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TRAC LARGE-BREAK LOSS-OF-COOLANT ACCIDENT ANALYSIS FOR THE AP600 DESIGN*

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ABSTRACT

A TRAC model of the Westinghouse AP600 advanced reactor design has been developed for analyzing large-break loss-of-coolant accident (LBLOCA) transients. A preliminary LBLOCA calculation of a 80% cold-leg break has been performed with TRAC-PF1/MOD2. The 80% break size was calculated by Westinghouse to be the most severe large-break size. The LBLOCA transient was calculated to 92 s. Peak clad temperatures (PCT) were well below the Appendix K limit of 1478 K (2200°F). Transient event times and PCT for the TRAC calculation were in reasonable agreement with those calculated by Westinghouse using their WCOBRA/TRAC code.

I. INTRODUCTION

The AP600 is an advanced passive 600 MWe reactor design being developed by Westinghouse in conjunction with the US Department of Energy Advanced Light Water Reactor Technology Program. The AP600 has been submitted for NRC design certification. In accordance with 10CFR52.47 for design certification, advanced reactor applicants are required to submit neutronic and thermal-hydraulic safety analyses over a sufficient range of normal operation, transient conditions and specified accident sequences. Review and confirmation of these analyses for the AP600 design constitute an important activity in the NRC's review for design certification. In the process of design certification, the NRC will use best-estimate thermal-hydraulic codes to perform audit calculations. The best-estimate code selected by the NRC for analyzing large-break loss-of-coolant accident (LBLOCA) transients is TRAC-PF1/MOD2,[1] developed by Los Alamos National Laboratory. Los Alamos was requested by the NRC to perform LBLOCA analyses with TRAC in support of the design certification review of the AP600.

The AP600 is a two-loop design with one hot leg, one steam generator, two reactor coolant pumps, and two cold legs in each loop. A pressurizer is attached to one of the hot legs. The reactor coolant pumps are a canned-motor design and are attached directly to the steam generator. The loop seal is eliminated with this design, an added safety feature in that core uncovery due to water-filled loop seals is eliminated during a postulated small-break LOCA The core is a low-power-density core consisting of 145 fuel assemblies with an active fuel length of 12 ft. The fuel assembly is a 17×17 array of fuel and control rods.

The AP600 incorporates totally passive safety systems that rely only on redundant/fail-safe valving, gravity, natural circulation, and compressed gas. There are no pumps, diesel, or other active machinery in these safety systems. During plant shutdown, all the passive safety features will be tested to demonstrate system readiness, flow, and heat removal performance. Two passive safety injection system (PSIS) trains, each with an accumulator and a core makeup tank (CMT), are connected directly to the reactor-vessel downcomer. After the accumulators and core makeup tanks are depleted, water injection is provided from an in-containment refueling water storage tank (IRWST). Long-term non-LOCA heat removal is provided by a passive residual heat removal heat exchanger (PRHR HX) that removes core heat through natural circulation. The IRWST provides the heat sink for the PRHR HX. The IRWST water volume is sufficient to remove decay heat for two hours. Additional safety systems include an automatic depressurization system (ADS) that permits a controlled pressure reduction of the reactor coolant system.

II. TRAC MODEL DESCRIPTION

The TRAC model of the AP600 is a finely noded, multidimensional model with 157 hydrodynamic components (over 1400 computational fluid cells) and 46

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heat-structure components in the model. The plant model is currently undergoing an independent quality-assurance check. The analysis presented herein was performed before the QA check so it should be treated as preliminary and subject to change.

The reactor vessel is modeled in three-dimensional cylindrical coordinates, with four radial rings, eight azimuthal sectors, and 17 axial levels. An isometric view of the reactor vessel model is shown in Fig. 1. Two TRAC vessel components are needed to model the reactor vessel in order to preserve the elevations of the hot-leg, cold-leg, and PSIS connections to the vessel. Otherwise, there would have to be a compromise on modeling the vessel true geometry. The first vessel component models the lower plenum, core, upper plenum, and upper head. The core region is modeled with the first two radial rings. The third radial ring models the reflector region. The fourth radial ring is used in the lower plenum and in the upper head but in the axial levels modeling the core and upper plenum it is not used. The second vessel component is used to model the downcomer annulus and is noded into two radial rings, eight azimuthal sectors, and 13 axial levels. Radial ring 1 is not used at all. Where possible, the same axial level noding heights are used in both vessel components. The two vessel components are connected together by short one-dimensional pipe components. Fuel-assembly guide-tube flow, upper-head cooling spray flow, and core bypass flow are modeled with one-dimensional pipe components.

A total of 31 TRAC heat structures components are needed to model the core and reactor vessel structure as shown in Fig. 2. The fuel rods are modeled with one powered heat structure. The fuel rods are combined and modeled as 16 lumped assemblies each with the same number of fuel rods. Supplemental hot-rod components are also modeled that represent the maximum-power fuel rods. The core decay power is calculated using reactivity feedback coefficients. Control-rod and reactivity feedback coefficients are from a 15×15-fuel large-break US/Japanese PWR model[2] since we did have not sufficient reactivity information for the AP600 design. Outer heat-structure surfaces are treated adiabatically. There is heat conduction between the downcomer annulus and the core region.

Figure 3 shows a modeling overview of reactor coolant loop 1, which is modeled with 33 hydro components and 181 1-D computational cells. Loop 2 has 34 components and 166 1-D cells, and is similar in noding to loop 1 except that there is no pressurizer and instead of pressurizer spray sources, core makeup tank pressure balance lines connect to the cold legs. There is also no PRHRS connection to the steam generator outlet plenum. Loop 2 also models the broken cold leg, which is modeled with a series of tee and valve components that allows for a more mechanistic modeling of a large break. The steam generator model reflects the AP600 Δ75 design, which is similar to the current Westinghouse Model F design but has a taller tube bundle and redesigned secondary-side risers and separators. Where specific component design data were not available for the AP600, components from a Westinghouse three-loop plant were used, such as the feedwater and steam lines and control systems. All external piping wall structure is modeled and an outer adiabatic boundary is assumed. In addition to the reactor coolant system, all major components of the passive safety systems are also modeled.

Figure 4 shows a modeling overview of the PSIS, ADS, PRHRS, and IRWST. Over 69 1-D hydro components (309 1-D cells) and one 3-D hydro component (135 3-D cells) are used to model the AP600 safety systems. There are two separate trains in each of the PSIS, ADS, and PRHRS, and each of the trains are modeled separately. Another vessel component is used to model the IRWST in anticipation that IRWST temperatures may vary spatially from PRHR HX and ADS heat rejection. The capability of TRAC to model IRWST temperature stratification and pluming will need to be assessed. The TRAC LBLOCA plant model includes only the accumulators, CMTs, CMT pressure balance lines, and injection lines, as these are the only safety components activated in the first few minutes of a LBLOCA transient. An intermediate-break plant model of the AP600 is also being developed that will include the rest of the safety systems. Figure 5 shows a plan view of the RCS, ADS, and PSIS. The break location is in cold leg 2b next to the reactor vessel as noted.

III. LBLOCA CALCULATION

A LBLOCA calculation was performed assuming an 80% double-ended guillotine break in a cold leg next to the reactor vessel. The analysis was performed with version 5.4 of TRAC-PF1/MOD2. TRAC-PF1/MOD2 is the latest TRAC version to be developed by Los Alamos National Laboratory for the NRC. Initial steady-state power was 100% and a break opening time of 0.1 s was assumed. A constant containment pressure of one atmosphere was assumed for the break boundary pressure. Pressurizer spray, heater controls, and makeup/letdown flow were nulled at the start of the transient. RC pump trip was assumed 15 s after the "S" signal, the safety injection trip signal. The LBLOCA was calculated out to 92 s, well into the reflood phase and by which time fuel rod cladding temperatures were decreasing.

The transient thermal-hydraulic behavior can be characterized in four major phases:

(1) Early blowdown, 0 to 10 s. During this phase, there is a very rapid system depressurization and a high rate of reactor coolant flow out the break. The core region becomes almost completely voided in about 2 s, and by 10 s, the core, upper plenum, and upper head regions are over 90% voided. The rapid loss of coolant causes fuel cladding temperatures to increase rapidly. Fuel clad temperatures reach a maximum at about 6 s and then decrease slightly from an increase in cooling. The increased cooling comes from a decrease in net mass-flow loss out of the reactor vessel caused by two-phase flow occurring at the break exits. This phenomena will be discussed in more detail when calculation results are presented.

(2) Late blowdown, 10 to 30 s. The system pressure has decreased to a level where the gas-pressurized accumulators can start discharging. The vessel net mass-flow loss starts to decrease and by 30 s, there is a net mass-flow gain, with more flow entering the vessel than is leaving. Fuel clad temperatures, however, increase gradually as the core, upper plenum, and upper head regions continue to void and core cooling becomes less effective.

(3) Refill, 30 to 45 s. The system has stopped depressurizing. The break flow is essentially all vapor. The lower plenum starts to refill from accumulator flow injection. Fuel temperatures continue to increase.

(4) Reflood, 45 to 200 s. The lower plenum has refilled and core reflood and quenching begins. The quenching and rewetting of the lower parts of the core generate higher vapor mass flows up through the core, which results in an increase in upper core cooling. Eventually, the fuel clad temperatures reaches a maximum and then start decreasing. The accumulators continue to inject until depleted of liquid. After the accumulators have emptied and depressurized, the core makeup tanks start to inject. When the core makeup tanks are empty, the IRWST drain lines are opened allowing flow injection from the IRWST. The TRAC calculation was terminated at 92 s, well before the accumulators are empty. At 92 s, the accumulators still contain half of their initial liquid volume.

Table I shows the sequence of events for the calculated transient. Figure 6 shows the calculated hot-rod and average-rod PCT. During the blowdown phase, PCT of 802 K (983°F) and 1053 K (1436°F) are calculated for the average rod and hot rod, respectively. In the reflood phase, both rods show a higher PCT than in the blowdown phase. For the average rod, the reflood PCT was 848 K (1067°F), and for the hot rod, the reflood PCT was 1210 K (1718°F). The calculated hot-rod PCT are well below the Appendix K limit of 1478 K (2200°F).

Calculation results for the blowdown phase are shown next. Figure 7 shows system pressures. Figure 8 shows vessel liquid volume fractions for the lower plenum, core, upper plenum, upper head, and downcomer. Figure 9 shows vessel mass flows, the total mass flow leaving the vessel, the total mass flow entering the vessel, and the net mass-flow loss (flow out - flow in). From about 1 s to 5 s, there is a reduction in net mass-flow loss due to an increase in mass flow entering the vessel. The increase in mass flow entering the vessel is because of two-phase flow occurring at the break exit, which reduces the mass flow out the break. This forced the flow in loop 1 to shift from the broken cold leg to the intact cold leg, thereby increasing the mass flow entering the vessel. The increase in mass flow entering the vessel reduced the mass flow leaving the core, which then improved core cooling bringing about a decrease in fuel rod temperatures. Peak clad temperatures decreased to 759 K (906°F) for the average rod and to 996 K (1333°F) before heating up again.

Figure 10 shows the CMT and accumulator mass flows for the total calculated transient. The CMT flows between 0 and 15 s are very low and different in the two trains. The reason for the low- or zero-flow delivery is because of the pressure balance line between the CMT and the cold leg. The cold-leg pressure-balance line serves to bypass any flow coming from the pressurizer and also decreases the pressure at the top of the CMT, such that there isn't sufficient pressure to open or keep open the CMT injection check valve. The different behavior in the two CMTs is due to the pressure at the top of each CMT. The top of CMT A is connected to intact cold leg 2a and therefore senses a higher pressure than the top of CMT B, which is connected to the broken cold leg 2b and, therefore, has a much lower pressure. The difference in pressure between the intact cold leg and broken cold leg can be seen in Fig. 7. In the late-blowdown phase, there is sufficient pressure differential to open the CMT check valves. However, CMT flow delivery does not last long, as the pressure in the PSIS discharge line increase from accumulator flow delivery, thereby closing the CMT check valves.

Figure 11 shows vessel liquid volume fractions for the total calculated transient. High flow oscillations occur in the reflood phase between the core and downcomer. Figure 12 shows average-power rod clad temperatures at selected rod elevations. The rod temperatures shown are for the sector cell in the inner radial ring at the azimuthal sector of the broken cold leg.

IV. COMPARISON WITH WCOBRA/TRAC RESULTS

The TRAC calculation results were compared to the Westinghouse WCOBRA/TRAC results presented in the AP600 Standard Safety Analysis Report.[3] Table II presents a summary comparison of the TRAC and WCOBRA/TRAC results for transient event times and selected calculated parameters The comparison shows reasonable agreement between the two calculations. The TRAC accumulator flows were higher than the WCOBRA/TRAC flows so refill and reflood event times are earlier than WCOBRA/TRAC event times. We did not have time to compare results in a more detailed and graphical form. There are differences in plant modeling assumptions that will be corrected for the QA plant model. The significant similarity is in the calculation of the hot-rod PCT. Both the TRAC and WCOBRA/TRAC calculations show the reflood PCT to be higher than the blowdown PCT.

A major difference in calculation results is in the cooling of average-powered rods during the late-blowdown phase. The WCOBRA/TRAC calculation showed a rewetting and quenching of average-powered rods during the late-blowdown phase, with average-rod clad temperatures being cooled down to saturation-temperature levels. The rods reheated during the reflood phase but results were not presented beyond 36 s of the transient. The TRAC calculation showed rewetting only in the cooler sections of the fuel rods as can be seen in Fig. 12.

V. SUMMARY

A TRAC model of the Westinghouse AP600 advanced reactor design has been developed and used to calculate a preliminary 80% DEGB cold-leg LBLOCA. Hot-rod PCT of 1053 K (1436°F) and 1210 K (1718°F) were calculated for the blowdown and reflood phases, respectively. Results from this calculation are in reasonable agreement with the same break size LBLOCA calculated by Westinghouse with WCOBRA/TRAC. The calculation was performed with a plant model that had not yet been subject to an independent quality assurance check. The 80% DEGB LBLOCA calculation will be repeated with a QA plant model. Other LBLOCA sensitivity calculations will also be performed.

REFERENCES

1. J. C. Lin, et. al., "TRAC-PF1/MOD2 Code Manual," Volumes 1-4, Los Alamos National Laboratory report LA-12031-M, NUREG/CR-5673 (in press).

2. P. R. Shire and J. W. Spore, "TRAC-PF1/MOD1 Analysis of a Minimum-Safeguards Large-Break LOCA in a US/Japanese PWR with Four Loops and 15x15 Fuel," Los Alamos National Laboratory report LA-2D/3D-TN-86-18 (December 1986).

3. Westinghouse Electric Corporation, "AP600 Standard Safety Analysis Report," prepared for the US Department of Energy, Document No. DE-AC03-90SF18495, Revision 0 (June 26, 1992).

Table I. LBLOCA Sequence of Events

Time (s)	Event
0 s	Break occurs.
0.1 s	Break fully developed (80% DEGB).
0.13 s	Reactor trip signal on low RC flow.
1.7 s	"S" signal. CMT isolation valves start to open. CMT check valves also start to open allowing CMT flow injection. Steam generator feedwater flow trip.
4.4 s	CMT-B check valve closes completely and remains closed until 16 s.
5.6 s	Maximum average-rod peak clad temperature during blowdown: 802 K (983°F).
5.8 s	Maximum hot-rod peak clad temperature during blowdown: 1053 K (1436°F).
8 s	Pressurizer empties.
12 s	Accumulators start to inject.
13 s	CMT-A check valve closes completely and remains closed until 16.3 s.
15 s	RC pumps tripped.
16.3 s	CMT-A check valve opens and then closes at 28 s, and remains closed for rest of transient.
16.7 s	RC pumps tripped.
17.2 s	CMT-B check valve opens and then closes at 27 s and remains closed for rest of transient.
31 s	Lower plenum starts to refill.
45 s	Core reflood begins.
58 s	Maximum average-rod peak clad temperature during reflood: 848 K (1067°F).
58 s	Maximum hot-rod peak clad temperature during reflood: 1210 K (1718°F).
92 s	Calculation terminated.

Table II. Comparison to WCOBRA/TRAC 80% DEGB LOCA

	TRAC	WCOBRA/TRAC
Reactor trip	0.13 s	<1 s
"S" signal (CMT valves start to open)	1.7 s	2.2 s
Pressurizer empties	8 s	7 s
Accumulators start to inject	12 s	12 s
RCP trip	16.7 s	17.2 s
Max. accumulator flow	370 kg/s (815 lb/s)	331 kg/s (730 lb/s)
Lower plenum starts to refill	31 s	34 s
Average-rod PCT during blowdown	802 K (983°F)	850 K (1070°F)
Hot-rod PCT during blowdown	1053 K (1436°F)	1073 K (1472°F)
Core reflood begins	45 s	56 s
Average-rod PCT during reflood	848 K (1067°F)	Not available[1]
Hot-rod PCT during reflood	1210 K (1718°F)	1125 K (1565°F)[2]
Time that hot-rod PCT occurs	58 s	102 s

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[1] Average-rod PCTs were shown only for the first 36 s of the transient.

[2] With code uncertainty included, the WCOBRA/TRAC PCT is cited to be 1254 K (1798°F)

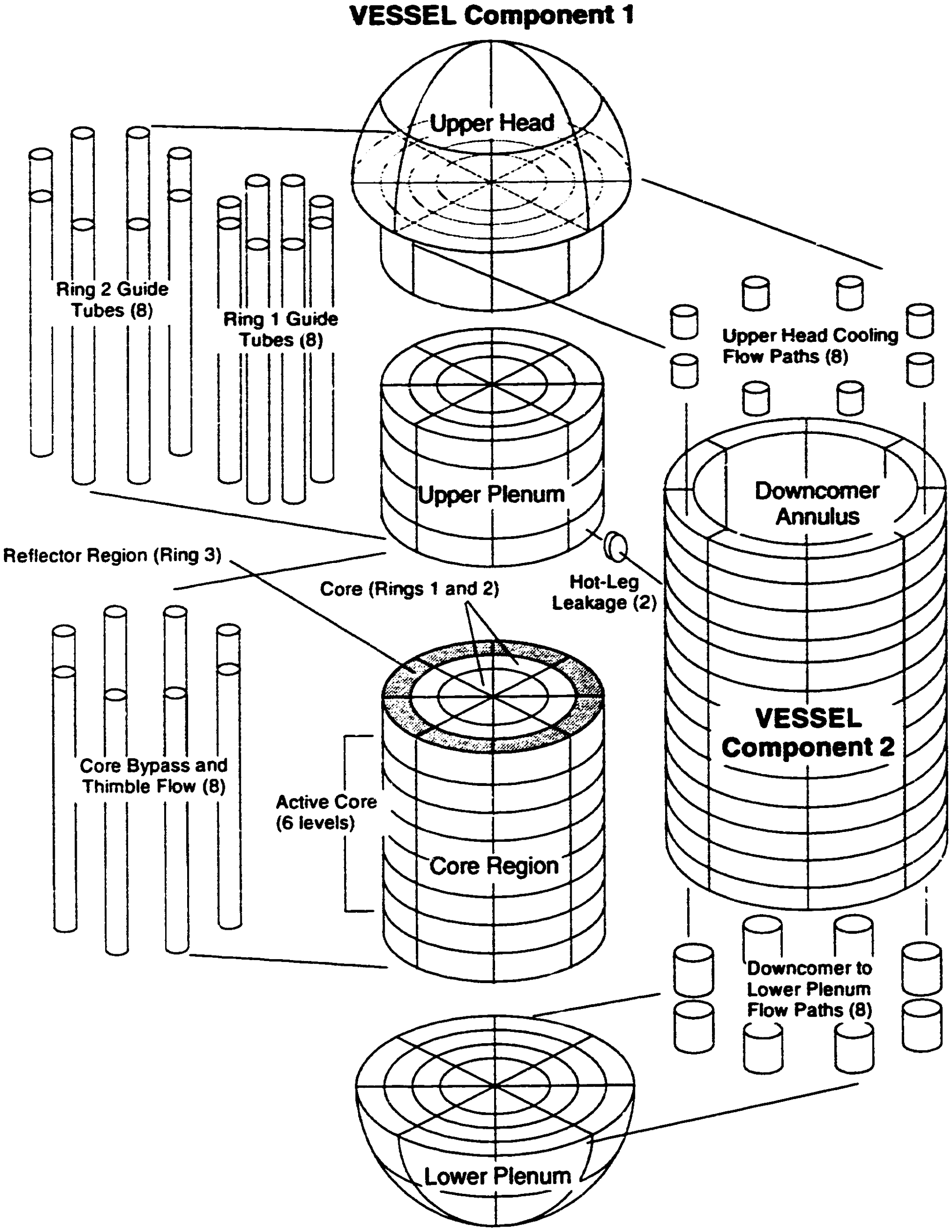


Fig. 1. Isometric view of reactor vessel model.

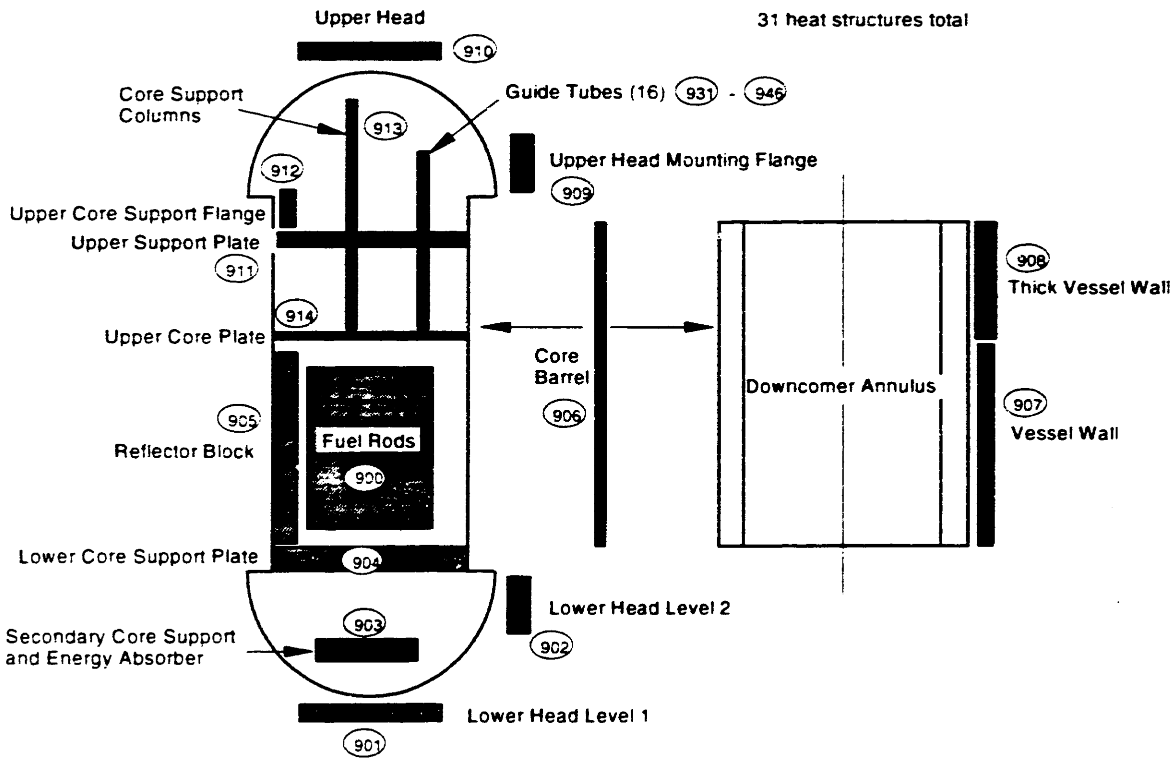


Fig. 2. Reactor vessel heat structure modeling.

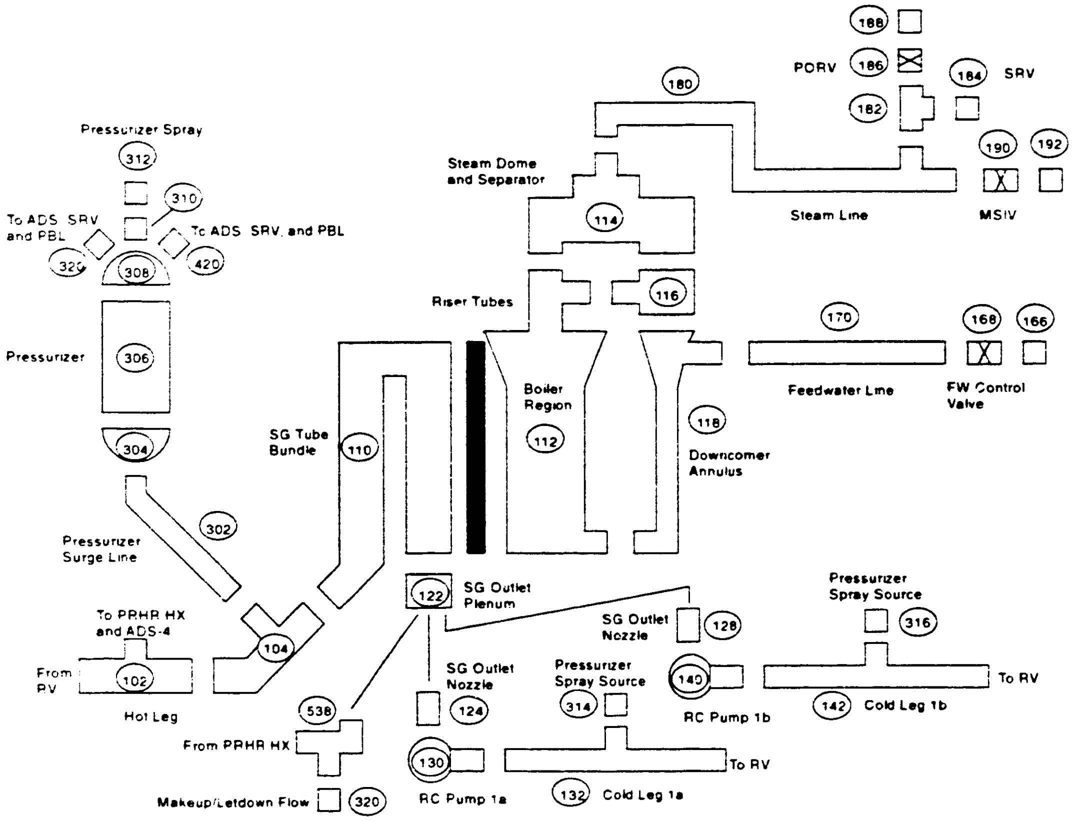
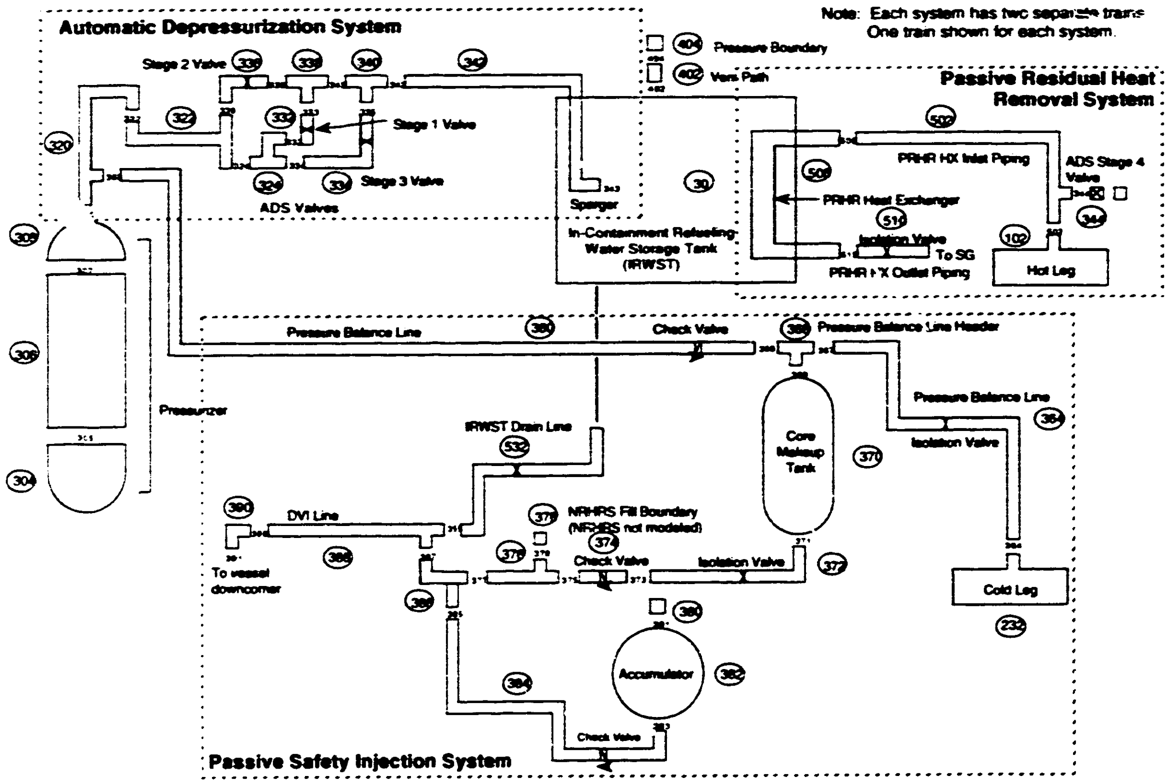


Fig. 3. Reactor coolant loop 1 modeling.



Note: Each system has two separate trains
One train shown for each system.

Fig. 4. AP600 safety systems modeling.

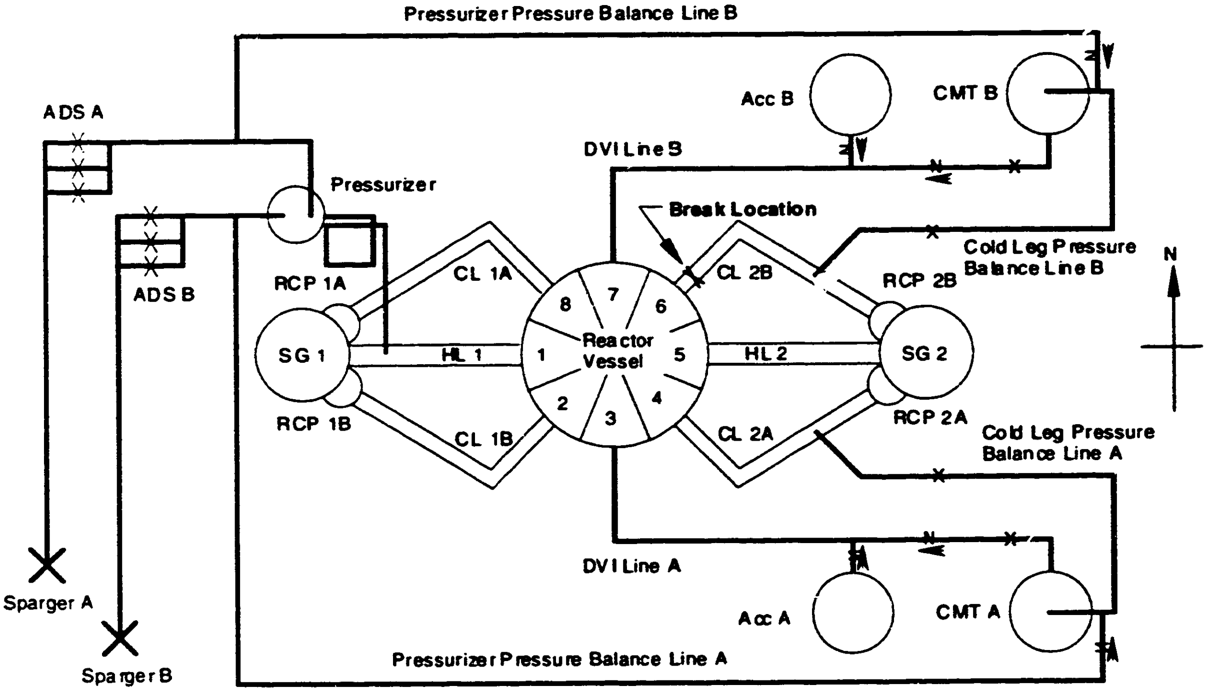


Fig. 5. Plan view of RCS, ADS, and PSIS.

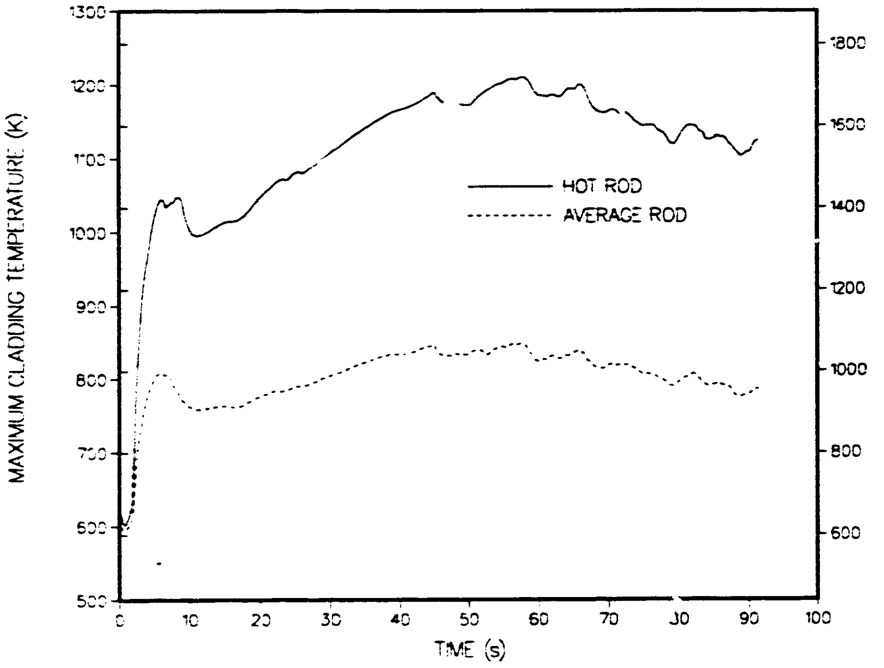


Fig. 6. Fuel-rod maximum cladding temperatures.

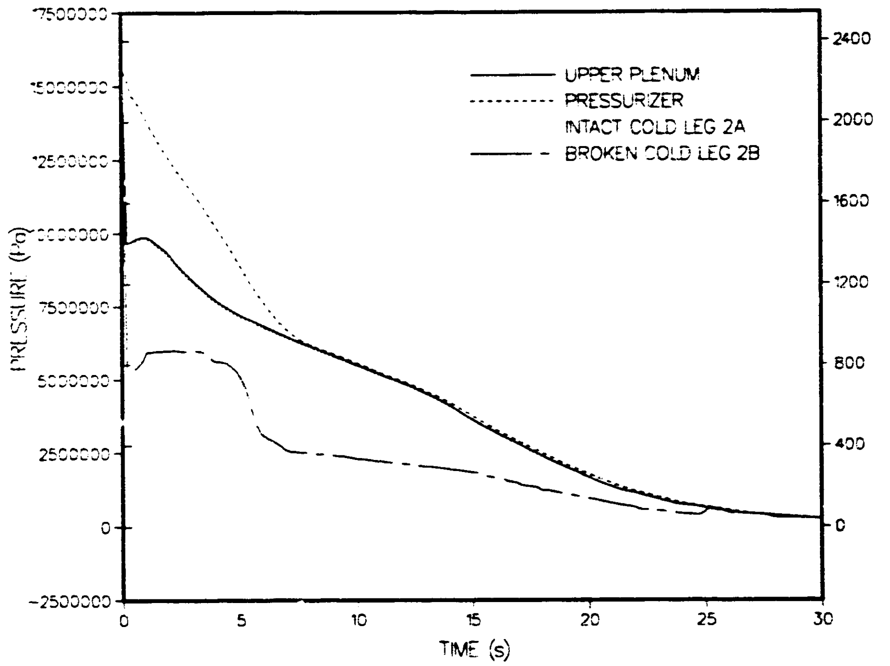


Fig. 7. Reactor coolant system pressures in blowdown phase.

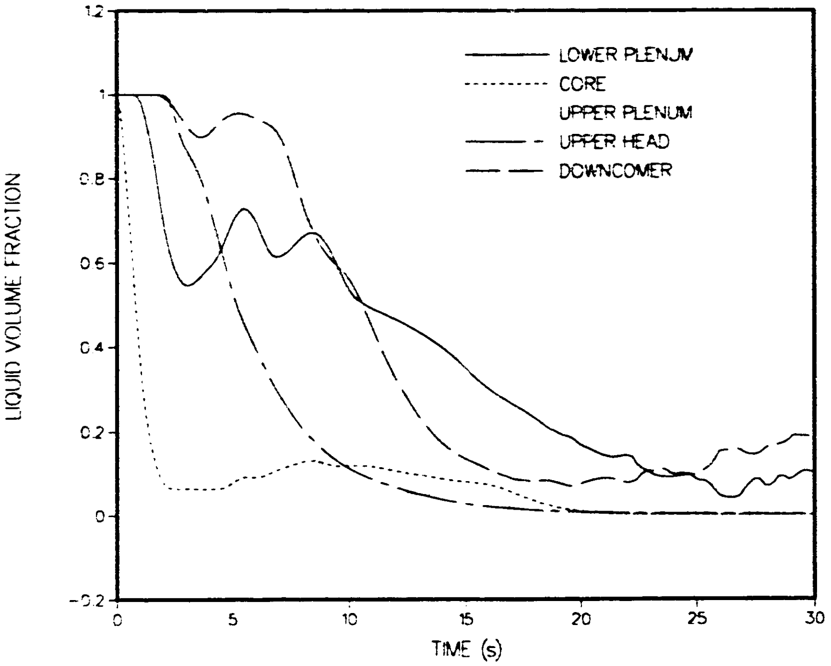


Fig. 8. Vessel liquid volume fractions in blowdown phase.

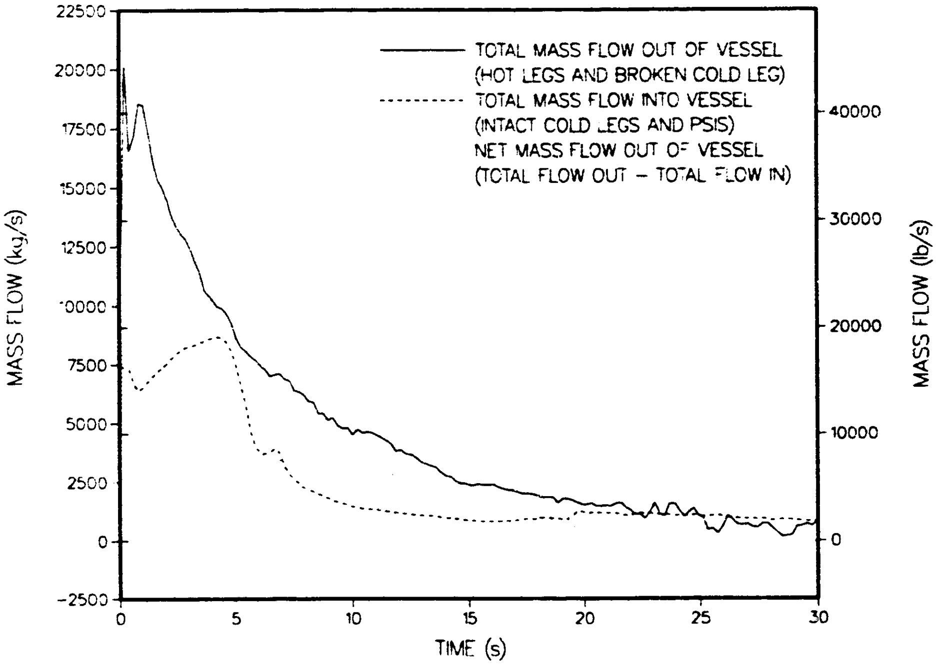


Fig. 9. Vessel mass flows in blowdown phase.

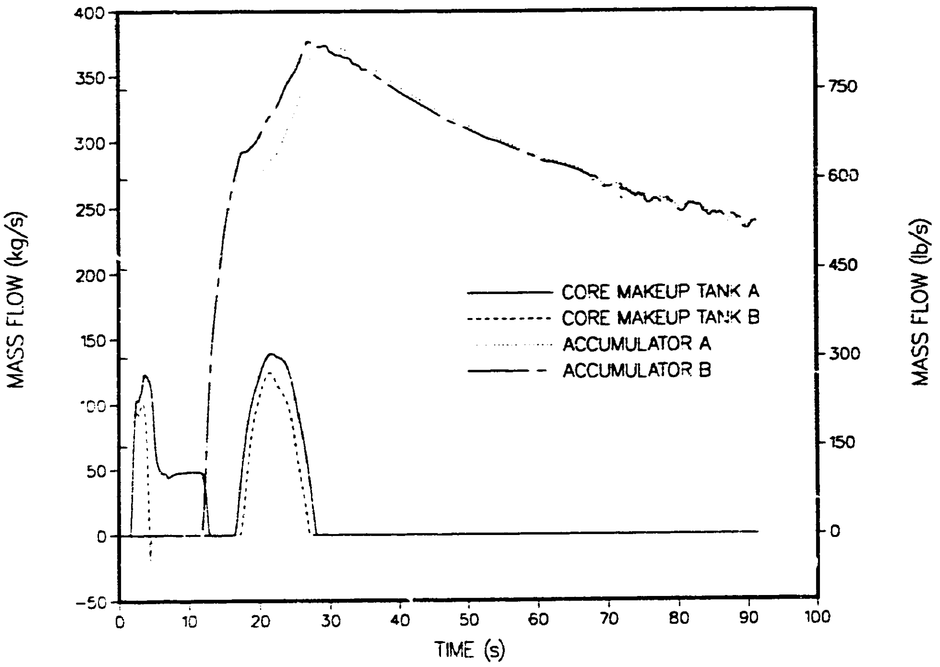


Fig. 10. CMT and accumulator mass flows.

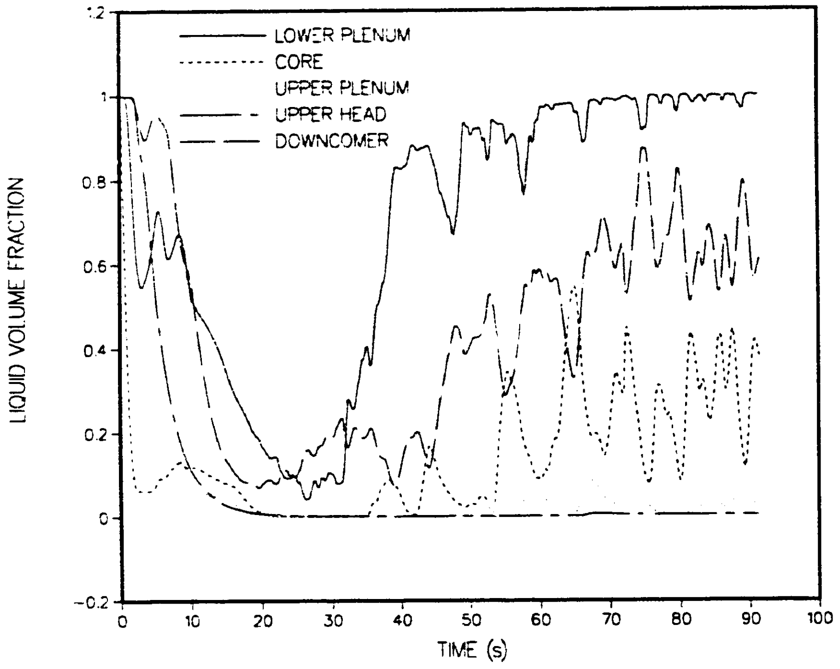


Fig. 11. Vessel liquid volume fractions for total calculated transient..

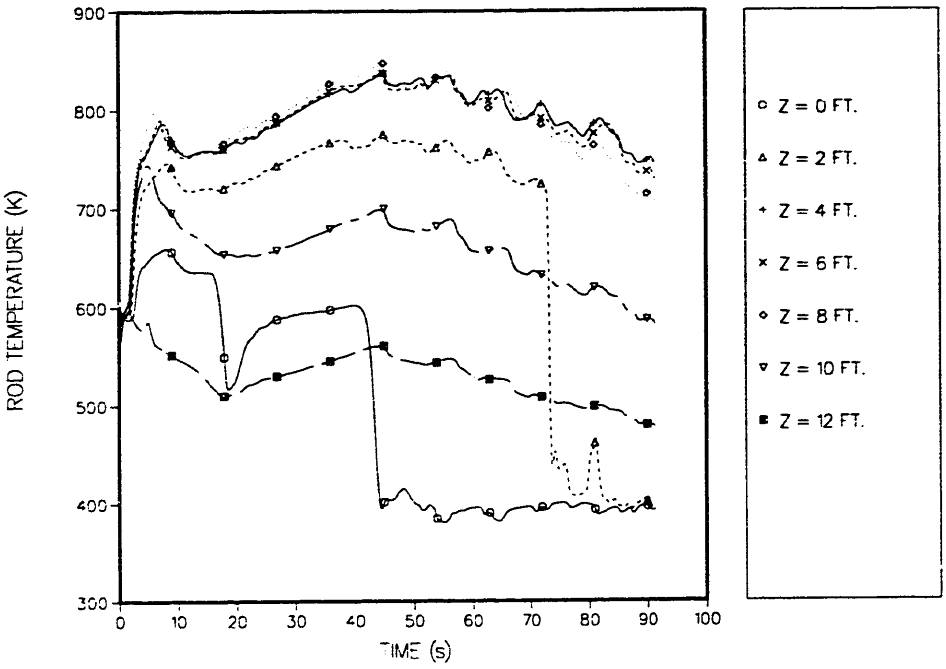


Fig. 12. Average-power rod cladding temperatures.

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