclear power to minimize charging and letdown requirements. Also, no challenges to the protection system result from normal operational transients.
- 5) **Feedwater Control Loop** – In a conventional PWR, the feedwater control loop maintains the steam generator water level at a predetermined setpoint during steady state operation; maintains the level within acceptable operating limits during operational transients; and restores normal water level following a trip. For IRIS, the HCSG level is not a significant process variable, and the feedwater control loop requires a program that uses total steam load as the main process variable.
- 6) **Steam Dump Control Loop** – The steam dump control loop reacts to prevent a reactor trip following a sudden loss of electrical load and brings the plant to equilibrium no-load conditions.
- 7) **Rapid Power Reduction** – Several advanced PWRs, such as the AP1000, feature a rapid nuclear cutback (often termed “partial trip”) for large rapid load rejection, to reduce the thermal power to a level that can be handled by the steam dump system. The same function is provided to IRIS.
- 8) **Defense-In-Depth Control** – The plant control system provides control of systems performing defense-in-depth functions.

It is evident from the previous list that the principal function of the plant control system is to “*establish, maintain or restore key process variables to their programmed value (i.e., within the acceptable deadband) following normal operating transients and avoid challenges to the protection system during normal operational transients.*”

The IRIS plant control system shall perform this principal function during different operating modes (power operation, startup, hot standby, safe shutdown, cold shutdown and refueling) for normal operating transients (step and ramp loads changes, load follow operation, grid frequency response, etc.) and with the permissible deviations defined in the plant Technical Specifications.

## V. Overview of IRIS Plant Control System Features and Plant Operation Strategy

Several of the control loops discussed in the previous section will not present significant difference from current PWR practice. However, due to the IRIS features discussed in section III, the design and specifications of some loops within the IRIS plant control system will differ from current practice. In particular, some of the most important differences are as follows.

### 1. Pressurizer Pressure and Level Control Loop

Due to the large volume available in the upper head region for the pressurizer, IRIS pressure and level control functions will rely more on the inherent response of the design rather than on the actuation of dedicated systems. Pressurizer sprays (with the exception of auxiliary sprays for use during shutdown operation) will not be included in the design, and no automatic function for the power-operated relief valves shall be provided. The system will rely on its large steam volume to mitigate pressure transients and satisfy the principal function discussed in section IV. The lack of a spray function will delay the restoration to initial conditions following some transients, since the system will rely on heat losses to restore the initial pressure. The level control loop will not present significant differences from current practice, and IRIS will make use of the large pressurizer volume to limit requirements on the charging and letdown system following reactor trip and large power reductions.

### 2. Reactor Power and Rod Control Loop

IRIS rod control function will not present significant deviations from current PWR practice. However, due to the large water inventory in the reactor coolant system, IRIS will respond to most of the operational transients (ramp and step load changes) through the rod control loop, to minimize the requirements on the charging and letdown system, essentially preventing, where possible, changes in the boric acid concentration in the reactor coolant system.

### 3. Feedwater Control Loop

The feedwater control loop will present significant differences from current PWRs, especially in comparison to those plants with recirculation steam generators. This control loop will be more similar to the Integrated Control System (ICS) of B&W plants and will rely on a more integrated control strategy than for other PWRs. A sliding Tavg program versus turbine load program will constitute the main basis for IRIS control strategy, with a feedwater program based on total steam load in the power range operation. Specific solutions will be implemented for the low and no-load power range to provide a stable plant operation in these regions.

## VI. Self-Validating Controller Design and Implementation Structure

The plant control system design for IRIS will build on recent advances in control theory. Specifically, it will use methods for automated generation of the control system that can be traced directly to the design requirements for the life of the plant.<sup>7)</sup> Implementation of these methods will capture the design requirements inside a control engine during the design phase. This control engine then not only will be capable of automatically designing the initial implementation of the control system, but it also can confirm that the original design requirements are still met during the life of the plant as conditions change.

As described in reference 7, the control engine captures the high-level requirements and stress factors that the control system must survive (e.g., a list of transients, or a requirement to withstand a single failure.) The control engine is able to subsequently generate the control-system algorithms and parameters that optimize a design goal and satisfy all requirements. As conditions change during the life of the plant (e.g., component degradation or subsystem failures), the control engine automatically “flags” that a requirement is not satisfied, and it can even provide recommendations for a modified configuration that would satisfy it.

The implementation of this control-engine design methodology requires the following steps:

- 1) Determination of design requirements related to control system performance
- 2) Representation of requirements in mathematical form
- 3) Access to (or development of) a control algorithm library
- 4) Development and validation of plant models
- 5) Automated control design generation
- 6) Evaluation of control architectures
- 7) Control design implementation
- 8) Implementation (or development) of diagnostics methods to update the plant model

To implement the control engine as part of a self-validating structure, the performance requirements are reformulated as mathematical constraints of a minimization problem. For example, one such constraint could be that the reactor T-average control system must survive an anticipated over-cooling event without scram. The control engine runs in the background in supervisory mode and continuously evaluates whether these constraints are satisfied given the current state of the plant. The state of the plant is represented by validated plant models. As diagnostic modules detect degradation (e.g., sensor drift or actuator sticking) or component failure, the plant simulation models are updated. When the plant condition undergoes sufficient changes to result in inability of the control system to satisfy one or more of the design requirements, the control engine starts an iterative minimization calculation that suggests to the operator optimal control parameter settings or even different control strategies if the current one is inadequate. Since changes to the plant over its 60 year life are slow in nature, it is not envisioned that the control engine would function in a closed loop by automatically changing control parameters or strategies. Its function would be more of an advisory nature through generation of an alert when the original control-system performance requirements are not satisfied under the present conditions (e.g., hardware failures or plant reconfiguration). In addition to the alert, the control engine can also suggest new control system settings that would satisfy the performance requirements under the present plant condition.

## VII. Supervisory Control Framework

To fully achieve the economic benefits of IRIS, it will be desirable to have a limited operational staff. The combined factors of a reduced operating staff and more complex dynamics means a different approach is needed for overall control of the plant. The solution is to develop a supervisory control system. The role of the supervisory control system is to act as an extension of the human operator to assure safe, reliable operation of the plant. The supervisory control system provides the framework for integrating algorithm-based controllers and diagnostics at the subsystem level with command and decision modules at higher levels that assume increased responsibility while accommodating the human operator’s analytical approach and need to be cognizant of the state of the plant.

The supervisory control structure envisioned for IRIS is hierarchical with a recursive nature. Each node in the hierarchy (except for the terminal nodes at the base) is a supervisory module. The supervisory control module at each level responds to goals and directions set in modules above it within the hierarchy and to data and information presented from modules below it within the hierarchy. Each module makes decisions appropriate for its level in the hierarchy and passes the decision and necessary supporting information to the modules above.

The human operator has the opportunity to interact and direct the goals and actions of the supervisory controller. This interaction may take place directly with any module in the hierarchy. This assures that the human operator can assume ultimate responsibility for the safety and operation of the plant.

In addition to the communications up and down the hierarchy, the supervisory controller must keep the operator informed about the status of the plant. To this end the supervisory controller must communicate information about the status of the plant, any data needed to support the information, any impending control actions, the reason for the control action, and the expected result of the action. The goal of this communication is to assure the operator is well informed about the status of the plant and the control system. The operator must have confidence that the plant is in a safe state and that the control system is functioning to keep the plant operational while meeting both short term and long term goals.

The self-validating controller structure described in section VI can be easily implemented at higher levels of the supervisory control architecture. By building in appropriate diagnostics, the supervisory control system can determine when subsystem performance has degraded to the point of possibly violating design goals. After the degradation has been diagnosed, corrective action can be taken by the supervisory control system, and the operator can be alerted.

### VIII. Conclusions

The IRIS plant concept has several unique characteristics and operational goals that can be best addressed through an intelligent plant control system which integrates control, diagnostics, and decision capabilities. The development approach established for the IRIS plant control system involves determination and verification of control strategies based on whole-plant simulation; identification of measurement, control, and diagnostic needs; development of an architectural framework in which to integrate an intelligent plant control system; and design of the necessary control and diagnostic elements for implementation and validation. The IRIS plant control system will employ several innovative structures and capabilities to facilitate the desired intelligent plant control. The design and implementation will provide the capability for self-

validation and adaptation throughout extended operational periods over the plant lifetime. In addition, the hierarchical supervisory control framework will support full integration of control, diagnostic, and decision modules to provide a high degree of automation and the basis for expanded autonomy in operations.

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