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L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

INSTRUMENTATION AND CONTROL SYSTEMS FOR CANDU-PHW NUCLEAR POWER PLANTS

Systèmes d'instrumentation et de contrôle pour les centrales nucléaires CANDU-PHW

R.M. LEPP and L.M. WATKINS

Paper presented at the IAEA Specialists' Meeting on "Acquisition of Control and Instrumentation Technologies for Countries Embarking on Nuclear Power Programmes", Madrid, Spain, 1981 November 30 to December 2.

Chalk River Nuclear Laboratories Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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Résumé

L'instrumentation et le contrôle des centrales nucléaires CANDU bénéficient des technologies de l'électronique moderne grâce à une grande utilisation d'ordinateurs pour effectuer les fonctions de contrôle et de dialogue homme-machine. Ces fonctions, ainsi que celles de quatre systèmes spéciaux de sécurité, sont décrites.

Rapport présenté au colloque sur "l'acquisition des technologies de contrôle et d'instrumentation dans les pays se dotant d'un programme électronucléaire". Ce colloque d'experts organisé par l'Agence internationale de l'énergie atomique (AIEA) a eu lieu à Madrid, Espagne, du 30 novembre au 2 décembre 1981.

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ABSTRACT

The instrumentation and control of CANDU nuclear power plants takes advantage of modern electronics technology in the extensive computerization of important control and man-machine functions. A description of these functions as well as those of the four Special Safety Systems is provided.

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1. INTRODUCTION

The instrumentation and control (I&C) of CANDU nuclear power plants uses modern electronics technology in the computerization of key control and man-machine functions. A detailed description of these functions as well as those of the Special Safety Systems is provided so that specialists from countries about to embark on a nuclear program can determine their long-term I&C manpower requirements.

It will be evident that although the CANDU I&C systems are based on modern electronics technology, their fault tolerant, redundant and modular design minimizes the number of specialists required for their maintenance.

The I&C systems described are those of the CANDU-PHW* 600 MWe power reactor [1] which is being marketed internationally. Currently there are 8 CANDU reactors of comparable size and design in operation, and 17 under construction. Of the 8 reactors in operation, 6 are ranked amongst the top ten in the Western World in annual load factor for reactors over 500 MWe, in the most recent comparisons published by Nuclear Engineering International [2].

This excellent performance can, in part, be attributed to the sophisticated instrumentation and control systems that have been continually improved since the first CANDU commercial demonstration plant in 1966. From the beginning, a "defence-in-depth" design philosophy has been employed on the reactor itself as well as the I&C systems by

- providing diversely functioning systems that can do the same job,
- using physical separation of the different backup systems, and
- annunciating and correcting minor system upsets before they become major.

---

* CANada Deuterium Uranium, Pressurized Heavy Water

The final elements in the "defense-in-depth" approach are the Special Safety Systems that shut down the reactor, provide long-term cooling of the fuel and contain potential releases of radioactivity. There are four Special Safety Systems:

- Shutdown System Number One (SDS-1)
- Shutdown System Number Two (SDS-2)
- Containment System (CS)
- Emergency Coolant Injection (ECI)

2. CANDU CONCEPT

The CANDU-PHW Reactor is a heavy water moderated, heavy water cooled, natural uranium fuelled reactor which utilizes the pressure tube concept. The pressure tubes containing the fuel run horizontally through the reactor core as shown in Figure 1. Pressurized heavy water carries the heat from the fuel to the steam generators.

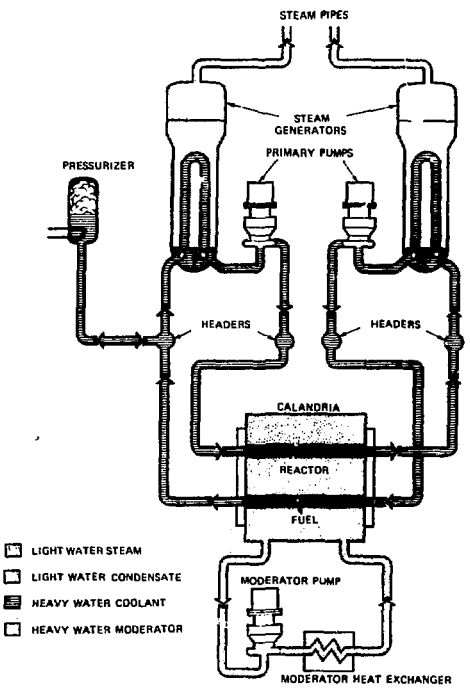

FIGURE 1: CANDU NUCLEAR STEAM SUPPLY SYSTEM

Each pressure tube is isolated and insulated from the heavy water moderator by a concentric calandria tube and a gas annulus. Consequently, the moderator system is operated at low temperature and pressure. The reactivity control and shutdown mechanisms reside in the low pressure moderator, thus simplifying their design, construction and maintenance and eliminating the possibility of their ejection in an accident situation. As well, this cool moderator can act as a heat sink under certain accident conditions.

The use of natural uranium fuel in a near optimum quantity, and heavy water as both moderator and coolant, combined with the capability to refuel the reactor while at full power, gives the CANDU reactor its good neutron economy and low excess reactivity. This results in a power reactor with very low fuel costs.

3. DESIGN PHILOSOPHY OF I&C

The "defense-in-depth" philosophy [3] employed in the design of CANDU instrumentation and control systems has resulted in systems of high reliability and availability that meet stringent safety and operational requirements.

An essential principle of CANDU I&C philosophy is that major plant control, annunciation and display functions should be computerized. The resulting high degree of automation and improved man-machine interface leave the operator free to concentrate on unusual occurrences, and have the additional advantage during commissioning of facilitating design improvements. A dual computer system concept, with one computer on hot-standby, is employed to provide the required high reliability. This high reliability is achieved by carefully selected and tested hardware, combined with the extensive self-checking system described in Appendix A.

Software and hardware faults are detected by internal self-monitoring plus an external "watchdog timer". Detection of a single control program fault results in the individual control task being transferred to the other computer. A restart system, which automatically reloads the core memory from the disc memory and restarts the computer, is combined with the fault detection to provide a system practically immune to transient faults.

The Special Safety Systems are, to the greatest extent possible, free from operational connection with any of the process systems, including the Reactor Regulating System. Each Special Safety System is completely independent from the others, with its own sensors, logic and actuators. As well, each

employs triplicated logic, meets the IAEA single failure criterion, and is designed with built-in features to facilitate on-line testing. A design objective has been to make the intervention of the shutdown systems unnecessary in all cases except real accidents in which public safety is in question.

The provision of two shutdown systems, either of which is capable of shutting the reactor down for the entire spectrum of postulated initiating events, is a unique feature of the CANDU I&C design. The two shutdown systems are physically and functionally independent of each other, and each is designed such that at least two, generally diverse, trips (trips based on functionally different measured variables) are activated by any single process failure.

Finally, there is "defense-in-depth" in the electrical power supplies. Each channel of the triplicated safety systems is fed from independent uninterruptible power supplies. Similarly each computer of the dual computer system is fed from a separate, independent, uninterruptible power supply to avoid loss of control capability due to a common power supply fault.

4. OVERALL PLANT CONTROL

To regulate the electrical output from a nuclear power plant, a large number of variables must be controlled in a co-ordinated way. These include

- reactor power,
- steam generator pressure and level,
- heat transport system pressure,
- pressurizer and deaerator levels, and
- moderator temperature.

Two identical, independent digital computers are used for direct digital control (DDC) and almost all major control functions are computer controlled. Each computer is capable of complete station control and will transfer control automatically to the other computer on detection of a fault. An availability of 99.88 percent has been achieved with this system [4].

The control of the turbine-generator output is accomplished by keeping the steam generator pressure constant. This is done by regulating both the reactor power and the steam generator level from the digital computer as is shown in Figure 2.

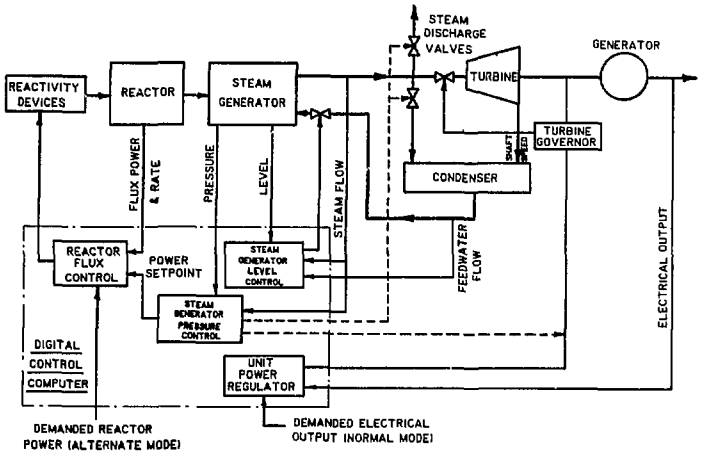

FIGURE 2: OVERALL PLANT CONTROL-BLOCK DIAGRAM

The overall plant control scheme, which is similar to that used in non-nuclear plants, operates in two modes:

- NORMAL is the usual control mode at high power. The turbine load is set to the desired value and the reactor power adjusts automatically to maintain constant steam generator pressure.

- ALTERNATE is the usual control mode at low power (below 2%) and during upset condition. The operator specifies the reactor setpoint and the plant steam loads are adjusted to maintain steam generator pressure.

The loss-of-line to the bulk electrical system and a turbine trip are two upsets that the control system must periodically cope with. This it does by rapidly reducing reactor power to 60%, combined with discharging steam to the turbine condenser, or to the atmosphere as is shown in Figure 3. Following such a transient the reactor system is capable of sustained operation at any load between 55% and 100% of rated capacity.

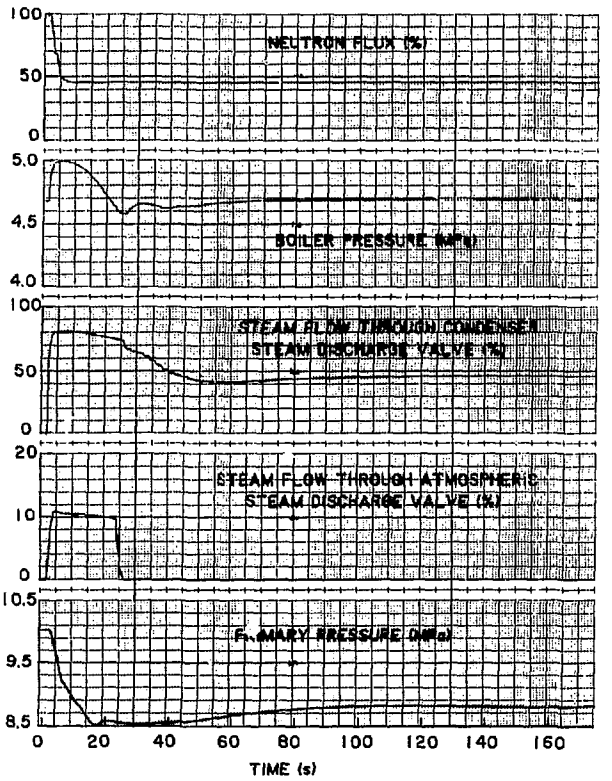

FIGURE 3: TURBINE TRIP FROM 100% FULL POWER OPERATION

5. REACTOR REGULATING SYSTEM

The Reactor Regulating System consists of that part of the overall plant control system that directly controls reactor power - either to an operator specified setpoint (ALTERNATE mode), or to the power level required to maintain steam generator pressure (NORMAL mode). A block diagram of the Reactor Regulating System is shown in Figure 4. It is designed to satisfy the following requirements:

(i) Provide automatic control of reactor power between 10^{-7} full power and full power.

(ii) Maintain the neutron flux distribution close to its nominal design shape so that the reactor can operate at full power without violating bundle or channel power limits.

(iii) Monitor important plant parameters and reduce reactor power quickly when any of these parameters are out of limits.

(iv) Automatically withdraw shutoff rods from the reactor when the trip channels have been reset following a reactor trip on Shutdown System No. 1.

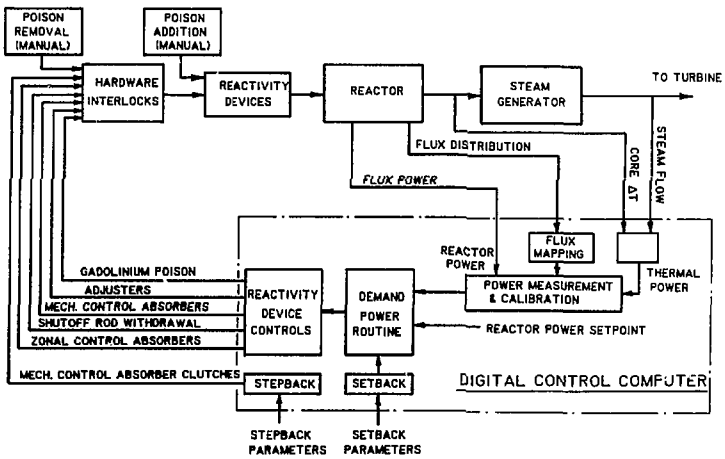

FIGURE 4: REACTOR REGULATING SYSTEM-BLOCK DIAGRAM

Reactor neutron power is controlled to a given set-point by means of the reactivity control devices, which for fast control include:

- 14 light-water zonal control absorbers
- 4 mechanical control absorbers, and
- 21 solid adjuster rods.

The main method for controlling reactor power is by adjustment of average water level in the 14 independently controllable zonal control absorbers. Differential adjustment

of levels in individual compartments is used for spatial control. Platinum in-core flux detectors provide the neutron flux feedback signals required by the digital control algorithms for both the bulk and spatial flux regulation.

The mechanical control absorbers, which are normally out of the core, are used in certain situations to provide additional negative reactivity. These situations include

- controlled shutdown of the reactor by the regulating system;
- ramped power reduction (SETBACK) during upset conditions to allow continued operation at reduced power;
- step power reduction (STEPBACK) during certain upset conditions to avoid a loss-of-regulation accident and hence actuation of one of the shutdown systems.

The adjuster rods are normally fully inserted in the core for flux shaping. They are withdrawn in symmetrical banks, under the control of the digital control computer, to provide positive reactivity for shimming the zonal control absorbers as well as for xenon override following a shutdown. Their reactivity worth is sufficient to start up the reactor within 30 minutes after shutdown from full power. As well, the adjusters permit sustained power reductions to 55% of full power. During periods of refuelling incapability, the adjusters can keep the plant operating for weeks by compensating for the loss of reactivity with fuel burnup.

Long-term negative reactivity is provided by the addition of soluble poison (boron or gadolinium) to the moderator. Boron is used to suppress the excess reactivity in a fresh core and gadolinium is used following a reactor "poison-out" to compensate for xenon burnout.

6. FLUX MAPPING

The platinum flux detectors used for spatial control do not accurately represent average zone power as they extend only over 3 lattice pitches. Therefore, a need exists for the accurate measurements of average zone power to calibrate these detectors. This is done with a system of 102 vanadium flux detectors distributed throughout the reactor core. Signals from these detectors are processed by the flux mapping routine, in the control computer, to obtain estimates of average zone flux.

The flux mapping routine also estimates the maximum flux levels in the core and uses this information to initiate a reactor setback if the power is too high in some fuel bundles.

The flux mapping routine also provides a channel power map, as well as estimates of the flux at Regional Overpower Trip (ROPT) detector sites. This gives the operator accurate information on the state of the core.

7. SPECIAL SAFETY SYSTEMS

The broad functions of the Special Safety Systems are to shut down the reactor, ensure a supply of cooling water to the fuel and contain any fission products that escape from the fuel elements. Two completely independent shutdown systems are provided to rapidly shut down the reactor when specified parameters enter an unacceptable range. One system drops solid rods into the core and the other injects poison into the moderator. The first is the preferred method of quickly terminating reactor operation because the "poison injection" method results in a reactor "poison-out" and an unavailability to the electrical grid for approximately 40 hours.

The other two Special Safety Systems, emergency coolant injection and containment, provide long-term protection against release of radioactivity to the environment.

Shutdown System Number One

In Shutdown System Number One (SDS-1), 28 spring-assisted, gravity-drop absorber elements are used as the basic shutdown devices. A 2 out of 3 'general' logic system senses the requirement for a reactor trip when any of 9 trip parameters exceed their trip settings. If a trip is required, the direct-current clutches on the shutoff rods are de-energized and the absorber elements drop into the moderator.

The 3 trip channels have completely independent and physically separated power supplies, trip parameter sensors, instrumentation trip logic, and annunciation. Thus no single failure can invalidate a called-for trip action. The redundant logic system fails to a safe condition on loss of ac power. The trip logic in each channel is a hybrid combination of microcomputers for the process trips requiring complex conditioning and relays for the neutronics and more straightforward process trips. Two microcomputers per trip channel are currently provided with the primary trip parameters fed into one microcomputer and the backup parameters in the other.

When any 2 of the 3 channels trip, the shutoff rods are dropped. With the general coincidence logic used, an entire channel trips when any measurement of any parameter reaches its trip setting. This approach makes testing easier and more complete as compared to local coincidence schemes.

Use is made of light-emitting diodes (LEDs) in the shutoff rod trip networks to indicate correct operation of the trip relays during testing. These LEDs are located on the SDS-1 instrumentation panel in the Control Room. On this panel are mounted

- all the annunciator alarms indicating the state of trip parameters and trip channels,
- the test LEDs and switches,
- the manual drive and test-drop handswitches for the shutoff units, and
- the manual trip button.

The unavailability requirement of 10^{-3} or less is met without taking credit for trip signals from more than one trip parameter at a time, even though diversity has been provided. Diversity is designed into the trip system by providing at least two effective trip parameters for each process failure, with the alternate trip parameter based on a different measurement principle from the primary parameter.

All trip parameters are connected through suitable isolating buffers to the sequence-of-events monitor on the main computers for "post-event" analysis.

Shutdown System Number Two

Shutdown System Number Two (SDS-2) provides a second method of quickly terminating reactor operation for the same spectrum of postulated initiating events as SDS-1. Provision of two functionally and physically independent shutdown systems, both designed for a very low unavailability (10^{-3}), virtually guarantees shutdown capability under all reactor accident circumstances.

SDS-2 employs two-out-of-three 'general' logic to sense the need for a reactor trip when any of 8 trip parameters exceed their trip settings. If a trip is required, the quick acting helium valves shown in Figure 5 are opened, and gadolinium nitrate "poison" is injected directly into the D_2O moderator.

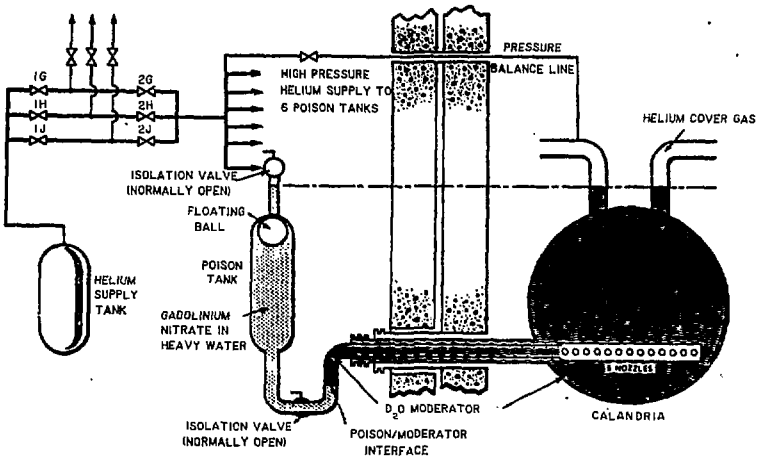

FIGURE 5: SHUTDOWN SYSTEM NO. 2 - LIQUID INJECTION

The selection of trip parameters is such that there are again, as with SDS-1, at least two trips for each process failure, and, in general, the alternate trip parameter is based on a different measurement parameter from the primary trip. As in SDS-1, a combination of microcomputers and relays is used to implement the required trip logic.

Prompt-responding, self-powered, platinum flux detectors, mounted horizontally in the core, are used to sense the need for a reactor overpower trip. These detectors are physically and electrically separated from both the regulating system and SDS-1 detectors. The detector outputs and their trip setpoints are displayed on the SDS-2 instrumentation panel in the control room.

As in SDS-1, ion chambers are used to provide the trip signal for excessive rate-of-change of power. However, these ion chambers are in a different location from those of SDS-1, and their amplifiers are from a different manufacturer. Testing of a complete trip channel is done the same way in both SDS-1 and SDS-2, by moving a shutter in front of the ion chamber to change its output rapidly enough to simulate a rate trip.

The other trip parameters are based on standard process instrumentation transmitters. In all cases, testing can be automatically initiated from the control room, and consists of applying appropriate test pressures to the relevant transmitter.

Testing also includes the periodic opening of the quick operating helium valves in one trip channel, as well as taking a poison tank out of service to check its gadolinium nitrate concentration.

Containment System

The containment system shown in Figure 6 comprises a pre-stressed, post-tensioned concrete structure, an automatic dousing system, automatic building air coolers, ventilation filters, access airlocks and an automatic containment isolation system.

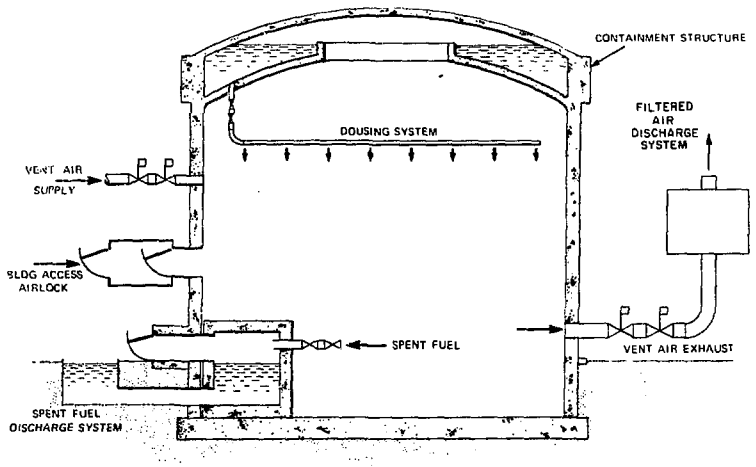

FIGURE 6: CONTAINMENT SYSTEM

The dousing system has built-in redundancy to ensure that unavailability targets can be met. Redundancy is provided through independence of sensors, spray headers, valves, plus the ability to periodically test the system. Containment isolation meets its unavailability targets through two-out-of-three logic.

Emergency Coolant Injection

The emergency coolant injection (ECI) system shown in Figure 7 is composed of three stages: high pressure, medium pressure, low pressure. The high pressure stage uses pressurized nitrogen to inject water into the reactor core from water tanks located outside the reactor building. The medium pressure stage supplies water from the dousing tank. When this water supply is depleted, the low pressure stage recovers water that has collected in the reactor building sump and pumps it back into the reactor core via the emergency cooling heat exchanger and the emergency cooling recovery pumps.

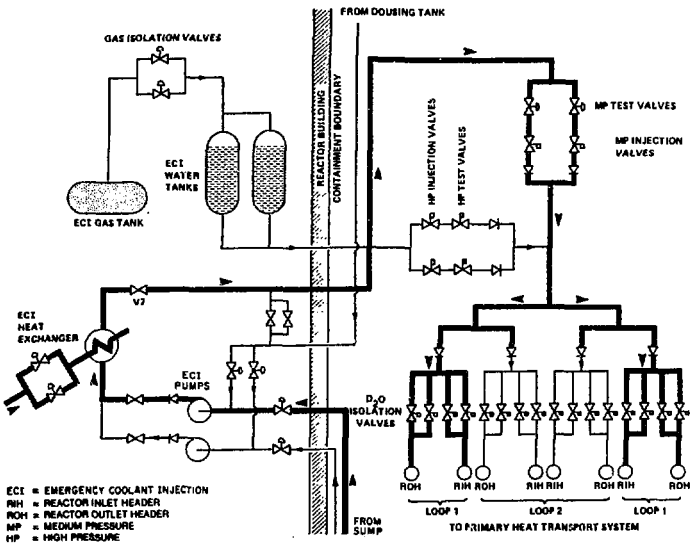

FIGURE 7: EMERGENCY COOLANT INJECTION SYSTEM - SHOWING LOW PRESSURE OPERATION FOR A LOCA IN LOOP 1

Since inadvertent triggering of emergency core cooling would be economically penalizing, precautions are taken in the logic design to prevent spurious initiation of ECI, while still providing the redundancy required to meet the unavailability target of less than 10^{-3}. Typical design features are:

(i) All instrumentation and associated control loops used to initiate ECI are triplicated and dedicated (i.e. not shared by other control or safety systems).

(ii) Local coincidence is used in the logic to help eliminate spurious trips of the system.

(iii) The logic for isolating each of the two separate heat transport loops during a loss-of-coolant accident is separate from the logic for other functions.

(iv) Redundant valves in parallel are used wherever power operated valves are required for ECI. Either one opening would be sufficient. Each valve of a pair is fed from an independent power supply, and annunciation is made of valve power supply failure.

(v) On-power testing facilities are provided to assure that the target unavailability is met.

8. CONTROL ROOM

Two major control areas are provided - the main control room shown in Figure 8, and the secondary control area. The main control room centralizes all the information and man-machine controls required for safe operation of the plant, including those items required for the Special Safety Systems.

The basic philosophy of design is to display sufficient information to allow the unit to be controlled from the control room. To achieve this goal, all indications and controls essential for operation (startup, shutdown and normal) are located on the control room panels.

Colour cathode ray tubes (CRTs), driven by the station computers, are extensively used in the main control room to replace many of the meters and recorders found on conventional panels [5, 6]. The use of computer driven displays results in less congested panels and allows easier correlation of information. However, sufficient conventional display, annunciation and recording of plant variables is included to allow the plant to be properly run in the shutdown condition with both computers out of service.

The alarm annunciation system consists of small direct-wired window annunciators, two colour CRTs for alarm message presentation and a facility to provide a printed record of all alarm conditions in chronological order of their occurrence. Individual alarm windows are used to indicate that a trip parameter has reached its trip limit or that some other parameter is 'off normal'.

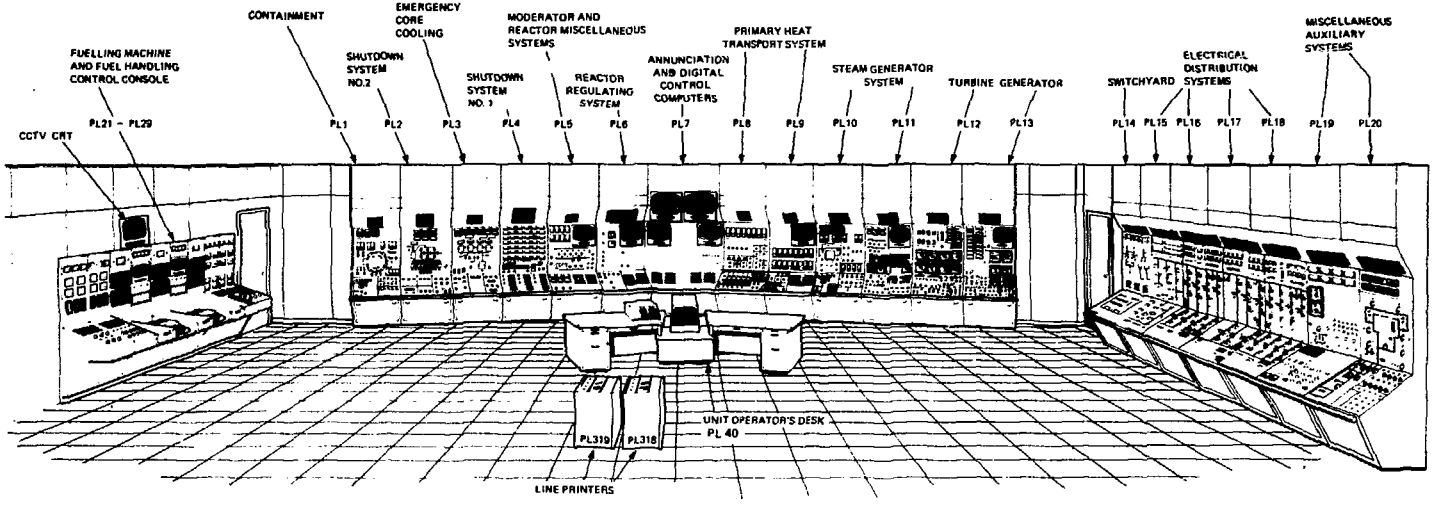

FIGURE 8: LAYOUT OF THE MAIN CONTROL ROOM

In case the control room becomes uninhabitable, enough display and control instrumentation is provided in the secondary control area to allow the plant to be shut down and maintained in a safe shutdown condition.

9. CONCLUSIONS AND FUTURE TRENDS

The I&C systems currently used for control and safety in CANDU-PHW reactors have been described. Basically the control functions are programmed into two centralized and redundant minicomputers while safety functions are covered with a combination of microprocessors and conventional, hard-wired relay logic.

Future trends are towards increased use of computer power to encompass more station I&C functions and meet new I&C requirements. An important consideration for these applications are computer architectures that permit easy change or addition, thus minimizing equipment obsolescence. These trends could affect both the control and safety systems in many ways. Features of these future systems, as seen from within the CANDU program [4, 5, 7], include

- distributed computer architecture connected by a low cost communications medium to reduce programming costs, increase reliability and reduce maintenance support requirements. In the Nuclear Steam Supply area alone, rather than two centralized computers there may be as many as twelve individual computers [7], to cope with the increased processing requirements. A high degree of standardization of both hardware and software is seen as the means of minimizing the maintenance function;

- use of remote multiplexing to decrease wiring costs and increase expansion flexibility;

- programmable logic instead of hardwired relay logic to reduce costs and increase flexibility;

- increased use of computer intelligence in safety systems to increase plant availability.

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APPENDIX A

COMPUTER FAULT CHECKING SYSTEMS

Each of the two identical, independent digital computers is capable of complete station control and will transfer control automatically either completely, or by function, to the other computer on detection of a fault. Software and hardware faults are detected by such features as:

Functional Program Checks

Key control programs perform rationality checks on their process inputs and also check the response of the computer output systems to their commands. Gross failures will result in transfer of the individual program to the standby computer.

Program Time Checks

Separate hardware countdown registers are used to check the execution time of all periodic programs. After two successive runs that exceed the allotted time, the functions of the failing program are switched to the hot-standby computer and the failing program is turned off.

Check Program

A typical test is the "wrap-around" test on process I/O equipment. A computer analog output is derived from software through a digital-to-analog converter and fed into the analog input multiplexer and the resulting output is compared to the original software-held value. This also acts as a check on part of the instruction set.

Parity Checking and Memory Protect

Parity checking is applied to all data transfers. A system restart is made for all parity errors. In addition, certain areas of the core memory are provided with memory protect.

Watchdog Timer

The overall functioning of a single computer is monitored by the watchdog timer. It comprises an external countdown timer which is reset periodically (∿ 1/2 second) by the executive program. If not reset in 3 seconds, it times out and transfers control of all computer functions to the standby computer.

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