Several vendors have recently been actively pursuing the development of integral pressurized water reactors (iPWRs) that range in power levels from small to large reactors. Integral reactors have the features of minimum vessel penetrations, passive heat removal after reactor shutdown, and modular construction that allow fast plant integration and a secure fuel cycle. The features of an integral reactor limit the options for placing control and safety system instruments. The development of instrumentation and control (I&C) strategies for a large 1,000 MWe iPWR is described. Reactor system modeling—which includes reactor core dynamics, primary heat exchanger, and the steam flashing drum—is an important part of I&C development and validation, and thereby consolidates the overall implementation for a large iPWR. The results of simulation models, control development, and instrumentation features illustrate the systematic approach that is applicable to integral light water reactors.

1. Introduction

The University of Tennessee (Knoxville, TN, USA) is engaged in research and development projects related to instrumentation and controls (I&C) for small modular reactors (SMRs) and integral pressurized water reactors (iPWRs). The technical approach incorporates the development of physics-based models for the control design, the development of nonintrusive sensors for flow monitoring, and placement of sensors to maximize fault detection and isolation. The results of research and development are illustrated with application to an integral inherently safe light water reactor (I2S-LWR) that is being developed under a United States (U.S.) Department of Energy-funded research and development project.

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Integral reactors have in-vessel space constraints and limited vessel penetrations [1]. Because of this, traditional instruments installed in the primary loop piping need to be placed elsewhere and necessitate the development of new approaches for measuring safety and nonsafety parameters. The overall objective of the work presented in this context is to identify and overcome I&C challenges posed by large scale integral platforms, and to demonstrate the applicability of monitoring and diagnostic strategies that should be incorporated in all future nuclear plant designs.

The I2S-LWR is a 1,000 megawatt-electric (MWe) iPWR, and incorporates some features of an earlier iPWR [2]. The complete plant is being designed and developed as part of the U.S. Department of Energy Integrated Research Project (IRP). The Georgia Institute of Technology (Atlanta, GA, USA) is the project lead with partners from universities, national laboratories, industry, and international organizations as collaborating institutions.

The I2S-LWR consists of a reactor core with a maximum uranium-235 (U235) enrichment of 5%. The steam generator system is divided into a primary heat exchanger and a flashing drum. The reactor vessel has eight microchannel heat exchangers that provide efficient primary coolant to secondary water liquid phase heat transfer [3]. The high-pressure secondary water is converted to steam in a flashing drum outside the primary vessel. In case of a structural breach, this design provides additional safety by minimizing steam water interaction inside the reactor pressure vessel (RPV). The compact design of the heat exchangers provides sufficient space for the installation of eight passive decay heat removal loops inside the vessel. The approximate overall vessel height is 21 meters and an overall vessel diameter of 5.25 meters.

The following control systems have been developed as part of the overall simulation model: (1) T-average controller on the primary side that changes reactor power using control rod reactivity; (2) flashing drum water level controller using feed flow manipulation; and (3) flashing drum pressure controller by turbine control valve actuation.

Simulation models describing the physics of various components are central to the development of I&C strategies and for testing the feasibility of these technical approaches.

One issue in the operation of integral reactors is the ability to measure key process parameters, especially when they are safety-related. The direct measurement of process variables such as the primary coolant flow rate is restricted because of the limited space and the penetrations of the RPV, thus making it difficult to install flow meters for direct measurement. Experimental studies and theoretical analysis [4] indicate a direct relationship between the flow rate and electrical power of the motor driving the pumps. The pump hydraulic power is a function of the pump head and flow rate; hence, pump discharge is a function of motor power.

An alternative approach for measuring the primary flow rate has been proposed for when there is access to the secondary (i.e., steam) side dynamics [5]. Some integral light water reactor designs have part of the steam generator system outside the primary vessel [6]. This provides access to the steam generator (SG) feed flow rate, and allows measurement of the SG inlet and outlet conditions. This information is used to make an enthalpy balance on the primary and the secondary sides, and is used to infer the primary coolant flow rate. This inferential technique can be implemented online.

A second issue is the placement of in-vessel instrumentation. Because of space limitation in integral reactors, it is necessary to manage the placement of process and neutron sensors, cable routing, and data transmission. The necessary in-vessel instrumentation includes core upper and lower plena temperatures, in- and ex-core neutron detectors, and primary coolant flow rate. Ex-vessel ultrasonic transit time flow meters are being developed, and are especially useful when the primary pumps are shut down during a severe accident condition. Studies are underway to determine the optimum locations and the types of transmitters needed for these measurements. In-core detector strings are being used in some current designs [7].

The following sections provide the development and results of I&C approaches through dynamic simulation of an integral, inherently safe light water reactor (I2S-LWR) system being developed under a U.S. Department of Energy research project, which is led by the Georgia Institute of Technology (Atlanta, GA, USA). General instrumentation strategy and sensor locations are outlined in Section 2. A new approach for primary flow measurement, which measures the ultrasonic reflection transit time, is described in Section 3. The dynamic modeling of key system components such as reactor core dynamics, microchannel heat exchanger, and flashing drum (i.e., SG system) is presented in Section 4. Concluding remarks and continuing future work are explained in Section 5.

2. **In-vessel instrumentation for I2S-LWR**

2.1. **System configuration and instrumentation**

In the integral design of the I2S-LWR, the primary coolant is restricted to the RPV, and thereby eliminates the possibility of a large pipe break loss of coolant accident occurring via coolant piping. To accomplish this, the secondary coolant must enter the RPV for heat transfer to occur. In small reactor designs, this is typically accomplished with a once-through SG that produces superheated or saturated steam. This type of SG is entirely contained within the RPV. To achieve this within the I2S-LWR, the pressure vessel would have to be unreasonably tall because of the high power rating of the reactor at 2,850 megawatts-thermal (MWth). One approach to resolve this issue is to use a liquid-to-liquid microchannel heat exchanger contained within the RPV, and a steam flashing drum outside the RPV to produce saturated steam from the high-pressure, high-temperature liquid secondary flow, which exits the heat exchanger and enters the flashing drum.

Fig. 1 illustrates the secondary fluid flow and its interface with the primary coolant, and its relative configuration with respect to the reactor vessel.

The numbers at various points in the fluid flow pathway in Fig. 1 are the locations of instrumentation placement. The measurements at these locations in the secondary heat transport system are listed in Table 1.
By using the primary side temperatures, the heat exchanger side temperatures, and the feed flow through the heat exchanger, and by accounting for losses due to heat transfer efficiency, the flow rate of the primary coolant can be estimated using the energy balance formula:

$$\eta (m_p c_p \Delta T_p) = (m_s c_s \Delta T_s)$$

in which $m$ is the coolant mass flow rate, $c_p$ is the heat capacity (at constant pressure) of the working fluid, and $\Delta T$ is the change in temperature of the working fluid because of heat transfer in the heat exchanger. The overall efficiency of the heat exchanger is specified by $\eta$. The upper-case subscripts “$S$” and “$P$” denote the secondary fluid and primary working fluid, respectively. This simplified relationship is inaccurate because the working fluid experiences a pressure drop across the exchanger. However, this discrepancy can be accounted for with experimentation and data-based model generation, and by treating $\eta$ as a correction factor rather than as strict efficiency of heat transfer. This correction factor needs to be established experimentally for normal and abnormal conditions. Eq. (1) can then be used to infer the primary coolant flow rate. For reactor control purposes, important parameters such as the primary coolant flow rate, must be measured by diverse techniques to increase the reliability of flow measurement. Ultrasonic flow meters will also be evaluated for direct measurement of the primary coolant flow rate within the RPV. This is discussed in Section 5.

An earlier work [5] demonstrated a direct relationship between pump flow rate and the motor power. The pump hydraulic power is directly correlated with the flow rate, but is not necessarily a linear function of the flow rate. The power drawn by an induction motor varies with the load, and can be measured online using three-phase motor currents and voltages. The motor signatures can be used on the primary coolant pumps to inferentially monitor the primary coolant flow rate.

### 2.2. Strategy for in-vessel instrumentation

Space limitations rather than technology are the greatest concern in measuring primary coolant temperatures. Resistivity temperature detectors (RTDs) and thermocouples are the established technology and can be used in the I2S-LWR. Concerns are where to place them and how many of them to use. A lack of coolant mixing in the riser and at the SG exit makes temperature measurements vulnerable to radial power variations; therefore, signal averaging may be required, which worsens response time. One solution is to place RTDs higher in the riser to allow for water exiting the core to mix

### Table 1 – Measurements in the secondary loop.

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature, pressure, flow rate, radiation</td>
</tr>
<tr>
<td>2</td>
<td>Temperature, pressure, flow rate</td>
</tr>
<tr>
<td>3</td>
<td>Temperature, pressure, flow rate</td>
</tr>
<tr>
<td>4</td>
<td>Drum liquid inventory/level</td>
</tr>
<tr>
<td>5</td>
<td>Temperature, pressure, flow rate</td>
</tr>
<tr>
<td>6</td>
<td>Motor power, current, voltage</td>
</tr>
</tbody>
</table>
somewhat before arriving at the hot leg temperature sensors and to shorten cable runs to these sensors and improve signal-to-noise (S/N) ratios. Core-exit thermocouples could be employed directly at the top of the core to acquire hot leg temperature data, but their accuracy and measurement uncertainty may not be sufficient for safety purposes.

In an accident, it is important to know how much primary coolant is in the RPV to ensure that the core remains submerged. Pressure taps can be employed, but require penetrations and thus present their own safety concerns.

Thermal probe level sensors (TPLS) rely on the difference in the thermal conductivity of liquid versus vaporized water, and thus determine the elevation of the coolant. The sensitivity is determined by how frequently the sensors are placed.

Another option is the torsional ultrasonic wave-based in-vessel level measurement system developed at the Oak Ridge National Laboratory (ORNL; Oak Ridge, TN, USA) for use in integral primary system reactors [8]. This system uses ultrasound to estimate regional densities in the RPV; in this way, it can determine the water level.

Fig. 2 is a conceptual layout of instrumentation and cabling for in-vessel measurements in the integral pressurized water reactor. As noted in Fig. 2, a suggestion is to piggyback cabling penetrations into the RPV for as much instrumentation as possible onto existing operating function penetrations such as the secondary working fluid inlet and the outlet penetrations. This is in accordance with the goal of an inherently safe design.

3. Ultrasonic transit time flow meter for primary coolant flow estimation

3.1. Development of the flow meter

Ultrasonic flow meters have been reviewed and a conceptual reflection transit time ultrasonic flow meter is being developed as part of a detailed review of the instrumentation needs for the I2S-LWR. The primary concept for achieving this is to locate an array of transit time ultrasonic flow meters to measure the flow in the down-comer region of the primary coolant flow path, after the coolant has passed the microchannel heat exchangers in the upper section of the RPV.

Ultrasonic flow meters operate by emitting ultrasonic pulses between two sets of transceivers. An ultrasonic transceiver is a transmitter and a receiver of ultrasonic pulses. One transceiver sends pulses against the flow while the other transceiver sends pulses in the direction of the flow. The flow velocity is then determined by measuring the difference between the times of flight of the two pulses. Ultrasonic flow meters provide advantages over other direct measurement techniques. These include the following: no pipe penetration; no obstruction in the coolant flow; multiple sensors can be applied to develop a liquid flow profile in the vessel; the devices can maintain their accuracy, despite fouling of the coolant conduit and; the devices are capable of measuring the flow rate of non-fully developed flows.

Applying ultrasonic flow meters to measure the primary coolant flow rate can offer many advantages over other measurement techniques. There may not be enough length to create a fully developed flow because there is a limited distance past the microheat exchangers. Transit time ultrasonic flow meters can be very useful for this application because they do not require a fully developed flow. Another advantage is that the velocity profile of the primary flow channel can be determined by using multiple sets of transceivers around the exterior of the pressure vessel. In addition, no penetrations to the reactor vessel will be needed to accommodate these meters if these transceivers are installed in a “clamp-on” fashion by which the meter is external to the fluid conduit and sends ultrasonic pulses through the conduit and the working fluid. They also present no obstructions to the primary coolant flow path within the conduit [9].

In the proposed application, the objective is to configure ultrasonic flow meters vertically along the reactor vessel wall, and directed toward the central axis of the core. In this arrangement, the transceivers generate pulses that penetrate the vessel wall, cross the flow, reflect off the core barrel, and return to another corresponding transceiver. This is a common configuration for ultrasonic flow meters that is referred to as the “reflection mode.” This allows the primary flow to be measured in the region below the heat exchangers in between the lower sections of the passive decay heat removal system. Placing these meters in this location also monitors core coverage by the primary coolant in case of a loss of coolant accident.

The transit time of an acoustic wave is dependent upon the density of the medium it travels through. If the core coolant level drops below the level of the highest ultrasonic pulse generator, the ultrasonic wave will consequently pass through some region of the lower plenum occupied by lower density gas, and thus significantly lengthen the transit time. This
would alert personnel responding to an accident of the core uncover condition. Furthermore, it should be possible to correlate the ultrasonic instrument response to the height of the liquid level in the region of monitoring, and provide accurate liquid primary coolant inventory within that section of the down-comer. Fig. 3 shows a conceptual design of the placement of ultrasonic instrumentation in the down-comer region of the I2S-LWR. Ultrasonic pulses are directed toward the core barrel in the direction of the flow and counter to the flow. The correlation of the received signals allows for calculation of the difference in transit time of the two pulses, which corresponds to the coolant transit time between the two transceivers. The known distance between the transceivers then yields the coolant velocity. Fig. 3 shows the orientation of the transceivers to the core, as mounted on the outside of the reactor vessel. The figure is not to scale.

3.2. Principle of measurement and pulse energy attenuation

As stated previously, ultrasonic flow meters measure the flow rate by evaluating the difference in transit times between an upstream and downstream pulse pathway. The total transit time for each pulse can be calculated by the following equations [3]:

\[ t_{\text{down}} = \frac{L}{c + V_{flow} \sin(\phi)} + t_p \]

\[ t_{\text{up}} = \frac{L}{c - V_{flow} \sin(\phi)} + t_p \]

\[ \Delta t = t_{\text{up}} - t_{\text{down}} \]

\[ V_{flow} = \frac{L \cdot \Delta t}{2 \sin(\phi) * t_{\text{down}} \cdot t_{\text{up}}} \]

in which \( \Delta t \) is the change in transit time between the upstream and downstream pulses; \( \phi \), the refracted pulse angle (of axis perpendicular to the flow direction); \( L \), the ultrasonic pulse path length in the coolant; \( t_{\text{down}} \), the transit time of the downstream pulse (i.e., in the direction of the flow); \( t_p \), the transit time of the pulse through the reactor vessel wall; \( t_{\text{up}} \), the transit time of the upstream pulse (i.e., opposite the direction of the flow); and \( V_{flow} \), the velocity of the coolant flow.

Estimation of the flow velocity is dependent only on the path length and transit times. The flow velocity measurement is independent of fluid properties such as pressure, temperature, and Reynolds number. These devices require minimum calibration after the initial installation because of the small number of parameters affecting flow measurement.

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**Fig. 4** – Primary side nodal model of the I2S-LWR reactor, which includes Mann’s model of core heat transfer and the MCHX nodal model. HX, heat exchange; I2S-LWR, inherently safe light water reactor; MCHX, microchannel heat exchanger.
An important issue in using this type of ultrasonic device is the attenuation of the pulse strength as it traverses various media. As the signal changes from one medium to another, part of the pulse is reflected while the remaining part is transmitted forward. This decreases the strength of the signal at each medium of transition. The ultrasonic transmitters can be placed around the RPV, thus allowing an estimation of an average reactor coolant flow rate.

3.3. Interface between the transmitter and the vessel wall

Measuring ultrasonic flow at high temperatures is challenging because of the restricted temperature tolerances of normal acoustic couplants. Acoustic couplant is a material that allows an ultrasonic pulse to travel from the transceiver to the conduit wall with little to no loss by matching the impedance of the steel with the impedance of the coupling material. Without the coupling, the ultrasonic pulse would be greatly dampened by the impedance mismatch between the steel conduit wall and air. There are applications of high-temperature couplants that have high temperature tolerance, can match the acoustic impedance of steel, and provide thermal shielding between the ultrasonic transducer and high-temperature conduits. An example outside the nuclear industry, which is of relevance to the potential application of this technology in the I2S-LWR concept, is the wave injector from FLEXIM (Flexim, Berlin, Germany) [10]. These ultrasonic meters are augmented with thermal shielding and acoustic coupling between the instrument housing and the surface of the working fluid conduit that allow them to measure very high temperature flows up to 600°C, while maintaining normal operating temperatures in the instrument. Proper calibration accommodates for the transit time effect of the thermal insulating material on the ultrasonic wave. This indicates that these devices are able to handle the peak temperatures of the primary coolant at approximately 330°C.

3.4. Nuclear plant applications

For the past few years, several nuclear utilities have begun using ultrasonic flow meters to measure feed water flow rates. In some cases, Venturi meters have been replaced by ultrasonic flow meters to help recover lost megawatts caused by errors in venturi flow measurements. A report by Caldon [a trademark of Cameron International (Houston, TX, USA)] details the history of their ultrasonic flow measurement technology, from its development by Westinghouse in the 1960s through its widespread application in the commercial nuclear power industry, which began with its use in measuring reactor coolant system (RCS) flow in Prairie Island Unit 2 (Red Wing, MN, USA) in 1974. Ultrasonic measurement techniques were also applied for RCS temperature and flow measurements at the R. E. Ginna Nuclear Power Plant (Ontario, NY, USA) and Watts Bar Nuclear Power Plant (Spring City, TN, USA), and achieved a 1% power uprate at Comanche Peak Nuclear Power Plant (Glen Rose, TX, USA) [11,12].

4. Development of the reactor core, microchannel heat exchanges, and flashing drum dynamic models

4.1. Interfacing reactor core dynamics and microchannel heat exchanger heat transfer models

The nodal models of the reactor core dynamics and the microchannel heat exchanger (MCHX) are presented in Fig. 4. The following are assumed in the dynamic equations for Mann’s model of fuel-to-coolant heat transfer: (1) nodal approximation of heat transfer in the reactor core and MCHX; (2) well-mixed fluid node with the node temperature the same as the node exit temperature; (3) a uniform heat transfer rate in each node of the core and the MCHX.

The core dynamics and MCHX use standard neutronics and heat transfer formulations. Figs. 5–7 show the transient behavior to a 5% decrease in the feed water flow rate with an active T-average controller. The latter changes the control reactivity to maintain a constant primary coolant average temperature of 314°C.

The responses are consistent with the behavior of neutron kinetics in a pressurized water reactor [2], which validates the stability of the model. These models are updated as additional needs for plant simulation are identified. For example, the capability to simulate sensor and process anomalies has been incorporated into the MATLAB-Simulink model.

4.2. Flashing drum model

The high-pressure water at 13.8 MPa flows from the MCHX into the flashing drum where it is flashed to a drum pressure of 8.4 MPa. The mixture quality is approximately 10%, and the water separated from the mixture is recirculated into the drum water volume.

The steam flashing drum is modeled in MATLAB/Simulink as an isenthalpic expansion process. The fraction of the inlet flow from the heat exchanger output that vaporizes into

![Fractional Reactor Core Power](image)

**Fig. 5** – Fractional reactor power for a 5% decrease in feed flow rate to the MCHX. MCHX, microchannel heat exchanger.
steam is a function of the enthalpies of the upstream flow, the downstream liquid, and the downstream vapor. This is expressed by the following ratio:

$$X_v = \frac{H_{MCHX} - H_{DL}}{H_{DV} - H_{DL}}$$

(3)

in which $H_{DL}$ is the enthalpy of the flashing drum liquid; $H_{DV}$, the enthalpy of the flashing drum vapor; $H_{MCHX}$, the enthalpy of the MCHX outlet flow; and $X_v$, the mass fraction vaporized.

The steam outlet pressure is modeled as the deviation from the steady-state pressure of 8.41 MPa by the Van der Waals model of nonideal subcritical gases. This relationship is expressed by the following formula:

$$P = \frac{kT}{v - b} - \frac{a'}{v^2}$$

(4)

in which $a'$ is the measure of net Van der Waals forces between gas particles; $b'$, the excluded volume per gas particle; $k$, Boltzmann's constant; $P$, pressure; $T$, the absolute temperature; and $v$, the volume per gas particle.

The steam outlet temperature is the saturation temperature at the operating pressure of the steam drum, which is dynamically calculated via functionalized steam tables that are based on the most recent iterative calculation of the steam pressure. Enthalpies of the steam drum liquid and vapor are also calculated by functionalized steam tables. This is valid because the flashing process renders liquid and vapor at saturation conditions. The equations used in the modeling are presented in this paper, along with preliminary simulation results in a 5°C step increase in the flashing drum inlet flow temperature. A nodal representation of the flashing drum model is shown in Fig. 8.

The time derivative of Van der Waals equation provides the dynamics of the pressure in the flashing drum, and is expressed by the following equation:

$$\frac{dP}{dt} = \left( \frac{R_g}{N_{Av}} \right) T_K \frac{dv}{v^2} + 2d \frac{dv}{v^3}$$

(5)

in which $N_{Av}$ is Avogadro’s number; $R_g$, the gas constant; and $T_K$, the saturation temperature of steam at the drum pressure, $P$ (in Kelvin).
4.3. Results of simulation of steam flashing drum dynamics

The results of the flashing drum response to a 10°C step increase in the flashing drum inlet flow temperature are shown in Figs. 9–11. In this simulation, the volume available to steam was held constant to demonstrate the drum dynamics under theoretically perfect drum level control. The next step is to tune the drum level controller.

Fig. 9 shows an immediate jump in the vaporization fraction as the enthalpy of the inlet flow experiences a step increase, after which the drum vapor and liquid inventories experience a similar increase in enthalpy, and restore the vaporization fraction to the pre-perturbation value. Fig. 10 shows increased steam pressure of approximately 1.4 Bars (1.4 × 10^5 Pa). Fig. 11 shows that the steam temperature increases by approximately 1.15°C. This perturbation causes an overall increase in the enthalpy of the steam supplied to the turbine. If the control requires that the steam pressure be maintained at a constant level, actuating the turbine control valve will achieve this.

5. Concluding remarks

A physics-based Simulink model of an integral light water reactor has been developed and tested using preliminary design data. The performance of the microchannel heat exchanger and the steam flashing drum models shows the validity of these models and their use for designing various controllers such as the drum water level control. Inferential and direct measurement approaches are both presented for primary coolant flow rate monitoring. Reflection transit time ultrasonic flow meter is a promising approach and provides a robust technique for continuous flow monitoring.

Ongoing research and development includes the design of steam flashing drum level control, optimal in-core sensor placements, and design of a prototype ultrasonic flow meter that accounts for physical and measurement limitations. The primary system model will be interfaced with a balance-of-plant model for evaluating the complete load-following operation of an I2S-LWR plant. Data generated from the model will be used to develop monitoring and diagnostic strategies for large scale integral reactors. An experiment to validate the ultrasonic flow measurement and inferential measurement is being developed as part of a senior design project at the University of Tennessee (Knoxville, TN, USA).

Conflicts of interest

There is no conflict of interest in referencing the senior design project.

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