NCSU PRESSURIZED WATER REACTOR PHYSICAL SIMULATOR

J.R. Caves, G.D. Miller, and B.W. Wehring
Department of Nuclear Engineering
North Carolina State University
Raleigh, North Carolina 27695-7909

R. W. Cornetti
Wandel and Goltermann
Research Triangle Park, North Carolina 27709-3585

Abstract

An operating model of a nuclear power plant has been designed and constructed by the Department of Nuclear Engineering at North Carolina State University. The thermal-hydraulic response of the simulator is driven by a physical system which has been scaled to model the operation of a commercial pressurized water reactor plant. Computers control power, flows, pressures and levels, monitor 32 channels of analog input and 48 channels of digital status, and simulate the action of plant protection systems.

Introduction

The Department of Nuclear Engineering at North Carolina State University has designed and constructed a 1/9 linear scale operating model of a commercial reactor system, which is referred to as the Freon Pressurized Water Reactor (PWR) Loop.[1] The PWR Loop is a physical simulation of the Prairie Island Nuclear Steam Supply System, a two-loop Westinghouse commercial nuclear power plant. The PWR Loop was designed to be used for training of commercial power plant operators and engineers. It will also be used in undergraduate and graduate education programs in nuclear engineering and in research projects on operator aids for advanced control room design.

The Loop utilizes electric heaters to simulate the nuclear core and uses refrigerant R-11 as the working fluid on both the primary and secondary sides of the system. Primary system components included in the PWR Loop are the reactor, pressurizer with electric heaters and sprays, two steam generators, and reactor coolant pumps. Secondary components include condensate, feed and auxiliary feed pumps, feed heater, feed regulating valves, and condenser. The reactor, pressurizer, steam generators and primary system piping contain viewing windows so students have the opportunity to observe physical phenomena associated with power plant operation, including nucleate boiling in the reactor core and flow stratification during two phase natural circulation, where visualization is important to increasing understanding of the effect.

The design incorporated the scaling laws of Ishii and Kataoka[2] which provide relationships between fluid properties, geometry, heat input, and operating parameters. This maintains similarity in thermal-hydraulic performance so the performance of the model (Loop) can be directly related to that of the prototype (plant). Conventional simulators utilize a computer to simulate the entire nuclear, thermal-hydraulic, and instrumentation responses of a system; the computer for the PWR Loop simulates the nuclear response of the system by controlling the power output of the electric heaters, while the thermal-hydraulic response of the simulator is driven by the physical system.

The functional capabilities of the system encompass normal and accident operations including start up, heat up, and power operations, with load following caused by reactivity induced power changes. Accident simulations that can be demonstrated include small break loss of coolant accidents on the primary system hot leg and cold leg, main steam line breaks, steam generator tube rupture, and other events where the interaction between facility design, control systems, and operator actions determine the effect of a perturbation on the system. The primary design criteria were that the PWR Loop must provide the proper tracking of parameters of interest in accident scenarios, the proper sequence of automatic protective actions except where intentionally overridden, and observation of the events must lead to the proper conclusion concerning how the consequences of the transient are affected by operator action.

The nominal operating condition for the primary system is an average temperature of 204 degrees F with a temperature rise across the core of eight degrees; the primary flow rate is 110 gallons per minute in each of the two loops. Reactor heater power is 80 kilowatts (nominal 100% power), with the capability to increase as high as 100 kilowatts when simulating an anticipated transient without scram (ATWS) event. Primary pressure is maintained at 130 PSIA by the electrically heated pressurizer at 230

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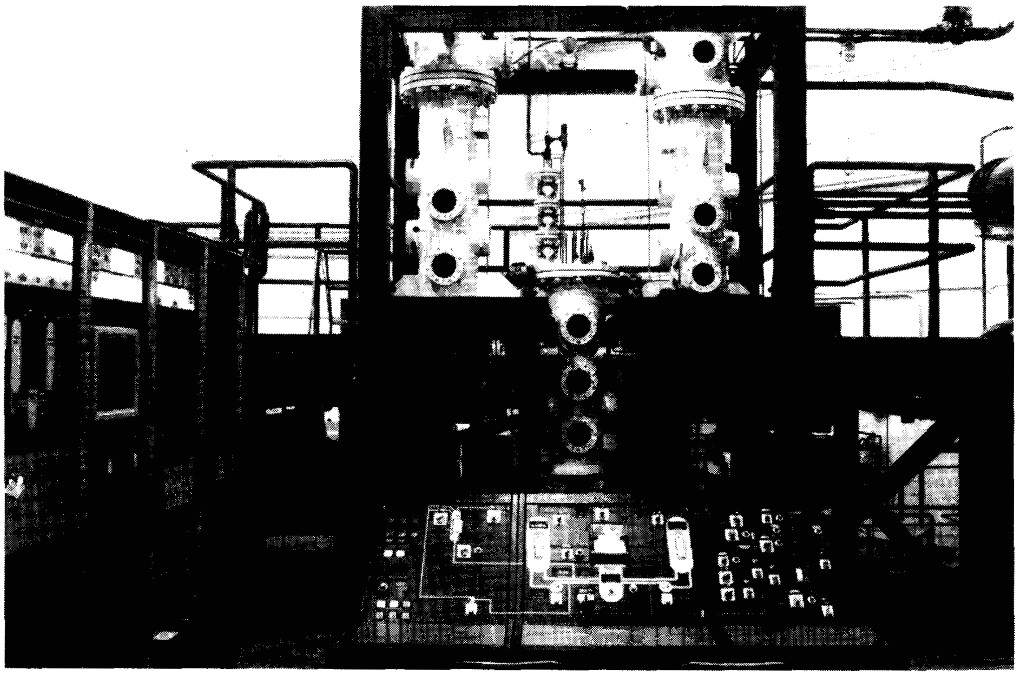

Figure 1. The Freon PWR Loop. Shown are the operators console (front, center), the annunciator alarm panels (left), and the PWR Loop vessels(background).

degrees. Steam generator pressure is 85 PSIA at 185 degrees, with the vapor reduced in pressure to 20 PSIA before being supplied to the condenser. Utilization of refrigerant R-11 at these conditions allows high fidelity modeling of the prototype plant and its thermal hydraulic behavior, without requiring the high temperatures and pressures of the operating plant.

Loop Instrumentation System

The instrumentation system requirements for the PWR Loop include measurement and display of temperatures, pressures, flows, powers, and levels at various locations in the Loop, sufficient to provide an accurate indication to the operator of the status of the plant at any time. In addition there are several control functions that are needed including core heater power, feed regulating valve position, and pressurizer heater power, as well as numerous digital outputs as control signals for pumps, valves, and safety shutdowns of the system.

This is accomplished by a hybrid system of analog and computer based instrumentation. Process parameters are measured using industry standard detectors and transmitter driving four-to-twenty milliamp current loops. Many of these analog channels provide signals to indicators on the control console, while all are digitized and fed to the control computer. This is accomplished by analog and digital distributed control modules (DCMs) which communicate with a personal computer (PC). Control calculations are performed on the PC and fed to the Loop via the DCMs.

Human Interface

The human interface includes the control console, annunciator alarm panel and the control computer. The control console displays a schematic piping diagram of the major systems, with operating parameters displayed at the location on the schematic where measured. Status of pumps and valves are indicated with lights on the console so students and operators can easily understand the current state of the plant. An annunciator panel provides alarms and indication of automatic control actions consistent with the prototype plant. The alarms are color coded to match the color of the pipes on the corresponding system, which is consistent with the color of the system on the piping mimic on the operators console.

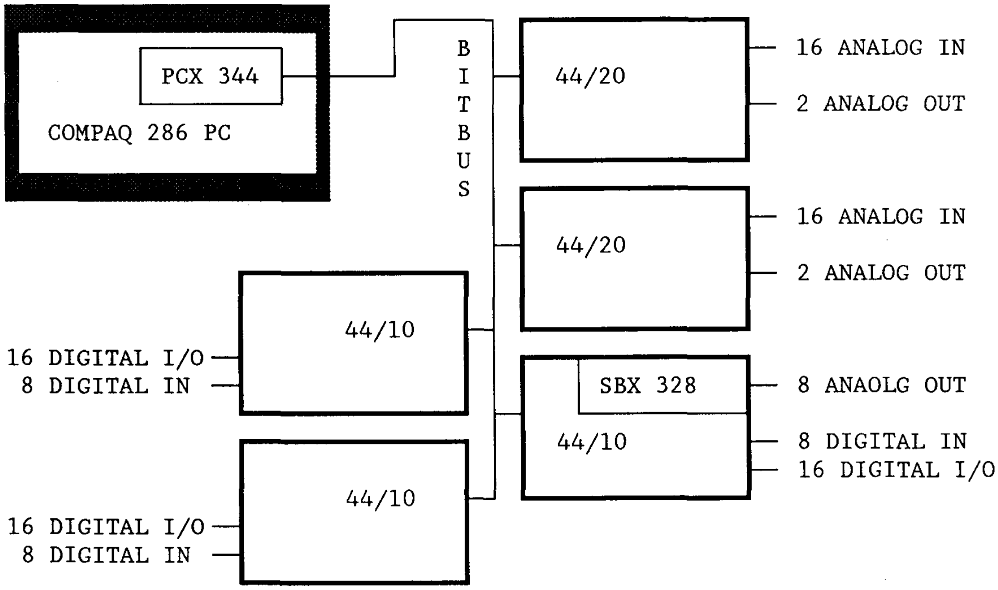

Figure 2. The Freon PWR Loop data acquisition and control system.

The PC has a Video Graphics Array (VGA) adapter and two monitors, one at the instructors station (with keyboard) and the other mounted in the instrumentation rack adjacent to the operator's console. Several status screens can be displayed giving an observer complete information concerning any individual system or control system action. The keyboard also provides access to control system parameters that can be changed during operation. This allows modification of reactivity feedback coefficients and control system gains for tuning of control algorithms.

Control System Requirements

The control system is required to simulate nuclear response of the reactor core by controlling core heater power, duplicate the action of the plant Reactor Protection System (RPS) including generation of annunciator signals, and to provide safety actions above and beyond the plant simulation to ensure the design requirements of the Loop itself are not challenged.

The simulation of the reactor core is accomplished by running a point kinetics algorithm on the PC, which accepts reactivity input from the control console for control rod position, from the power measurement system for doppler feedback, and from measured Loop temperatures for moderator temperature effects. Following a reactor trip (scram), the heater power is reduced to that of scaled decay heat using the American Nuclear Society Standard model for post-shutdown heat production.

Control requirements for the pressurizer, feed, auxiliary feed, charging, and safety injection systems are consistent with those of the prototype. The PC generates control signals to vary the power of the pressurizer heater in response to changes in primary system pressure. Signals are also generated to operate normal and auxiliary sprays in the pressurizer in response to high primary pressure conditions. Alarms are generated to warn the operator of high or low pressure conditions prior to and at the time of actuation of automatic protective actions. Feed regulating valve (FRV) position is modulated by a three-element control algorithm to control feed flow. The control algorithm evaluates the time-dependent behavior of steam generator level, steam flow, and feed flow to determine the appropriate FRV position. The FRV controllers for each of the two loops are independent of each other.

A single pump is used to provide the functional operation of the plant charging and safety injection systems. A charging flow control valve is modulated to provide the appropriate charging flow when operating in the normal mode. During safety injection, the valve is controlled to match the head and flow characteristic curves for the safety injection pumps.

Operation of the plant RPS is accomplished in software on the PC, with the PC generating the appropriate annunciations signals to inform the operator of plant status. Plant protection actions including reactor trips, turbine trips, and safety injection are modeled. All of the automatic actions can be defeated by the instructor if it is desired to show the effects of a perturbation without the primary form of protection for that event.

The control system also provides alarms and protective actions above and beyond those necessary to simulate the prototype reactor plant, to avoid challenging the design limits of the Loop itself. The PWR Loop is designed and constructed in accordance with all requirements of section eight of the ASME Boiler and Pressure Vessel Code. In addition, all requirements of ANSI 31.5, the code specifying conditions and limitations for refrigeration systems were met as a consequence of the utilization of refrigerant as the working fluid. To ensure that design temperatures and pressures are never exceeded, automatic heater shutdowns and valve operations are implemented in hardware. The PC need not be energized for these control functions to be active. Actuation of these plant protection functions are also accompanied by annunciations.

Data Acquisition and Control System

To support the operation of the PWR Loop a microcomputer based, distributed-intelligence, data acquisition and control system was designed and implemented. The data acquisition and control system consists of a Compaq DeskPro 286 personnel computer (PC), five Intel Distributed Control Modules (DCMs), and an Intel analog output module. The PC is interfaced to the DCMs via Intel's Bitbus interconnect. See figure 2 for a schematic of the hardware system. The control program is divided between the PC and three of the DCMs. The section which executes on the PC controls all aspects of the user interface, data logging, control calculations, and error handling. The executable code on the DCMs controls the acquisition of analog data and the operation of the analog output module.

Hardware

The PC operating under MS-DOS 3.1 is the master node on the Bitbus interconnect; the DCMs are configured as slave nodes. The eight-MHz PC utilizes an Intel 80286 processor, 80827 numerics coprocessor, and 1 megabyte of ram. An Intel iPCX 344 board is installed in the PC to perform all tasks associated with communication via the Bitbus.

Two types of DCMs are utilized in this system, the iRCB 44/20 Analog I/O Remote Controller and the iRCB 44/10 Digital I/O Remote Controller. In addition, one of the 44/10's I/O capabilities is expanded by the installation of an iSBX 328 Analog Output Multimodule. The DCMs are microprocessor based I/O controller boards with provision for user installed executable code and data memory. Each board is provided with transparent communications control, a real time executive which provides for priority based scheduling of user written tasks, and a resident Remote Access and Control (RAC) task for I/O port data memory control.

The Bitbus interconnect is a SDLC implementation with proprietary protocols layered on the SDLC information frame. The PWR Loop implementation operates at 2 MHz in a synchronous mode with a single bus master and multiple slaves. Use of the Bitbus interconnect protocol frees the programmer from the onerous task of controlling inter-nodal communications.

The iRCB 44/20 boards are equipped with 16 single-ended, 12-bit analog input channels. These inputs are configured for 0-10 volt input. The 44/20's also have two channels of 12-bit output configured for 4-20 mA current loop operation. The inputs are utilized for monitoring the PWR Loop process variables while the outputs are used for valve position and heater power control.

The iRCB 44/10 boards are equipped with three 8-bit, TTL-level, digital I/O ports. Two of the ports are bit programmable for input or output. The third port is a dedicated input port. The inputs are used to monitor various switch and relay positions for control purposes. The outputs are used for pump and valve control and annunciator actuation.

Additional analog output is provided by an iSBX 328 Analog Output Multimodule. This module provides eight channels of 12-bit resolution analog output configured for 4-20 mA current loop operation. The 328 is installed on the expansion connector of one of the 44/10s. Control of the 328 is achieved by an execution module on the host 44/10. The 328's outputs are used for valve position control, reactor power control, and rod position indication.

Software

The software that operates the Loop control and instrumentation system is written in two principle sections. The first section executes on the PC and is written in Borland Turbo Pascal (version 5.0); the second section executes on three of the DCM modules and is written in PLM-51, an Intel proprietary language. The PASCAL code presents the user interface, requests data from the DCMs, displays and archives the data, and performs control calculations. The PLM-51 modules execute as tasks on the DCM boards and control the analog data acquisition from the Loop and analog data output to the loop.

The PC portion of the control program is divided into three functional sections. The first section, the monitor, provides individual commands for accessing the DCMs. The second section, the real-time control loop, provides control of the PWR Loop during normal operation. The final section, the filer, gives the user access to the loop control configuration and data files.

The monitor is implemented as a command line interpreter and is modeled after the Intel Bitbus Monitor program. It is used when the control of the PWR Loop is in the manual mode and for calibration, tuning, and troubleshooting of the control systems. The user prompt is presented when the control program is executed, which provides the user with a series of commands for accessing the DCM Bitbus nodes. Lower level routines supporting these commands are also used by the real-time control loop for DCM I/O during operation.

Using the monitor, the user can access DCM memory, control I/O points, and make adjustments to the iSBX 328 module gains and calibrations. User input is extensively error checked before being placed into the proper message format for transmission across the Bitbus interconnect. In the event of erroneous input, an error message and a list of valid commands are displayed along with a message concerning the use of the system help functions. Once a command has been entered and syntax checked, it is sent to the destination node and the control program waits for a response. If the response is not received within a reasonable period of time or if a protocol error occurs, an error message is displayed.

The real-time control loop provides all message transactions for obtaining the I/O data from the DCMs, sends output values to the DCMs, logs data to the PC hard disk, performs control calculations and safety functions, and handles display of analog and digital I/O data during normal operation. This complete cycle occurs approximately 17 times per second. Analog data is collected from the 44/20s by reading the board's data memory. Executable code on the 44/20s controls the analog-to-digital converters and places the resulting values in the boards memory. Analog output values are directed to the appropriate I/O locations by the write I/O command. Digital values are input from and output to the 44/10 by the read and write I/O commands. The analog output values for the iSBX 328 module are written to the host 44/10's memory where resident code can read the values and output them to the 328.

In the event of an error condition, recovery is attempted by the software. If recovery is not possible, the control loop is terminated and the user is notified that manual control of the PWR Loop is necessary. Hardware protection is provided to prevent damage to the PWR Loop in the event the operator can not recover proper operation of the Loop.

The acquired analog data are in ADC steps and are converted by the software to engineering units for the control calculations and comparison to safety set points. The resulting control values are converted from engineering units to steps for output by the DACs. The digital ports are converted to boolean values on a bit-by-bit basis. The data are logged to disk in engineering units and boolean format in real time.

The user displays are textually oriented and grouped into three screens. The default screen is for the primary system. Additional displays show the secondary system parameters and the digital values for both input and output. The primary and secondary system displays are designed to mimic the physical layout of the PWR Loop.

The filer is a command line interpreter much like the monitor. It is activated from the monitor with the "Filer" command to create, edit, and view the set point and control calculation constant files. It also provides for viewing of data log files and gives the user access to various MS-DOS file and directory commands.

DCM processing power is used to execute code on the 44/20s and on one of the 44/10s. Identical tasks execute on the two 44/20s which control the acquisition of analog data. The code is written as an infinite loop which executes approximately seventeen times per second. This loop scans each analog-to-digital conversion channel and writes the converted value to a predetermined memory location. These memory locations are read by the PC during loop operations when current process values are needed. The conversion control loop executes at a low priority. An incoming Bitbus message will activate the communications control task, a high priority task, thus suspending the conversion control loop. When the communications control task is done, it relinquishes control of the DCM to the conversion control task.

The 44/10 which is host to the iSBX 328 executes a low priority task which is similar to the one on the 44/20s. However, this task controls the operation of the 328 module. Data, written to DCM memory by the PC real-time control loop, are read, formatted, and passed to the 328 for output.

<u>Planned Utilization</u>

The project has been funded by Carolina Power and Light, Duke Power, and Virginia Power Companies for use in training of their operations personnel as an extension of the Reactor Operator Training programs currently offered by the Nuclear Reactor Program. The Loop will be used as a training tool for demonstration and study of system transient response by utility operators and engineers, as well as in the nuclear engineering education program. Benefits for the student includes the ability to observe through viewing windows, the fluid in the reactor vessel, pressurizer, and steam generators. It will complement classroom and simulator training, and enhance understanding of complicated transient phenomena.

The PWR Loop will be extensively utilized as a teaching laboratory in undergraduate nuclear engineering courses dealing with reactor heat transfer, nuclear reactor design, nuclear plant systems, and nuclear safety. Exposure to the operational aspects of a power reactor system is expected to have a significant positive impact on the effectiveness of newly degreed engineers, as well as increasing their level of understanding of plant transient response.

A side benefit of the project is its usefulness to research underway in the Nuclear Engineering Department. The PWR loop will be used as a test bed for new ideas associated with operator aids for advanced control room design. A project that is currently in progress includes the master computer sharing information with a workstation (DEC Vaxstation 2000) that is running an expert systems program for fault diagnosis. The PC will be linked to the workstation via bus-to-bus communication links, each computer having access to dual port RAM. The expert system compares the data to output from a detailed thermal hydraulic analysis code running on a mini-supercomputer (Alliant FX-4) and makes recommendations to plant operators for corrective actions.

Conclusions

The Freon PWR Loop is an innovative project with many potential benefactors. It is expected to be very valuable to students as they gain understanding of integrated system response, which makes them more valuable to future employers. Utility operators and engineers will have the opportunity to strengthen their understanding of thermal hydraulic phenomena which has implications of improving safety at operating plants. Researchers will have a test bed for investigation of advanced control algorithms, reactor thermal hydraulic models, and expert system based operator aids.

[1] J. R. Caves, B. W. Wehring, J. M. Doster, and P. J. Turinsky, "PWR Thermal Hydraulics Training Facility for Engineers and Operators", Trans. Am. Nuc. Soc., 52, (June, 1986).

[2] M. Ishii and I. Kataoka, "Scaling Criteria for LWR's Under Single-Phase and Two-Phase Natural Circulation," Argonne National Laboratory Report ANL-83-32, NUREG/CR-3267, March (1983).

Exabyte Helical Scan Devices at Fermilab(*)

Penelope Constanta-Fanourakis, Ken Kaczar, Gene Oleynik, Don Petravick,
Margaret Votava, Vicky White
Online and Data Acquisition Software Groups
Fermi National Accelerator Laboratory

George Hockney
Theoretical Physics Group
Fermi National Accelerator Laboratory

Steve Bracker
University of Toronto, Toronto, Ontario

Jussara M. de Miranda
Centro Brasileiro de Pesquisas Fisicas

I. INTRODUCTION

Exabyte 8mm helical scan storage devices are in use at Fermilab in a number of applications. These devices have the functionality of magnetic tape, but use media which is much more economical and much more dense than conventional 9 track tape.

II. HELICAL SCAN TAPE SYSTEMS

Helical scan recorders write very narrow tracks at an acute angle to the edge of tape in a diagonal pattern on the tape. This technology results in very high tracks per inch which, when combined with a high linear flux density result in extremely high areal density and data storage capacity. A single 8mm tape cassette, comparable in size to an audio cassette, may hold over two gigabytes of data, and costs under seven dollars.

The device in use at Fermilab is the Exabyte EXB-8200 CTS (Cartridge Tape System). The Exabyte drive uses the Small Computer System Interface (SCSI) bus for command and data transmission. Two SCSI Interface alternatives are available, standard single ended, and differential SCSI Interface. The single ended interface is most used at Fermilab. If a SCSI port is not available on a system then an adaptor board from that system's particular bus to SCSI is required. An Exabyte system (drive plus adaptor) targeted for either VME, Q-bus or Unibus application costs below $6,000 with space requirements (including the power supply) no greater than a large shoe box.

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III. USES FOR HELICAL SCAN TAPE SYSTEMS

8mm tape technology offers smaller size (easily stored and shipped), economy, larger capacity (fewer tape mounts) than 9 track tape. Additionally, this technology retains the most desirable characteristic of 9 track tape, the ability to be read on a number of computers. Unlike the international standard 9track tape, it has the disadvantage however of a sole supplier.

During the next accelerator run experiments will collect a large amount of data. Although the amount of data written by an individual Experiment at Fermilab varies, during the next fixed target run, a typical experiment is expected to write enough data to fill 6000 9 track, 6250 b.p.i. tapes, and one experiment intends to take enough data to fill 200,000 such tapes.

Analysis of all these raw data will generate a large number of Data Summary Tapes (DSTs), which may be needed in replicates, since these are sometimes analyzed at an experimenter's home institution.

The Theoretical Physics Group at Fermilab performs Lattice Gauge Theory calculations on four-dimensional lattices and generates enormous amounts of data to represent gauge configurations and quark propagators. Since these configuration and propagator objects are used many times by subsequent analysis programs (not always in the order they are created) a large data-storage system is needed. A typical run will involve 50 configurations with 5 propagators created from each configuration. Each of these objects is on the order of 10 Megabytes, so an Exabyte tape file system has the size needed to do the job.