EGG-M-92236

Conf-9209?3--7

EGG-M--92236

LARGE BREAK LOCA CALCULATIONS FOR THE AP600 DESIGN[a]

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ABSTRACT

This paper presents the application of RELAP5 to the calculation of a Large Break (200% double-ended rupture) Loss-of-Coolant-Accident (LBLOCA) at the reactor vessel inlet for the proposed Westinghouse AP600 design. A parametric calculation was also performed to determine effects of loss of a complete Emergency Core Cooling System (ECCS) train. These calculations were performed over the core blowdown, refill, and reflood phases of the LBLOCA and did not address long term cooling. RELAP5 was shown to be adequate for system response calculation over the period of interest. The passive safety systems were predicted to effectively mitigate the consequences of LBLOCAs; the calculations showed less severe thermal responses than for a current generation Pressurized Water Reactor (PWR) plant. The two primary differences between the AP600 design and a current generation plant that affect LBLOCA response are the lower core thermal power, which results in lower temperatures during the blowdown phase, and the long duration accumulator injection, which provides ample core inventory makeup for final quenching.

INTRODUCTION

The U. S. Nuclear Regulatory Commission (USNRC) is performing exploratory analyses to evaluate the performance of the proposed Westinghouse Advanced Passive 600 MWe (AP600) reactor design. AP600 is a two-loop pressurized water reactor with one hot leg, one steam generator, two reactor coolant pumps, and two cold legs per loop.[1] The major difference between this and typical PWR designs is the passive nature of safety and support systems. Conventional accumulators are present; however, the remainder of the safety injection, residual heat removal, containment cooling, containment spray, and emergency ventilation systems rely solely on gravitational forces (elevation-driven liquid injection and buoyancy-driven natural circulation cooling). The Idaho National Engineering Laboratory (INEL) has performed Large Break (200% double-ended rupture) Loss-of-Coolant-Accident (LBLOCA) calculations for the proposed design, using RELAP5/MOD2.5. These were best estimate (BE) scoping calculations, intended to characterize the response of AP600 to this class of accident and determine overall system performance. This paper presents descriptions of the AP600 passive safety features and of the RELAP5 model used for the calculation, a discussion of the LBLOCA scenario itself, an interpretation of the results, and the conclusions of the study.

[a]Work supported by the U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, under DOE Idaho Field Office Contract DE-AC07-76ID01570.

DESCRIPTION OF AP600 PASSIVE SAFETY FEATURES

The following is a description of the features and functioning of the passive safety systems.[2,3] Two Core Makeup Tanks (CMTs) replace the high pressure injection systems, one In-containment Refueling Water Storage Tank (IRWST) replaces the low pressure injection systems, and a full-pressure, full decay power, Passive Residual Heat Removal (PRHR) system, with a heat exchanger submerged in the IRWST, replaces the decay heat removal system. Two conventional, spherical accumulators are present. All valves in the safety system are check valves, fail-safe air operated valves, or motor operated valves supplied from redundant battery banks. During normal operation, the CMTs are vented to the pressurizer; the Safety Injection Actuation ("S") signal causes the opening of pressure equalization valves to vent the CMTs to the cold legs in the loops opposite the pressurizer. The "S" signal also opens injection valves connecting the CMTs to the Passive Safety Injection System (PSIS) lines which inject liquid directly into the reactor vessel downcomer. As the CMT level drops, four stages of the Automatic Depressurization System (ADS) are initiated in succession to reduce Reactor Coolant System (RCS) pressure to a level which allows IRWST draining and long term cooling. Stages 1-3 vent the pressurizer to spargers submerged in the IRWST. Stage 4 vents the loop hot legs directly to the containment. The accumulators, as well as the IRWST, are connected to the PSIS lines by check valves. Accumulator injection occurs during depressurization, as in a conventional Pressurized Water Reactor (PWR). The elevated, gravity-drain IRWST is available when RCS pressure drops to near that of the containment. The containment itself includes a passive cooling system (the PCCS) and a sump valve system which returns liquid to the primary coolant system. There are other differences between AP600 and present generation PWRs. Each steam generator and its associated pair of reactor coolant pumps are integrated into a single structure. This design eliminates the pump suction loop seal and simplifies the support structure. Also, the pressurizer has been enlarged to supply leakage makeup and to better withstand transients. In summary, AP600 represents a significant departure from conventional PWR design primarily because of gravity-driven emergency core cooling and injection systems.

DESCRIPTION OF RELAP5 MODEL

A preliminary RELAP5 AP600 model has been developed which represents all of the major primary, secondary, and passive safety systems components,[4] and is shown in Figure 1. The design data for the model represents the best available information effective August 1991. Both loops are explicitly modeled, including the hot leg, steam generator, and the two cold legs and associated pumps.

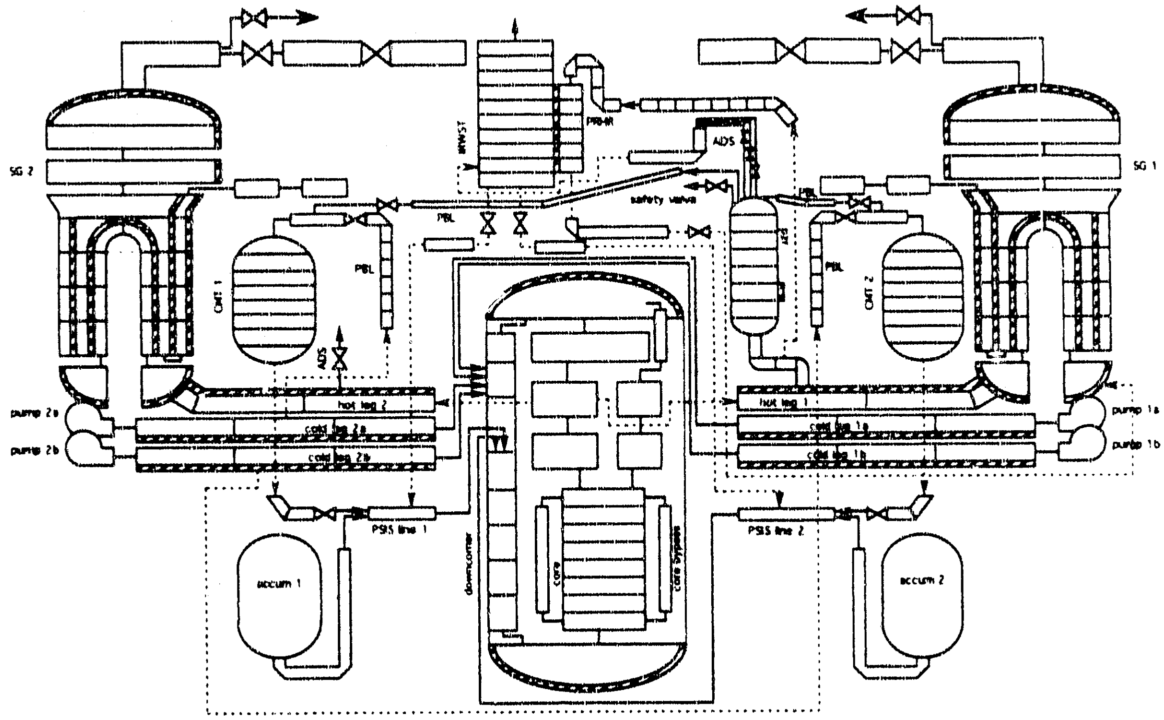

Figure 1. RELAP5 Nodalization Scheme for AP600.

The loop designated "1" has the pressurizer and the PRHR system connections, and the "2" loop cold legs have the CMT pressure balance line connections. Modified Westinghouse "F" type steam generators are used; they were taken from an existing RELAP5 model and modified to incorporate the known design features of the AP600 steam generators. The reactor coolant pump models contain the AP600 homologous curves for single-phase operation. Two-phase head and torque multipliers and degradation data were from Combustion Engineering pump data, because they were thought to be more representative than Semiscale pump data. Hydraulic torque and inertia were set to obtain AP600 design values for pump heating and coastdown characteristics.

The reactor vessel model is accurately detailed and contains representations of all internal components; hydraulic volumes represent the downcomer, lower plenum, core, reflector, guide tubes, upper plenum, and upper head regions. The fuel region was represented by a single stack of six axial levels of heat structures with the axial power peak at the level above the core midplane. The axial peaking factor was estimated as 1.29; actual power profile information was not available. Other heat structures represented the reflector, core barrel, and the metal masses of the vessel, lower and upper heads, and guide tubes and other structures in the upper plenum and upper head regions. The downcomer is a pseudo-two-dimensional component represented by a ring of eight annular sectors connected using crossflow junctions in the horizontal direction, as shown in Figure 2. This modeling scheme allows a limited multidimensional flow representation: horizontal momentum flux and spacial acceleration are neglected but temporal acceleration and friction terms are included. All major vessel bypass paths are included except for outlet nozzle leakage. Because of the elevated cold leg configuration, this path could not be represented without imposing a severe courant limit on the calculational time step. Flow through this path was incorporated

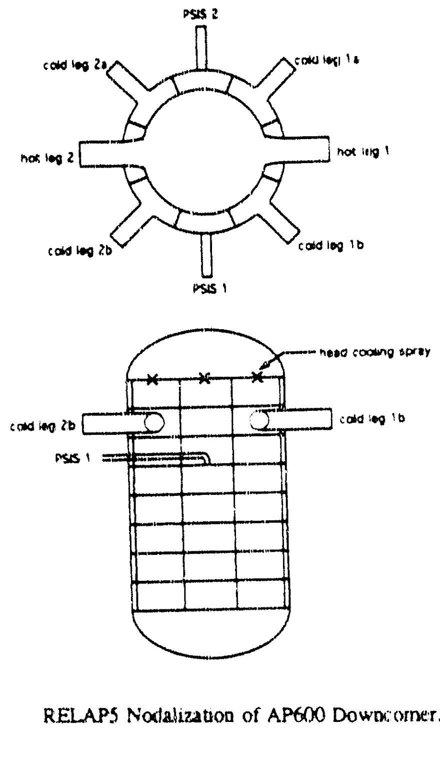

Figure 2. RELAP5 Nodalization of AP600 Downcomer.

in the upper head cooling spray bypass. Other bypass paths are the guide thimble flow, core cavity bypass, and reflector cooling flow. The total bypass flow is representative of the Westinghouse design value. The passive safety features were modeled using available Westinghouse design data for elevations, liquid volumes, and line losses. No details of ADS piping losses are yet available and the RELAP5 accumulator model does not presently include the capability for spherical geometry.

TRANSIENT DESCRIPTION

The break location was at the point where one loop cold leg attaches to the reactor vessel inlet nozzle. It is the most severe location for a large-break LOCA in a current generation PWR because a flow stagnation occurs in the core within the first few seconds of the transient. This is brought about by the reversal of fluid flow direction in the downcomer which causes a relatively low pressure region in the core. Steam expands upward into the upper core region as the upper plenum fluid empties into the loop hot legs, and downward into the lower core region as the core liquid drains. This steam blanketing, or flow stagnation, occurs during the redistribution of fuel stored energy and results in a cladding temperature excursion. Liquid drainback from the upper head provides temporary core cooling and a partial or complete core rewet. A second temperature excursion follows the end of drainback, and is driven by core decay heat. Successful response of the emergency core cooling systems (ECCS) is necessary to replenish vessel liquid inventory and reestablish core cooling in order to mitigate this second thermal excursion. In AP600, the accumulators represent the key safety system for mitigating a large break. Because of the absence of pumped Low Pressure Safety Injection (LPSI), the system hydraulic response must achieve core reflood and fuel bundle quenching by the time the accumulators are empty. If not, the remaining gravity-head injection systems may not supply the driving head required to achieve core liquid penetration. For this reason, two calculations were performed: the first was a base case, with normal ECCS function, and the second was with an entire ECCS train disabled. In this way, the effectiveness of the accumulators to reflood the core could be shown.

RESULTS

Normal ECCS Function (base case)

The calculated chronological sequence of events is shown in Table 1. After the break opened, the calculational results showed

Table 1. Chronology of Events

Event	Time (s)
Scram, trip RCPs, Isolate SGs	1.5
Safeguards Signal	2.3
Begin Accumulator Injection	10.
Begin Core Reflood	28.
Complete Fuel Quenching	60.
End Accumulator Injection	116.

rapid depressurization to the reactor scram setpoint. The turbine stop valves were closed and the main feedwater flow was terminated upon reactor scram, and the Reactor Coolant Pumps (RCPs) were tripped. The Safeguards "S" signal then occurred, which opens the valves in the CMT pressure balance and injection lines to trigger the actuation of the passive safety systems. The pressurizer was essentially emptied in the first six seconds. By this time, as shown by Figure 3,

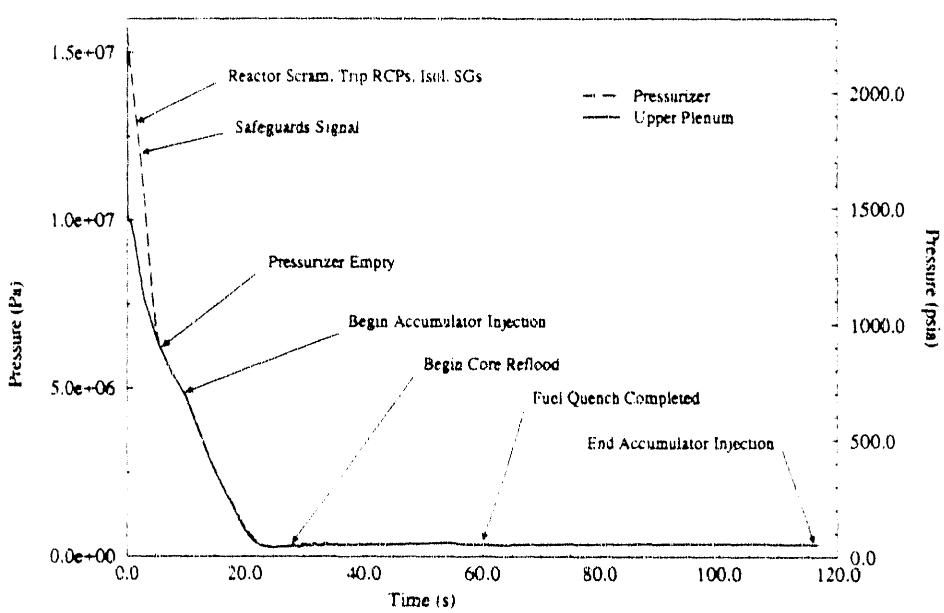

Figure 3. Pressurizer and Upper Plenum Pressure Responses.

system pressure was down to ~6.9 MPa (1000 psia); it reached accumulator pressure by ~10 seconds. Accumulator injection caused increased decompression rate; system pressure was down to that of containment and break flow was essentially stopped at ~22 seconds, thus ending the blowdown phase of the transient.

The draining of the core and lower plenum and the refill and reflood are shown by the core and lower plenum collapsed liquid level responses, Figure 4. The core was essentially emptied by ~7 seconds. The small level recovery shown between 7 and 12 seconds was due to liquid draining from guide tubes and upper head. The lower plenum refill began at 23 seconds and core reflood started at 28 seconds. Core quench was completed by 60 seconds. Final core level was stabilized at ~3 m (9.8 ft) below the hot leg centerline, resulting in a core collapsed liquid level of about 70% of core height. Accumulator injection was completed at ~116 seconds.

Cladding temperature response, shown by Figure 5, indicates the two heatup periods previously discussed. The early heatup began at about 3 seconds into the transient; it was predicted to occur only at the first and second axial level (the lowest third of the core), and resulted in a maximum cladding temperature of 598K (617°F). Heatup was prevented in the upper core region by liquid from the guide tubes. This liquid cooled the upper core rather than being swept out the broken loop hot leg because CMT injection flow, starting at 2.3 seconds, caused condensation in the downcomer and reduced the local pressure. This pressure reduction reduced the dynamic head responsible for the core flow stagnation and permitted the entry of cooling liquid from above. A total core rewet occurred at about 9 seconds due to cooling from liquid supplied by the guide tubes and upper head. The second heatup began at 17 seconds, at which time core and vessel inventory was nearly depleted, and resulted in a maximum cladding temperature of 569K (565°F), a value significantly lower than for the early heatup. As shown, the lower half of the core was quenched at 45 s, the hot plane at 53 s, and the highest axial level at 60 s.

The calculations were ended when the accumulators were depleted. There were two reasons for this, both related to RELAP5 performance. First, the code encounters a numerical failure when the pressurizing gas exits the accumulator. Thus, the effects of nitrogen pressurization on the downcomer cannot be simulated. Secondly, condensation effects associated with the CMTs are overpredicted, thus distorting the pressure distributions in the system. When CMT injection begins, condensation occurs in the top of each CMT, which is connected to a loop cold leg and pressure-equalized with it. The overprediction arises from a known weakness of RELAP5, i.e. each phase present in a volume is represented by a single temperature. Temperature gradients established within the phases, which should limit subsequent condensation, are not represented. As a result, the condensation calculated by the code is overpredicted because the temperature difference is too high. The effect is large oscillations, or spikes, in the pressure solution, thus distorting the available driving head for CMT flow. Therefore, the transient calculation was ended prior to the long term cooling phase of the transient.

ECCS Train Failure

The difference in maximum cladding temperature responses between the case with ECCS failure and the base case are shown in Figure 6. The early heatup was predicted as more severe and resulted in a maximum cladding temperature of 657K (723°F). The maximum occurred at the third axial level from the bottom of the core (immediately below the core midplane); this heat structure showed no excursion in the base case. The difference stems from reduced CMT injection in the first few seconds of the transient. The

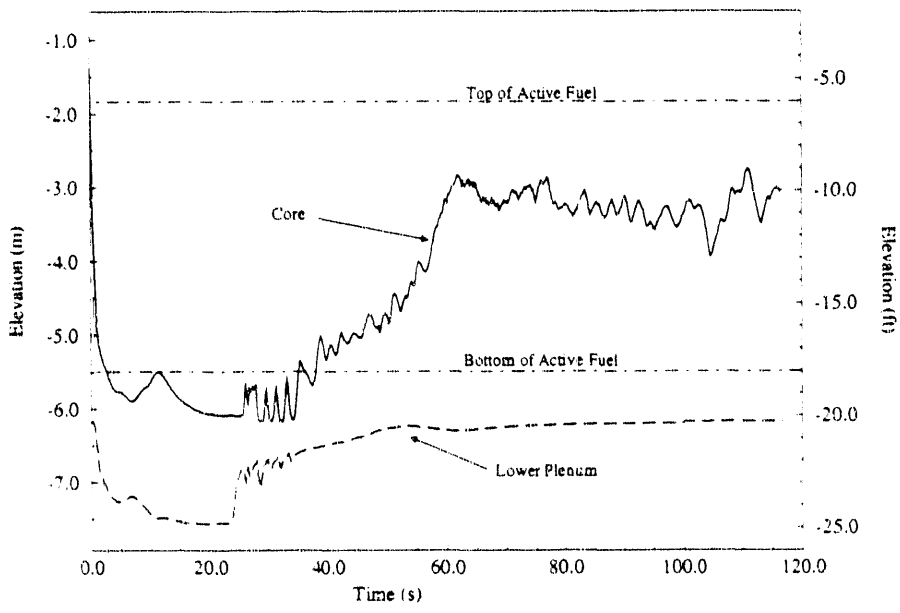

Figure 4. Core and Lower Plenum Collapsed Liquid Level Relative to Hot Leg Centerline.

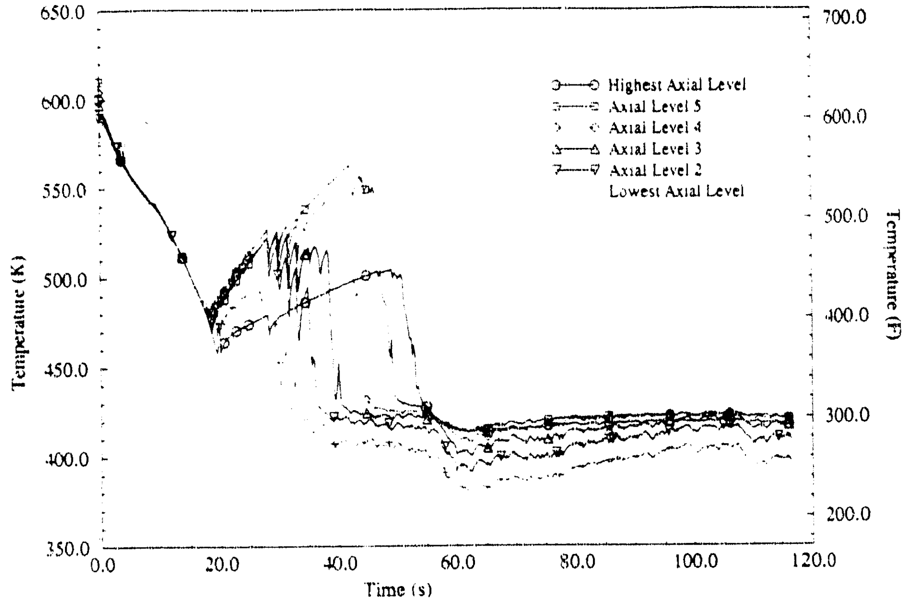

Figure 5. Cladding Surface Temperature Responses.

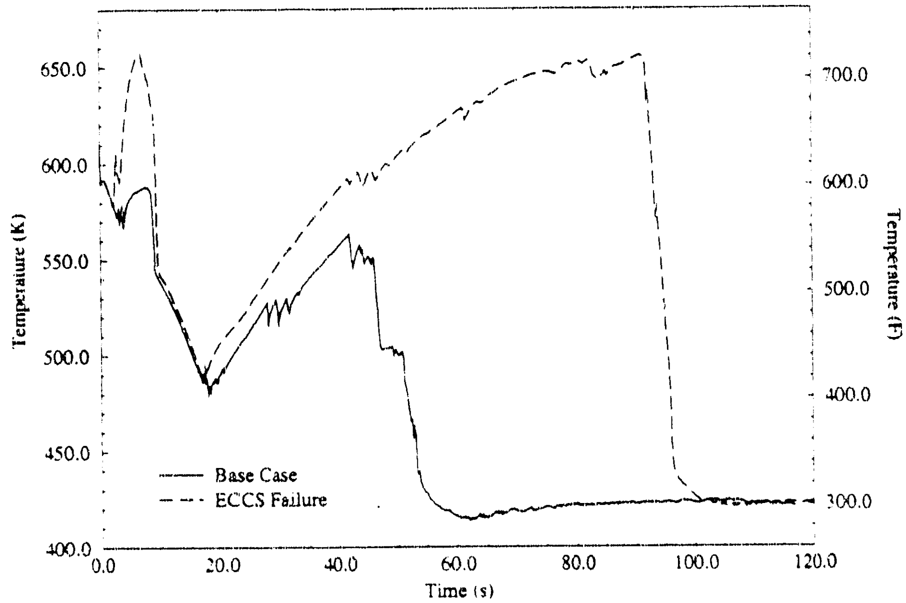

Figure 6. Maximum Cladding Surface Temperatures for Base Case and ECCS Failure.

DISCLAIMER

downcomer condensation due to liquid from a single CMT was significantly less compared to the base case; the pressure in the downcomer remained higher, and the dynamic head in the core did not decrease as quickly. This caused less driving head for liquid flow from the guide tubes into the core, and the cooling flow did not penetrate below the core midplane. Therefore the fuel heatup region was more widespread, and extended to a region with higher heat flux.

The differences seen in cladding temperature responses during the late heatup were directly related to the core inventory difference. Nevertheless, with the single accumulator available, there was sufficient inventory makeup to produce a successful core quench. The maximum cladding temperature was 655K (719°F), and occurred at the fifth axial level (first level above the core hot plane).

DISCUSSION AND CONCLUSIONS

There are two major differences between this LBLOCA calculation and the behavior expected of current generation PWRs, as determined from calculations and from the LOFT Loss-of-Coolant Experiments.[5,6] First, significantly reduced peak cladding temperature values are calculated. For a current generation 3400 MWt PWR, the cladding temperature peak during blowdown is in the neighborhood of 870K (1100°F).[7] Because the dominant phenomenon affecting the magnitude of this excursion is fuel stored energy, the lower temperatures are directly attributable to the lower thermal power in AP600.

The second major difference, compared to the behavior of a current generation PWR, is that the duration of accumulator injection is substantially longer in AP600. In a current generation PWR, accumulators are depleted well before core quenching is completed. As noted, the accumulators are critical to the successful mitigation of the LBLOCA in AP600, because of the absence of pumped injection systems. As indicated by the results of the simulation, the accumulators provide adequate inventory replacement to accomplish core reflood, even with reduced ECCS availability.

RELAP5 adequately predicted the system response for the blowdown, refill, and reflood portions of the LBLOCA. Long term cooling calculations are beyond the present capabilities of the code. The results of the calculations substantiate mitigation of the LBLOCA transient in the AP600 design, which is attributed to the sizing of core thermal power and the inventory makeup capability of the passive safety systems.

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