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TITLE: TRAC CALCULATIONS OF OVERCOOLING TRANSIENTS IN PWRs FOR PRESSURIZED THERMAL-SHOCK ANALYSIS

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TRAC CALCULATIONS OF OVERCOOLING TRANSIENTS IN PWRs

FOR PRESSURIZED THERMAL SHOCK ANALYSIS*

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ABSTRACT

This paper briefly describes the overall pressurized thermal shock (PTS) program at Los Alamos with emphasis on TRAC-PF1 calculations of severe overcooling transients in pressurized water reactors (PWRs). Overcooling transients for both the Oconee-1 and Calvert Cliffs-1 nuclear plants have been performed. A summary of results for several calculations are presented for the Oconee-1 PWR along with detailed discussions of two of the most severe overcooling transients predicted [main steam-line break and turbine-bypass valve (TBV) failures]. The calculations performed were plant specific in that details of both the primary and secondary sides were modeled in addition to a detailed model of the plant integrated control system (ICS). For the Oconee-1 main steam-line break transient, a minimum downcomer fluid temperature of ~405 K was predicted. For the transient involving the failure of one bank of TBVs to close after initially opening following reactor and turbine trips, an extrapolated downcomer fluid temperature of ~365 K was estimated. The latter temperature is at the nil-ductility temperature (NDT) limit (~365 K) for Oconee-1.

*Work performed under the auspices of the US Nuclear Regulatory Commission.

INTRODUCTION AND SUMMARY

Pressurized thermal shock (PTS) in pressurized water reactors (PWRs) has been identified by the Nuclear Regulatory Commission (NRC) as an unresolved safety issue. Because of this, the NRC has a major program distributed among several organizations to help resolve the PTS issue. The goal of this project is to determine the potential risk of older reactor vessels to severe overcooling transients that rapidly cool the primary system. The concern over PTS arises because the vessel wall material properties change after many years of neutron irradiation.[1] The vessel wall becomes embrittled and the nil-ductility temperature (NDT) increases. If during a severe overcooling transient, cold high-pressure injection (HPI) liquid cools the vessel wall below the NDT, the possibility exists that flaws in the vessel welds could be transformed into larger cracks that could lead to a vessel rupture.

The Los Alamos contribution to this project is to use the multidimensional, two-fluid, non-equilibrium numerical simulation code, TRAC-PF1[2], to provide accurate thermal-hydraulic conditions during postulated PTS accidents. TRAC-PF1 has been used to predict the thermal-hydraulic response of both the Oconee-1 and the Calvert Cliffs-1 PWRs to selected overcooling scenarios. Oconee-1 is a Babcock & Wilcox (B&W) designed plant with once-through steam generators, and Calvert Cliffs-1 is a Combustion Engineering (CE) PWR. Because the risk of initiating or propagating flaws in the vessel wall depends on the coupling of the thermal stresses produced by overcooling with the mechanical stresses from repressurization, detailed system models are required. Modeling both the primary and secondary systems of the reactor plant is necessary to properly analyze the PTS phenomena. The steam generator (SG) secondary-side inlet conditions directly affect primary temperature, pressure, and the emergency core-coolant injection. Secondary-side inlet conditions are highly dependent on main-feed pump and SG control valve operation and on the termination of the extracted steam supply to the feedwater heaters. Other important systems modeled in the TRAC-PF1 input decks include models of the Integrated Control System (ICS) used in the plants. The ICS monitors the primary flows and temperatures to determine the feedwater demand. The ICS regulates the main and startup flow-control valves, the main-feedwater (MFW) pumps, and the turbine-bypass valves (TBVs).

Several overcooling transients have been identified by Oak Ridge National Laboratory (ORNL),[3] and additional transients may be specified after these initial results are evaluated. The initial transients include a main steam-line break (MSLB) with a delay in isolating the affected SG, a small-break LOCA [full-open failure of the power-operated relief valve (PORV)] with failure of the ICS to throttle MFW flow and trip the reactor coolant pumps

(RC), and TBV transients with SG overfeed. An actual plant tran ent (Oconee-3 turbine trip) was also simulated by TRAC-PF1 to co are with actual plant data to verify the code models of the primar side. In addition, several small hot-leg breaks were analyzed to investigate the effects of accumulator and low-pressure injection flows on downcomer fluid temperatures.

Although a number of transients have been calculated for both types of PWRs, only two transients for the Oconee-1 plant are presented in detail. All Oconee-1 calculations showed significant primary-system depressurization followed by repressurization depending whether or not the HPI was throttled. Also, the system repressurization was dependent on the break size for the small hot-leg break cases. Some overcooling was obtained in all calculations as evidenced by highly subcooled liquid temperatures in the downcomer.

As an example of severe overcooling PTS transients, the MSLB transient and one of the TBV transients for Oconee-1 will be discussed. These transients resulted in the lowest downcomer fluid temperatures for any of the transients calculated because of the severity of the ORNL-specified boundary conditions and assumed operator actions. For further information, detailed descriptions of all the Oconee-1 PTS transients calculated by TRAC-PF1 can be found in Ref. 4.

INPUT MODEL DESCRIPTION

The TRAC-PF1 input models for the Oconee-1 plant primary and secondary systems are shown in Figs. 1 and 2, respectively. The primary-side model of the Oconee-1 plant includes a three-dimensional representation of the reactor-pressure vessel which proved to be important for the MSLB and TBV transients because of symmetry considerations. The three-dimensional vessel noding allows the calculation of asymmetrical loop flows and fluid conditions during some of the overcooling transients such as the MSLB. These important effects cannot be calculated in a one-dimensional vessel model in which the fluid is always completely mixed.

Two primary-system loops are modeled, with one hot leg, one SG and two cold legs per loop. A detailed model of the SGs includes the aspirated feedwater flow, steam-exit annulus, and a port for injection of emergency feedwater. The HPI flow is dependent on primary pressure with slightly different flows for each loop as in the actual plant. Accumulator flow is modeled and is regulated by static-check valves.

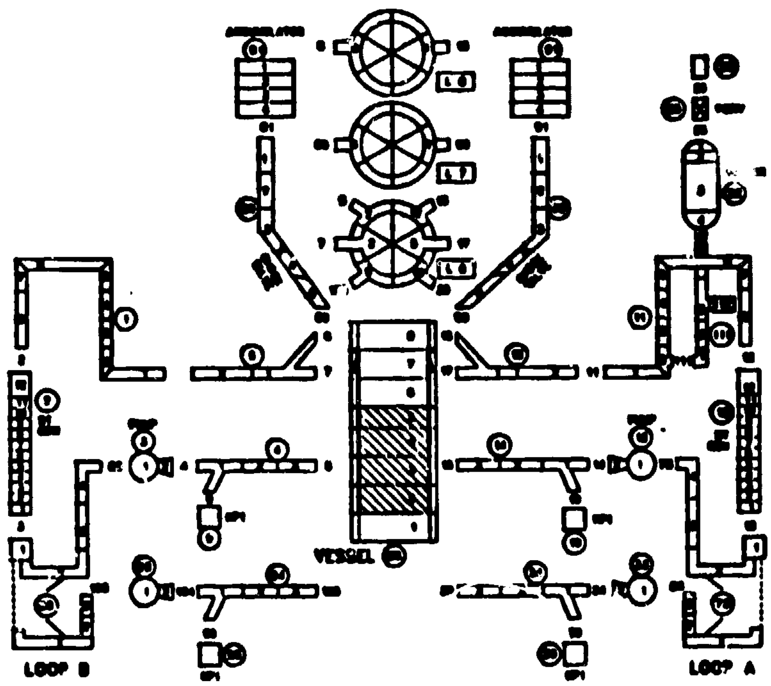

Fig. 1. Oconee-1 plant model - primary side.

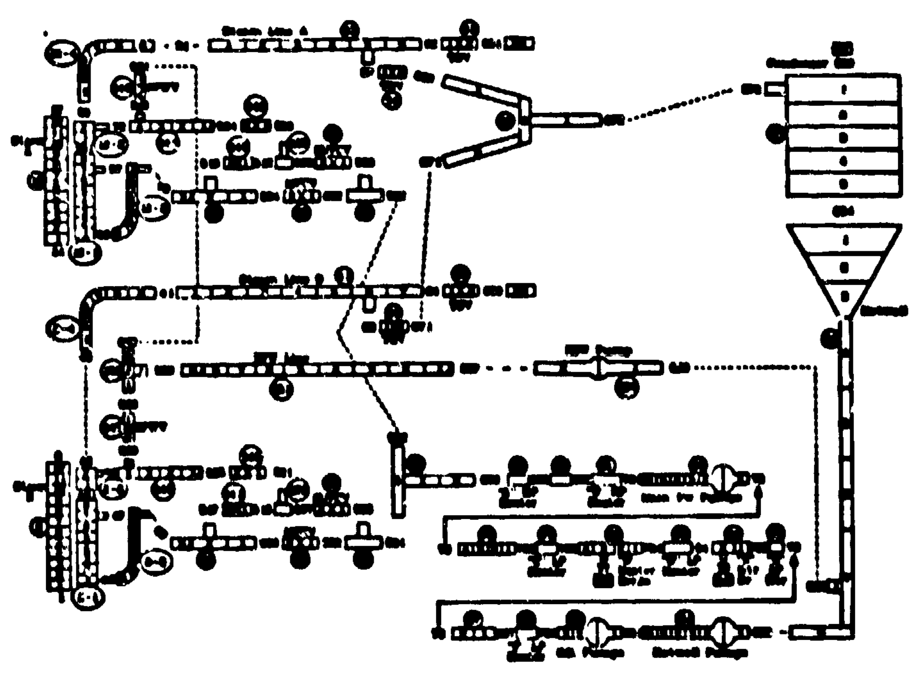

Fig. 2. Oconee-1 plant model - secondary side.

On the secondary side, the main-steam lines from each SG to the turbine stop valves (TSVs) are modeled. The turbine-bypass lines lead to the condenser through the TBVs. The hotwell and condensate-booster pumps deliver the condensate to the feedwater heaters. These heaters are modeled as pipes with three heat-conduction nodes in the pipe wall. The first node models the metal walls of the heat exchanger tubes, and the outer two nodes model the volume of saturated water on the shell side of the heaters. A volumetric heat source is included in the third node to account for the extracted steam supply until the turbine is tripped.

A portion of the B&W ICS used at the Oconee-1 plant is included in the TRAC model. The portion of the ICS modeled monitors the primary flows and temperatures to determine the feedwater demand. The ICS regulates the main and startup flow-control valves and the MFW pumps.

MSLB TRANSIENT RESULTS

The steam-line break is modeled in the SG A steam-line shown in Fig. 2 (component 68). The TSV (component 42) is fixed open, and all steam from SG A passes through the TSV to atmospheric pressure. In the unaffected steam-line (SG B) the TSV is closed and the TBV system operates as designed. The significant features, assumptions, and initial conditions for the MSLB transient are:

1. Full reactor power.
2. Nominal temperatures and pressures in primary/secondary.
3. Decay heat - 1.0 times ANS standard.
4. Reactor and turbine trips coincident with MSLB.
5. Operator fails to isolate feedwater to both SGs until 600 s.
6. Operator restores unaffected SG (SG B) at 900 s.
7. RCPs restarted after 42 K subcooling reached.
8. HPI throttled to maintain 42 ± 12.5 K subcooling.

Key events calculated during the transient are presented in Table 1. The transient was initiated by fixing the TSV in loop A open and modeling the break in the steam-line downstream from the TSV. The turbine and reactor were then tripped followed by a feedwater - heater flow/drain trip. HPI initiation occurred at ~21 s after the primary system pressure had decreased to 10.44 MPa. At ~29 s the ICS detected a low-level limit in SG A, and the emergency-feedwater (EFW) pump was started. At ~47 s the MFW pumps tripped on low-suction pressure. At ~51 s, the RCPs were tripped (30 s after HPI initiation). The 42 K liquid subcooling margin in all primary system loops was reached at ~526 s, and HPI was throttled. Also, RCPs A1 and B1 were restarted at this time. Per the transient specifications[3], the SG

Table 1. Event Sequence for MSLB Transient

	Event	Time (s)
1.	MSLB - loop A steam line	0.0
2.	Turbine and reactor trip; TSV loop B closes	0.5
3.	TBV loop B opens (setpoint 7.063 MPa)	5.0
4.	HPI initiation (setpoint 10.44 MPa)	21.2
5.	SG A low level limit reached; EFW pump starts; loop A SG EFW flow initiated	29.4
6.	TBV loop B closes	39.9
7.	MFW pump trip on low suction pressure	47.8
8.	SG B low-level limit reached; loop B EFW flow initiated	48.7
9.	RCPs trip (30 s after HPI initiation)	51.2
10.	Condensate booster pump trip (low suction pressure)	53.9
11.	SG B level at 50%; loop B EFW valve closed	346.7
12.	RCPs (A1, B1) restart (42 K subcooling reached); HPI throttled	526.0
13.	Loop A, B accumulator setpoints reached (setpoint 4.17 MPa)	530.9
14.	Loop A, B accumulators off	537.9
15.	SG A, B isolated; EFW pump and hotwell pump tripped off	600.0
16.	SG B restored	900.0
17.	PORV setpoint reached (setpoint 16.9 MPa) - PORV opens and closes for remainder of calculation	4678-7200.0
18.	TBV loop B opens (setpoint 7.063 MPa) - TBV opens and closes for remainder of calculation to maintain setpoint pressure	5462-7200.0
19.	SG B level drops below 50% operating range; EFW initiated - EFW pump on/off for remainder of calculation to maintain level at 50%	6121-7200.0
20.	Calculation terminated	7200.0

secondary sides were isolated at 600 s. At 900 s, SG B was restored to allow the EFW and TBV systems to operate if needed. At ~4678 s, the PORV setpoint was reached (16.9 MPa), and the PORV cycled opened and closed for the remainder of the transient to maintain the setpoint pressure. The calculation was terminated at 7200 s, and the primary system was full of liquid. At this time, the decay power produced in the core was being removed through the unaffected steam generator (SG B).

The pressurizer pressure history is shown in Fig. 3. Initially, the primary-system pressure decreased rapidly because of the rapid secondary-side blowdown in SG A following the MSLB. The depressurization was terminated by ~100 s when natural-circulation flows were established following pump coastdown and RCP trip at ~51 s. The primary system then began to repressurize slightly until the RCPs were restarted at ~526 s. The enhanced heat transfer through the SGs, condensation of the steam in the loop B candy cane, and throttling of the HPI after the RCPs were restarted caused the primary-system pressure to decrease to the minimum value for the transient (~3.5 MPa). After the SGs were isolated at 600 s, the primary system repressurized to the PORV setpoint (16.9 MPa) at ~4678 s.

Downcomer liquid temperatures are presented in Fig. 4 at the top axial downcomer level just below the cold-leg inlet nozzles. Because of the severe overcooling in the affected loop (loop A), asymmetrical liquid temperatures are calculated in the vessel downcomer. The fluid temperatures in the downcomer cells associated with the loop A cold legs were calculated to be ~20 K colder than the cells on the loop B side (Fig. 4). The minimum

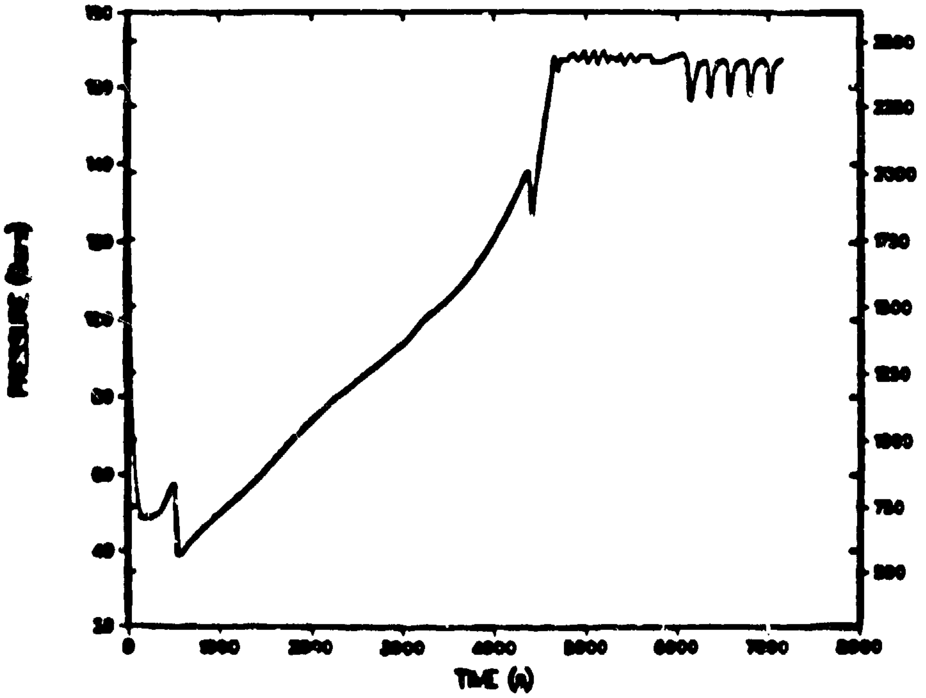

Fig. 3. Pressurizer pressure.

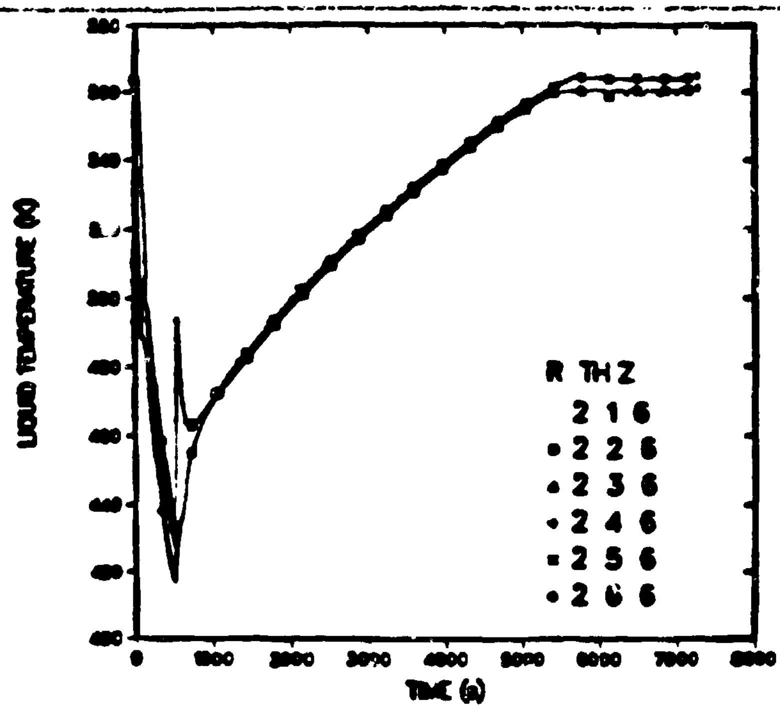

Fig. 4. Downcomer liquid temperatures at vessel axial level 6 (all azimuthal sectors).

downcomer fluid temperature calculated was ~405 K at ~526 s when the RCPs were restarted.

Figures 5 and 6 show the hot-leg mass flows and candy-cane void fractions respectively. The natural-circulation flows calculated in loop A were significantly larger than in loop B for much of the transient (~150-525 s) because of the MSLB in loop A and the resulting enhanced heat transfer in the affected SG. The flow in loop B stagnated at ~150 s because the candy-cane in this loop reached saturation and voided (Fig. 6). The fluid temperatures in loop B were much warmer than in loop A because of incomplete fluid mixing in the vessel (three-dimensional vessel model). After the RCPs were restarted and the HPI throttled (~526 s), the void in the loop B candy cane condensed and was swept out (Fig. 6). The subcooling margin never decreased below 42 K for the remainder of the transient, thus the HPI was never turned back on nor were the RCPs tripped again.

Detailed results of key system parameters in the affected SG (SG A) are shown in Figs. 7 through 9. Figure 7 shows the secondary-side water mass in SG A, and Fig. 8 shows the secondary-side pressure history. The secondary side depressurized to essentially atmospheric pressure by ~85 s, and this time corresponded to the minimum water-mass inventory. After the

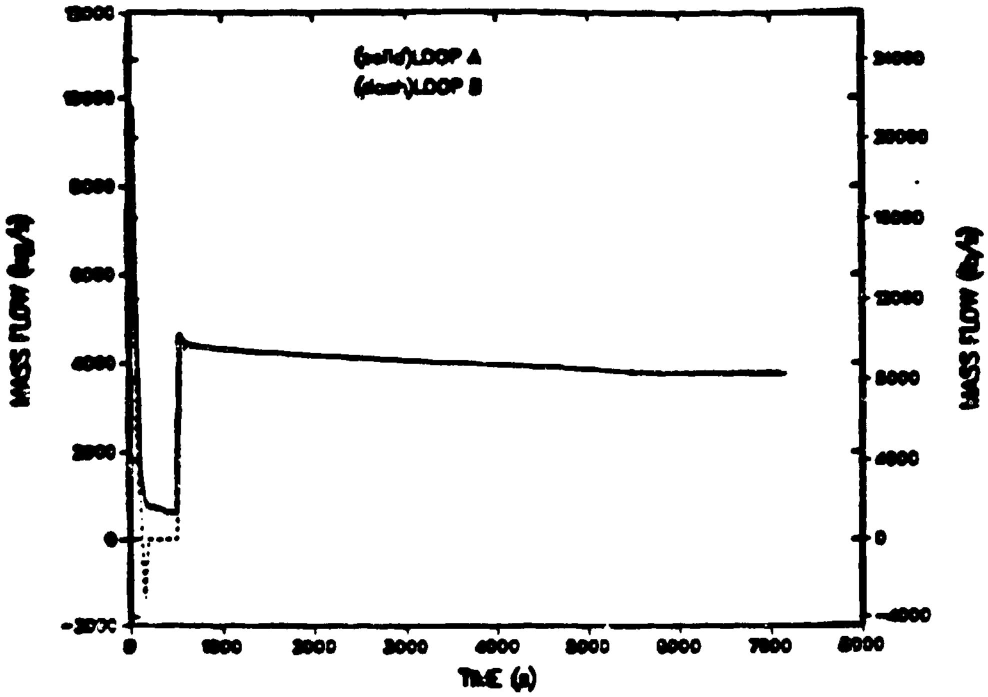

Fig. 5. Hot-leg mass flows.

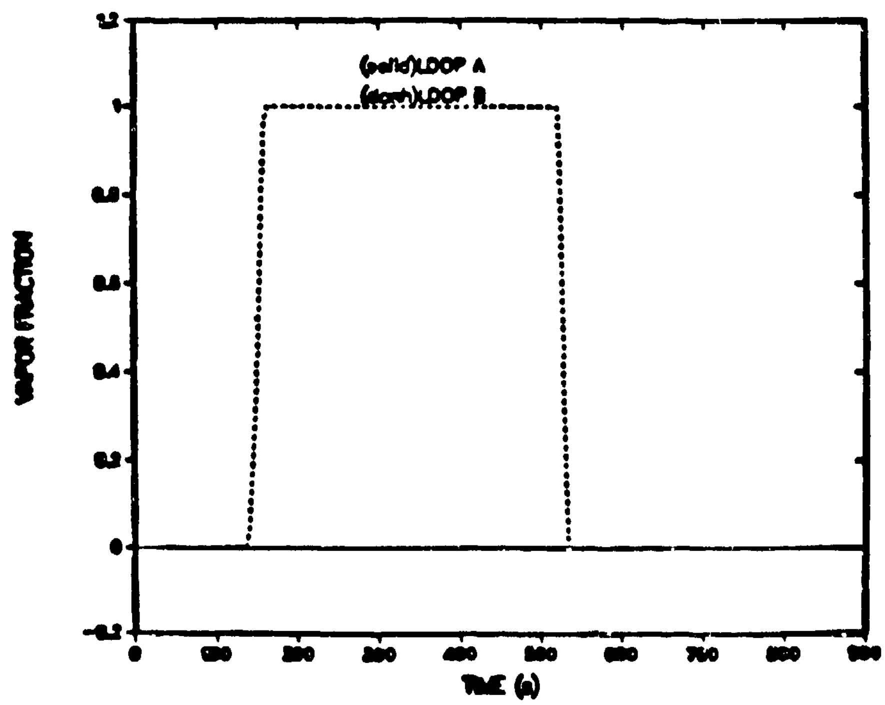

Fig. 6. Candy-cane void fractions.

secondary side had depressurized sufficiently (~100 s), the EFW penetration increased, and the water inventory began increasing (Fig. 7) as a smaller amount of EFW was bypassed out the broken steam line.

Figure 9 presents some detailed plots to explain the EFW penetration phenomena. The top plot in Fig. 9 compares the TRAC-calculated vapor velocity at the EFW injection point to the complete flooding curve predicted by the Wallis-Kutateladze correlation (K = 3.2) for various pressures in the SG A secondary side. This plot shows that EFW penetration will not occur until the vapor velocity is less than ~8 m/s, and this velocity was not reached in the TRAC-PF1 calculation until the secondary side had depressurized to ~0.5 MPa. The bottom plot in Fig. 9 gives the TRAC-PF1 liquid-vapor velocity correlation at the EFW injection point location. This plot shows that EFW penetration as calculated by TRAC-PF1 did not occur until the vapor velocity decreased to ~7.5 m/s, which closely agrees with the Wallis-Kutateladze correlation.

In summary, the overcooling of the primary system of the Oconee-1 plant caused by a full double-ended steam-line break in one of the steam lines was simulated with TRAC-PF1. The minimum downcomer fluid temperature calculated was ~405 K which is close to the NDT limit (~365 K) for Oconee-1. In the next section,

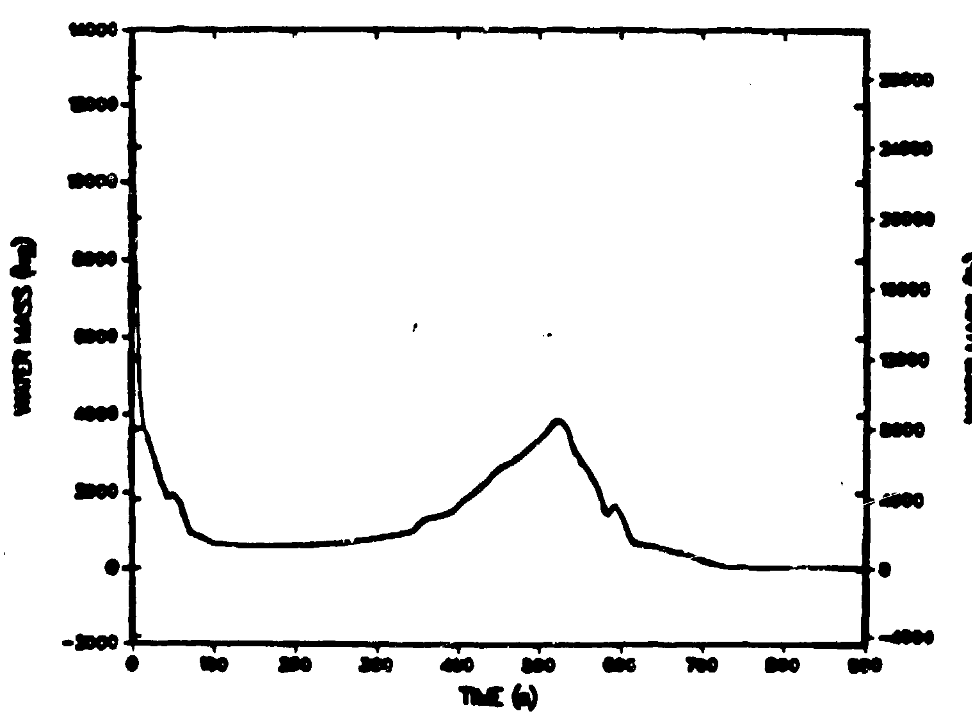

Fig. 7. SG A secondary-side water inventory.

overcooling of the primary system caused by TBV failures is discussed.

TBV TRANSIENT RESULTS

The class of overcooling transients discussed in this section results from a depressurization of the Oconee-1 secondary system through TBVs that have failed to reseat after initially opening. Although a number of TBV transients were calculated, only one will be presented in detail. The relative severity of the remaining TBV transients examined will be briefly discussed for completeness.

A total of six cases were calculated; two base cases and two parametric studies for each base case. The base cases differed only in the number of TBV failures. An identical set of additional failures were specified for the two base cases. Additional conditions assumed were failure of the EFW level control system to maintain the setpoint level in the affected SG, failure of the operator to restart the RCPs, and failure of the operator to throttle the HPI system. The parametric cases examined the system response as the number of additional failures was reduced. The base case selected for discussion is characterized by one bank of TBVs (two valves on one steam line) failing to reseat following trips of both the reactor and turbine. ORNL is currently estimating that the probability of the base case transient occurring is extremely low (2.1×10^{-11}/year compared with 9.0×10^{-4}/year for main steam-line break).

The calculated event times for the transient are shown in Table 2. Following reactor and turbine trip, the TBVs closed, the secondary pressure rose, and the TBVs in both steam lines opened for the first time at ~4 s. The secondary pressure peaked and then decreased permitting the loop B TBV to reseat at ~45 s. The loop A TBV failed to reseat and remained open for the rest of the transient.

The pressurizer pressure is presented in Fig. 10. The PORV opened at ~1037 s when its pressure setpoint was exceeded. The PORV then cycled for the remainder of the calculated transient to maintain the primary system pressure at or below the PORV setpoint. The primary system pressure will remain near the PORV setpoint until the core decay heat can be removed through the affected steam generator.

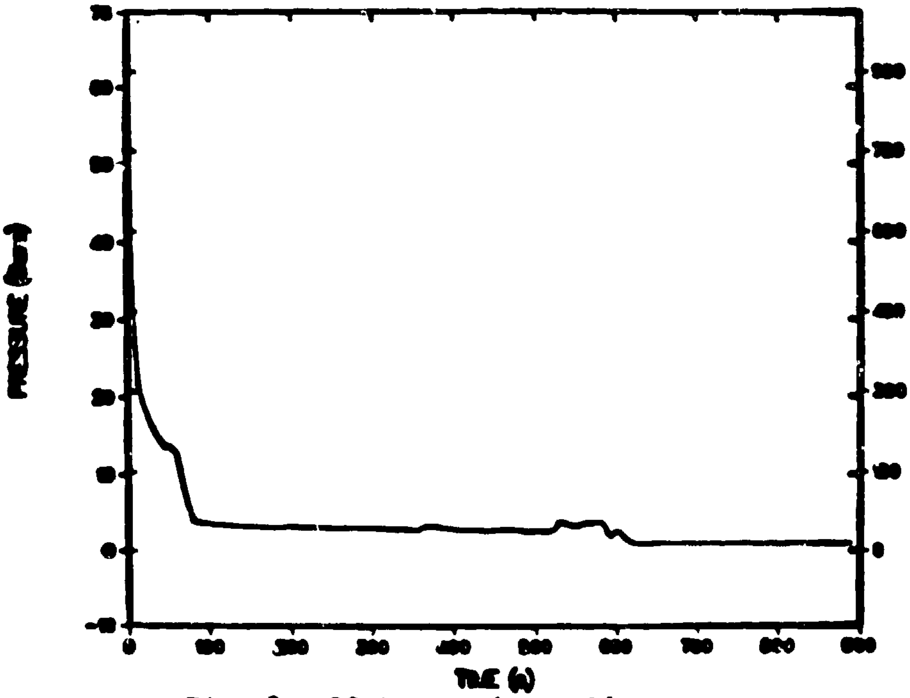

Fig. 8. SG A secondary-side pressure.

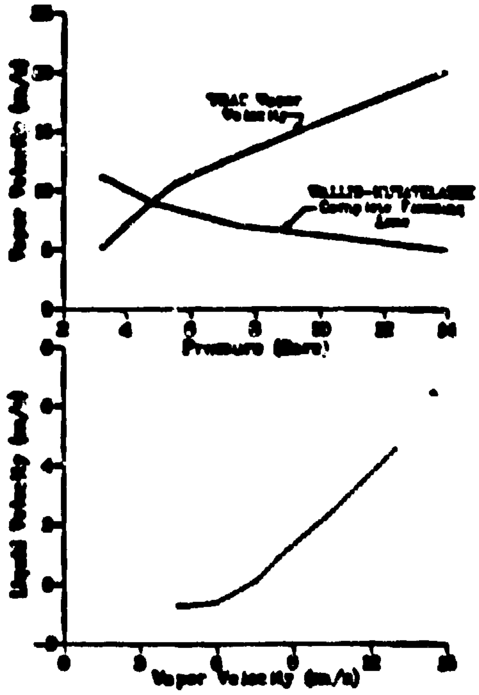

Fig. 9. CCFL phenomena in affected steam generator (SG A).

Table 2. Event Sequence for TBV Transient

	Event	Time (s)
1.	Turbine and reactor trip	0.5
2.	Turbine stop valves close	0.5
3.	Loop A TBV opens (fails to reseat thereafter)	4.1
4.	Loop B TBV opens for first time	4.3
5.	MFW pump trip on high SG A liquid level	60.7
6.	HPI started following trip on low pressure	153.1
7.	RCPs trip on 30 s delay after HPI actuation	183.0
8.	Feedwater realignment trip	183.0
9.	Main flow-control valves overriding trips	183.0
10.	Low MFW discharge pressure signal	208.9
11.	Emergency feedwater pump on	209.1
12.	Loop B EFW valve shut on high SG liquid level	460.8
13.	PORV opens	1036.7
14.	Calculation terminated	1500.0
15.	Calculation extrapolated	7200.0

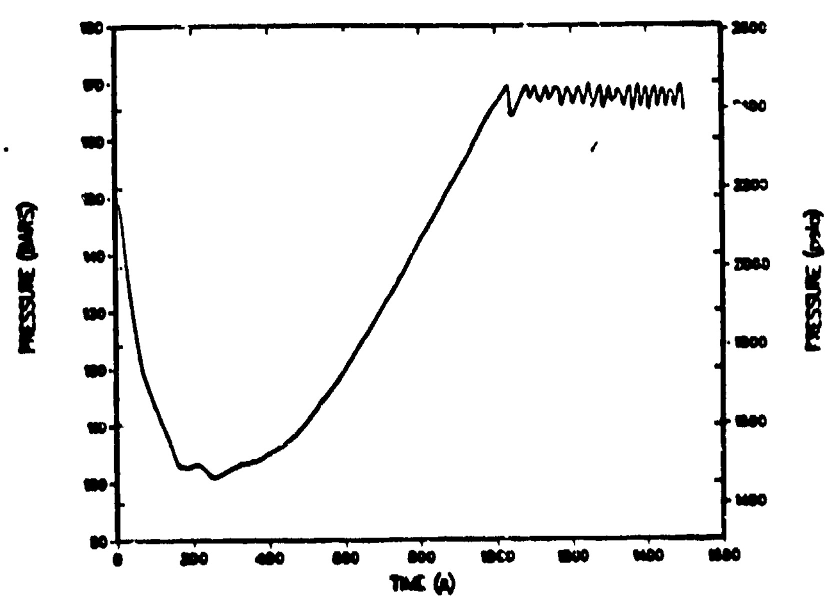

Fig. 10. Pressurizer pressure.

The downcomer liquid temperature history for the base case is shown in Fig. 11. The temperature trace consists of two segments; a calculated transient to 1500 s and an extrapolated transient from 1500 s to 7200 s. At the end of the calculated transient (1500 s) the minimum temperature is ~458 K. The maximum azimuthal temperature variation around the downcomer periphery is ~8 K. The extrapolated cooldown rate from 1500 s was reduced at 2500 s to account for depletion of the surge-tank inventory. The extrapolated downcomer liquid temperature at 7200 s is ~365 ± 30 K. The most limiting case calculated (defined as resulting in the lowest downcomer liquid temperature) was the remaining base case calculation for which both banks of TBVs (four valves; two on each steam line) failed to reseat. As in the base case detailed in this paper, all the additional failures previously described were included, and a minimum downcomer liquid temperature of ~442 K at 1500 s was predicted. The extrapolated downcomer liquid temperature at 7200 s was ~350 ± 30 K.

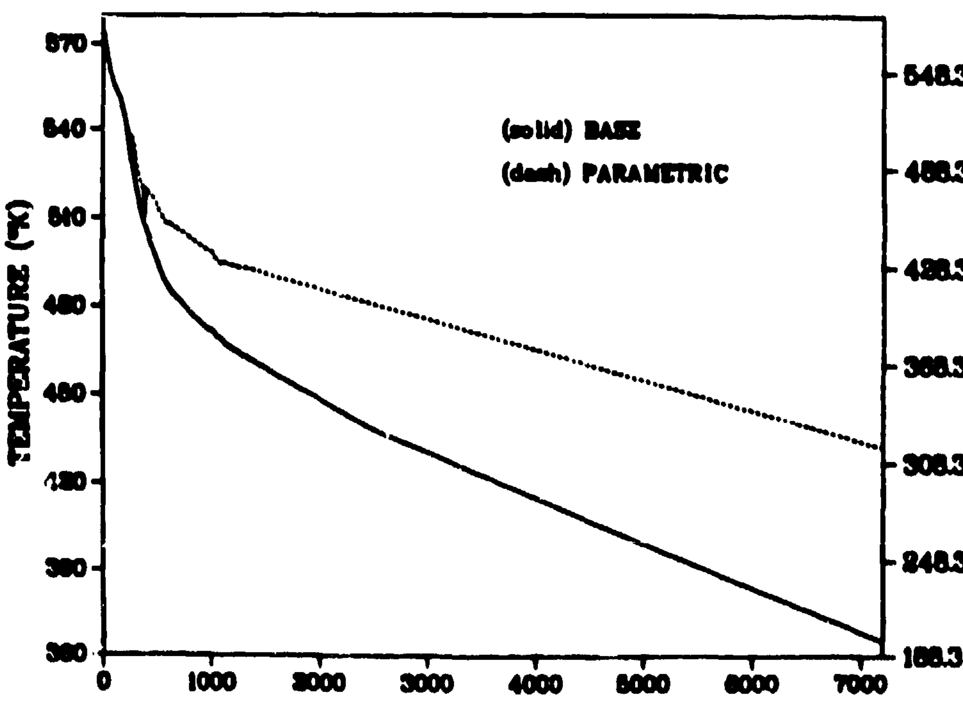

Fig. 11. Minimum downcomer liquid temperatures following failure of a single TBV train to reseat.

CONCLUSIONS

The Los Alamos contribution to the overall PTS program is to provide detailed thermal-hydraulic conditions for input to ORNL stress-analysis calculations. Using TRAC-PF1, several severe overcooling transients for both the Oconee-1 and Calvert Cliffs-1 nuclear plants have been performed. These calculations are being used to resolve this important NRC safety question.

As an example of one of the most severe overcooling transients calculated by TRAC-PF1, the overcooling of the primary side of the Oconee-1 plant caused by a full double-ended steam-line break in one of the steam lines was simulated. The main forcing function for the overcooling was the delay by the operator in isolating the affected steam generator coupled with a delay in throttling the HPI flow. The case analyzed had all plant protection and control systems operate as designed. The minimum downcomer fluid temperature calculated was ~405 K, very close to the NDT limit (~365 K) for Oconee-1. Repressurization of the primary system to the PORV setpoint was calculated following an initial depressurization to ~3.5 MPa.

As another example of an overcooling transient having a very low probability of occurrence because of no operator intervention, the failure of one bank of TBVs to close after initially opening was investigated. An extrapolated downcomer fluid temperature of ~365 K was estimated for this transient which is at the NDT limit for Oconee-1.

These calculations hopefully have provided some insight into the primary system thermal-hydraulic behavior during postulated severe overcooling transients. These thermal-hydraulic calculations coupled with stress-analysis calculations will form the basis for assessing PTS risk at Oconee-1 and Calvert Cliffs-1.

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