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TITLE COOLDOWN TO RESIDUAL HEAT REMOVAL ENTRY CONDITIONS USING ATMOSPHERIC DUMP VALVES AND AUXILIARY PRESSURIZER SPRAY FOLLOWING A LOSS-OF-OFFSITE POWER AT CALVERT CLIFFS - UNIT 1

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ACRONYMS

ADV	Atmospheric dump valve
AFAS	Auxiliary feedwater actuation signal
AFW	Auxiliary feedwater
APS	Auxiliary pressurizer spray
BG&E	Baltimore Gas & Electric
C-E	Combustion Engineering
CST	Condensate storage tank
CEA	Control element assembly
EOP	Emergency operating procedure
HPI	High-pressure injection
LOSP	Loss-of-offsite power
LPI	Low-pressure injection
MFBV	Main-feedwater bypass valves
MFRV	Main-feedwater relief valve
MFW	Main feedwater
MSIV	Main-steam isolation valve
NRC	Nuclear Regulatory Commission
PORV	Power-operated relief valve
PWR	Pressurized water reactor
RCP	Reactor coolant pump
RHR	Residual heat removal

RWST	Refueling water storage tank
SC	Steam generator
SGIS	Steam-generator isolation signal
SI	Safety injection
SIAS	Safety-injection actuation signal
SIT	Safety-injection tank
SRV	Safety relief valve
TAP	Task Action Plan
TBV	Turbine bypass valve
TRAC	Transient Reactor Analysis Code
TSV	Turbine stop valve
USI	Unresolved safety issue

COOLDOWN TO RESIDUAL HEAT REMOVAL ENTRY CONDITIONS USING ATMOSPHERIC DUMP VALVES AND AUXILIARY PRESSURIZER SPRAY FOLLOWING A LOSS-OF-OFFSITE POWER AT CALVERT CLIFFS - UNIT 1

by

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ABSTRACT

An investigation of cooldown using atmospheric dump valves (ADVs) and auxiliary pressurizer spray (APS) following loss-of-offsite power at Calvert Cliffs-1 showed residual heat removal entry conditions could not be reached with the plant ADVs alone. Use of APS with the plant ADVs enhanced depressurization, but still provided insufficient cooldown. Effective cooldown and depressurization was shown to occur when rated steady state flow through the ADVs was increased by a factor of four.

EXECUTIVE SUMMARY

An investigation of cooldown using atmospheric dump valves (ADV) and auxiliary pressurizer spray (APS) following loss-of-offsite power (LOSP) at Calvert Cliffs-1 showed residual heat removal (RHR) entry conditions could not be reached with the plant ADVs alone.

Preliminary analysis showed that initial cooldown was more than sufficient using current plant valves. In fact, initial ADV flow had to be throttled considerably to limit the cooldown rate. However, extended calculations showed that even though cooldown continued, primary pressure failed to decline. This may be a "compression effect" as liquid pumped into the primary coolant by make-up flow compressed vapor in the pressurizer. Make-up flow started in response to low pressurizer liquid level, and unmodulated, caused the pressurizer level to rise after initial system liquid contraction. The rising liquid interface, like a piston, compressed the pressurizer vapor. Once normal pressurizer level was reached, make-up continued, maintaining level in response to system shrinkage. This inhibited primary depressurization. Without pressure relief this holdup in depressurization would continue, making RHR entry unlikely. In addition, relatively stagnant conditions in the pressurizer with relatively low heat transfer between liquid and vapor allows the vapor to remain saturated at a high temperature and pressure. Thus, the pressurizer functions much as it would during normal operation and keeps the primary system pressure elevated.

To reduce the primary pressure, operation of the APS was modeled. Although primary pressure reduction was greatly enhanced by this measure, the primary cooldown rate diminished to a level for which entry to RHR temperature was unattainable. ADV sizing became an important issue at this point. The size of the ADVs limited heat removal such that secondary liquid temperature and pressure had reached an equilibrium level at which no further decrease was foreseen. This was explained by considering the mass flows in the steam generators.

As liquid in the steam generator reached the high-level setpoint, auxiliary feedwater (AFW) flow was reduced to maintain steam-generator inventory. At the same time ADV flow responded to both secondary pressure decrease and flow area limitations in such a manner that net ADV outflow was reduced. A combination of reduced ADV outflow and reduced AFW inflow significantly reduced secondary-side heat removal capability. This was because both flows contributed to heat removal; ADV flow by removing steam with high heat content, and AFW flow by injecting cool (300 K) liquid. Valves currently installed at Calvert Cliffs were thus shown to be ineffective using this type of cooldown procedure.

Various larger sizes were studied as possible substitutes for the present valves representing increases in rated steady-state flow from 200% to 500%. The 500% increase was more than sufficient to bring the plant to RHR entry. In fact, 400% increase in rated ADV flow allowed RHR entry within 3 1/2 hours of the initiating event. By contrast, 200% increase in rated flow was insufficient to allow RHR entry, indicating minimum rated valve flow for RHR entry between these two values.

1. INTRODUCTION

The adequacy of shutdown decay heat removal in pressurized water reactors (PWRs) is currently under investigation by the Nuclear Regulatory Commission (NRC). This area has been identified as an unresolved safety issue (USI A-45) and a task action plan (TAP) has been defined to resolve USI A-45. Activities have been defined in TAP A-45 that investigate alternative means of decay heat removal in PWR plants, including but not limited to using existing equipment. Two objectives of TAP A-45 are to evaluate the feasibility of alternative measures for improving decay heat removal systems and assessing the value of the most promising alternative measures.

Previous work at Los Alamos National Laboratory has investigated the value of primary system feed-and-bleed procedures that could be used if the normal cooling mode through the steam generators was unavailable.[1]

In this report we evaluate the feasibility of operator-initiated atmospheric dump valve (ADV) control as a means of providing cooldown and depressurization following a loss-of-offsite power event for a Combustion Engineering (CE) plant. An investigation of the use of auxiliary pressurizer spray (APS) coincident with ADV control is also given. The overall objective was to determine what, if any, combination of these two operator actions could bring the plant to residual heat removal (RHR) entry conditions, 422 K and 2.02 MPa (300 °F and 300 psia), respectively, and how long it would take. In addition, several parametrics involving changes in ADV flow rate were studied to ascertain the effect on primary cooldown and depressurization.

The central issue for this study was whether or not effective operator control of ADVs and APS following a LOSP event could bring the primary liquid to RHR entry. Of equal concern was whether or not sufficient condensate storage tank (CST) inventory would be available to supply AFW during the cooldown to RHR transition period. A recent Nuclear Safety article[2] predicted RHR entry for Calvert Cliffs Unit-1 would occur after about 120 hours. The same article indicated a CST consumption time of 1[illegible] hours. Thus, the ADV valve size was deemed inadequate to provide sufficient cooldown before CST inventory was exhausted.

The study presented in this report was initiated to identify, using deterministic methods, the adequacy of current Calvert Cliffs ADV size and proposed operator cooldown strategies.

The following section describes the plant system. Section III addresses the technical approach followed including a discussion of the calculations performed. The results for both cases and the ADV parametrics are given in Section IV. Conclusions are given in Section V as well as recommendations for additional work.

II. PLANT SYSTEMS DESCRIPTION

Calvert Cliffs-1 is a Combustion Engineering (C-E) PWR operated by Baltimore Gas and Electric Company (BG&E). Design thermal power of the reactor is 2700 MWt. The reactor-coolant system consists of two closed heat-transfer loops. A process flow diagram of the primary system is given in Fig. 1. The reactor coolant is circulated by four vertical, electric-motor-driven, single-bottom-suction, single-stage, horizontal-discharge, centrifugal reactor coolant pumps (RCPs). An electrically-heated pressurizer is connected to one hot-leg loop. Primary overpressure protection is provided by power-operated relief valves (PORVs) and spring-loaded safety relief valves (SRVs) connected to the pressurizer. SRV and PORV discharge is released under water in the quench tank where the steam discharge is condensed. The two steam generators are vertical shell and U-tube units rated at 2.558×10^6 kg/h (5.635×10^6 lb/h) of steam. Steam is generated in the shell side and flows upward through moisture separators. The secondary-coolant system is designed to produce steam at a pressure of 5.9 MPa (850 psia).

The secondary-side feedwater and steam-process-flow diagram is given in Fig. 2. Under normal full-power steady-state operation, condensate is pumped from the hotwells of the three main condensers. The condensate is pumped through a series of low-pressure heaters where extraction steam is used to heat the condensate prior to its entrance into the steam generators (SGs). Following a normal reactor/turbine trip from full power conditions, the main-feedwater regulating valves (MFRVs) will close and the main-feedwater bypass valves (MFBVs) will open to a fixed position corresponding to a 33% stem position.

The main-steam system is controlled by five types of valves: the turbine-stop valves (TSVs), the turbine-bypass valves (TBVs), the main-steam isolation valves (MSIVs), the ADVs and the SRVs. The arrangement of these valves in the steam-supply system is shown in Fig. 2. The TSVs are used to control turbine-inlet pressure and to rapidly close in 0.25 s following a turbine trip. The TBVs are used to control main steam line pressure following a turbine trip. The

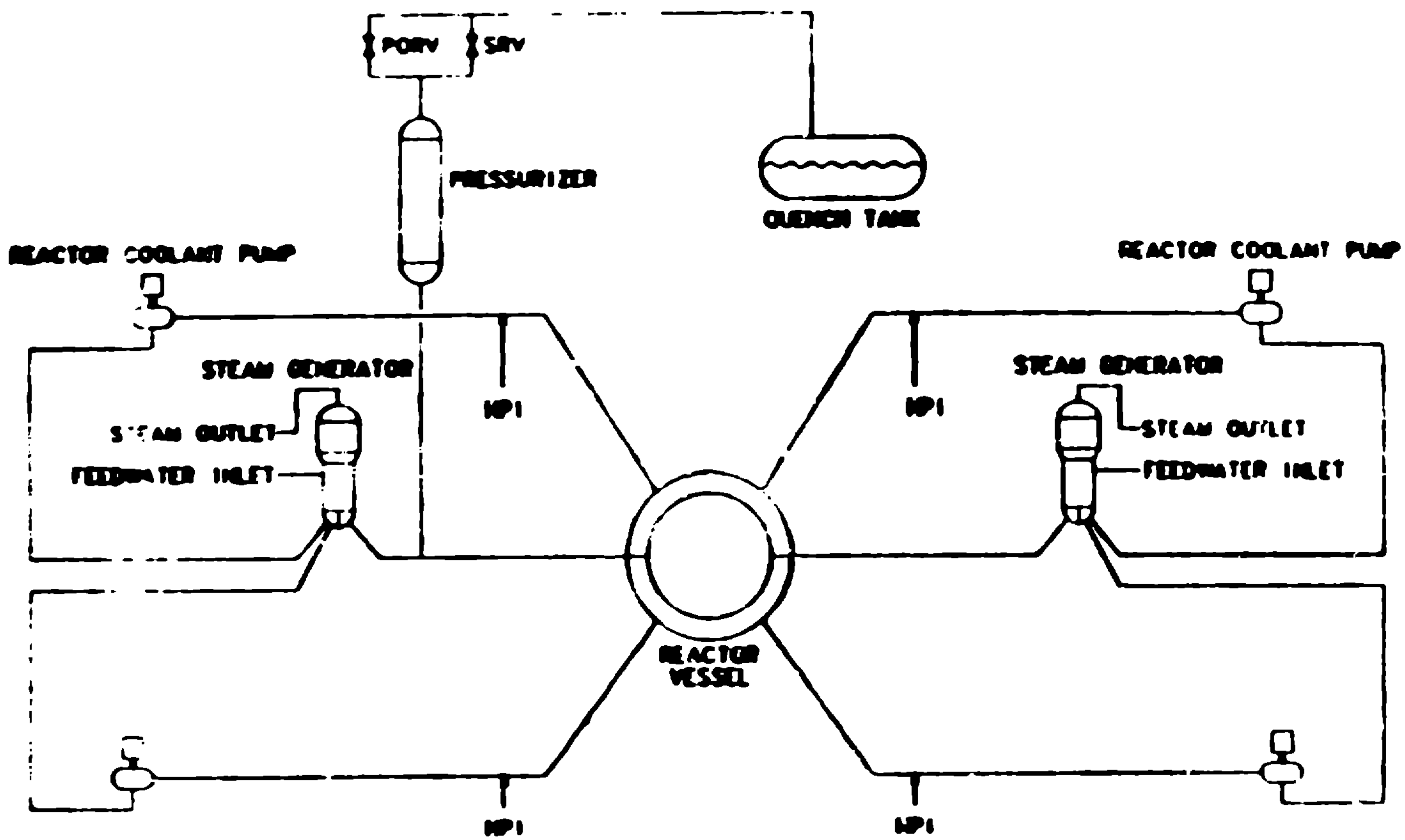

Fig. 1.
Calvert Cliffs-1 reactor-coolant system.

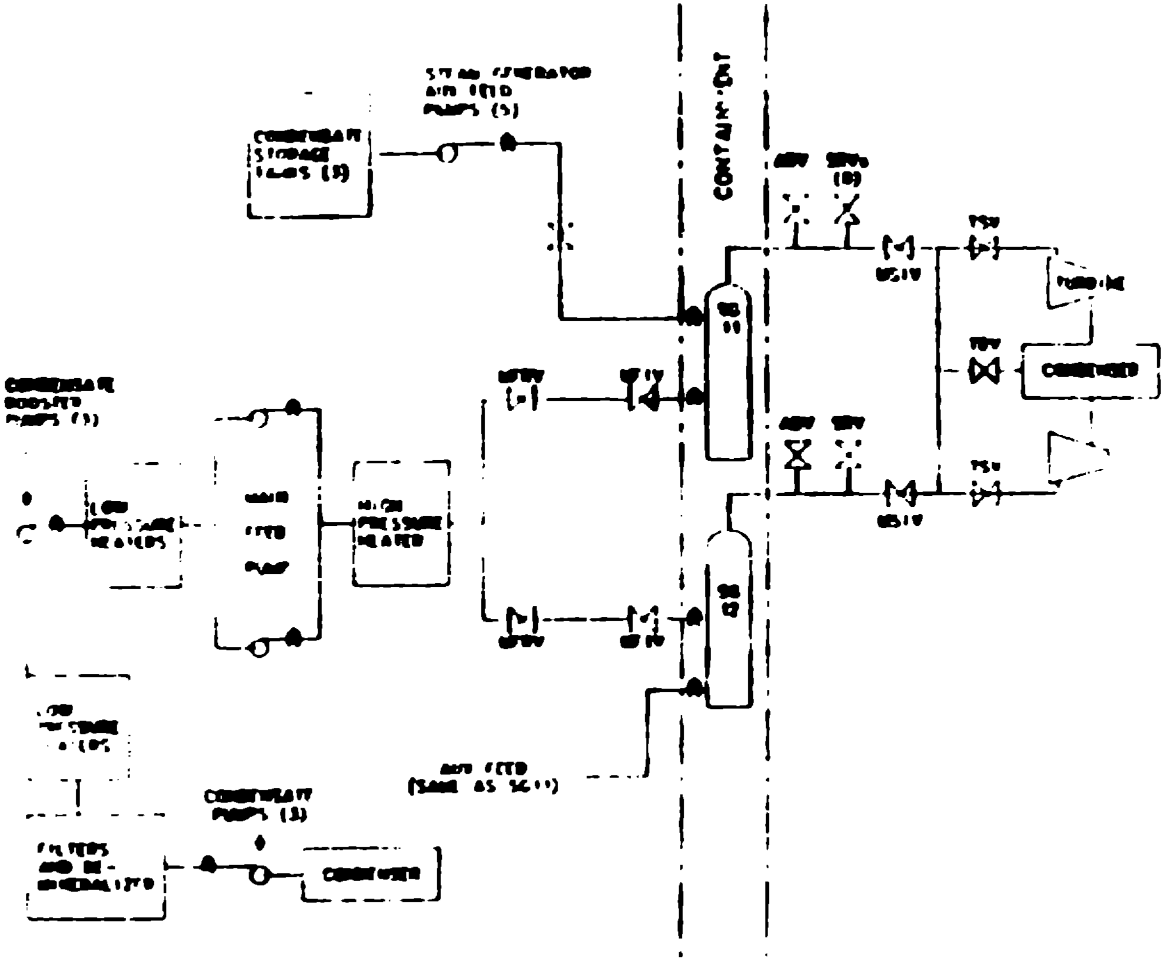

Fig. 2.
Calvert Cliffs secondary-side feedwater and steam-process-flow diagram.

MSIVs are required to close in 3.5 s following a steam-generator isolation signal (SGIS). Upon overpressure conditions, the SRVs begin to open at 6.89 MPa (1000 psia) and are fully open at 7.45 MPa (1080 psia). Each SRV is capable of relieving 763 kg/s (6×10^6 lbm/h) of saturated steam with an upstream pressure of 7.45 MPa (1080 psia). The ADVs are trip-activated and controlled by the average reactor temperature. They are designed to open following a reactor turbine trip when the average reactor temperature exceeds 552 K (535 °F).

A process diagram of the primary make-up and letdown system is given in Fig. 3. During steady state, makeup/letdown (charging) flow is injected or withdrawn to maintain a specified level in the pressurizer. If the pressurizer level drops more than 0.23 m (9 in.) below its setpoint, the charging flow is injected at a constant flow rate of 3.2 kg/s (7.0 lb/s) into one cold leg of each loop. If a safety-injection actuation signal (SIAS) occurs during the transient, charging flow is increased to a constant rate of 8.2 kg/s (18 lbm/s), independent of primary system pressure. These positive displacement pumps draw water from either the volume control tank or the boric acid storage tanks. Letdown water flows through a regenerative heat exchanger, a letdown heat exchanger for further cooling, and then undergoes a cleanup and discharges to the volume control tank.

The Calvert Cliffs-1 safety injection (SI) system includes high-pressure injection (HPI) and low-pressure injection (LPI) capability as well as charging flow and safety injection tanks (SITs) of accumulation. The SI system is initiated when either the pressurizer pressure drops below 12 MPa (1740 psi) or the containment pressure rises above 0.028 MPa (4 psig). The HPI and LPI process flow diagram is given in Fig. 4. Upon SI initiation, both the LPI and HPI pumps are started. The HPI centrifugal pumps have a shutoff head of 8.8 MPa (1275 psia). Above this pressure, only charging flow is possible. Four SITs are provided, each connected to one of the four reactor-inlet lines. Each tank has a volume of 56.6 m^3 (2000 ft^3) of borated water at refueling concentration and 28.3 m^3 (1000 ft^3) of nitrogen at [illegible] MPa ([illegible] psig). In the event of a large loss of coolant accident, the borated water is forced into the primary system by the expansion of the nitrogen. The water from three tanks adequately cools the entire core. Borated water is also injected into the primary system by two LPI and up to three HPI pumps taking suction from the refueling water storage tank. Only two of the three HPI pumps are automatically started upon receipt of a SIAS. For reliability, the design capacity from the [illegible]

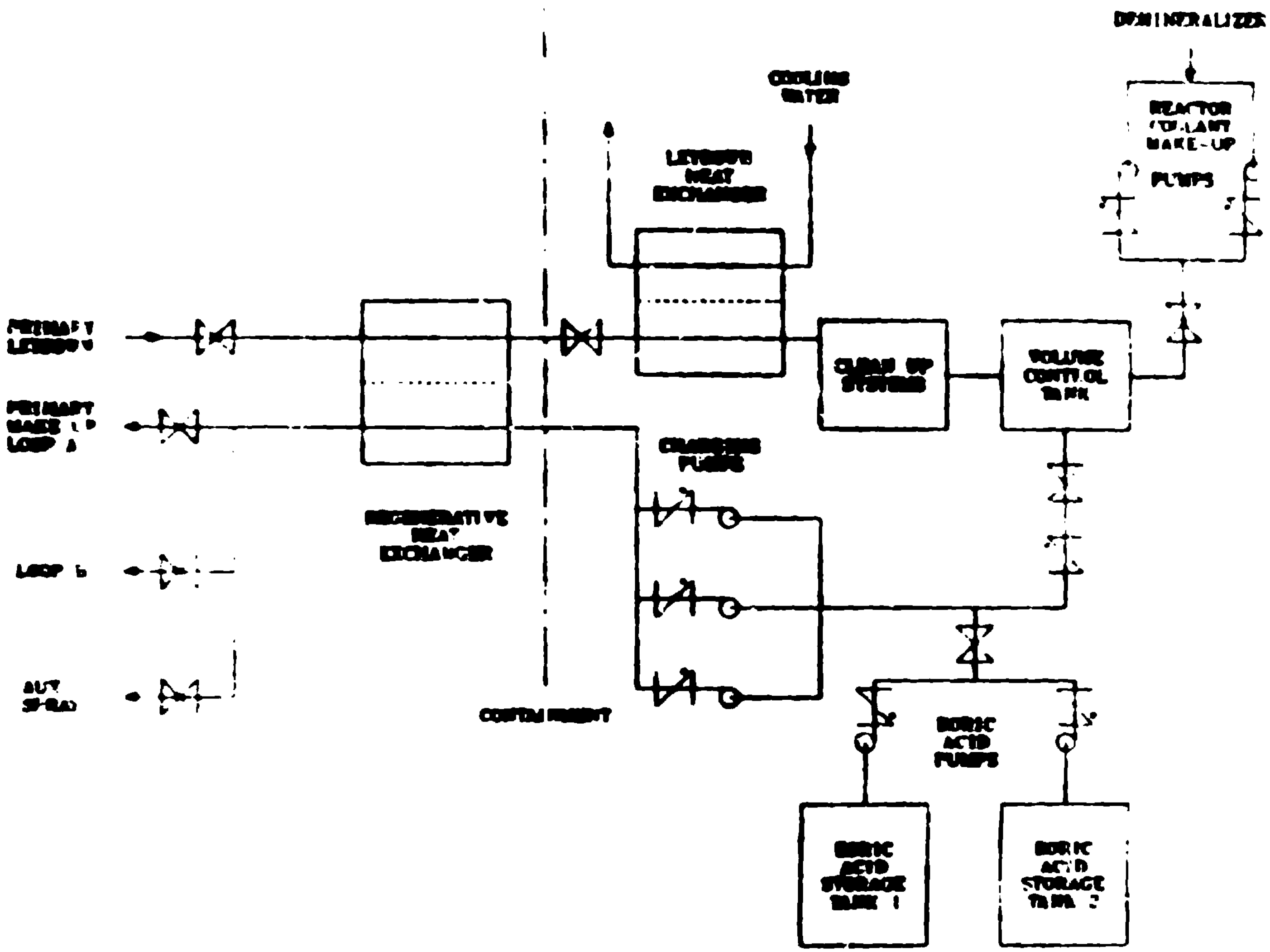

Fig. 3.
Calvert Cliffs primary make-up and letdown system process flow diagram.

operation of one high-pressure and one low-pressure pump provides adequate injection flow for any loss-of-coolant accident. In the event of a design-basis accident, at least one high-pressure and one low-pressure pump will receive power from the emergency-power sources if normal power is lost and one of the emergency diesel generators is assumed to fail. Upon depletion of the refueling water storage tank (RWST) supply, the high-pressure pump suction automatically transfers to the containment pump and the low-pressure pumps are shut down. The high-pressure pump has sufficient capacity to cool the core adequately at the start of recirculation.

III. TECHNICAL APPROACH

Loss-of-offsite power (LOSP) initiates the accident for each case with accompanying turbine, main feedwater (MFW), RCP, and main condensate booster pump trips. AFW is assumed to be available throughout the event, and the ADV on each steam generator "quick opens" shortly after emergency diesel power becomes available. Primary letdown and PORV relief are disabled as pressure and inventory reduction methods to focus on the effectiveness of the secondary-side cooling methods. In addition, SIAS is assumed to be disabled by the operator in order to allow depressurization below safety injection setpoints. The make-up flow provided by the charging system is available and functions to add primary inventory as the system cools. The charging system is assumed to deliver 3.2 kg/s (7.0 lb/s) into one cold leg of each loop throughout each transient.

We examine the ability of the atmospheric steam dump system to cool and depressurize the primary to conditions at which the shutdown decay heat removal heat exchangers can be used to place the plant in a stable, long-term cooling mode. The limiting condition for operating in this mode is 422 K (300°F) with respect to temperature. The operating pressure for the RHR system is 2.08 MPa (300 psia). We assume that once the RHR entry conditions are reached, the operators would initiate the RHR system and long-term cooling would be assured.

The following sections identify and describe the calculations performed the computer code, and the plant model used.

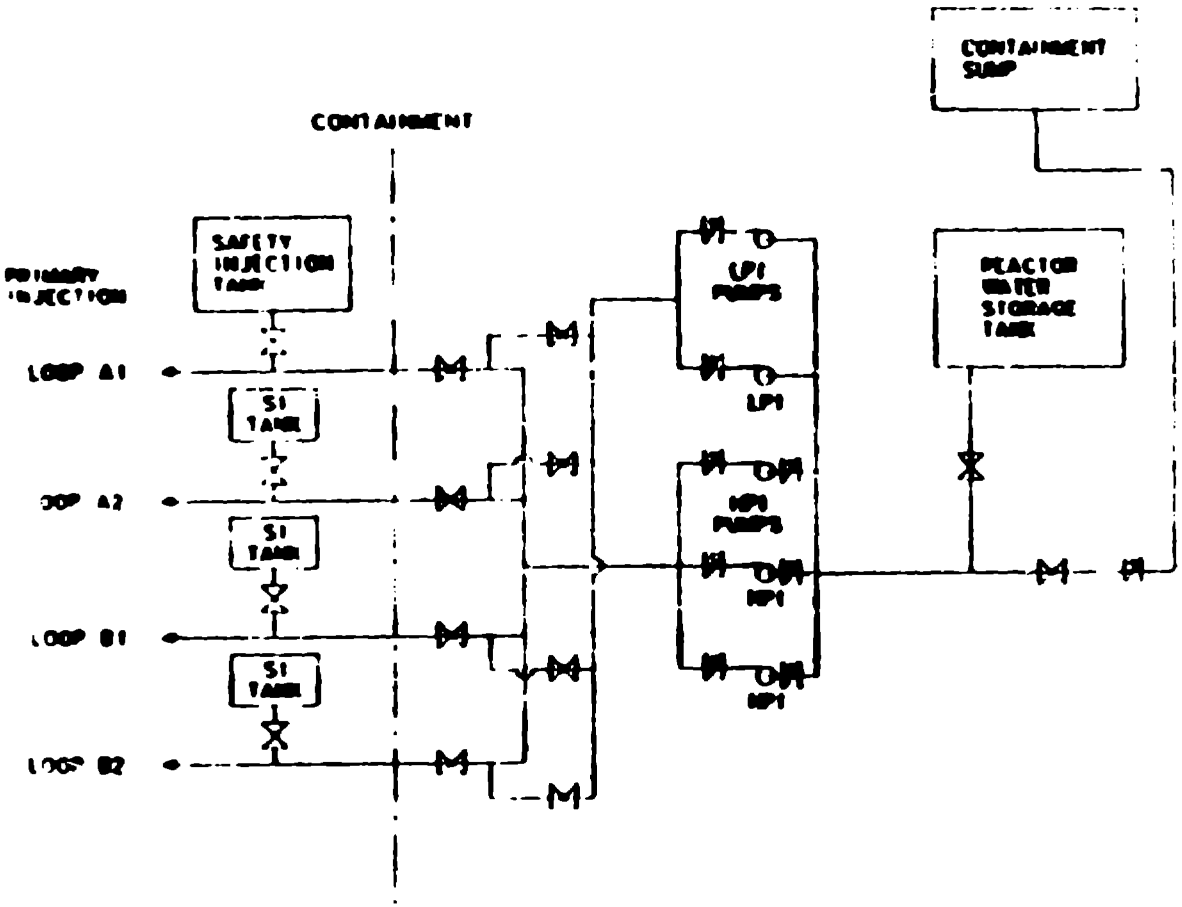

Fig. 4.
Calvert Cliffs safety injection systems process flow diagram.

A. Calculations Performed

A total of five calculations were performed to examine the effectiveness of the atmospheric steam dump system in cooling and depressurizing the Calvert Cliffs-1 PWR plant to RHR entry conditions. The initiating event in each case was LOSP. Case 1 assumed use of only ADVs and AFW to provide secondary-side cooling. Both steam generators were available and SRVs on each responded to brief initial pressure relief before ADVs were sent the quick open signal. No parametric studies of case 1 were made.

Case 2 assumed additional operator action in the form of APS initiation. In this situation the operator modulated APS flow to control depressurization, AFW flow to control SG level and ADV flow to control cooldown. Both SGs were available for this case as well. Three parametric studies of Case 2 were completed. Case 2A assumed ADV capacity was increased 200%. Cases 2B and 2C assumed ADV capacity increases of 400% and 500%, respectively.

B. Computer Code

The TRAC-PF1/MOD1 computer code[3] was used to perform the calculation. The specific code version used and summary description of this code are provided in App. A.

C. Plant Model

The model used in this study was developed for and first applied in a study of potential pressurized thermal shock transients in Calvert Cliffs-1 PWR plant.[4] This program was a multi-organizational program in which several organizations including C-E and the plant owner, BG&E, participated. A summary description of the plant model, including noding diagrams, is provided in App. B.

IV. RESULTS

Results for Case 1 are provided in detail as plant response is identical up to the time of operator action. The first operator action occurs 600 s (10 min) after the initiating event. Figures will be provided for Case 1 and repeated for the remaining cases. However, the discussions for the remaining cases will be abbreviated and will emphasize how the remaining cases differ.

A. Case 1

An event sequence for our analysis is given in Table 1. Beginning with the LOSP initiating event at time zero, a series of trips were modeled to simulate the plant transient. In response, the reactor and all four coolant

TABLE 1

CASE 1 EVENTS

Time (s)	Event
0.0	LOSP event
0.1	Reactor trip
	MFW Pump 11 trip
	MFW Pump 12 trip
	MFW pump 11 valve closes
	MFW pump 12 valve closes
	Turbine trip
	MFW pump 11 valve trip
	MFW pump 12 valve trip
	Reactor coolant pumps 14 and 44 trip
	Reactor coolant pumps 24 and 34 trip
	ADV trip signal but action delayed 14.5 s
0.52	TBV trip
14.73	ADVs quick-open after 14.5 s delay
600.9	AFW actuation signal
	AFW delivered to SG22 (loop A)
	AFW delivered to SG12 (loop B)
2000	END OF CALCULATION

pumps trip on the primary side and both MFW pumps and the turbine trip on the secondary side.

After sufficient time has passed to allow emergency diesel generators to power up, ADVs on both steam generators "quick open" and modulate to maintain average reactor coolant temperature at normal operating value.

No operator action is taken until 10 minutes (600 s) after the initiating event per ANSI N660 that establishes the minimum time margin that shall elapse from the event initiation and alarm until operator actions can be considered for initiation of safety functions. At this time the operator manually activates the AFW pumps to provide 20.61 kg/sec flow to each steam generator. Approximately 1 minute later (at 660 s) the operator begins control of ADVs on both steam generators to start the cooldown process. An additional operator action is modeled after 12 minutes (720 s) which allows control of the backup pressurizer heaters to maintain subcooling margin if it falls below a given level.

At the onset of this analysis, it was speculated that aggressive secondary steam generator cooldown, limited only by excessive cooldown considerations, would be sufficient to achieve SDR entry without the need for APS. This seemed credible because recent C-E calculations, discussed in CEN-239, showed that small break loss-of-coolant accidents without high pressure injection could be mitigated by rapid, aggressive secondary side cooling.

The cooldown capability of Calvert's ADVs is demonstrated in Fig. 5, which shows the cooldown rate with ADVs full open. We found there was excess cooldown capability, indicated by the fact that cooldown had to be limited to 100 °F/hr to reduce the chance of overcooling and possible damage to the reactor vessel. With ADV flow controlled on a cooldown rate of 100 F/hr, primary and secondary coolant temperatures drop as shown in Figs. 6 and 7. The modulation of ADVs by the operator in response to fluctuations in cooldown rate is evident after 660 s. Before that time, cooldown is the result of combined effects of drop in reactor power and the initial quick open response of the ADVs.

Pressure, on the other hand, does not decrease. Primary and secondary pressures are depicted in Fig. 8 which indicate, in fact, a slight repressurization effect. This does not follow the speculated course envisioned early on, even though secondary depressurization is very evident.

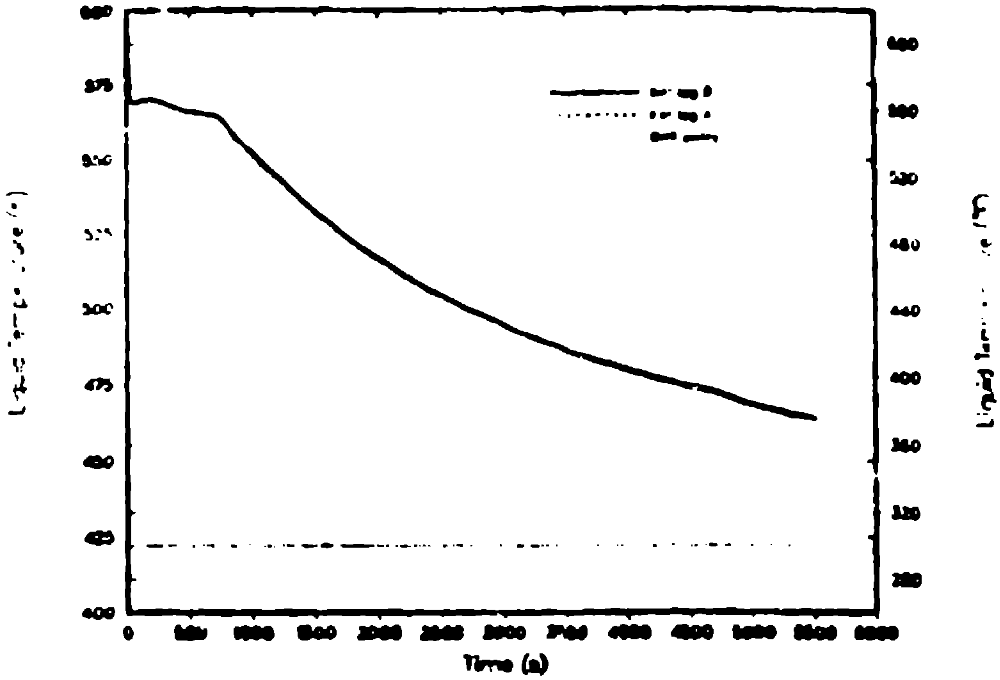

Fig. 5.
Primary hot-leg temperatures, Unthrottled ADV.

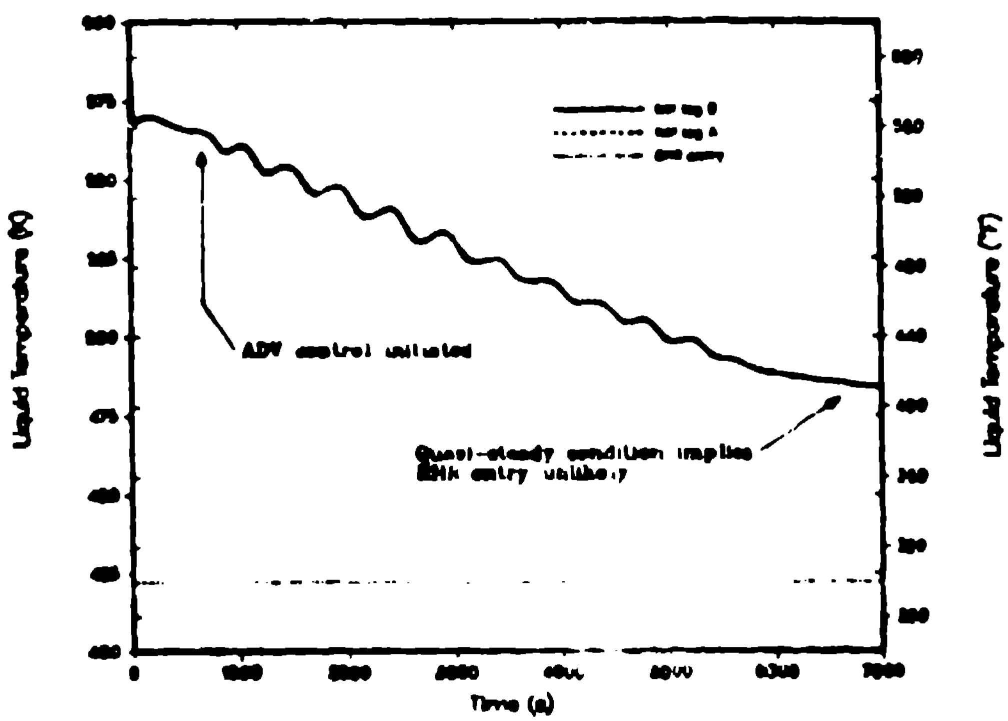

Fig. 6.
Primary hot-leg temperatures, Case 1.

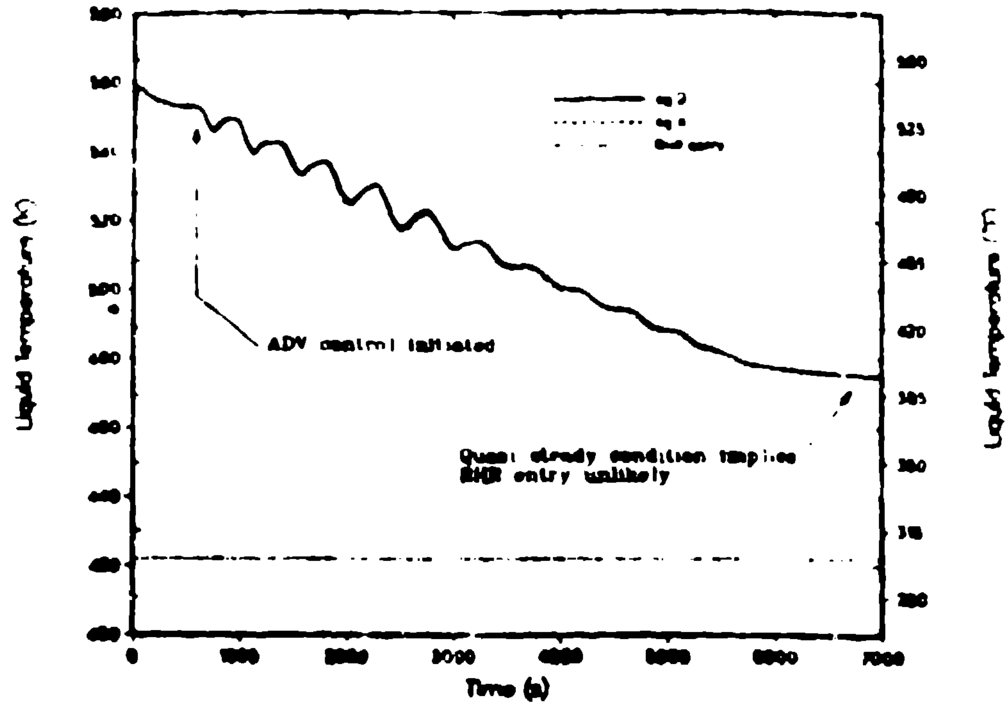

Fig. 7.
Secondary liquid temperature, Case 1.

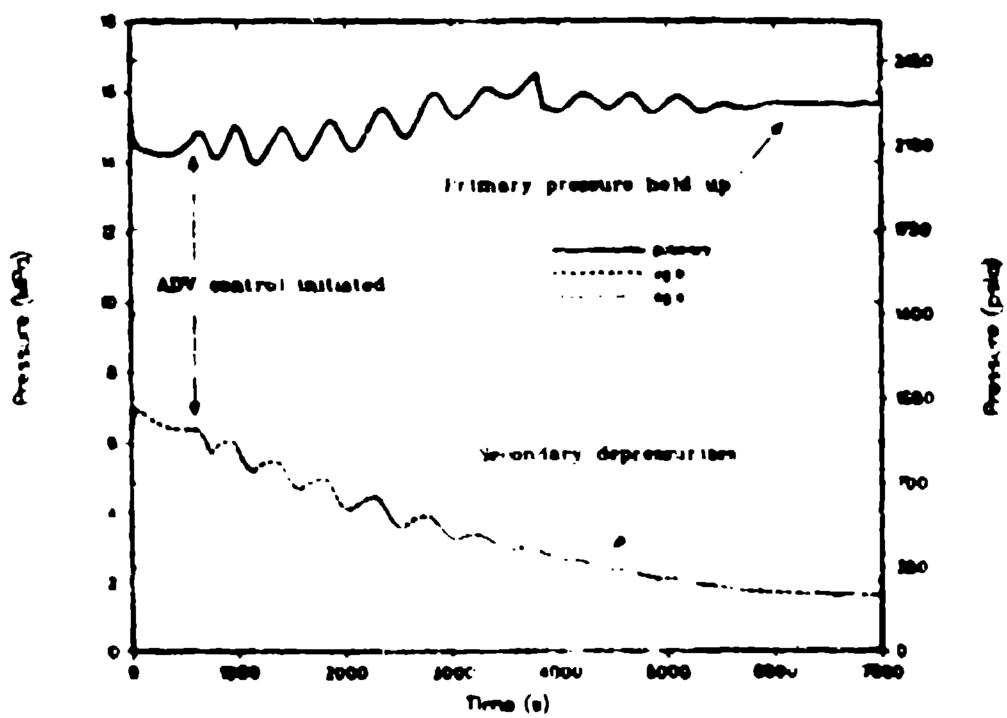

Fig. 8
Primary and secondary pressures, Case 1.

Several explanations for this behavior are possible. One is that, due to the relatively stagnant conditions in the pressurizer, little heat transfer is made between the liquid levels and the vapor. The consequence of this is that the vapor remains saturated at a high temperature and a correspondingly high pressure. This acts to maintain the pressure in the system, much as the pressurizer functions during normal operation.

In addition to the pressurization effect, Fig. 9 indicates that the effect of a rising water level in the pressurizer may contribute to a "compression effect". As the level increases due to primary inventory additions from makeup flow, the vapor above the liquid in the pressurizer undergoes compression with subsequent increase in pressure.

One of these mechanisms may be more important than the other as a contributor to the repressurization observed. It is not clear without further analysis whether or not elimination of makeup flow during this period would allow the primary to depressurize.

Of particular concern in any analysis involving AFW is the depletion of the CST inventory. Figure 10 shows liquid mass in the CST compared to the

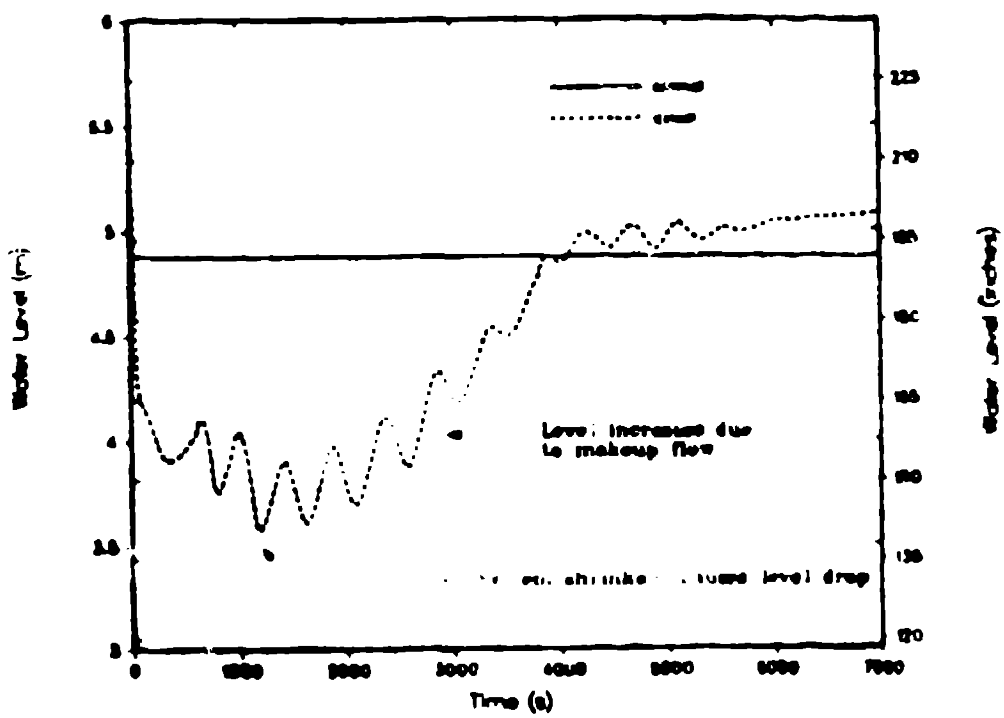

Fig. 9
Pressurizer collapsed liquid level, Case 1.

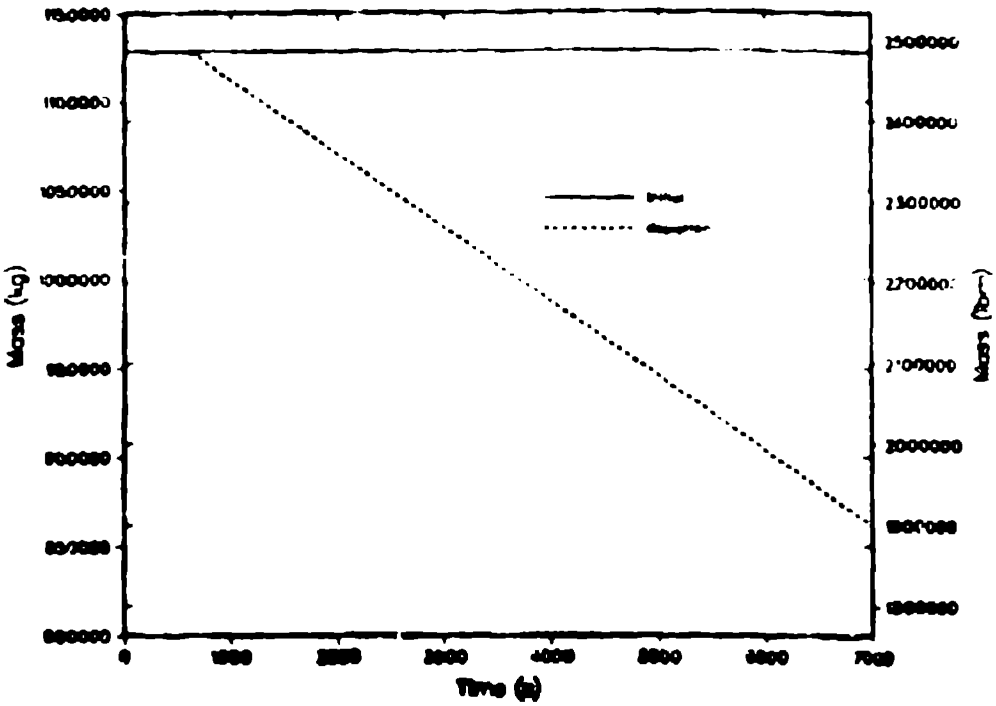

Fig. 10.
CST liquid inventory, Case 1.

original inventory. Since AFW is injected at a constant rate during the calculation, there is a linear decrease in mass.

To project when the CST would be drained, we draw from extended calculations for Case 2 (to be discussed) which indicate ADV flow may stabilize at about 3 kg/s. This is in response to reduced energy removal requirements as well as decreased ADV flow rate with reduced secondary side pressure. This is partially offset by the decreased AFW flow as throttling occurs upon reaching steam generator high-level point. By the time throttling occurs approximately 128 640 kg were removed from CST. With inventory being maintained after that point, we can assume AFW flow will amount to 10 kg/s per steam generator. With about 799,360 kg remaining, approximately 40,000 s (11.1 hrs) additional would be required to deplete the CST inventory.

Additional calculations could be performed which might indicate a slow depressurization and eventual drop to RHR entry without APS. However, due to the observed pressurization and compression effects, it was deemed more economically feasible to pursue the case involving operator-initiated APS to promote depressurization of the primary. Since all RCPs were tripped by loss-of-ac-power, flow was maintained only by natural circulation. Among the immediate actions listed in the LOSP emergency operating procedures (EOPs) for Calvert Cliffs 1 and 2[5] are the following:

1. Insure that all full-length control element assemblies (CEAs) are fully inserted into the core, the turbine has tripped, and the generator output, generator field and exciter field breakers have tripped.
2. Verify that the diesel generators have started.
3. Stop condensate pumps, condensate booster pumps, and heater drain pumps.

Thus, the operator is instructed to check for reactor shutdown, insure that backup electrical power will be available for important safety equipment, and stop condensate flow. No further operator actions were considered until 600 s (10 min) following the initiating event.

In summary, the atmospheric steam dump procedure was found to be ineffective in cooling the plant. When the operator initiated the procedure at 600 s, initial cooldown was very satisfactory, but primary pressure was held up by pressurizer vapor compression effects. Continued cooldown only increased the degree of subcooling with depressurization to RHR deemed unlikely. In the next section the effect of operator-initiated APS to reduce primary pressure is investigated.

B. Case 2

The event sequence for our analysis is given in Table 2. The LOSP initiating event occurs at time zero, followed by trips modeled to simulate the plant transient. In response, the reactor and all four RCPs trip on the primary side and both MFW pumps and the turbine trip on the secondary side.

After sufficient time has passed to allow emergency diesel generators to power up, ADVs on both steam generators "quick open" and modulate to maintain average reactor coolant temperature at normal operating value.

The difference between this case and Case [illegible] is primarily the additional operator control of APS to allow primary depressurization. To provide a simple approximation to operator response, A[illegible] after 720 s (12 min) to maintain 13.9 to 16.7 K (25 to 30 °F) subcooling. The only other limit placed on APS control was that no APS could be initiated when pressurizer level (as measured by pressure differential) was above 5.46 m (17.9 ft).

Also, to provide a simple approximation to operator behavior, when APS was required, the makeup flow was turned off, so that full available makeup flow available was diverted to the APS.

Previous similar analyses[6] at Los Alamos involving steam generator tube rupture studies showed dramatic pressure decreases could be induced in the pressurizer with very little spray flow.

Because the condensation model in TRAC requires liquid velocities at cell boundaries in excess of 4 m/sec and no depressurization calibration has been done, the APS inlet flow area was adjusted to allow a liquid velocity meeting the criterion for the condensation model.

The cooldown capability of Calvert's ADVs is again demonstrated in Figs. 11 and 12, which show the cooldown rates of primary and secondary with ADVs modulated to produce a primary coolant cooldown of 100 F/hr. The modulation of ADVs by the operator in response to fluctuations in cooldown rate is evident after 660 s. Before that time, cooldown is the result of combined effects of drop in reactor power and the initial quick open response of the ADVs.

As expected, APS initiated after 720 s in response to high subcooling (high pressure) produced a rapid depressurization as shown in Fig. 13. As in Case 1, the primary pressure initially drops very rapidly in response to rapid system cooldown and contraction and concurrent with the drop in pressurizer level. Until initiation of APS injection at 720 s, the pressure follows the pressurizer liquid level, increasing with liquid level increase. Following APS initiation, primary pressure is reduced from about 15 to 8 MPa (2176 to 1160 psia) in approximately 600 s (10 min).

The desired reduction in primary pressure was achieved. However, as the transient progressed, the cooldown rate diminished to a level for which entry to RHR temperature was unattainable. ADV sizing became an important issue at this point. The size of the ADVs limited heat removal such that secondary liquid temperature and pressure had reached an equilibrium level at which no further decrease was foreseen. This was explored by considering the mass flows to the steam generators.

As liquid in the steam generator reached the high-level setpoint, at approximately 8150 s, AFW flow was reduced to maintain steam generator inventory. At the same time ADV flow responded to both secondary pressure decrease and flow area limitations in such a manner that net ADV outflow was reduced. A combination of reduced ADV outflow and reduced AFW .

TABLE 2

[illegible] 2 EVENTS

Time (s)	Event
0.0	LOSP event
0.1	Reactor trip
	MFW Pump 11 trip
	MFW Pump 12 trip
	MFW pump 11 valve closes
	MFW pump 12 valve closes
	Turbine trip
	MFW pump 11 valve trip
	MFW pump 12 valve trip
	Reactor coolant pumps 14 and 44 trip
	Reactor coolant pumps 24 and 34 trip
	ADV trip signal but action delayed 14.[illegible] s
0.52	TBV trip
14.73	ADVs quick-open after 14.5 s delay
600.9	AFW actuation signal
	AFW delivered to SG22 (loop A)
	AFW delivered to SG[illegible] (loop B)
7[illegible]3.	APS on [illegible]
11500	END OF CALCULATION

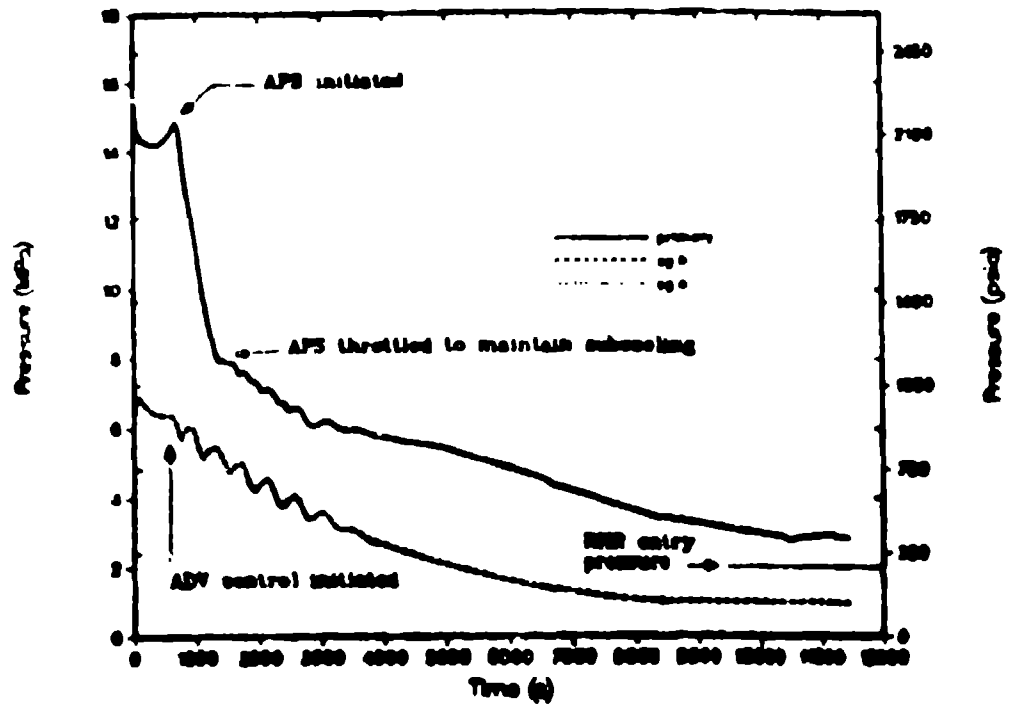

Fig. 13.
Primary and secondary pressures, Case 2

significantly reduced secondary-side heat removal capability. This was because both flows contributed to heat removal; ADV flow by removing steam with high heat content, and AFW flow by injecting cool (300 K) liquid.

Figures 14 and 15 depict the pressurizer liquid level and the CST inventory, respectively for this case. Valves currently installed at Calvert Cliffs were thus shown to be ineffective using this type of cooldown procedure.

C. Case 2 Parametrics

Three parametric studies using Case 2 as the base were completed. In these studies various larger ADV sizes were studied as possible substitutes for the present valves representing increases in rated steady-state full power flow from 200% to 500%.

1. Case 2A.

For the case in which rated steady-state full-power ADV full-open steam flow was doubled, the primary pressure reduction capability increased. The primary cooldown, however, was held up by secondary liquid cooldown limitations.

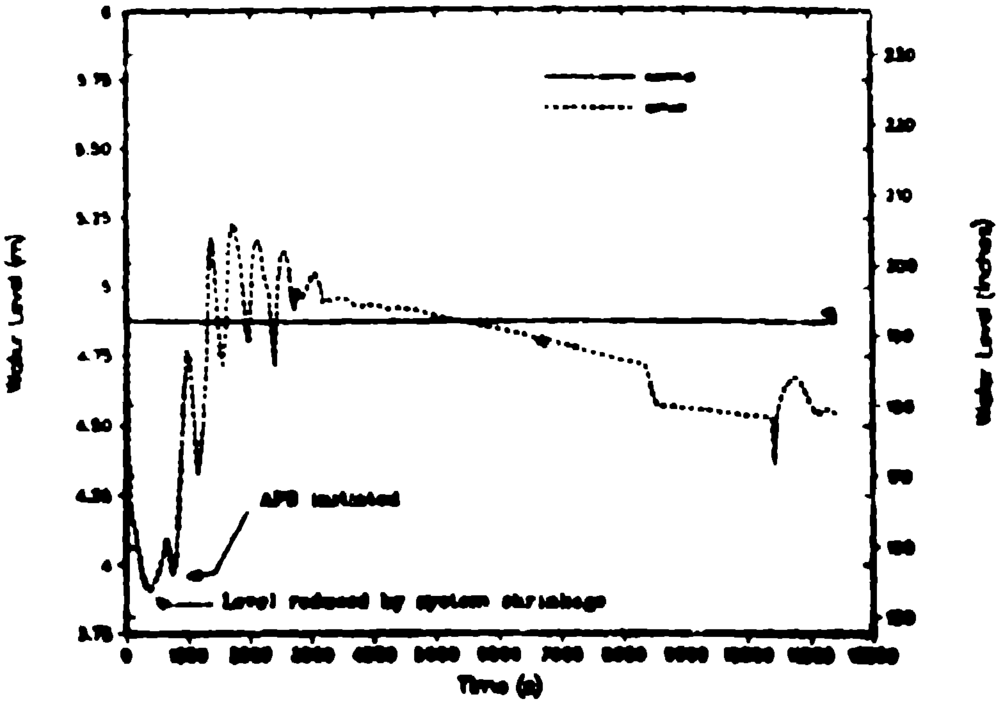

Fig. 14.
Pressurizer collapsed liquid level, Case 2.

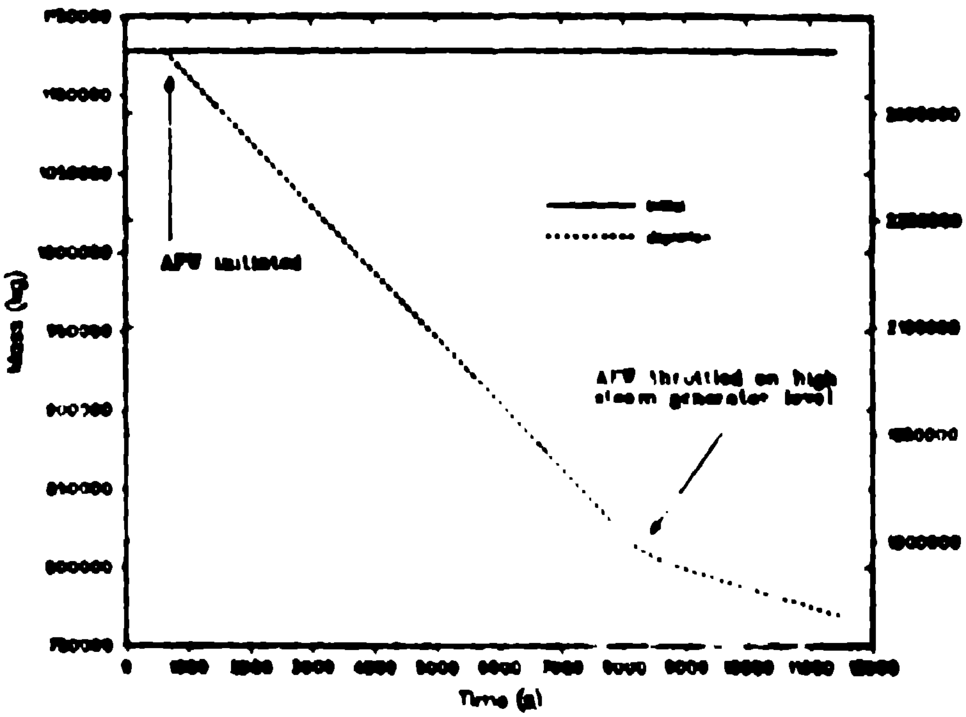

Fig. 15.
CST liquid inventory, Case 2.

Figures 16 and 17 show primary and secondary liquid temperatures for this configuration. AFW was throttled later than for Case 2 because larger ADV flow area allowed more SG inventory to be removed, postponing the AFW cutback. Figure 18 shows primary and secondary pressure. Since the secondary liquid temperature leveled off at a value higher than RHR entry, cooldown would not be be sufficient to allow successful primary liquid temperature reduction to RHR conditions. Behavior of the pressurizer liquid level is shown in Fig. 19, and the CST inventory is given in Fig. 20.

2. Case 2B.

Results for this configuration with a 400% increase in rated steady state ADV flow demonstrated that effective cooldown to RHR entry could be achieved within 3 1/2 hours of the initiating event. Figures 21 and 22 show the primary and secondar, te:peratures, and Fig. 23 gives the primary and secondary pressures. Pressurizer liquid level is given in Fig. 24. The CST inventory is shown in Fig. 25 and confirms the availability of surplus coolant for AFW injection.

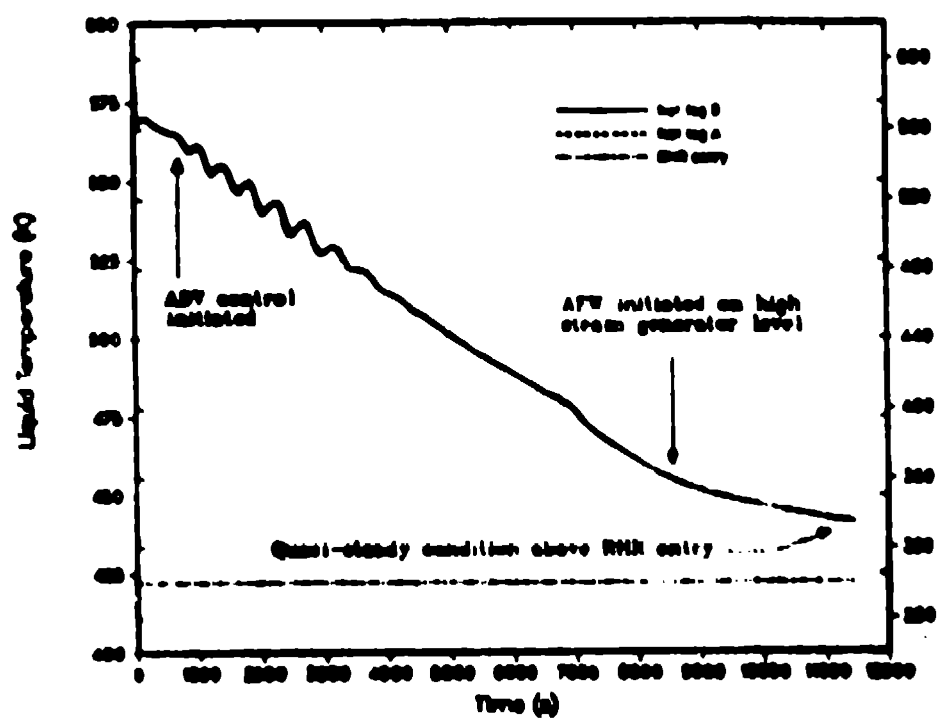

Fig. 16.
Primary hot-leg temperatures, Case 2A

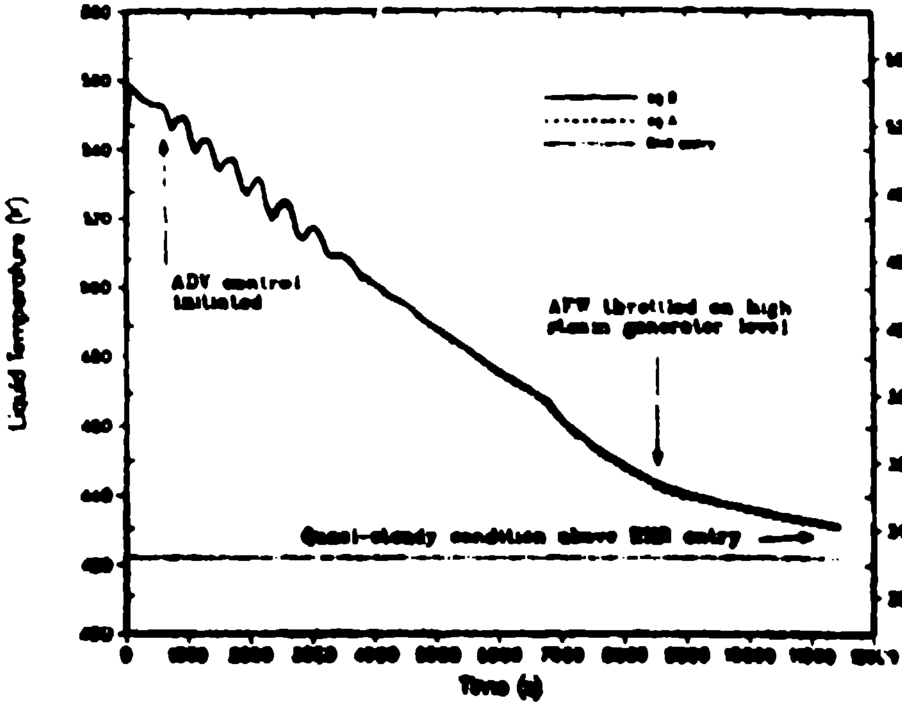

Fig. 17.
Secondary liquid temperature, Case 2A

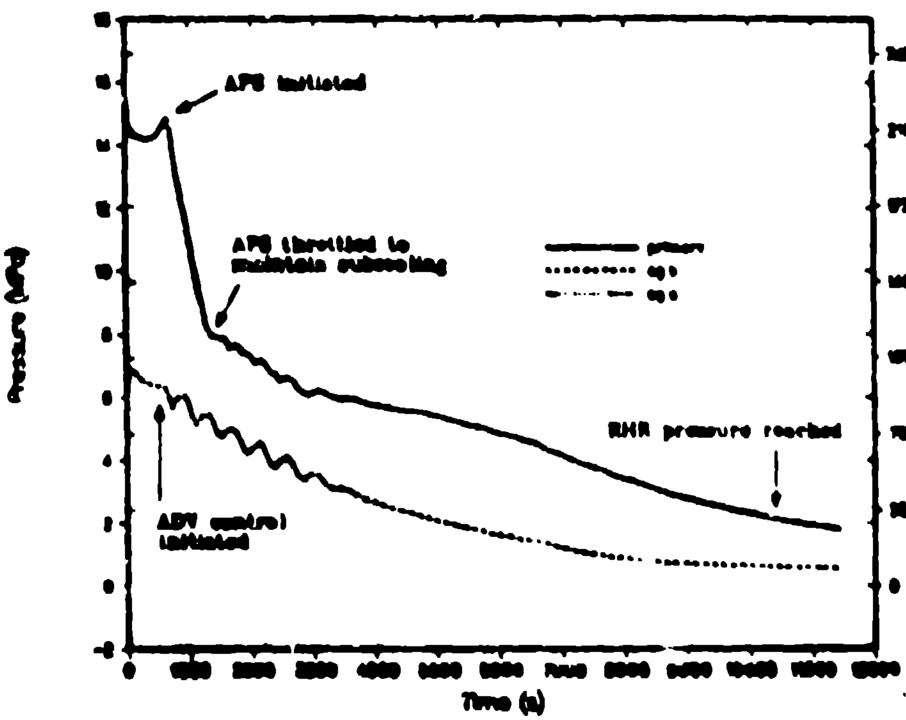

Fig. 18.
Primary and secondary pressures, Case 2A

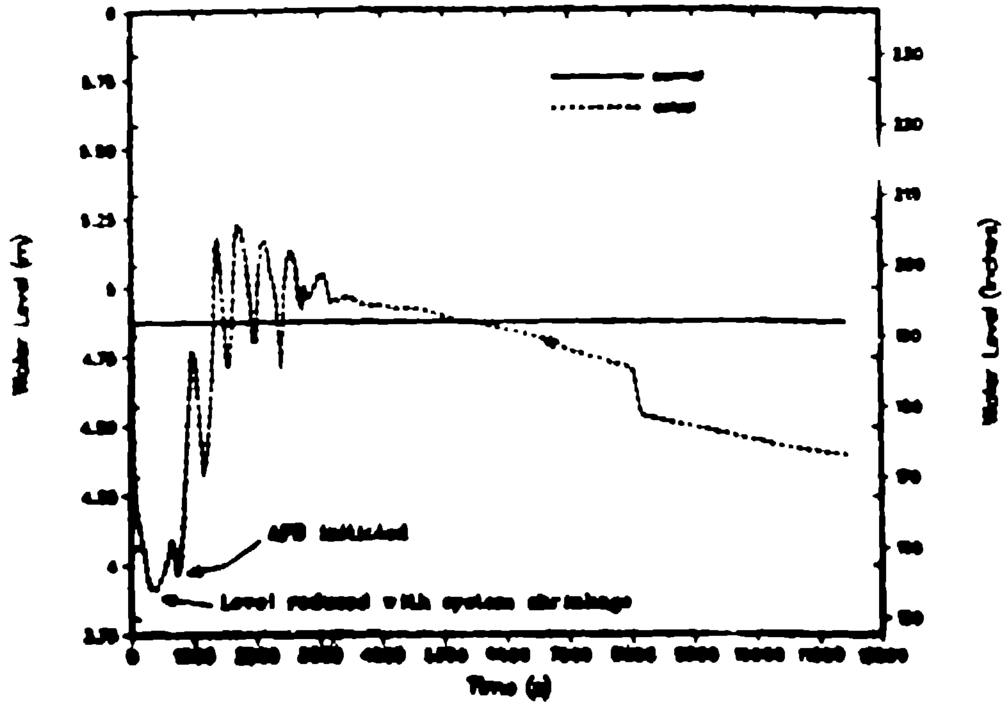

Fig. 19.
Pressurizer collapsed liquid level, Case 2A

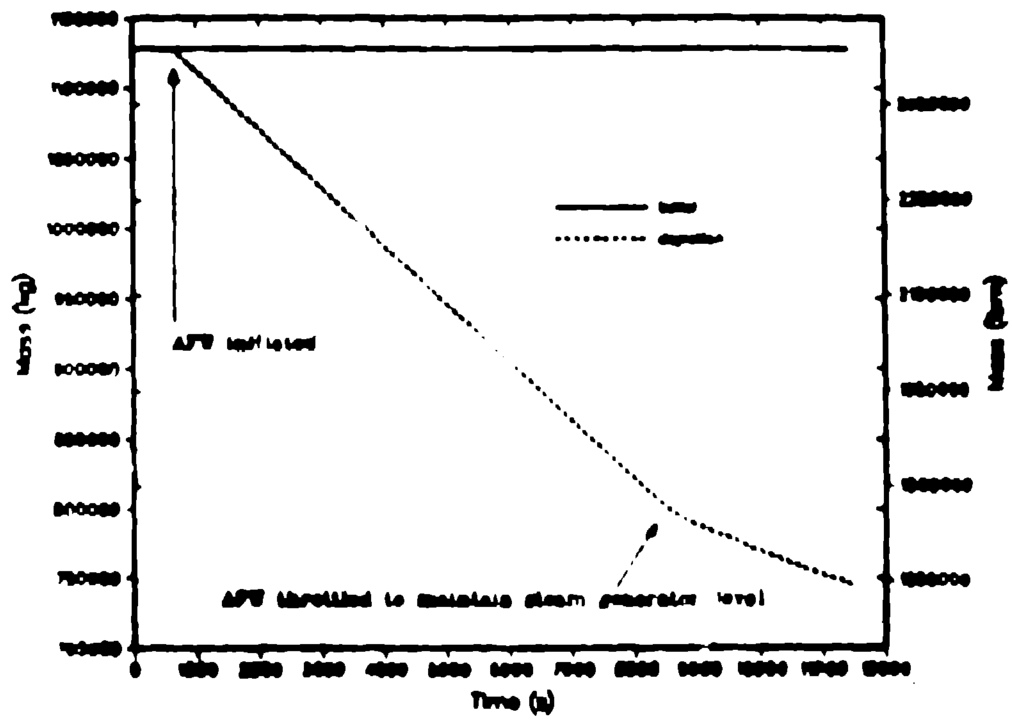

Fig. 20.
CST liquid inventory, Case 2A.

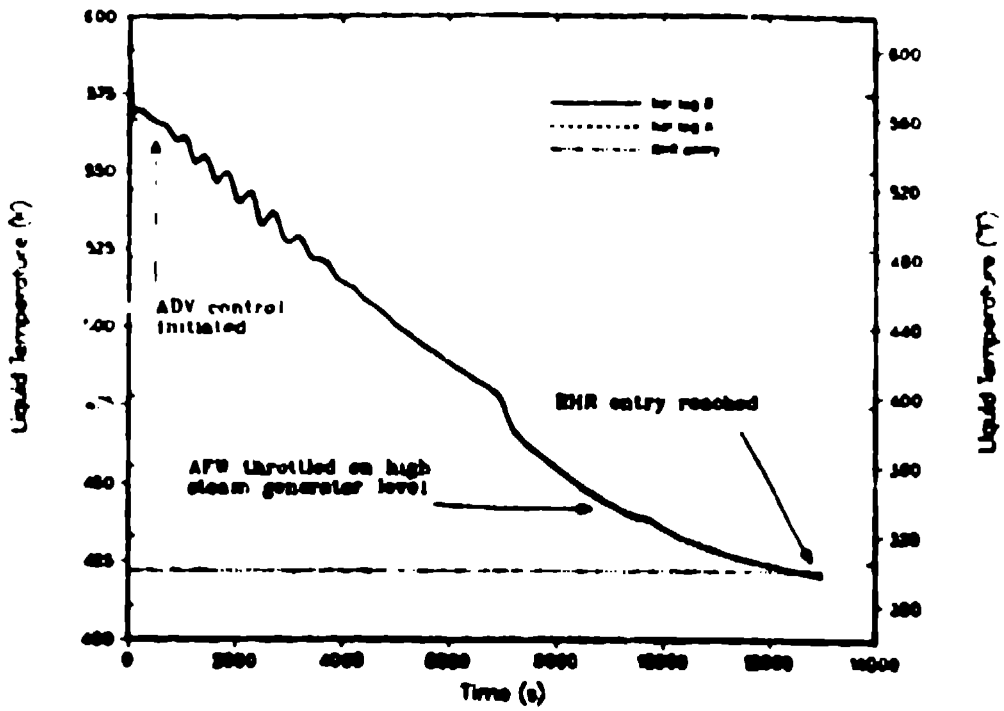

Fig. 21.
Primary hot-leg temperatures, Case 2B.

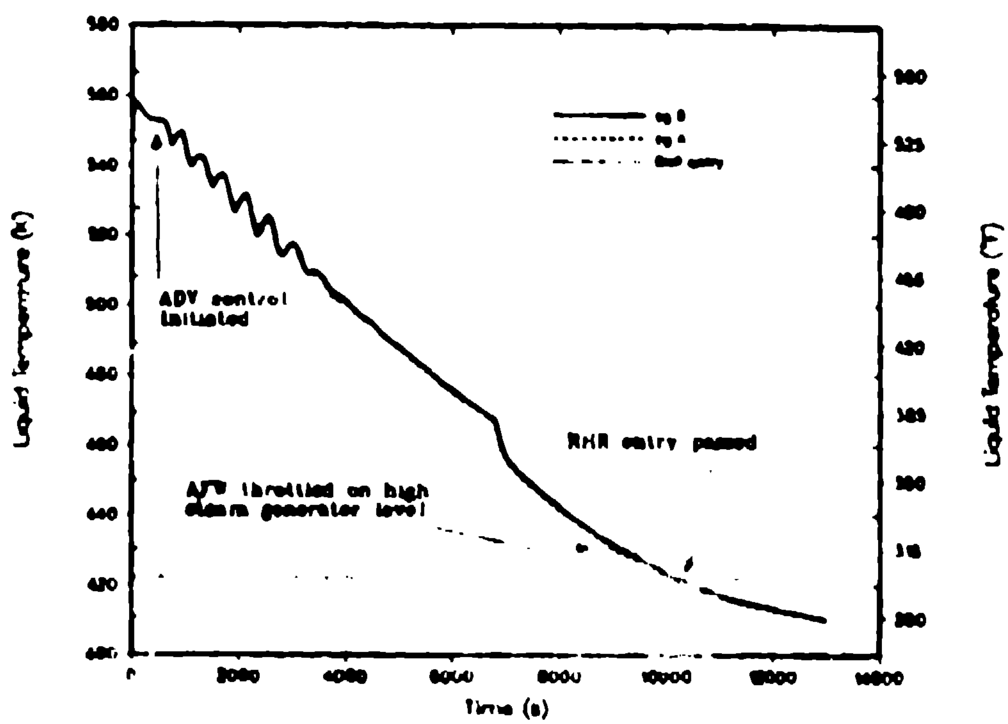

Fig. 22.
Secondary liquid temperature, Case 2B

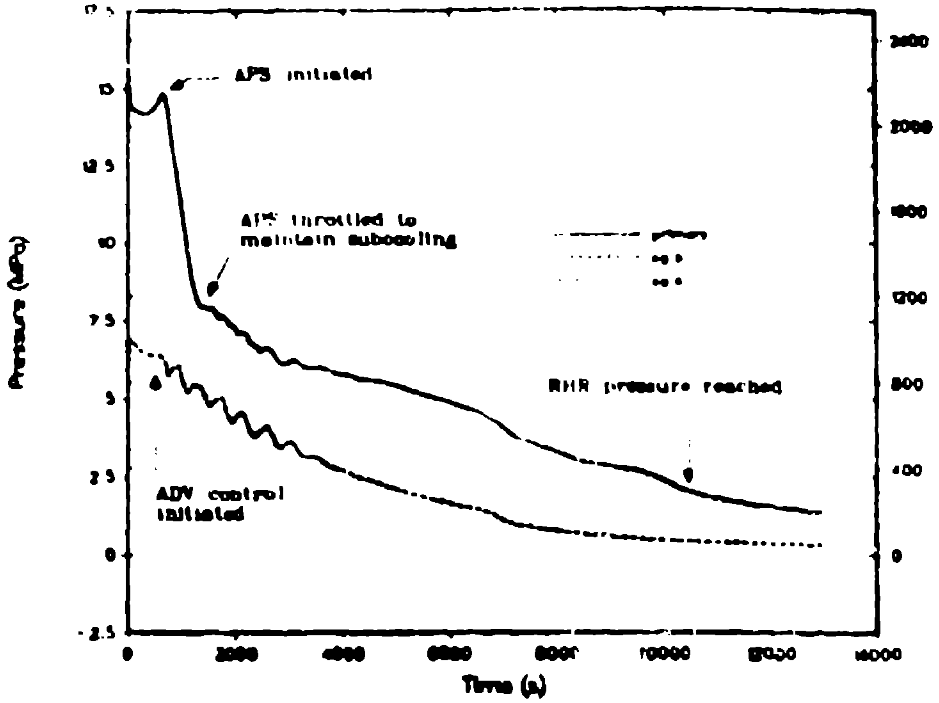

Fig. 23.
Primary and secondary pressures, Case 2B.

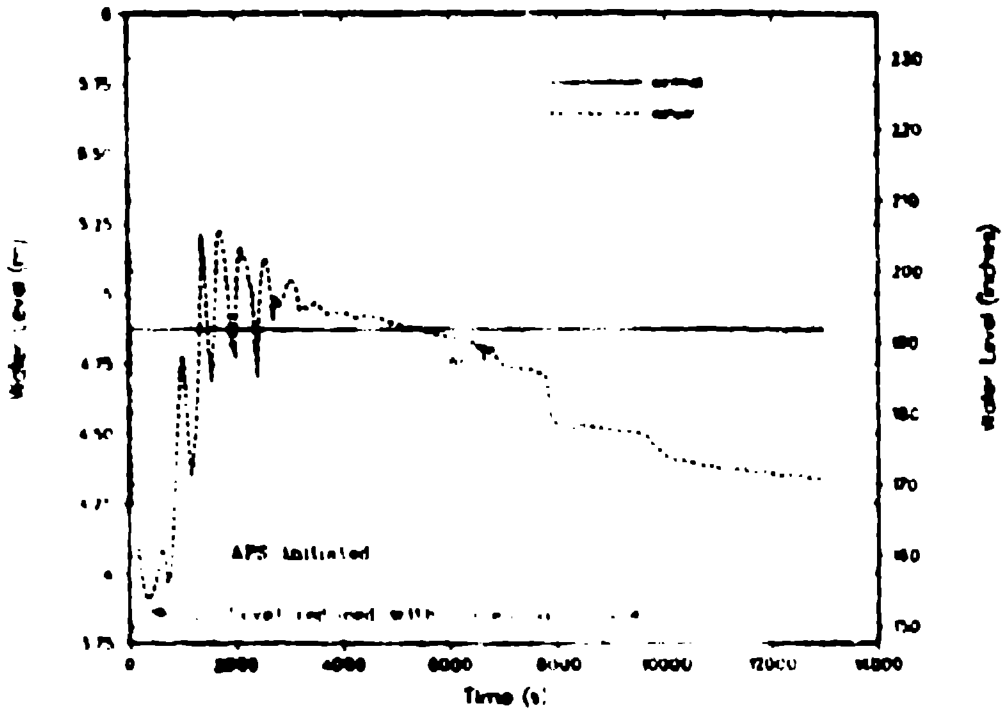

Fig. 24.
Pressurizer collapsed liquid level, Case 2B.

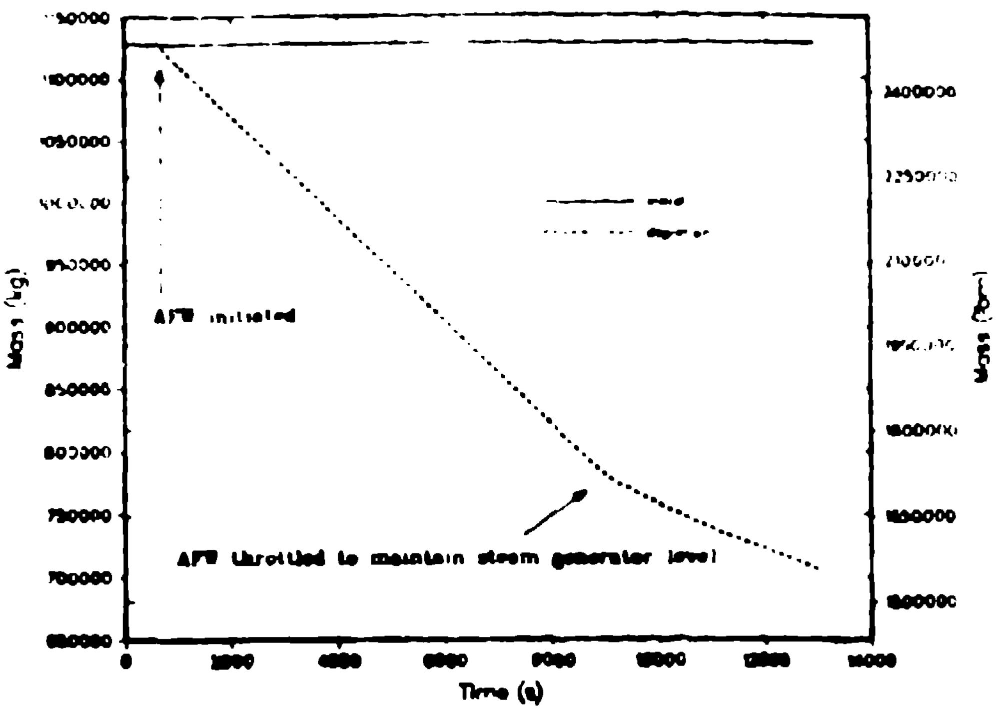

Fig. 25.
CST liquid inventory, Case 2B.

[illegible] Case 2C.

An additional calculation was performed with ADV rated steady-state flow increased to 500% of present value to bracket values used in a previous hand calculation.[6] In the hand calculation, Millstone Unit 2, which is another CE plant of similar vintage, was found to be capable of RHR entry with both ADVs [illegible] hours after the initiating event. The 400% and 500% flow increase cases were conducted to approximately bracket the Millstone configuration with respect to ADV flow.

RHR entry occurred at about [illegible] hours. Figures 26, 27 and 28 give the cooldown and depressurization information. Pressurizer level is indicated in Fig. 29. [illegible] sufficient coolant [illegible] available for AFW operation.

Comparison to RHR entry time for Millstone shows the TRAC value to be longer by about 1 hour. Considering the differences between the plants and the methods employed, the agreement is good. It should be noted that the [illegible] calculation neglected sensible heat removal which may represent a significant part of the energy removal requirements.

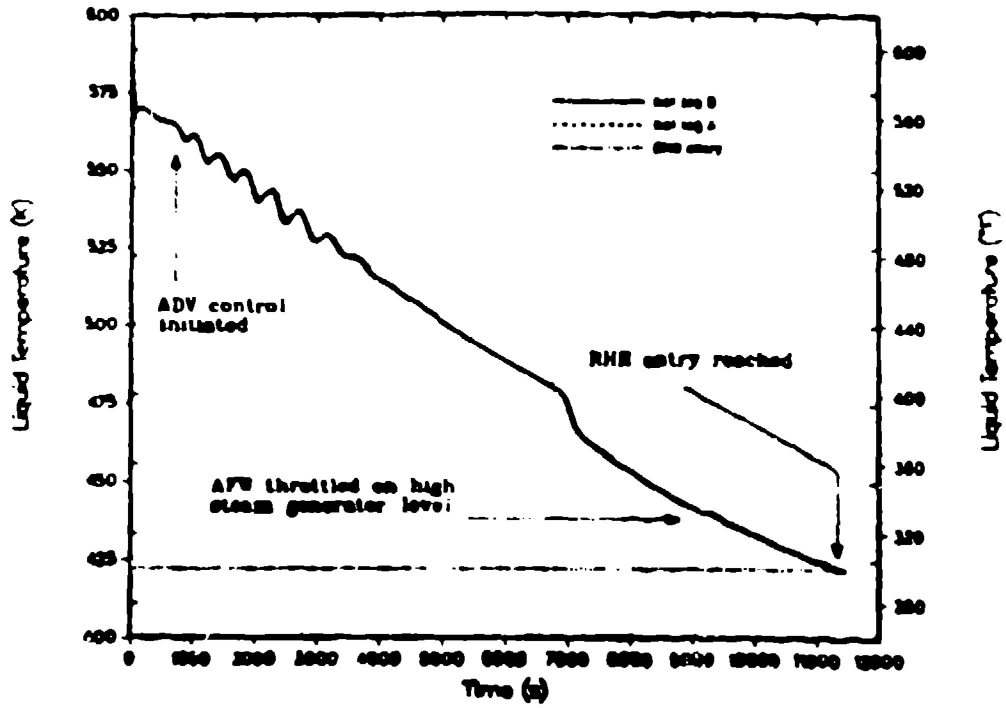

Fig. 26.
Primary hot-leg temperatures, Case 2C.

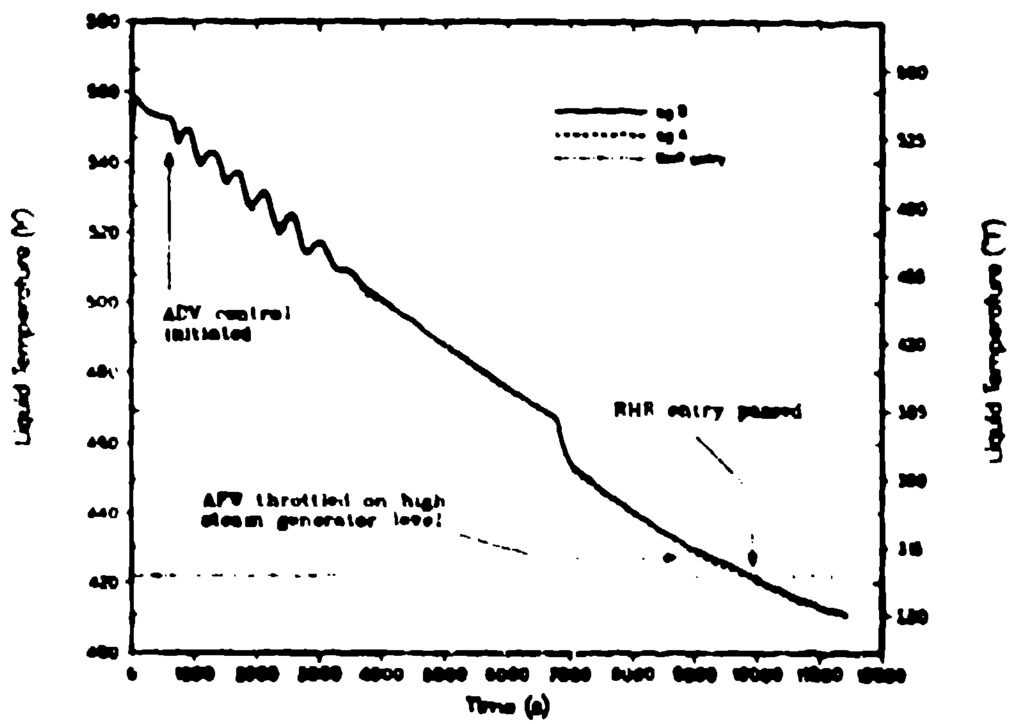

Fig. 27.
Secondary liquid temperature, Case 2C.

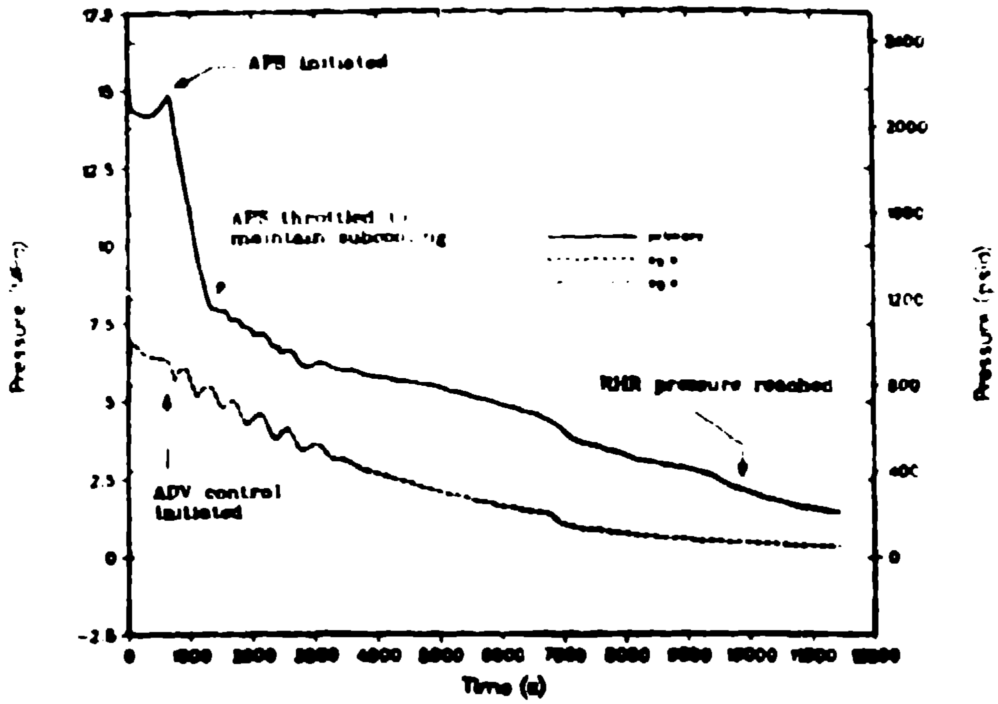

Fig. 28.
Primary and secondary pressures, Case 2C.

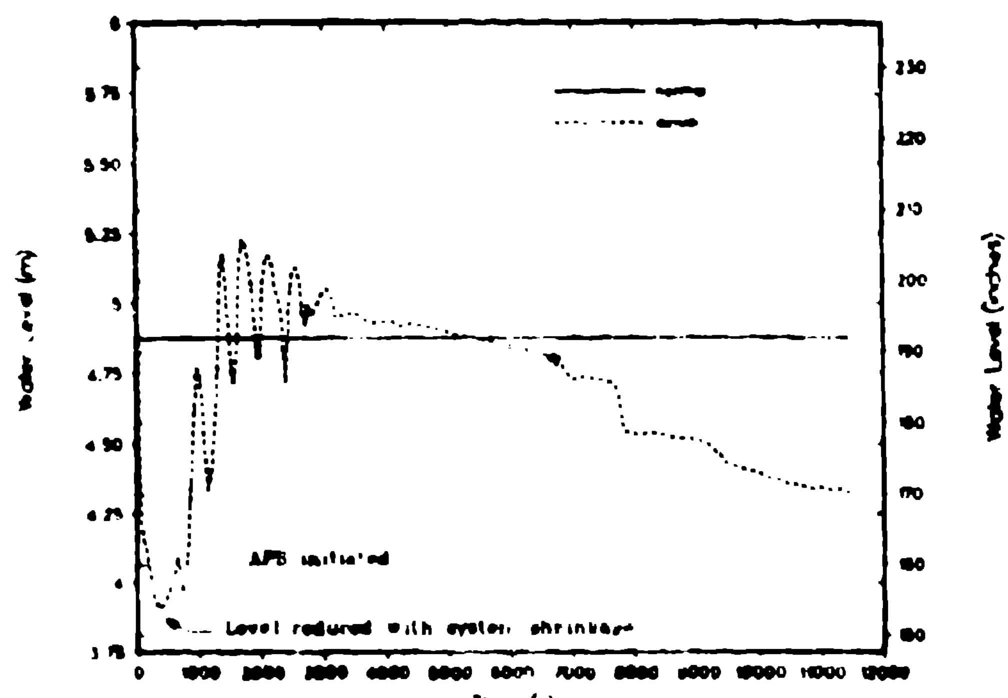

Fig. 29.
Pressurizer collapsed liquid level, Case 2C.

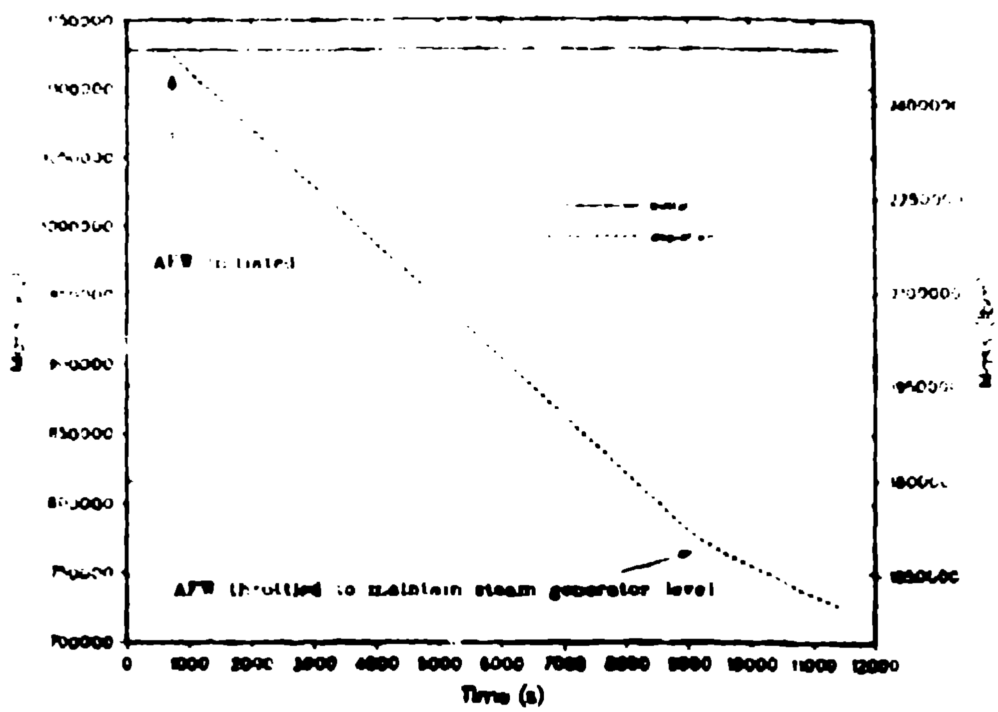

Fig. 30.
CST liquid inventory, Case 2C.

V. [illegible] AND RECOMMENDATI[illegible]

We have examined the use of an atmospheric steam dump procedure to cool and depress[illegible]ze a Combustion Engineering plant, Calvert Cliffs [illegible] a loss-of-offsite power accident. Major [illegible]nclusions are as follows:

1. [illegible]ldown and depressurization to RHR entry [illegible] does [illegible] for the case where operat[illegible] only existing plant A[illegible] and [illegible]
2. If the operator uses APS in addition to existing ADVs, depressurization is improved, but RHR entry is still [illegible] because [illegible] side cooldown and depress[illegible] limitations.
3. [illegible]ling the ADV capacity still [illegible] provide suffi[illegible] capability to bring secondary pressure and temperature down [illegible] enough to allow primary cooldown to RHR entry conditions.
4. By increasing the ADV capacity to 400% the plant can reach RHR entry conditions within 3 1/2 hours from the initiating event. A [illegible] reduces this entry time to about 3 hours.

We believe that there are several additional studies that deserve consideration. Studying the effect of elimination of makeup flow for Case 1 to allow possible depressurization might be worthwhile. Although the long term depressurization may still be impeded due to the fact that the operator must maintain pressurizer level at some specified value, the effect of reduced makeup could be studied. The results would indicate the impact of reduced makeup flow on depressurization.

Also, a study to determine the effects of using letdown and the tried makeup for Case 2 would provide valuable information. Since primary cooldown is important, this mode of limited primary cooling would allow a reduction in pressurizer level. With pressurizer level decrease APS flow could be increased (subject to subcooling limitations), and thereby add cooler APS water to the primary system.

There has also been some speculation that RHR entry might be possible without APS, but with the greater ADV flows examined in Case 2B and Case 2C. While this seems unlikely, based on Case 1 results, TRAC calculations could be performed to simulate this condition easily and provide much insight into ADV sizing effects on the primary system.

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3. Safety Code Development Group, "TRAC-PF1/MOD1 An Advanced Best Estimate Computer Program for Pressurized Water Reactor Thermal Hydraulic Analysis," Los Alamos National Laboratory report (DRAFT), to be issued.

4. Gregory D. Spriggs, Jan E. Koenig, and Russell C. Smith, "TRAC-PF1 Analyses of Potential Pressurized-Thermal-Shock Transients in a Combustion-Engineering PWR," Los Alamos National Laboratory report LA-UR-84-2083 (August 1984).

5. "EOP-15, Loss of Off-Site A.C. Power," Rev. 4, Calvert Cliffs-1 (June 11, 1982).

6. T. Bott and E. Barts, "Steam Generator Tube Rupture Calculations for a Combustion Engineering Plant," Los Alamos National Laboratory Report (DRAFT), to be issued.

APPENDIX A

TRAC VERSION

I. TRAC DESCRIPTION

The Transient Reactor Analysis Code (TRAC) is being developed at the Los Alamos National Laboratory under the sponsorship of the U.S. Nuclear Regulatory Commission to provide advanced best-estimate predictions of postulated accidents in light-water reactors. The TRAC-PF1 code provides this capability for PWRs and for many thermal-hydraulic experimental facilities. Some distinguishing characteristics of TRAC-PF1 are summarized herein. Within restrictions imposed by computer running times, attempts are being made to incorporate state-of-the-art technology in two-phase thermal hydraulics.

A. Variable-Dimensional Fluid Dynamics

A full three-dimensional (r, θ, z) flow calculation can be used within the reactor vessel; the flow within the loop components is treated one dimensionally. This allows an accurate calculation of the complex multidimensional flow patterns inside the reactor vessel that are important during accidents. For example, phenomena such as ECC downcomer penetration during blowdown, multidimensional plenum and core flow effects, and upper-plenum pool formation and core penetration during reflood can be treated directly. However, a one-dimensional vessel model may be constructed that allows transients to be calculated very quickly because the usual time-step restrictions are removed by the special stabilizing numerical treatment.

B. Nonhomogeneous, Nonequilibrium Modeling

A full two-fluid (six-equation) hydrodynamics model describes the steam-water flow, thereby allowing important phenomena such as counter-current flow to be treated explicitly. A stratified-flow regime has been added to the one-dimensional hydrodynamics, and a seventh field equation (mass balance) describes a noncondensable gas field.

C. Flow-Regime-Dependent Constitutive Equation Package

The thermal-hydraulic equations describe both the transfer of mass, energy, and momentum between the steam-water phases and the interaction of these phases with the system structure. Because these interactions are dependent on the flow topology, a flow regime dependent constitutive equation package has been incorporated into the code. Although this package undoubtedly will improved in future code versions, assessment calculations performed ... indicate that many flow conditions can be handled adequately with this ...

D. Comprehensive Heat Transfer Capability

The TRAC-PD2 program provides detailed heat transfer analyses ... vessel and for the loop components. Included is a two-dimensional ... treatment of fuel rod heat conduction with dynamic fine-mesh rezoning ... both bottom flood and falling film quench fronts. The heat transfer from the fuel rods and from other system components is calculated using flow regime dependent heat-transfer coefficients obtained from a generalized boiling curve based on local conditions.

E. Consistent Analysis of Entire Accident Sequences

An important TRAC feature is its ability to address entire accident sequences, including computation of initial conditions, in a consistent and continuous calculation. For example, the code models the blowdown, refill, and reflood phases of a LOCA. In addition, steady-state solutions provide self-consistent initial conditions for subsequent transient calculations. Both steady state and transient calculations can be performed in the same run, if desired. This modeling eliminates the need for calculation by different codes to analyze a given accident.

F. Component and Functional Modularity

The TRAC program is completely modular. The components in a calculation are specified through input data; available components allow the user to model ... any PWR design or experimental configuration. This gives TRAC great versatility in application to varied problems. It also allows component modules to be ... modified, or added without disturbing the remainder of the code. ... component modules currently include accumulators, pipes, pressurizers, ... generators, tees, valves, and vessels with associated internals ... lower plenum ... plenum, etc.

... program ... that is, major aspects of the calculations are performed ... example, the basic ... temperature ... heat transfer ... and other functions are performed ... separate ... accessed by ... to be upgraded readily as ... and experiments ... available.

II. VERSION

The TRAC version used in this study was TRAC-PF1, version 11.6.

III. INPUT FILES

The files necessary for recreating the TRAC results presented in this report are stored on the following Los Alamos National Laboratory nodes.

Assembled Code:

/A45/CALVERT/LOSP/CODES/TRAK116

Steady State Input:

/A45/NATC/CALVERT/STEADY/TINSS

Transient Input:

All transient input files are labeled TINRSTX where X identifies the number of the transient input deck for a given case. For example, TINRST2 is the second transient input deck used. A letter following the number indicates modified deck (modeling change, input change, etc.). The case files are:

1. Case 1 /A45/CALVERT/LOSP/CASE1
2. Case 2 /A45/CALVERT/LOSP/CASE2
3. Case 2A /A45/CALVERT/LOSP/CASE2A
4. Case 2B /A45/CALVERT/LOSP/CASE2B
5. Case 2C /A45/CALVERT/LOSP/CASE2C

APPENDIX B

THE TRAC-PF1 MODEL OF CALVERT CLIFFS-1

TRAC-PF1 is a best-estimate finite-difference computer code capable of modeling thermal-hydraulic transients in both one and three dimensions. The code solves the full set of field equations for mass, momentum and energy conservation for both steam and liquid. The Calvert Cliffs model made full use of the capabilities of TRAC-PF1.

Calvert Cliffs/Unit 1, located on the Chesapeake Bay in Maryland, began operation in January 1975. Unit 1 has a 2 x 4 loop arrangement: two hot legs and two steam generators with four cold legs and four reactor-coolant pumps. The plant operates at 2700 MW.

From a PTS standpoint, the following are important features of Calvert Cliffs:

1. the HPI pumps have a low shutoff head of 8.9 MPa (1270 psig);
2. the charging-flow pumps are positive-displacement pumps and are capable of pressurizing the primary system to above the PORVs pressure setpoint;
3. AFW flow is valved out to the lower-pressure SG when a pressure differential greater than 0.8 MPa (115 psia) exists between the two SGs;
4. isolation valves on both the feedwater lines and steamlines isolate both SGs if a low pressure of 4.6 MPa (653 psig) is sensed in either SG.
5. the two SGs have relatively large liquid inventories (102000 kg (225000 lb) at HZP and 63000 kg (138600 lb) at FP).

The Calvert Cliffs-1 TRAC model had several evolutionary steps during its development. Most of the changes resulted from efforts to improve the fidelity of various system components such as the SGs [illegible] the pressurizer. The following describes the current model of Calvert Cliffs-1.

A. Primary Side

Figure B.1 shows the TRAC noding diagram of the primary side. Table B.1 gives the metal masses for the primary system that were used in the TRAC model

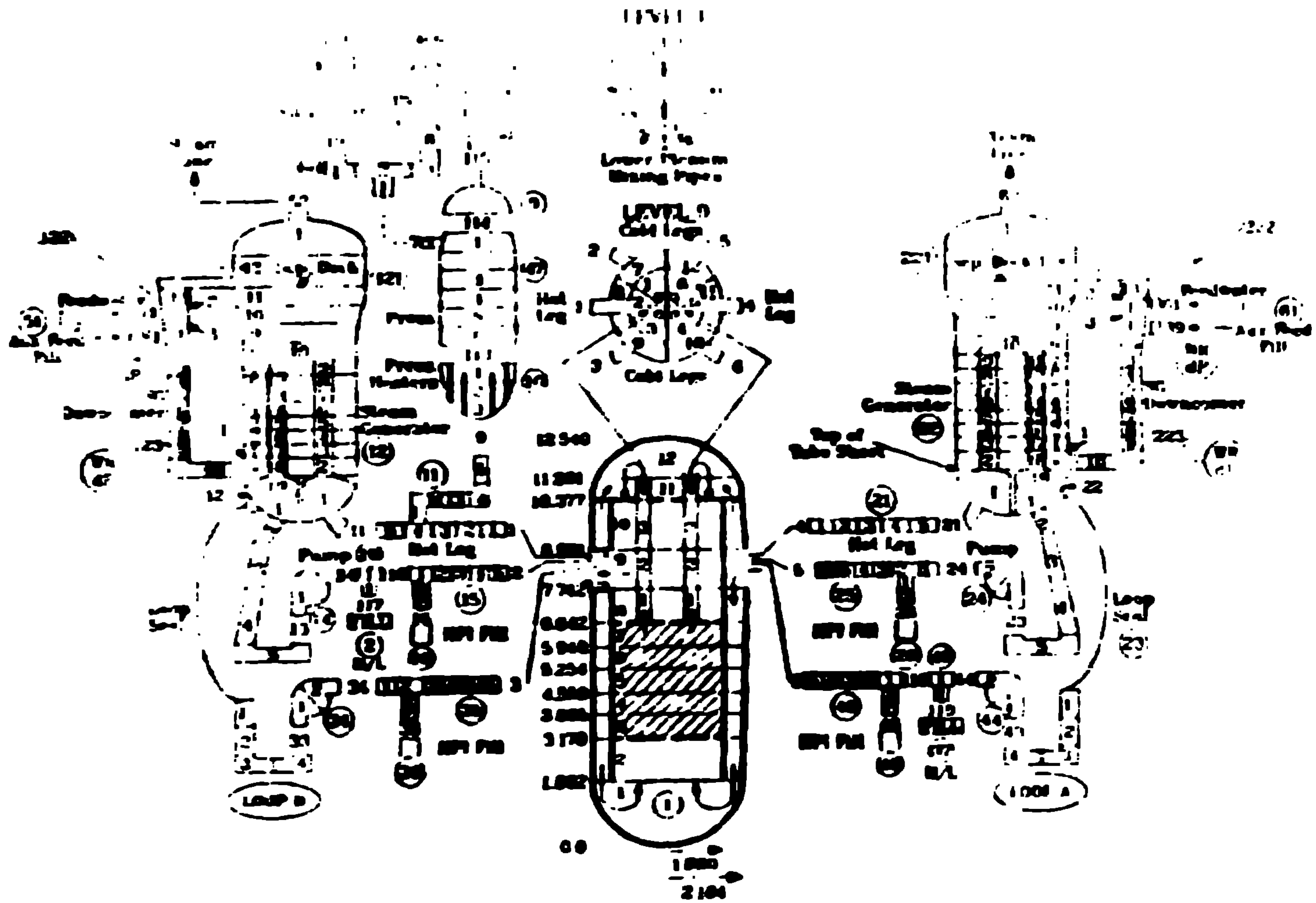

Fig. B.1.
TRAC noding diagram for the primary-side at Calvert Cliffs-1.

TABLE B-1

PRIMARY SYSTEM METAL MASS

Component	Mass kg	Mass lb
Vessel	482 954	1 064 431
Hot leg (each)	37 322	82 258
SG tubes only (each)	161 558	356 074
Cold leg (each)	130 932	288 574
Total	812 766	1 791 332

1. Vessel. The reactor vessel of Calvert Cliffs-1 was modeled three-dimensionally with twelve axial level, two radial rings, and six theta segments. The vessel model totaled 144 calculational-mesh cells.

a. Radial Rings. The vessel was divided into two radial rings, as shown in Fig. B.2. The inner ring represented the core region, located within the core-support barrel. The outer ring represented the annular downcomer region, located between the vessel wall and the core-support barrel. The vessel wall was modeled as a heat slab that interacted with the fluid in the vessel but it did not occupy any of the volume in the downcomer.

b. Azimuthal Segments. The vessel was divided into six symmetric azimuthal segments - one segment for each penetration (four cold legs and two hot legs). All six penetrations are located at the same elevation (level 9 in the TRAC noding diagram shown in Fig. B.2).

c. Axial Levels. The vessel was divided into 12 axial levels. Using the bottom of the vessel as a reference point, the top of the first level corresponded to the bottom of the core support barrel. The top of the second level corresponded to the bottom of the fuel column. Hence, the bottom end fitting of each fuel assembly was located in level 2. The active core height, [illegible], was divided into five equal axial sections. The gas plenum of each fuel rod and the [illegible] fuel assembly were located in level 8. The top of level 8 was at the same height as the bottom of the hot leg penetrations and the top of level 9 corresponded to the top of the hot-leg penetrations. The top of level 10 was at an elevation slightly above the top of the control-element assembly (CEA) grid-support plate. The top of level 11 corresponded to the top of the CEA shrouds. The CEA shrouds extended

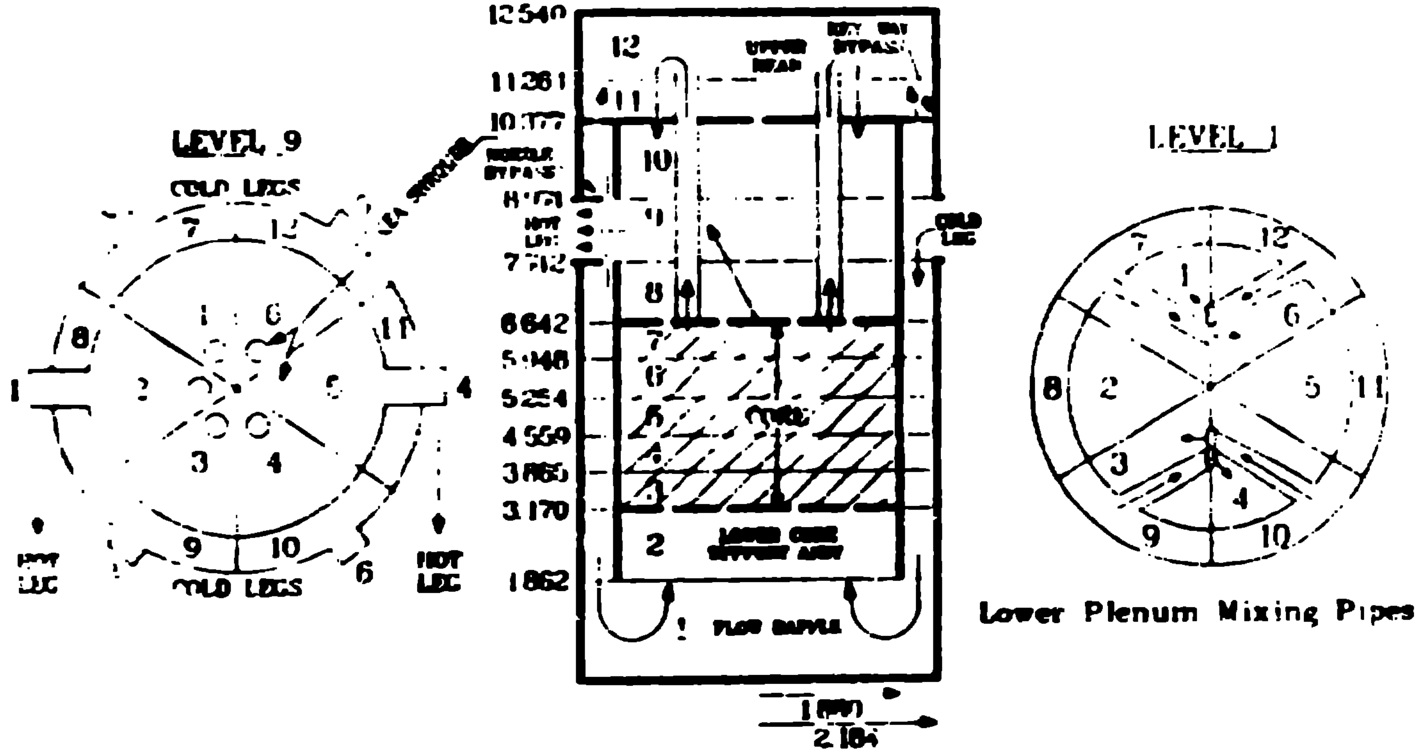

Fig. B.2.
TRAC noding diagram for the reactor vessel at Calvert Cliffs-1.

approximately 1 m (3.28 ft) into the upper head. The top of level 12 corresponded to the total vessel height of 12.54 m (41.1 ft).

d. CEA Shrouds and Bypass Flows. In the reactor vessel, a small portion of the total flow (~1.9%) goes through the CEA shrouds located in the upper plenum into the upper-head region and is referred to as bypass flow. The flow recirculates back into the upper plenum through 19 small holes located in the CEA grid support plate. The CEA shrouds were modeled in the TRAC input deck using six pipes - one for each of the six azimuthal segments in the upcomer region.

A small bypass flow (~.1%) occurs between the core-support barrel and the upper head at the keyways at the upper-head mating surface. In addition, a small bypass flow (~.6%) occurs at the mating surface between the hot-leg nozzles and the core-support barrel. Both of these bypass flows were modeled in the vessel model of Calvert Cliffs-1.

e. Fluid Mixing in Vessel. C-E performed a series of experiments to measure the amount of fluid entering a vessel similar to the Calvert Cliffs vessel via one loop and exiting via the other loop. Under the conditions of uniform flow in each cold leg and equal cold-leg temperatures, C-E measured a mixing fraction of 27%. To force the TRAC model to predict this mixing, four pipe components were placed in level 1 to induce flow from one loop to the other. The flow area of each pipe was adjusted until the mixing fraction of approximately 27% was obtained.

f. Heat Slabs. The heat slabs for the Calvert Cliffs reactor vessel were carefully defined. The volume and characteristic thickness of each component were calculated using the nominal dimensions obtained from the drawings supplied by C-E.

2. Hot Legs. The hot legs have an inner diameter of 1.2 m (48 in.) at the core barrel converging to 1.0 m (42 in.) outside the vessel. The surge line to the pressurizer was connected to the hot leg in Loop B. Both 5.8-m (18.9 ft) hot legs are divided into five calculational cells.

3. Pressurizer. The pressurizer was represented by three TRAC components. The first, PIPE component 1[illegible], [illegible] the part of the pressurizer containing the proportional and backup heaters. Control of these heaters is described in Sec. C.2. TEE component 4[illegible] was the major part of the pressurizer with a connection to the PORVs and primary SRVs. This component contained six cells, which were found to be adequate for modeling the liquid/steam interface.

PRIZER component 9, the third of these, fixed the pressure at 15.51 MPa (2250 psia) during a steady-state calculation. The liquid level in the pressurizer was controlled by makeup/letdown (also known as charging) flow during steady state. The liquid level was measured with pressure taps located in cell 1 of component 47 and cell 3 of component 10.

4. SGs. Calvert Cliffs has two U-tube SGs with 8519 tubes of 0.02 m (0.75 in.) outer diameter. TRAC modeled the tubes as a single flow path. The heat-transfer area was adjusted 10% so the TRAC calculation would match the steady-state conditions supplied by BG&E. The SG model in this study consisted of 20 primary cells and 26 secondary cells. Seventeen cells modeled the primary side of the tubes. The outlet plenum was divided into two cells so that the flow split of the cold-legs was at the correct location.

The secondary side had three TEE components with a separate injection port for the MFW and AFW flow. The downcomer converged rapidly at the third cell of the downcomer TEE. The correct recirculation flow was obtained using correct geometrical data and adjusting the additive friction factor. The moisture separator model in TRAC did not function properly at the time of the study and so phase-separation had to be induced artificially. Only two transients (the double-ended MSLBs) met conditions when the moisture-separators and dryers did not separate the steam from the liquid. For these transients, normal liquid entrainment was calculated. In the other transients a very large flow area was placed in the steam dome to prevent any liquid carryover into the steamlines following a break.

Two liquid-level-measurement instruments were modeled on the secondary. The "narrow range" level indicator used pressure taps in the steam dome and in cell [illegible] of the downcomer TEE. This level indicator was used for the reactor [illegible] trips and for controlling the MFW flow. The "wide-range" level indicator was used for AFW initiation (AFAS). Because of numerical problems not readily identified (conjectured to be caused by the interphasic drag), neither the narrow range by the interphasic drag nor wide range [illegible] level-measurement accurately simulated the expected be[illegible] [illegible] tests calculated later, the liquid inventory on the secondary was used to [illegible] AFAS. The method used is specified in each transient section.

5. Cold Legs. The pump suction [illegible] m (6.5-ft) U shaped pipe leading to the RCPs. The rest of the piping is horizontal, with the HPI and charging flow injecting downstream of the RCP. Each cold leg was modeled

separately and represented the piping from the SG to the vessel. Single-phase homologous curves for the head and torque of the RCPs were supplied by C-E. Coastdown data were also given. Two-phase homologous head and torque curves were not anticipated to be needed for the 12 transients that were specified.

6. Charging Flow. During steady state, makeup/letdown (charging) flow is injected or withdrawn to maintain a specified level in the pressurizer. If the pressurizer level drops more than 0.23 m (9 in.) below its setpoint, the charging flow is injected at a constant flow rate of 3.2 kg/s (7.0 lb/s) into one cold leg of each loop. If a SIAS occurs during the transient, charging flow is increased to a constant rate of 4.1 kg/s (9.1 lb/s) in each loop. Normally the operator terminates flow once the pressurizer level has recovered. However, for the transients in this study, it was specified that the operator would fail to do so. Thus, a charging flow of approximately 8.3 kg/s (18.3 lb/s) was injected throughout the transient.

7. HPI Flow. The HPI pumps at Calvert Cliffs have a low shutoff head of 8.[illegible] MPa (1270 psig), which is advantageous from a PTS standpoint. This limits the rate at which the system is capable of repressurizing. HPI is injected into all four cold legs based on delivery curves supplied by C-E. HPI was modeled as a mass flow vs pressure boundary condition with the fluid at a temperature of [illegible] K ([illegible]°F). The warmer fluid in the HPI lines inside (322 K (120°F)), and outside ([illegible] K (85°F)) of containment was also taken into account. When HPI was initiated, the warmer liquid was pumped into the system before the colder liquid from the storage tank filled the HPI lines.

B. Secondary Side

It was necessary to include parts of the secondary side of Calvert Cliffs in the TRAC model. This included the steam lines up to the TSVs and TBVs and about half of the feedwater train. The AFW injection line and tanks were modeled approximately.

1. Feedwater Train. Figure B.3 shows the major components of the complete main feedwater/condensate train of the [illegible] Cliffs Power Plant. The geometry of the feedwater system [illegible] isometrics and piping and instrumentation drawings supplied by BG&E. The [illegible]-pressure (HP) heaters were modeled as one heater as were the low-pressure heaters. Over 1000 m (3280 ft) of pipe length was modeled with 170 fluid cells. Cell lengths were limited to less than 10 m (32.8 ft) to minimize numerical diffusion effects. Each of the two main feedwater pumps was modeled separately. This allowed one pump to [illegible]

in manual and the other pump in automatic. The pump curves for the main feedwater pumps were obtained from Science Applications, Inc. and converted into TRAC form. Two-phase flow through the pumps was not considered possible for the PTS transients in this study and therefore two-phase homologous curves were not included in the model. The speed of the one MFW pump operating in automatic was controlled within the TRAC model using the control-system model. The TRAC feedwater/condensate train model was programmed to simulate the following operating behavior of the integral feedwater/condensate train.

Under normal full-power steady-state operation, condensate is pumped from the hotwells of the three main condensers. The condensate is pumped through a series of LP heaters and one set of HP heaters where extraction steam is used to heat the condensate prior to its entrance into the SGs. The extraction steam that condenses during the condensate-heating process in LP heaters 11, 12, and 13 is subcooled in the drain coolers and returned to the condenser/hotwells. The extraction steam that condenses in LP heaters 14 and 15, and HP heater 16 is drained into a holding tank and subsequently injected directly back into the MFW train at a point between the last two LP heaters.

Following a turbine trip from FP conditions, the bleeder trip valves in the steam extraction lines close, isolating each LP and HP heater. The drain system on each heater will continue to drain condensed extraction steam from the heater until a low liquid level is obtained, at which time the valve on the drain line will close to prevent the heater from completely draining. The drain pumps (which were injecting condensed extraction steam back into the main feedwater) will begin to "run back" and will eventually trip on low level in the drain tanks. Under these conditions, the temperature of the feedwater being supplied to the SGs will begin to decrease at a rate that is dependent on both the rate at which the feedwater is being swept out of the feedwater line and the total stored energy associated with the heat capacity of the pipe walls and the residual amount of condensed and uncondensed extraction steam remaining on the shell side of each heater.

Simultaneous to the changes that occur in the HP and LP heater sections of the feedwater/condensate train following a [illegible] turbine trip, the MFRVs will close and the MFBVs will open to a fixed position corresponding to a 33% stem position. The one MFW pump that is operated in automatic mode will run back in an effort to maintain a [illegible] MPa ([illegible] psid) pressure drop across the feedwater-valve system via the automatic control system. The other MFW pump will continue to operate at its initial constant speed of 485 rad/s (4631 rpm). This leads to a pressure drop across the feedwater valve system which exceeds .72 MPa (105 psid), and subsequently causes the automatically-[illegible] feedwater pump to run back to its minimum speed of 314 rad/s (3000 rpm). [illegible] combination of one feedwater pump operating in manual at a constant speed of 485 rad/s (4631 rpm) and the other feedwater pump operating at a [illegible] of 3[illegible] rad/s (3000 rpm) results in a net feedwater flow of approximately [illegible] rated feedwater flow (that is, ~30 kg/s (2.38 x 10^{6} lb/h) per SG).

Depending upon the initial condition specified for each transient, portions of the model shown in Fig. B.3 were deleted or altered prior to the initiation of the transient if they were superfluous. This improved the running time for the integral model. For transients initiated from hot-zero-power steady-state condition, the entire model upstream of the MFW isolation valves (MFIVs) was replaced with a constant mass-flow boundary condition of ~5 kg/s (11 lb/s) per SG for the time in which the MFIVs were open. This is justified for this initial condition because of the small changes that can occur via the automatic control system at this low power level.

For all of the transients analyzed from FP conditions (with the exception of the runaway-MFW cases), the feedwater/condensate train model upstream of the heater-tank-drain-line injection point was replaced with a constant-temperature boundary condition coupled with a variable-pressure boundary condition. The variable-pressure boundary condition was used to simulate the aggregate pressure response produced by the pumps upstream of this point during periods of time in which the flow through those pumps was changing.

The constant-temperature boundary condition was justifiable provided that [illegible] occurred within a couple thousand seconds. The total fluid swept out of the feedwater/condensate train in 1000 s (assuming a flow rate of approximately [illegible] of rated flow following a turbine trip) represented less than 60% of the total mass of fluid within the feedwater/condensate [illegible] from the discharge of LP heaters 14 to the inlet of the [illegible]. The temperature of the liquid entering the SGs [illegible], [illegible] [illegible]letely determined by the temperature distribution formed in the feedwater pipes during the initial steady state, and, for the 1000 s interim, was unaffected by the temperature of the liquid specified at the boundary condition.

In the runaway-main-feedwater transients, a special boundary condition was derived from the entire feedwater/condensate model shown in Fig. B.3. This special boundary condition is explained more fully in Sec. VII of this report.

2. Steamlines. Figure B.4 shows the TRAC model noding diagram of the steamlines. The model did not include the steamlines that supply the MFW- and AFW-pump turbines. Furthermore, some liberty was taken with the arrangement of the line to the TBV. The line to the TBV is actually between the Loop-A MSIV and the lines to the high-pressure turbines. The relative position of the lines to the TBV and HP turbines is inconsequential because both lines are downstream of the MSIVs and the TBVs and TSVs are never open at the same time.

Venturi-flow restrictors were located between cells 1 and 2 in components 52 and 62 about 10 m (32.8 ft) from the SGs. They were calibrated to deliver 170% of FP steam flow under choked-flow conditions with 5.7 MPa (850 psia) SG pressure.

Five sets of valves are in the steamlines: the TSVs, MSIVs, SRVs, ADVs, and TBVs. The two TSVs in the TRAC model represented four actual valves and closed in 0.25 s following a turbine trip. The TBVs were calibrated to deliver FP steam flow with a SG pressure of 5.86 MPa (850 psia). The MSIVs closed in 3.5 s following SGIS and never reopened. The SRVs represented a bank of pressure-modulated valves. They began to open when the upstream pressure reached 6.89 MPa (1000 psia) and were wide open when the pressure reached 7.45 MPa (1080 psia). A flow area vs pressure table was specified to simulate the behavior of the actual bank of valves. Each SRV was calibrated to deliver 763 kg/s (6×10^6 lb_m/h) of saturated steam when the valve was wide open and the upstream pressure was 7.45 MPa (1080 psia).

The ADVs were trip-activated and controlled by the average reactor temperature. They opened in 3.0 s following a reactor/turbine trip when the average reactor temperature exceeded 552 K (535°F). The flow area varied linearly with the average reactor temperature between 552 K and 565 K (535°F and 557°F). The small hysteresis between the closing and reopening temperature was not modeled and the stroke rate was limited to 33%/s. The TBVs were trip-activated and controlled by either the average reactor temperature or the steamline pressure upstream of the valves. The TBV represented four actual valves, and its stroke rate was also limited to 33%/s. During steady-state the TBV was regulated to limit the steamline pressure to 6.24 MPa (905 psia); in practice, the TBV is fully closed during full power and ~1 open during hot zero

Fig. [illegible]

[illegible] diagram for the feedwater train at [illegible]

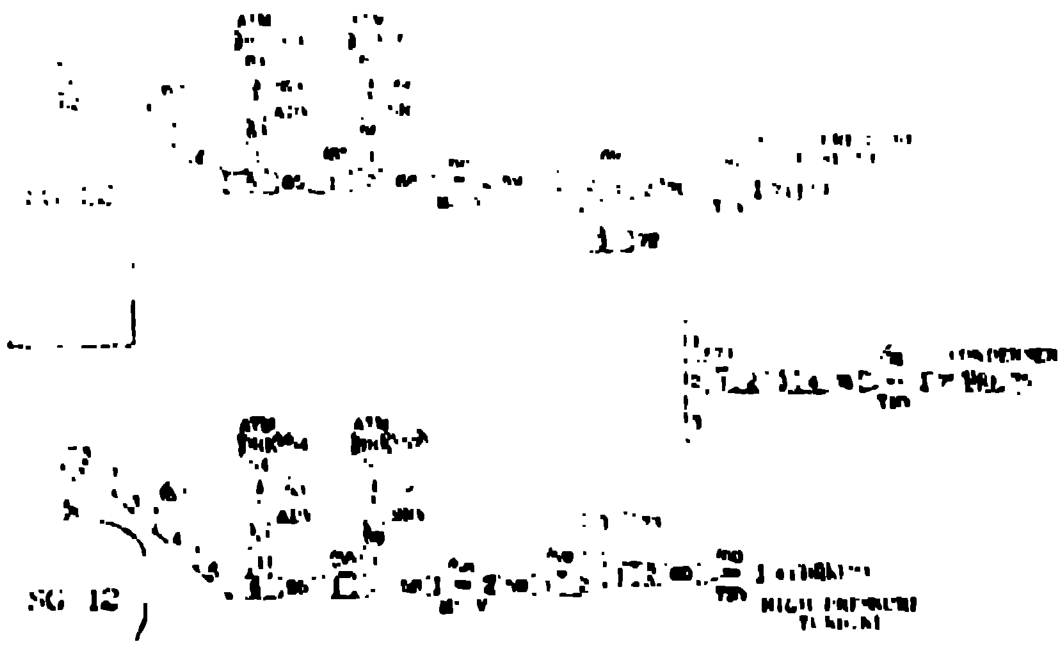

Fig. [illegible].6.
TRAC noding diagram for the steamlines at Calvert Cliffs-1.

[illegible]

[illegible] steamline pressure [illegible] in the [illegible] [illegible]. The average [illegible] temperature was [illegible] temperature in each loop. The temperature in each loop was [illegible] the temperature in the hot leg with that [illegible] of the [illegible]

[illegible] and Trips

[illegible] the [illegible] for the trips as [illegible] addition to modeling these [illegible] components explicitly [illegible] of systems that were [illegible] behavior of the water [illegible] condensate at large [illegible] flow is [illegible] flow when the [illegible] this way, [illegible] large auxiliary systems are modeled [illegible] effort.

[illegible]

TABLE [illegible]

SE[illegible] FOR [illegible]PS AND SIGNALS

[illegible]	Setpoints
[illegible]	
1. Reactor tri[illegible]	a. P_{PRI} [illegible] MPa [illegible] (psia) b. SG level [illegible] (-[illegible] in.) (on narrow range instrume[illegible]) c. Asymmetric [illegible] pressure signal d. SGIS e. Turbine trip
2. [illegible] on [illegible] thermal margin	P_{PRI} < 1[illegible].1 MPa ([illegible] psig)
3. HP[illegible] flow	P_{PRI} < 8.8 MP[illegible] ([illegible] psig)
4. [illegible]arging flow (3 pumps)	SIAS
[illegible] Pa tri[illegible]	SIAS + 30 s (as specified by ORN[illegible])
[illegible] open	P_{PRI} > 16.[illegible] MPa (2400 psia)
[illegible]ondary side	
T[illegible]bine trip	a. Reactor trip b. SG-level > +1.27 m (+50 in.) (on narrow-range instruments)
	$P_{[illegible]}$ < 4.6 MPa (653 psig) P_{cont} > 0.[illegible]27 MPa (4 psig)
[illegible] close	SGIS
[illegible]	[illegible] trip

Trips	Setpoints
5. MFRVs open to [illegible]%	Turbine trip
6. MFW pump trip	a. [illegible] b. Low suction pressure resulting from low liquid inventory in hotwell (less than 1 kg (2.2 lb)) c. liquid in line to turbine-pump (a fictitious trip included to account for potential MFW-turbine damage)
7. AFA (method varied in calculations)	a. SG level < −4.3 m (−170 in.) (on wide-range instruments) or b. SG liquid inventory < 45000 kg (99 000 lb)
8. Asymmetric-SG-pressure [illegible]	ΔP_{SG} > 0.8 MPa (115 psid)
9. AFW flow	AFAS = flow valved out to SG at lower pressure if asymmetric-SG-pressure signal has been received
10. MSIVs close	SGIS
11. ADVs modulate	552 K < T_{PRI} < 565 K (535°F < T_{PRI} < 557°F)
12. [illegible] modulate	552 K < T_{PRI} < 565 K (535°F < T_{PRI} < 557°F) or 6.17 MPa < P_{SEC} < 6.24 MPa (895 psia < P_{SEC} < 905 psia), whichever normalized value is higher
13. SRVs open	P_{SEC} > 6.9 MPa (1000 psia)
14. [illegible] close	Turbine trip

a. Power. During full power operation the reactor thermal power is a constant 2700 MW, and the RCP thermal power is 17.38 MW. The primary temperature adjusts itself to the value necessary to effect transfer of the power to the secondary system. A reactor trip will occur if at least one of the following conditions is satisfied:

(a) the primary pressure is less than 14.5 MPa (2100 psia);

(b) the narrow-range SG level is less than -1.27 m (-50 in.);

(c) the SG pressures differ by more than 0.8 MPa (115 psid);

(d) SGIS occurs; or

(e) the turbine trips.

All these trips were modeled.

Following a reactor trip, the turbine trips and the steam dump/bypass system regulates the ADVs and TBVs to control the average reactor temperature. Above 565 K (557°F) the valves are wide open; below 552 K (535°F) they are fully closed, and between these limits, the flow area is adjusted linearly with temperature.

b. Pressure. The primary pressure normally is controlled by the pressurizer heater/sprayer system. Although the heaters were modeled in the steady state TRAC model, the sprayer was not. However, for the LOSP transient, APS was modeled with three components: a pipe, valve and a fill. Excessive pressure relief was provided by the trip-controlled PORVs, which opened fully in 1.0 s after the pressure reached 16.5 MPa (2400 psia) and closed completely 1.0 s after the pressure fell below 15.7 MPa (2280 psia).

Operation of the proportional and backup heaters was prohibited whenever the pressurizer level fell below 2.56 m (101 in.); if the level subsequently rose above 2.56 m (101 in.), the proportional heaters, but not the backup heaters*, were reactivated. The proportional heaters have a setpoint of 15.5 MPa (2250 psia) and deliver a maximum of 100 kW at their setpoint to compensate for steady-state heat losses from the system. Therefore, the proportional heaters were modeled as a heat source/sink that delivered power to the pressurizer liquid linearly between a maximum of 150 kW at 15.3 MPa (2225 psia) and a minimum of -150 kW at 15.7 MPa (2275 psia).

*In the plant, two of the four banks of backup heaters come back on automatically if the level recovers. However, we did not model this as pressurization was not required beyond that obtained by throttling APS flow.

c. Flow. The RCPs were modeled to operate at constant speed until the operators tripped them 30 s after SIAS, as specified by Oak Ridge National Laboratory. The SIAS trip occurred when the pressure fell below 12.1 MPa (1740 psig).

d. Volume. The primary system volume is normally controlled by the makeup/letdown system. In the event of a severe depressurization, however, SIAS overrides the makeup/letdown system, and the safety-injection system begins injecting borated water into the system.

The makeup/letdown flow was determined by a proportional pressurizer-level controller. The control setpoint was 5.5 m (215 in.) during full power and 3.7 m (144 in.) during hot zero power, and the controller gain was 28.34 kg/s-m (11.45 gpm/in.). The maximum make-up flow rate of 6.48 kg/s (103 gpm) was achieved when the level fell .23 m (9 in.) below the setpoint, while the maximum letdown flow of 8.3 kg/s (132 gpm) was achieved when the level increased 0.23 m (9 in). above its setpoint. The makeup/letdown flow was split evenly between two diagonally-opposite cold legs. Following any SIAS signal, the charging flow was increased to 8.3 kg/s and was not controlled automatically by pressurizer level. The SIAS was disabled in the transient calculation to simulate operator action to prevent activation of this system which would hold up system pressure and prevent depressurization. Furthermore letdown was disabled to limit primary inventory loss and allow examination of a closed system.

2. Secondary-Side Controllers. This subsection describes the parts of the control system that regulate the pressure, flow, and volume on the secondary side.

a. Pressure. During full power, the secondary pressure was determined by the inlet pressure to the turbine and it was not directly controlled. Following a turbine trip, the pressure was controlled only if it exceeded 6.17 MPa (895 psia), in which case the flow area of the TBV was adjusted to maintain the pressure between 6.17 MPa and 6.24 MPa (895 psia and 905 psia). Normally the action of the steam dump/bypass system vents enough steam to maintain the secondary pressure well below 6.17 MPa (895 psia) following a turbine trip. During hot zero power, the flow area of the TBV was adjusted to maintain the secondary pressure between 6.17 MPa and 6.24 MPa (895 psia and 905 psia).

b. Flow. The MFW flow is regulated by an instantaneous level error, integrated level error, and instantaneous feed-steam mismatch. The TRAC control system uses these same signals with the addition of the integrated feed-steam mismatch to regulate the MFW flow. The reset time of both the level error and feed-steam mismatch integrators was 240 s (4 min), the gain on level control was 100%/m, and the gain on feed-steam mismatch was 0.2%/kg/s. Following a turbine trip, the MFRVs closed in 20.0 s and the MFBVs opened to a stem position of 33% in 1.33 s. During hot zero power the MFW flow was held constant.

During full power, the MFW pump speed was regulated to maintain the pressure drop across the MFRV to Loop-A SG at 0.72 MPa (105 psid). The integral controller had a minimum output of 314.16 rad/s (3000 RPM), a maximum output of 586.4 rad/s (5600 RPM), and an option to hold the speed of Loop-B MFW pump constant.

c. Volume. As discussed previously, during full power the SG level is normally controlled by regulating the MFW flow. In the event of loss of SG mass, a low SG-level indication by the wide-range instrument would initiate AFW delivery to prevent SG dryout.

Because the temperature of the MFW entering the SGs decays when flow from the heater-drain tank ceases, it is important to know the inventory of the tank. Although the tank was not modeled explicitly, the steady-state inventory, the inlet, and the outlet flow were all known. Before a turbine trip, the inlet and outlet flow were assumed to balance; but after a turbine trip, the inlet flow became zero. Therefore, a heater drain-tank mass integrator began reducing the steady-state tank inventory by the known outlet flow following a turbine trip. When the residual tank inventory fell below a specified value, the outlet flow was tripped off to simulate the low-tank-level pump trip that would occur.

In the event of a steamline break, steam that normally would remain in the system escapes, and the condenser/hotwell inventory would fall below a specified value, thus it was necessary to know the inventory of the condenser/hotwell. Although the tank was not modeled explicitly, the steady-state inventory and the inlet and outlet flows were all known. Therefore, a condenser/hotwell mass inventory calculator was constructed with control-block operators to indicate when depletion of the inventory would trip the MFW pumps.

Although the AFW condensate storage tanks were not modeled explicitly, the initial inventory and AFW flow rate were known. Therefore, an AFW mass flow integrator was used to reduce the initial inventory until the residual inventory was less than 1.0 kg, at which time the AFW flow was reduced to zero.

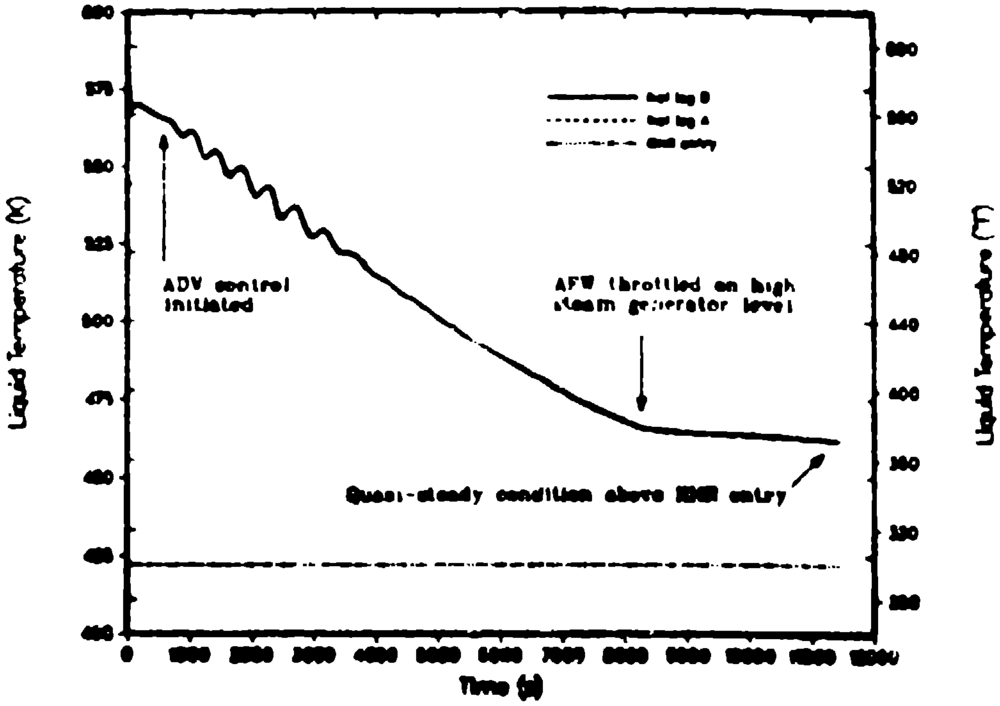

Fig. 11.
Primary hot-leg temperatures, Case 2.

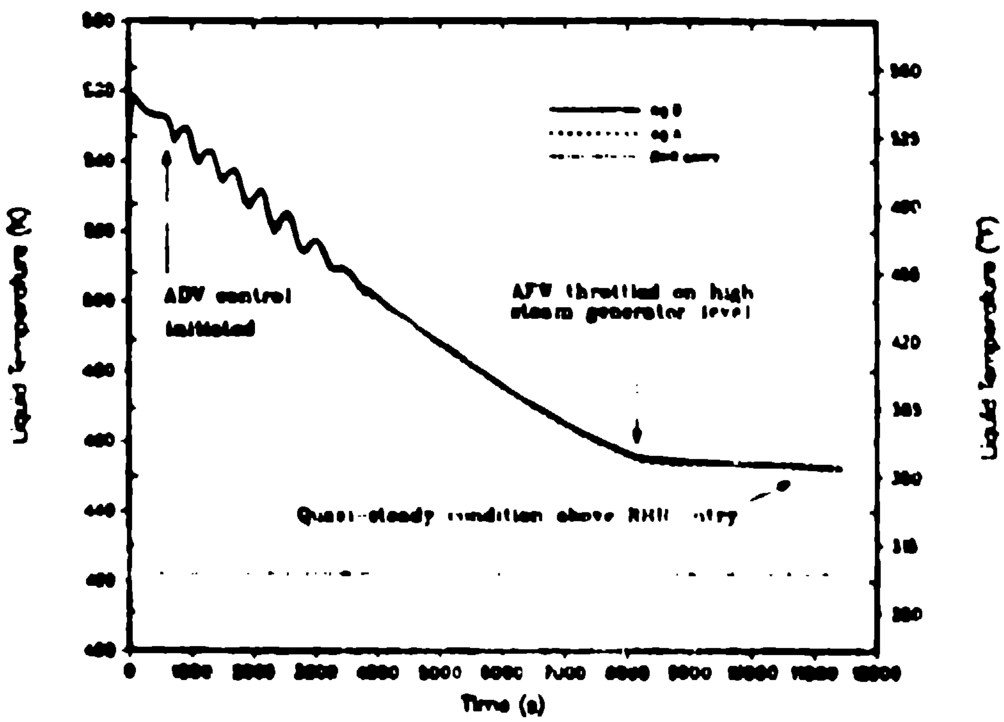

Fig. 12.
Secondary liquid temperature, Case 2.