Chapter 7

Operational Considerations

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ABSTRACT

Nuclear operational personnel are the ultimate beneficiaries of the research, design, and safety studies which are being described this week. While these people must be aware of such items as the kind of protection provided by a particular trip parameter and the significance of the associated trip setpoint, they are generally unfamiliar with the details of the critical heat flux calculation which may have determined the selection of both parameter and setpoint. By the same token, many people involved in the study of thermalhydraulics are not conversant in the operational states and procedures of a commercial nuclear power plant. This paper will describe in general terms the operating states of a typical system, the procedures by which it is manoeuvred between states, a selected set of plant transients, and the general commissioning procedure. By developing an appreciation of operational procedures, it is hoped that the design of nuclear stations will be enhanced.

7.1 INTRODUCTION

The primary objective of nuclear power plant operating personnel is to maintain adequate cooling to the reactor fuel under all operating conditions. The production of electricity resulting from this heat removal is a secondary, albeit important, consideration. While the major objectives are rather simply stated, their realization requires a rigorous maintenance schedule, continuous review and update of system design, adequate training of operational staff, and a comprehensive set of approved operational procedures. For each system, an Operating Manual, outlining these procedures, is written. Each manual:

- outlines system policies and principles which are intended to ensure that the system is operated within design limitations and licensing requirements.

- details standard operating states and operational procedures such as system startup and shutdown.

- details non-standard operating states and operational procedures such as a malfunction of a piece of system equipment.

- lists trips and alarms associated with the system and gives the appropriate operator response.

- specifies routine tests to be performed on the system.

- describes the chemical control for the system.

- lists the effects of auxiliary service (ie, service water, electrical power, instrument air) failures on the system.

Even a quick glance at a station's Operating Manuals will indicate that there are a large number of states into which a nuclear power plant could conceivably be placed under non-accident conditions. This is due to both the number of major systems and the variety of states into which each system can be placed. For instance, with the reactor at power, it is possible for the turbine/generator to be outputting power to the grid as it normally does or to be completely shutdown as it might be under poison prevent operation. Therefore, this discussion will be limited primarily to the operating states of a single hydraulic system. For the purpose of being somewhat more specific, the description that follows will concentrate on the Bruce NGS-A primary heat transport system.

7.2 OPERATIONAL LEVELS

The heat transport system at Bruce is shown schematically in Figures 1 and 2. The main circuit follows the standard CANDU figure-of-eight design with 480 reactor channels. On leaving the boilers and passing through the main circulating pumps the flow is split. Part is directed through the preheaters or their bypasses and thence through the reactor inner zone channels. The other portion is sent directly through the reactor outer zone channels from the pumps. One of the reactor outlet headers is connected to the pressurizer which is instrumental in the control of pressure. The feed and bleed circuit functions control the pressurizer level. It does this by bleeding off excess inventory, condensing it in the bleed condenser, cooling it in the bleed cooler, purifying it by means of filters and ion exchange columns and storing it in the D_2O storage tank. Feed flow to make up deficiencies in inventory is supplied at high pressure by two feed pumps. The various configurations into which these systems can be placed are described in detail in Reference 1 and summarized in Table 1.

7.2.1 Full Power

The pressurizer is filled with liquid to a height of 6.7 m in equilibrium with a cover of D_2O vapour at the desired pressure. Pressure is controlled by either releasing steam to the bleed condenser via steam bleed valves or generating more steam by means of heaters immersed in the liquid. The liquid level is itself controlled by the feed and bleed valves which add water to or remove it from the main circuit. The reactor inlet temperature is determined primarily by secondary side conditions, specifically boiler pressure while reactor power determines the temperature rise across the reactor. The main circuit flow depends mostly on the status of the main circulating pumps and hence is fairly constant. Control of the entire unit is in NORMAL (reactor-following-turbine) mode in which the generator outputs the power demanded by the operator via the digital control computers (DCCs) and reactor power is manoeuvred to maintain constant boiler pressure.

7.2.2 Low Power Hot

The configuration of the heat transport system is essentially the same as full power with three notable exceptions. With heat input from the fuel and heat output to the secondary side essentially zero, all temperatures have come into equilibrium with the saturation temperature in the boilers. The pressurizer level is now 4.5 m reflecting the fact that the pressurizer level setpoint is automatically reduced from 6.7 m at 100% full power to 4.5 m at 0% by an analog control loop to (partially) compensate for the coolant shrinkage which accompanies the power reduction. The flow through the purification circuit is manually adjusted to maximum flow reflecting the fact that activity release from the fuel invariably accompanies any plant manoeuvre. Pressure control would usually be via the pressurizer although SOLID mode control is possible. In this latter mode, the pressurizer is isolated from the main circuit and pressure is maintained by the feed and bleed valves. Control of the entire unit would probably be in ALTERNATE mode in which reactor power is controlled at a level selected by the operator and the station loads (turbine, atmospheric steam discharge valves or ASDVs and condenser steam discharge valves or CSDVs) are manipulated to maintain boiler pressure.

7.2.3 Warm Standby

The reactor is at low power and boiler pressure has been reduced resulting in primary side temperatures around 160°C. At these temperatures, the pressure produced in the bleed condenser by the bleed flow is insufficient to push the water through the purification circuit to the D_2O storage tank. For this reason and because the bleed cooler has sufficient capacity to handle these temperatures, the bleed condenser is bypassed and the main circuit pressure provides the flow.

7.2.4 Cold Pressurized-Shutdown Cooling

The Shutdown Cooling System at Bruce NGS-A is a secondary side light water circuit which can be valved into the preheaters transferring heat absorbed there from the primary side to lake water through the use of dedicated pumps and heat exchangers. This circuit requires the PHT main circulating pumps to be running.

7.2.5 Cold Pressurized-Maintenance Cooling

The Maintenance Cooling System (MCS) is a heavy water circuit which can be valved into the main PHT circuit at the outlet headers, main circulating pump suctions, and pump discharges. The MCS takes water directly from the pump circuit and transfers its heat to lake water before pumping it back. The main PHT pumps are shut down to allow the MCS pumps to provide the flow.

7.2.6 Cold Depressurized

The NORMAL mode of pressure control using the pressurizer is designed to control pressures in the 5 to 10 MPa range. Hence, to depressurize the system, pressure control is put into SOLID mode and the pressurizer is taken out of service in one of two ways. If pressurizer maintenance is not required, the vessel is simply isolated from the main circuit by means of a valve on the surge line. If a return to a pressurized state is imminent, pressure is maintained by means of the heaters. Otherwise, heat losses to the surroundings will result in a slow pressure decay. However, if pressurizer maintenance is required, a faster cooldown of the pressurizer may be necessary. This is achieved by closing the surge line isolating valve at the start of cooldown and establishing a flow path from the reactor inlet header through the pressurizer to the bleed cooler by means of the pressurizer spray and drain valves. After depressurization, the feed pumps are shut down and purification flow is maintained by valving the MCS directly into the purification circuit.

7.2.7 Main Pump Maintenance (High Level)

By venting the main circuit to atmosphere at the main circulating pumps and then pumping heavy water to the D_2O storage tank via the MCS and the purification circuit, the water level in the main pump suction and discharge legs is lowered sufficiently to allow access to the main pumps for maintenance purposes. All the MCS flow is now through the reactor core as opposed to the previous two states where some flow bypasses the core via the boilers. However, the boilers are kept full on the primary side by atmospheric pressure at the vent locations.

7.2.8 Boiler Maintenance (Low Level)

The draining procedure can be continued until the main boilers are emptied on the primary side. However, to provide a suitable flow path through the reactor, the water level is maintained above inlet header level.

7.3 SHUTDOWN

The shutdown procedures which take the PHT system between the states described previously are discussed in Reference 1 and briefly summarized in Figure 3. The reactor shutdown systems are used to quickly reduce reactor power under emergency conditions. Otherwise, station policies and principles require them to remain in a poised state. Hence, during a normal shutdown, the transition from full power to low power would usually be through a controlled reduction in reactor power via the station control computers. The reactor can then be allowed to poison out. Because the lower boiler pressures associated with a shutdown can lead to excessive steam moisture and pitting of the blades in the turbine, the turbine is tripped before cooldown begins.

The cooldown from low power hot to warm standby is also carried out by the DCCs at a rate chosen by the operator. The DCCs manipulate the condenser steam discharge valves and/or atmospheric steam discharge valves to release steam from the boilers, reducing pressure and hence permitting additional heat to be absorbed from the primary side. The cooldown rates at Bruce NGS-A are carefully controlled as per Figure 4. Such a cooldown temperature profile must be followed to minimize thermally induced piping stresses, particularly of the boiler steam drums. The drums at Bruce NGS-A are known to exhibit top-to-bottom temperature differentials due to differing heat transfer characteristics of the vapour-to-metal and liquid-to-metal interfaces.

Boiler pressure reduction becomes an inefficient cooldown mechanism as the warm standby state of 500 kPa or 160°C is approached. Below this level, the shutdown cooling system is valved in to provide a temperature reduction to 50°C. The Maintenance Cooling System is then valved in and the PHT main circuit depressurized and drained as maintenance plans require.

The shutdown of the PHT is, of course, accompanied by parallel operations in the rest of the plant. Gadolinium is added to the moderator to ensure sufficient hold-down reactivity once the Xenon load has decayed to zero and to provide Xenon simulation upon startup. The turbine will run down to turning gear within an hour of the trip and most turbine auxiliaries can be shut down. Condenser vacuum can be broken and the pumping capacity of the feedwater train reduced. Once the turbine is tripped, the unit's electrical loads are supplied from the grid.

7.4 THERMALHYDRAULIC CHARACTERISTICS DURING OPERATIONAL TRANSIENTS

Each unit of a multi-unit station can exhibit a unique response to the same initiating event. This is because controller setpoints, handswitch positions, valve stroking characteristics, etc, may differ slightly from unit to unit. What follows is a brief description of some of the transients which could occur in a nuclear power plant and the associated operator actions.

7.4.1 Reactor Trip and Recovery

A reactor trip will occur whenever certain important process variables exceed predefined setpoints. At Bruce NGS-A, there are two reactor safety systems: SDS 1 which employs shutoff rods to reduce power and SDS 2 which incorporates gadolinium injection into the moderator.

The operator would be alerted to the fact that the reactor has tripped by numerous alarm windows, CRT messages and a horn. In many cases, he may not have been aware that a trip was imminent. His first action is not to determine the cause of the trip but to ensure that the trip is successful (ie, all shutoff rods have fallen in, power is reducing quickly, etc) and that the rest of the unit is responding accordingly (ie, the turbine has unloaded and boiler pressure is being maintained at its setpoint).

The main thermalhydraulic transients involve the boiler level, PHT pressure, and pressurizer level pictured in Figure 5. Immediately after the trip, boiler level decreases rapidly due to the collapse of bubbles associated with the decreased heat transfer from the primary side. The level then recovers as water is made up by the Boiler Level Control program in the DCCs. The pressurizer level and PHT pressure show a similar rapid decrease. The heavy water shrinkage produced by the power reduction from 100% to 0% results in a decrease to about 1.5 m and the original level control incorporated this figure as the zero power level setpoint. However, the proximity of the low pressurizer level trip setpoints resulted in the new zero power setpoint of 4.5 m to which the level is restored by the feed flow. Following the initial decrease the pressure recovers more or less to the setpoint as the vapour is compressed during the refilling period. However, the water refilling the pressurizer is well below saturation temperature. Heat loss from the vapour to the pressurizer walls and the enthalpy drop due to cool liquid produces a second pressure decrease which is gradually eliminated by action of the heaters.

After the operator has assured that the unit is in a reasonably stable state, he can then investigate the cause of the trip. According to Reference 2, design simulations have shown that reactor power must be raised to 60% no later than 35 minutes after the trip if a poison outage is to be avoided. To withdraw the shutoff rods, insert the boosters and raise power to 60% requires a minimum of 14 minutes leaving 21 minutes D and A (decision and action) time. When one considers that energy replacement costs for a unit which has poisoned out run into several hundreds of thousands of dollars as well as the strict requirement that the unit is returned to power only if safe operation can be assured, one can begin to appreciate the pressure which such an event can place on operating personnel.

7.4.2 Load Rejection

In a load rejection, the generator is disconnected from the grid while maintaining power to the unit service loads. While such an event could be caused by a transmission line fault, load rejections have become an important test routinely performed not only to check station capabilities but also to verify analysis codes (Reference 4). A load rejection at Bruce NGS-A initiates a reactor stepback to a nominal value of 60% FP. This is accomplished by dropping control absorbers into core and serves to bring the reactor heat production down to within the design heat removal capacity of the CSDVs while still preventing a poison outage. At the same time, the turbine electro-hydraulic governor rapidly closes the turbine governing valves to reduce steam flow and hence prevent any excessive turbine overspeed which could result in a trip. When the overspeed transient has passed, the governor valves will be reopened to maintain adequate turbine speed and, in so doing, provide adequate power to the station loads. The power mismatch between the reactor and turbine is handled by the CSDVs. The governor valve closure causes an initial increase in boiler pressure (Reference 4) before the CSDVs are opened by the DCCs and bring the pressure back to near the setpoint. The primary side pressure decreases because the shrink caused by the reactor stepback dominates over the reduced heat transfer in the boilers caused by the secondary pressure rise.

Theoretically, there is nothing which prevents operation in this mode for an extended period. The reactor power is maintained at a sufficiently high level to avoid a poison outage, the supply of demineralized water on the secondary side is maintained through the use of the CSDVs which vent excess steam to the condenser, adequate feedwater heating is achieved by supplying poison prevent steam from the boilers to the deaerator and electrical power to the station loads is maintained by the generator.

7.4.3 Total Loss of Class IV Power

The electrical systems serve as support for virtually all other station systems. For each unit, the internal electrical supply distribution systems are divided into four categories according to different reliability requirements on the supply or the load's drawing power from that supply:

Class IV - Power or loads which can be interrupted indefinitely without affecting the safety of the station or its personnel. These include the main boiler feed and heat transport circulating pumps.

Class III - Power or loads which can be interrupted with the unit on load for 1 to 3 minutes without affecting the safety of the station or its personnel. These loads include the heat transport feed pumps.

Class II - Power or loads which can be interrupted with the unit on load for 0.25 seconds without affecting the safety of the station or its personnel. Typical loads are the DCCs and reactor shutdown systems.

Class I - Power or loads which can never be interrupted with the unit on load without affecting the safety of the station or its personnel. Typical loads include protective relaying and circuit breaker control circuits.

While even a loss of Class IV is rare, it could occur if power was not available from the unit's own generator, the generators of the other units in a multi-unit station or from the electrical grid. For the purposes of our discussion, the most important loads at Bruce NGS-A supplied by Class IV power include the main moderator, heat transport, and boiler feed pumps. On a total loss of Class IV power, all these pumps will be lost. The opening of the PHT main circulating pump breakers will initiate a stepback to 65% of present power. However, the reduced flow will bring in reactor trips on low gross flow or high heat transport pressure within 10 seconds (Reference 5). Adequate reactor decay heat removal is maintained by energy stored in the pump flywheels. After rundown of the pumps, flow across the fuel is maintained by thermosyphoning. At Bruce NGS-A the moderator pumps are similarly supplied with flywheels to ensure adequate cooling to the boosters immediately after the trip. Thereafter Class I moderator auxiliary pumps maintain flow. On the secondary side, Class III auxiliary boiler feed and condensate extraction pumps ensure adequate boiler inventory.

Assuming that Class IV power cannot be restored, the main operator action is to reduce secondary side pressure. This provides sufficient protection against primary side boiling which could degrade, on some occasions break down, full-loop thermosyphoning.

7.5 COMMISSIONING

Commissioning of each unit at Bruce NGS-A was divided into four phases: A, B, C, and D (Reference 6). Phase A (pre-critical) included that work which had to be completed prior to the first approach to critical. The procedures were primarily those of bringing the individual equipment and systems to the operating state. The major steps were as follows:

1. Place the Auxiliary Service Systems in Operation
2. Unit Control Computers and Annunciation Checks
3. Add Heavy Water to Moderator System and Commission
4. Add Heavy Water to Heat Transport System and Commission
5. Commission Boiler Steam and Feedwater
6. Safety System Checks
7. Fuel Loading
8. Final Heat Transport Commissioning
9. Training

Although heavy water, fuel, and boosters are added during Phase A, the Unit is prevented from going critical.

Phase B (Low Nuclear Power) includes the first approach to critical and low nuclear power measurements. Tests will be made to establish the reactivity rate and depth of both Reactor Shutdown Systems and confirm the adequacy of the Reactor Control System.

Phase C (Power Run-up) includes those tests that are performed at increasing thermal power and electrical output until full power operation is achieved.

During this phase, most of the steam raising equipment, including the turbine and regenerative feed heating, are operated for the first time. The operation of the control and safety systems are checked at various levels up to full power.

Phase D (Power Shakedown) includes tests, adjustments, and modifications where necessary to establish heat balances and prepare the unit for high capacity factor operation.

7.6 CONCLUSION

Operating personnel are responsible for the safe and efficient operation of nuclear power plants. The ease with which these people can carry out the required operations depends primarily on the quality of the station design and ultimately on the research and safety studies which determine that design.

References

1. Bruce NGS-A Operating Manual 33000, Heat Transport and Main Steam

2. Bruce NGS-A Operating Manual 60040, Unit Control

3. Bruce NGS-A Simulator Performance Data, Volume 2, Manual Reactor Trip

4. Bruce NGS-A HT and Feedwater/Steam Data from Turbine Load Rejection Test at 83% Full Reactor Power, CNS-IR-331-20

5. Ontario Hydro Nuclear Generation Division, Central Nuclear Services, Information Report CNS-IR-330-9

6. Bruce Generating Station A General Systems Commissioning Procedure 06010-1

List of Abbreviations

ASDV: Atmospheric steam discharge valves. These are used by the station control computers to vent the boilers to atmosphere to control boiler pressure.

CSDV: Condenser steam discharge valves. These vent steam from the boilers to the condenser to control boiler pressure. They can only be used when condenser vacuum has been established and do not result in a loss of demineralized water from the secondary loop.

DCC: Digital computer controller. There are two DCCs for each unit and they perform the bulk of the control functions such as reactor and boiler pressure control.

MCS: Maintenance cooling system. This is a heavy water system connected to the main heat transport loop at the inlet and outlet headers. It is primary for use below 50°C and is the main heat sink in the depressurized state.

SDS: Shutdown system. At Bruce there are two totally independent shutdown systems. SDS1 drops neutron absorbing rods into core to reduce power while SDS2 injects a neutron absorber into the moderator.

Table 1: Standard Operating States

State	Main Circuit				Pressurizer Level (m)	Pressure Control Mode	Bleed Condenser Pressure	Purification Flow (kg/s)	Shutdown Cooling System	Maintenance Cooling System
	Pressure (MPa)	Temperature (C)								
		ROH	R1H 1Z	R1H OZ						
1. Full Power	9.18	302	252	265	6.7	Normal	1.72	8.3	O/S	O/S
2. Low Power Hot	9.18	260	260	260	4.5	Normal	1.72	41.0	O/S	O/S
3. Warm Standby	9.18	160	160	160	4.5	Normal	Bypassed	41.0	O/S	O/S
4. Cold Pressurized Shutdown Cooling	9.18	50	50	50	4.5	Normal	Bypassed	8.3	I/S	O/S
5. Cold Pressurized Maintenance Cooling	9.18	50	50	50	4.5	Normal	Bypassed	8.3	O/S	I/S
6. Cold Depressurized	0.1	50	50	50	Isolated	Solid	Bypassed	Via MCS	O/S	I/S
7. Pump Maintenance (High Level)	0.1	50	50	50	Isolated	Solid	Bypassed	Via MCS	O/S	I/S
8. Boiler Maintenance (Low Level)	0.1	50	50	50	Isolated	Solid	Bypassed	Via MCS	O/S	I/S

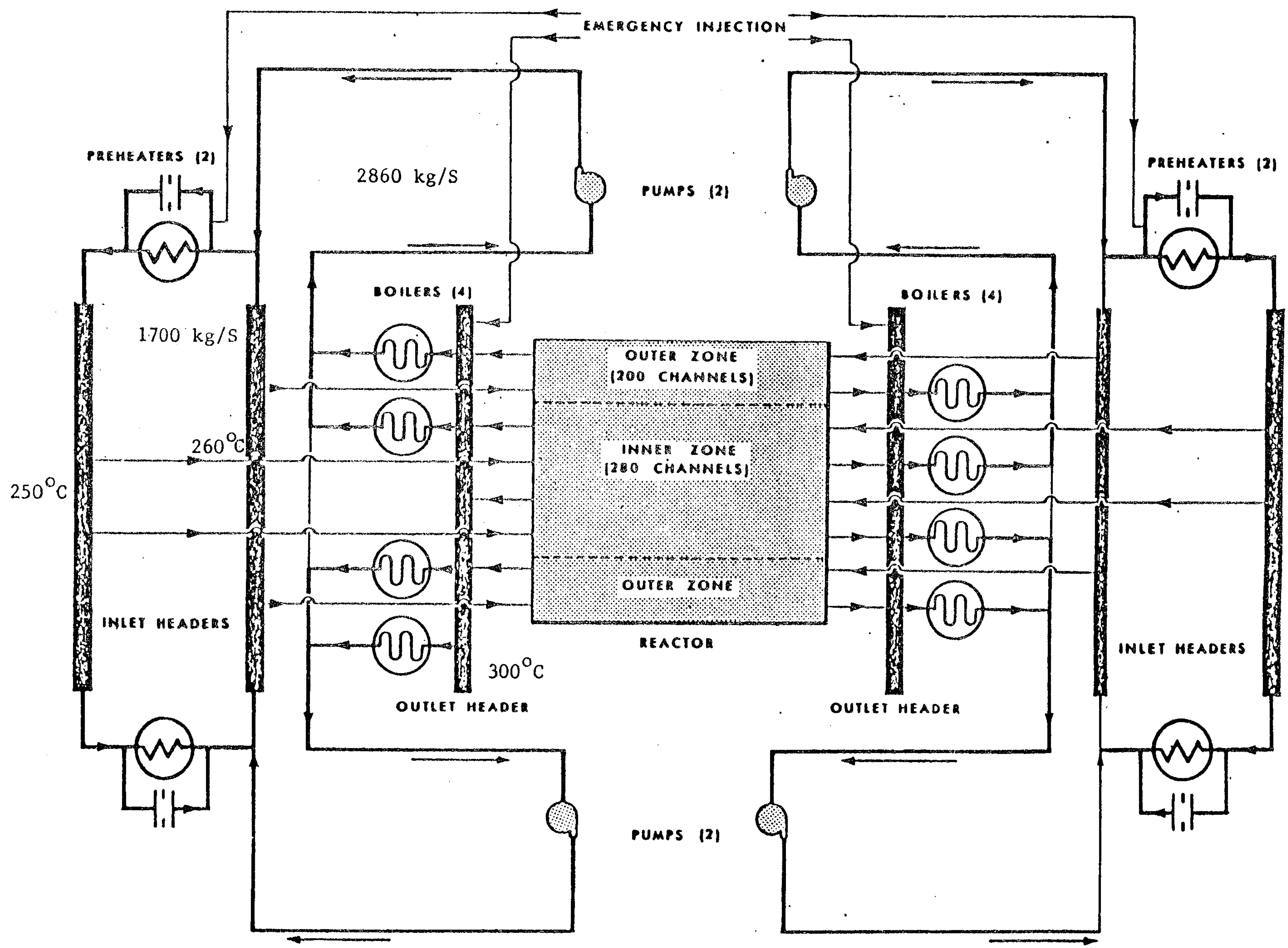

FIGURE 1 HEAT (ANSPORT SYSTEM

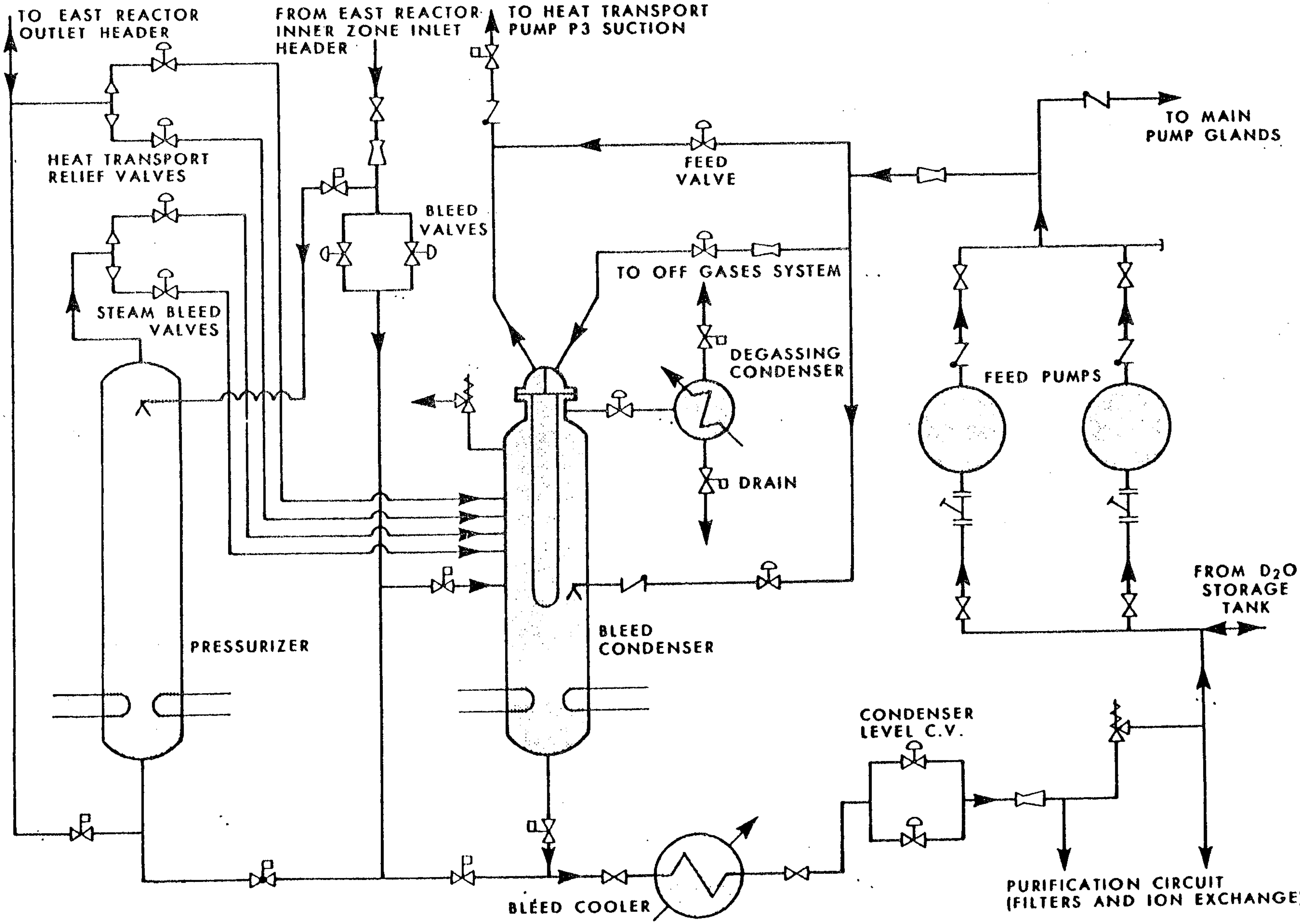

Fig 2. HEAT TRANSPORT PRESSURIZER, FEED, BLEED AND RELIEF CIRCUITS

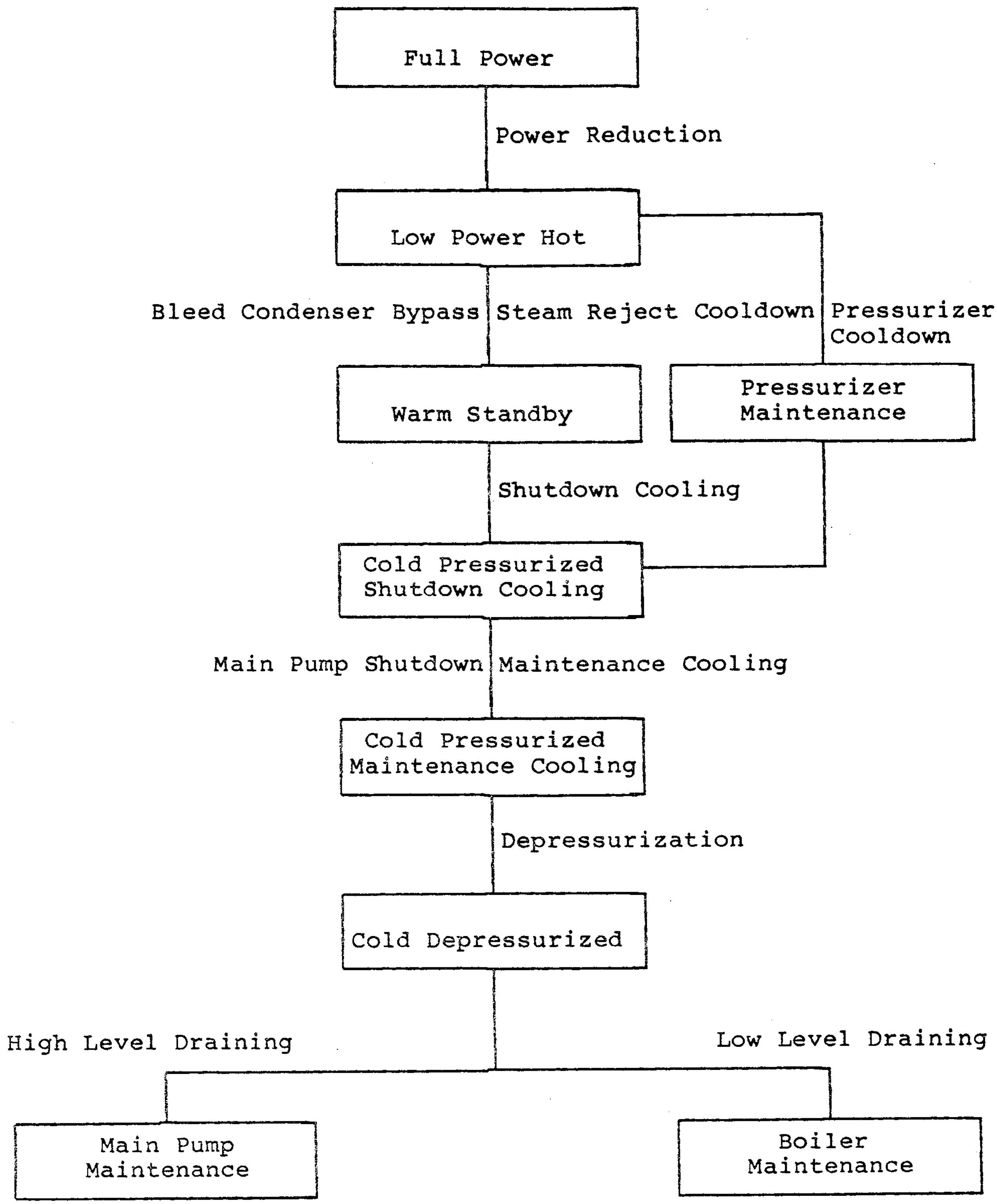

Figure 3: Shutdown

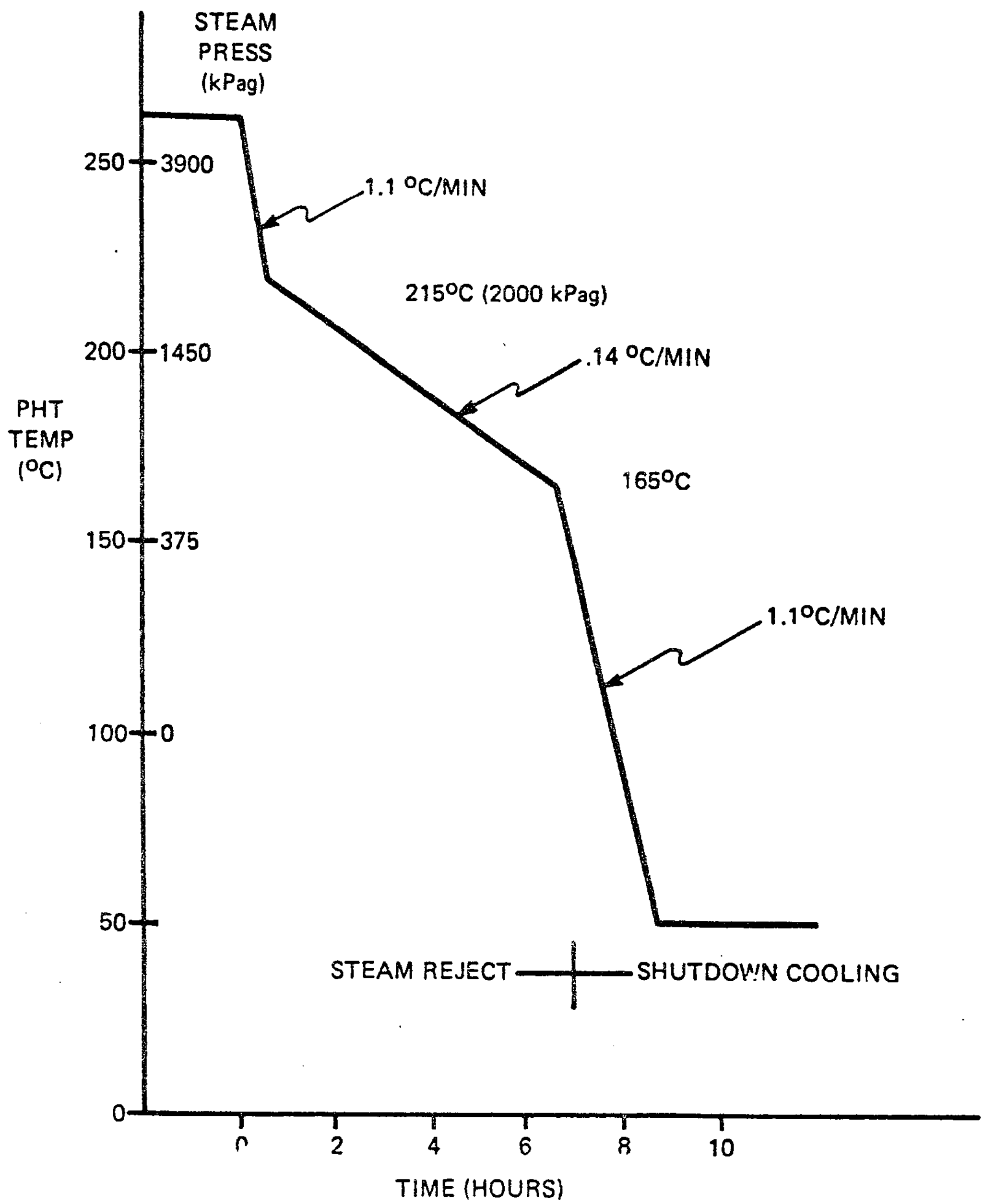

FIGURE 4: COOLDOWN TEMPERATURE PROFILE

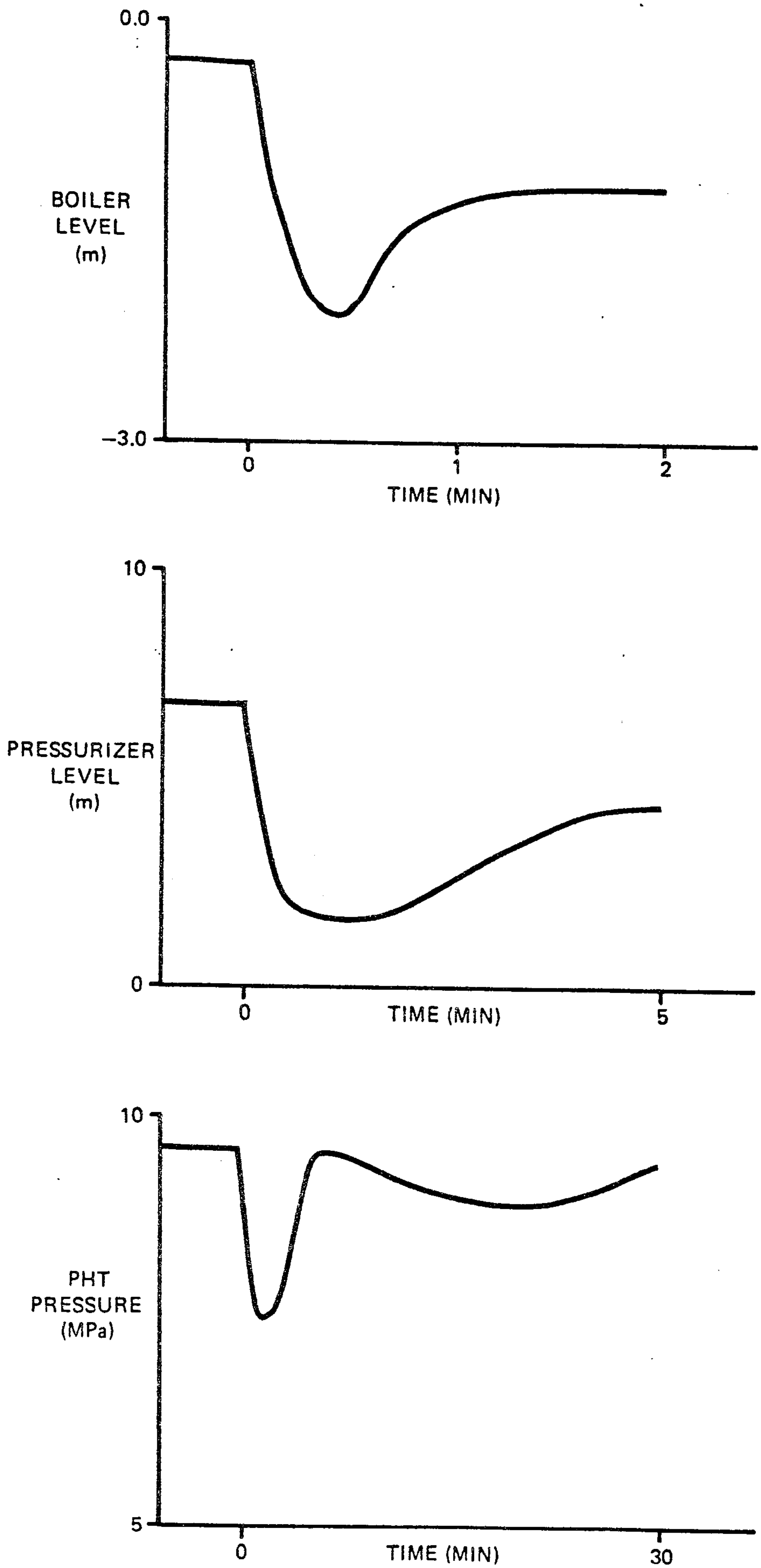

FIGURE 5: RESPONSE TO REACTOR TRIP