NOTES AND REFERENCES

Module 4

CONTROL/COOL/CONTAIN PHILOSOPHY

OBJECTIVES:

After completing this module you will be able to:

CRO 4.1 State and explain the principle behind the Control/Cool/Contain philosophy. ⇔ *Page 2*

CRO 4.2 List and describe three engineered levels of control and protection designed to prevent excessive heat production in the fuel. ⇔ *Page 3*

CRO 4.3 State why RRS must be continuously available when the reactor is not in the GSS. ⇔ *Page 4*

CRO 4.4 State why all automatic shutdown capability must be continuously available when the reactor is not in the GSS. ⇔ *Page 6*

CRO 4.5 State two reasons why power indication is a requirement at all power levels. ⇔ *Page 7*

CRO 4.6 State the preferred state for fueling and explain the potential consequences of not fueling in this state. ⇔ *Page 8*

CRO 4.7 State why a fuel heat sink must always be available, regardless of reactor operating state. ⇔ *Page 8*

CRO 4.8 Explain why primary and backup heat sinks must be independent of each other. ⇔ *Page 10*

CRO 4.9 State the possible consequence of loss of heat sink. ⇔ *Page 11*

NOTES AND REFERENCES

INTRODUCTION

The following has been called the golden rule of Reactor Safety:

Obj. 4.1 ⇔ ***There is no threat to the public and environment from reactor fuel provided that at all times:***

1. ***The reactor power is controlled***
2. ***The fuel is cooled***
3. ***The radioactivity is contained***

In Module 4, the basis for these requirements will be explained.

Control/Cool/Contain and Nuclear Safety

Fuel temperature is stable when the rate of heat generation *in* the fuel equals the rate of heat removal *from* the fuel. This equilibrium can be upset with a resulting fuel temperature excursion either by reactor power increasing beyond the existing heat sink capacity (loss of *control*), or by an impairment of the existing heat sink capacity (loss of *cool*). Fuel temperature is critical to nuclear safety, as explained below.

Because the fuel ceramic is a poor conductor of heat, fuel center-line temperature (typically 1800 degrees Celsius) is significantly higher at power than the pellet surface temperature (typically 400 degrees Celsius). If the fuel overheats due to a loss of either *control* or *cool,* such that center-line melting of the pellets occurs (at about 2800 degrees Celsius), then the massive inventory of fission products trapped in the ceramic begins to escape. Simultaneously, the fuel sheath loses its strength. The internal pressure created by the gases escaping the fuel pellets can then cause the sheath to balloon and burst, releasing radioactivity to the coolant. Thus a loss of *control* or *cool* which causes fuel failures also results in a partial loss of *contain,* as fission products have breached the first two physical barriers—ceramic and sheath. Public safety now depends on the three remaining barriers—the heat transport system boundary, the containment boundary, and the exclusion zone.

A severe power excursion or sustained loss of heat sink could also fail the heat transport boundary 9third barrier), causing a LOCA, which would challenge the integrity of the containment boundary (fourth barrier). These conditions would further elevate the risk to the public. The preceding argument shows the importance of the *control/cool/contain* operating philosophy to nuclear safety. *Control, cool,* and *contain* are <u>essential</u> under all operating conditions--at all reactor power levels, and at all times, including during normal operation, unit shutdowns, and any unit upset.

NOTES AND REFERENCES

Control Of Reactor Power

There are three engineered levels of control and protection to ensure that the fuel does not produce more heat than can be removed:

⇔ *Obj. 4.2*

1. normal power regulation by RRS
2. setback and stepback functions
3. automatic shutdown via the shutdown system(s)

These must be available at all times unless the reactor is in the Guaranteed Shutdown State (except for any grace period per operating instructions--typically 24 hours, to effect repairs on setback or stepback).

1. Reactor Regulating System (RRS)

The regulating system is the active process system which normally controls reactor power—ie, corrects for normal, minor deviations from desired power by normal control action. RRS is shown in functional blocks in Figure 4.1.

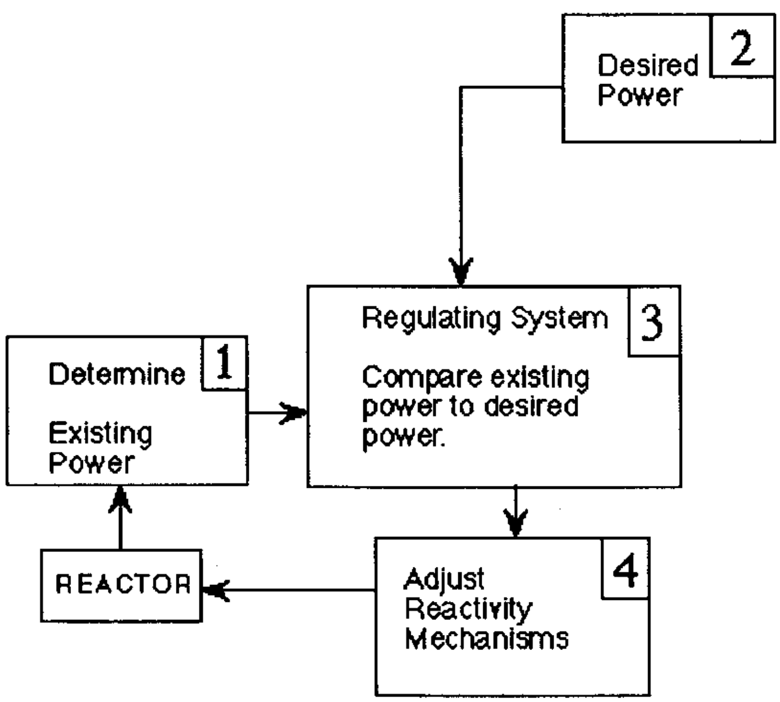

Figure 4.1: Schematic Control Loop For Reactor Power

NOTES AND REFERENCES

In Box 1, neutron power is measured by measuring the neutron flux, which is proportional to the fission rate, using:

1. Ion chambers at low power levels, typically below 15% full power. (Ion chambers do provide a signal at high power, but it is useless for flux tilt control. The ion chambers also provide a log N rate signal used for bulk reactor power control and stepback functions even at high power levels.)

2. In-core detectors at high power levels, typically above 15% full power set point for reactor power.

In Box 2, the desired power is entered by the Operator from the computer keyboard. (When the unit control mode is *reactor lagging the turbine*, the boiler pressure control program determines the setpoint for reactor power.)

In Box 3, the computer calculates the power error--the difference between the measured power and the desired power. Reactivity mechanisms are manipulated (Box 4) in order to reduce the power error, ie, to make actual power equal to desired power.

Obj. 4.3 ⇔

The Regulating System must be continuously functioning to enable continuous automatic control of reactor power when the reactor is not in the GSS. If the Regulating System is impaired such that it cannot reliably control power, the reactor must be placed in the guaranteed shutdown state.

2. Setbacks and Stepbacks

Setback or stepback reduces reactor power in the event that a moderate mismatch between heat production and removal is detected (see Figure 4.2). The initiating parameters vary from station to station, but the intention is always to ensure that the fuel does not overheat.

NOTES AND REFERENCES

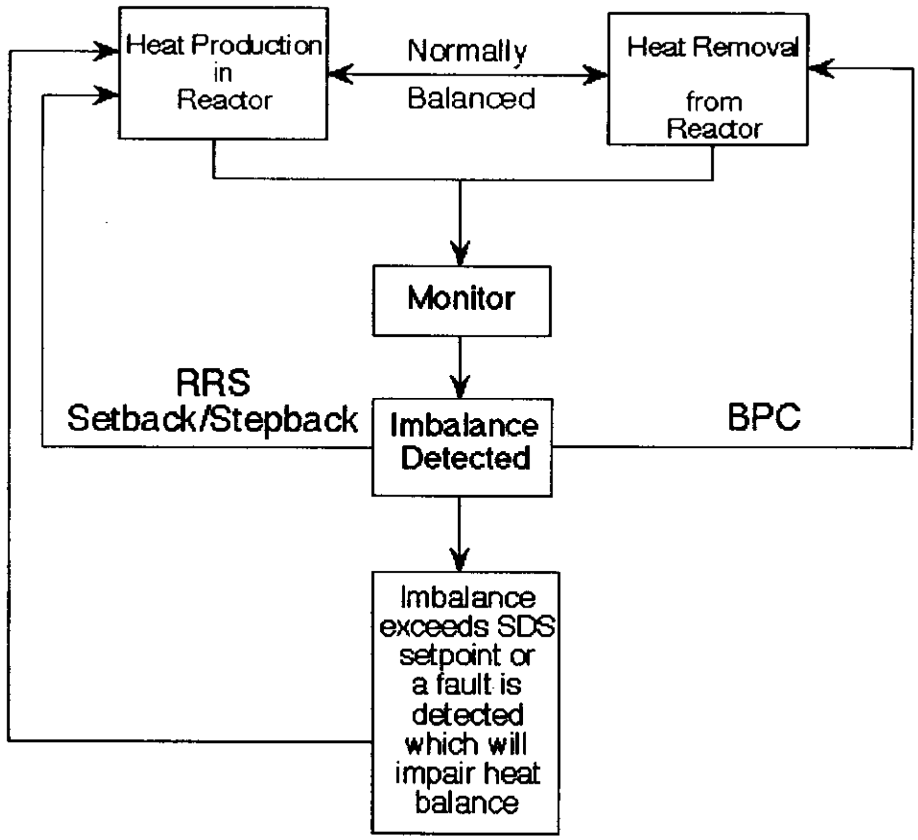

Figure 4.2: Poised Systems Which Ensure that Heat Production Does Not Exceed Heat Removal Capability

Setback is a gradual ramping down of the reactor power set point by RRS, with RRS reducing power by normal control action. ***Stepback*** is a sudden reduction in power achieved by dropping the control absorbers into core. This large, rapid insertion of negative reactivity sends the reactor substantially subcritical, and the neutron flux rapidly collapses, along with the fission rate.

Consider a setback on boiler high pressure as an example of how a mild imbalance in heat production and removal is dealt with. If boiler pressure increases, more heat is being put into the boiler than is being removed via the turbine--ie, the fuel is producing too much heat for the available heat sink. This imbalance would normally be detected and compensated for by the boiler pressure control program, by further opening the governor valves. However, if boiler pressure deviates far enough above set point, reactor setback is initiated (at some stations) to bring thermal power within the heat sink capability.

NOTES AND REFERENCES

The cause of such an imbalance could be in the reactor regulating system, or in the heat removal system. In the event that overall unit stability were restored at a reduced power level, reactor power could be returned to normal with the Shift Supervisor's approval, after the cause of the upset has been identified and corrected.

3. Shutdown Systems

In the event of a severe mismatch between heat production and removal (or removal capability), as detected by one or more operating parameters exceeding trip set points, SDS action rapidly inserts a large negative reactivity worth into core, taking the reactor deeply subcritical. This rapidly halts fission heat production.

Obj. 4.4 ⇔

The regulating system must be backed up by continuous Shutdown System availability to ensure the rapid termination of an uncontrolled power increase in the event of a loss of regulation (LOR). If the Regulating System is impaired such that it cannot control power, or if a Shutdown System is unavailable, the reactor power control is jeopardized. The reactor must then be placed in a guaranteed shutdown state.

Reactor trips from high power on such parameters as neutron overpower, Log N rate, and high HT pressure prevent a large heat imbalance caused by too much heat production. The trip occurs before excessive overheating of the fuel. Trips on such parameters as low HT coolant flow, low HT coolant pressure, and low boiler level, anticipate fuel overheating caused by inadequate heat removal capability. Trips on such parameters as high boiler room pressure, low HT coolant pressure, and low pressurizer level, eliminate fission heat in the event of a LOCA, so that backup heat sinks only have to remove decay heat.

Reactor trips protecting the fuel against power excursions from low power levels include high count rate on start-up instrumentation, high rate log N, high log N, and high HT pressure. These trips can occur before the reactor reaches high power.

The cause of an upset which exceeds shutdown system set points, must be thoroughly evaluated, understood, and the condition confirmed to no longer exist, before any consideration can be given to resetting the trip and raising power.

NOTES AND REFERENCES

SUMMARY OF THE KEY CONCEPTS

1. The Control, Cool, Contain philosophy applies as follows:

   a) heat generated by the fuel is controlled by the regulating system, at power. During shutdown, fission heat production is negligible, but decay heat is still produced;

   b) fuel must be cooled whether the reactor is at power or shutdown, in order to preserve the integrity of the pellet and sheath containment barriers in the fuel;

   c) radioactivity is contained by the five engineered barriers to environmental releases to the public.

2. Heat sinks must always be available to ensure the heat produced by the fuel is removed.

3. The Regulating System must be continuously functioning when the reactor is not in the GSS to ensure continuous automatic control of the reactor power.

3. Shutdown Systems must be continuously available to ensure rapid termination of reactor power excursions due to loss of regulation.

4. If either the Regulating System, or a Shutdown System is unavailable, the reactor must be placed in the guaranteed shutdown state.

Reactor Power Indication

Reactor power indication is required in the control room at all times and power levels for two reasons: ⇔ *Obj. 4.5*

1. To provide indication that the operator would monitor on an intermittent basis during normal operating conditions, in order to confirm that reactor power is being controlled within available heat sink capacity.

2. To provide the operator with continuous confirmation during accident conditions that reactor power is adequately controlled, or that the reactor is shut down.

NOTES AND REFERENCES

Reactor Fueling

Obj. 4.6 ⇔

Fueling a reactor should take place **with the reactor critical, preferably at high power**. Operations Manager approval is required for shutdown fueling on a case-by-case basis. The reason for this is that **fueling** the reactor **causes reactivity changes** within the reactor. With the reactor at power, these changes can be immediately identified, and compensation can be made by RRS. With the **reactor shutdown, there is no indication of unusual reactivity effects** which could cause a reactor to go critical earlier than expected or cause abnormal flux distribution and local zone overpower.

Cooling The Fuel

Obj. 4.7 ⇔

Fuel heat production with the reactor at power is made up of two components--fission heat and decay heat. The fission heat varies with neutron power, which is controlled by RRS, while the decay heat depends only on core power history--ie, on how long the unit has been operating at what power levels and with what mix of fresh and irradiated fuel. Following unit shutdown, fission heat is eliminated, but decay heat continues to be produced in sufficient quantity to damage the fuel in the absence of cooling. Therefore, whether the reactor is at power or shut down, **a fuel heat sink must ALWAYS be available**.

Fuel temperature is determined by the rate at which fuel heat is removed versus the rate at which it is produced. Fuel temperature will rise unless the rate of heat removal at least equals the rate of heat production. As fuel temperature rises, the probability of fuel failures due to center-line melting and sheath rupture increases.

The fuel temperature depends on five parameters which are under operator control:

1. Neutron Power

- The neutron power, proportional to the average neutron flux in core, determines the rate of fission heat production in the fuel
- Heat generation by the fuel must not exceed capability of the in-service heat sinks, or fuel temperature will rise.

2. Coolant Inventory

- The coolant is the means by which heat is transported for removal and must be present for effective fuel cooling.

NOTES AND REFERENCES

3. Coolant Pressure

- **Non-boiling Coolant:** *Subcooling margin* is the amount by which coolant temperature is below boiling point at the prevailing coolant pressure. *Saturation margin* is the amount by which coolant pressure is above the saturation pressure at the prevailing coolant temperature. Both terms refer to the margin to boiling conditions.

- **Boiling Coolant:** Coolant pressure and void fraction must be controlled to prevent fuel dryout, which would result in rapidly rising fuel temperatures.

4. Coolant Flow

- If the HT coolant flow is disrupted, coolant and fuel temperatures will rise, unless there is a corresponding decrease in reactor power.

5. Heat sinks

- Without an adequate heat sink, HT coolant temperature and pressure would rise, causing an increase in fuel temperatures.

Heat Removal Chains

A heat removal chain consists of a series of linked heat transport loops--eg, the following full power heat removal chain:

First link:	Fuel heat to boilers via PHT coolant
Second link:	Boiler heat to turbine/generator/condenser via steam/feedwater circuit
Third link:	Condenser heat to lake via condenser circulating water (CCW)

The viability of each link/heat transport loop in a heat removal chain depends on the following factors:

- Heat input;
- Coolant inventory in the loop;
- Coolant pressure and temperature;
- Coolant flow;
- Heat sink

NOTES AND REFERENCES

Reactor thermal power must not exceed the capacity of the weakest link in the heat removal chain.

Examples:

1. Full power heat sink:
   HT forced circulation with main boiler feed train in service.

   Heat removal capability = 100% reactor thermal power.

2. Shutdown heat sink:
   HT forced circulation with auxiliary boiler feed train in service.

   Heat removal capability = 3% reactor thermal power.

Back-up Heat Sinks

Obj. 4.8 ⇔ OP&Ps require that at all times a heat sink and heat transport method shall be in use, and an independent back-up system shall be available. **The back-up heat sink must be independent of the primary heat sink so that no single equipment failure can impair both heat sinks.** This means that one heat removal chain must be in use and one poised at all times.

Example: Heat removal chain in use at full power:

HTS + Main HT Pumps / Boilers + Main Feedwater Pumps + Turbine Generator + CCW Pumps + Class IV Power

Example: Heat removal chain following reactor trip due to loss of class IV electrical power:

HTS + Thermosyphoning / Boilers + Auxiliary Boiler Feedwater Pumps, or (IUFWT) + Atmosphere Via Steam Discharge Valves + Class III Power

The boilers must be part of the heat removal chain whenever the reactor is operated at power. If heat cannot be transported to or from the boilers, the reactor must be shut down. All back-up heat removal methods can handle only decay power. The shutdown systems will operate on loss of required heat sink capacity. The purpose of shutting down the reactor when the main heat sink is impaired, is to bring reactor power within the capacity of the back-up heat sinks.

NOTES AND REFERENCES

For minor impairments of the full power heat transport chain a shutdown may not be necessary. Automatic protective action via setback or stepback may reduce power to a level that the heat sink can handle. A heat imbalance may also be corrected by increasing heat removal. For example, the Boiler Pressure Control Program may open steam discharge valves (SRVs or ASDVs) to let some heat be dissipated.

The priorities when a heat sink impairment occurs at power are:

1. Reduce thermal power to a level which the heat sink can handle;

2. If the full power heat removal chain cannot be used, the reactor must be shutdown and a decay power heat removal chain must be established;

3. Notify the Shift Supervisor;

4. Ensure an independent back-up heat removal chain is available.

If a loss of heat sink prevents heat removal from the HTS, coolant pressure, temperature and void fraction (in the case of boiling conditions) rise. Therefore, fuel temperature also rises, putting fuel integrity at risk. To compensate for the loss of heat sink, reactor power must be reduced, or the reactor towards shut down to reduce power input to the HTS. In addition, **adequate heat removal must be accomplished either via the original heat sink or via a back-up heat sink.**

⇔ *Obj. 4.9*

Containment Of Radioactivity

The first two barriers to fission product release are the fuel pellet ceramic and the fuel sheath. Even if fuel temperature is always kept within acceptable limits, small quantities of radioactive fission products routinely escape through any holes (defects) in the fuel sheath. Any radioactivity released from the fuel sheath collects in the heat transport system, whose boundary acts as a further barrier between radioactivity and the environment.

Thus the HTS pressure boundary:

- forms the third barrier for fission products;
- is necessary to ensure the integrity of the first two barriers;
- is the first barrier against the release of tritium.

NOTES AND REFERENCES

The fourth barrier is the Containment system. It limits the release to the environment if a failure of the first three barriers occurs, as in the case of a LOCA or fuel handling accident. The containment system also provides protection against tritium releases.

The fifth barrier is the exclusion zone around the station. Any radioactivity which does escape from containment will be diluted before reaching members of the public. This dilution reduces the dose that members of the public receive. At stations where the exclusion zone is used by the public for recreation (e.g., park land), the public address system becomes part of the fifth barrier. The public address system is required to notify the public that the exclusion zone must be evacuated.

SUMMARY OF THE KEY CONCEPTS

- Two reasons for requiring power indication at all power levels are:

  1. to provide indication that reactor power is being controlled within heat sink capacity during normal operation.

  2. to provide continuous confirmation during accident conditions that the reactor is shut down and power is adequately controlled;

- Fueling should take place when the reactor is at power, because fueling causes reactivity changes which can be immediately identified and compensated for by RRS. With the reactor shutdown, there is no indication of unusual reactivity effects.

- The back-up heat sink must be independent of the primary heat sink so that no single equipment failure can impair both heat sinks.

- A loss of heat sink for the primary coolant results in impaired fuel cooling, placing the fuel at risk.

NOTES AND REFERENCES

ASSIGNMENT

1. Carefully prepare detailed answers to the Module 4 learning objectives.

2. List the elements of the primary heat removal chain for full-power operation, and identify the action priorities in the event that the primary heat sink is impaired.

3. Identify and briefly describe the <u>three</u> engineered layers of control and protection which ensure that the fuel in a reactor never produces more fission heat than the full-power heat sinks can remove.

4. The <u>two</u> primary factors which affect fuel temperature are heat production and heat removal; describe the various contributors to each of these two factors, indicating how they are controlled, and derive the rationale for ensuring that a primary and an independent back-up heat sink is always available.