WESTINGHOUSE TECHNOLOGY ADVANCED MANUAL LESSON PLAN	
Ch. 4.7	Title: ATWS
Written by: Van Sickle	Date: 04/01

	References: 1. Westinghouse Systems Manual (RPS) 2. 10CFR50.62 (ATWS Rule) 3. NUREG-1000, "Generic Implications of ATWS Events at the Salem Nuclear Power Plant" (1983) 4. NUREG-460, "Anticipated Transients Without Scram for Light Water Reactors" (1980) 5. NUREG-1560, "Individual Plant Examination Program: Perspectives on Reactor Safety and Plant Performance" (1997) 6. Draft Report: Regulatory Effectiveness of the Anticipated Transient Without Scram Rule" (2000) 7. NUREG/CR-4674, "Precursors to Potential Severe Core Damage Accidents: 1991"
6. Included in lesson plan	
	Learning Objectives: 1. Define the term "anticipated transient without scram" (ATWS). 2. Describe the most limiting (most severe) ATWS case for a pressurized water reactor (PWR). 3. List three parameters or components that affect a plant's sensitivity to an ATWS event. 4. Describe the modification made to Westinghouse reactor trip breakers after the Salem ATWS. 5. State the functions of the ATWS mitigation system. 6. List three event tree considerations (headings) used in estimating the conditional core damage probability of ATWS sequences.

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Introduction	**4.7.1 Introduction**
Learning Objective 1	1. Definition: anticipated operational occurrence (AOO) as defined in 10CFR50.62, Appendix A, followed by failure of reactor trip portion of protection system specified in GDC 20 of Appendix A. 2. AOO def. (from 10CFR50, App. A definitions): those conditions of normal operation that are expected to occur one or more times during life of nuclear power unit (e.g., main generator trip, LOOP, etc.).
RPS Design	**4.7.2 Reactor Protection System Design**
Fig. 4.7-1	1. Tripping of one reactor trip breaker is enough to trip reactor. 2. Bypass breakers are installed to allow testing of RPS without tripping reactor. 3. Trip actuation: a. Input signals from transmitters received in analog section and compared to setpoint in bistables. b. If bistable trip setpoint is met or exceeded, trip signal is sent to logic cabinets. c. When proper coincidence is reached, power is removed from undervoltage coils, and reactor trips.
ATWS Historical Background	**4.7.3 ATWS Historical Background**
	1. Possible source of concern in plants as early as 1968 in discussions between ACRS, regulatory staff, reactor instrument designers. 2. Separation of control and protection functions found to be adequate.

	3. In 1969, emphasis placed on (a) evaluating likelihood of common-mode failures of RPS and (b) analyzing consequences of postulated ATWS events.
Learning Objective 2	4. Worst case for PWR: loss of feedwater ATWS. Analysis:
	a. After loss of feed, without trip on loss of heat sink protection signal, heat input from reactor and loss of heat removal in SGs increase RCS temperature.
	b. Coolant expansion due to RCS temperature increase causes large insurge into PZR, which compresses steam bubble and causes pressure to rise rapidly. Control systems not assumed to operate to limit pressure.
	c. RCS temperature increase causes steam pressure to increase to point of lifting SG safety valves. AFW cannot keep up with steam flow, and SGs dry out. RCS temperature increases at faster rate.
	d. If MTC is negative, some negative reactivity added by increasing RCS temperature, but not enough to prevent PZR from going solid. RCS pressure increases rapidly to > 3000 psia.
	e. Concerns include exceeding RCS design pressure, degradation of ECCS interfaces.
Learning Objective 3	f. Severity (peak pressure reached) affected by:
	• Value of MTC - determines whether & how much negative reactivity is added w/ temperature increase. Worst at BOL. • PZR volume - affects time to reach solid conditions. • PZR safety valve capacity - determines coolant outflow when plant is solid, affects ultimate pressure reached. • Secondary inventory - affects dryout time for Sgs. • Whether turbine trips - tripping lengthens dryout time for SGs.

Operational Occurrences Salem ATWS	**4.7.4 Operational Occurrences**

4.7.4 Operational Occurrences

4.7.4.1 Salem ATWS

1. First event (02/22/83): Salem Unit 1 at 20% power w/ one main feed pump operating & second pump at minimum speed.

   a. During transfer of loads from offsite to main generator, limit switch failure causes loss of nonvital distribution bus - affects operating MFP control power, one RCP, CR lighting, 125-Vac miscellaneous distr. panel.

   b. Loss of distr. panel causes loss of nonvital indications in CR, including MFP indications, steam & feed flows.

   c. SG levels decrease to low-low level trip setpt.; trip breakers fail to open.

   d. Operator manually trips reactor 3.5 sec later, masking failure of auto trip.

2. Second event (02/25/83): Salem at 12% power w/ manual feed control.

   a. W/ difficulty in controlling levels, one SG drops to low-low level setpt. No auto trip, but first-out annunciator indicates trip.

   b. After another operator notices no trip, plant is tripped 23 sec after auto trip signal developed.

   c. Tests are performed to verify proper operation of RPS. Trip breakers fail to open on demands by auto trip signals. Mechanical interference in trip breaker mechanisms prevents proper operation.

Breaker Malfunction	**4.7.4.2 Breaker Malfunction**
Fig. 4.7-2	1. Normal operation of breaker design at time of Salem event: a. When no trip signal, undervoltage coil is energized & holds main trip shaft such that breaker is closed. b. Trip signal de-energizes UV coil. c. Spring pulls up on arm, which causes main trip shaft to rotate in counterclockwise direction. d. Rotation of main trip shaft allows trip spring to pull trip bar to the left, which opens trip breaker and removes power from CRDMs. At Salem, UV coils operated properly, but mechanical interference in mechanisms prevented trip breakers from opening. e. On manual trip, shunt trip coil is energized in addition to UV coil being de-energized. Energizing shunt trip coil pushes bar attached to main trip shaft to the right, causing counterclockwise rotation of main trip shaft and the rest of the mechanical sequence described above. Manual trip worked at Salem. 2. Similar breaker problems found at McGuire in 1987. NRC Bulletin 88-01 issued as result.
Plant Modifications	**4.7.5 Plant Modifications**
Reactor Trip Breakers Fig. 4.7-3 Learning Objective 4	**4.7.5.1 Reactor Trip Breakers** 1. Westinghouse trip breaker design modified so that auto trip redundantly de-energizes UV coil & energizes shunt trip coil.

ATWS Rule Requirements	**4.7.5.2 ATWS Rule Requirements**
	1. Diverse trip system required as defense-in-depth measure for CE, B&W plants.
	a. Required to be independent of RPS from sensor output to interruption of power to control rods.
	b. Required for CE, B&W because of high percentage of time operating w/ positive or slightly negative MTC.
	c. Not required for Westinghouse because of larger PZR safety valves and low percentage of time operating w/ positive or slightly negative MTC.
	2. ATWS mitigation system
Learning Objective 5	a. Required by ATWS Rule to auto initiate AFW & initiate turbine trip under conditions indicative of an ATWS, with equipment from sensor to final actuation device that is diverse from reactor trip system.
	b. Typically non-safety-related, nonvital powered, microprocessor based.
Fig. 4.7-4	c. Trojan AMSAC: Actuates on low-low level in 3/4 SGs (25-sec delay) within 6 min of turbine load having exceeded 40%.
Fig. 4.7-5	d. Indian Point 3 AMSAC: Like Trojan's, except substitute main FW flows for SG levels.
	e. IP3 AMSAC software problems from poor maintenance practices & poor quality assurance.

PRA Insights

Historical

Draft report is included in this lesson plan.

4.7.6 PRA Insights

4.7.6.1 Historical

1. NUREG-460, ATWS Task Force, SECY-83-293.

2. Conclusions of draft report issued by Nuclear Regulatory Research:

   a. Required hardware modifications have been implemented (1986 - 1990 typical). DSS or something may have to be revisited for Westinghouse if fuel changes mean more operation with less negative MTCs.

   b. Goal of 1.0E-05/RY for P(ATWS) has been met for all reactor types. Large decrease in frequency of auto trips. Better than expected improvements in RPS reliability.

   c. Trip breaker reliability is key. Industry programs to maintain reliability still needed.

   d. Large uncertainty in RPS reliability estimates; much more operating experience needed to generate sufficient system demands. Hence, ATWS Rule requirements still needed.

   e. Costs of implementation much less than expected. Fewer than expected spurious trips caused by ATWS mitigation equipment.

3. NUREG-1560 conclusions:

   a. ATWS not an important contributor to total CDF at most plants.

   b. ATWS is important contributor at 2 Westinghouse plants (Beaver Valley 1 & Indian Point 3) because they operate w/ some or all PORV block valves closed.

Plant Event	**4.7.6.2 Plant Event**
	1. Harris 1 event (06/03/91):
	a. RCS low flow trip signal developed during calibration; B trip breaker opened, but A breaker did not.
	b. Cause of failure: failed circuit board due to improper maintenance.
Fig. 4.7-6(a) shows event significance (in CCDP) vs. other Harris events.	c. Had both trip breakers not opened, conditional core damage probability: 6.6E-06.
Fig. 4.7-6(b) shows Harris ATWS event tree. Function headings provide answer to Objective 6.	d. 4 ATWS sequences result in core damage. Dominant sequence is sequence 2 in Fig. 4.7-6(b), which is ATWS*(failure to manually insert control rods)*(primary pressure is limited)*(AFW successfully actuates)*(failure of emergency boration)
Summary	**4.7.7 Summary**

TRANSIENT 5.01
RAMP LOAD INCREASE, 50 - 100%, 5%/MIN

Initial Conditions:

BOL
T_{avg}: 570.3°F
Pressurizer Pressure: 2235 psig
Nuclear Power:50%

Bank D Rod Position: 84 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: 5%/min load increase

Point	Explanation
1.	**Generator load** increases as the control valves open in response to the 5%/min load increase command input by the operator at the turbine EHC station.
2.	**Bank D rod position** increases as outward motion is called for by the power mismatch (turbine load increasing relative to nuclear power) and temperature mismatch ($T_{ref} > T_{avg}$) circuits of the rod control system.
3.	**Nuclear power** increases in response to the positive reactivity added by rod withdrawal.
4.	**Pressurizer level** drops slightly at the start of the transient due to the slight cooling of the reactor coolant caused by the power mismatch, with turbine load > nuclear power. Note: The decrease in T_{avg} cannot be distinguished on the T_{avg} plot.
5.	T_{avg} increases as the rods are withdrawn and nuclear power increases. Over the time interval in which T_{avg} is increasing, nuclear power exceeds turbine load.
6.	T_{ref} increases with generator load (T_{ref} varies linearly with turbine P_{imp}).
7.	**Charging flow** initially increases as the pressurizer level drops relative to the setpoint (which is unchanged at the start of the transient with no change in T_{avg}). Charging flow continues to increase with pressurizer level less than the level setpoint (both the level and the setpoint are constantly changing during the transient). Later, charging flow decreases when the actual level exceeds the setpoint.
8.	**Bank D rod position** increases at a slower rate (and sometimes stops) during the 10 - 13-min interval as the total error input to the rod control system becomes small. During the intervals of constant rod position, the power mismatch circuit calls for rod insertion (due to the nuclear power increasing faster than the rate of turbine load increase), while the temperature mismatch circuit still calls for rod withdrawal ($T_{ref} > T_{avg}$). (Note: Although it is difficult to see on the plots, close inspection of the recorded data for this transient reveals that there are half-minute intervals in this time frame when the temperature error exceeds 2°F [enough for slow rod motion], but rods don't move. This means that during those intervals the power mismatch is of comparable magnitude and opposite sign.)

TRANSIENT 5.01 (CONT'D)

Point Explanation

9. **Steam flow** increases as the control valves open to increase load.

10. **Steam generator level** initially swells with the load increase.

11. **Feed flow** increases steadily throughout the transient as the steam generator water level control system attempts to match steam and feed flows. The slight decrease in feed flow very early in the transient is the result of the level control system response to the initial swell in steam generator level.

12. **Steam pressure** decreases as the control valves are opened. $dQ/dt = UA(T_{avg} - T_{stm})$; T_{avg} is increasing and T_{stm} (also P_{stm}) is decreasing throughout the load change as dQ/dt increases.

Note 1: The starting bank D rod position of 84 steps is not typical for a plant operating at 50% power. The rods were initially diluted in to their starting positions so that the power change could be completed with all control systems in automatic and with T_{avg} maintained on program throughout. Trojan's relaxed axial offset technical specification is not very restrictive on AFD, so starting with the bank D rods ~ halfway in does not place the plant in an action statement.

Note 2: At steady state at the end of the transient, nuclear power = secondary load, so Tavg is unchanging. As for the reactivity balance, the negative reactivity added by the power defect associated with the power change is balanced by the positive reactivity added by the rod withdrawal, so that the net endpoint $\rho = 0$.

What this transient illustrates:

1. The plant response to a normal power increase controlled at the turbine EHC system station.
2. The actions of the rod control and pressurizer level control systems.
3. The initial swell in steam generator level associated with a power increase.
4. The programmed increase in T_{avg} and decrease in steam pressure associated with a power increase.

TRANSIENT 5.02
RAMP LOAD DECREASE, 100 - 50%, 5%/MIN

Initial Conditions:

BOL
T_{avg}: 585.3°F
Pressurizer Pressure: 2235 psig
Nuclear Power:100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: 5%/min load decrease

<u>Point</u> <u>Explanation</u>

1. **Generator load** decreases as the control valves close in response to the 5%/min load decrease command input by the operator at the turbine EHC station. The "holdup" in the load decrease over the second and third minutes of the transient appears to be characteristic of the turbine EHC system.

2. **Bank D rod position** decreases as inward motion is called for by the power mismatch (turbine load decreasing relative to nuclear power) and temperature mismatch ($T_{ref} < T_{avg}$) circuits of the rod control system.

3. **Nuclear power** decreases in response to the negative reactivity added by rod insertion.

4. **Pressurizer level** increases slightly at the start of the transient due to the slight heatup of the reactor coolant caused by the power mismatch, with turbine load < nuclear power. Note: The increase in T_{avg} is difficult to distinguish on the T_{avg} plot.

5. T_{avg} decreases as the rods are inserted and nuclear power decreases. Over the time interval in which T_{avg} is decreasing, nuclear power is less than turbine load.

6. T_{ref} decreases with generator load (T_{ref} varies linearly with turbine P_{imp}).

7. **Charging flow** initially decreases as the pressurizer level rises relative to the setpoint (which is unchanged at the start of the transient with little change in T_{avg}). Charging flow later increases when the actual level decreases relative to the setpoint (both the level and the setpoint are constantly changing during the transient).

8. **Steam flow** decreases as the control valves close to decrease load.

9. **Feed flow** decreases as the steam generator water level control system closes the main feed regulating valves to match steam and feed flows.

10. **Steam pressure** increases as the control valves close. $dQ/dt = UA(T_{avg} - T_{stm})$; T_{avg} is decreasing and T_{stm} (also P_{stm}) is increasing throughout the load change as dQ/dt decreases.

TRANSIENT 5.02 (CONT'D)

Note 1: For this transient only, the turbine EHC system was modified to permit a rate-controlled load decrease. Typically, with a GE EHC system, a load decrease proceeds as fast as the control valves can close in response to the operator pushing the load decrease pushbutton or decreasing the valve position limit with the potentiometer.

Note 2: At steady state at the end of the transient, nuclear power = secondary load, so T_{avg} is more or less unchanging. As for the reactivity balance, the positive reactivity added by the power defect associated with the power change is balanced by the negative reactivity added by the rod insertion, so that the net endpoint $\rho = 0$.

What this transient illustrates:

1. The plant response to a normal power decrease controlled at the turbine EHC system station.
2. The actions of the rod control and pressurizer level control systems.
3. The programmed decrease in T_{avg} and increase in steam pressure associated with a power decrease.

TRANSIENT 5.03
RAPID LOAD DECREASE, 100 - 90%

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2235 psig
Nuclear Power:100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Rapid closure of turbine control valves with the valve position limiter

Point	Explanation
1.	**Generator load** decreases as the control valves close in response to the rapid reduction of the valve position limiter potentiometer setpoint by the operator at the turbine EHC station. The decrease in load occurs much more slowly than the almost instantaneous control valve closure, apparently due to the relatively large amount of steam (downstream of the control valves in the high pressure turbine and in the MSRs) that is still available to drive the turbine elements.
2.	T_{ref} decreases with generator load (T_{ref} varies linearly with turbine P_{imp}).
3.	**Bank D rod position** decreases at or near the maximum rate (72 steps/min) as rapid inward rod motion is called for by the power mismatch (turbine load decreasing relative to nuclear power) and temperature mismatch ($T_{ref} < T_{avg}$) circuits of the rod control system.
4.	**Nuclear power** decreases in response to the negative reactivity added by rod insertion and (to a small extent) by the increase in reactor coolant temperature (discussed in point 5 below).
5.	**Pressurizer level** increases at the start of the transient due to the heatup of the reactor coolant caused by the power mismatch, with turbine load < nuclear power.
6.	T_{avg} increases at the start of the transient due to the power mismatch, with turbine load < nuclear power. Note that, although it is somewhat difficult to see on the plots, the increase in the T_{avg} indication lags the increase in pressurizer level (which indicates the increase in actual T_{avg}) because of the RTD manifold arrangement and loop transport time.
7.	**Charging flow** initially decreases as the pressurizer level rises relative to the level setpoint (which is unchanged at the start of the transient with T_{avg} > full-load T_{avg}).
8.	**Steam flow** decreases as the control valves close to decrease load.
9.	**Feed flow** decreases as the steam generator water level control system closes the main feed regulating valves to match steam and feed flows.
10.	**Steam generator level** initially shrinks with the load decrease.

TRANSIENT 5.03 (CONT'D)

Point Explanation

11. **Feed flow** increases in response to the level error resulting from the initial shrink.

12. **Steam pressure** increases as the control valves close. $dQ/dt = UA(T_{avg} - T_{stm})$; T_{stm} (also P_{stm}) is increasing as the turbine load (and dQ/dt) is decreased. The increase in T_{stm} is exaggerated a bit by the increase in T_{avg}.

13. Rod insertion and a small mismatch between nuclear power and secondary load bring $\mathbf{T_{avg}}$ down toward T_{ref}.

Note: At steady state at the end of the transient, nuclear power = secondary load, so T_{avg} is more or less unchanging. As for the reactivity balance, the positive reactivity added by the power defect associated with the power change is balanced by the negative reactivity added by the rod insertion, so that the net endpoint $\rho = 0$.

What this transient illustrates:

1. The plant response to a short, rapid power decrease initiated at the turbine EHC system station with the valve position limiter.
2. The actions of the rod control and pressurizer level control systems.
3. The initial shrink in steam generator water level associated with a power decrease, and the response of the steam generator water level control system.
4. The programmed decrease in T_{avg} and increase in steam pressure associated with a power decrease.

TRANSIENT 5.04
RAPID LOAD DECREASE, 100 - 15%

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Rapid closure of turbine control valves with the valve position limiter

Point	Explanation
1.	**Generator load** rapidly decreases as the control valves close in response to the rapid reduction of the valve position limiter potentiometer setpoint by the operator at the turbine EHC station.
2.	**T_{ref}** decreases with generator load (T_{ref} varies linearly with turbine P_{imp}).
3.	**Bank D rod position** decreases at the maximum rate (72 steps/min) as rapid inward rod motion is called for by the power mismatch (turbine load decreasing rapidly relative to nuclear power) and temperature mismatch ($T_{ref} << T_{avg}$) circuits of the rod control system.
4.	**Nuclear power** decreases rapidly in response to the negative reactivity added by rod insertion and by the increase in reactor coolant temperature, as discussed in point 7.
5.	**Pressurizer level** increases at the start of the transient due to the heatup of the reactor coolant caused by the power mismatch, with secondary load < nuclear power.
6.	**Pressurizer pressure** rises as the steam bubble is squeezed by the thermal expansion of the reactor coolant. The pressure increase is stopped by pressurizer spray.
7.	**T_{avg}** increases at the start of the transient due to the power mismatch, with secondary load < nuclear power. Note that, although it is somewhat difficult to see on the plots, the increase in the T_{avg} indication lags the increase in pressurizer level (which indicates the increase in actual T_{avg}) because of the RTD manifold arrangement and loop transport time. The increase in T_{avg} is limited by the actuation of the steam dumps, which limits the total primary-to-secondary power imbalance.
8.	**Charging flow** initially decreases sharply as the pressurizer level rises relative to the level setpoint (which is unchanged at the start of the transient with T_{avg} > full-load T_{avg}).
9.	**Steam dump demand** increases rapidly with the rapid reduction in T_{ref} (the $T_{avg} - T_{ref}$ difference rapidly increases). The maximum steam dump demand ($T_{avg} - T_{ref} = 16.4$°F) is reached at 12 sec. All 12 steam dump valves open fully, as discussed in point 13.

TRANSIENT 5.04 (CONT'D)

Point Explanation

10. **Steam flow** initially decreases rapidly as the control valves close to decrease load.

11. **Feed flow** decreases as the steam generator water level control system closes the main feed regulating valves to match steam and feed flows.

12. **Steam generator level** initially shrinks with the rapid load decrease.

13. **Steam flow** increases (stops decreasing) as all steam dump valves open fully with a loss-of-load arming signal (from the rapid reduction in turbine load) and maximum demand.

14. **Feed flow** rapidly increases in response to the rapid increase in steam flow and to the level error resulting from the initial shrink.

15. **Steam pressure** increases as the control valves close. $dQ/dt = UA(T_{avg} - T_{stm})$; T_{stm} (also P_{stm}) is increasing as the turbine load (and dQ/dt) is decreased. Note that the rise in steam pressure is limited by steam dump operation; after the dumps actuate, total secondary load is always > turbine load.

16. **Bank D rod position** stays constant over ~ 24 sec during the second minute. At this point, the initial large input to the power mismatch circuit from the reduction in turbine load has died off, nuclear power has been decreasing faster than turbine load, and T_{avg} is > T_{ref}. The total error input to the rod control system is < 1 °F, and rod motion stops.

17. **Bank D rod position** decreases again, at a slower rate than earlier in the transient, with T_{avg} > T_{ref}.

Note 1: Steady-state conditions do not appear to have been reached by the end of the plotted four minutes of parameter values. Bank D rods are still being inserted by the rod control system to bring T_{avg} down to T_{ref}, and nuclear power is still decreasing as a result. As T_{avg} decreases, the steam dump demand will trend toward 0, and secondary load will return to turbine load only. The steam dumps have been armed by a loss-of-load arming signal and will remain armed until they are reset by the operator.

Note 2: This transient is essentially identical to supplemental transient 5.0A (Rapid Load Decrease, 100 - 50%), except that many of the parameter responses are exaggerated because of the greater magnitude of the load decrease. The early-transient increases in T_{avg}, pressurizer level, pressurizer pressure, and steam pressure are greater than in transient 5.0A, the intervals of maximum-speed rod insertion and 100% steam dump demand are longer, and the oscillation in SG level is greater. The plant conditions at the end of the four-minute span are farther from steady state than in transient 5.0A but are changing in a similar fashion.

TRANSIENT 5.04 (CONT'D)

What this transient illustrates:

1. The plant response to a rapid power decrease initiated at the turbine EHC system station with the

valve position limiter.

2. The actions of the rod control ,pressurizer level control, and pressurizer pressure control systems.
3. The initial shrink in steam generator water level associated with a power decrease, and the response of the steam generator water level control system.
4. The actions of the steam dump control system in response to a large loss of load.
5. The increase in T_{avg} when nuclear power >> secondary load.
6. The programmed decrease in T_{avg} and increase in steam pressure associated with a power decrease.

TRANSIENT 5.11
MANUAL REACTOR TRIP

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power:100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Operator depresses manual trip pushbutton

Point Explanation

1. **Bank D rod position** falls to 0 in ~ 2 sec when the opening of the reactor trip breakers kills power to all rod drive system coils.

2. **Nuclear power** initially decreases rapidly in concert with the prompt drop in neutron flux associated with the trip. At ~ 15 sec, the rate of power decrease follows the decay of delayed neutron precursors.

3. **Generator load** decreases rapidly to 0 when the turbine trips. The turbine trip input comes from the P-4 contact of the reactor protection system.

4. **Pressurizer level** decreases with the increase in reactor coolant density. Reactor coolant temperature is decreasing rapidly in response to the mismatch between nuclear power (decreasing to decay heat level with the trip) and secondary load (momentarily at maximum steam dump capacity). The minimum level reached is 18.9%.

5. The decrease in **pressurizer pressure** reflects the expansion of the steam bubble associated with the drop in pressurizer level.

6. **Charging flow** responds to pressurizer level control system commands. Immediately following the trip, charging flow initially increases with pressurizer level < the level setpoint, then sharply decreases with level > the level setpoint (pressurizer level is decreasing with the increase in reactor coolant density, and the level setpoint is decreasing with the decrease in auctioneered high T_{avg}, but level and level setpoint are not in step with each other). Later, the large "bulge" in charging flow reflects the decrease in pressurizer level to below the no-load level setpoint (25%).

7. **Steam dump demand** follows the T_{avg} - T_{ref} difference. The steam dump demand increases to maximum immediately after the trip as T_{ref} quickly decreases to the no-load value, then decreases as the steam dump actuation reduces T_{avg} below the no-load value.

TRANSIENT 5.11 (CONT'D)

Point Explanation

8. **Steam flow** (1) decreases to 0 as the turbine steam admission valves close with the turbine trip, then (2) increases as the steam dump valves blast open in response to the turbine trip arming signal and large demand, and finally (3) returns to 0 as the steam dump valves modulate closed in response to the reduction in demand.

9. **Steam generator level** shrinks to below the bottom of the narrow-range indicating range with the closure of the turbine steam admission valves.

10. The steam generator level control system at first decreases **feed flow** in response to the reduction in steam flow with the trip, and then increases feed flow in response to (1) the increase in steam flow with steam dump actuation and (2) the steam generator level error (level < setpoint) resulting from the trip-induced shrink.

11. The rapid reduction in **feed flow** reflects feedwater isolation on reactor trip coincident with low T_{avg} (564°F). All feedwater regulating valves and feedwater isolation valves close with the isolation signal.

12. The indicated **feed flow** reflects operation of the AFW system.

13. **Steam pressure** tracks toward P_{sat} (1092 psig) for no-load T_{avg}. During most of the interval defined by this point, the steam dump valves are closed, there is relatively little heat transfer from the reactor coolant in the SGs, and decay heat increases the reactor coolant temperature and, in turn, steam pressure. Toward the end of the interval, the reactor coolant temperature has increased to the no-load T_{avg} value, and the steam dump valves are modulating to maintain the no-load T_{avg}/steam pressure. Ultimately, the rate of energy removal from the reactor coolant by the SGs/steam dumps equals the rate of energy addition from decay heat.

What this transient illustrates:

1. The plant response to a reactor trip.
2. The actions of the pressurizer level control system.
3. The initial shrink in steam generator water level associated with a turbine trip, and the response of the steam generator water level control system.
4. The actions of the steam dump control system in response to a turbine trip and the maintenance of no-load T_{avg}/steam pressure after a turbine trip.

TRANSIENT 5.12
RAPID LOAD DECREASE, 100 - 50%, RODS IN MANUAL

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power:100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
Rod bank selector switch placed in manual
Initiating Event: Rapid closure of turbine control valves with the valve position limiter

Point	Explanation
1.	**Generator load** rapidly decreases as the control valves close in response to the rapid reduction of the valve position limiter potentiometer setpoint by the operator at the turbine EHC station.
2.	T_{ref} decreases with generator load (T_{ref} varies linearly with turbine P_{imp}).
3.	**Bank D rod position** does not change with the rod control system in manual.
4.	**Pressurizer level** increases at the start of the transient due to the heatup of the reactor coolant caused by the power mismatch, with secondary load < nuclear power.
5.	**Pressurizer pressure** rises as the steam bubble is squeezed by the thermal expansion of the reactor coolant. The pressure increase is stopped by pressurizer spray.
6.	T_{avg} increases at the start of the transient due to the power mismatch, with secondary load < nuclear power. Note that, although it is somewhat difficult to see on the plots, the increase in the T_{avg} indication lags the increase in pressurizer level (which indicates the increase in actual T_{avg}) because of the RTD manifold arrangement and loop transport time. The increase in T_{avg} is limited by the actuation of the steam dumps, which limits the total primary-to-secondary power imbalance. Without rod insertion to suppress nuclear power as in supplemental transient 5.0A (Rapid Load Decrease, 100 - 50%), T_{avg} attains a higher value than is reached in that transient.
7.	**Nuclear power** decreases in response to the negative reactivity added by the increase in T_{avg}. Nuclear power drops to about 93% and stays approximately constant over the last three minutes of the transient, when there is little change in reactivity effects.
8.	**Charging flow** initially decreases sharply as the pressurizer level rises relative to the level setpoint (which is unchanged at the start of the transient with T_{avg} > full-load T_{avg}).
9.	**Steam dump demand** increases rapidly with the rapid reduction in T_{ref} (the T_{avg} - T_{ref} difference rapidly increases). The maximum steam dump demand (T_{avg} - T_{ref} = 16.4°F) is reached at 23 sec. All 12 steam dump valves open fully, as discussed in point 13.

TRANSIENT 5.12 (CONT'D)

Point Explanation

10. **Steam flow** initially decreases rapidly as the control valves close to decrease load.

11. **Feed flow** decreases as the steam generator water level control system closes the main feed regulating valves to match steam and feed flows.

12. **Steam generator level** initially shrinks with the rapid load decrease.

13. **Steam flow** rapidly increases as all steam dump valves open fully with a loss-of-load arming signal (from the rapid reduction in turbine load) and maximum demand.

14. **Feed flow** rapidly increases in response to the rapid increase in steam flow and to the level error resulting from the initial shrink.

15. **Steam generator level** increases with (1) the increase in the boiling rate in the SGs during the recovery from the initial shrink, (2) the swell in level resulting from steam dump actuation, and (3) feed flow > steam flow (note that feed flow exceeds the steam flow value of ~ 3×10^6 lbm/hr for the last half of the first minute).

16. $\mathbf{T_{avg}}$ (and $\mathbf{T_{avg} - T_{ref}}$) stays constant over the last minutes of the transient, as nuclear power is equal to total secondary load. Turbine load = ~ 40%; nuclear power = ~ 90%.

Note: At steady state at the end of the transient, nuclear power = total secondary load (turbine load + steam dumps), so T_{avg} is unchanging. As for the reactivity balance, the positive reactivity added by the decrease in fuel temperature associated with the relatively small power change is balanced by the negative reactivity added by the increase in coolant temperature, so that the net endpoint $\rho = 0$.

What this transient illustrates:

1. The generator load response to a rapid power decrease initiated at the turbine EHC system station with the valve position limiter.
2. The actions of the pressurizer level control and pressurizer pressure control systems.
3. The initial shrink in steam generator water level associated with a power decrease, and the ensuing recovery in SG level as the boiling rate increases with increasing T_{avg}.
4. The actions of the steam dump control system in response to a large loss of load, and steam dumps serving as a significant portion of total secondary load.
5. The increase in T_{avg} when nuclear power >> secondary load.

TRANSIENT 5.13
RAPID LOAD DECREASE, 100 - 50%, STEAM DUMPS OFF

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
Steam dump bypass interlock switches placed in off position
Initiating Event: Rapid closure of turbine control valves with the valve position limiter

Point Explanation

1. **Generator load** rapidly decreases as the control valves close in response to the rapid reduction of the valve position limiter potentiometer setpoint by the operator at the turbine EHC station.

2. **Bank D rod position** decreases at the maximum rate (72 steps/min) as rapid inward rod motion is called for by the power mismatch (turbine load decreasing rapidly relative to nuclear power) and temperature mismatch ($T_{ref} << T_{avg}$) circuits of the rod control system.

3. **Pressurizer level** increases greatly at the start of the transient due to the heatup of the reactor coolant caused by the power mismatch, with turbine load < nuclear power.

4. **Pressurizer pressure** rises as the steam bubble is squeezed by the thermal expansion of the reactor coolant. The pressure increase is slowed by pressurizer spray. Pressure reaches the pressurizer PORV lift setpoint (2335 psig), after which it drops sharply.

5. T_{avg} increases at the start of the transient due to the power mismatch, with turbine load < nuclear power. Note that, although it is somewhat difficult to see on the plots, the increase in the T_{avg} indication lags the increase in pressurizer level (which indicates the increase in actual T_{avg}) because of the RTD manifold arrangement and loop transport time. Note that rod insertion is not as effective as steam dump actuation in limiting the increase in T_{avg}, as T_{avg} attains a higher value than is reached in transient 5.12 (Rapid Load Decrease, 100 - 50%, Rods in Manual).

6. **Nuclear power** decreases in response to the negative reactivity added by the rod insertion and the increase in T_{avg}.

7. **Steam dump demand** increases rapidly to maximum with the rapid reduction in T_{ref} (the T_{avg} - T_{ref} difference rapidly increases). No steam dump valves open, as shown by the steam flow trace, as the steam dump bypass interlock switches have been placed in the off positions.

8. **Steam flow** initially decreases rapidly as the control valves close to decrease load.

9. **Steam generator level** initially shrinks with the rapid load decrease.

TRANSIENT 5.13 (CONT'D)

Point Explanation

10. **Steam pressure** increases rapidly with the closure of the turbine control valves and the large increase in T_{avg}. Once the new control valve position is reached, turbine load and heat transfer in the SGs are essentially constant, so steam pressure must constantly increase. $dQ/dt = UA(T_{avg} - T_{stm})$; with an increasing T_{avg}, T_{stm} (and P_{stm}) must increase for a constant dQ/dt.

11. **Steam generator level** increases with (1) the increase in the boiling rate in the SGs during the recovery from the initial shrink and (2) feed flow > steam flow.

12. The change in **bank D rod position** slows as the inputs to the rod control system from the temperature and power mismatch circuits almost cancel. T_{avg} is >> T_{ref}, so the temperature mismatch circuit is calling for rod insertion, but nuclear power has been decreasing at a fast rate with turbine load constant for over a minute, so the power mismatch circuit is calling for rod withdrawal.

13. The turbine trips (as indicated by the step drop in **generator load**) on high steam generator water level (69%).

14. The reactor trips (as indicated by the step drop in **bank D rod position**) with the turbine trip and power > the P-7 setpoint.

15. **Feed flow** drops to 0 as feedwater is isolated on high steam generator water level.

16. **Feed flow** over the last two minutes of the transient reflects AFW system operation.

17. **Steam pressure** twice increases above the setpoint for the lowest set safety valve (1170 psig), once at ~ 1 min, 45 sec, and again shortly after 3 min.

18. Large increases in **steam flow** after the trip reflect openings of the PORV and the lowest set safety valve, with most of the flow attributable to the MSSV.

19. With the steam dumps unavailable, $\mathbf{T_{avg}}$ will ultimately be maintained at the saturation temperature for the PORV lift pressure instead of at no-load T_{avg}.

TRANSIENT 5.13 (CONT'D)

What this transient illustrates:

1. The generator load response to a rapid power decrease initiated at the turbine EHC system station

with the valve position limiter.

2. The actions of the rod control, pressurizer level control, and pressurizer pressure control systems.
3. The initial shrink in steam generator water level associated with a power decrease, and the ensuing recovery in SG level as the boiling rate increases with increasing T_{avg}.
4. The increase in T_{avg} when nuclear power >> secondary load.
5. That rod insertion (starting with bank D rods almost completely withdrawn) is not as effective as steam dump actuation in limiting the increase in T_{avg} with nuclear power >> secondary load.

TRANSIENT 5.14
RAPID LOAD DECREASE, 100 - 50%, STEAM DUMPS OFF, RODS IN MANUAL

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2231 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
Steam dump bypass interlock switches placed in off position, rod bank selector switch placed in manual
Initiating Event: Rapid closure of turbine control valves with the valve position limiter

Point Explanation

1. **Generator load** rapidly decreases as the control valves close in response to the rapid reduction of the valve position limiter potentiometer setpoint by the operator at the turbine EHC station.

2. **Pressurizer level** increases greatly at the start of the transient due to the heatup of the reactor coolant caused by the power mismatch, with secondary load < nuclear power.

3. **Pressurizer pressure** rises as the steam bubble is squeezed by the thermal expansion of the reactor coolant. Pressure reaches the pressurizer PORV lift setpoint (2335 psig) twice and decreases quickly after each lift.

4. T_{avg} increases at the start of the transient due to the power mismatch, with secondary load < nuclear power. Note that, although it is somewhat difficult to see on the plots, the increase in the T_{avg} indication lags the increase in pressurizer level (which indicates the increase in actual T_{avg}) because of the RTD manifold arrangement and loop transport time. With no rods and no steam dumps available to limit the increase in primary temperature, T_{avg} attains a higher value than that reached in transient 5.12 (Rapid Load Decrease, 100 - 50%, Rods in Manual) and in transient 5.13 (Rapid Load Decrease, 100 - 50%, Steam Dumps Off).

5. **Nuclear power** decreases in response to the negative reactivity added by the increase in T_{avg}.

6. **Steam flow** initially decreases rapidly as the control valves close to decrease load.

7. **Steam generator level** initially shrinks with the rapid load decrease.

8. **Steam pressure** increases rapidly with the closure of the turbine control valves and the large increase in T_{avg}. Once the new control valve position is reached, turbine load and heat transfer in the SGs are essentially constant, so steam pressure must constantly increase. $dQ/dt = UA(T_{avg} - T_{stm})$; with an increasing T_{avg}, T_{stm} (and P_{stm}) must increase for a constant dQ/dt.

TRANSIENT 5.14 (CONT'D)

Point Explanation

9. **Steam generator level** increases with (1) the increase in the boiling rate in the SGs during the recovery from the initial shrink and (2) feed flow > steam flow.

10. The reactor trips (as indicated by the step drop in **bank D rod position**) on high pressurizer level.

11. The large increase in **steam flow** after the trip reflects openings of the PORV and the lowest set safety valves, with most of the flow attributable to the MSSVs.

12. **Pressurizer pressure** drops rapidly after the trip with the expansion of the steam bubble that accompanies the rapid cooling of the reactor coolant.

13. The **charging flow** trace about halfway through the second minute is characteristic of an ESF actuation. The normal charging line is isolated, and charging flow is governed by the position of flow control valve FCV-121 and the flow restrictions provided by the RCP seals (seal injection flow is maintained after the ESF actuation). The ESF actuation results from pressurizer pressure reaching the low pressure ESF actuation setpoint.

14. **Pressurizer level** increases with ECCS injection and isolation of letdown.

What this transient illustrates:

1. The generator load response to a rapid power decrease initiated at the turbine EHC system station with the valve position limiter.
2. The actions of the pressurizer level control and pressurizer pressure control systems.
3. The initial shrink in steam generator water level associated with a power decrease, and the ensuing recovery in SG level as the boiling rate increases with increasing T_{avg}.
4. The increase in T_{avg} when nuclear power >> secondary load.
5. The characteristic charging flow response with an ESF actuation.

TRANSIENT 5.21
DROPPED ROD
(SHUTDOWN BANK A ROD M-14)

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Shutdown bank A rod M-14 drops completely into the core

Point Explanation

1. **Nuclear power** drops in response to the negative reactivity insertion associated with the dropped rod. Of the two power range channels plotted, the power drop is greatest on channel NI-44 because it is closest to the dropped rod and measuring power in the most affected quadrant of the core. (Shutdown bank A rod M-14 is very close to the core "corner" adjacent to NI-44. See the attached core map.)

2. **Bank D rod position** increases with the power mismatch circuit of the rod control system calling for outward rod motion (nuclear power is decreasing relative to turbine load). The rod motion stops when bank D rods reach the automatic-rod-stop interlock setpoint of 223 steps.

3. **T_{avg} (all loops)** decreases with the power mismatch caused by the dropped rod, with nuclear power < turbine load. The decrease in T_{avg} continues until enough positive reactivity has been added from MTC to make nuclear power = to turbine load. (The drop in coolant temperature and the positive reactivity associated with it indicate that the positive reactivity associated with the rod withdrawal of point 2 above is not enough to counteract the negative reactivity of the dropped rod.) Note the spread in the loop temperatures: loop #3, closest to the dropped rod, is affected the most (its T_{avg} undergoes the greatest drop); loop #2 is next closest; loop #4 is third closest; and loop #1, which "flows" through the core quadrant diametrically opposite from the quadrant containing the dropped rod, is affected the least. (Don't be fooled by the relative T_{avg} values and the expanded scale: the loop #4 T_{avg} starts out and stays higher than the other three loop T_{avg}'s, but it decreases more than the loop #1 T_{avg}.) The temperature spread graphically illustrates that complete coolant mixing in the reactor and in the reactor vessel upper plenum does not occur.

4. The positive reactivity from the coolant temperature drop and (to a small extent) from the rod withdrawal increases **nuclear power.** The effect of MTC is most obvious in the quadrant measured by NI-43, which is diametrically opposite from the location of the dropped rod.

TRANSIENT 5.22 (CONT'D)

Point Explanation

5. **Steam pressure** drops as heat transfer conditions in the SGs change due to the reduced T_{avg}. The lower T_{avg} cannot continue to support steam pressure at its initial value. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually decreasing to maintain the same ΔT across the SG tubes.

6. **Generator load** gradually falls off with the degraded steam pressure. The Trojan GE turbine EHC system does not employ first stage pressure feedback, so the control valves remain at their initial positions, and load becomes a function of steam pressure.

Note 1: The dropped rod is located closer to the edge of the core than any other rod, except for its symmetrical counterparts. At 100% power, any dropped rod closer to the center of the core causes a high negative flux rate trip. The core map on the MID panel in the simulator effectively illustrates the rod location.

Note 2: At steady state at the end of the transient, the negative reactivity from the dropped rod is balanced by the positive reactivity from the decrease in coolant temperature and from the slight decrease in fuel temperature associated with the slight decrease in power. The following summarizes the trends in many of the major plant parameters during this transient, steady state to steady state:

Auctioneered high T_{avg} drops from 585.1°F to 583.3°F.
Steam pressure drops from 792 psig to 770 psig.
Generator load drops from 1162 MW to 1143 MW (98.5%).
NI-44 power drops to 91.8%.
NI-43 power increases to 100.8%.

What this transient illustrates:

1. The negative reactivity associated with a dropped rod.
2. The spread in coolant temperatures between core quadrants, illustrating that the dropped rod affects the portions of the core closest to it the most.

TRANSIENT 5.22
FAST ROD WITHDRAWAL, 45% LOAD

Initial Conditions:

BOL
T_{avg}: 568.7°F
Pressurizer Pressure: 2237 psig
Nuclear Power: 50%

Bank D Rod Position: 103 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Rod control system controller failure withdraws bank D rods at 72 steps/min

Point	Explanation
1.	**Bank D rod position** increases at 72 steps/min in response to the controller failure.
2.	**Nuclear power** increases with the positive reactivity associated with the rod withdrawal. The increase in power is tempered somewhat by the negative reactivity associated with the increase in reactor coolant temperature.
3.	**T_{avg}** increases with the power mismatch caused by the rod withdrawal, with nuclear power > turbine load. The increase in T_{avg} is also evident in the increase in pressurizer level.
4.	**Steam pressure** increases as heat transfer conditions in the SGs change due to the increased T_{avg}. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually increasing to maintain the same ΔT across the SG tubes.
5.	**Steam dump demand** steadily increases to maximum with $T_{avg} >> T_{ref}$. Steam dump actuation does not occur (there is no change in steam flow at this point), as there is no loss-of-load arming signal.
6.	**Pressurizer level**, which is increasing because of the decrease in reactor coolant density (T_{avg} is increasing), reaches the high level trip setpoint.
7.	Steam dump actuation brings **T_{avg}** toward no-load T_{avg}. The steam dumps are armed by the turbine trip, and the large initial demand (T_{avg} - no-load T_{avg}) causes all 12 steam dump valves to open. The valves modulate closed as the steam dump demand is decreased.
8.	**Pressurizer pressure** drops rapidly with the expansion of the pressurizer steam bubble associated with the post-trip reactor coolant contraction. The decreased reactor coolant temperature caused by steam dump operation increases the coolant density.
9.	The **charging flow** perturbation reflects an ESF actuation. The low pressurizer pressure ESF actuation is caused by the rapid expansion of the pressurizer steam bubble resulting from the rapid reactor coolant volume contraction following the trip.

TRANSIENT 5.22 (CONT'D)

Note 1: The "blip" in generator load at ~ 2 min reflects the voltage/current spike accompanying the opening of the output breakers.

Note 2: This transient is essentially the same as supplemental transient 5.2A (Slow Rod Withdrawal, 45% Load), except that the parameters change more quickly and that the reactor trip and ESF actuation occur sooner.

What this transient illustrates:

1. The response of the plant to a fast rod withdrawal at power, particularly the increases in reactor coolant temperature, pressurizer level, and steam pressure.
2. A high pressurizer level reactor trip.
3. A low pressurizer pressure ESF actuation.

TRANSIENT 5.23
FAST ROD WITHDRAWAL FROM SOURCE RANGE

Initial Conditions:

BOL
T_{avg}: 558.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 551 cps in S.R.

Bank D Rod Position: 105 steps
Charging flow provided by one centrifugal charging pump
Normal plant configuration for hot standby, except S.R. and I.R. trips are bypassed at NI cabinets
Initiating Event: Rod control system controller failure
· withdraws bank D rods at 72 steps/min

Point	Explanation
1.	**Bank D rod position** increases at 72 steps/min in response to the controller failure.
2.	**Source range power** increases with the positive reactivity associated with the rod withdrawal.
3.	**Intermediate range power** also registers the increase in power caused by the rod withdrawal.
4.	**Nuclear power (power range)** is on scale when rod withdrawal has increased neutron flux sufficiently. The point of adding heat has been reached.
5.	**Pressurizer level** and T_{avg} increase slightly after the point of adding heat has been reached. Heat transfer from the fuel to the coolant is now great enough to raise coolant temperature.
6.	The reactor trip (indicated by the step drop in **bank D rod position)** is caused by a high positive flux rate. The turbine trip and P-7 reactor trip is not a possible reactor trip, because the source range plot illustrates that the source range instruments have not been de-energized by P-10 at any time during the transient.

Note: The increase in reactor power caused by the rod withdrawal raises T_{avg} to a peak of 559.2°F. The increase in coolant temperature and corresponding increase in steam pressure do increase steam flow through the steam dump valves (the steam dumps are operating in the steam pressure mode of control), but the steam flow value is two orders of magnitude less than the range of indication and thus cannot be distinguished on the steam flow plot.

What this transient illustrates:

1. The response of the plant to a fast rod withdrawal starting in the source range, particularly the increase in power as measured by all three ranges of excore instruments.
2. A high positive flux rate reactor trip.

TRANSIENT 5.31
LOOP #1 COLD-LEG RTD FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 585.2°F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Loop #1 cold-leg RTD fails high

Point	Explanation
1.	**Auctioneered high T_{avg}** undergoes a rapid increase to > 620°F. The loop #1 T_{avg} becomes auctioneered high T_{avg}; that loop has a T_c of 630°F (the upper limit of the instrument range) because of the failed-high cold-leg RTD and a T_H of > 610°F (normal).
2.	**Bank D rod position** decreases at the maximum rate (72 steps/min) because of the large temperature mismatch input to the rod control system calling for fast rod insertion. The large temperature mismatch results from the failed-high auctioneered high T_{avg}.
3.	**Nuclear power** decreases due to the negative reactivity associated with rod insertion. The positive reactivity insertion resulting from the decrease in reactor coolant temperature, as discussed in point 4 below, is not enough to counteract it.
4.	**Actual T_{avg}** decreases due to the large imbalance between nuclear power and secondary load, with nuclear power decreasing rapidly. To maintain secondary load, energy must be taken from the reactor coolant, reducing its temperature.
5.	The **pressurizer level** decrease reflects the reduction in reactor coolant volume caused by the decrease in coolant temperature.
6.	**Charging flow** increases greatly with pressurizer level low relative to the level setpoint, which remains at the maximum value (61.5%) with auctioneered high T_{avg} > 584.7°F.
7.	**Steam dump demand** increases to 100% with the RTD failure. The T_{avg} - T_{ref} input to the loss-of-load controller is maximized with $T_{avg} >> T_{ref}$. Note that at this time the dumps have not actuated, as there is no loss-of-load arming signal (no drop in turbine load yet).
8.	**Pressurizer pressure** drifts lower as the pressurizer steam bubble expands with reactor coolant contraction. The pressurizer heaters cannot maintain normal operating pressure.
9.	**Steam pressure** drops as heat transfer conditions in the SGs change due to the reduced T_{avg}. The lower T_{avg} cannot continue to support steam pressure at its initial value. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually decreasing to maintain the same ΔT across the SG tubes.

TRANSIENT 5.31 (CONT'D)

Point Explanation

10. **Generator load** gradually falls off with the degraded steam pressure. The Trojan GE turbine EHC system does not employ first stage pressure feedback, so the control valves remain at their initial positions, and load becomes a function of steam pressure. Note: the faster dropoff in load just prior to the turbine trip reflects the response of the initial pressure limiter, a GE turbine EHC system feature which closes the control valves in response to a throttle pressure that decreases to less than 90% of a manually adjustable setpoint.

11. **Steam flow** increases sharply at approximately 1 min, 30 sec. The reduction in turbine load discussed in point 10 arms the dumps on the loss-of-load controller, and the existing 100% demand causes all 12 dump valves to blast open. The steam flow increase results.

12. The reactor trip (indicated by the step drop in **bank D rod position)** is caused by an ESF actuation on high steam flow plus low steam pressure. The high steam flow setpoint is reached with the steam dump valves blasting open, and the low steam pressure setpoint is reached as the steam pressure constantly decreases. Note that the ESF actuation takes place when the steam pressure is ~ 685 psig; the input to the low steam pressure bistable reaches the low steam pressure setpoint before actual pressure does because of the lead-lag circuit through which the steam pressure signal is processed. Note also that the other ESF actuation signals are not possible: pressurizer pressure and T_{avg} are not low enough yet, there is no steam line ΔP, and there is nothing causing containment pressure to increase.

13. The **charging flow** perturbation reflects the ESF actuation. The initial drop in flow reflects charging line isolation; the flow settles at the relatively high value governed by the maximum opening of charging flow control valve FCV-121 (the pressurizer level is low throughout most of the transient) and the flow restriction of the RCP seals (the only path left for injection from the CVCS).

14. **Pressurizer level** recovers with ECCS flow and letdown isolation following the ESF actuation.

15. **Feed flow** after the trip reflects AFW system operation (main feedwater is now isolated).

16. **Steam flow** decreases to 0, reflecting the MSIV closure associated with the high steam flow ESF actuation.

Note 1: The "blip" in generator load shortly after 2 min reflects the voltage/current spike accompanying the opening of the output breakers.

TRANSIENT 5.31 (CONT'D)

Note 2: For pt. 12, the lead-lag unit changes a ramp of $f(t) = kt$ into $k[t + (\tau_1 - \tau_2)(1 - e^{-t/\tau_2})]$ for a lead constant of τ_1 and a lag constant of τ_2. For the low steam pressure portion of the high steam flow ESF actuation, $\tau_1 = 50$ sec, $\tau_2 = 5$ sec. So, after the exponential term dies out, ramp kt becomes k(t + 45 sec).

What this transient illustrates:

1. The responses of the rod control, pressurizer level control, and steam dump control systems to a failed-high cold-leg RTD.
2. The decrease in T_{avg} when nuclear power << secondary load.
3. A reactor trip and ESF actuation on high steam flow + low steam pressure.

TRANSIENT 5.32
LOOP #1 HOT-LEG RTD FAILS HIGH, ~ 25% LOAD

Initial Conditions:

BOL
T_{avg}: 562.7°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 32%
Bank D Rod Position: 187 steps
Charging flow provided by one centrifugal charging pump
Steam dumps armed due to previous load rejection
Initiating Event: Loop #1 hot-leg RTD fails high

Point	Explanation
1.	**Auctioneered high T_{avg}** increases rapidly to ~ 600°F. The loop #1 T_{avg} becomes auctioneered high T_{avg}; that loop has a T_H of 650°F (the upper limit of the instrument range) because of the failed hot-leg RTD, an increase of some 80°F above its initial value. This increase in T_H increases T_{avg} by ~ 40°F.
2.	**Charging flow** increases greatly with pressurizer level low relative to the level setpoint, which has increased to the maximum value (61.5%) with auctioneered high T_{avg} > 584.7°F.
3.	**Steam dump demand** increases to 100% with the RTD failure. The T_{avg} - T_{ref} input to the loss-of-load controller is maximized with $T_{avg} >> T_{ref}$. As discussed in point 4 below, the dump valves open immediately, as the steam dump control system is already armed in the T_{avg} mode.
4.	**Steam flow** increases sharply after the first several sec. With the dumps already armed and a 100% demand, all 12 dump valves blast open.
5.	**Steam pressure** decreases sharply with all 12 dump valves opening and relieving steam to the condenser.
6.	The reactor trip (indicated by the step drop in **bank D rod position**) is caused by an ESF actuation on high steam flow plus low steam pressure. The high steam flow setpoint is reached with the steam dump valves blasting open, and the low steam pressure setpoint is reached as the steam pressure constantly decreases. Note that the ESF actuation takes place when the steam pressure is ~ 887 psig; the input to the low steam pressure bistable reaches the low steam pressure setpoint before actual pressure does because of the lead-lag circuit through which the steam pressure signal is processed. Note also that the other ESF actuation signals are not possible: pressurizer pressure and T_{avg} are not low enough yet, there is no steam line ΔP, and there is nothing causing containment pressure to increase.
7.	The **charging flow** perturbation reflects the ESF actuation. The initial drop in flow reflects charging line isolation; the flow settles at the relatively high value governed by the maximum opening of charging flow control valve FCV-121 (the pressurizer level is below the setpoint level [61.5%] throughout the transient) and the flow restriction of the RCP seals (the only path left for injection from the CVCS).

TRANSIENT 5.32 (CONT'D)

Point Explanation

8. **Steam flow** decreases to 0, reflecting the MSIV closure associated with the high steam flow ESF actuation.

Note 1: The "blip" in generator load at ~ 48 sec reflects the voltage/current spike accompanying the opening of the output breakers.

Note 2: This transient is essentially the same as transient 5.3A (Loop #1 Hot-Leg RTD Fails High, 100%) and transient 5.3B (Loop #1 Cold-Leg RTD Fails High, 100%), except that the starting power level is lower than in those transients.

What this transient illustrates:

1. The responses of the pressurizer level control and (already armed) steam dump control systems to a failed-high hot-leg RTD.
2. A reactor trip and ESF actuation on high steam flow + low steam pressure.

TRANSIENT 5.33
POWER RANGE CHANNEL NI-41 FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Power range channel NI-41 fails high

Point	Explanation
1.	**Nuclear power (from NI-41)** increases to maximum (initiating event).
2.	**Bank D rod position** decreases at the maximum rate (72 steps/min). The failed-high power range channel becomes auctioneered high nuclear power, and its step increase relative to a constant turbine load develops a large rod insertion signal in the power mismatch circuit of the rod control system.
3.	Actual **nuclear power** decreases due to the negative reactivity associated with rod insertion. The positive reactivity insertion resulting from the decrease in reactor coolant temperature, as discussed in point 4 below, is not enough to counteract it during this phase of the transient.
4.	**T_{avg}** decreases due to the large imbalance between nuclear power and turbine load, with nuclear power decreasing rapidly. To maintain turbine load, energy must be taken from the reactor coolant, reducing its temperature. The reduction in T_{avg} is also evident in the decreasing pressurizer level and pressurizer pressure.
5.	**Steam pressure** drops as heat transfer conditions in the SGs change due to the reduced T_{avg}. The lower T_{avg} cannot continue to support steam pressure at its initial value. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually decreasing to maintain the same ΔT across the SG tubes.
6.	**Generator load** gradually falls off with the degraded steam pressure. The Trojan GE turbine EHC system does not employ first stage pressure feedback, so the control valves remain at their initial positions, and load becomes a function of steam pressure.
7.	**Bank D rod position** stops decreasing. Over the first minute or so of the transient, the large negative input to the rod control system from the initial "spike" in auctioneered high nuclear power has been decaying off, while a large positive input due to the decrease in auctioneered high T_{avg} relative to T_{ref} has been building in. These inputs essentially cancel at ~ 1 min, and rod motion stops. For several seconds prior to this point, the rod insertion speed is slowing, showing that the total error calling for rod insertion has decreased greatly from the initial error associated with the NI-41 failure.

TRANSIENT 5.33 (CONT'D)

Point Explanation

8. **Bank D rod position** remains constant over the last three min of the transient. Ordinarily, outward rod motion would result from the continued decrease in T_{avg} and the continued decay of the nuclear power spike, but the failed channel exceeds the overpower rod stop setpoint (103%), and this rod stop requires only a one-out-of-four coincidence.

9. **Nuclear power** increases with the positive reactivity insertion associated with the reduction in coolant temperature after rod insertion stops.

10. T_{avg} remains constant over the final two min of the transient. At this point, nuclear power and turbine load are essentially equal, meaning that a power mismatch that would change T_{avg} no longer exists.

Note: By the end of the 4 plotted min, new steady-state conditions have essentially been reached: the negative reactivity from the rod insertion is balanced by the positive reactivity from the reduction in fuel temperature associated with the power change and from the reduction in coolant temperature,. and T_{avg} is constant with nuclear power equal to the turbine load, which has decreased from its initial 100% value because of the degraded steam pressure. Final steady-state values: nuclear power = 91.2%, generator load = 1079 MW, T_{avg} = 568.2°F.

What this transient illustrates:

1. The response of the rod control system to a failed-high power-range NI.
2. The decrease in T_{avg} when nuclear power < secondary load.
3. An overpower rod stop.
4. Steady-state to steady-state reactivity balances with changing parameters.

TRANSIENT 5.34
STEAM DUMP LOSS-OF-LOAD CONTROLLER FAILS TO MAXIMUM DEMAND

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2233 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
Steam dumps armed due to previous load rejection
Initiating Event: Steam dump loss-of-load controller fails to maximum demand

Point Explanation

1. The initiating event increases **steam dump demand** to 100%.

2. **Steam flow** increases sharply as the steam dump valves open. The dumps are already armed, and the 100% demand resulting from the controller failure causes all 12 dump valves to blast open.

3. **Steam generator level** swells as the steam dump valves open.

4. **Steam pressure** drops with the additional steam release associated with steam dump operation.

5. **Generator load** gradually falls off with the degraded steam pressure. The Trojan GE tubine EHC system does not employ first stage pressure feedback, so the control valves remain at their initial positions, and load becomes a function of steam pressure.

6. The reactor trip (indicated by the step drop in **bank D rod position**) is caused by an ESF actuation on high steam flow plus low steam pressure. The high steam flow setpoint is reached with the steam dump valves blasting open, and the low steam pressure setpoint is reached as the steam pressure constantly decreases. Note that the ESF actuation takes place when the steam pressure is ~ 750 psig; the input to the low steam pressure bistable reaches the low steam pressure setpoint before actual pressure does because of the lead-lag circuit through which the steam pressure signal is processed. Note also that the other ESF actuation signals are not possible: pressurizer pressure and T_{avg} are not low enough yet, there is no steam line ΔP, and there is nothing causing containment pressure to increase.

7. The **charging flow** perturbation reflects the ESF actuation. The initial drop in flow reflects charging line isolation; the flow then returns to a relatively high value governed by the maximum opening of charging flow control valve FCV-121 (the pressurizer level is low immediately after the ESF actuation) and the flow restriction of the RCP seals (the only path left for injection from the CVCS).

TRANSIENT 5.34 (CONT'D)

Point Explanation

8. **Charging flow** gradually decreases as the pressurizer level is increased by ECCS injection. FCV-121 gradually closes to its minimum opening as the pressurizer level error (level > setpoint) continues to increase.

9. **Steam dump demand** returns to 0 after the turbine trip. The turbine trip which accompanies the reactor trip puts the turbine trip controller in play, and the steam dump demand falls as T_{avg} decreases to < the no-load value.

Note: This transient is very similar to transient 5.32 (Loop #1 Hot-Leg RTD Fails High, 25% Load), transient 5.3A (Loop #1 Hot-Leg RTD Fails High, 100%), and transient 5.3B (Loop #1 Cold-Leg RTD Fails High, 100%). In those transients, the already armed steam dump control system opens all steam dump valves when auctioneered high T_{avg} fails high, which results in a large steam dump demand.

What this transient illustrates:

1. The response of the (already armed) steam dump control system to a loss-of-load controller demand failure.
2. A reactor trip and ESF actuation on high steam flow + low steam pressure.

TRANSIENT 5.35
IMPULSE PRESSURE CHANNEL PT-505 FAILS LOW

Initial Conditions:

BOL
T_{avg}: 585.2°F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Impulse pressure channel PT-505 fails low

Note: This impulse pressure channel feeds the rod control system (T_{ref} for the temperature mismatch circuit and P_{imp} for the power mismatch circuit), the steam dump control system (T_{ref} for the loss-of-load controller), and the steam generator water level control system (the level setpoint varies linearly with P_{imp} from 0 - 20% load); provides one input to the P-13 permissive (turbine at-power permissive); establishes the high steam flow setpoint for the high steam flow + low-low T_{avg} or low steam pressure ESF actuation in protection channel I; and supplies the C-5 interlock (automatic rod withdrawal block < 15% load).

Point Explanation

1. **T_{ref}** undergoes a rapid decrease to its minimum value of 557°F (programmed T_{avg} for no load).

2. **Bank D rod position** decreases at the maximum rate (72 steps/min) because of the large temperature mismatch ($T_{ref} << T_{avg}$) and large power mismatch (turbine load decreasing rapidly relative to nuclear power) inputs to the rod control system calling for fast rod insertion. The large mismatches result from the failed-low impulse pressure channel.

3. **Nuclear power** decreases due to the negative reactivity associated with the rod insertion. The positive reactivity insertion resulting from the decrease in reactor coolant temperature, as discussed in point 4 below, is not enough to counteract it.

4. **T_{avg}** decreases due to the large imbalance between nuclear power and turbine load, with nuclear power decreasing rapidly. To maintain turbine load, energy must be taken from the reactor coolant, reducing its temperature.

5. The **pressurizer level** decrease reflects the reduction in reactor coolant volume caused by the decrease in coolant temperature.

6. **Charging flow** increases greatly with pressurizer level low relative to the level setpoint. Both the pressurizer level and the level setpoint (a function of auctioneered high T_{avg}) are decreasing, but the pressurizer level remains below the level setpoint.

7. **Steam dump demand** increases to 100% with the impulse pressure failure. The T_{avg} - T_{ref} input to the loss-of-load controller is maximized with $T_{avg} >> T_{ref}$. Note that at this time the dumps have not actuated, as there is no loss-of-load arming signal (no drop in turbine load yet).

TRANSIENT 5.35 (CONT'D)

Point Explanation

8. **Pressurizer pressure** drifts lower as the pressurizer steam bubble expands with reactor coolant contraction. The pressurizer heaters cannot maintain normal operating pressure.

9. **Steam pressure** drops as heat transfer conditions in the SGs change due to the reduced T_{avg}. The lower T_{avg} cannot continue to support steam pressure at its initial value. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually decreasing to maintain the same ΔT across the SG tubes.

10. **Generator load** gradually falls off with the degraded steam pressure, and, after ~ 1 min 24 sec, with throttling of the turbine control valves in response to the initial pressure limiter. The Trojan GE turbine EHC system does not employ first stage pressure feedback, so at first the control valves remain at their initial positions, and load becomes a function of steam pressure. Later, the initial pressure limiter closes the control valves in response to a throttle pressure that has decreased to less than 90% of setpoint.

11. **Steam flow** decreases first with the reduction in steam pressure and later with closure of the turbine control valves by the initial pressure limiter.

12. **Steam generator level** decreases with the reduction in feed flow (the failed-low impulse pressure channel has driven the steam generator water level setpoint to its minimum programmed value of 33%, so feed flow is decreased to bring level down to the new setpoint) and the slow shrink associated with the continued decrease in T_{avg}.

13. **Bank D rod position** stays constant over the last interval of the transient. At this point, the primary-to-secondary power mismatch has driven T_{avg} close to the minimum T_{ref} value (decreasing the temperature mismatch calling for rod insertion), the large initial input to the power mismatch circuit from the failed transmitter has died off, and nuclear power has been decreasing faster than turbine load for a fairly long period (a power mismatch calling for rod withdrawal). The total error input to the rod control system thus drops below 1°F, and rod motion stops. Also, any developing total error that would cause rod withdrawal is prevented from affecting rod position by the C-5 (auto rod withdrawal block) interlock (the input to C-5 is from the failed-low channel).

TRANSIENT 5.35 (CONT'D)

Note: The protection channel I high steam flow setpoint is exceeded immediately with the impulse pressure channel failure because the setpoint is driven to its minimum programmed value, but a high steam flow ESF actuation is avoided because the reduction in steam pressure is not large enough to reach the low steam pressure setpoint.

What this transient illustrates:

1. The responses of the rod control and steam dump control systems to a failed-low impulse pressure channel.
2. The decrease in T_{avg} when nuclear power < secondary load.

TRANSIENT 5.36
IMPULSE PRESSURE CHANNEL PT-505 FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 569.5°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 50%
Bank D Rod Position: 148 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Impulse pressure channel PT-505 fails high

Note: This impulse pressure channel feeds the rod control system (T_{ref} for the temperature mismatch circuit and P_{imp} for the power mismatch circuit), the steam dump control system (T_{ref} for the loss-of-load controller), and the steam generator water level control system (the level setpoint varies linearly with P_{imp} from 0 - 20% load); provides one input to the P-13 permissive (turbine at-power permissive); establishes the high steam flow setpoint for the high steam flow + low-low T_{avg} or low steam pressure ESF actuation in protection channel I; and supplies the C-5 interlock (automatic rod withdrawal block < 15% load).

Point Explanation

1. T_{ref} undergoes a rapid increase to its maximum value of 584.7°F (programmed T_{avg} for full load).

2. **Bank D rod position** increases at the maximum rate (72 steps/min) because of the large temperature mismatch ($T_{ref} >> T_{avg}$) and large power mismatch (turbine load increasing rapidly relative to nuclear power) inputs to the rod control system calling for fast rod withdrawal. The large mismatches result from the failed-high impulse pressure channel.

3. **Nuclear power** increases due to the positive reactivity associated with the rod withdrawal. The negative reactivity insertion resulting from the increase in reactor coolant temperature, as discussed in point 4 below, is not enough to counteract it.

4. T_{avg} increases due to the large imbalance between nuclear power and turbine load, with nuclear power increasing rapidly. As the turbine load is essentially unchanging, energy must be added to the reactor coolant, increasing its temperature.

5. The **pressurizer level** increase reflects the expansion in reactor coolant volume caused by the increase in coolant temperature.

6. **Charging flow** decreases greatly with pressurizer level high relative to the level setpoint. Both the pressurizer level and the level setpoint (a function of auctioneered high T_{avg}) are increasing, but the pressurizer level remains above the level setpoint.

7. **Pressurizer pressure** increases as the pressurizer steam bubble is squeezed by the reactor coolant expansion. Pressurizer spray limits the pressure increase.

TRANSIENT 5.36 (CONT'D)

Point Explanation

8. **Steam pressure** increases as heat transfer conditions in the SGs change due to the increased T_{avg}. $dQ/dt = UA(T_{avg} - T_{stm})$; dQ/dt is essentially constant with the turbine control valve position unchanging, so T_{stm} (and P_{stm}) is gradually increasing to maintain the same ΔT across the SG tubes.

9. The **steam dump demand** increase indicates that the increase in nuclear power has driven T_{avg} higher than T_{ref} by > 5°F, even though T_{ref} is much higher than its initial value. Note that at this time the dumps have not actuated, as there is no loss-of-load arming signal (no drop in turbine load).

10. **Bank D rod position** decreases as the outputs of the temperature mismatch circuit ($T_{avg} > T_{ref}$) and power mismatch circuit (the large initial input from the failed transmitter has died off, and nuclear power has been increasing faster than turbine load for a fairly long period) call for rod insertion.

11. **T_{avg}** is decreasing as the rod insertion decreases nuclear power and narrows the primary-to-secondary power mismatch. At steady-state (not yet reached at 4 min), nuclear power will have been made equal to turbine load, and the plant will be operating at ~ 50% power with the full-load programmed T_{avg} value. The new steady state will involve both a higher bank D rod position and a higher coolant temperature, with the associated reactivity changes canceling each other.

Note 1: The starting bank D rod position of 148 steps is not typical for a plant operating at 50% power. The rods were initially diluted in to their starting positions so that the response to the failure would be more dramatic. Trojan's relaxed axial offset technical specification is not very restrictive on AFD, so starting with the bank D rods deeply inserted does not place the plant in an action statement. If this transient is started from the normal 100% conditions, the rods would be withdrawn to the 223-step auto withdrawal limit and then stop, and the slight change in reactivity would minimally affect other plant parameters, making for quite an uninteresting transient.

Note 2: The undershoot in pressurizer pressure during the second minute is caused by "overzealous" spraying. T_{avg} and pressurizer level are still increasing at this point, so steam bubble expansion cannot be contributing to the drop in pressure. (Info provided in case students ask.)

What this transient illustrates:

1. The responses of the rod control and steam dump control systems to a failed-high impulse pressure channel.
2. The increase in T_{avg} when nuclear power > secondary load.

TRANSIENT 5.41
CONTROLLING PRESSURIZER PRESSURE CHANNEL FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 584.7°F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling pressurizer pressure channel (PT-455) fails high

Point Explanation

1. Actual **pressurizer pressure** trends down with maximum pressurizer spray. The pressurizer pressure control system is responding to a pressure input of 2500 psig (well above the pressure setpoint of 2235 psig) from the failed channel.

2. The **pressurizer level** increase over the first ~ 2.5 min of the transient appears to be due primarily to reactor coolant expansion into the pressurizer resulting from the decreased density of the coolant caused by the pressure reduction. See the discussion which follows the point explanations for a more detailed explanation of this point. Also contributing to the indicated level increase is the fact that, at pressures lower than the 2235-psig setpoint, the indicated level overstates the actual level. See the attached figures for a more detailed explanation of this phenomenon. The corresponding decrease in **charging flow** over the same time interval is caused by pressurizer level exceeding the level setpoint (61.5%).

3. **Generator load** decreases after 2 min due to an OTΔT runback. The decreasing pressure on the three "good" channels is lowering the OTΔT trip and runback setpoints.

4. **Bank D rod position** and **nuclear power** decrease as the rod control system calls for inward rod motion in response to the turbine load decrease resulting from the runback (both the temperature mismatch and power mismatch circuits are calling for inward rod motion).

5. The reactor trips (indicated by the step drop in **bank D rod position**) on OTΔT. Pressurizer pressure is not low enough at the time of the trip to make low pressurizer pressure a plausible trip.

6. The low **pressurizer pressure** ESF actuation setpoint is reached at ~ 2 min, 55 sec.

7. **Charging flow** makes its characteristic response to an ESF actuation. The post-ESF charging flow value is relatively low because the pressurizer level is near the no-load setpoint and thus charging flow control valve FCV-121 is not wide open.

8. **Pressurizer level** increases with ECCS flow and letdown isolation at the end of the transient.

TRANSIENT 5.41 (CONT'D)

Detailed explanation for point 2:

At time 0, pressurizer pressure ≅ 2235 psig, pressurizer level = 61.5%.
At time 2 min, 31 sec (approximate end of level increase), pressurizer pressure ≅ 1985 psig, pressurizer level = 65.2%.
Apparent increase in reactor coolant volume = (65.2 - 61.5%)(130 gal/% pzr lvl) = 481 gal.

From system description, RCS water volume at full power = 91,629 gal (includes 61.5% pressurizer level).
Specific volume of H_2O at 585°F, 2235 psig = 0.02251 ft^3/lbm (interpolated from subcooled H_2O property tables).
Specific volume of H_2O at 585°F, 1985 psig = 0.02263 ft^3/lbm (interpolated from subcooled H_2O property tables).
Assuming constant water mass, $\frac{\text{Vol. (end)}}{\text{Spec. vol. (end)}} = \frac{\text{Vol.(start)}}{\text{Spec. vol. (start)}}$.

Calculated increase in reactor coolant volume = Vol. (end) - Vol. (start);

$$= \frac{[\text{Vol. (start)}] \times [\text{Spec. vol. (end)}]}{[\text{Spec. vol. (start)}]} - \text{Vol. (start)};$$

$$= (91,629 \text{ gal}) \frac{(0.02263 \text{ ft}^3/\text{lbm})}{(0.02251 \text{ ft}^3/\text{lbm})} - 91,629 \text{ gal};$$

= 488 gal.

Note the substantial agreement between the results of the two sets of calculations. The absolute closeness of the two results is a bit fortuitous. A difference of one unit in the last decimal place of either interpolated specific volume changes the final result by ~ 40 gal. Also, the calculated increase in coolant volume does not account for the fact that charging flow is less than letdown during the time interval of interest (a cumulative charging deficit of ~ 35 - 40 gal over the first 2.5 min), or for the difference between indicated and actual levels when pressurizer pressure is different from the 2235-psig setpoint. The calculations are intended to show that the explanation for the observed parameter response is reasonable, not that the response is precisely predictable.

What this transient illustrates:

1. The response of the pressurizer pressure control system (maximum spray) to a failed-high controlling pressurizer pressure channel.
2. An increase in indicated pressurizer level with a decrease in coolant density.
3. An OTΔT reactor trip.
4. A low pressurizer pressure ESF actuation.

TRANSIENT 5.42
CONTROLLING PRESSURIZER LEVEL CHANNEL FAILS LOW

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling pressurizer level channel (LT-459) fails low

Point	Explanation
1.	**Charging flow** increases to maximum as charging flow control valve FCV-121 opens fully. The pressurizer level control system is responding to a level input of 0%, which is well below the level setpoint of 61.5%.
2.	**Pressurizer level** increases rapidly with maximum charging and no letdown (one letdown isolation valve and the previously open orifice isolation valve have been closed in response to the < 17% level of the failed channel).
3.	The reactor trip (as indicated by the step drop in **bank D rod position**) is caused by high pressurizer level (92%), as indicated by the 2 "good" level channels.
4.	**Charging flow** increases after the trip because plant pressure drops as T_{avg} decreases to < no-load T_{avg}. The operating charging pump's output increases when the discharge pressure drops (characteristic of centrifugal pump operation).
5.	**Pressurizer level** recovers after the trip due to (a) continued charging (at a high rate) and plant heatup and (b) continued charging alone after the plant heatup is stopped at no-load T_{avg} by steam dump operation (the end of the post-trip heatup accounts for the slope change in the pressurizer level recovery). Letdown is still isolated. The pressurizer eventually fills completely.
6.	After ~ 30 min, continued charging increases **pressurizer pressure** to the PORV lift setpoint, indicating that the plant is now solid. Note that the solid plant conditions are obtained several minutes after the indicated pressurizer level reaches 100%. At the low pressure (~ 1860 psig for several minutes) and lower pressurizer water temperatures (pressurizer heaters have been turned off in response to the < 17% level of the failed channel) experienced during much of this transient, the indicated level overstates the actual level. See the attached figures for a more detailed explanation of this phenomenon. In addition, the pressurizer is not completely filled when the level reaches the upper taps of the level detectors.
7.	**Charging flow** decreases after 30 min as plant pressure increases and charging pump output decreases.

TRANSIENT 5.42 (CONT'D)

Point Explanation

8. The **pressurizer pressure** and **charging flow** "squiggles" between 32 and 36 min indicate PORV lifts.

9. **VCT level** drops during the interval of 0 - 19 min because maximum charging and isolated letdown are depleting the VCT inventory. The change in slope at ~ 3 min indicates initiation of automatic makeup, which slows but does not stop the VCT level decrease. Also, there is a less-than-obvious increase in the rate of VCT inventory depletion shortly after 14 min which reflects the increase in charging flow at that time.

10. **VCT level** recovers after 19 min with continued automatic makeup and seal return because the VCT outlet valves have shut on low VCT level (the charging pump suctions are now supplied by the RWST). The change in slope in the VCT level increase at ~ 24 min indicates the cutoff of automatic makeup; the level continues to increase with seal return alone. (If seal return were supplied to the suction of the charging pumps, then recovery of the VCT would end with the cutoff of automatic makeup.)

What this transient illustrates:

1. The response of the pressurizer level control system (maximum charging) to a failed-low controlling pressurizer level channel.
2. A high pressurizer level reactor trip.
3. The depletion and recovery of VCT level.
4. The development of solid plant conditions due to overfilling of the RCS.

TRANSIENT 5.43
CONTROLLING PRESSURIZER PRESSURE CHANNEL FAILS LOW

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling pressurizer pressure channel (PT-455) fails low

Point Explanation

1. Actual **pressurizer pressure** trends up with maximum heater output from both variable and backup heaters. The pressurizer pressure control system is responding to a pressure input of 1700 psig (well below the pressure setpoint of 2235 psig) from the failed channel.

2. On five different occasions, the **pressurizer pressure** increases to the PORV lift setpoint. Only PORV PCV-456 lifts; the 2-out-of-2 coincidence for PCV-455A cannot be met with one of its inputs (pressure channel 455) failed low. With each PORV lift, pressure drops about 40 psig, the PORV recloses in a few seconds, and the upward trend in pressure resumes with maximum heater output.

3. The decrease in **pressurizer level** reflects the increasing reactor coolant density associated with the increasing pressure. Recall the detailed explanation for the trend in pressurizer level in transient 5.41 (Controlling Pressurizer Pressure Channel Fails High). In that transient, pressurizer level increases with a decrease in pressure and corresponding decrease in coolant density. In this transient, pressurizer level decreases with an increase in pressure and corresponding increase in coolant density. Also contributing to the indicated level decrease is the fact that, at pressures higher than the 2235-psig setpoint, the indicated level understates the actual level.

4. The five short-term increases ("blips") in **pressurizer level** are coincident with the PORV lifts. Each PORV lift results in a decrease in reactor coolant density and corresponding increase in pressurizer level.

What this transient illustrates:

1. The response of the pressurizer pressure control system (maximum heaters) to a failed-low controlling pressurizer pressure channel.
2. The responses of pressurizer pressure, pressurizer level, and charging flow to several PORV lifts.

TRANSIENT 5.51
CONTROLLING STEAM GENERATOR LEVEL CHANNEL FAILS LOW

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling SG #1 level channel (LT-519) fails low

Point	Explanation
1.	**Feed flow to SG #1** increases to maximum as the main feed regulating valve opens in response to the controlling level input falling well below the 44% level setpoint.
2.	**Steam generator level in SG #1** increases rapidly with the feed flow increase and no change in steam flow.
3.	The turbine trip (as indicated by the step drop in **generator load**) is caused by high steam generator water level (the level measured by the two "good" level detectors on SG #1 reaches the 69% level turbine trip setpoint).
4.	The reactor trip (as indicated by the step drop in **bank D rod position**) is caused by the turbine trip with plant power above the P-7 setpoint.

What this transient illustrates:

1. The response of the steam generator water level control system (maximum feed regulating valve position) to a failed-low controlling steam generator level channel.
2. A turbine trip on high SG level.
3. A reactor trip on a turbine trip + P-7.

TRANSIENT 5.52
CONTROLLING STEAM GENERATOR LEVEL CHANNEL FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling SG #1 level channel (LT-519) fails high

Point	Explanation
1.	**Feed flow to SG #1** decreases to minimum as the main feed regulating valve closes in response to the controlling level input rising well above the 44% level setpoint.
2.	**Steam generator level in SG #1** decreases rapidly with the feed flow decrease and no change in steam flow.
3.	The reactor trips (as indicated by the step drop in **bank D rod position**) on low steam generator water level (25.5%, as measured by the two "good" SG #1 level channels) and steam flow/feed flow mismatch.

What this transient illustrates:

1. The response of the steam generator water level control system (minimum feed regulating valve position) to a failed-high controlling steam generator level channel.
2. A reactor trip on low SG level + steam flow/feed flow mismatch.

TRANSIENT 5.53
CONTROLLING STEAM GENERATOR FEED FLOW CHANNEL FAILS LOW

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling SG #1 feed flow channel (FT-510) fails low

Point	Explanation
1.	**Feed flow to SG #1** increases to maximum as the main feed regulating valve opens in response to the large steam flow/feed flow mismatch (feed flow < steam flow) input to the steam generator water level control system.
2.	**Steam generator level in SG #1** increases with the feed flow increase and no change in steam flow. Even after feed flow begins to decrease (as explained in point 3 below), steam generator level continues to rise as long as feed flow exceeds steam flow.
3.	The large (integrated) level error causes **feed flow to SG #1** to decrease, overriding the still-present steam flow/feed flow mismatch. This trend in feed flow illustrates that steam generator water level control is level dominant.
4.	**Steam generator level in SG #1** decreases with feed flow less than steam flow. The level error input to steam generator water level control brings level back to setpoint (44%).
5.	**Steam generator level in SG #1** remains constant at setpoint over the final 10 min of the transient. The integrated level error from the first 10 min of the transient (level > setpoint) counteracts the steam flow/feed flow mismatch (controlling feed flow channel still failed low) during this interval.

What this transient illustrates:

1. The response of the steam generator water level control system to a failed-low controlling steam generator feed flow channel.
2. That steam generator water level control is a level-dominant system.

TRANSIENT 5.54
CONTROLLING STEAM GENERATOR FEED FLOW CHANNEL FAILS HIGH

Initial Conditions:

BOL
T_{avg}: 585.1 °F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Controlling SG #1 feed flow channel (FT-510) fails high

Point	Explanation
1.	**Feed flow to SG #1** decreases as the main feed regulating valve closes in response to the large steam flow/feed flow mismatch (feed flow > steam flow) input to the steam generator water level control system.
2.	**Steam generator level in SG #1** decreases with the feed flow decrease and no change in steam flow. The change in SG level in this transient is not as great as that seen in transient 5.53, as the flow error input to the water level control system is not as large. (Feed flow failing high goes from 3.7 X 10^6 lbm/hr to 5 X10^6 lbm/hr; feed flow failing low goes from 3.7 X 10^6 lbm/hr to 0.) Even after feed flow begins to increase (as explained in point 3 below), steam generator level continues to drop as long as steam flow exceeds feed flow.
3.	The (integrated) level error causes **feed flow to SG #1** to increase, overriding the still-present steam flow/feed flow mismatch. This trend in feed flow illustrates that steam generator water level control is level dominant.
4.	**Steam generator level in SG #1** increases with feed flow greater than steam flow. The level error input to steam generator water level control brings level back to setpoint (44%).
5.	**Steam generator level in SG #1** remains constant at setpoint over the final few minutes of the transient. The integrated level error from the first several minutes of the transient (level < setpoint) counteracts the steam flow/feed flow mismatch (controlling feed flow channel still failed high) during this interval.

What this transient illustrates:

1. The response of the steam generator water level control system to a failed-high controlling steam generator feed flow channel.
2. That steam generator water level control is a level-dominant system.

TRANSIENT 5.61
TRIP OF #1 MAIN FEED PUMP

Initial Conditions:

BOL
T_{avg}: 585.1°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: #1 main feed pump trips

Point	Explanation
1.	**#1 MFP flow rate** decreases to 0 with the trip of the pump.
2.	**#2 MFP flow rate** increases to compensate for the tripped pump. With the loss of discharge pressure from the #1 pump, the ΔP across the main feed regulating valves decreases, and the feed pump speed control system increases the speed of the still operating pump to boost feedwater pressure and regulating valve ΔP.
3.	**Generator load** decreases rapidly to less than 60% on the loss-of-feed-pump turbine setback. The setback feature of the turbine EHC system reduces load at 2%/sec by rapidly reducing the input to the load limit circuit.
4.	**Bank D rod position** decreases at the maximum rate (72 steps/min) in response to the power mismatch circuit (turbine load decreasing rapidly) and temperature mismatch circuit ($T_{ref} < T_{avg}$) of the rod control system.
5.	**Nuclear power** decreases in response to the negative reactivity added by rod insertion and, to a small extent, by the increase in T_{avg}.
6.	**Steam dump demand** increases to a large value with the drop in T_{ref} accompanying the turbine setback and the increase in T_{avg} resulting from the power mismatch (nuclear power > secondary load).
7.	**Steam flow** decreases in response to the closure of the turbine control valves resulting from the setback, then increases with steam dump actuation. The steam dumps are armed by the setback-induced rapid load reduction, and a large demand exists, as described in point 6 above. The steam dump demand and arming signal exist for several seconds prior to the increase in steam flow at ~ 36 sec; before this time steam dump operation is masked by the rapid control valve closure.
8.	**Steam dump demand** decreases, first rapidly and then steadily, as rod insertion brings T_{avg} down to T_{ref}.

TRANSIENT 5.61 (CONT'D)

Point Explanation

9. The change in **bank D rod position** slows as the inputs to the rod control system from the temperature and power mismatch circuits almost cancel. T_{avg} is > T_{ref}, so the temperature mismatch circuit is calling for rod insertion, but nuclear power has been decreasing with turbine load constant, so the power mismatch circuit is calling for rod withdrawal.

What this transient illustrates:

1. A loss-of-feed-pump turbine setback.
2. Steam dump actuation to handle the difference between nuclear power and secondary load.

TRANSIENT 5.62
INADVERTENT MSIV CLOSURE

Initial Conditions:

BOL
T_{avg}: 567°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 50%
Bank D Rod Position: 194 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: The MSIV in the main steam line from the #1 SG inadvertently shuts

Point Explanation

1. **Steam flow from the #1 SG** rapidly decreases to near 0 as the MSIV shuts. The MSIV closes in about 2 sec.

2. **Steam generator level in the #1 SG** shrinks rapidly in response to the large reduction in steam demand from that SG with the MSIV closure.

3. **Feed flow to the #1 SG** rapidly decreases as the #1 SG water level control system responds to the rapid drop in steam flow by closing the #1 SG main feedwater regulating valve.

4. **Steam pressure in the #1 main steam line** increases rapidly, as steam is bottled up in the #1 SG and its associated main steam line.

5. The removal of flow resistance associated with the isolation of the #1 main steam line causes **steam flow from the #4 SG** (as well as from the #2 and #3 SGs) to increase.

6. **Steam generator level in the #4 SG** (as well as in the #2 and #3 SGs) swells in response to the increase in steam demand from that SG.

7. **Feed flow to the #4 SG** (as well as to the #2 and #3 SGs) increases as the #4 SG water level control system responds to the increase in steam flow by opening the #4 SG main feedwater regulating valve.

8. **Steam pressure in the #4 main steam line** (as well as in the #2 and #3 main steam lines) decreases in response to the increased heat transfer in (and increased steaming from) that SG. The 3 unaffected SGs are attempting to maintain the turbine load at the original level and cannot support the necessary steam flow at the original steam pressure.

9. The reactor trips (as indicated by the step drop in **bank D rod position**) on low-low steam generator water level in the #1 SG. The level shrink and reduction in feed flow quickly drop the water level off-scale low in that SG.

TRANSIENT 5.62 (CONT'D)

What this transient illustrates:

1. The effects of a closed MSIV: reduced steam flow, SG level shrink, increased steam pressure.
2. Increased steam flow from the other 3 main steam lines to "pick up the slack."

TRANSIENT 5.63
RCP TRIP

Initial Conditions:

BOL
T_{avg}: 563.2°F
Pressurizer Pressure: 2235 psig
Nuclear Power: 28%
Bank D rod position: 178 steps

Charging flow provided by one centrifugal charging pump
Feed reg. valve for SG #1 is in manual and maintaining ~60% level initially; it is placed in auto after the SG level reaches its minimum value as a result of the initial shrink
All other control systems in automatic
Initiating Event: The RCP in loop #1 trips

Point Explanation

1. **RCS flow in loop #1** decreases to 0 as the reactor coolant pump coasts down with flywheel inertia.

2. **RCS flow in loop #4** (as well as in loops #2 and #3) increases with the decrease in flow resistance from loop #1 and the development of reverse flow in that loop supplied by the discharge of the 3 running pumps.

3. The reduction in **steam flow in steam line #1** reflects the degradation of heat transfer in SG #1. The reduction of the reactor coolant flow rate in the tubes of that SG reduces the heat transfer coefficient for primary-to-secondary heat transfer, thereby reducing the boiling rate, and steam flow drops rapidly.

4. The relative absence of boiling in SG #1 and its associated flow resistance allows feedwater to flow into the tube bundle region from the downcomer (where SG level is measured), and the drop in **steam generator level in the #1 SG** results. Contributing to the level drop is the reduction in recirculation flow from the moisture separators to the downcomer with the reduction in steam flow. Note: the manual manipulation of SG level prior to the initiation of the transient prevents a reactor trip on low-low SG level.

5. The increase in **RCS flow in loop #1** reflects the development of reverse flow in that loop. Discharge from the 3 running pumps is supplied to the cold leg of the idle loop via the reactor vessel annulus.

TRANSIENT 5.63 (CONT'D)

Point Explanation

6. The decreased value of **loop #1 T_{avg}** that exists at the end of the 4 plotted minutes also reflects the development of reverse flow in that loop. Once reverse flow in the idle loop is fully developed, the flow in that loop enters the SG (from the cold leg) with a temperature ~ equal to the T_c of the other 3 loops and exits (to the hot leg) a little colder. At this point, the greatly reduced flow and altered pressure drops in loop #1 mean that the actual loop conditions are transmitted to the bypass manifold RTDs with a much greater time lag and that the calculated T_{avg} may not be a true average loop temperature. However, the time span denoted by this point is a fairly long time after the development of reverse flow, and the actual loop #1 T_H and T_c differ by only a few degrees because of the minimal heat transfer in that loop's SG, so the indicated T_{avg} at the end of the 4 minutes should be very close to the transient endpoint T_{avg} in this loop.

7. **Steam flow in steam line #4** (as well as in steam lines #2 and #3) increases as heat transfer in the SGs in the loops with the running RCPs increases to maintain the unchanged turbine load. The increased steam flow is supported by a core ΔT which is a few degrees larger than its initial value now that the core mass flow rate has decreased to ~ 3/4 of its initial value ($dQ/dt = dm/dt\ [T_H - T_c]$).

What this transient illustrates:

1. The reduction in RCS loop flow associated with an RCP trip and the subsequent development of reverse flow in that loop.
2. The shrink in SG level in the loop with the tripped RCP.

TRANSIENT 5.71
SG SAFETY VALVE FAILS OPEN

Initial Conditions:

BOL
T_{avg}: 558.2°F
Pressurizer Pressure: 2233 psig
Nuclear Power: ~10^{-8} amps in I.R.

Bank D Rod Position: 103 steps
Charging flow provided by one centrifugal charging pump
Normal plant configuration for startup
Initiating Event: One safety valve on main steam line #1 fails to 100% open

Point Explanation

1. **Steam flow in main steam line #1** increases to the safety valve capacity for no-load steam pressure.

2. **Steam generator level in SG #1** swells with the surge in steam demand associated with the safety valve failing open.

3. **Steam pressure in main steam line #1** decreases as the failed safety valve discharges to the atmosphere.

4. $\mathbf{T_{avg}}$ decreases due to the cooldown of the reactor coolant caused by the additional steaming through the safety valve.

5. **Steam pressure in main steam line #4** (as well as the other intact main steam lines) decreases but lags the steam pressure in main steam line #1. The other three main steam lines cannot feed the failed-open safety valve because the check valve in main steam line #1 prevents backflow, but the cooldown of the reactor coolant (see explanation for point 4 above) is reducing the steam pressures in the intact steam lines.

6. **Intermediate range power** increases in response to the positive reactivity insertion associated with the decrease in reactor coolant temperature. The increase is rather small: 2.47 X 10^{-8} amps to 2.71 X 10^{-8} amps.

7. The reactor trip (indicated by the step drop in **bank D rod position**) and ESF actuation (indicated by the characteristic perturbation in **charging flow**) is caused by high steam line ΔP. At ~19 sec, the ΔP between steam line #1 and at least two of the other steam lines has reached the 100 psi setpoint.

8. The decrease in **steam generator level in SG #1** reflects dissipation of that SG's inventory through the failed-open safety valve.

TRANSIENT 5.71 (CONT'D)

Point Explanation

9. **Feed flow** during the latter few minutes of the transient reflects AFW system operation. The AFW system actuation is caused by the ESF actuation. The AFW flow to SG #1 is a little larger than that to the other 3 SGs because of the lower pressure in SG #1.

What this transient illustrates:

1. The relatively slow dissipation of one SG's inventory through a failed-open safety valve.
2. The isolation of the steam break from the other 3 SGs by the faulted SG's check valve.
3. A steam-break-induced cooldown of the RCS.
4. An increase in reactivity associated with a decrease in RCS temperature.
5. A high steam line ΔP ESF actuation and the characteristic response of charging flow.

TRANSIENT 5.72
LARGE STEAM BREAK INSIDE CONTAINMENT WITH LOOP, 10^{-8} AMPS IN I.R.

Initial Conditions:

BOL
T_{avg}: 558.2°F
Pressurizer Pressure: 2232 psig
Nuclear Power: ~10^{-8} amps in I.R.
Bank D Rod Position: 103 steps

Charging flow provided by one centrifugal charging pump
Normal plant configuration for startup
Initiating Event: Large break on main steam line #1 (8.72 X 10^6 lbm/hr) and LOOP occur simultaneously at ~5 sec.

Point Explanation

1. **Steam flow in main steam line #1** increases off-scale high with the steam break.

2. **Steam generator level in SG #1** swells off-scale high with the surge in steam demand associated with the steam break.

3. **Steam pressure in main steam line #1** decreases as steam is discharged to the containment atmosphere.

4. **Steam pressure in main steam line #4** (as well as the other intact main steam lines) remains at or near its initial value. The other three main steam lines cannot feed the break because the check valve in main steam line #1 prevents backflow.

5. **T_{avg}** decreases due to the cooldown of the reactor coolant caused by the additional steaming through the break.

6. **Charging flow** decreases to 0 very rapidly with the LOOP; the CCP which has been operating is now unpowered.

7. The reactor trip (indicated by the step drop in **bank D rod position**) is caused by the LOOP, which interrupts nonvital power to the rod drive coils. All stationary grippers "let go," and all control rods fall into the core.

8. **Charging flow** returns after the emergency diesel generators have started and attained rated speed, the EDG output breakers have closed, and the CCPs have restarted. The CCPs are the first pieces of emergency equipment to be started by the DBA sequencer, which is initiated by a high steam line ΔP ESF actuation. (The ΔP between steam line #1 and at least two of the other steam lines reaches the 100 psi setpoint about 3 sec after the start of the accident.) The CCPs are now operating in the HPI mode; the plotted charging flow reflects seal injection to the RCPs (normal charging is isolated) and a constant charging flow control valve position (see the note below).

TRANSIENT 5.72 (CONT'D)

Point Explanation

9. **Feed flow to SG #1** increases with actuation of the AFW system (the AFW system is actuated by the ESF actuation). The flow to that SG is initially higher than that to the other three SGs because of its lower pressure. The AFW flow to SG #1 then decreases when each AFW flow control valve to that SG closes in response to the high flow (> 500 gpm) sensed in its supply line. The train B flow control valve closes before the train A valve does, hence the "step-down" nature of the AFW flow reduction.

10. The decrease in **steam flow in main steam line #1** reflects the decrease in driving force for steam flow with the reduction in steam pressure in that steam line and the increase in containment pressure.

11. The decrease in **steam generator level in SG #1** reflects the rapid dissipation of that SG's inventory through the steam break.

12. **Containment pressure** increases as steam is discharged from main steam line #1 to the containment atmosphere. The pressure increase is tempered by containment fan cooler operation.

Note : The slowly increasing post-ESF charging flow illustrates the reaction of many plant controllers to a loss of power. These controllers revert to manual and maintain the last auto demands called for when non-vital power is lost. Thus, the controller for the charging flow control valve (FCV-121) holds the valve at the last automatically demanded position; the slowly increasing charging flow reflects the slowly decreasing RCS pressure. With power available, the FCV-121 controller responds to pressurizer level errors, and sharply increasing charging flow would be expected in this case. (Info provided in case students ask.)

What this transient illustrates:

1. The dissipation of one SG's inventory through an unisolable break upstream of the MSIV.
2. The isolation of the steam break from the other 3 SGs by the faulted SG's check valve.
3. A steam-break-induced cooldown of the RCS.
4. A high steam line ΔP ESF actuation and the characteristic response of charging flow.
5. LOOP-induced effects: the delay in starting the charging pumps after the ESF actuation and the controller responses.
6. The "feed-only-good-generator" feature of the AFW flow control valves.

TRANSIENT 5.73
LARGE STEAM BREAK INSIDE CONTAINMENT, 100% POWER

Initial Conditions:

BOL
T_{avg}: 558.2°F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: Large break on main steam line #1 (8.72 X 10^6 lbm/hr) inside containment

Point Explanation

1. **Steam flow in main steam line #1** increases off-scale high with the steam break.

2. **Steam generator level in SG #1** swells with the surge in steam demand associated with the steam break.

3. **Steam pressure in main steam line #1** decreases as steam is discharged to the containment atmosphere.

4. The removal of flow resistance associated with the isolation of the #1 main steam line (because of closure of its check valve) causes **steam flow from the #4 SG** (as well as from the #2 and #3 SGs) to increase.

5. The reactor trip (indicated by the step drop in **bank D rod position**) and ESF actuation (indicated by the characteristic perturbation in **charging flow**) is caused by high steam flow plus low steam pressure. The high steam flow setpoint is exceeded with the break in steam line #1 and the increased flow in the other 3 steam lines (see the explanation for point 4 above), and the low steam pressure setpoint is reached as the steam pressure decreases in all steam lines. Note that the ESF actuation takes place when the steam pressure is ~ 750 psig in the intact steam lines; the input to the low steam pressure bistable reaches the low steam pressure setpoint before actual pressure does because of the lead-lag circuit through which the steam pressure signal is processed. Note also that the other ESF actuation signals are not possible: pressurizer pressure and T_{avg} are not low enough yet, and steam line ΔP and containment pressure are not large enough yet. However, one other reactor trip signal is possible: a turbine trip + P-7, with the turbine tripping on high SG level.

6. The closure of the steam line check valves and MSIVs allows **steam pressure in main steam line #4** (as well as in steam lines #2 and #3) to recover following the reactor trip and ESF actuation.

7. **T_{avg}** decreases due to the cooldown of the reactor coolant caused by the steam release through the break. Note that the cooldown in RCS loop #1 (which contains the SG which is feeding the break) leads the cooldowns in the other loops.

TRANSIENT 5.73 (CONT'D)

Point Explanation

8. **Feed flow to SG #1** increases with actuation of the AFW system (the AFW system is actuated by the ESF actuation). The flow to that SG is initially higher than that to the other three SGs because of its lower pressure. The AFW flow to SG #1 decreases to 0 in two steps when each AFW flow control valve to that SG closes in response to the high flow (> 500 gpm) sensed in its supply line to that SG. The two steps are due to the train A and train B valves closing at different times.

9. The decrease in **steam flow in main steam line #1** and in **steam break flow** reflects the decrease in driving force for steam flow with the reduction in steam pressure in that steam line and the increase in containment pressure.

10. The decrease in **steam generator level in SG #1** reflects the rapid dissipation of that SG's inventory through the steam break.

11. **Containment pressure** increases as steam is discharged from main steam line #1 to the containment atmosphere. The pressure increase is tempered by containment fan cooler operation.

Note: The "blip" in generator load at ~ 50 sec reflects the voltage/current spike accompanying the opening of the output breakers.

What this transient illustrates:

1. The dissipation of one SG's inventory through an unisolable break upstream of the MSIV.
2. The isolation of the steam break from the other 3 SGs by the faulted SG's check valve and by MSIV closure.
3. A steam-break-induced cooldown of the RCS.
4. A high steam flow + low steam pressure ESF actuation and the characteristic response of charging flow.
5. The "feed-only-good-generator" feature of the AFW flow control valves.

TRANSIENT 5.74
LARGE STEAM BREAK DOWNSTREAM OF MSIVs, 10^{-8} AMPS IN I.R.

Initial Conditions:

BOL
T_{avg}: 558.2°F
Pressurizer Pressure: 2232 psig
Nuclear Power: ~10^{-8} amps in I.R.

Bank D Rod Position: 103 steps
Charging flow provided by one centrifugal charging pump
Normal plant configuration for startup
Initiating Event: Large break (8.72×10^6 lbm/hr) downstream of the MSIVs

Point	Explanation
1.	**Steam flow** (all main steam lines) increases rapidly with the steam break.
2.	**Steam pressure** decreases with the unrestricted steam flow through the break.
3.	The reactor trip (indicated by the step drop in **bank D rod position**) is caused by an ESF actuation on high steam flow plus low steam pressure. The high steam flow setpoint is reached with the increase in steam flow through the break (the high steam flow setpoint is at its minimum value with no turbine load), and the low steam pressure setpoint is reached as the steam pressure constantly decreases. Note that the ESF actuation takes place when the steam pressure is ~ 980 psig; the input to the low steam pressure bistable reaches the low steam pressure setpoint before actual pressure does because of the lead-lag circuit through which the steam pressure signal is processed. Note also that the other ESF actuation signals are not possible: pressurizer pressure and T_{avg} are not low enough yet, and, because the break is downstream of the MSIVs, there is no steam line ΔP, and it does not cause containment pressure to increase.
4.	The **charging flow** perturbation reflects the ESF actuation (isolation of normal charging and diversion of some HPI flow through the seal injection lines).
5.	The additional steam flow through the break cools the reactor coolant; the **pressurizer level** decrease reflects the reduction in reactor coolant volume caused by the decrease in coolant temperature.
6.	**Steam flow** decreases to 0, reflecting the MSIV closure associated with the high steam flow ESF actuation.
7.	**Source range power** comes on scale when both source range detectors are energized by both I.R. channels reaching the P-6 setpoint (10^{-10} amps) following the trip.
8.	**Pressurizer level** increases with injection from the CCPs and letdown isolated following the ESF actuation.

TRANSIENT 5.74 (CONT'D)

What this transient illustrates:

1. The feeding of a steam break downstream of the MSIVs by all SGs.
2. A high steam flow + low steam pressure ESF actuation and the isolation of all main steam lines.
3. A steam-break-induced cooldown of the RCS.
4. The energizing of the source range detectors when intermediate range power reaches the P-6 setpoint.

TRANSIENT 5.75
SGTR IN SG #1

Initial Conditions:

BOL
T_{avg}: 585.3°F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%
Bank D Rod Position: 219 steps

Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: 700-gpm tube rupture in SG #1 (~1.75 times the leak flow through 1 tube, per the simulator malfunction)

Point	Explanation
1.	**Pressurizer level** drops with the loss of coolant inventory from the RCS.
2.	**Pressurizer pressure** decreases with the expansion of the pressurizer steam bubble associated with the inventory loss.
3.	**Charging flow** increases to a very high value as the pressurizer level control system opens charging flow control valve FCV-121 in response to the low level, and the discharge flow from the operating CCP is enhanced by the low RCS pressure.
4.	**Steam generator level in SG #1** increases by a few percent with the leakage of reactor coolant into that SG. The level is brought back to setpoint as the level error input to the SG water level control system reduces feed flow to SG #1 (see point 5 below).
5.	**Feed flow to SG #1** decreases in response to the level error input to the SG water level control system.
6.	**Generator load** decreases in response to OTΔT runbacks. The OTΔT runback sepoint is greatly reduced by the decrease in pressurizer pressure. A close inspection of the plot reveals 3 separate runbacks. In the turbine EHC system each runback is accomplished by the reduction of the load demand by ~ 5% in a 2.3-sec interval; runbacks continue every 30 sec as long as the runback condition persists.
7.	The reactor trips (indicated by the step drop in **bank D rod position**) on low pressurizer pressure (the setpoint is 1865 psig).
8.	The low pressurizer pressure (1807-psig setpoint) ESF actuation (as indicated by the perturbation in **charging flow**) occurs a few seconds after the reactor trip. The shift in the charging flow value is exaggerated because the beginning and ending charging flows are so high due to the large charging demand (FCV-121 is wide open) and low RCS pressure.

TRANSIENT 5.75 (CONT'D)

Point Explanation

9. **Pressurizer pressure** decreases even faster after the pressurizer empties. With the steam bubble/coolant interface now in the surge line, the surface area available for evaporation is greatly reduced, and the rate of pressure decrease is now hardly affected by evaporation at the interface. Also contributing to the pressure drop at this point are the continued inventory loss and coolant volume contraction as T_{avg} is brought to the no-load value. The minimum pressure reached is ~ 1090 psig.

10. **Pressurizer pressure** recovers after about 10 min as total ECCS flow from the CCPs and the safety injection pumps exceeds the flow through the tube rupture. The decrease in RCS pressure has both increased injection flow and reduced the driving force for tube leakage. Existing steam bubbles in the RCS are being squeezed.

11. The increase in **pressurizer level** reflects the recovery of coolant inventory with ECCS flow > tube leakage.

12. **Steam generator level in SG #1** comes back on scale first because it is filling with AFW flow and reactor coolant leakage, while the other 3 SGs are filling with AFW flow alone. (All SG level indications had gone off-scale low due to post-trip shrinks.)

What this transient illustrates:

1. The loss of inventory from the RCS and the reduction in RCS pressure associated with an SGTR, and the resulting protection system responses.
2. A low pressurizer pressure ESF actuation and the characteristic response of charging flow.
3. OTΔT runbacks.
4. The development of saturated conditions in the RCS.
5. The filling of the RCS and the SGs by ESF systems.

TRANSIENT 5.76
6-IN. COLD-LEG BREAK

Initial Conditions:

BOL
T_{avg}: 585.2°F
Pressurizer Pressure: 2232 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Initiating Event: 40,000-gpm (~6-in. diameter) break in cold leg of loop #1

Point Explanation

1. **Pressurizer level** drops rapidly with the loss of coolant inventory from the RCS.

2. **Pressurizer pressure** decreases rapidly with the expansion of the pressurizer steam bubble and then complete emptying of the pressurizer.

3. The reactor trips (indicated by the step drop in **bank D rod position**) on low pressurizer pressure (the setpoint is 1865 psig).

4. The low pressurizer pressure (the setpoint is 1807 psig) ESF actuation (as indicated by the perturbation in **charging flow**) occurs immediately after the reactor trip. The shift in the charging flow value is exaggerated because the beginning and ending charging flows are so high due to the large charging demand (FCV-121 is wide open) and low RCS pressure.

5. **Pressurizer pressure** "hangs up" at ~ 940 psig. The saturation temperature for this pressure is ~ 540°F; a great deal, if not all, of the reactor coolant has reached saturation. This means that flashing is occurring at many locations in the RCS, and the formation of steam bubbles holds up the pressure decrease.

6. **Containment pressure** increases rapidly as the hot coolant is released into the containment volume. The maximum pressure reached is ~35 psia.

7. The large value of **cold-leg break flow** illustrates the rapid rate of inventory loss at the outset of the accident.

8. The rapid increase in **BIT flow** reflects the initiation of high pressure injection; the CCPs are the first pieces of emergency equipment started by the DBA sequencer following an ESF actuation (one CCP is already running at the start of the transient).

TRANSIENT 5.76 (CONT'D)

Point	Explanation
9.	**Safety injection system flow** at first increases rapidly with the initiation of intermediate head injection (the safety injection pumps are started by the DBA sequencer a few seconds after the CCPs). This illustrates that the RCS depressurizes quickly to below the shutoff head of the pumps. SI system flow then gradually increases as the pump discharge pressure decreases (characteristic of centrifugal pumps).
10.	The drop in **cold-leg accumulator level** reflects the emptying of the accumulators when the RCS pressure falls below the accumulator nitrogen cover pressure (600 psig).
11.	**RHR flow** remains at 0 over the time span of the transient as the reactor coolant pressure stays above the shutoff head of the RHR pumps. The RHR pumps were started by the DBA sequencer shortly after the start of the accident and are recirculating to their suctions.
12.	**Containment pressure** decreases as the containment fan coolers remove heat from and condense steam in the containment volume. The highest pressure reached in containment (~20 psig) does not exceed the containment spray initiation setpoint.

What this transient illustrates:

1. The loss of inventory from the RCS and the reduction in RCS pressure associated with a LOCA, and the resulting protection system responses.
2. A low pressurizer pressure ESF actuation and the characteristic response of charging flow.
3. The development of saturated conditions in the RCS.
4. The responses of the ECCSs and the different pressures at which they inject.
5. The reduction in containment pressure due to containment fan cooler operation.

TRANSIENT 5.77
LOSS-OF-FEEDWATER ATWS

Initial Conditions:

BOL
T_{avg}: 585.3 °F
Pressurizer Pressure: 2230 psig
Nuclear Power: 100%

Bank D Rod Position: 219 steps
Charging flow provided by one centrifugal charging pump
All control systems in automatic
Reactor trip breakers are failed in the closed position
Initiating Event: Simultaneous trip of both main feed pumps

Point	Explanation
1.	**Feed flow** drops to 0 rapidly with the loss of both main feed pumps.
2.	**Generator load** decreases rapidly with the turbine setback (acts through the load limit circuit) initiated by the feed pump trips.
3.	**Steam generator level** rapidly decreases out of the narrow-range level indicating range as a result of (1) shrink and (2) the stoppage of feed flow and continued steaming.
4.	**Feed flow** comes back on scale with the initiation of AFW on low-low SG level.
5.	**Generator load** drops to 0 when the turbine is tripped by the ATWS mitigation system actuation circuit (AMSAC). In accordance with the design of the Trojan AMSAC, the trip occurs 25 sec after 3 of the SG levels reach the low-low level setpoint.
6.	T_{avg} increases with the power mismatch resulting from continued nuclear power generation and the loss of the turbine load. Even the development of full-blast steam dump flow within the first minute cannot halt the increasing trend.
7.	**Bank D rod position** decreases as the rod control system inserts the rods at the maximum rate (72 steps/min) in response to large inputs from the power mismatch circuit (setback and turbine trip) and from the temperature mismatch circuit ($T_{avg} >> T_{ref}$).
8.	**Nuclear power** decreases rapidly due to the negative reactivity associated with the rod insertion and the coolant temperature increase.
9.	**Steam dump demand** rapidly increases to maximum with the large T_{avg} - T_{ref} difference. The steam flow graph indicates that the dumps are first armed by a loss-of-load arming signal and then remain armed by a turbine trip arming signal following the turbine trip.
10.	**Steam flow** and **steam pressure** decrease as the SG inventories are boiled off to near empty.
11.	The increase in T_{avg} accelerates as the SG heat sink is almost completely gone.

TRANSIENT 5.77 (CONT'D)

Point	Explanation
12.	**Pressurizer pressure** reflects PORV and safety valve lifts as the pressurizer is solid and coolant temperature is still increasing. At least some of the valve lifts probably result in water release.
13.	**Feed flow** increases when the SG pressure has dropped below the condensate pump discharge pressure.
14.	T_{avg} decreases rapidly with the abrupt increase in SG heat transfer associated with the introduction of condensate flow. At this point the core heat ouput has been reduced to decay heat levels by the rod insertion.
15.	**Pressurizer level** drops rapidly with the rapid contraction of the reactor coolant associated with the coolant temperature decrease.
16.	**Pressurizer pressure** rapidly drops to below the low pressure ESF actuation setpoint (1807 psig) with the expansion of the steam bubble accompanying the coolant contraction.
17.	The rapid increase in **BIT flow** (followed closely by the rapid increase in **safety injection system flow**) reflects the ESF actuation and the low RCS pressure.
18.	**Pressurizer level** increases as ECCS flow (with letdown isolated) fills the pressurizer.
19.	**Pressurizer pressure** increases to the PORV lift setpoint as the pressurizer goes solid again. Note that the solid plant conditons are attained ~ 5 min after the indicated pressurizer level reaches 100%. At the very low pressure experienced throughout much of this transient (~ 900 psig), the indicated level greatly overstates the actual level. See the attached figures for a more detailed explanation of this phenomenon. In addition, the pressurizer is not completely filled when the level reaches the upper taps of the level detectors.
20.	**Pressurizer pressure** "squiggles" reflect PORV lifts after the pressurizer goes solid. Instrument air to containment has been isolated on the ESF actuation, but the pressurizer PORVs are equipped with air accumulators.

What this transient illustrates:

1. The large reduction in heat removal capability with the loss of main feedwater, and the inability of AFW alone to hold T_{avg} at normal operating values at high reactor powers.
2. An ESF actuation and the responses of ESF systems.
3. The development of solid plant conditions due to overheating and overfilling of the RCS.
4. A turbine setback caused by the loss of a main feed pump.