THE HEAT TRANSPORT SYSTEM

IN A HEAVY WATER NUCLEAR REACTOR.

By

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ABSTRACT

Nuclear power provided 10% of the world's electricity. In Ontario Nuclear provides the base electrical load on the grid. Nuclear power is very unique. It is able to release a tremendous amount of power if it is not controlled properly. There is three objectives that are required to be meet at all times when running a Nuclear power plant. These are called the three C's. The three C's are Control, Cool and Contain. The nuclear reaction in a power plant is required to be controlled, at all times. This is completed by maintaining the nuclear fission reaction in the reactor. The Nuclear fission reaction releases radioactivity. This radioactivity needs to be contained in the reactor and not released in the environment, at any cost. The reactor is required to be cooled at all times. This report will provide a basis on controlling the heat on a nuclear reactor. This design of the Instrumentation and Control of the Heat Transport System for a CANDU REACTOR, will be discussed in detail in this report. The Heat transport system is responsible to maintain the coolant mass balance of the nuclear power plant. The main control goal is to stabilize the water level at a reference value and to suppress the effect of various disturbances.

ACKNOWLEDGMENTS

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1.1 INTRODUCTION

The pursuit of nuclear energy for electricity generation began soon after the discovery in the early 20th century that radioactive elements, such as radium, released immense amounts of energy. The current increase in consumption of fossil fuels such as coal, lignite, petroleum, and natural gas leads to shrinking natural resources. This phenomenon required the development of new energies taking into account renewable energy and nuclear power, which is able to provide energetic security for years to come.

Nuclear power is based on the obtaining energy from heavy fission elements nuclei, especially uranium, which possesses great concentration of energy therein. Uranium fuel constitutes one of the most common elements on earth. When a large fissile atomic nucleus such as uranium-235 or plutonium-239 absorbs a neutron, it may undergo nuclear fission. The heavy nucleus splits into two or more lighter nuclei, the fission products, releasing kinetic energy, gamma radiation, and free neutrons.

The power output of the reactor is adjusted by controlling how many neutrons are able to create more fissions. Control rods that are made of a neutron poison are used to absorb neutrons. Absorbing more neutrons in a control rod means that there are fewer neutrons available to cause fission, so pushing the control rod deeper into the reactor will reduce its power output, and extracting the control rod will increase it.

In North America there are three different reactors that are most commonly used.

Pressurized Water Reactors (PWR) which use pressure vessel to contain the nuclear fuel, control rods, moderator, and coolant. They are cooled and moderated by high-pressure liquid water. The hot radioactive water that leaves the pressure vessel is looped through a steam generator, which in turn heats a secondary (non-radioactive) loop of water to steam that can run turbines.

Boiling Water Reactors (BWR) are like a pressurized water reactor without the steam generator. A boiling water reactor is cooled and moderated by water like a PWR, but at a lower pressure, which allows the water to boil inside the pressure vessel producing the steam that runs the turbines. Unlike a PWR, there is no primary and secondary loop. The thermal efficiency of these reactors can be higher, and they can be simpler, and even potentially more stable and safe.

Pressurized Heavy Water Reactors (PHWR) are a Canadian design these reactors are heavy-water-cooled and -moderated pressurized-water reactors. Instead of using a single large pressure vessel as in a PWR, the fuel is contained in hundreds of pressure tubes. These reactors are fueled with natural uranium and are thermal neutron reactor designs. PHWRs can be refueled while at full power, which makes them very efficient in their use of uranium.

CHAPTER 1 – INTRODUCTION

This report analyzes the instrumentation and control of the Heat transport system of a CANDU Reactor. The CANDU (short for Canada Deuterium Uranium) reactor is a Canadian-invented, pressurized heavy water reactor. The acronym refers to its heavy water moderator and its use of natural, non-enriched, uranium fuel. CANDU reactors were first developed in the late 1950s and 1960s by a partnership between Atomic Energy of Canada Limited (AECL), the Hydro-Electric Power Commission of Ontario (now Ontario Power Generation), Canadian General Electric (now GE Canada), and other companies. All power reactors built in Canada are of the CANDU type.

1.2 OVERVIEW OF THE HEAT TRANSPORT SYSTEM

Pressure tubes containing fuel pass through the calandria. Large pumps move heavy water coolant through these fuel channels, removing heat from the fuel. The coolant carries the heat from the core to the boilers, where it makes steam. Coolant is the main link in this heat removal chain.

The heavy water coolant removes heat from the fuel and transfers it to the boilers. In normal operation, this is a single task, but it is really two separate functions.

a) The heavy water coolant transfers heat from the fuel to the boilers. This is an essential step leading to steam production and power generation.
b) The heavy water coolant removes heat from the fuel. This task is extremely important, whether or not the reactor is making steam. Keeping the fuel wet protects the fuel. Without adequate cooling, the fuel will fail, releasing hazardous radioactive materials.

Figure 1 shows a typical heat transport system layout. The main circulation pumps take cooled D2O from the boilers and pump it to a reactor inlet header. The header distributes the coolant through feeder pipes to the individual fuel channels.

Hot coolant leaves each channel through an outlet feeder. The outlet header collects the hot coolant from these feeders and directs it to the boilers (steam generators). The hot coolant gives up its heat through the boiler tube walls. The coolant continues from the boiler outlet to a second pump. Another inlet header, feeders and fuel channels take the coolant back to the first boiler.

The boiler produces steam at about 250^{o}C for the turbine. The coolant enters the boiler somewhat hotter than this, roughly 300^{o}C or so. Its temperature drops about 40^{o}C as it passes through the boiler. It regains the higher temperature as it passes through the reactor core.

To prevent D2O at 310^{o}C from boiling, the pressure must be about 10MPa. The main circulating pumps do not produce this pressure; they supply coolant flow. They generate enough pressure to overcome fluid friction in the fuel channels and boiler tubes.

Each loop supplies coolant to half the core. There are two large pumps and two large boilers in each loop. If one pump in a loop fails, it may be possible to continue operation at reduced power with a single pump.

Such large boilers and pumps were not always available. Older stations use larger numbers of smaller boilers and pumps. This sometimes includes standby pumps or boilers. Designs that are more recent do not include standby equipment in the main HTS.

Fuel cooling must continue always, even with the reactor shut down.

Without cooling, heat produced by decay of fission products in the fuel can fail the fuel, releasing fission products. A shutdown cooling system cools the fuel when the main pumps or boilers are either unavailable or not required. The size of the substitute pumps and alternate heat exchangers is adequate to remove decay heat.

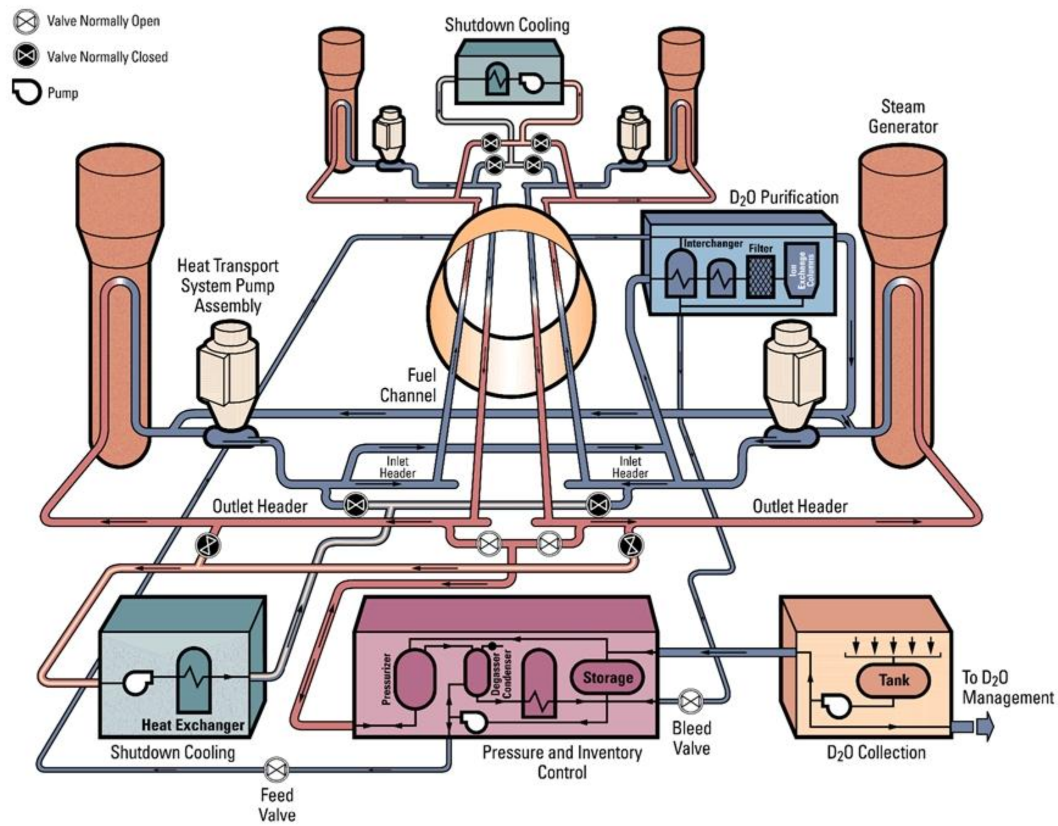

Figure 1: Overview of the Heat Transport System

Chapter 2 – Instrumentation

INSTRUMENTATION

Instrumentation is the art of measuring the value of some plant parameter, pressure, flow, level or temperature and supplying a signal that is proportional to the measured parameter. The output signals are standard signal and can then be processed by other equipment to provide indication, alarms or automatic control. There are a number of standard signals; however, those most common in a nuclear plant are the 4-20 mA electronic signals and the 20-100 kPa pneumatic signals.

2.1 PRESSURE MEASUREMENT

Pressure is probably one of the most commonly measured variables in the power plant. It includes the measurement of steam pressure; feed water pressure, condenser pressure, lubricating oil pressure and many more. Pressure is actually the measurement of force acting on area of surface. We could represent this as:

$$\text{PRESSURE(P)} = \frac{\text{FORCE(F)}}{\text{AREA(A)}}$$

The units of measurement are either in pounds per square inch (PSI) in British units or Pascals (Pa) in metric. As one PSI is approximately 7000 Pa, we often use kPa and MPa as units of pressure.

Pressure varies depending on altitude above sea level, weather pressure fronts and other conditions. The measure of pressure is, therefore, relative and pressure measurements are stated as either gauge or absolute. A gauge pressure device will indicate zero pressure when bled down to atmospheric pressure. Absolute pressure includes the effect of atmospheric pressure with the gauge pressure.

Absolute Pressure = Gauge Pressure + Atmospheric Pressure

The object of pressure sensing is to produce a dial indication, control operation or a standard (4 - 20 mA) electronic signal that represents the pressure in a process.

To accomplish this, most pressure sensors translate pressure into physical motion that is in proportion to the applied pressure. The most common pressure sensors or primary pressure elements are described below.

2.1.1 Bourdon Tubes

Bourdon tubes are circular-shaped tubes with oval cross sections (refer to Figure 2). The pressure of the medium acts on the inside of the tube. The outward pressure on the oval cross section forces it to become rounded.

Because of the curvature of the tube ring, the bourdon tube then bends as indicated in the direction of the arrow.

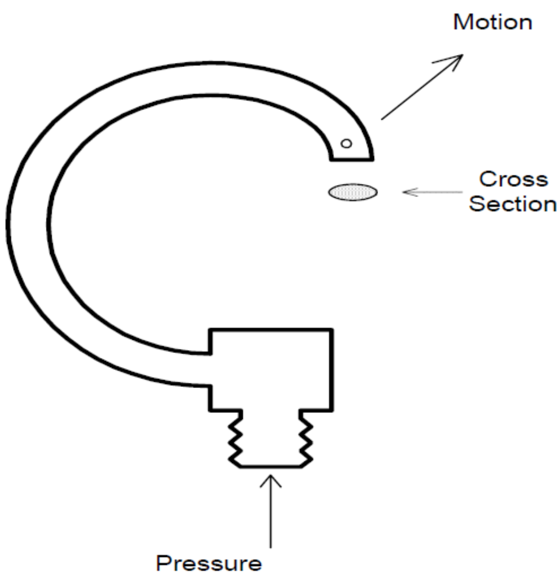

Figure 2: Bourdon Tube

Due to their robust construction, bourdon are often used in harsh environments and high pressures, but can also be used for very low pressures; the response time however, is slower than the bellows or diaphragm.

2.1.2 Bellows

Bellows type elements are constructed of tubular membranes that are convoluted around the circumference (see Figure 3). The membrane is attached at one end to the source and at the other end to an indicating device or instrument. The bellows element can provide a long range of motion (stroke) in the direction of the arrow when input pressure is applied.

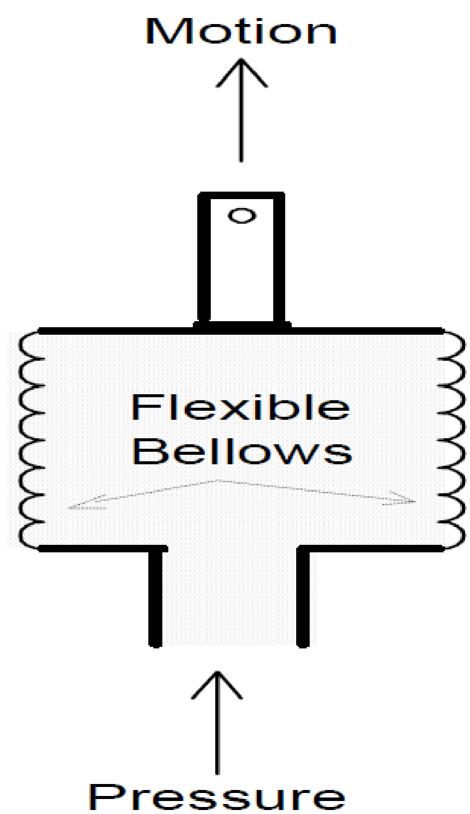

Figure 3: Bellows

2.1.3 Diaphragms

A diaphragm is a circular-shaped convoluted membrane that is attached to the pressure fixture around the circumference (refer to Figure 4). The pressure medium is on one side and the indication medium is on the other.

The deflection that is created by pressure in the vessel would be in the direction of the arrow indicated.

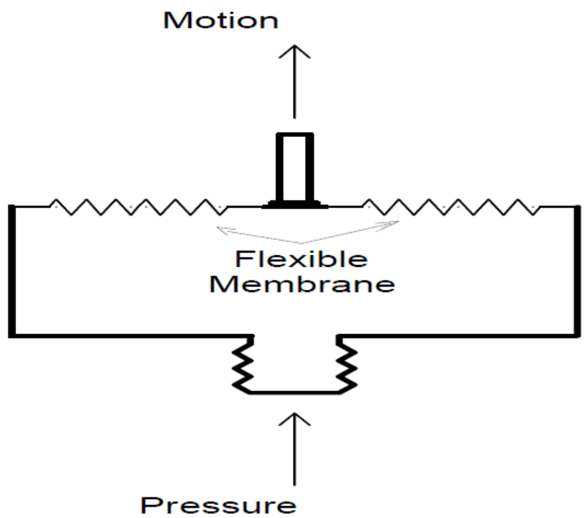

Figure 4: Diaphragm

Diaphragms provide fast acting and accurate pressure indication. However, the movement or stroke is not as large as the bellows

2.1.4 Capsules

There are two different devices that are referred to as capsule. The first is shown in figure 5. The pressure is applied to the inside of the capsule and if it is fixed only at the air inlet it can expand like a balloon. This arrangement is not much different from the diaphragm except that it expands both ways.

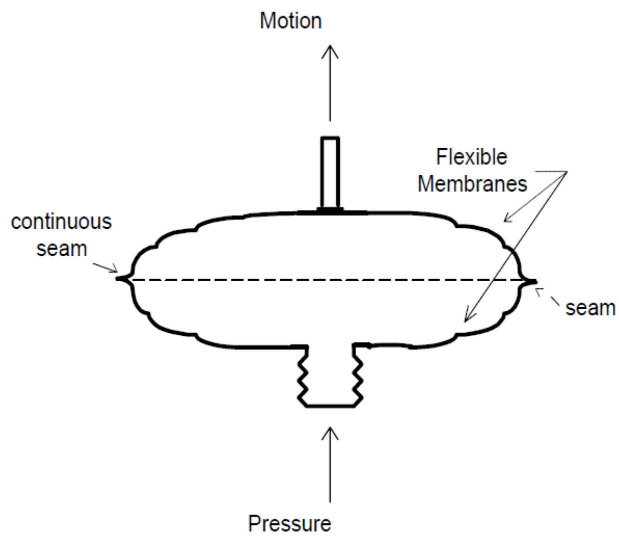

Figure 5: Capsule

The capsule consists of two circular shaped, convoluted membranes (usually stainless steel) sealed tight around the circumference. The pressure acts on the inside of the capsule and the generated stroke movement is shown by the direction of the arrow.

The second type of capsule is like the one shown in the differential pressure transmitter (DP transmitter) in figure 7. The capsule in the bottom is constructed with two diaphragms forming an outer case and the interspace is filled with viscous oil. Pressure is applied to both side of the diaphragm and it will deflect towards the lower pressure.

To provide over-pressurized protection, a solid plate with diaphragm matching convolutions is usually mounted in the center of the capsule. Silicone oil is then used to fill the cavity between the diaphragms for even pressure transmission.

Most DP capsules can withstand high static pressure of up to 14 MPa (2000 psi) on both sides of the capsule without any damaging effect. However, the sensitive range for most DP capsules is quite low. Typically, they are sensitive up to only a few hundred kPa of differential pressure.

Differential pressure that is significantly higher than the capsule range may damage the capsule permanently.

2.1.5 Differential Pressure Transmitters

Most pressure transmitters are built around the pressure capsule concept.

They are usually capable of measuring differential pressure (that is, the difference between a high pressure input and a low pressure input) and therefore, are usually called DP transmitters or DP cells.

Figure 6 illustrates a typical DP transmitter. A differential pressure capsule is mounted inside a housing. One end of a force bar is connected to the capsule assembly so that the motion of the capsule can be transmitted to outside the housing. A sealing mechanism is used where the force bar penetrates the housing and also acts as the pivot point for the force bar. Provision is made in the housing for high-pressure fluid to be applied on one side of the capsule and low-pressure fluid on the other.

Any difference in pressure will cause the capsule to deflect and create motion in the force bar. The top end of the force bar is then connected to a position detector, which via an electronic system will produce a 4 - 20 ma signal that is proportional to the force bar movement.

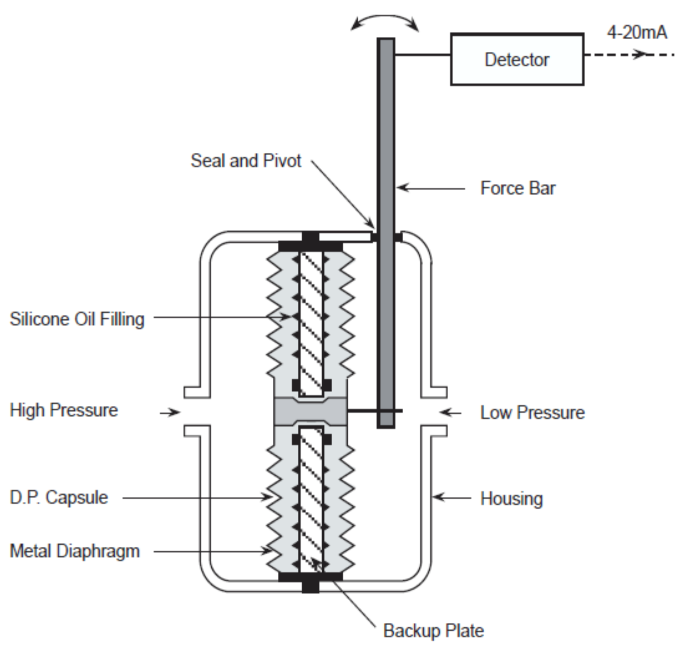

Figure 6: Typical DP Transmitter Construction

This DP transmitter would be used in an installation as shown in Figure 7.

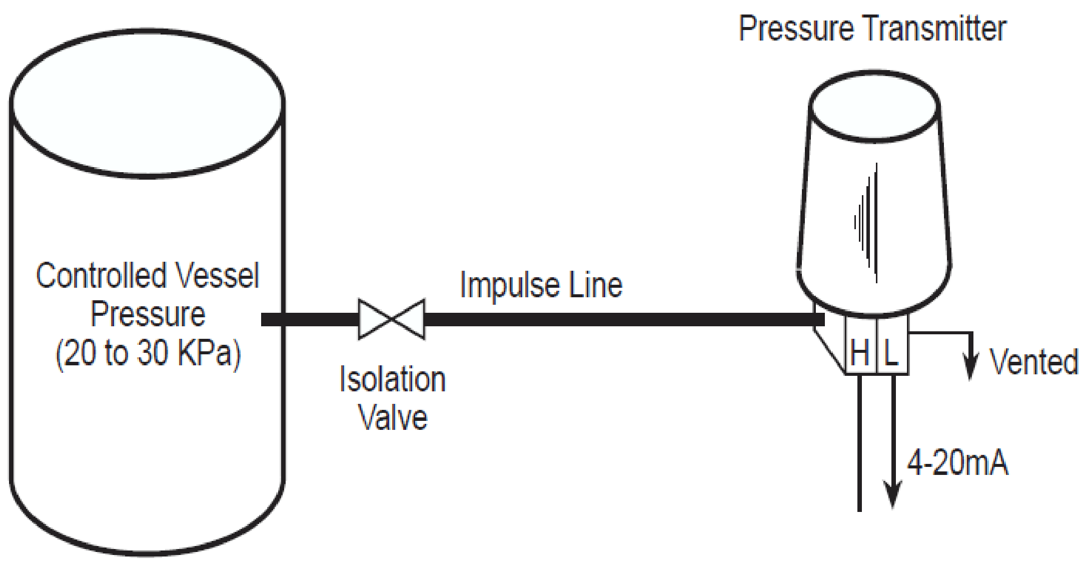

Figure 7: DP Transmitter Application

DP transmitter is used to measure the gas pressure (in gauge scale) inside a vessel. In this case, the low-pressure side of the transmitter is vented to atmosphere and the high-pressure side is connected to the vessel through an isolating valve. The isolating valve facilitates the removal of the transmitter.

The output of the DP transmitter is proportional to the gauge pressure of the gas, i.e., 4 mA when pressure is 20 kPa and 20 mA when pressure is 30 kPa.

2.1.6 Capacitance Capsule

A capacitance cell measures changes in electrical characteristic. As the name implies the capacitance cell measures changes in capacitance. The capacitor is a device that stores electrical charge. It consists of metal plates separated by an electrical insulator. The metal plates are connected to an external electrical circuit through which electrical charge can be transferred from one metal plate to the other.

The capacitance of a capacitor is a measure of its ability to store charge.

The capacitance of the capacitance of a capacitor is directly proportional to the area of the metal plates and inversely proportional to the distance between them. It also depends on a characteristic of the insulating material between them. This characteristic, called permittivity is a measure of how well the insulating material increases the ability of the capacitor to store charge.

$$C = \varepsilon \frac{A}{D}$$

C is the capacitance in Farads

A is the area of the plates

D is the distance of the plates

ε is the permittivity of the insulator

By building a DP cell capsule so there are capacitors inside the cell capsule, differential pressures can be sensed by the changes in capacitance of the capacitors as the pressure across the cell is varied.

2.2 FLOW MEASUREMENT

To measure the rate of flow by the differential pressure method, some form of restriction is placed in the pipeline to create a pressure drop. Since flow in the pipe must pass through a reduced area, the pressure before the restriction is higher than after or downstream. Such a reduction in pressure will cause an increase in the fluid velocity because the same amount of flow must take place before the restriction as after it. Velocity will vary directly with the flow and as the flow increases a greater pressure differential will occur across the restriction. So by measuring the differential pressure across a restriction, one can measure the rate of flow.

2.2.1 Orifice Plate

The orifice plate is the most common form of restriction that is used in flow measurement. An orifice plate is basically a thin metal plate with a hole bored in the center. It has a tab on one side where the specification of the plate is stamped. The upstream side of the orifice plate usually has a sharp, edge. Figure 8 shows a representative orifice plate.

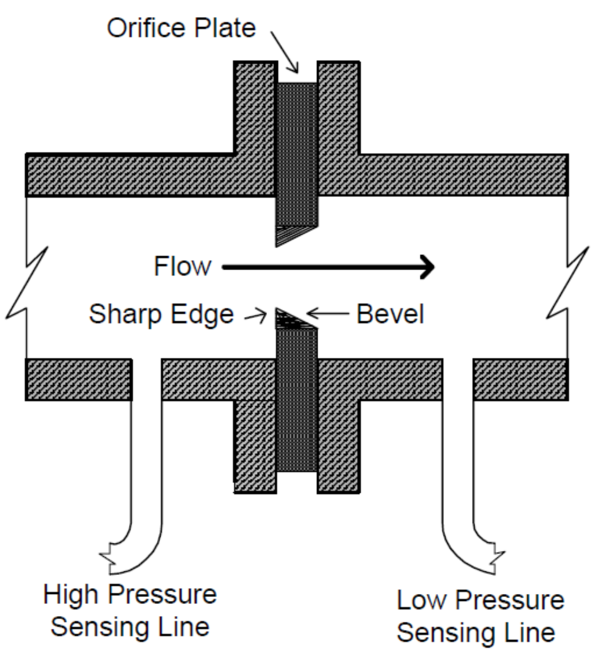

Figure 8: A Typical Orifice Plate

When an orifice plate is installed in a flow line (usually clamped between a pair of flanges), increase of fluid flow velocity through the reduced area at the orifice develops a differential pressure across the orifice. This pressure is a function of flow rate.

With an orifice plate in the pipe work, static pressure increases slightly upstream of the orifice (due to back pressure effect) and then decreases sharply as the flow passes through the orifice, reaching a minimum at a point called the vena contracta where the velocity of the flow is at a maximum. Beyond this point, static pressure starts to recover as the flow slows down. However, with an orifice plate, static pressure downstream is always considerably lower than the upstream pressure. In addition some pressure energy is converted to sound and heat due to friction and turbulence at the orifice plate. Figure 9 shows the pressure profile of an orifice plate installation.

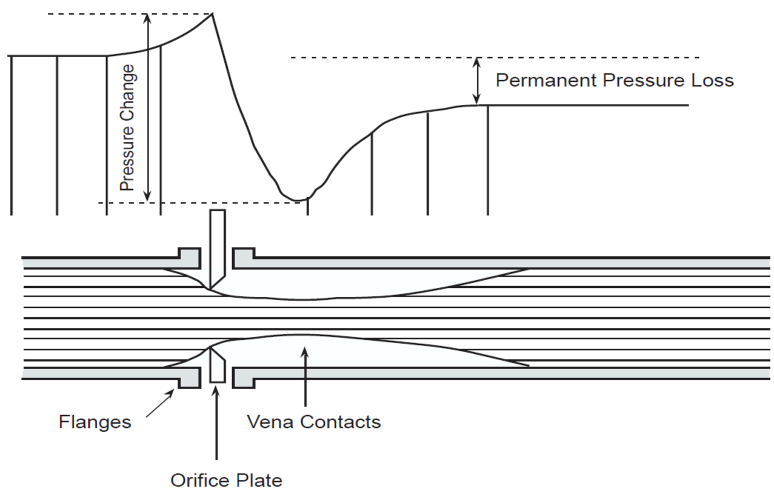

Figure 9: Orifice Plate Installation with Pressure Profile

On observing Figure 9, one can see that the measured differential pressure developed by an orifice plate also depends on the location of the pressure sensing points or pressure taps.

2.2.2 Flange Taps

Flange taps are the most widely used pressure tapping location for orifices.

They are holes bored through the flanges, located one inch upstream and one inch downstream from the respective faces of the orifice plate. A typical flange tap installation is shown in Figure 10. The upstream and downstream sides of the orifice plate are connected to the high pressure and low-pressure sides of a DP transmitter. A pressure transmitter, when installed to measure flow, can be called a flow transmitter. As in the case of level measurement, the static pressure in the pipe-work could be many times higher than the differential pressure created by the orifice plate.

In order to use a capsule that is sensitive to low differential pressure, a three valve manifold has to be used to protect the DP capsule from being over ranged.

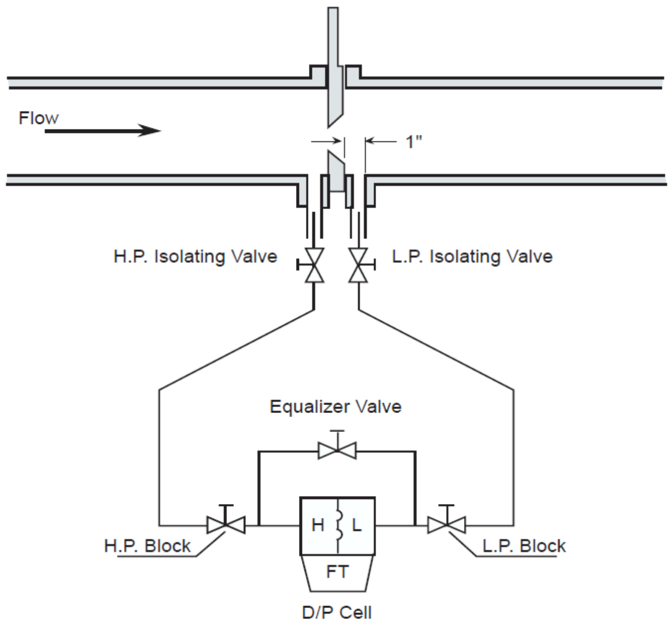

Figure 10: Orifice Plate with Flange Taps and Three Valve Manifold

2.2.3 Square Root Extractor

The high and low-pressure taps of the primary device (orifice type shown above) are fed by sensing lines to a differential pressure (D/P) cell. The output of the D/P cell acts on a pressure to milliamp transducer, which transmits a variable 4-20 ma signal. The D/P cell and transmitter are shown together as a flow transmitter

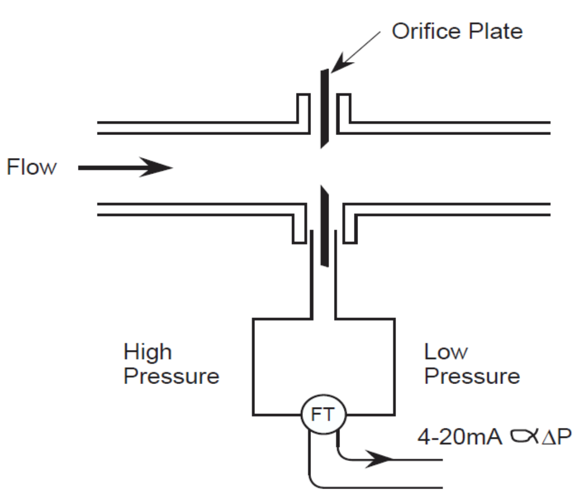

Figure 11: A Flow Loop with Orifice Plate

This simple system although giving an indication of the flow rate (Q), is actually transmitting a signal proportional to the differential pressure (ΔP).

However, the relationship between the volume of flow Q and ΔP is not linear. Thus such a system would not be appropriate in instrumentation or metering that requires a linear relationship or scale.

In actuality the differential pressure increases in proportion to the square of the flow rate.

We can write this as: ΔP x Q^2

In other words the flow rate (Q) is proportional; to the square root of the differential pressure.

Volumetric Flow Rate = Q x Δ P

To convert the signal from the flow transmitter, to one that is directly proportional to the flow-rate, one has to obtain or extract the square root of the signal from the flow transmitter. Figure 12 illustrates the input - output relationship of a square root extractor.

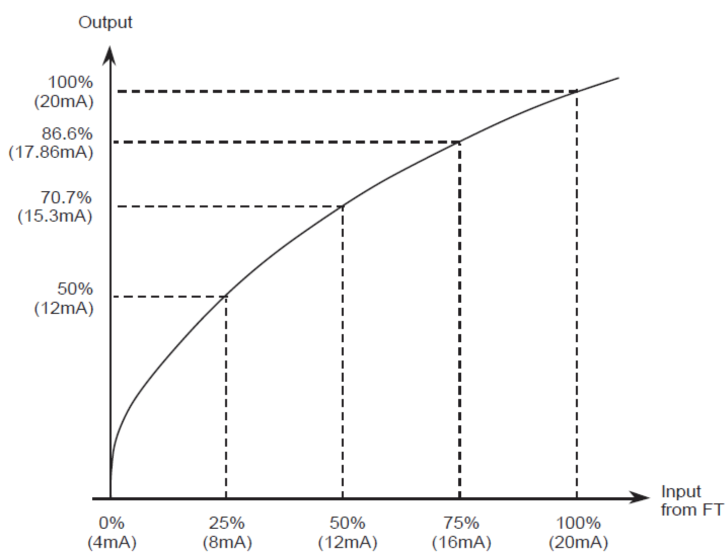

Figure 12: Square Root Extractor Input and Output

The square root extractor is an electronic (or pneumatic) device that takes the square root of the signal from the flow transmitter and outputs a corresponding linear flow signal. A typical square root extractor installation is shown in below. This system would produce a 4-20-ma signal that is linear with the flow rate.

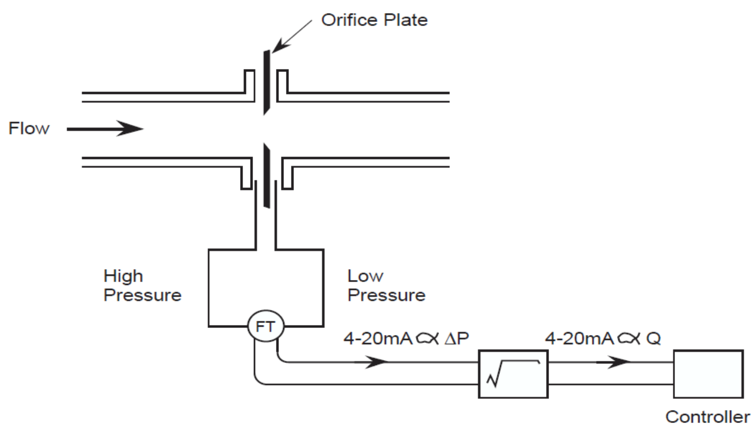

Figure 13: A Typical Square Root Extractor Installation

Square root extractors are usually current operated devices so they can be connected directly in the 4-20 mA current loop of a flow transmitter. The output of the square root extractor is again a 4-20 mA signal. This signal is directly proportional to the flow-rate in the pipe-work. The signal from the square root extractor usually goes to a controller. The controller (which can be regarded as an analog computer) is used to control the final control element, usually a valve.

2.3 LEVEL MEASUREMENT

Very simple systems employ external sight glasses or tubes to view the height and hence the volume of the fluid. Others utilize floats connected to variable potentiometers or rheostats that will change the resistance according to the amount of motion of the float. This signal is then inputted to transmitters that send a signal to an instrument calibrated to read out the height or volume.

The pressure at the base of a vessel containing liquid is directly proportional to the height of the liquid in the vessel. This is termed hydrostatic pressure.

As the level in the vessel rises, the pressure exerted by the liquid at the base of the vessel will increase linearly. Mathematically, we have:

$$P = S \times H$$

Where

P = Pressure (Pa)

S = Weight density of the liquid (N/m3) = ρg

H = Height of liquid column (m)

ρ = Density (kg/m3)

g = acceleration due to gravity (9.81 m/s2)

The level of liquid inside a tank can be determined from the pressure reading if the weight density of the liquid is constant.

Differential Pressure (DP) capsules are the most commonly used devices to measure the pressure at the base of a tank. When a DP transmitter is used for the purpose of measuring a level, it will be called a level transmitter.

2.4 TEMPERATURE MEASUREMENT

Every aspect of our lives, both at home and at work, is influenced by temperature. Temperature measuring devices have been in existence for centuries. The age-old mercury in glass thermometer is still used today.

2.4.1 Resistance Temperature Detector (RTD)

Every type of metal has a unique composition and has a different resistance to the flow of electrical current. This is termed the resistively constant for that metal. For most metals the change in electrical resistance is directly proportional to its change in temperature and is linear over a range of temperatures. This constant factor called the temperature coefficient of electrical resistance is the basis of resistance temperature detectors. The RTD can actually be regarded as a high precision wire wound resistor whose resistance varies with temperature. By measuring the resistance of the metal, its temperature can be determined.

Several different pure metals (such as platinum, nickel and copper) can be used in the manufacture of an RTD. A typical RTD probe contains a coil of very fine metal wire, allowing for a large resistance change without a great space requirement. Usually, platinum RTDs are used as process temperature monitors because of their accuracy and linearity.

To detect the small variations of resistance of the RTD, a temperature transmitter in the form of a Wheatstone bridge is generally used. The circuit compares the RTD value with three known and highly accurate resistors.

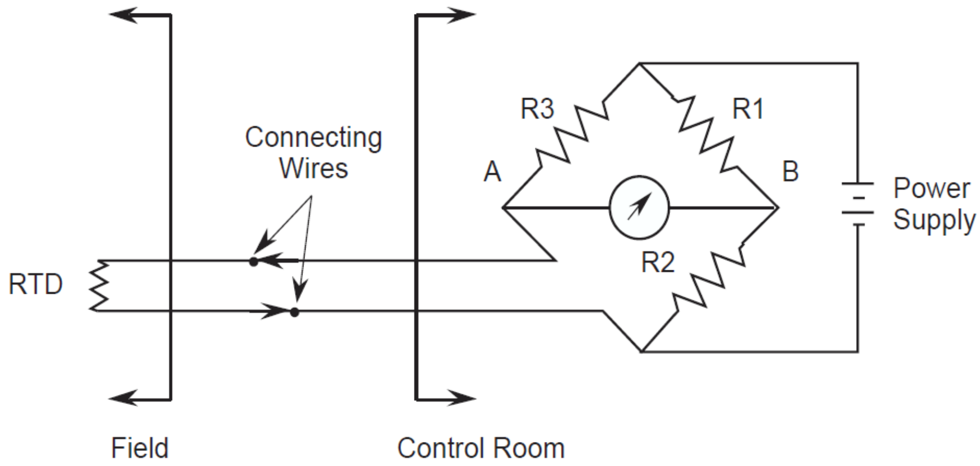

Figure 14: RTD using a Wheatstone Bridge

A Wheatstone bridge consisting of an RTD, three resistors, a voltmeter and a voltage source. In this circuit, when the current flow in the meter is zero (the voltage at point A equals the voltage at point B) the bridge is said to be in null balance. This would be the zero or set point on the RTD temperature output. As the RTD temperature increases, the voltage read by the voltmeter increases. If a voltage transducer replaces the voltmeter, a 4-20 mA signal, which is proportional to the temperature range being monitored, can be generated.

2.4.2 Thermocouple

A thermocouple consists of two pieces of dissimilar metals with their ends joined together (by twisting, soldering or welding). When heat is applied to the junction, a voltage, in the range of milli-volts (mV), is generated. A thermocouple is therefore said to be self-powered. Shown below is a completed thermocouple circuit.

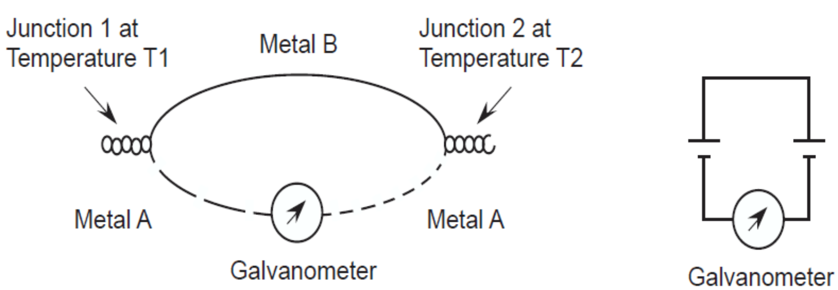

Figure 15: A Thermocouple Circuit

The voltage generated at each junction depends on junction temperature. If temperature T1 is higher than T2, then the voltage generated at Junction 1 will be higher than that at Junction 2. In the above circuit, the loop current shown on the galvanometer depends on the relative magnitude of the voltages at the two junctions.

In order to use a thermocouple to measure process temperature, one end of the thermocouple has to be kept in contact with the process while the other end has to be kept at a constant temperature. The end that is in contact with the process is called the hot or measurement junction. The one that is kept at constant temperature is called cold or reference junction. The relationship between total circuit voltage (emf) and the emf at the junctions is:

Circuit emf = Measurement emf - Reference emf

If circuit emf and reference emf are known, measurement emf can be calculated and the relative temperature determined.

To convert the emf generated by a thermocouple to the standard 4-20 mA signal, a transmitter is needed. This kind of transmitter is called a temperature transmitter.

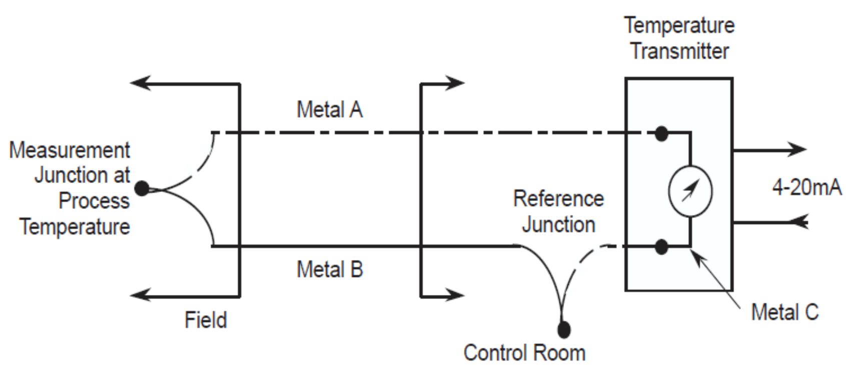

Figure 16: A Simplified Thermocouple Temperature Transmitter

In Figure 16 above, the temperature measurement circuit consists of a thermocouple connected directly to the temperature transmitter. The hot and cold junctions can be located wherever required to measure the temperature difference between the two junctions.

Chapter 3 – Heat Transport Control

HEAT TRANSPORT CONTROL

The purpose of the Heat Transport System (HTS) is to transfer the heat generated by the fission process in the reactor to the steam generators. The heat transfer medium is pressurized heavy water and the principle control for this system will be the regulation of the pressure within the heat transport system.

The heat transport system must be able to respond to disturbances from either the reactor (source) or turbine side (sink) of the energy balance. The means of pressure control varies and is either a feed & bleed or a pressurizer vessel as the primary control system, but with feed and bleed for inventory control.

3.1 Feed and Bleed Pressure Control

The HTS is essentially an enclosed loop system (Figure 1) normally maintained at a pressure of approximately 10 MPa.

Any deficiencies in pressure will be corrected by feeding additional D2O into the system from the pressurizing pumps. Conversely, any excess of pressure will be countered by bleeding D2O from the system to the bleed condenser. The system must be capable of being controlled over the range 0 - 10 MPa, (i.e., from a cold shutdown state to a pressurized, hot condition. Control over this wide range is divided into two regions: wide (0- 12 Mpa) and narrow (6-12 MPa).

(a) Wide Range Control is used when warming-up or cooling-down the system up to or from its normal operating state. It is a “coarse", lower gain (say 0-12 Mpa), control system.

(b) Narrow Range Control is used to control the system pressure at its normal operating set point, i.e., a "fine", higher gain (say 6-12 Mpa) , control system.

The basic method of control both in wide and narrow ranges is to drive the feed and bleed valves from a single control signal, i.e., a split range control system.

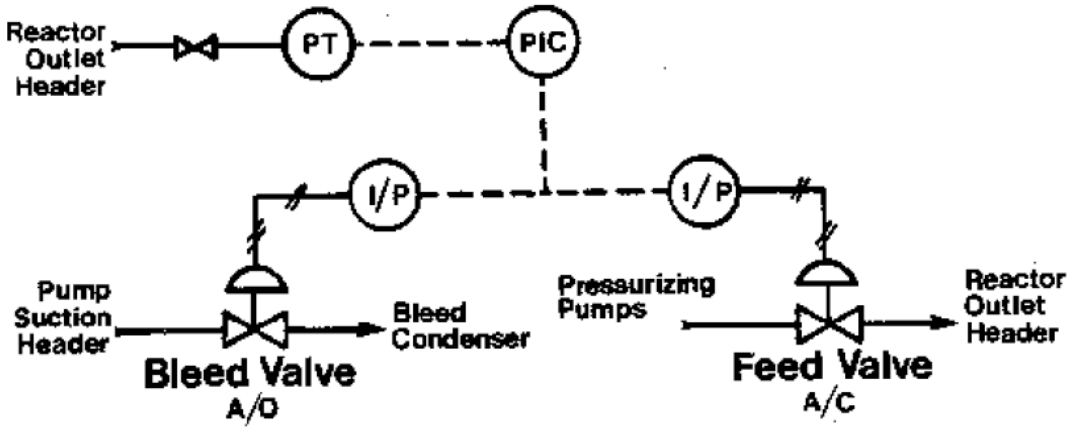

Figure 17: Simplified Split Range Feed and Bleed Control System.

The reactor outlet header pressure is sensed by a pressure transmitter (PT). This pressure signal is fed to the direct acting pressure controller (PIC) the output of which is split ranged to a fail-closed bleed valve and a fail open feed valve via two I/P transducers. With the pressure at the set point (50% - 12 mA signal) neither feed nor bleed action is required and both valves could be closed.

If the pressure is above the set point, the increased signal from the PIC would drive the bleed valve open (with feed valve closed) – so pressure can be bled off.

The opposite would be true for too low a pressure in the HTS, i.e., feed valve opens on the decreasing signal from the pressure controller while the bleed valve is closed - pressure builds up.

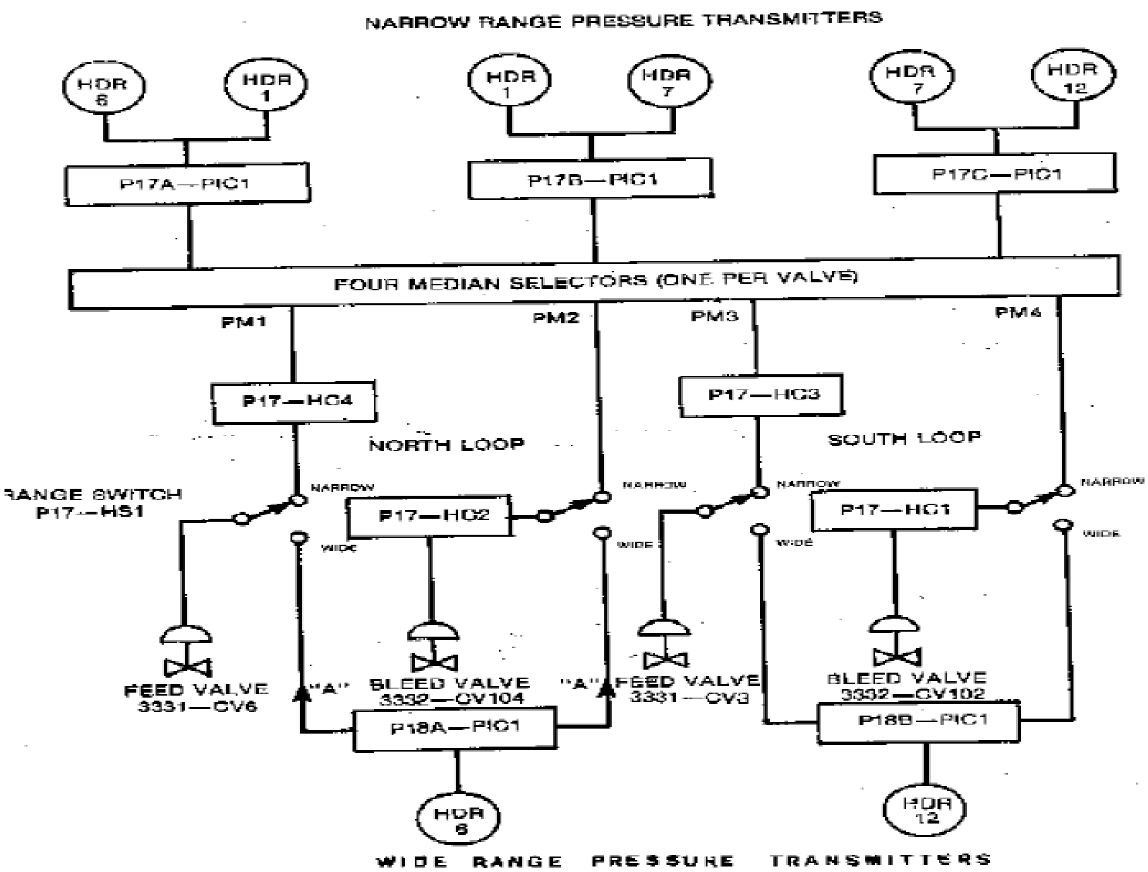

Figure 18: Heat Transport Pressure Control Scheme.

3.1.1 Wide Range Control

There are two pressure transmitters, which provides a signal to a pressure controller, each of which drives a feed and bleed valve combination.

This wide range control is used only for warm-up and cool down operations.

Essentially in the warm-up condition the bleed valve will be opened continuously with feed valves closed in response to the rising system temperature causing inventory swell & pressure increase. This excess D2O is routed via the bleed valves to the D2O storage tank.

Conversely, during cool down operations the feed valve will need to be opened with bleed valve closed to provide makeup D2O in order to maintain the HTS inventory as it shrinks.

3.1.2 Narrow Range Control

Range pressure control of the HTS is required at the operating state to provide the necessary pressure regulation and to prevent large pressure transients. The narrow range pressure control system drives the feed and bleed valves with a median control signal selected from three controllers which accept averaged signals from six pressure transmitters (Figure 18).

The narrow range system can be considered as consisting of three measurement branches: P17A, P17B, and P17C.

These two current signals are averaged and input as the measurement signal for control P17A - PIC1. Similarly, the averaged pressure measurement signals are compared to the set points by the three controllers and corrective control signals are produced.

The three narrow range pressure set points are staggered to prevent the controllers 'fighting' for control. These control output signals are applied to four median select relays which will select the median control signal (reject the high and low signals). The four median selectors should block any irrational signals caused by instrumentation faults.

The normal setup will be for P17B-PIC1 to be set to the system set point as its inputs are from both the north and south loops of the HTS. The median control signal passes to the bleed valves manual stations HC-1, and HC-2 via the wide/narrow range switch contacts. If narrow range pressure control is selected, the same median control signal will be applied to all four control valves. The bleed valves (CV102, CV104) have an adjustable bias provision so that an extra constant component can be added to the median signal.

The bias value will cause the bleed valves to be more open than the median control signal would request. Increasing the bias will increase the bleed rate, raising the purification flow.

3.2 PRESSURE CONTROL BY PRESSURIZER

For a system equipped with a pressurizer, control is still divided into two modes.

The solid mode, which is the wide range control system, is used for warm-up and cool-down operations. The pressurizer is isolated from the system by an isolating valve and controls is by a feed and bleed split range pressure control system as previously described.

Under normal mode, at power, operating conditions pressure control is provided by the pressurizer.

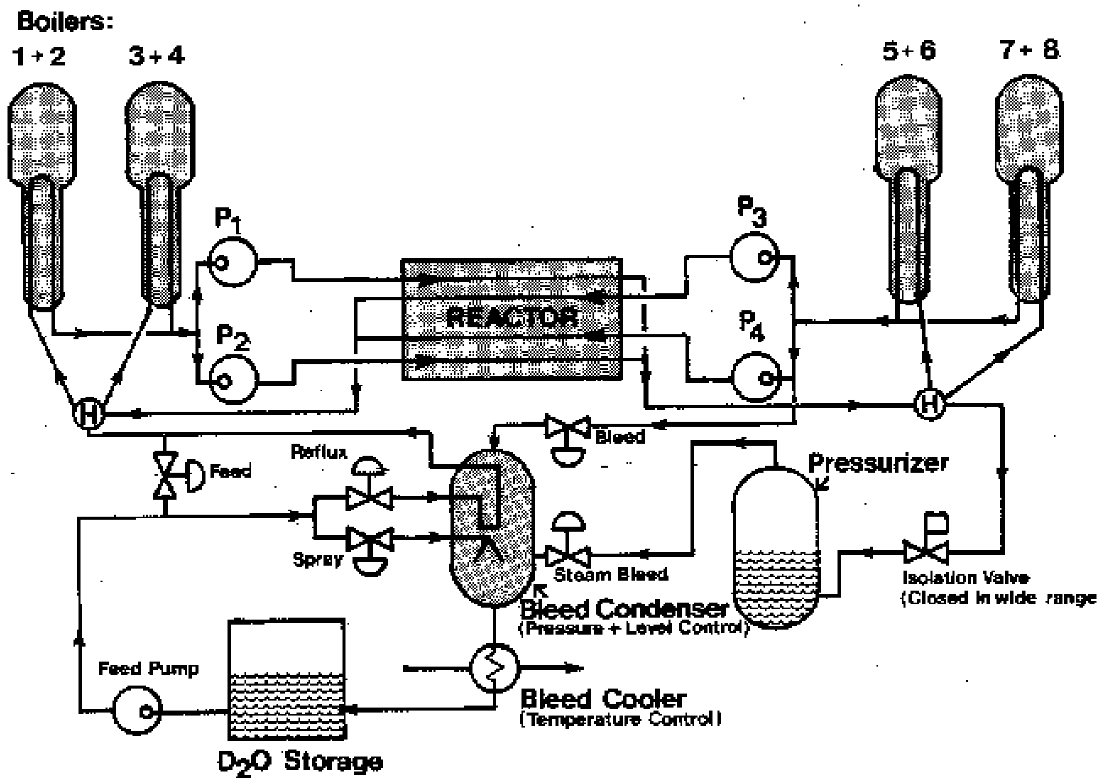

Figure 19: CANDU Heat transport System with Pressurizer.

3.2.1 Wide Range Control

When in the solid mode, saturation conditions are established in the pressurizer (9.9 MPa(g), 310° C). This saturation pressure is established by a combination of electric heaters and steam bleed valves.

If the pressure is too high, the control system will switch off all heaters, if the pressure continues to rise, the control system will then open the steam bleed valves. Usually the pressure is maintained relatively constant with one variable heater on for ambient losses and the steam bleed valves closed.

The opposite occurs if the pressure is too low, i.e., steam valves close and heaters are progressively switched on. It is also necessary to prevent heater operation if an insufficient level of D2O is present in the pressurizer. If the level is too low all heaters will switch off by the logic control.

3.2.2 Narrow Range (Normal Mode) Control

Pressure control under normal mode is performed exclusively by the pressurizer. The isolation valve is opened and the HTS pressure is controlled by manipulation of the heaters and the steam bleed valves. The feed and bleed system is controlled on pressurizer level and is used only for purification and inventory control purposes.

During power increases the heat transport fluid expands and the excess flows into the pressurizer. It is most important that the pressurizer should never become full of liquid as it must always have a vapour (steam) space in order to be able to absorb pressure changes.

The reactor power should be able to be manoeuvred up or down without requiring a change to the feed and bleed valve positions. If the pressurizer level deviates from the characterized set point level curve, the control system will operate the feed and bleed valves to correct for the inventory disturbance.

3.3 Pressurizer Instrumentation and Control Logic

Heat transport system pressure is sensed by six pressure transmitters PT1-6 arranged three to each reactor outlet header. Paired transmitters, one from each header, have their outputs routed via a high signal selector (Hl) eliminating the effect of a transmitter which fails to zero output (the usual failure mode).

Each of the three high signals is then routed to a direct acting pressure controller (PIC1 - 3), the outputs of which are fed to a median select circuit which provides the signal for the steam bleed valves and the variable heater. Low pressure is sensed by current sensors (CA1-3) which will switch on the on/off heaters to raise pressure. The "heater on" signals are dependent on there being sufficient D_2O in the pressurizer. This conditioning is achieved by the triplicated level transmitters (LT1 - 3) and the two out of three logic (2/3) module, i.e., low level - heaters switched off.

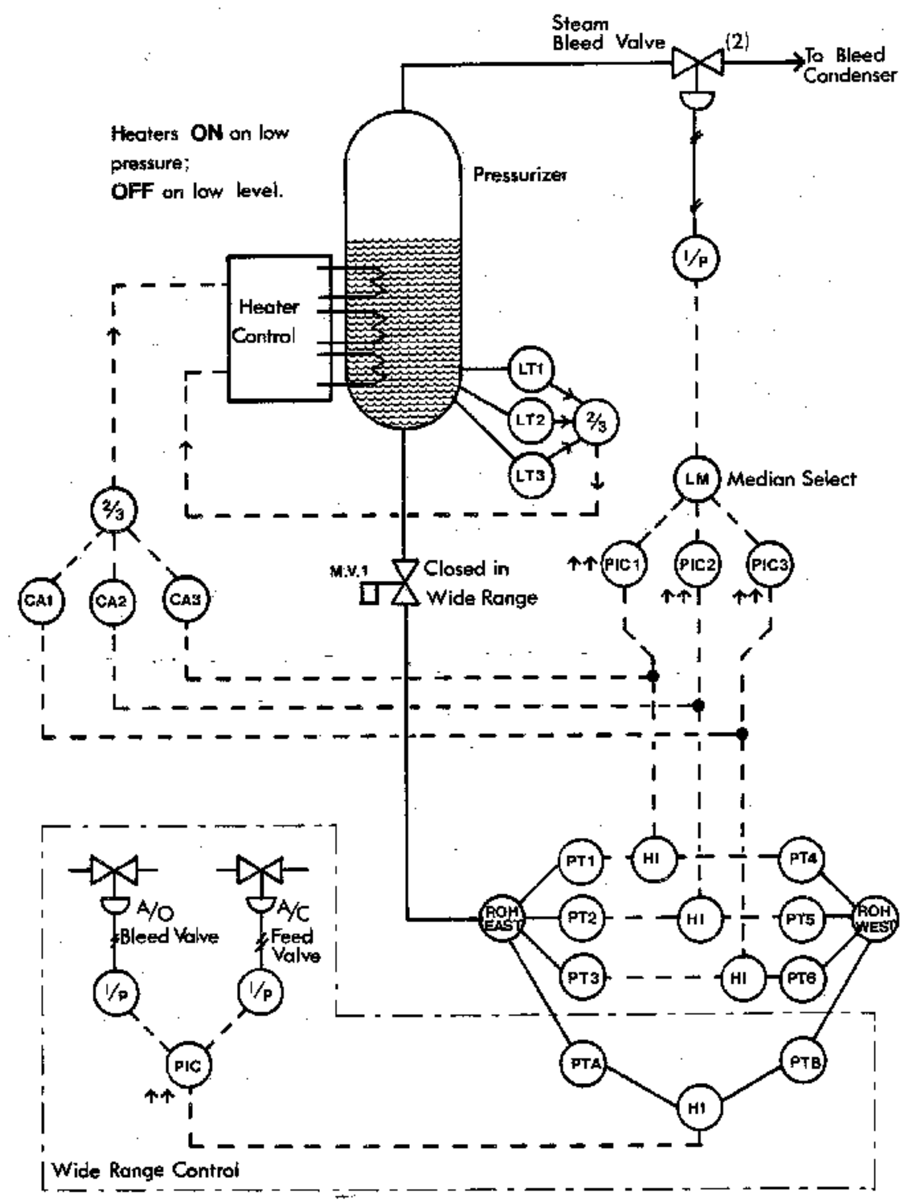

Figure 20: Pressure control by pressurizer

The level in the pressurizer is characterized to rise as power level is increased to accommodate the HTS inventory expansion. This is done for two reasons:

(a) To minimize the use of the feed and bleed system and thus ensure the bleed condenser and bleed cooler have a reasonably constant load.
(b) To provide an immediate inventory make-up to the HTS to maintain pressure control in the event of a reactor trip when D2O shrinkage, due to the loss of heat source, is at a maximum.

The pressurizer is also fitted with pressure release valves. In the event that the pressurizer pressure rises above its normal control limits, these pressure relief valves discharge to the bleed condenser, protecting the pressurizer from an overpressure condition while ensuring that there is no loss of fluid from the heat transport system.

3.4 HEAT TRANSPORT BLEED CONTROL

Any bleed flow from the Heat Transport System as a result of either too high a pressure or deliberately induced bleed flow for clean up purposes must be reduced in pressure and temperature before passing through the ion exchange systems and on to D2O storage.
This is accomplished by the combination of the bleed condenser and bleed cooler with control requirements as follows:

a) To lower pressure and temperature from approximately 9.0 MPa at 265° C to approximately 2 MPa and 205° C in the bleed condenser, i.e., Bleed Condenser Pressure Control.
b) To maintain an adequate inventory in the bleed condenser, i.e., Bleed Condenser Level Control.
c) To lower the temperature of Bleed outflow from the bleed condenser to approximately 45°C before passing through the I/X columns, i.e., Temperature Control of Bleed Cooler.

3.4.1 Bleed Condenser Pressure Control

The preferred method of bleed condenser pressure control is by throttling the reflux valve (CV111). The backup method of pressure control, spray valve (CV113) regulation, is not as desirable because it results in extra flow through the IX columns and promotes degassing of the D2O in the condenser.
Both the reflux and the spray valve are equipped with air to open actuators. Both reflux and spray controllers have direct control actions so that the control signal will increase as the pressure rises above the set point.
The set points of the two pressure control loops are staggered with the reflux set point the lowest (approximately 1.6 MPa).

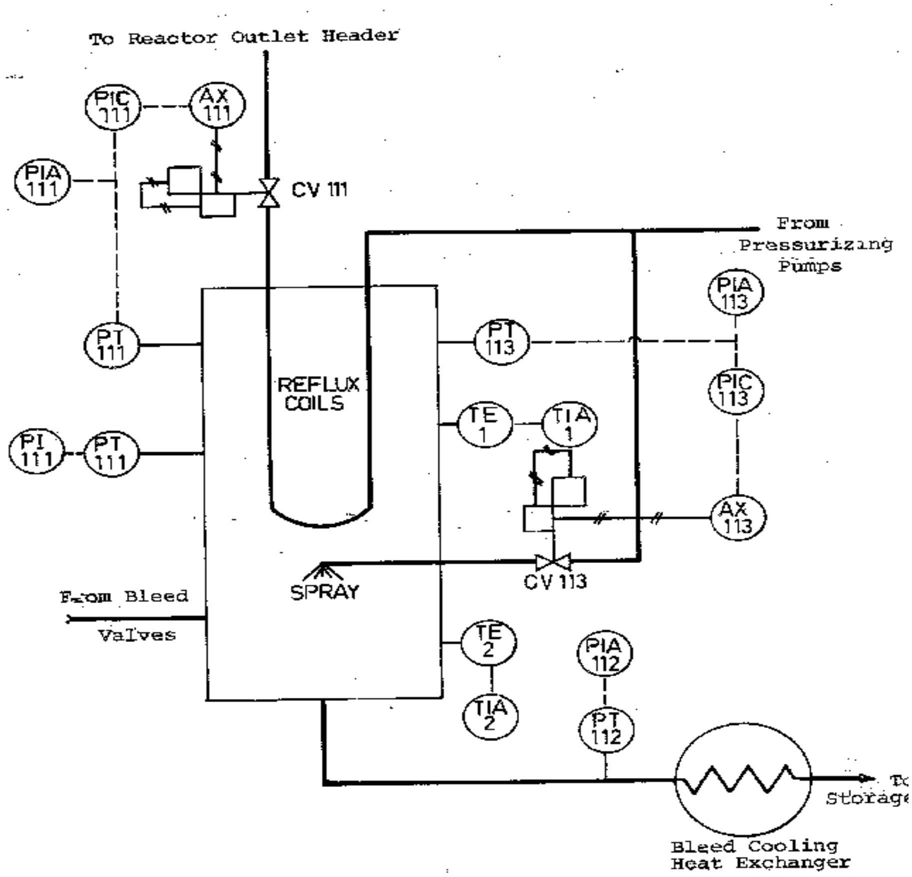

Figure 21: Bleed Condenser Pressure Control

As long as the pressure is successfully controlled by the reflux method, the spray valve will not be opened (i.e. pressure will be below the spray controller set point). The set point for the spray controller is approximately 1.9 MPa or 300 kPa above the reflux set point.

Should the bleed condenser pressure rise unchecked by the reflux system, the spray controller will begin to drive the spray valve open. A high bleed condenser pressure condition will be annunciated when the bleed condenser pressure rises to 2.24 Mpa.

The spray valve opening is inhibited on high bleed condenser level to avoid filling the condenser solid and pressurizing to spray valve discharge pressures.

3.4.2 Bleed Condenser Level Control

During normal system operation, the bleed condenser level is regulated by throttling an outflow control valve (CV122 or CV123).

This control problem can be considered, in general, as the level control of a tank by outflow regulation where the tank is supplied with a non constant inflow. A duplicated system is employed with staggered set points for the identical level loops. Consider the level loop identified with tag number 122 (LT-122 to CV122) in Figure 22

The control valve (CV122) on the outflow line is an air to open globe valve. If the level in the bleed condenser sensed by LT-122 is too high, the valve must be driven more open - LC122 is a direct acting controller.

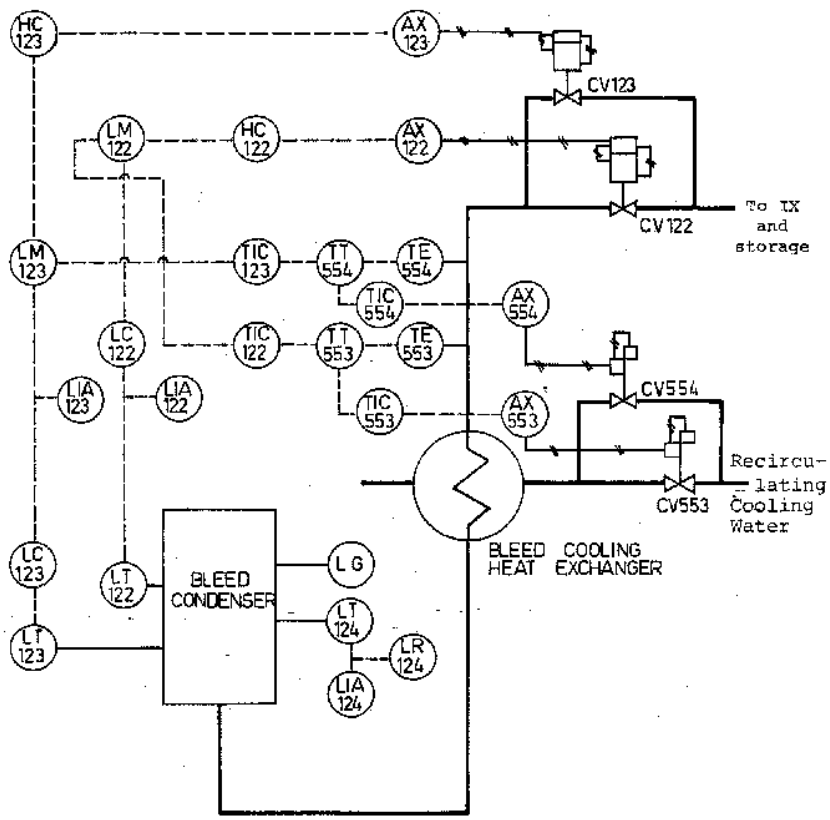

Figure 22: Bleed Condenser Level and Bleed Temperature Control.

The signal from the direct acting LC-122 is fed to a low select relay which will pass the lowest of the two signals applied, (e.g., 10 mA and 12 mA input, 10 mA output).

Assume at this time that the level control signal is the lowest signal input to relay. The selected lowest signal is directed from relay to an auto/manual station controller so that manual control of the outflow valve is possible if the controller becomes inoperative.

The control signal from the auto/manual station controller then drives an I/P transducer (AX122) which allows the electronic loop to be interfaced with the pneumatic actuator of CV122.

The operation of the level loop tagged 123 is identical to 122 except that the set point is approximately twenty percent higher. As long as the level is regulated by loop 122, the backup loop 123 will be inactive and CV-123 will remain closed.

These set points can be alternated on a duty cycle basis to ensure equal work periods for both loops.

3.4.3 Bleed Cooler Effluent Temperature Control

The effluent temperature of the bleed cooler is regulated by a duplicated system consisting of the control loops tagged 553 and 554. Consider the loop tagged 553 in Figure 23.

The effluent temperature is sensed by an RTD which produces a change in resistance proportional to the measured change in temperature. This change in resistance is then converted to a corresponding mA signal by TT-553. The current signal from the temperature transmitter is applied as the input to two temperature controllers (TIC-553, TIC-122) which are connected in series in the transmitter circuit. The function of TIC-122 will be discussed in the next section on temperature override.

Temperature control valve (CV-553) is an air-to-open valve.

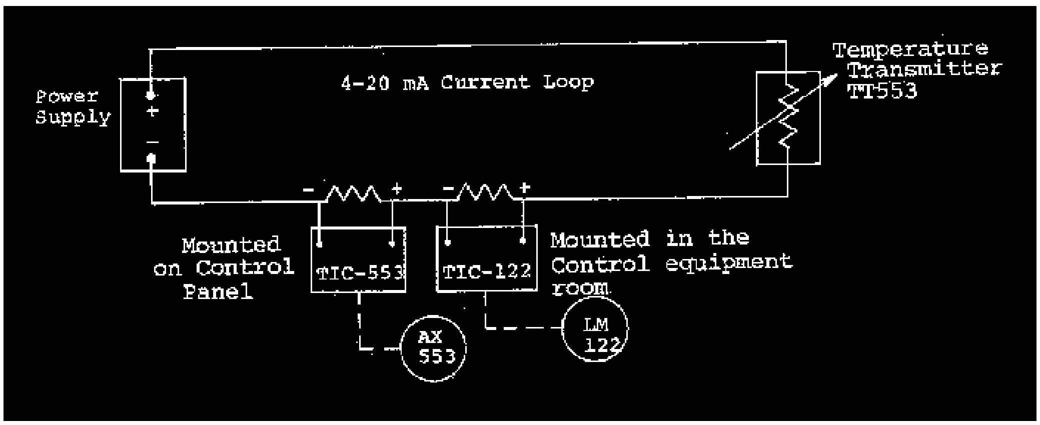

Figure 23: Two Controllers Monitoring the Same Current Signal.

Temperature controller 553 is direct acting so that an increase in effluent temperature will cause the air to open control valve (CV-553) on the recirculating cooling water line to be driven more open. The temperature control loops are identical but with staggered set points. The set point for the backup controller (TIC-554) is approximately 6° C higher than the set point for TIC-553.

For normal operation, TIC-553 will be able to maintain the desired temperature by throttling CV-553. Control loop 554 will appear inoperative with CV-554 closed unless the temperature begins to rise well above the TIC-553 set point.

This control application has also used a small CV in parallel with a large CV with both valves driven by a common control signal. The small TCV accommodates low bleed flow conditions while the large CV will drive open if large bleed loads are applied.

3.4.4 Temperature Override of Level

The bleed cooler effluent temperature must not rise to 60° C or chloride ions will be released from the IX resin. Chloride ions can cause stress corrosion cracking in the system materials.

For normal operation, the bleed cooler outflow valve (CV-122) is positioned as a function of the control signal from direct acting LC-122. Temperature controller TIC-122 has reverse action.

Low select relay (LM-122) selects the lowest of the signals from direct acting LIC-122 and reverse acting TIC-122.

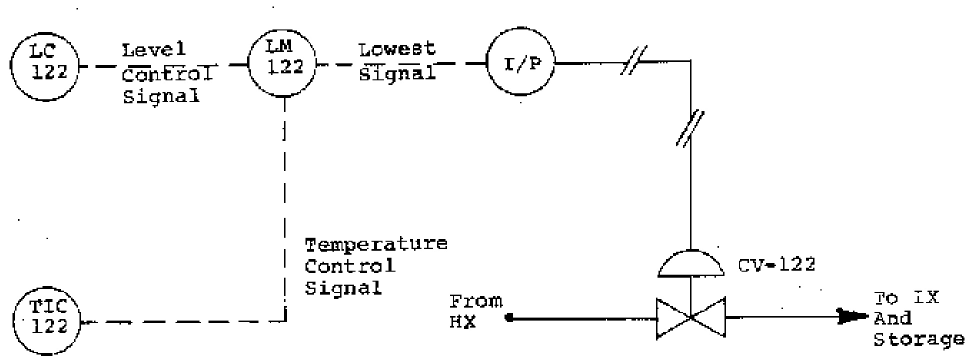

Figure 24: Interconnection of the Level and Temperature Controllers.

Assume that the bleed rate is increased due to some transient condition so that the bleed condenser level begins to rise. Since the level controller is direct acting, the level control signal will increase as the level rises. Air-to-open CV-122 will be driven more open to increase the bleed condenser outflow rate. The bleed cooler effluent temperature will now begin to rise due to the increased bleed flow.

Temperature controller TIC-122 is reverse acting so that as the temperature rises, the control signals decreases. The rising level control signal and the falling temperature control signal are input to the low select relay. Once the signal from TIC-122 becomes the lowest of the two signals sensed by LM-122, then the temperature controller will be regulating the control valve (CV-122) position.

The air-to-open CV-122 now drives more closed due to the lower signal selection. In this manner, the temperature control signal overrides the level control signal. The reduced flow of hot bleed and the increased flow of cooling water to the heat exchanger will now be able to return the effluent temperature to the set point.

A low limit is applied to the temperature controller signal (TIC-122) to limit the closing of the level valve (CV-122) to 10% of stroke. This prevents the complete closure of the level valve by the temperature override signal and the accidental lock-up of a hot pocket of bleed at the temperature detectors.

Chapter 4 – Response

4.1 Response to a Reactor Trip

For a feed and bleed type system, a reactor trip would cause an increase in feed valve opening with bleed valves going to a minimum opening position (i.e. the bias value) in an attempt to prevent inventory shrinkage due to the gross energy mismatch that exists under such conditions while the turbine is still removing heat from system.

It is necessary to reachieve the energy balance as soon as possible by reducing the magnitude of the heat sink applied. The reduced bleed action will require a control response from the bleed condenser level controller - the level will drop a little below the set point and the level valves will close.

The reduced outflow from the bleed condenser will also reduce the load on the bleed cooler enabling a reduction in service water flow to the shell side of the cooler. Where pressure control is by pressurizer the initial shrink in HTS inventory following the reactor trip will be supplied from the pressurizer.

4.2 Response to Turbine Trip

In this case the energy input source is greater than the unit heat sink. Consequently, the HTS system inventory will begin to swell due to the increased temperature causing the pressure to rise.

A feed and bleed system will require maximum bleed action with the feed valves going to the fully closed position. This extra bleed will require additional pressure control action in the bleed condenser possibly by commencement of spray action. The additional bleed, plus any spray flow, will require an increased outflow from the bleed condenser to maintain level.

This increased outflow will, in turn, increase the cooling requirements from the bleed cooler. The temperature override of bleed condenser level control may be initiated for a short period of time depending upon the degree of energy mismatch.

For a pressurizer system the HTS swell will be accommodated by the pressurizer with the steam bleed valves opening to relieve the pressure. A turbine trip will initiate a reactor stepback thus reducing the energy input to the system. If for any reason this stepback does not happen, the high pressurizer level condition will cause a reactor setback.

Chapter 5 – Conclusion

As stated before to operate a nuclear power plant the fundamental are the three C's. At all times while the plant is operating or shutdown, it is required to Control the reaction, Cool the reactor and Contain the radioactivity.

The heat transport system in a nuclear power plant is a fundamental system in cooling the reactor; therefore it is essential part of the Three C's. This system ensures that the plant is operating within its design parameters at all times and it ensures that the reactor is not affected by any disturbances.

The unique engineering aspect of the Heat Transport system is that it applies all the fundamental concept of engineering. This system incorporates electrical engineering and mechanical engineering design. It demonstrates how various engineering subjects can correlate and function and operate in real life.

The heat transport show it is evidence on how the electrical fundamental, such as PI control, instrumentation and electrical energy, are effective functioning to control and operate a system that its design is based on the mechanical fundamentals of fluid dynamics and thermodynamics. This system was design in the late 20th century and considering today's advances on digital technology this system might be considered straightforward. Digital technology has barely scratched the surface on the Nuclear Industry. This is due to the high reliability and safety requirements on the design of a Nuclear power plant. The straightforward technology used in the heat transport system is a proven design and reliable as proven by years of operation and engineering fundamental practices. The digital technology is still evolving it does not have a long track record therefore it is not proven to be as reliable as the analog technology. Nuclear energy is very unique due to the vast amount of power it contains; therefore its design is based on the soundest engineering fundamentals.

The reason that I choose this topic is that even though on the Engineering high level scheme this system is straightforward compared to today's modern day technology, it's a system that daily ensures that our society is safe and electricity is being provided to the society. It's a system that demonstrates that fundamental of engineering are and always will be our base knowledge and should be fundamental knowledge for every engineer, and shall not be forgotten.

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Glossary - Acronyms

HTS - Heat Temperature System

PWR - Pressurized Water Reactors

BWR - Boiling Water Reactors

PHWR - Pressurized Heavy Water Reactors

CANDU - Canada Deuterium Uranium

DP - Differential Pressure

RTD - Resistance Temperature Detector

PT- Pressure Transmitter

PIC - Direct Acting Pressure Controller

HC - Hand Controller

LT- Level Transmitter

CA- Current Sensor

CV - Control Valve

TT- Temperature Transmitter

LC - Level Controller

TIC- Temperature Controller

LM- Low Selected Relay