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TRAC ANALYSIS OF DESIGN BASIS
EVENTS FOR THE ACCELERATOR
PRODUCTION OF TRITIUM
TARGET/BLANKET

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TRAC ANALYSIS OF DESIGN BASIS EVENTS FOR THE ACCELERATOR PRODUCTION OF TRITIUM TARGET/BLANKET

by

J. C. Lin and Jay Elson

ABSTRACT

A two-loop primary cooling system with a residual heat removal system was designed to mitigate the heat generated in the tungsten neutron source rods inside the rungs of the ladders and the shell of the rungs. The Transient Reactor Analysis Code (TRAC) was used to analyze the thermal-hydraulic behavior of the primary cooling system during a pump coastdown transient; a cold-leg, large-break loss-of-coolant accident (LBLOCA); a hot-leg LBLOCA; and a target downcomer LBLOCA. The TRAC analysis results showed that the heat generated in the tungsten neutron source rods can be mitigated by the primary cooling system for the pump coastdown transient and all the LBLOCAs except the target downcomer LBLOCA. For the target downcomer LBLOCA, a cavity flood system is required to fill the cavity with water at a level above the large fixed headers.

INTRODUCTION

A two-loop primary cooling system was designed to mitigate the heat generated in the tungsten neutron source rods inside the rungs of the ladders and the shell of the rungs. The Transient Reactor Analysis Code¹ (TRAC) was used to analyze the thermal-hydraulic behavior of the primary cooling system during a pump coastdown transient; a cold-leg, large-break loss-of-coolant accident (LBLOCA); a hot-leg LBLOCA; and a target downcomer LBLOCA.

The TRAC analysis was based on a two-loop primary cooling system, which was an old model designed by the Babcock & Wilcox company. The main differences between this primary cooling system and the current one are the component size and the plant layout. However, a total power of 62.9 MW, which is almost the same as the current design, was used in the analysis. The main objective of the analysis was to study the heat removal capability of the two-loop primary cooling system. As long as the total power is the same as the current design, and the deviation in component size is small, the heat removal capability of this system can be used to predict the heat removal capability of the current design.

TRAC CODE VERSION

TRAC-PF1/MOD2, version 5.4.18, which is the most recent version of TRAC and includes error corrections to earlier versions, was used to perform the analyses.

DESCRIPTION OF TRAC INPUT MODEL

The primary cooling system consists of two primary cooling loops, a pressurizer, an accumulator, two residual heat removal (RHR) loops, two fixed headers, a supply manifold, a return manifold, and a lumped ladder with three rungs. Also, each primary cooling loop and each RHR loop consists of a pump and a heat exchanger.

The overall system model consists of 119 one-dimensional components, 99 junctions, and 22 heat structures with specified initial and boundary conditions.

Figure 1 shows the TRAC model for loop 1 of the primary cooling system. The loop consists of a hot leg, a pump, a heat exchanger, a cold leg, a pressurizer, and a surge line. The hot leg was modeled with 4 PIPE components, and the pump was simulated with a PUMP component. The pump discharge pipe and the heat exchanger inlet pipe were modeled with two PIPE components. The primary side of the heat exchanger was modeled with 5 PIPE components and 4 HEAT-STRUCTURE components for modeling the heat transfer from the primary to the secondary of the heat exchanger. The secondary of the heat exchanger was modeled with 2 PIPE components, a FILL component, and a BREAK component. The cold leg was modeled with 4 PIPE components and a TEE component. The pressurizer was modeled with a PIPE component and a BREAK component to simulate the pressure boundary condition. The surge line was modeled with a PIPE component.

The TRAC model for loop 2 of the primary cooling system is similar to loop-1 of the primary cooling system except that a VALVE component was added between the accumulator and the surge line to simulate the check valve.

Figure 2 shows the TRAC model for the target ladder system. The target ladder system consists of a hot-leg fixed header, a cold-leg fixed header, a supply manifold, a return manifold, a lower connecting pipe, and 10 ladders with a different number of rungs that contain many tungsten rods. The hot-leg fixed header, the cold-leg fixed header, the supply manifold, the return manifold, and the lower connecting line were modeled with the PLENUM component. The 10 target ladders were lumped into one ladder and all the rungs were lumped into 3 rungs. The downcomer of the lumped target ladder was modeled with 3 TEE components. Similarly, the riser of the lumped target ladder was modeled with 3 TEE components. The 3 lumped rungs were modeled with 3 PIPE components and 6 HEAT-STRUCTURE components to simulate the tungsten rod and the shell of the rungs.

Figure 3 shows the TRAC model for the loop-1 RHR system. The Loop-1 RHR system consists of a pipe connecting from the hot-leg fixed header to the pump

Fig. 1. The TRAC model for loop 1 of the primary cooling system.

suction, a pump, a pipe connecting from pump discharge to the inlet of the heat exchanger, a heat exchanger, and a pipe connecting from the exit of the heat exchanger to the cold-leg fixed header. The pipe connecting from the hot-leg fixed header to the pump suction was modeled with 3 PIPE components. The pump was modeled with a PUMP component, and the pipe connecting from pump discharge to the inlet of the heat exchanger was modeled with two PIPE components. The primary side of the heat exchanger was modeled with 4 PIPE components and 3 HEAT-STRUCTURE components to simulate the heat transfer from the primary side and the secondary side. The secondary side of the heat exchanger was modeled with two PIPE components, a FILL component, and a BREAK component. The pipe connecting from the exit of the heat exchanger to the cold-leg fixed header was modeled with 4 PIPE components. The TRAC model for the loop-2 RHR system is the same as the loop-1 RHR system.

Fig. 2. The TRAC model for the target ladder system.

The TRAC model for a downcomer LBLOCA is the same as the cold-leg or hot-leg LBLOCA except for the target-ladder model, which consists of two target ladders. One simulates a single hot ladder with 3 lumped rungs, and the other simulates the remaining 9 ladders. The break is on the single, hot ladder; the break flow leaks into two PIPE components, which simulate the cavity.

INITIAL AND BOUNDARY CONDITIONS

The initial and boundary conditions for the pump coastdown transient and the LBLOCAs are given in Table 1. All the calculations terminated at 600 s because the transient either approaches quasi steady state or the rod is cooled. After the power was tripped, a power decay curve² calculated by a physics computer code was used to calculate the instantaneous local power.

Fig. 3. The TRAC model for the loop-1 RHR system.

TABLE 1
INITIAL AND BOUNDARY CONDITIONS FOR THE PUMP COASTDOWN
TRANSIENT AND LBLOCAs

Initial pressurizer pressure	1.0568 MPa
Initial total power	62.9 MW
Initial total primary cooling system mass flow	430.3 kg/s
Initial hot-leg fluid temperature	363.15 K
Initial cold-leg fluid temperature	323.15 K
Pump trip	1.0e-5 s
Beam trip for pump coastdown transient	1.0e-5 s
Beam trip for LBLOCAs	Cold-leg pressure drops below 9.6945 Pa
Beam trip delay time for pump coastdown transient	0.0 s
Beam trip delay time for LBLOCAs	0.2 s
Break location for LBLOCAs	Cold leg, component 63; Hot leg, component 23; Downcomer, component 220
Break flow area for LBLOCAs	200%

RESULTS

The TRAC calculated results for the pump coastdown transient, the cold-leg LBLOCA, the hot-leg LBLOCA, and the target downcomer LBLOCA are discussed below.

Pump Coastdown Transient

The five cases shown in Table 2 were analyzed for the pump coastdown transient to study the effect of the RHR flow on the primary cooling system thermal-hydraulic behavior. The result from case 1 is discussed below because the result from other cases is similar except the quasi-steady-state loop flow, which is summarized in Table 3.

Figure 4 shows the time history of pump speed. The pump speed decreases rapidly after the pump is tripped at 10^{-5} s, and coasts down to zero at ~50 s. The same trend is observed in the other cases.

Figure 5 shows the loop mass flow in the primary cooling loop 1. The mass flow decreases very fast to zero at ~40 s and keeps decreasing to ~-5 kg/s at ~50 s. The mass flow starts to reverse and becomes positive at ~250 s. After 250 s, the loop flow is in a natural-circulation mode. The natural-circulation rate is ~1.2 kg/s. The system flow approaches to a quasi steady state at ~600 s.

Figure 6 presents the target ladder mass flows. The total mass flow in the target ladder decreases rapidly during the pump coastdown period and approaches a quasi-steady-state value of 9.9 kg/s at 600 s. The quasi-steady-state mass flows in the primary cooling loop 1 and 2, target, and RHR loop 1 and 2 are given in Table 3. The natural-circulation mass flow rate in primary loop 1 and 2, and RHR mass flow bypassing through the two primary cooling loops, are also included in Table 3.

TABLE 2
CASES FOR PUMP COASTDOWN TRANSIENT STUDY

Cases	Loop 1 RHR Flow % of Total Primary Cooling System Mass Flow	Loop 2 RHR Flow % of Total Primary Cooling System Mass Flow
1	1	1
2	1.5	1.5
3	2	2
4	2	0
5	0	0

Note: Case 5 is a basic two-loop configuration without any RHR systems.

TABLE 3
PRIMARY COOLING SYSTEM MASS FLOW

Component	Loop Name	Loop Mass Flow Rate (kg/s)				
		Case 1	Case 2	Case 3	Case 4	Case 5
111	Target	9.901e+0	1.199e+1	1.273e+1	1.010e+1	6.309e+0
119	Target	9.900e+0	1.199e+1	1.274e+1	1.011e+1	6.306e+0
20	Loop 1	1.172e+0	-2.768e-1	-2.264e+0	1.058e+0	3.149e+0
64	Loop 1	1.232e+0	-2.854e-1	-2.104e+0	1.123e+0	3.179e+0
700	Loop 1	8.364e-2	7.493e-2	1.631e-1	8.485e-2	5.486e-2
25	Loop 2	9.618e-2	-6.787e-2	-2.296e+0	-8.259e-2	3.152e+0
69	Loop 2	9.216e-2	-6.959e-2	-2.321e+0	-8.546e-2	3.126e+0
800	Loop 2	-1.170e-7	-3.216e-8	-7.033e-6	-8.468e-9	1.278e-8
621	RHR 1	4.302e+0	6.453e+0	8.607e+0	8.605e+0	--
662	RHR 1	4.292e+0	6.447e+0	8.598e+0	8.593e+0	--
625	RHR 2	4.300e+0	6.453e+0	8.627e+0	4.837e-1	--
665	RHR 2	4.298e+0	6.454e+0	8.589e+0	4.818e-1	--
Percentage of diverted RHR Flow		0.0%	7.41%	26.4%	0.81%	0.0%
Loop 1 Natural-Circulation Flow (kg/s)		1.172e+0	0.0	0.0	1.058e+0	3.149e+0
Loop 2 Natural-Circulation Flow (kg/s)		9.618e-2	0.0	0.0	0.0	3.151e+0

Figure 7 shows the maximum average-rod temperatures of tungsten rods in the upper, middle, and lower rungs for case 1. The rod temperature decreases rapidly to ~340 K after power is turned off and keeps decreasing to ~337 K at ~25 s. The rod temperature then increases to an equilibrium temperature of 380 K at ~50 s. This increase in temperature results from the rod decay power, and is slightly higher than the heat removed by the coolant when the pump is completely coasted down. After 50 s, the rod temperature decreases very slowly because the power decays continuously. The tungsten rods continue to be cooled throughout the transient.

Figure 8 shows the maximum average-structure temperatures for the wall of the rungs. The trend is very similar to the rod temperature because the wall heat transfer is controlled by the coolant flowing inside the rung. The rung walls transport the heat to the same coolant, i.e., they share the same boundary condition.

Fig. 4. The time history of pump speed for case 1 of the pump coastdown transient.

Fig. 5. The primary cooling loop 1 mass flows for case 1 of the pump coastdown transient.

Fig. 6. The target ladder mass flows for case 1 of the pump coastdown transient.

Fig. 7. The rod surface temperature of tungsten rods in the upper, middle, and lower rungs for case 1 of the pump coastdown transient.

Fig. 8. The structure temperatures of the wall of the upper, middle, and lower rungs for case 1 of the pump coastdown transient.

Figure 9 shows the void fractions in the top lumped rung. The void fraction is zero throughout the transient. The void fractions in the middle and the bottom rungs are also zero, which implies that there is no boiling in the rungs.

Table 3 shows mass flows in the primary cooling loop 1 and 2, target, and RHR loop 1 and 2. The primary cooling loops are in a natural-circulation mode for the case with no RHR system and for the case where both RHR systems are flowing at 1% of the total primary cooling system mass flow. When the RHR system mass flow is higher than 1% of the total primary cooling system mass flow, the natural circulation in the primary cooling loops is broken down, and some of the RHR flows are diverted into the primary cooling loops. The percentage of diverted flow increases as the RHR flow increases. However, more RHR flow results in more flow through the rungs of the target ladder and provides a better cooling for the tungsten rods and the wall of the rungs. When only one RHR flows at 2% of total primary cooling system mass flow, one primary cooling loop is in natural-circulation mode, and a small amount of RHR flow is diverted into the other primary cooling loop.

For all cases, there is enough circulating flow in the target to transport the heat generated in the target to the heat exchanger. The target is cooled by single-phase, forced-convective heat transfer, and there is no vapor being generated in the target.

Fig. 9. The target-ladder, upper-rung void fractions for case 1 of the pump coastdown transient.

Cold- and Hot-Leg LBLOCAs

Two cold-leg LBLOCAs were performed to study the effect of RHR flow on the thermal-hydraulic behavior of the primary cooling system. In case 1, the RHR pump is turned off during the LOCA. In case 2, only one RHR system is in operation, and the RHR mass flow is at 2% of total primary cooling system mass flow during the LOCA.

Figure 10 shows the mass flow in the primary cooling loop 1 (broken loop). The hot-leg mass flow decreases very rapidly to ~ 50 kg/s and keeps at that flow rate until ~ 40 s. After 40 s, the mass flow decreases rapidly to ~ 25 kg/s at ~ 50 s when the pump is completely coasted down. After 50 s, the mass flow decreases gradually to 0 kg/s at 315 s when the pressurizer and accumulator are empty. From 315 s to ~ 385 s, the flow becomes negative and the mass flow is ~ 13 kg/s. This implies the liquid in the hot leg is flowing backward into the hot-leg fixed header. The cold-leg mass flow discharges from the break and decreases gradually to 0 kg/s during the first 315 s. From 315 s to ~ 385 s, the mass flow increases to ~ 13 kg/s, which is about the same amount of mass flow as the hot-leg back flow. This implies that all the mass flow from the hot leg is flowing out through the break.

The liquid level in the accumulator decreases to near the bottom where the liquid head is sustained by the atmospheric pressure and remains at that level throughout the transient. This liquid height results in a natural circulation in the target ladder during the late part of the transient.

Fig. 10. The broken-loop mass flows for case 1 of the cold-leg LBLOCA.

Figure 11 shows the mass flow in the primary cooling loop 2 (intact loop). The mass flow in the hot and cold legs decreased rapidly during the pump coastdown period. After ~50 s, the hot-leg mass flow reverses and becomes negative flow, but the mass flow is small in comparison with the cold-leg mass flow. This implies that a small amount of mass flow is flowing backward from the hot leg to the hot-leg fixed header. The mass flow reverts to positive again when the pressurizer and accumulator are empty. After 315 s, a natural circulation is established in the loop at a flow rate of 3.85 kg/s.

Figure 12 shows the target ladder mass flows. The mass flow decreases rapidly during the pump coastdown period. After pump coastdown, the mass flow almost always keeps at a constant mass flow ~10 kg/s until ~315 s. The flow reverses when the pressurizer and accumulator are empty. The amount of mass flow is ~2 kg/s. At ~385 s, the mass flow reverts to positive flow, which means the flow is flowing from the downcomer to the riser through the rungs. After 385 s, the flow oscillates until the end of the transient.

Figure 13 shows the void fractions in the upper rung. There is no void being generated in the middle and lower rungs throughout the transient. There is some void being generated in the upper rung for a short duration at ~5 s when the flow is stagnant at ~410 s, as shown in Fig. 12.

Fig. 11. The intact-loop mass flows for case 1 of the cold-leg LBLOCA.

Fig. 12. The target-ladder upper-rung void fraction for case 1 of the cold-leg LBLOCA.

Fig. 13. The target-ladder upper-rung void fraction for case 1 of the cold-leg LBLOCA.

Figure 14 shows the maximum average-rod temperatures of the tungsten rods. The rod temperature decreases to ~ 330 K during the pump coastdown period and then heats up to ~ 342 K at ~ 75 s because of decreased mass flow in the rungs. After 75 s, the rod temperature decreases gradually to ~ 332 K until ~ 240 s. During 75 to 240 s, the flow is almost at constant but the power is decaying; therefore, the rod temperature decreases. From 240 to 315 s, the flow decreases and this decreasing flow results in an increase in rod temperature. The rod temperature increases rapidly during the flow reversal period. The rod temperature of the upper rung reaches a saturation temperature ~ 391 K at ~ 410 s when the flow is stagnant. After 410 s, the rod temperature oscillates between 330 and 345 K because of flow oscillation.

In case 2, the mass flows in the primary cooling loops and in the target ladder are similar to case 1 except the flow in the target ladder is stagnant during the 315 to 385 s period. During this period, void is generated in the upper and middle rungs, and the rod temperature increases rapidly to the saturation temperature in correspondence with the local pressure. After 385 s, a positive flow is established again, the boiling in the rungs ceases, the rod is cooled down, and the rod temperature oscillates between 325 and 332 K.

Fig. 14. The rod surface temperatures of tungsten rods in the upper, middle, and lower rungs for case 1 of the cold-leg LBLOCA.

Two hot-leg LBLOCAs, which are the same as the cold-leg LBLOCAs, were calculated. The hydraulic behavior is similar to the cold-leg LBLOCA except that there is no flow reversal. The tungsten rods are subcooled throughout the transient, and no boiling occurs in the rungs.

Target-Ladder Downcomer LBLOCA

One target downcomer large break was performed. The mass flow in the two loops decreases rapidly during the pump coastdown period, and then the mass flow decreases gradually during the pressurizer and accumulator emptying period. During these two periods, the mass flow rates in the rungs are large enough to cool the rods and the shell of the rungs.

Figure 15 shows the mass flow in the primary cooling loop 1. The mass flow decreases rapidly during the pump coastdown period, and then the mass flow decreases gradually during the pressurizer and the pressurizer surge line emptying period. The mass flow decreases rapidly again to a very small flow when the pressurizer surge line becomes empty (~265 s). At this time, loop 1 starts voiding. The mass flow in the primary cooling loop 2 is similar to loop 1, but the loop starts voiding at much later time (~520 s).

Fig. 15. The mass flows in the primary cooling loop 1 for the downcomer LBLOCA.

Figure 16 shows the mass flows in the intact target ladder. The mass flow decreases rapidly during the blowdown period and then the mass flow decreases gradually during the pressurizer and the pressurizer emptying period. From 265 s to ~370 s, the flow becomes stagnant. After ~370 s the flow reverts to a small positive flow because of natural circulation.

The mass flow in the broken target ladder is different from the intact ladder in that liquid keeps flowing out through the break. The magnitude of the break flow is large enough to sweep out the vapor generated in the rungs and to keep the rods subcooled.

Figure 17 shows the vapor fraction in the middle rung of the intact target ladder. Some vapors are generated during the stagnant flow period, as shown in Fig. 16. The vapor fractions in the upper and lower rungs are similar to the middle rung.

The vapor fraction in the broken target ladder is almost zero throughout the transient except for the upper rung. From 350 to 375 s, some vapor is generated in the upper rung.

Figure 18 shows the rod temperatures of the intact target ladder. The rod temperature is ~325 K before the pressurizer surge line becomes empty at ~265 s. After 265 s, the rod temperatures increase rapidly to the saturation temperature corresponding to the local pressure. The rapid increase in temperature results from

Fig. 16. The mass flows in the intact target ladder for the downcomer LBLOCA.

Fig. 17. The vapor fraction in the middle rung of the intact target ladder for the downcomer LBLOCA.

Fig. 18. The rod surface temperatures of tungsten rods in the upper, middle, and lower rungs for the downcomer LBLOCA.

the flow stagnation, as shown in Fig. 16. The rod temperatures decrease as a positive flow is reestablished until the RHR pump is degraded because of air being sucked in the RHR system. After that time the rod temperatures increase slowly. The rod temperatures of the broken target ladder are similar to the intact target ladder except that the rod temperatures are lower than the saturation temperature during the flow stagnation period.

CONCLUSIONS AND RECOMMENDATIONS

The recommended two-loop primary cooling system has been evaluated under different accident scenarios and RHR flow rates. From the above result, we concluded that the two-loop primary cooling system with an RHR system performs well and can cool the target for an external LBLOCA and a pump coastdown transient. However, for an internal large break, the system may be broken down when air is propagated into the RHR system. We need to prevent this either by flooding the cavity quickly to the level above the large fixed header or by opening a vent valve connecting to the atmospheric pressure so that the liquid level in the primary loop maintains above the two large fixed headers.

The TRAC model should be updated when the primary cooling system and the plant layout are finalized. The same analysis for design basis events should be performed.

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