Commonwealth Edison Company
Byron Generating Station
4450 North German Church Road
Byron, IL 61010-9794
Tel 815-234-5441

July 6, 2000

ComEd

LTR: BYRON 2000-0099
File: 1.10.0101

James E. Dyer, Regional Administrator
United States Nuclear Regulatory Commission
Region III
801 Warrenville Road
Lisle, IL 60532-4351

Byron Station, Units 1 and 2
Facility Operating License Nos. NPF-37 and NPF-66
NRC Docket Nos. STN 50-454 and STN 50-455

Subject: Initial License Examinations Post-Examination Review

Byron Station has completed the post examination review of the initial license examinations administered during the weeks of June 19, 2000, and June 26, 2000.

Enclosed with this letter are the documents requested by the NRC as outlined in Section ES-501 of NUREG 1021, Revision 8.

If you have any questions regarding this matter, please contact Mr. Brad Adams, Regulatory Assurance Manager at (815) 234-5441, extension 2280

Respectfully,

William Levis
Site Vice President
Byron Station

WL/RC/dpk

Enclosures: Graded written examination (scantron) sheets plus a copy of the sheets prior to grading
Applicant comments and references
Seating Chart
Written Exam Performance Analysis
Questions asked by applicants during the written examination

cc: NRC Senior Resident Inspector – Byron Station

Byron Station Staff/Applicant Comments
Regarding the NRC Initial Written Examination

COMMENT #1

Question RO #33 and SRO #8

Answer D

Comment: Distractor A is stated "EDG's have a high availability rate and are 100% redundant". One reason the site qualifies as an AAC station is that the EDGs have a reliability rate of .95 and are 100% redundant. The wording of this distractor is such that a high availability rate could be interpreted to be a reliability of >.95.

Resolution: Accept distractor A as an alternate answer.

Reference: BCA 0.0 Lesson Plan

COMMENT #2

Question RO #74 and SRO #49

Answer C

Comment: Distractor D is the correct answer for this question. The question asks for the initial response of the unit due to a trip of a reactor coolant pump. Hot leg temperature in the unaffected loops will increase since the same reactor heat input is being absorbed by less total core flow. This causes Tavg to initially increase.

Resolution: Accept distractor D as the only correct answer.

Reference: 1.RCP Chapter 13 Lesson Plan
2. Fundamentals Lesson Plan Chapter 7, Steady State, Normal and Abnormal Transients. (pg 54-61)

BYRON PWR OPERATIONS
FUNDAMENTALS
(Cover Page)

HEAT TRANSFER
MODULE

7: STEADY STATE OPERATIONS, NORMAL AND ABNORMAL TRANSIENTS
CHAPTER

2
REVISION

[signature]
REVISED BY

1-6-99
DATE

II. CONCEPT DESCRIPTION (Con't)

Example 8

Due to a problem with the Circulating Water System, turbine power was reduced from 950 MW to 800 MW in 10 minutes. What is the effect of this load rejection on T_{avg}, if rods are left in manual and no boration or dilution is initiated

1. Over the next 15 minutes?
2. Over the next 40 hours?

Solution 8

- Immediately after the transient, T_{avg} will rise, adding negative reactivity. This offsets the positive reactivity added by Doppler, when fuel temperature decreased, due to the reactor power decrease. (Refer to Figure HT-7-20b).

- Soon after the load rejection Xenon will start to build in since it is not being burned out as rapidly. The moderator temperature will decrease, adding positive reactivity to offset the negative reactivity of the Xenon. This will drop T_{avg} below the value attained above. Eventually, the Xenon level will peak (≈ 4hrs) and start to fall off. This will drive T_{avg} back up. When the reactivity due to Xenon reaches the level prior to the load rejection (≈ 10hrs), T_{avg} will have risen to the same level as above. Xenon level, however, will continue to decrease to a new equilibrium value (at ≈ 40 hrs) lower than that prior to the load rejection. This will result in a final T_{avg} somewhat higher than the level reached in the first part of the question.

II. CONCEPT DESCRIPTION (Con't)

Example 9

Answer the questions posed in the example above if the control rods are in automatic.

Solution 9

E. Abnormal Transients

The principles of thermal-hydraulics are well applied to certain abnormal plant conditions. Analysis of such situations as tripping a Reactor Coolant Pump, closure of a Reactor Coolant Loop Stop Isolation Valve, and closure of a Main Steam Isolation Valve with the unit at power can aid the operator in understanding the thermal response of the plant to unexpected conditions.

Steady-State Operation With One Idle Reactor Coolant Pump

During normal four-loop operation, the RCPs provide work to the primary system equivalent to the head loss through the reactor vessel, steam generator, and primary

II. CONCEPT DESCRIPTION (Con't)

system piping. The total pressure drop due to head loss is approximately 85 psi. Although not administratively allowed, it is physically possible to operate at steady-state power levels with one idle loop. In a four-loop plant, one idle loop implies only three RCP's are operating. (Byron Station is not allowed critical operation with only three RCP's operating because this situation is not analyzed in the UFSAR.)

When one pump is stopped, the flow rate through the core is reduced. According to the law of continuity, the velocity of the coolant also decreases. As a result, the pressure drop across the core and reactor vessel decreases. Because the head loss decreases, flow rate increases in the three loops with an operating RCP. As a result, flow rate to the reactor vessel (maintained by three RCPs) is greater than three-fourths of the original flow.

In the idle loop, the driving head for flow is the pressure difference across the reactor vessel. Pressure is low in the hot leg and high in the cold leg. Furthermore, when primary water from the three operating loops reaches the reactor vessel, this water can flow either downward past the core barrel or out through the cold leg of the idle loop. Although the majority of the water flows downward past the core barrel, a certain percentage flows out the idle loop. As a result, the direction of flow in the idle loop

II. CONCEPT DESCRIPTION (Con't)

is reversed and the flowrate through the core is less than the flowrate to the vessel. When flow from the hot leg returns to the vessel, it bypasses the core by exiting through the remaining hot leg nozzles (to the other loops).

Since flow in the idle loop completely bypasses the core, the temperature in that entire loop is reduced to T_C. Consequently, the heat transfer rate across the idle loop steam generator is reduced. Less steam is produced on the secondary side of that steam generator and the steam flowrate from that steam generator becomes negligible. Since total steam demand has not changed, steam flow from the other three generators must increase. As steam flow increases, the pressure and temperature in each of the three steam generators decreases. In the primary system, the same power must be transferred with a reduced flow rate. As a result the ΔT across the core must increase.

Example 10

With one Reactor Coolant Pump idle, the mass flow through the core is reduced to 9.45×10^7 lbm/hr. Assuming steam demand remains constant at 100 percent, find T_H, T_C and ΔT across the core. What is the steam pressure in each of the steam generators in an operating loop? Assume $\dot{Q}_{RX}$ (100%) = $\dot{Q}_{SG}$ (100%) = 3411 Mwt.

II. CONCEPT DESCRIPTION (Con't)

Solution 10

$$\dot{Q} = \dot{m}_{RCS}\ C_p\ \Delta T = \dot{m}$$

$$\Delta T = \frac{\dot{Q}}{\dot{m}_{RSC}\ C_p}$$

$$C_p = 1.4\ \frac{BTU}{lbm\text{-}^{\circ}F}\ for\ RCS$$

$\dot{Q}$ = 3411 Mw for 4-loop plant at 100 percent power.

$$\Delta T = (3411\ \ Mw)\left(\frac{3.413\ x\ 10^6 BTU/hr}{MW}\right)\left(\frac{hr}{9.45\ x\ 10^7\ lbm}\right)\left(\frac{lbm\ \ ^{\circ}F}{1.4\ BTU}\right)$$

= 88°F

Assuming T_{avg} remains constant because steam demand remains constant and no long term reactivity changes occur,

$$\Delta T = 88^{\circ}F = T_H - T_C$$

$$T_{avg} = \frac{T_H + T_C}{2}$$

$$T_H = 88^{\circ}F + T_C$$

II. CONCEPT DESCRIPTION (Con't)

$$88°F + T_C + T_C$$

$$580.0°F = \frac{88°F + T_C + T_C}{2}$$

$$T_C = 536.0°F$$

$$T_H = 624.0°F$$

With all heat transfer across only three steam generators, the total steam generator heat transfer surface area is reduced by one-fourth

$$\dot{Q}_{S/G} = UA\ (T_{avg} - T_{stm})$$

$$\dot{Q}_{S/G} = U\left(\frac{3}{4}\right)A(T_{avg} - T_{stm})$$

At normal 100 percent power,

$$T_{avg} - T_{stm} = 582.0 - 533.0 = 49.0°F$$

With one idle loop,

$$T_{avg} - T_{stm} = \frac{4}{3}(49°F) = 65.3°F$$

II. CONCEPT DESCRIPTION (Con't)

Assuming a constant T_{avg},

$$T_{stm} = T_{avg} - 65.3°F$$
$$= 582.0°F - 65.3°F$$
$$= 516.7°F$$

If T_{stm} = 516.7°F, P_{stm} = 789.8 psia.

In reality, the affected steam generator pressure cannot fall this low since it is crosstied to the other steam generators. It will stay at some pressure lower than the other generators due to headloss in its steamlines as illustrated in Figure HT-7-22a. This Figure tracks the steam generator pressure in the affected and unaffected loops for the duration of a trip of the "1B" RCP B at 30% power. Since the affected loop, due to the crosstie, simply mimics the unaffected loop, it is most meaningful to analyze the unaffected loop. Recall that the heat transfer across the steam generator is described by the equation:

$$\dot{Q}_{S/G} = U\ A\ (T_{avg} - T_{stm})$$

As the example shows, the reduced area requires a greater ΔT. The increased ΔT is produced by a rapid initial increase in T_{avg} and decrease in T_{stm}. Figure HT-7-22a illustrates the initial rapid drop in S/G pressure (T_{stm}). This corresponds exactly with the

rapid steam flow increase in the unaffected steam generators illustrated on Figure HT-7-22b. In this Figure the affected steam generator flow actually goes negative. This is because the cold primary water now flowing to it collapses the mixture in the S/G riser and the downcomer level shrinks as the steam generator mass cools. With the rapid addition of cold feedwater to an unheated generator this generator drops lower in temperature (and pressure) than the others, and the others begin to feed it resulting in a negative steam flow.

Figure HT-7-22c illustrates primary temperatures during this transient. T_H and T_{avg} see an initial rapid rise in both the affected and unaffected loops due to increased core residence time as the tripped RCP coasts down. Once the RCP coasts down, reverse flow begins and T_H of the affected loop drops rapidly to a value even lower than T_C in that loop. (For this transient, T_C is nearly the same in all the loops.) Because of reverse flow through a cold generator the hot leg will be cooled to a value below the cold leg temperature. Initially, T_C in the affected loop drops because of the increased residence time in the steam generator. T_H continues to increase in the unaffected loops since the same reactor heat output is being absorbed by less total core flow. This increases T_{avg} and later T_C. The increased T_{avg} now provides more effective heat transfer across the steam generator and results in the increased steam generator pressure and temperature (T_{stm}) observed at about one minute as shown in Figure HT-7-22a. The increased T_{avg} also adds negative reactivity to the core which reduces reactor power. Reduced steam generator pressure causes the gradual reduction of T_{avg} until the final condition of Figure

II. CONCEPT DESCRIPTION (Con't)

HT-7-22c will be that outlined in the example - an increased T_H a decreased T_C and a relatively constant T_{avg}. T_{avg} returns near to its original value since no reactivity changes occurred that would require a change in T_{avg}. Rod position, reactor power, Boron concentration and Xenon are all unchanged.

Loop Stop Isolation Valve Closure

An abnormal transient very similar in nature to the trip of an RCP is an inadvertent closure of a Loop Stop Isolation Valve (LSIV) in a reactor coolant loop cold leg. In a reactor coolant loop, the cold leg LSIV is just downstream of the discharge of the Reactor Coolant Pump. Figures HT-7-23 a - c illustrate the effect of LSIV closure on the same variables analyzed for the RCP trip. Figures HT-7-23a and b show that steam generator pressure and steam flow respond essentially the same as for the RCP trip and for the same reasons. Steam flow increases in the unaffected loops to compensate for the flow lost from the affected loop. Steam pressure drops rapidly, increases as T_{avg} increases, then drops to a final, lower value as T_{avg} drops back down.

The major differences between the LSIV closure and the RCP trip lie in the temperatures of Figure HT-7-23c. For the LSIV closure, as core mass flow decreases, T_H, and therefore T_{avg}, increase as before. T_C follows later. This negative reactivity addition is slower to reduce reactor power because in this case the decrease in core flow is less so

II. CONCEPT DESCRIPTION (Con't)

the increase in T_H is less. As reactor power is decreased, T_H and T_{avg} decrease. This, in conjunction with the lowered steam generator pressure, causes T_C to drop. The eventual result is an increased T_H, a decreased T_C and a constant T_{avg}. In the affected loop T_H initially increases as the core flow decreases, then with no flow in the loop, T_H decreases slowly as heat is lost to the cold steam generator. T_C in the affected loop initially increases as the energy added during the RCP coastdown heats the water. T_C then decreases rapidly due to the cooldown occurring in that loop's steam generator. Reactor power will once again increase back to its original value prior to the transient.

Figure HT-7-24 compares the total core flow for the RCP trip to total core flow for the LSIV closure. For the LSIV closure core flow drops to 80% and for the RCP trip it drops to approximately 70%. In neither case does the flow drop to exactly 75% as might be expected. When the LSIV closes the isolation of one loop drops the flow entering the core. This flow decrease reduces the pressure drop across the core which allows each RCP to pump more flow than previously. Now only three pumps are operating but each is pumping more flow, so the total core flow is greater than 75%.

For the RCP trip, each pump once again increases its flow such that total pump flow is greater than 75%. The reverse flow in the idle loop bypasses the core such that total core flow drops to less than 75% as seen in Figure HT-7-24. This indicates that at least 10% of the flow from the three operating RCP's bypasses the core to flow backward through the idle loop.

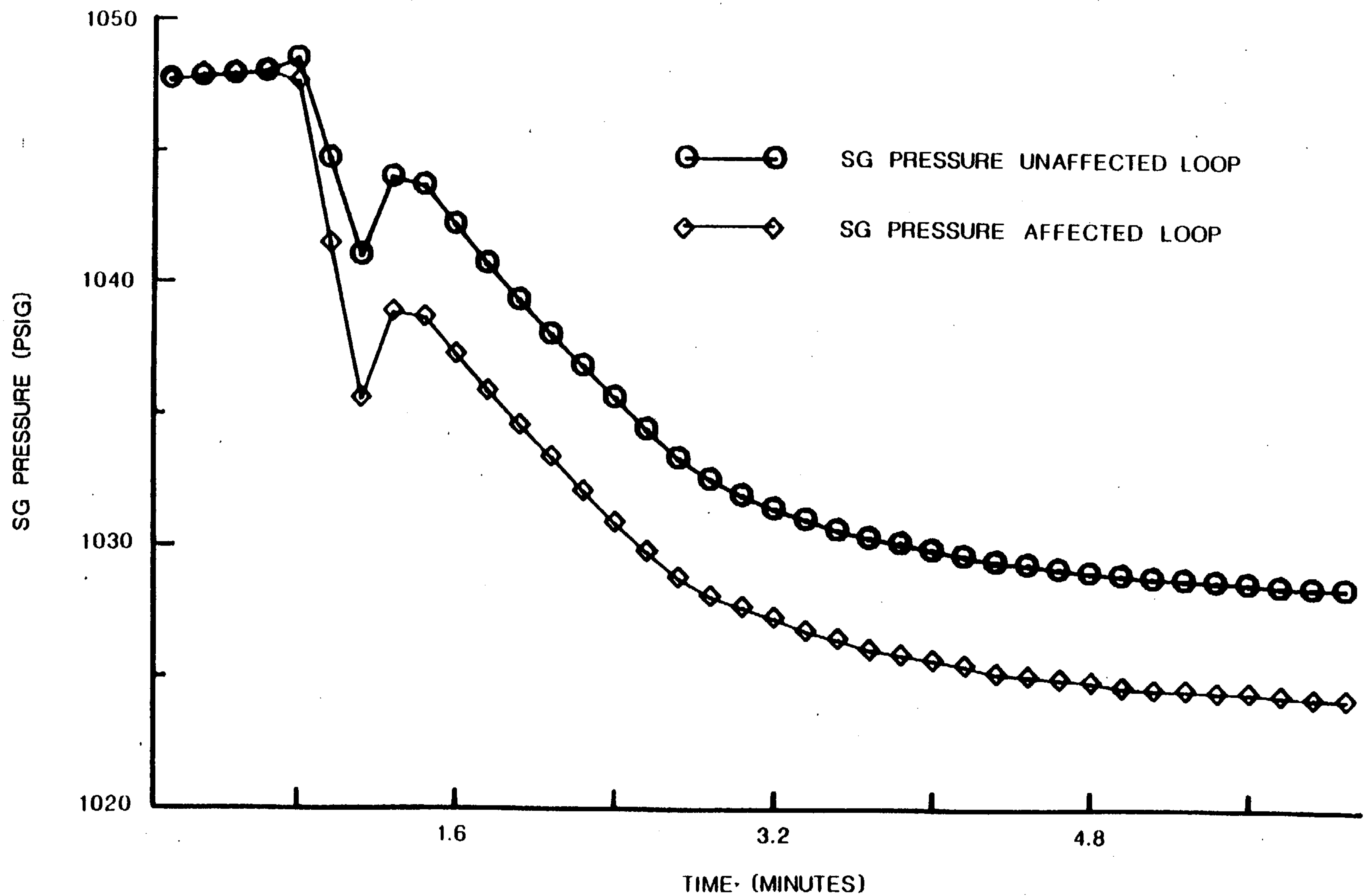

FIGURE HT-7-22a RCP B TRIP MANUAL RODS

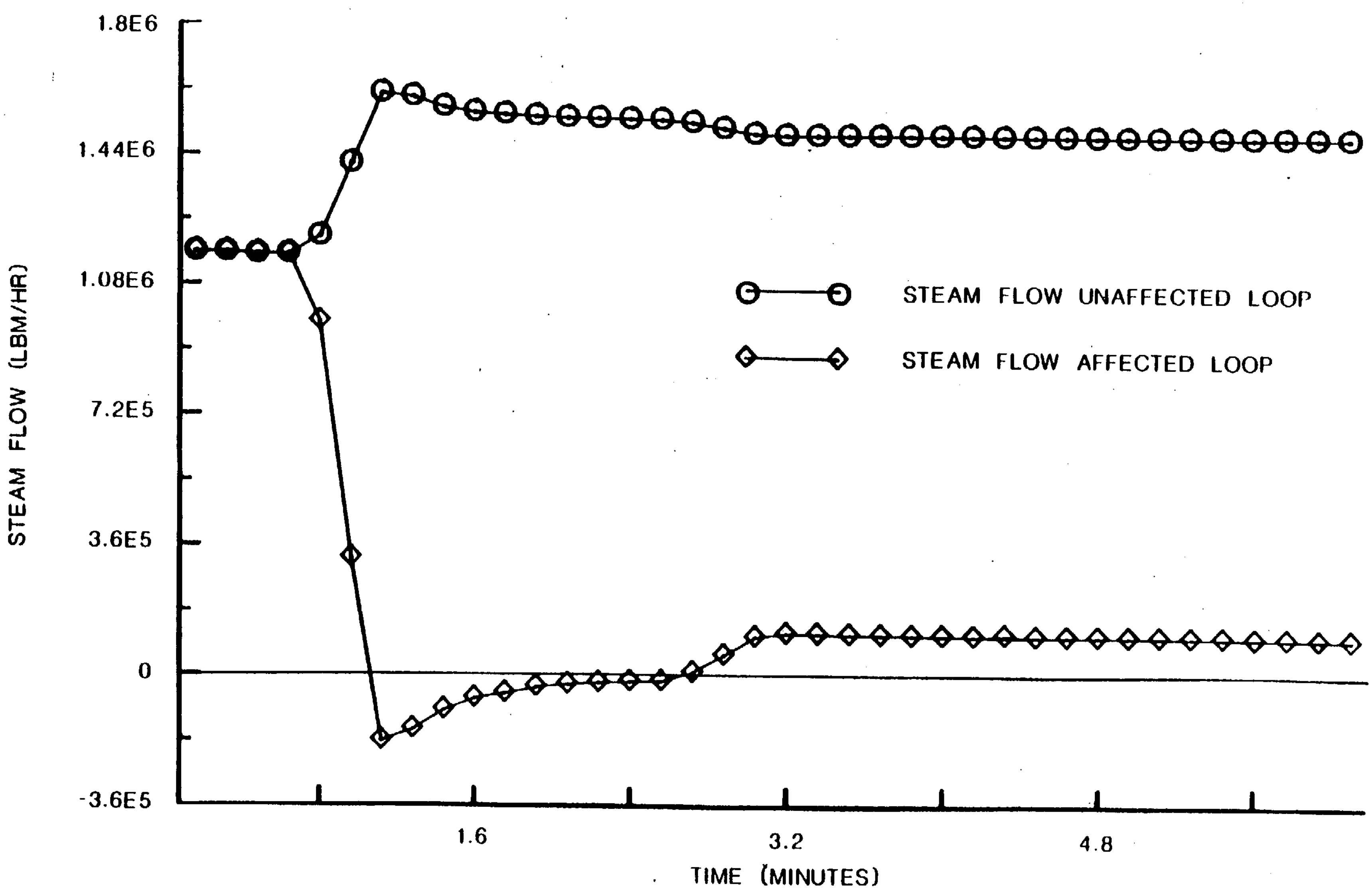

FIGURE HT-7-22b RCP B TRIP MANUAL RODS

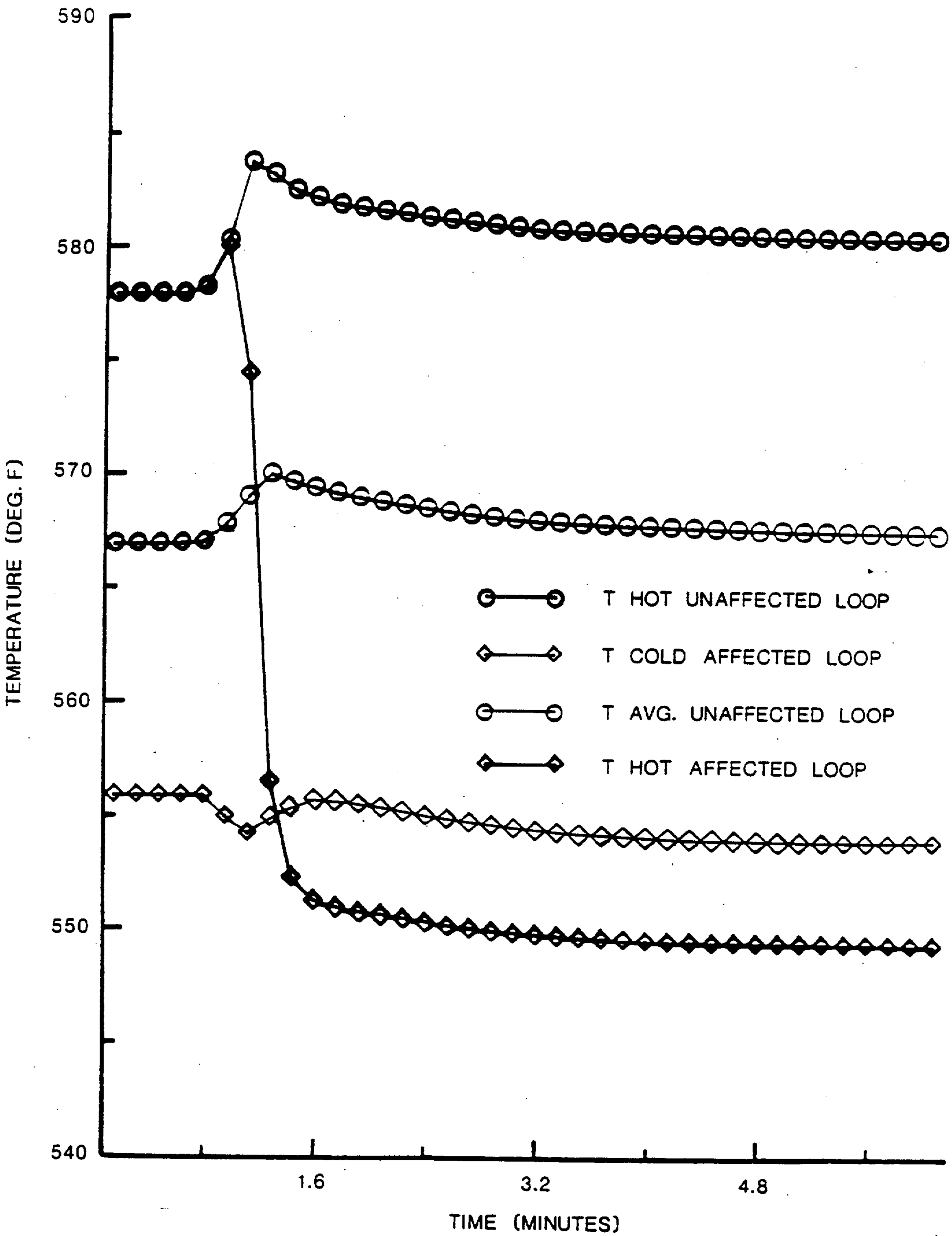

FIGURE HT-7-22c RCP B TRIP MANUAL RODS

COMMONWEALTH EDISON

Course/Program: Fundamentals — Rev.: 02, 12/31/98

Module/Unit: Chp 7, Steady State Operation, Normal and Abnormal Transients — By: T. Demmitt

Prerequisites: ILT Fundamentals

ILT KNOWLEDGE OBJECTIVE(S):

At the completion of the lesson, the student shall be able to:

1. SUMMARIZE the interrelationship of thermal hydraulic equations as applied to the major components of the primary and secondary systems. (A.HX7-01)

2. DEFINE secondary plant efficiency and overall plant efficiency and discuss factors affecting each. (A.HX7-02)

3. EXPLAIN the basis for ramped T_{avg} as opposed to constant T_{avg} or constant T_{steam} control. (A.HX7-03)

4. EXPLAIN how secondary mass flow rate changes with power changes and COMPARE it to steady state primary flow rate. (A.HX7-04)

5. DISCUSS the effects of RCS temperature, pressure and power level on RCS subcooling. (A.HX7-05)

6. SUMMARIZE the thermal-hydraulic aspects of a plant heatup including: (A.HX7-06)

   a. Method of initial RCS heatup and pressurization (A.HX7-06-A)
   b. Point Of Adding Heat (POAH) (A.HX7-06-B)

7. EXPLAIN RCS temperature control and reactor power control both before and after the POAH. (A.HX7-07)

8. EXPLAIN the reaction of a typical PWR to normal up and down power transients with and without automatic rod motion. (A.HX7-08)

9. Qualitatively ANALYZE the thermal-hydraulic effects of the following: (A.HX7-09)

   a. Reactor Coolant Pump Trip (A.HX7-09-A)
   b. Loop Stop Isolation Valve closure (A.HX7-09-B)
   c. Main Steam Isolation Valve closure (A.HX7-09-C)

ESTIMATED TEACHING TIME: 8 hours

REFERENCES: Thermal-Hydraulic Principles and Applications to the Pressurized Water reactor, Chapter 12, Westinghouse Electric Corporation, April 1983

Fundamentals Heat Transfer Text

A. Content/Skills

I. INTRODUCTION

A. Basis for the Chapter

1. All electric industry reactor plants must be designed and operated with two goals in mind:
   a. Operate safely such that no undue risk to health and safety of the public is created.
   b. Operate efficiently (minimize the cost of producing electricity).

2. Concern for both safety <u>and</u> efficiency requires that operator understand the basic design considerations for the plant.
   a. This understanding allows the operator to determine consequences of operating outside major design limits.

3. Operator must also be able to anticipate response of plant during normal transients so he/she can determine whether plant is responding as it should (i.e. diagnose problems) and to then take appropriate actions.

4. To maximize efficiency of operator actions, various abnormal transients that have significant probabilities of occurrence should be thought out by the operator prior to the assignment of operating a unit.

3. Examples of plant responses to be anticipated:

Scenario	Should Anticipate
1. Power Changes	• AFD (ΔI) response
2. Load Rejection	• SG response
3. RCP Trips	• Natural circulation & core response

B. These knowledge requirements form the basis for major topics in this Chapter.

1. This Chapter alone does not cover the full scope of topics but relies on previous knowledge from Thermodynamics, Fluid Flow and Reactor Theory.

2. Further understanding will also be attained in systems.

C. General Assumptions

1. To minimize the complexity of calculations and yet get meaningful results, certain assumptions may be made when analyzing plant performance.

   a. A common assumption is that the total heat transfer in steam generators is equal to the heat transfer in the reactor core.

   b. Another common assumption is that all steam flow into the turbine continues to the condenser.

B. **Display TP HT-7-1**, "Knowledge Objectives"

1. **Display TP HT-7-2**, "Chapter 7 Outline"

C. **Display TP HT-7-3**, "Thermal Hydraulic Equations for Components of The Primary and Secondary Systems" (Figure HT-7-1).

a. This assumption causes little error as long as RCP heat addition is approximately equal to the heat losses of the primary to ambient. At full power, inaccuracy caused is less than ½%.

NOTE: *Actual RCP heat addition is not equal to ambient losses. To be discussed later.*

II. CONCEPT DESCRIPTION

A. PWR Design Considerations

1. General

a. Single component that establishes energy requirements for the PWR is the turbine generator (TG).

1) Controls for the turbine modulate governor valves to maintain preset electrical loading on generator.

2) Modulation of governor valves controls rate that steam is drawn from SG's and therefore heat rate demand on primary.

b. Heat required for given electrical load depends on turbine efficiency.

c. Turbine efficiency depends on ability to maintain steam pressure as close as possible to the most efficient steam pressure for particular turbine.

1) To maintain constant SG pressure from 0 to 100% power, average RCS temperature would be required to increase significantly causing extreme variation in coolant volume (hence Pressurizer level).

2) Extreme changes in RCS temperature also necessitate considerable control rod motion due to the moderator temperature effects.

d. Temperature program for RCS is therefore a compromise between effects on the primary and secondary sides of the PWR.

THIS PAGE INTENTIONALLY LEFT BLANK

2. Temperature Program

   a. Heat transfer across SG as power changes is limited by the terms in the equation: $\dot{Q}_{SG} = UA\ (T_{avg} - T_{stm})$.

      1) Ramping T_{avg} up and T_{stm} down as power is increased minimizes the unwanted effects of changing either.

   b. Constant T_{avg} advantages.

      1) No RCS volume change.

      2) No α_T reactivity changes.

   c. Constant T_{avg} disadvantages.

      1) Very high no-load steam pressure.

      2) Difficult to design an efficient turbine.

   d. Constant steam pressure advantages.

      1) Maintains η_{sec} high.

   e. Constant steam pressure disadvantages.

      1) Requires large T_{avg} changes.

         a) Large RCS volume changes.

         b) Large α_T reactivity changes.

   f. The ramped T_{avg} program is a compromise to keep steam pressure high at high power levels.

   g. Temperature range.

      1) T_{avg} increases from 557°F to 582°F from 0-100% power.

      2) T_H increases from 557°F to 610°F from 0-100% power.

      3) T_C decreases from 557°F to ~~554~~°F from 0-100% power. 552°F

2. **Display TP HT-7-4**, "Advantages and Disadvantages of Ramped T_{avg} Program".

2. Explain the basis for ramped T_{avg}.

2) α_T = Moderator Temperature Coefficient

Display TP HT-7-5, "Programmed T_{avg}" (Figure HT-7-3).

4) Steam pressure decreases from 1092 psig (557°F) to 890 psig (533°F) from 0-100% power.

5) All changes are approximately linear.

3. Pressurizer Level Program

a. RCS is a constant mass system (simplifies the accident analysis)

b. The 25°F increase in T_{avg} as power increases causes a large expansion of the RCS

c. Results in an increased Pressurizer level

d. Level increases from 25% to 60% from 0-100% power

e. Level is controlled by charging system and takes an input from the value of T_{avg}.

1) If T_{avg} increases, PZR level is programmed to increase.

4. Determination of steady-state primary and secondary mass flow rate in the PWR.

a. Heat transfer into secondary water of the S/G is described by:

1) $\dot{Q}_{S/G} = \dot{m}_{stm} (h_{in\ turb} - h_{feedwater})$

b. S/G pressure decreases as power level increases (turbine governor valves are opened)

1) S/G outlet enthalpy, h_{in} turb, actually increases as pressure drops in this pressure region.

3. **Display TP HT-7-6**, "Pressurizer Level Program" (Figure HT-7-4).

d. PZR level control will be thoroughly discussed in systems.

b. **Display TP HT-7-7**, "S/G Outlet Pressure Characteristic Curve" (Figure HT-7-5).

c. Feedwater temperature increases as power level increases (governor valves opened) due to increased effectiveness of feedwater heating.

   1) Feedwater specific enthalpy increases also.

d. Feedwater specific enthalpy increases more rapidly than S/G outlet specific enthalpy as power increases such that Δh of secondary decreases as power increases.

e. A decreasing Δh requires an increasing $\dot{m}_{stm}$ as power increases.

f. Primary design flow depends upon:

   1) ΔT across the reactor core (specifically core outlet temperature)

      a) Need to increase $\dot{m}$ to decrease ΔT.

   2) Cost of pumping power

      a) Increased flow results in a cubed increase in power requirements for the pump.

      b) Rather than change pump speed more loops and pumps can be used to increase $\dot{m}$.

      c) More loops means more equipment expense and maintenance.

   3) A constant flow rate of 1.5×10^8 lbm/hr is chosen.

g. $\dot{m}_{RCS}\, C_p \Delta T = \dot{m}_{stm}\, (h_{in\ turb} - h_{feedwater})$

   1) Δh is ten times the valve of $C_p\, \Delta T$

      a) at 100% power $\Delta h \approx 776$ BTU/lbm

      b) $C_p\, \Delta T \approx 80$ BTU/lbm.

   2) $\dot{m}_{RCS}$ is therefore $\approx$ ten times $\dot{m}_{stm}$ at 100% power:

      a) $\dot{m}_{RCS} = 1.5 \times 10^8$ lbm/hr.

      b) $\dot{m}_{stm} = 1.5 \times 10^7$ lbm/hr.

c. **Display TP HT-7-8**, "Final Feedwater Temperature vs NSSS Power" (Figure HT-7-6).

d. **Display TP HT-7-9**, "Flow Rate and Enthalpy Change Across the Steam Generator" (Figure HT-7-7).

d. Explain how Δh of the steam generator changes as power level changes.

e. The Δh decreases most rapidly at low power levels because the feedwater temperature increases most rapidly at low power levels.

g. Compare primary and secondary steady-state mass flow rates.

h. Example 1

The primary coolant in a 4-loop plant is reduced from 608°F to 552°F in the Steam Generator while transferring 1.58×10^9 BTU/hr across each Steam Generators into the secondary water. Secondary feedwater enters the Steam Generator at 435°F and exits as 99.79 percent quality steam at 905 psia. What is the secondary mass flow rate required in each Steam Generator?

5. Determination of Primary System Pressure

   a. Primary water is separated from secondary system.

   b. Primary must be maintained subcooled to prevent fuel damage.

      1) Normal pressure 2250 psia ± 15 psi.

      2) Subcooling is saturation temperature for the actual pressure minus the actual temperature, T_{Hot}.

      3) 653°F - 610°F = 43°F subcooling.

   c. Subcooling decreases as temperature increases or as pressure decreases.

B. Plant Efficiency

1. There are two types of plant efficiency.

   a. Secondary plant efficiency is based only upon the secondary water system.

   b. $$\eta_{sec} = \frac{\dot{Q}_{S/G} - \dot{Q}_{Rej}}{\dot{Q}_{S/G}} = \frac{\dot{W}_{Turb} - \dot{W}_{pumps}}{\dot{Q}_{S/G}}$$

h. Solution 1 (Not in student text)

$\dot{Q} = \dot{m}_{stm}\Delta h$

$$\dot{m}_{stm} = \frac{\dot{Q}}{(h_{out} - h_{in})}$$

h_{out} at 905 psia and 99.79% quality

$h_{out} = h_f + xh_{fg}$

$h_{out} = 528 + 0.9979\ (668.1)$

$h_{out} = 1195$ BTU/lbm

$h_{in} = 414$ BTU/lbm

$$\dot{m}_{stm} = \frac{1.58 \times 10^9\ BTU/hr}{(1195 - 414)\ BTU/lbm}$$

$\dot{m}_{stm} = 2.02 \times 10^6$ lbm/hr

Discuss the effects of RCS temperature and pressure on RCS subcooling.

c. **Display TP HT-7-10**, "Subcooling in the Primary System" (Figure HT-7-8).

1. Define secondary plant efficiency.

b. **Display TP HT-7-11**, "Thermodynamic Boundaries" (Figure HT-7-2).

c. Has the major impact on true plant efficiency.

d. 100% power value is approximately 35%.

2. True plant efficiency

a. True plant efficiency encompasses the entire plant.

b. $\eta_p = \frac{\dot{W}_{net}}{\dot{Q}_{Rx}} = \frac{\dot{W}_{Gen} - \dot{W}_{house\ loads}}{\dot{Q}_{Rx}}$

c. $\dot{W}_{\text{House loads}}$ includes secondary pumps plus all other loads in the plant including:

1) RCPs

2) Circulating Water Pumps

3) WS Pump

4) CCW Pumps

5) all other in house loads

d. House loads are approximately 45 MW.

e. True plant efficiency ≈ 33%.

1) True plant efficiency is always less than secondary plant efficiency due to the energy requirements of the non-secondary system pumps.

C. Secondary System Effects on Plant Operation and Efficiency

1. General Approach

a. Entire PWR secondary plant comprises a Rankine Regenerative Reheat Cycle.

b. Various components and states of water around this cycle must be considered to evaluate effects on efficiency.

d. $$\eta_{sec} = \frac{3427.6 - 2224MW}{3427.6\ MW}(100)$$

$\eta_{sec} = 35.1\%$

2. Define overall plant efficiency.

3) WS - Non-Essential Service Water

4) CCW - Component Cooling Water.

e. $$\eta_p = \frac{1175MW - 45MW}{3411\ MW}(100)$$

$\eta_p = 33.1\%$

2. Condenser Effects

a. Of all the components under the operator's control, the condenser has the greatest effect on plant efficiency.

b. Low condenser pressure reduces h_{out} of the LP turbine and maximizes turbine output per pound mass of steam flow.

c. Use air ejectors and vacuum hogging pumps to remove non-condensibles.

1) This improves heat transfer across condenser tubes and ultimately lowers condenser pressure.

d. Lowered condenser pressure means more work out of the turbine for the same steam flow and a more efficient plant.

1) Heat rejected in the condenser decreases.

e. $\dot{Q}_{Rej} = U_{cond} A_{cond} (T_{stm.\ cond} - T_{avg\ cw})$.

f. Example 2

One Circulating Water Pump has been out of service and the unit output was reduced to 80%. The pump has now been returned to service and restarted. What effect will the restart of the Circulating Water Pump have on the amount of heat rejected to the cooling pond if the turbine is maintained at 80% power?

2. Braidwood condenser pressure has been ≈ 1.5 in. Hg absolute.

Q: How does operation of air ejectors affect the η?

A: Correct functioning of the air ejectors removes the non-condensibles from the condenser. This allows better heat transfer from the steam and therefore a greater condensation rate. A greater rate of condensation produces better vacuum and results in increased efficiency.

b. **Display TP HT-7-12**, "LP Turbine Pressure vs Power" (Figure HT-7-9).

f. Solution 2 (Answer in text).

Initially upon restart the increased circulating water flow absorbs more heat for rejection. This increased heat rejection with the same steam flow into the condenser can only be accomplished by lowering the condenser pressure and temperature. A lowered condenser pressure means that h_{out} of the LP turbine is lowered and more work per pound mass of steam is done in the turbine. For the same turbine output the mass flow of steam through the turbine must be reduced. The reduced steam flow will reduce the rejected heat to below the level rejected prior to the restart of the pump (this assumes that the amount of condensate subcooling is not increased by restarting the pump.)

g. Example 3

During an outage, 20% of the condenser tubes are plugged due to major corrosion problems. Assuming that after the outage the turbine output is returned to its previous level before the outage, explain the effect this action will have on the circ water outlet temperature.

g. Solution 3 (Not in student text)

In the equation $\dot{Q}_{Rej} = U_{cond} A_{cond} (T_{stm.\ cond} - T_{avg\ cw})$ the value of A will decrease, U is constant.

Therefore for the same $\dot{Q}_{Rej}$, $(T_{stm.\ cond} - T_{avg\ cw})$ must increase. T_{avg} will not increase unless more heat, per lbm is transferred to the circ water. Thus, T_{stm} must increase. The other effect of plugging tubes is an increased resistance to CW flow so that $\dot{m}$ cw decreases. To reject the same amount of heat as before, a higher outlet temperature is reached per the equation: $\dot{Q}_{Rej} = \dot{m}_{cw} C_p (T_{out} - T_{in})$. This means that $T avg_{cw}$ has increased.

The higher $T avg_{cw}$ combined with higher ΔT $(T_{stm} - T_{avg})$ requirement to reject the same amount of heat both require that T_{stm} increase. This necessitates higher P_{stm} and therefore higher exit enthalpy from the LP Turbines. This means less work is done with $\dot{Q}_{Rej}$ constant (η decreased) and the turbine control system must increase steam flow to maintain the same initial turbine power.

Q: How does leakage from a SG safety valve affect secondary η? T_{cold}? (assume no rod motion)

A: Secondary η decreases because energy is lost from the secondary that must be made up by greater $\dot{Q}_{Rx}$ with no increase in $\dot{W}_{turb}$. Since $\dot{Q}_{Rx}$ increases $(T_H - T_C)_{RCS}$ must increase. T_C will decrease since more heat is being removed from the primary.

3. Steam Pressure Effects

a. Steam pressure can be kept high by increasing T_{avg} as power increases.

1) This leads to the RCS volume fluctuation concerns discussed earlier.

b. The important steam pressure is at the turbine inlet, not at the SG outlet.

1) Opening the governor control valves increases turbine inlet pressure and decreases SG pressure.

2) Turbine inlet pressure is commonly referred to as first stage impulse pressure because it is measured at the first stage of the turbine.

3) If T_{avg} was not raised as the governor control valves were opened, SG pressure would fall further.

4) Increased first stage impulse pressure means less entropy of the entering steam.

a) The decreased entropy is due to less throttling losses across the governor control valves.

b) The LP turbine extracts more work per pound mass of entering steam.

(1) This is illustrated in Figure HT-7-12.

b. **Display TP HT-7-13**, "First Stage Impulse Pressure vs Power" (Figure HT-7-10).

Q: Turbine power is increased by opening the governor control valve. How will steam pressure differ if:

a. T_{avg} stays constant

b. T_{avg} increases

A: A constant T_{avg} requires a drop in T_{stm} (SG pressure).

If T_{avg} is increased then T_{stm} need not decrease as much and SG pressure will not decrease as much.

4) **Display TP HT-7-15**, "Turbine Process at Different Power Levels" (Figure HT-7-12).

In HT-7-12, with lower entropy steam entering the turbine (at high flows), more work is done in the LP turbine per pound mass steam. This is due to the greatly decreased outlet enthalpy of the steam in the LP turbine.

*NOTE: During Byron's recent operation in accordance with the T-Hot reduction program, the governor control valves were operated fully open to maximize MW output with the lowered steam generator pressure. It was found that plant efficiency was relatively unchanged. Apparently the efficiency reduction inherent in a lowered SG pressure was offset by the increased efficiency effect of eliminating the throttling losses in the control valve. It appears that the secondary system is designed to be most efficient when operated with the control valves full open at > 100% power (1175 MW) (Possibly in anticipation that the legal limit on Rx power will be raised in the future, or that steam generator tubes will be plugged or that W can meet their guarantee that the secondary side can actually produce 1175 MW. Overdesigning allows them some margin).

Therefore, raising steam temperature to increase η will only work if the governor valves are full open.

c. Plant efficiency increases as power level increases for two reasons:

1) Increased work output of LP turbine as throttling losses decrease (as just discussed).

2) Effects of extraction steam.

4. Extraction Steam Effects

a. Extraction steam pressure and temperature increases as first stage impulse pressure increases.

b. Result is that feedwater temperature increases.

c. This provides for most of the increased efficiency of Figure HT-7-13.

1) $$\eta = \frac{\dot{Q}_{SG} - \dot{Q}_{Rej}}{\dot{Q}_{SG}} = 1 - \frac{\dot{Q}_{Rej}}{\dot{Q}_{SG}}$$

2) A large decrease in $\dot{Q}_{Rej}$ relative to $\dot{Q}_{SG}$ contributes to increasing plant efficiency as power increases.

d. Efficiency is also improved by sending condensate from the feedwater heater shells to the suction of the feedwater pumps.

e. Loss of a heater string reduces plant efficiency.

1) Causes reduced feedwater temperatures.

2) Can cause turbine damage from unbalanced steam flow.

3) May result in derating the turbine to a lower maximum load.

c. **Display TP HT-7-16**, "Plant Efficiency vs Power" (Figure HT-7-13).

2) Even though feedwater flow increases as power level increases, the extraction steam flow increases relatively the same amount due to the increased pressure in the turbine which drives more steam to the feedwater heaters. The overriding effect is for feedwater temperature to increase because of the increased temperature of the extraction steam.

c. Q: How would the addition of another FW heater affect secondary efficiency?

A: Secondary efficiency would increase, however, the added cost would not be recovered in savings.

d. At low powers there is not enough pressure on the shell side of each feedwater heater to force the condensate on to the next heater. As a consequence, the heaters fill up and overflow individually to the condenser.

5. Moisture Separator-Reheater effects.

   a. Moisture separation process improves plant efficiency and protects turbine blading by removing moisture.

   b. Reheating does not help efficiency (because it robs steam from the HP turbine) but its sole function is to reduce turbine moisture and protect the blading.

   c. MSR adds to the cost and complexity of the secondary system.

   d. MSR reduces flexibility of operation (shouldn't run without it).

6. Turbine Efficiency

   a. Affected by:

      1) number of stages.

      2) blading shape.

      3) blade speed.

      4) inlet pressure and temperature.

      5) blade tip leakage losses

      6) moisture

   b. Operator has little control over efficiency.

   c. Moisture content has the greatest negative effect on turbine efficiency.

   d. Decreased condenser pressure (better vacuum) results in increased moisture content at the turbine outlet.

      1) Decreases the turbine efficiency but at the same time increases the Rankine Cycle efficiency.

      2) Increased Rankine Cycle efficiency is the preferred effect.

Have students answer practice problem #10 at back of the Chapter.

Q: What is the effect of taking extraction steam from HP turbine exhaust rather than LP turbine extraction to heat the 12 heaters?

A: Heating will be done with a higher ΔT across the heat exchanger. This is less efficient thermodynamically and thus the cycle will be less efficient.

Q: What if steam is taken from Main Steam instead of HP extraction to heat 17 heater?

A: Same as above.

Q: In cold weather or low flow conditions, how do we determine if a circ water pump should be tripped in order to increase efficiency?

A: Look at condensate depression, power requirements of circ pump, effect of degraded vacuum on efficiency and determine net effect on total plant efficiency.

7. Pump Efficiency

   a. Small amount of energy relative to total cycle heat - minor effect on efficiency.

   b. Run optimum number of pumps to reduce power requirements.

   c. Run pumps at the best efficiency point.

8. Example 4

During an outage 10% of the tubes in one steam generator are plugged due to stress corrosion cracking. The plant is returned to 1175 MW. How will the new steam pressure for this steam generator change for this situation when compared to the original steam pressure at 1175 MW? How will turbine impulse pressure change compared to its original value?

8. Solution 4 (Answer in text). Assuming the ramped T_{avg} program is maintained as before, analysis of the equation: $\dot{Q}_{SG}$ - UA (T_{avg} - T_{stm}), reveals a constant heat rate, $\dot{Q}_{SG}$, for the entire plant, a constant T_{avg} due to the ramped program and a reduced total area, although confined to one steam generator. The heat transfer coefficient, U, will likely increase slightly due to more vigorous boiling but not enough to eliminate a required drop in T_{stm}. The affected steam generator will supply less heat load than the others even though it will be at essentially the same T_{avg} and steam pressure. Decreasing T_{stm} corresponds to a decrease in steam generator pressure. A decreased steam generator pressure will reduce flow through the governor control valves and they will need to be opened up farther to regain the initial turbine load. The first stage impulse pressure will return to its original value with the opening of the governor valves.

9. Example 5:

Due to design deficiencies in the steam generator moisture separators, the outlet quality of the steam is reduced to 99.1% from the guaranteed value of 99.75%. What effect will this have on plant efficiency and on the operation of secondary plant components?

9. Solution 5 (Answer not in text)

Increased moisture content of the steam entering the HP turbine will lead to more moisture induced turbine blade pitting, an obvious disadvantage. More moisture entering the HP turbine means more moisture extracted and less steam flow entering the LP turbine for the same mass flow from the steam generator. This reduces the work output of the LP turbine. In order to get the same work output from the turbine set the mass flow rate in the secondary must be increased. Increased secondary mass flow rate means more heat addition in the steam generator. Greater $\dot{Q}_{SG}$ with the same turbine output results in decreased efficiency.

Q: Why on the thermal data sheets does LP turbine inlet steam temperature decrease as plant power increases?

A: LP turbine inlet steam temperature is heated by main steam. Main steam pressure/temperature drops as power increase.

NOTE: *Actual operation of the MSR overrides this effect because the inlet steam temperature is never allowed to go above T_{stm} at 100% power (533°F).*

Summarize the thermal-hydraulic aspects of initial RCS heatup and pressurization.

Q: How does isolation and bypass of a heater string affect feed flow?

A: T_{FW} drops, less steam is extracted so more work is done in the turbine for the same governor valve position. For constant $\dot{W}_T$ the governors must throttle back. Steam flow (and feed flow) must then decrease, however the plant is less efficient and more heat is added in the SG.

D. Normal Transients

1. Transient operation is any change from steady state.

2. Establishing Normal Operational Parameters.

   a. During heatup heat is added (from RCP's) faster than it leaves (ambient losses and steam dumps). .

   b. Initial heatup is rapid.

      1) Heatup rate decrease as RCS temperature increases.

   c. Losses increase as ΔT to environment increases and C_p increase for every BTU/lbm.

   d. PZR controls pressure, may have steam bubble or be water solid.

      1) If water solid, a bubble must be drawn using the heaters.

      2) A bubble exists when sprays will reduce pressure.

      3) Heaters and sprays control pressure at 2250 psia.

   e. BHP of RCP's is 20.9 MW.

   f. Fluid horsepower (FHP) of RCP's is 14 MW

   g. 20.9 MW - 14 MW = 6.9 MW

   h. Just happens that heat losses to ambient are ≈ 6.9 MW, therefore the energy addition of the RCP's to the RCS is taken as 14 MW. (FHP only)

   i. RCS output is 3411 MW (Rx) + 14 MW (RCPs) equals 3425 MW.

   j. Steam dumps will maintain at 1092 psig (T_{sat} of 557°F) therefore an RCS temperature of 557°F.

   k. Maintains at no load conditions - 557°F, 2250 psia.

h. Actual ambient losses are less than the internal energy addition of RCPs.

i. Actual RCS output is 3427.6 MW as shown on Byron caloric. See letter W Handout #1.

3. Point of Adding Heat (POAH) - The point at which the heat-up rate of the primary water increases significantly due to the fission rate.

   a. Reactor is brought critical by dilution or rod withdrawal.

   b. Reactor is critical when supercriticality is indicated by:

      1) constant positive startup rate

      2) steadily increasing neutron level with

      3) no reactivity addition.

   c. POAH occurs between one and two percent reactor power on the Power Range instrumentation.

4. Inherent Reactivity Effects of the PWR

   a. Doppler adds negative reactivity as fuel heats up, positive as fuel cools.

   b. Moderator temperature coefficient (α_T) adds negative reactivity as the moderator heats up, positive as the moderator cools.

      1) For normal operating temperatures and Boron Concentrations.

   c. Void coefficient adds negative reactivity as voids increase, positive as voids decrease.

   d. Fission product poisons add negative reactivity as the core ages.

      1) Xenon reactivity changes (with lag time) as reactor power changes.

3. **Display TP HT-7-17**, "Point of Adding Heat" (Figure HT-7-14).

b. Solid line is RCPs heat.

Dash line is fuel heat.

b. **Display TP HT-7-18**, "Effects of a Reactivity Addition at POAH" (Figure HT-7-14a).

5. Operation at POAH

   a. Below POAH

      1) Steam dumps control RCS Temperature (primarily T_{cold}) by maintaining a steam generator pressure of 1092 psig ($\approx T_{cold} = 557°F$).

      2) Rods control power.

         a) Any reactivity change (Xenon, Boron, cooldown etc) will also affect power.

         b) Reactivity changes do not affect temperature unless power increases above the POAH.

   b. Above POAH with generator synchronized and steam dumps off

      1) Inherent reactivity effects begin to influence.

      2) Increased steam flow causes reactor power to increase.

         a) Increased steam flow → decreased T_C → positive reactivity addition → reactor power increase.

         b) With no rod motion this results in:

            (1) increased reactor power.

            (2) reduced T_{avg}.

            (3) higher fuel temperature-negative Doppler addition.

            (4) Total reactivity from beginning to end is unchanged.

            (5) Steam demand always determines Rx power above POAH.

      3) Rod withdrawal adds positive reactivity →

         a) Rx power increases → RCS heats up → Doppler adds negative reactivity → Rx power decreases to previous level

1) Manually increasing steam dump flow will add positive reactivity to the core. If this increases reactor power above the POAH then the temperature decrease from the cooldown will be tempered by the heat being added to the coolant. otherwise, increased steam dump flow will only cool down the RCS as long as Rx power is below POAH.

2) Withdrawing control rods adds positive reactivity to the core which increases power (neutron level). As long as power stays below POAH, the RCS temperature will not be changed.

1) Explain RCS temperature control and reactor power control below the POAH.

b. Explain RCS temperature control and reactor power control above the POAH.

NOTE: *If simulator time is available, show the effects of above/below POAH.*

b) Result is a higher RCS T_{avg} with rods farther out of the core.

(1) negative reactivity addition of Doppler to offset the positive reactivity addition of lowered moderator temperature

(2) Reactor power constant - steam flow constant.

4) Example

Explain what happens to reactor power and T_{avg} if rods are driven in 10 steps, assume 100% power.

5) Effects from Xenon or Boron are the same as those from rod motion.

c. Above POAH with steam dumps in steam pressure mode. (Generator may or may not be synchronized)

1) Increase Steam flow

a) Roll turbine, open PORV, or open steam dumps manually.

b) SG pressure decrease → T_c decreases → positive reactivity is added.

c) Reactor power increases to match the increased steam flow

d) Positive reactivity addition of moderator is offset by negative ρ addition of Doppler.

2) Add Positive Reactivity due to rods, Boron or Xenon

a) Increases Rx heat output

b) RCS Temperature increases

c) SG Temperature increases → steam dumps open further to maintain 1092 psig.

d) Increased steam flow maintains the initial increases in Rx power.

e) Final result → increased T_{avg} with increased Rx power.

4) Solution

The negative effect of rods would cause power to decrease, causing T_H to decrease, T_C would then decrease to maintain ΔT. This adds positive reactivity returning reactor power to 100%. Net effect is power unchanged and lower T_{avg}.

d. Example 6

The reactor is critical at 10^{-8} amps (well below POAH). Describe the effect on both T_{avg} and reactor power if:

a) Xenon is decaying away

b) Boron concentration increases

c) A Reactor Coolant Pump trips.

e. Example 7

What effect will be seen on T_{avg} and reactor power if a Steam Generator Atmospheric Relief Valve fails open while the reactor is critical below POAH?

d. Solution 6 (Answer in text)

a. Decay of Xenon will add positive reactivity which will cause reactor power to increase. No effect should be seen on T_{avg}, until power increases above POAH.

b. Increasing Boron concentration will add negative reactivity which will serve to shutdown the reactor with no effect on T_{avg}.

c. Tripping a Reactor Coolant Pump will have no effect on reactor power since there is no reactivity change occurring. The other three pumps will add enough heat to overcome any losses of the RCS to ambient. The steam dumps will automatically throttle back on steam flow from the steam generators to maintain the previous steam generator pressure and thus T_{stm}. T_{avg} will decrease slightly since in the equation, $\dot{Q}_{S/G} = UA\,(T_{avg} - T_{stm})$, U, A, and T_{stm} are constant. Since $\dot{Q}$ decreased, T_{avg} will show a slight (but likely imperceptible) decrease.

e. Solution 7 (Answer not in text)

The increased steam flow will decrease RCS T_{avg} since the water returning to the reactor vessel has had more heat removed from it. Reduced T_{avg} will add positive reactivity to the core and reactor power will increase.

6. Normal Up-Power Transient

   a. Only valid above the POAH.

   b. Generator is synchronized to the grid.

   c. Control valves open → S/G pressure and temperature decreases, T_{cold} decreases → positive reactivity is added to the core → reactor power increases to match the additional heat transfer across the S/G.

      1) $Q_{Rx} = m_{RCS}\, C_p\, \Delta T$

         a) ΔT must increase to transfer the additional heat.

         b) T_C decreases and T_H increases without rod motion.

         c) Operation on the ramped T_{avg} program produces a relatively constant T_C and a greater increase in T_H.

   d. Residence time of water in the RCS is approximately 11 seconds.

      1) Eleven second delay time exists before effects are felt at the initiating point.

   e. Load increase with manual rods.

      1) Turbine power was increased 400MW/min from 855MW → 1010MW

         a) Controller overshot

         b) DEH Controller produced MW fluctuations.

      2) The first thing is more stm flow, steam gen. pressure decreased. T_{cold} in reactor must drop. Rx power followed due to positive reactivity added by reduced moderator temperature.

      3) Negative reactivity added by Doppler, due to fuel heatup as Rx power increases, must be offset by a positive reactivity addition.

         a) So moderator temperature (T_{avg}) decreases.

6. All the following data for each transient was taken from the simulator and plotted.

d. **Display TP HT-7-19**, "Reactor Coolant System Transport Time (Seconds)" (Figure HT-7-15).

e. **Display TP HT-7-20**, "150 MW Load Increase Manual Rods (Turbine Power)" (Figure HT-7-16).
Display TP HT-7-21, "150 MW Load Increase Manual Rods (Reactor Power)" (Figure HT-7-17).
Display TP HT-7-22, "150 MW Load Increase Manual Rods (Temperatures)" (Figure HT-7-18).
***Note**: *All remaining diagrams in this Chapter were made using data taken from the simulator.*
This situation exemplifies the T_H reduction program utilized at Byron, Unit 1 during Cycle 1 operations.

e. Explain the reaction of a typical PWR to normal up-power transients without automatic rod motion.

4) The core ΔT increases.

5) $\approx$ 2 minutes into the oscillation T_{avg} increases due to the increase in reactor power.

6) Lowered secondary steam pressure reduces secondary plant efficiency.

7) Steam pressure must be increased by either rod withdrawal or dilution since these both raise T_{avg}.

f. Load increase with automatic rod control

1) Rod control fed by:

a) auctioneered high T_{avg}.

b) nuclear power.

c) T_{Ref} - based upon first stage impulse pressure (turbine power).

2) If rate of increase in turbine power exceeds rate of increase in nuclear power then rods withdraw.

3) If T_{Ref} (programmed T_{avg}) exceeds T_{avg} then rods withdraw.

4) Steam flow increases $\rightarrow$ S/G temperature decreases $\rightarrow$ T_C decreases $ T_{avg} decreases $\rightarrow$ rods withdraw $\rightarrow$ Rx power increases due to rod withdrawal and colder T_C $\rightarrow$ RCS heats up $\rightarrow$ negative reactivity addition stops power increase $\rightarrow$ RCS heats up due to rod withdrawal.

5) Eventually, Rx power increase equals turbine power increase.

a) Rods raise T_{avg} to the programmed level (T_{Ref}), T_H is higher, T_C is $\approx$ constant.

b) Greater core ΔT.

4) **Display TP HT-7-23**, "20% Increase in Turbine Power/Automatic Rod Control" (Figure HT-7-19).

4) Explain the reaction of a typical PWR to normal up-power transients with automatic rod motion.

7. Normal Down-Power Transient

   a. Analyzed the opposite of the up-power transient.

   b. Load decrease, no rod motion

      1) Steam flow decreases → steam pressure and temperature increase → T_C increases → Rx power decrease → RCS temperature increases at a decreasing rate until it turns and starts to decrease → Rx power decreases.

      2) Eventual result is an increased T_C, increased T_H, increased $T_{avg.}$ and a decreased ΔT.

      3) Safeties lifted and produced the large turbine/reactor power mismatch. (Figure HT-7-20a)

      4) Rx/Turbine initial power mismatch was due to secondary plant inefficiencies.

      5) Increased T_{avg} must be decreased by inward rod motion or by boration.

   c. Load decrease with automatic rod control

      1) Steam flow decreases → RCS heats up → rods insert → reactor power decreases due to heatup and rod insertion → RCS cools down.

      2) Final condition is Rx power matched to turbine power, T_{Hot} and T_{avg} decreased, T_C slightly higher, core ΔT decreased.

b. **Display TP HT-7-24**, "150 MW Load Decrease, Manual Rods/No Stm Dumps/No PORVs - Turbine and Reactor Power" (Figure HT-7-20a).
Display TP HT-7-25, "150 MW Load Decrease, Manual Rods/No Stm Dumps/No PORVs - Temperature" (Figure HT-7-20b).

b. Explain the reaction of a typical PWR to normal down-power transients without automatic rod motion.

c. **Display TP HT-7-26**, "10% Decrease in Turbine Power/Automatic Rod Control" (Figure HT-7-21).

c. Explain the reaction of a typical PWR to normal down-power transients with automatic rod motion.

d. Example 8

Due to a problem with the Circulating Water System, turbine power was reduced from 950 MW to 800 MW in 10 minutes. What is the effect of this load rejection on T_{avg}, if rods are left in manual and no boration or dilution is initiated

a. Over the next 15 minutes?

b. Over the next 40 hours?

d. Solution 8

a. Immediately after the transient, T_{avg} will rise adding negative reactivity. This is to offset the positive reactivity added by Doppler when fuel temperature decreased due to the reactor power decrease. (See Figure HT-7-20b).

b. Soon after the load rejection Xenon will start to build in since it is not being burned out as rapidly. The moderator temperature will decrease, adding positive reactivity to offset the negative reactivity of the Xenon. This will drop T_{avg} below the value attained in part a. Eventually, the Xenon level will peak (≈4 hrs) and start to fall off. This will drive T_{avg} back up. When the reactivity due to Xenon reaches the level prior to the load rejection (≈10 hrs), T_{avg} will have risen to the same level as in part a above. Xenon level, however, will continue to decrease as 40 hrs are approached and stabilize at a level lower than that prior to the load rejection. This will result in a final T_{avg} somewhat higher than the level reached in part a.

e. Example 9

Answer the questions posed in Example 8 if the control rods are in automatic.

E. Abnormal Transients

1. Steady State operation with one idle RCP and Rx Critical

a. The four loop PWR can operate with only three RCP's in operation.

1) This will not cause a Rx trip when below 30% power.

2) Not allowed administratively - since not analyzed in the accident analyses.

b. Stopping one pump causes:

1) Less total system flow

2) More flow per pump from remaining pumps

3) Less headloss in core due to less flow

4) Less total resistance due to reverse flow in the idle loop.

5) Idle loop temperature goes to T_C and affected S/G pressure decreases and S/G steam flow decreases.

6) Only 3 S/G's to produce steam

7) Lowered S/G pressure due to increased flows

8) Same power/less RCS flow greater core ΔT

e. Solution 9

a. Immediately after the transient, T_{avg} will again rise adding negative reactivity. Rods will also step in adding negative reactivity. Rx power will decrease, fuel temperature will drop and positive reactivity will be added by Doppler. Rods will adjust their position to compensate for the differing reactivity change between Doppler and α_t and also bring T_{avg} to the lower programmed value.

b. As Xenon builds in, T_{avg} will drop, Rods will step out to raise T_{avg} to the programmed value. When Xenon level peaks and starts to decay away, rods will reverse direction and step in, all the time keeping T_{avg} at the programmed value. As Xenon decays to a level lower than that prior to the load rejection, rods will step in further than their position prior to the load decrease and stay there while keeping T_{avg} at the programmed value.

c. Example 10

With one Reactor Coolant Pump idle, the mass flow rate through the core is reduced to 9.45×10^7 lbm/hr. Assuming steam demand remains constant at 100 percent, what is the ΔT across the core? What is the steam pressure in each of the steam generators in an operating loop? Assume the following:

$\dot{Q}$ (100%) = $\dot{Q}$ (100%) = 3411 Mwt

c. Solution 10 (Answer in Text)

$$\dot{Q} = \dot{m}_{RCS} C_p \Delta T$$

$$\Delta T = \frac{\dot{Q}}{\dot{m}_{RCS} C_p}$$

$$C_p = 1.4 \frac{BTU}{lbm\text{-}°F} \text{ for RCS}$$

$\dot{Q}$ = 3411 MW for 4-loop plant at 100% power

$$\Delta T = (3411 MW)\left(\frac{3.413 \times 10^6 BTU/hr}{MW}\right)\left(\frac{hr}{9.45 \times 10^7 lbm}\right)\left(\frac{lbm°F}{1.4\ BTU}\right)$$

$$= 88°F$$

Assuming T_{avg} remains constant because steam demand remains constant and no long term reactivity changes occur,

$\Delta T = 88°F = T_H - T_C$

$$T_{avg} = \frac{T_H + T_C}{2}$$

$T_H = 88°F + T_C$

$$582.0°F = \frac{88°F + T_C + T_C}{2}$$

$T_C = 538.0°F$

$T_H = 626.0°F$

With all heat transfer across only three steam generators, the total steam generator heat transfer surface area is reduced by ¼.

$\dot{Q}_{SG} = UA\,(T_{avg} - T_{stm})$

$$\dot{Q}_{SG} = U\left(\frac{3}{4}\right)A(T_{avg} - T_{stm})$$

c. Qualitatively analyze the thermal-hydraulic effects of a reactor coolant pump trip.

d. $\dot{Q} = UA\,(T_{avg} - T_{stm})$

1) Reduced U requires increases in $(T_{avg} - T_{stm})$

2) T_{stm} (S/G pressure) drops

3) Initially T_{avg} increases due to reduced core flow

4) Affected Loop steam flow goes negative

a) Affected S/G is cold and becomes a heat sink

b) It has 'shrunk' due to the collapse of bubbles in its riser and is being filled with cold feedwater.

c) T_H in that loop comes back colder than T_C due to this cooling by the feedwater.

5) T_H initially rises and T_C of affected loop decreases due to increased transport time.

a) T_H remains elevated since the same heat is now being removed by less flow.

At normal 100% power,

$$T_{avg} - T_{stm} = 582.0 - 533.0 = 49°F$$

With one idle loop,

$$T_{avg} - T_{stm} = \frac{4}{3}(49°F) = 65.3°F$$

Assuming a constant T_{avg},

$$T_{stm} = T_{avg} - 65.3°F$$

$$= 582.0°F - 65.3°F$$

$$= 516.7°F$$

If T_{stm} = 516.7°F, P_{stm} = 789.8 psia in unaffected loop.

d. **Display TP HT-7-27**, "RCP B Trip, Manual Rods (SG Pressure)" (Figure HT-7-22a).

Display TP HT-7-28, "RCP B Trip, Manual Rods (Steam Flow)" (Figure HT-7-22b).

Display TP HT-7-29, "RCP B Trip, Manual Rods (Temperature)" (Figure HT-7-22c).

Q: How can the affected S/G be at a lower pressure and yet steam?

A: Since it steams very little there is little headloss in its line. With little headloss, less pressure is required to drive steam out.

b) T_{avg} increases → adds negative reactivity → Rx power decreases slightly.

c) T_H, T_C & T_{avg} gradually drop over time due to drop in T_{steam} but core ΔT is increased.

d) T_{avg} returns near to its original value.

6) Initial increase in T_{avg} causes the peak in steam pressure.

2. Loop Stop Isolation Valve Closure

a. Instantaneous closure of the cold leg LSIV ~~trips the associated RCP.~~

b. Steam flow and feed flow same as for RCP trip and for same reasons.

c. No reverse flow in this condition.

d. Core ΔT increases as ṁ decreases - T_H increases, T_C decreases.

e. Initially increased T_{avg} reduces Rx power, all temperatures gradually drop and Rx power slowly comes back to its initial level.

f. Affected loop temperatures drop as loop gives up heat to the cold SG.

g. Core Flow greater for LSIV closure

1) For LSIV closure core flow drops to 80%.

2) For RCP trip core flow drops to 70%.

3) Never goes to 75%.

4) In both cases total pump flow is > 75%.

5) At least 10% of total pump flow is diverted through the idle loop when one RCP trips.

d) In this analysis Rx power never returned to its original value. It remains 0.8% below its original value (possibly due to an increased secondary efficiency from reduced throttling losses). This reduced reactor power could be the cause of the slightly elevated T_{avg}.

d) Qualitatively analyze the thermal-hydraulic effects of a Loop Stop Isolation Valve closure.

2. **Display TP HT-7-30**, "LSIV B Closure Manual Rods (S/G Pressure)" (Figure HT-7-23a).

Display TP HT-7-31, "LSIV B Closure Manual Rods (Steam Flow)" (Figure HT-7-23b).

Display TP HT-7-32, "LSIV B Closure Manual Rods (Temperatures)" (Figure HT-7-23c).

g. **Display TP HT-7-33**, "Core Flow - LSIV Closure/RCP Trip" (Figure HT-7-24).

Q: In which case is total pump flow greater?

A: RCP trip has greater flow since headloss in loop is less than core and also constitutes a parallel path.

3. Example 11

The plant is operating at 30 percent power, one Reactor Coolant Pump trips due to an electrical fault. The control systems are all in automatic. The bank D rods are initially at 161 steps. Assume the plant does not trip due to this transient. Discuss what happens to the following plant parameters (direction only) as read in the Control Room.

a) Turbine power

b) Reactor power

c) Core ΔT

d) T_{avg} (affected loop)

e) T_{avg} (unaffected loops)

f) Steam Generator pressure (affected loop)

g) Steam Generator pressure (unaffected loops)

h) ΔT (affected loop)

i) ΔT (unaffected loops)

j) Affected loop flow

3. **Display TP HT-7-34** through **HT-7-36**, "RCP Trip at 25% Power/Automatic Rod Control" (Figure HT-7-25a-c).

Solution 11 (Answer in text)

The response to this abnormal transient is very similar to the response without automatic control systems. For this case the major difference lies in the movement of the control rods. Figure HT-7-25a illustrates the RCS temperatures during this transient. Figure HT-7-25b illustrates the control rod motion and Figure HT-7-25c depicts steam generator level.

a. Turbine power will remain constant since the turbine control system is unaffected.

b. Reactor power shows rapid responses to control rod motion since rod motion represents rapid reactivity changes. Figures HT-7-25a and b can be used to study the response of reactor power. The initial response of the plant is identical to that discussed earlier - T_H and T_{avg} increase, T_{stm} and steam generator pressure decrease as steam flow increases. The difference lies in the response of the control rods. The rod control program is fed by the highest T_{avg} of the four loops (Auctioneered High T_{avg}). When T_{avg} goes high with no changes in turbine or reactor power, the rods step in as Figure HT-7-25b shows. This drives reactor power down which rapidly reduces T_H, T_{avg}, and finally T_C.

   This, however, reduces T_{avg} below the programmed value and rods consequently step back out. This raises reactor power and in turn all the RCS temperatures. After these fluctuations dampen themselves out the reactor power will return to its original level consistent with the present turbine power.

c. As before, the ΔT across the core must increase since $\dot{Q}_{Rx}$ is the same and the core flow has decreased. As Figure HT-7-25a depicts, T_H increases and T_C decreases.

d. T_{avg} in the affected loop (with reverse flow) will go to approximately the value of T_C.

e. T_{avg} of the unaffected loops eventually returns to its original value since rod control will return it to its original value (equal to T_{ref}).

THIS PAGE INTENTIONALLY LEFT BLANK

f. In the affected loop, the cooldown of the primary during the flow reversal collapses the bubbles in the riser region of the generator. This shrinks the downcomer level. The level control system refills the generator, overshooting slightly. The now high level in this generator decreases slowly due to the lack of steaming in the steam generator. The steam generator pressure decreases.

g. Steam Generator pressure in the unaffected loops decreases as before. Figure HT-7-25c illustrates the effects of these pressure changes on steam generator level. In the unaffected S/G the initial flow increase causes a swell. Soon, though, the increased flow starts to empty the generator and the level drops until the level control system can reverse the level decrease and bring the generator back to its programmed level.

h. ΔT of the affected loop goes to zero (or negative).

i. ΔT of the unaffected loop, as stated earlier, increases.

j. Once again, the flow is reversed and passes at least 10% of the flow from the operating loops.

Note to Instructor: *Final rod position is not easily discernable in this transient. Rod control will bring T_{avg} back to the ramped T_{avg} program. In this case auctioneered high T_{avg} will be loop T_{avg} instead of core T_{avg}. Because of the cold water returning to the vessel head from the affected loop, core T_H must be higher than the unaffected loop T_H. If this is so, then core T_{avg} is higher than loop T_{avg} therefore, must be higher than it was prior to the transient beginning. This constitutes a negative reactivity addition so rods must be farther out at the completion of the transient. This analysis is too complex and integrated to be included at this point in the training program.*

4. MSIV Closure

   a. Steam flow in affected generator drops to zero then continues later as PORV opens.

   b. Other S/G's increase flow and drop in pressure.

   c. Unaffected T_C decreases in accordance with the drop in T_{stm}.

   d. T_H drops & ΔT increases due to the opening of the PORV.

   e. Affected T_C rises near to T_H.

   f. Affected T_{avg} drops with T_C & T_{stm}.

   g. As affected S/G pressure drops, the PORV eventually closes.

      1) PORV will likely cycle.

5. Example 12

You are operating at 50 percent power with turbine control in automatic and rods in manual. One Main Steam Isolation Valve shuts. No plant shutdown or trip occurs. Disregarding SG Safety Valves or Atmospheric Relief actuation, calculate what happens to the following plant parameters (magnitude and direction).

At 50% power

T_H = 583°F

T_{avg} = 568.5°F

T_C = 554°F

T_{stm} = 545°F

1) Turbine power

2) Reactor power

3) T_H (affected loop)

4. **Display TP HT-7-37** through **HT-7-39**, "MSIV B Closure Manual Rods/No Steam Dumps" (Figures HT-7-26a-c).

4. Qualitatively analyze the thermal-hydraulic effects of a Main Steam Isolation Valve closure.

5. Solution 12 (Answer in text)

1. Turbine power is constant at 50% power. ↔
2. Reactor power will fluctuate around 50%. ↔
3. Without actuation of the S/G PORV or Safeties, T_H in the affected loop must stay constant at 583°F. $T_{H\,AFF}$ ↔
4. T_H in all the loops must be the same, so the unaffected T_H must also be 583°F. $T_{H\,UNAFF}$ ↔ $= T_{H\,AFF}$
5. T_C in the affected loop will eventually go to T_H of that loop or 583°F (assuming Safeties do not lift). $T_C = T_H$
6. T_C (non-affected loops) - Overall T_C entering the core must remain constant since $\dot{Q}_{Rx}$ is constant and T_{hot} stays constant. $\dot{m}$ of the affected loop returns to 583°F which is 30°F hotter than the original T_C. The other three loops must drop 10°F to bring the overall T_C back to its original value of 554°F. The T_C in the unaffected loops is than 554 - 10 = 544°F.
7. T_{avg} (affected loop) → 583°F = T_H = T_C $T_{AVG} = T_H = T_C$

8. T_{avg} (non-affected loops) =

$$\frac{583 + 544}{2} = 563.5°F$$

9. Core T_{avg} must be constant at 568.5°F since T_H is constant at 583°F and the T_C entering the core is constant at 554°F.

10. Core ΔT will also be constant at 29°F

$$\dot{Q} = \dot{m}C_p\Delta T; \quad \Delta T = \dot{Q}/\dot{m}C_p$$

$\dot{Q}$, $\dot{m}$, *and* C_p *are all constant.*

11. S/G pressure (affected loop) - $T_{stm} \rightarrow 587°F$ $P_{stm} \approx$ 1400 psig (from Steam Tables).

12. S/G pressure (non-affected loop)

$\dot{Q}_1 = \dot{Q}_2 \qquad A_2 = 3/4\ A_1$

$U_1\ A_1\ \Delta T_1 = U_2\ A_2\ \Delta T_2$

$A_1\ \Delta T_1 = 3/4\ A_1\ \Delta T_2;\ U_1 - U_2$

$\Delta T_1 - 3/4\ \Delta T_2$

$\Delta T_1 = T_{avg1} - T_{stm1}$

$\Delta T_1 = 568 - 545$

$\Delta T_1 = 23°F$

$\Delta T_2 = 4/3\ (23.5°F)$

$\Delta T_2 = 30.9°F$

$563.5 - T_{stm2} = 30.9$

$T_{stm2} = 532.6$

$P_{stm2} \approx$ 900 psig or 914.7 psia

4. **Display TP HT-7-37** through **HT-7-39**, "MSIV B Closure Manual Rods/No Steam Dumps" (Figures HT-7-26a-c).

4. Qualitatively analyze the thermal-hydraulic effects of a Main Steam Isolation Valve closure.

5. Solution 12 (Answer in text)

   1. Turbine power is constant at 50% power.
   2. Reactor power will fluctuate around 50%.
   3. Without actuation of the S/G PORV or Safeties, T_H in the affected loop must stay constant at 583°F.
   4. T_H in all the loops must be the same, so the unaffected T_H must also be 583°F.
   5. T_C in the affected loop will eventually go to T_H of that loop or 583°F (assuming Safeties do not lift).
   6. T_C (non-affected loops) - Overall T_C entering the core must remain constant since Q_{Rx} is constant and T_{hot} stays constant. $\dot{m}$ of the affected loop returns to 583°F which is 30°F hotter than the original T_C. The other three loops must drop 10°F to bring the overall T_C back to its original value of 554°F. The T_C in the unaffected loops is than 554 - 10 = 544°F.
   7. T_{avg} (affected loop) $\rightarrow$ 583°F = T_H = T_C

4) T_H (non-affected loops)

5) T_C (affected loop)

6) T_C (non-affected loops)

7) T_{avg} (affected loop)

8) T_{avg} (non-affected loops)

9) Core T_{avg}

10) Core ΔT

11) S/G pressure (affected loop)

12) S/G pressure (non-affected loops)

8. T_{avg} (non-affected loops) =

$$\frac{583 + 544}{2} = 563.5°F$$

9. Core T_{avg} must be constant at 568.5°F since T_H is constant at 583°F and the T_C entering the core is constant at 554°F.

10. Core ΔT will also be constant at 29°F

$$\dot{Q} = \dot{m}C_p\Delta T; \quad \Delta T = \dot{Q}/\dot{m}C_p$$

$\dot{Q}$, $\dot{m}$, and C_p *are all constant.*

11. S/G pressure (affected loop) - $T_{stm} \rightarrow 587°F$ $P_{stm} \approx$ 1400 psig (from Steam Tables).

12. S/G pressure (non-affected loop)

$\dot{Q}_1 = \dot{Q}_2 \qquad A_2 = 3/4\ A_1$

$U_1\ A_1\ \Delta T_1 = U_2\ A_2\ \Delta T_2$

$A_1\ \Delta T_1 = 3/4\ A_1\ \Delta T_2;\ U_1 - U_2$

$\Delta T_1 - 3/4\ \Delta T_2$

$\Delta T_1 = T_{avg1} - T_{stm1}$

$\Delta T_1 = 568 - 545$

$\Delta T_1 = 23°F$

$\Delta T_2 = 4/3\ (23.5°F)$

$\Delta T_2 = 30.9°F$

$563.5 - T_{stm2} = 30.9$

$T_{stm2} = 532.6$

$P_{stm2} \approx 900$ psig or 914.7 psia

III. SUMMARY

A. Review and address the importance of the individual KO's.

1. Summarize the interrelationship of thermal hydraulic equations as applied to the major components of the primary and secondary systems.

    a. Student should be able to apply all the equations of Figure HT-7-1. Very broad objective designed to include analysis of various conditions including normal transients.

2. Define secondary plant efficiency and overall plant efficiency and discuss factors affecting each.

    a. Student should also be able to calculate secondary plant efficiency.

    b. Should understand difference between secondary and plant efficiency.

3. Explain the basis for ramped T_{avg} as opposed to constant T_{avg} or constant T_{stm} control.

    a. Should be able to list the advantages and disadvantages of each.

    b. Understand the importance of the programs operationally and how they relate to $\dot{Q} = UA\ (T_{avg} - T_{stm})$.

4. Explain how secondary mass flow rate changes with power changes and compare it to steady state primary flow rate.

    a. Should be able to use calculations and/or steam table data to compare the difference.

III. **Display TP HT-7-40**, "Formulas" Appendix A. Discuss these formulas with the summary.

5. Discuss the effects of RCS temperature, pressure and power level on RCS subcooling.

   a. Understand how RCS Temperature (T_H) and power level are related. (Can change T_H without changing power).

6. Summarize the thermal-hydraulic aspects of a plant heatup including;

   a. Method of initial RCS heatup and pressurization

   b. Point of Adding Heat (POAH)

      1) Stress the use of RCP's to produce heatup in contrast to decay heat.

      2) Understand how steam dumps control pressure.

7. Explain RCS temperature control and reactor power control both before and after the POAH.

   a. Understand how steam flow/pressure and reactivity changes affect pressure and T_{avg} in all three conditions:

      1) Subcritical or critical but below the POAH.

      2) Above the POAH but steam dumps still in pressure mode (may or may not be synchronized)

      3) Synchronized and steam dumps are no longer controlling pressure.

8. Explain the reaction of a typical PWR to normal up and down power transients with and without automatic rod motion.

   a. Explain the reactivity feedback that changes power.

5. If simulator time was utilized, discuss the effects seen when changing T_H/power.

b. Explain how total reactivity must always balance to zero in a critical reactor.

c. Should be able to briefly discuss what causes rods to move.

d. Emphasis is on final changes instead of transitory phenomena.

9. Qualitatively analyze the thermal-hydraulic effects of the following:

   a. Reactor Coolant Pump trip

   b. Loop Stop Isolation Valve closure

   c. Main Steam Isolation Valve closure

      1) Emphasis is on final parameter changes (increase/decrease, etc.) instead of transitory effects.

      2) Should be able to apply these to analyze other parameters (ie. DNBR, ECC position, etc.)

As a final note, ask if there are any questions about KO's and if students need any more examples.

IV. LIST OF ILLUSTRATIONS

THIS PAGE INTENTIONALLY LEFT BLANK

Transparency	Figure	Title
TP HT-7-23	HT-7-19	20% Increase in Turbine Power/Auto Rod Control
	HT-7-20	Load Decrease With Manual Rods
TP HT-7-24		a. Reactor and Turbine Power
TP HT-7-25		b. Temperatures
TP HT-7-26	HT-7-21	10% Decrease in Turbine Power/Auto Rod Control
	HT-7-22	RCP B Trip/Manual Rods
TP HT-7-27		a. S/G Pressure
TP HT-7-28		b. S/G Steam Flow
TP HT-7-29		c. Temperatures
	HT-7-23	Loop Stop Isolation Valve B Closure/Manual Rods
TP HT-7-30		a. S/G Pressure
TP HT-7-31		b. S/G Steam Flow
TP HT-7-32		c. Temperatures
TP HT-7-33	HT-7-24	Core Flow - LSIV Closure/RCP Trip
	HT-7-25	RCP Trip at 25% Power/Automatic Rod Control
TP HT-7-34		a. Temperatures
TP HT-7-35		b. Bank D Rod Position
TP HT-7-36		c. SG Level
	HT-7-26	MSIV Closure
TP HT-7-37		a. S/G Steam Flow
TP HT-7-38		b. S/G Steam Pressure
TP HT-7-39		c. Temperature
TP HT-7-40		Formulas - Appendix A
	HT-7-27	Crack Growth Rate

THIS PAGE INTENTIONALLY LEFT BLANK