23 Reactivity Mechanisms

Fuel fails if it is not kept wet. Fuel will also fail if it generates too much power. Reactivity mechanisms control reactor power. This module describes the reactivity control devices and how they work

Reactivity mechanisms change the value of the neutron multiplication factor in the reactor core. Most affect the parasitic absorption of thermal neutrons in the core. When a device increases the parasitic absorption in a core it is said to be adding negative reactivity. If a devices is decreasing the parasitic absorption it is adding reactivity.

Reactivity mechanisms are devices that increase or decrease neutron losses. Most such devices absorb neutrons. Some devices alter neutron leakage from the core. The reactivity worth of a device is the amount it can change Δk. Changing the core reactivity controls the reactor power output.

Power production uses up fissile atoms in the fuel. This decreases the reactivity of the core. On the short term, an increase in the number of neutrons can offset the loss of fissile atoms. Replacement of spent fuel with fresh fuel maintains the long-term reactivity of the core. Power production can continue for about a week without refueling.

These factors are summarized in Table 23.1. Fuel burnup causes a slow reactivity decrease. The other factors listed change reactivity more quickly. Temperature changes can alter reactivity in seconds or minutes. The effects listed as intermediate can change reactivity over several minutes. These reactivity variations, once started, may continue over hours or days.

Table 23.1 Factors Causing Δk Changes in the Core

Factor	**Time for Δk Change**
Fuel; Burn-up	Long
Refuelling Channel	Intermediate
Xenon Change Following a Power Change	Intermediate
Flux Oscillations	Intermediate
Temperature Change in the Core	Short

The reactivity control devices perform two general functions:

a) Reactor Power Regulation

b) Reactor Protection

Protective reactivity mechanisms, also called shutdown systems, have the single purpose of shutting down the reactor quickly in an emergency. Each unit has two independent shutdown systems. This makes certain that the reactor will shut down if required.

Reactor power regulation devices adjust reactivity to hold the reactor power steady at the demanded power output. The devices also respond to requests for a reactor power change. This could be a power change to match a change in electrical output or it could be a power reduction required because some system is unable to handle the heat the reactor produces.

23.1 Summary Of Key Ideas

- When Δk (reactivity) is positive, reactor power increases. When Δk is negative, reactor power decreases.

- Daily refuelling replaces the reactivity lost by fuel burnup, maintaining long-term reactivity of the core.

- Some reactivity mechanisms shut the reactor down quickly in an emergency. These are for reactor protection.

- Some reactivity mechanisms adjust reactivity in a controlled way to hold the reactor power at the demanded output. These devices can change reactor power. They are for reactor power regulation.

23.2 Reactivity Mechanisms

23.2.1 Fine Reactivity Control

The liquid zone control system provides fine control of k to regulate reactor power. This system holds the power at the demanded setpoint or changes it in a controlled way. It also operates to limit flux oscillations.

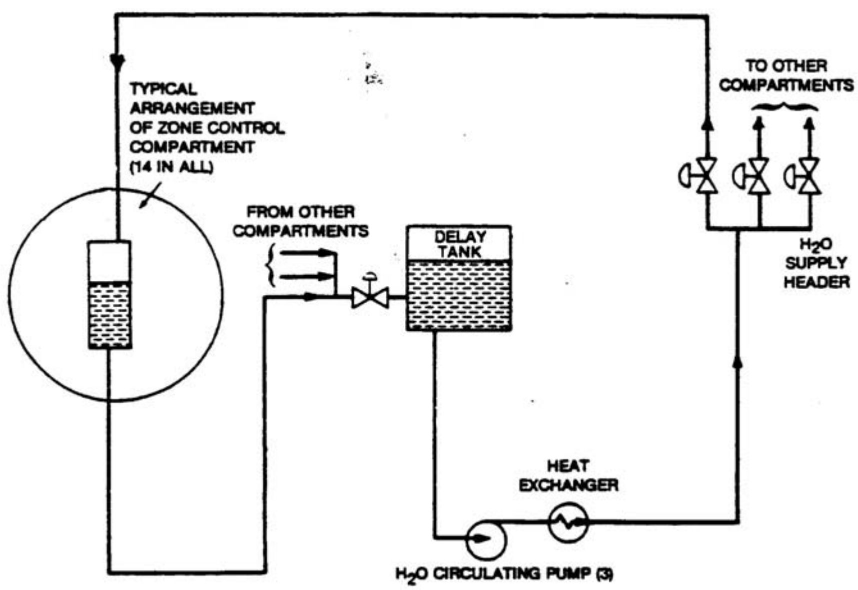

Figure 23.2
Liquid Zone control System (Simplified)

There are fourteen control zones in a CANDU core. Figure 23.2 shows how the liquid zone control system regulates reactivity in one of these regions. A variable level light water compartment sits near the centre of each zone. Signals from the control computer adjust the water flow control valves. This raises or lowers the water level from its nominal half full position. H_2O absorbs neutrons, so raising the water level in a zone compartment decreases reactivity. Reactivity increases when the water level drops.

Bulk reactor power is regulated by adjusting the H_2O level in all fourteen zone compartments together. Independent adjustment of the fourteen zone compartments smoothes out local flux variations. This is necessary to damp out flux oscillations. The Nuclear Theory course describes flux oscillations.

23.2.2 Coarse Reactivity Control

The liquid zone control system continually responds to power measurements and makes small reactivity adjustments. It cannot make large or rapid changes in reactivity. It completely fills or drains as it tries to respond to large reactivity requirements.

Neutron absorbing rods (control absorbers and adjuster rods) are regulating devices that can change reactivity by large amounts. Moderator level adjustments (used at Pickering A only) similarly are able to make large controlled reactivity adjustments.

Control Absorbers

These are neutron-absorbing rods made of cadmium tubes sheathed in steel. Their normal position is out of core. They drive into the core to reduce reactivity. (Reactivity increases as they come back out).

Figure 23.4 shows the control absorber rod equipment A guide tube guides the moving rod between the calandria tubes in the moderator. Cables attached to motor drives on the reactivity mechanism deck above the reactor raise and lower the rods.

These rods reduce reactivity to control power at the demanded value when zone levels cannot do it. They also reduce power gradually to a prearranged low level if certain equipment fails.

On some severe faults, these rods drop quickly into the core. This rapid power reduction is part of the normal power regulation function.

Absorbers are used at all CANDU reactors except Pickering A units.

Moderator Level Control (Pickering A Only)

Moderator level control is part of the regulation system on dump tank units. Figure 23.3 shows the regulating valves and dump valves. Neutron leakage from the core increases as the moderator level drops'. This reduces reactor power. (Reactivity increases as the calandria refills to its normal operating level).

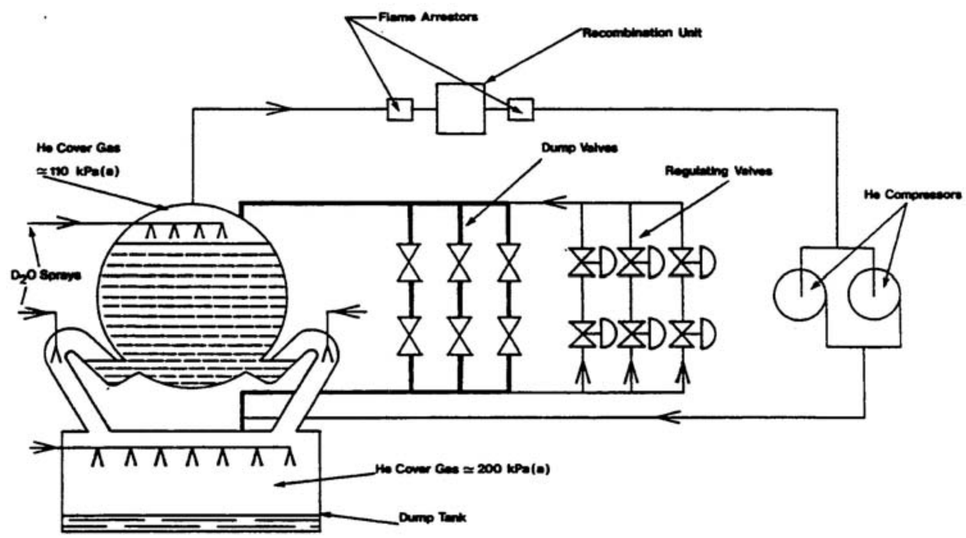

Figure 23.3
Moderator Dump and Level Control at Pickering A

The concepts of moderator level control and moderator dump were introduced previously. Dump tank pressure holds the moderator water in the calandria. The regulating valves adjust the moderator level by controlling the pressure difference between the dump tank and the top of the calandria. This controls the rate of heavy water flow from the calandria into the dump tank. (Pumps, not shown in figure 23.3, return water from the dump tank to the calandria).

Adjuster Rods

Adjusters rods are neutron-absorbing rods similar to the control absorbers in Figure 23.4. They are made of cobalt at some stations and stainless steel elsewhere. Stable cobalt 59 absorbs neutrons and becomes cobalt 60. This radioactive isotope is used to treat certain cancers. The sale of Co-60 partly offsets the cost of lost fuel burnup that results from the absorption of neutrons in the adjusters.

Their normal position is in core. In their normal position, adjusters flatten (that is, adjust) the neutron flux by absorbing neutrons in the central region of the core.

Another function of adjusters is to provide positive reactivity when the reactor regulating system requires it. Withdrawing adjusters from the core removes absorbing material and adds positive reactivity. They were originally designed to allow some ability to prevent poison outages by removing adjusters from the core as the xenon built up.

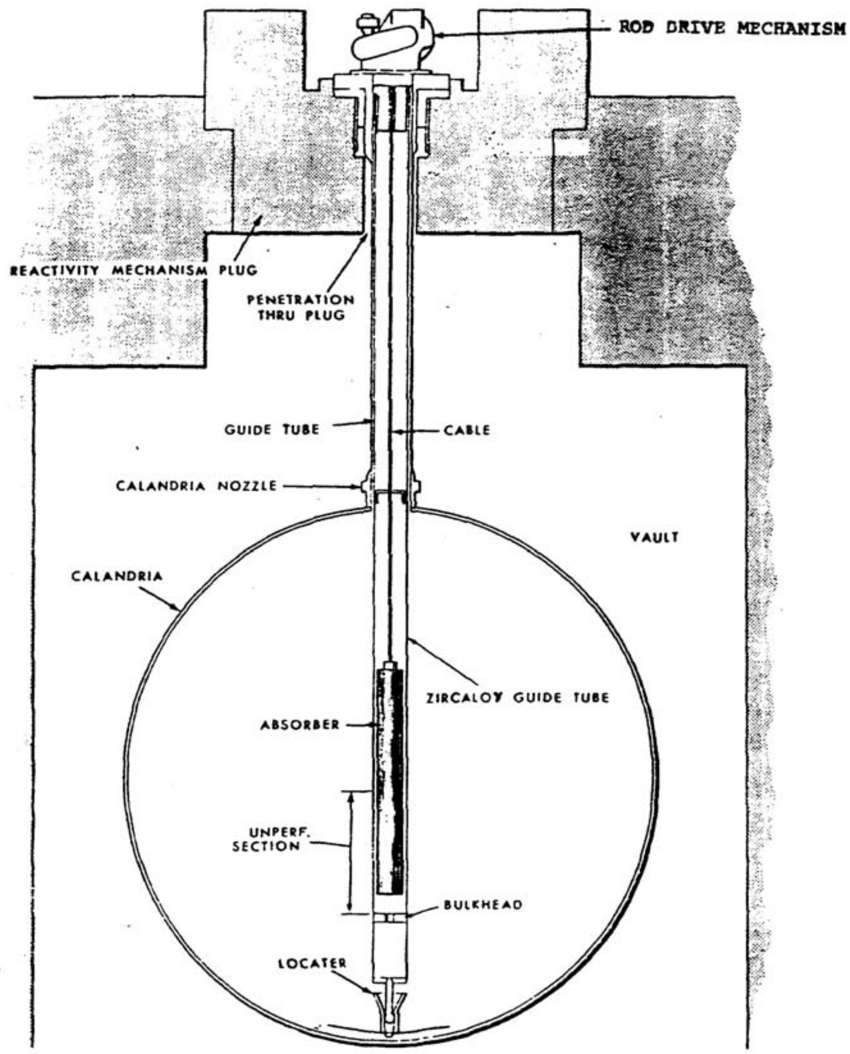

Figure 23.4
Control Absorber, Adjuster and Shutoff Rod Arrangement

A large positive reactivity insertion is required after a large power decrease. Power reductions increase the amount of neutron absorbing xenon in the fuel. The Nuclear Theory course describes these xenon transients. Adding positive reactivity to overcome absorption by xenon is called xenon override.

All CANDU reactors except Bruce A have adjusters. Bruce A was designed to use booster rods for xenon override, but these are no longer used.

23.2.3 Manual and Automatic Reactivity Adjustments

The reactivity device positions in normal reactor operation are: adjusters in the core, calandria full, absorbers out of the core and the zone compartments near half full. The regulating system requests the coarse regulating devices to operate when zone compartment levels are too high or too low. Most of these devices respond automatically.

Operators can prevent unnecessary automatic device movement if they keep the zone levels from deviating too far from middle of their operating range. Operators change liquid zone levels indirectly by manually adding neutron absorber to the moderator with the liquid poison addition system, or removing it with the moderator purification system. For example, when the liquid poison addition system is used to add poison, the regulating system holds reactor power steady by lowering the zone levels.

A combination of poison concentration adjustment and regular fuelling keeps the zone levels in their normal operating range.

23.2.4 Automatic Shutdown Systems

Instruments monitor reactor conditions such as heat transport system pressure, reactor power and coolant flow. Any measurement that shows possible risk of damaging the fuel, or other unsafe operating condition, triggers a reactor shutdown. A shutdown by a protective system is called a reactor trip. A trip occurs automatically whenever a trip parameter (measurement) exceeds its trip set point (safe operating limit). The operator can trip the reactor manually if necessary.

Shutdown system instruments and mechanisms are completely separate from devices used for reactor power regulation. CANDU reactors haves two separate shutdown systems for reactor protection. All units use shut off rods for Shutdown System 1 (SDS#1). All CANDUs except Pickering A use Liquid Poison Injection for Shutdown System 2 (SDS#2). Figure 23.5 shows these two common systems. Pickering A uses moderator dump as a backup to its shutoff rods.

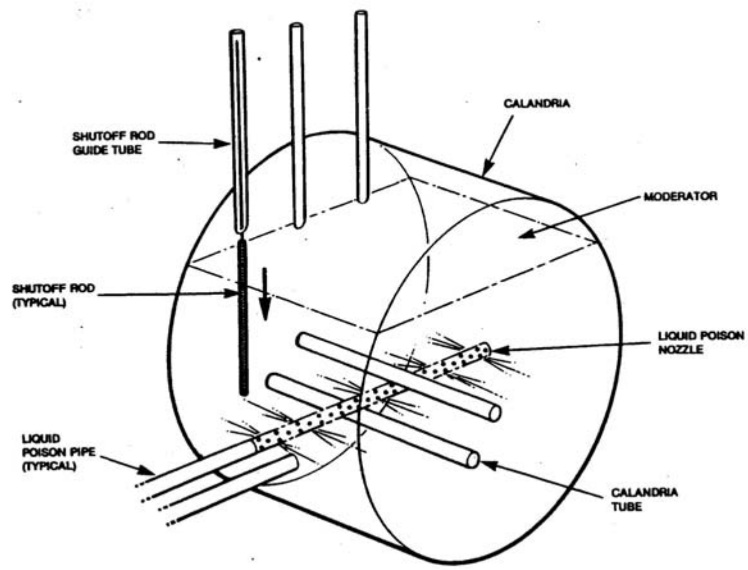

Figure 23.5
Sketch of Shutoff Rods and Liquid Poison Injection

Shutoff Rods
The SDS1 shutoff rods are neutron absorbing rods, nearly identical to the control absorber rods in Figure 23.4. An electromagnetic clutch holds them in their normal, poised, position in the guide tube above the core. A reactor trip signal cuts off the electricity to the clutches. The rods drop into core in about two seconds. Most stations use fast-acting, spring-loaded shutoff rods.

Liquid Poison Injection System
Figure 23.6 shows the liquid poison injection system (SDS#2). SDS#2 automatically injects a large quantity of neutron absorbing poison in a couple of seconds. Do not confuse this protective system with the liquid poison addition system, used for small manual additions of poisons.

A reactor trip signal opens the quick opening valves shown in Figure 23.6. High-pressure helium forces the gadolinium solution from poison tanks into the moderator. The poison enters through horizontal tubes, one tube per tank. Nozzles disperse poison into the calandria along the length of each tube. As a tank discharges, a floating ball rides the liquid surface down the tank and seals the discharge line. This prevents the helium from reaching the calandria and raising its pressure too high.

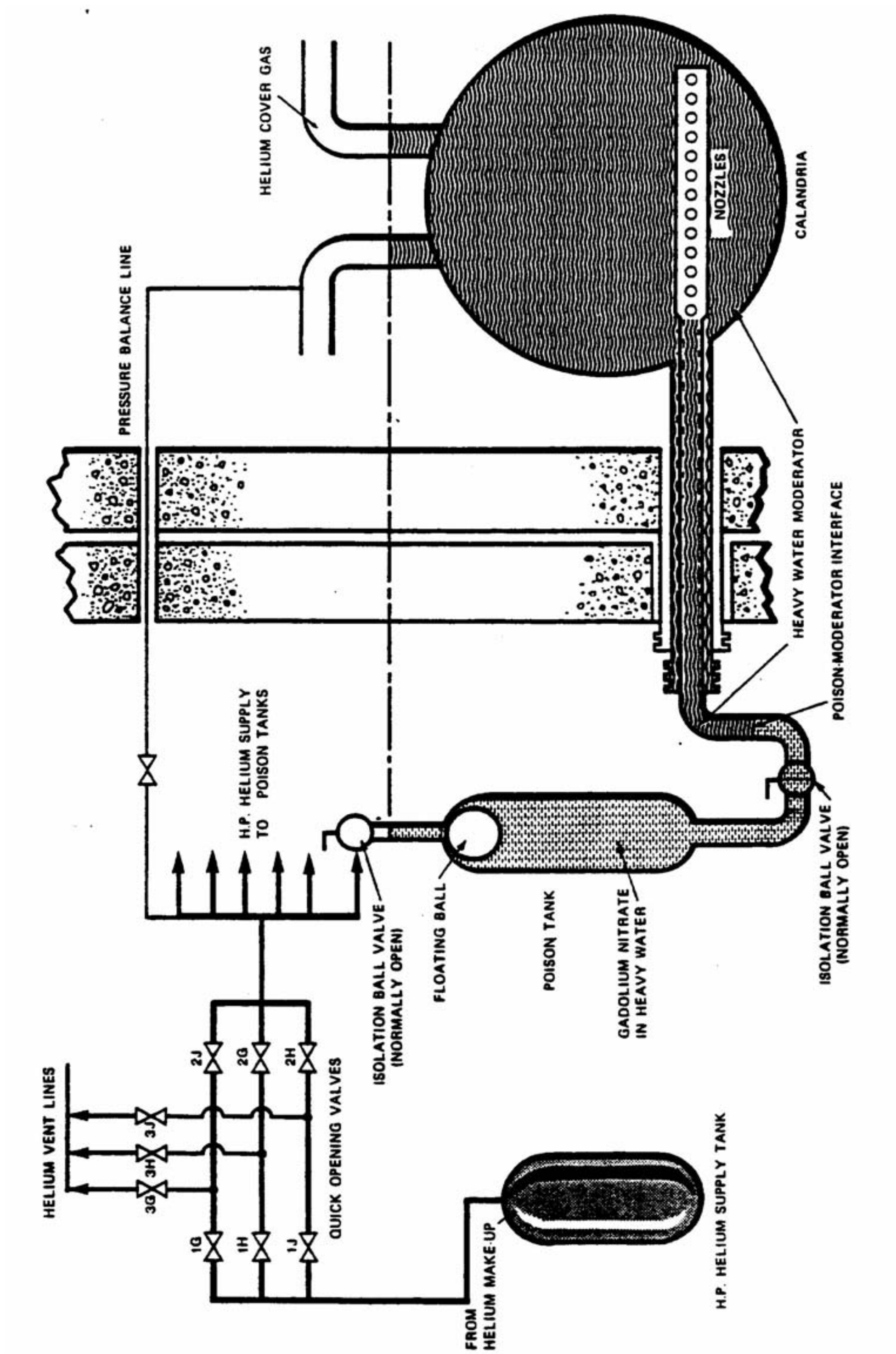

Figure 23.6
The Liquid Poison Injection System

Moderator Dump (Picketing A Only)
Figure 23.3 shows the moderator dump system. introduced in a previous module. On a reactor trip, the large dump valves open. This equalizes the pressure in the calandria and dump tank. Without dump tank pressure to support it, the moderator fails through the dump ports into the dump tank. As the level drops, neutron leakage increases. Without a moderator to slow them, fast neutrons leak away, or are absorbed without causing fissions.

23.3 Reactivity Mechanism Principles of Operation

Table 23.2 summarizes the principles underlying each of the reactivity mechanisms.

Table 23.2 Reactivity Adjustment Operating Principles

Operating Principle	Reactivity Mechanism
Change in the amount of fissile material in the core	Fuelling
Adjust Neutron Leakage from the core	Moderator Level Control
	Moderator Dump
Adjust Neutron Absorption in the core	Liquid Zone Control
	Control Absorbers
	Adjusters
	Shut Off Rods
	Liquid Poison Addition & Moderator Purification
	Liquid Poison Addition

23.4 Summary of Key Ideas

- The liquid zone control system regulates reactor power during normal operation. It regulates bulk power output and helps flatten out local power fluctuations.
- Sometimes effective reactor regulation requires larger or faster reactivity changes than the liquid zone control system provides. Adjuster rods provide reactivity increases. Absorber rods (moderator level at Pickering A) provide reactivity decreases.
- The operator can lower the zone levels indirectly by adding neutron absorbers with the poison addition system. The regulating system, automatically holding reactor power at setpoint, lowers the zone levels to keep the reactivity constant. Similarly, by removing poison from the moderator, the operator can indirectly increase the zone levels.
- Operating staff use fuelling, poison removal (purification) or poison addition to keep the zone levels from becoming too full or too empty.
- Absorbers (or moderator level) operate to hold power at setpoint when the liquid zones are too full to do so. They also can reduce power, in either a gradual reduction or a sudden drop.
- Xenon reactivity effects may be too large for the liquid zone control. Adjusters provide xenon override. Adjusters also have a second purpose. They flatten flux in the central region of the core.
- Shutoff rods, liquid poison injection and moderator dump (at Pickering A) provide rapid reactor shutdown in an emergency.
- Neutron absorbing shutoff rods drop into the core when a trip signal de-energizes the clutches. This is shutdown system one (SDS#l).
- High-pressure helium forces a neutron absorbing solution into the moderator when valves open between the helium tank and the injection tanks. This is shutdown system two (SDS#2).
- At Pickering A, large dump valves open to relieve pressure in the dump tank. The moderator D_2O falls out of the core into the

dump tank. Without moderator, neutrons from fission escape from the core, or are absorbed without causing fissions.

23.5 Two-Out-Of-Three Trip System

The shutdown systems must stop the fission process quickly in an emergency. The reactor should shut down when required, but should not shut down unnecessarily. Spurious trips are expensive. After many SDS#l trips and all SDS#2 trips it is impossible to restart the reactor within the next 35 to 40 hours. Apart from the cost of replacement power, the sudden power reduction is hard on equipment.

The shutdown systems are made with very reliable equipment Maintenance programs and frequent testing make certain that the shutdown systems operate correctly.

An important part of the reliability of these systems is the tripping mechanism. Figure 23.7shows the two-out-of-three trip logic. Figures 23.3 (Moderator Dump) and Figure 23.6 (Liquid Injection Shutdown System) both show this valve arrangement The electronic contacts that open the rod clutches to trip SDS#l have a similar arrangement.

Consider the trip system in Figure 23.7. It has three helium lines. Each line has two valves in series. Three independent channels, labeled A, B and C send the trip signal to the valves. Signal A opens the two A valves, signal B opens the two B valves and signal C opens the two C valves.

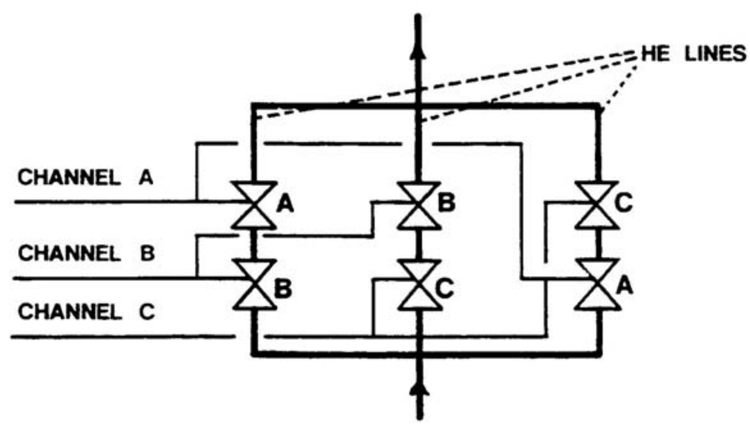

Figure 23.7
Typical Trip Logic

On a normal trip, all three channels simultaneously send trip signals. All valves open. Helium flows through all three lines, causing a shutdown by poison injection or by moderator dump.

The system also operates if only one or two helium lines open on a trip. Why then have three lines? There are three reasons for the arrangement of Figure 23.7

a) There is no reactor trip on a spurious signal in any one channel.

Suppose one channel fails, producing a spurious trip signal. For example, a fault in a signal transmitter in channel A could open the channel A valves. With just one set of open valves, helium cannot pass through any of the three lines. There is no reactor trip.

An unnecessary trip caused by this type of equipment failure requires simultaneous failures in two channels. Reliable equipment is used, and it is tested and maintained regularly. This makes a single fault unlikely. The chance of two channels failing simultaneously is extremely small.

b) A trip occurs even if one channel fails to respond to a real trip situation.

On a valid trip, if any one channel fails to provide a trip signal the system still operates. For example, a faulty transmitter in channel A could fail to send a signal to the channel A valves. The other four valves, operated by signals B and C, do open. Flow of helium through the line with no A valve will cause a reactor trip.

Again, reliable equipment that is carefully tested and maintained makes a single fault unlikely. Simultaneous failures in two channels, which could make the system fail, are extremely unlikely.

If one shutdown system does fail, the other shutdown system will shut down the reactor. Reactor shutdown in a real emergency is almost certain.

c) Two-out-of-three trip Logic allows for maintenance and testing at power without any loss of protection.

A single channel can be tested by tripping it to see if it works. This does not trip the reactor, provided testing is done on one channel at a time. There is no loss of trip coverage should a real emergency arise during testing. A trip signal on any other channel will trip the reactor.

There is an increased risk of an unnecessary shutdown, caused by a spurious trip on another channel during testing. This does not harm reactor safety, but it is expensive.

Some on power maintenance can be done, one channel at a time, with the channel tripped. In this state, a trip signal on either of the other channels will cause a shutdown. There is no loss of trip coverage should a real emergency arise during maintenance. Again, there is an increased risk of an unnecessary shutdown.

There is a safety advantage if equipment that fails causes a channel trip signal. Failures that cause the equipment to operate are called fail safe. The channel A transmitter failure example in a) above failed safe, causing the A valves to open. The transmitter failure in example b) was not fail safe. Nothing was observed until the system was needed, and then the A valves did not open.

A safety system built with components that fail-safe is more reliable. Suppose a real emergency occurs, producing trip conditions on all three channels. In the first example, because channel A is tripped, a signal on any second channel trips the reactor. In the second example, if either channel B or C fails to trip, the reactor will not trip.

When equipment fails safe, as in a), it is usually obvious that a failure has occurred. The operator can immediately order repairs. When equipment fails passively, as in b), the fault may not be noticed until it is discovered by routine testing. In the interval, the system is not quite as reliable. Frequent testing to discover faults improves reliability.

23.6 Summary of Key Ideas

- In a two-out-of-three trip system, the devices that trip the reactor are operated by channelized signals.

- The tripping devices and channelized trip signals are arranged so any two of three channelized signals will cause a reactor trip.

- A single equipment fault cannot trip the reactor. Two or three channel trips are required for a reactor trip. This limits the number of unnecessary shutdowns.

- An equipment single fault cannot prevent the reactor from tripping. The other two channel trip signals are enough to trip the reactor.

- Shutdown system maintenance and testing can be carried out one channel at a time without loss of trip coverage. The reactor tripping devices are activated in the channel under test or maintenance. Any one other channel trip signal will trip the reactor.

- Shutdown system equipment is very reliable. Careful maintenance keeps it that way so simultaneous equipment faults are rare. Testing finds single faults so maintenance can be done.

- Fail safe components are components that are designed to operate when they fail. Safety systems made from such components are more reliable. The fault is likely to be noticed immediately and quickly corrected, meanwhile, the system continues to provide full trip coverage even if the fault is not found and corrected.

23.7 Assignment

1. a) State two general functions of reactivity mechanisms.

   b) State two general principles of operation of reactivity mechanisms.

2. List five causes of reactivity variations other than reactivity mechanisms. Classify the effects as long, intermediate, or short term.

3. Make a table showing the function and principle of operation of each of the eight reactivity mechanisms.

4. Name the reactivity mechanism used especially for xenon override.

5. State 3 reasons for using a 2 out of 3 trip system.

6. Describe how the 2 out of 3 trip logic works to provide a reactor trip:

   a. When all the equipment is operating normally,

   b. When one channel fails to trip when required.

7. What is a fail-safe device, and how does fail-safe operation of safety system equipment contribute to reactor safety?