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ANALYSIS OF AN AP600 INTERMEDIATE-SIZE LOSS-OF-COOLANT ACCIDENT*

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ABSTRACT

A postulated double-ended guillotine break of an AP600 direct-vessel-injection line has been analyzed. This event is characterized as an intermediate-break loss-of-coolant accident. Most of the insights regarding the response of the AP600 safety systems to the postulated accident are derived from calculations performed with the TRAC-PF1/MOD2 code. However, complementary insights derived from a scaled experiment conducted in the ROSA facility, as well as insights based upon calculations by other codes, are also presented. Based upon the calculated and experimental results, the AP600 will not experience a core heat up and will reach a safe shutdown state using only safety-class equipment. Only the early part of the long-term cooling period initiated by In-containment Refueling Water Storage Tank injection was evaluated. Thus, the observation that the core is continuously cooled should be verified for the later phase of the long-term cooling period when sump injection and containment cooling processes are important.

INTRODUCTION

The AP600 is an advanced passive 600 MWe reactor design being developed by Westinghouse in conjunction with the US Department of Energy's Advanced Light Water Reactor Technology Program. The AP600 has been submitted to the United States Nuclear Regulatory Commission (NRC) for design certification. In accordance with the design certification requirements of 10CFR52.47, advanced reactor applicants are required to submit neutronic and thermal-hydraulic safety analyses over a sufficient range of normal operation, transient conditions, and specified accident sequences. Review and confirmation of these analyses constitute an important activity in the NRC's AP600 design certification effort. In support of its design certification activities, the NRC performs audit calculations using best-estimate thermal-hydraulic codes. The NRC uses the TRAC code for analyzing AP600 large-break loss-of-coolant accidents (LBLOCAs). In addition, TRAC is being used to evaluate the AP600's response to an intermediate-break LOCA (IBLOCA). In this paper, the response of the AP600 to an IBLOCA event, a double-ended guillotine break (DEGB) of a direct-vessel-injection (DVI) line, is analyzed. The TRAC DVI-line IBLOCA is a direct counterpart to the Westinghouse calculation of an AP600 DVI-line IBLOCA.[1]

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The AP600 is a two-loop design with one hot leg, one steam generator, two reactor coolant pumps (RCP), and two cold legs in each loop (Fig. 1). A pressurizer is attached to one of the hot legs. The reactor coolant pumps, a canned-motor design, are integrated into the outlet plena of the steam generators. The loop seal is eliminated with this design. The core is designed for a low power density. The design incorporates passive safety systems (Fig. 2) that rely only on redundant/fail-safe valving, gravity, natural circulation, and compressed gas. Two Passive Safety Injection System (PSIS) trains connect directly to the reactor-vessel downcomer through DVI lines. Attached to each DVI line are an accumulator (ACC), a Core Makeup Tank (CMT), and lines to large, safety-class water pools residing in the In-containment Refueling Water Storage Tank (IRWST) and sump.

Depressurization of the primary system is an essential process that is required to ensure long-term cooling of the AP600. The accumulators inject coolant into the reactor coolant system (RCS) only after the primary pressure has decreased to 4.83 MPa (700 psia). Coolant injection from the IRWST and sump can occur only after the reactor coolant system pressure decreases enough that the gravitational head of each pool is sufficient to force coolant into the DVI line. An Automatic Depressurization System (ADS) ensures the needed RCS pressure reduction. The ADS has four redundant stages. The first three stages connect the top of the pressurizer and the IRWST. The fourth stage connects the top of each hot leg and the containment. A direct discharge path to the containment is needed to ensure that the RCS pressure will equilibrate with the containment pressure so that the head-driven IRWST and sump injection can proceed.

The AP600 containment plays an essential role in the long-term cooling of the primary. Steam entering the containment, through either a break in the RCS or ADS operation, condenses on the inside of the steel containment shell. The condensate drains downward and a large fraction is delivered via gutters to either the IRWST or the sump. Heat transfer on the outside of the containment steel shell is by evaporation of liquid sprayed near the top of the steel reactor containment dome, and by convection to an air stream induced by buoyancy-driven flow.

For non-LOCA accidents, long-term heat removal is provided as the Passive Residual Heat Removal System (PRHRS), which removes core heat through buoyancy-induced circulation. Isolation valves on the PRHRS lines open upon receipt of the safeguards (S) signal and a buoyancy-induced flow transports primary coolant through the PRHRS. The PRHRS is ineffective for LBLOCAs, has a limited interval of effectiveness for IBLOCAs, and has an extended period of effectiveness for SBLOCAs.

TRAC CODE DESCRIPTION

The TRAC-PF1/MOD2 code,[2] Version 5.4, was used for this calculation. The TRAC code series was developed at Los Alamos to provide advanced, best-estimate predictions for postulated accidents in pressurized-water reactors. The code incorporates four-component (liquid water, water vapor, liquid solute, and noncondensible gas), two-fluid (liquid and gas), and nonequilibrium modeling of thermal-hydraulic behavior. TRAC features flow-regime-dependent constitutive equations, component modularity, multidimensional fluid dynamics, generalized heat structure modeling, and a complete control systems modeling capability. The code also features a three-dimensional (3D), stability-enhancing, two-step method, which removes the Courant time-step limit within the vessel solution. Throughout the years of its development, the TRAC code has been assessed using data from a variety of experimental facilities and applied to a number of pressurized light reactor systems.

Code adequacy must be addressed when first applying a computer code to a new reactor type, e.g., AP600. One such approach is to (1) identify representative AP600 transient and accidents sequences; (2) identify the key systems, components, processes, and phenomena associated with the sequences; (3) conduct a bottom-up review of the individual code models and correlations; (4) conduct a top-down review of the total or integrated code performance relative to the needs assessed in steps 1 and 2; and (5) correct significant identified deficiencies. The bottom-up review determines the technical adequacy of each model by considering its pedigree, applicability, and fidelity to separate-effects or component data. The top-down review determines the technical adequacy of the integrated code by considering code applicability and fidelity to integral test facility data. A review of the TRAC-PF1/MOD2 code, such as that just described, is planned to assess code adequacy for the AP600 LBLOCA application. For the IBLOCA application, using TRAC to support confirmatory analyses will depend, in part, upon the significance of multidimensional phenomena during the transient. At present, the role of TRAC is complementary to other NRC analysis tools. Thus, the determination of adequacy for the IBLOCA application will largely rest on the similarity of processes and phenomena occurring in the AP600 during LBLOCA and IBLOCA events.

TRAC MODEL DESCRIPTION

The TRAC model of the AP600 is a finely-noded, multidimensional model of 184 hydrodynamic components [three vessel components and 181 one-dimensional (1D) components] encompassing 1,136 3D and 990 1D computational fluid cells, and 55 heat-structure components. The plant model has undergone an independent quality-assurance check. The TRAC AP600 plant model reflects the AP600 design information available on November 15, 1994.

A DEGB of DVI-line A (DVI-A) at the nozzle connecting DVI-A to the reactor vessel is assumed (Fig. 2). The vessel-side break area is constricted by a nozzle. The DVI-line side of the break is the pipe cross-sectional area. The nozzle orifice area is 5.1% of the total ADS discharge area. The DVI break disables one-half of the PSIS capacity of the AP600. A constant containment pressure of 0.31 MPa (45 psia) is assumed.

IBLOCA ANALYSIS—TRAC RESULTS

The key processes occurring in an AP600 during a postulated DVI-line IBLOCA are primary coolant system depressurization, inventory depletion, inventory replacement via emergency core coolant (ECC) injection, maintenance of continuous core cooling, and long-term decay heat rejection to the atmosphere. With due consideration for these key processes, four periods have been selected to characterize the AP600 IBLOCA transient: (1) break-dominated depressurization, (2) depressurization via ADS discharge to the IRWST, (3) depressurization via ADS discharge to the containment, and (4) long-term cooling. The selected periods (Fig. 3) provide a rational partitioning of the IBLOCA sequence because system depressurization is required to bring the AP600 to a safe shutdown condition. The sequence of events is provided in Table I.

Period 1 - Break-Dominated Depressurization

The first period is an interval of *break-dominated depressurization* initiated by a DEGB in DVI-A. The RCS rapidly depressurizes (Fig. 3) as mass and energy are lost through the break. The vessel-side break flow rapidly diminishes (Fig. 4) because fluid near the break flashes, increasing the resistance to flow through the break. As coolant flashes to vapor in the hotter parts of the RCS, the rate of primary depressurization rapidly slows and then stalls. However, coolant discharge from the vessel-side of the DEGB proceeds, continuing the reduction in RCS inventory (Fig. 5) and contributing to voiding in the higher elevations of RCS. The postulated break disables one-half of the PSIS capability, specifically the A train. The inventories of ACC-A, CMT-A and the coolant delivered by one IRWST discharge line (Fig. 6) are lost through the break and are discharged into the containment. Coolant recirculation begins immediately after the CMT isolation valves are opened following receipt of the S signal 9.2 s after break initiation. During the recirculation mode, the CMTs remain full. The intact CMT (CMT-B) continues to recirculate throughout this period and thus does not drain. However, the recirculation period of CMT -A lasts only a few seconds, after which it begins to drain as coolant is lost through the break at a faster rate than can be replenished through PBL-A, which feeds CMT-A. The break-dominated depressurization period ends at 172.6 s when the first-stage ADS is activated following the reduction of the inventory of CMT-A to the inventory set point (67% of initial inventory) at which the ADS actuation signal is generated.

Period 2 - Depressurization Via ADS Discharge to the IRWST

The second period of this transient is characterized by *depressurization via ADS discharge to the IRWST.* The period begins when the first-stage ADS actuates at 172.6 s and concludes when the fourth-stage ADS actuates at 482.7 s. Each of the first three ADS stages consist of two trains, which discharge primary system mass (Fig. 7) and energy into the IRWST. Failures of one first-stage and one third-stage train are assumed as a counterpart to the Westinghouse analysis of the same postulated accident.[1] First-stage ADS actuation releases sufficient mass and energy to restart primary system depressurization, even with one train inoperable (Fig. 3). The rate of depressurization is moderate, but increases further when the second-stage ADS starts to open at 242.7 s, a preset 70 s interval following first-stage ADS actuation. The second-stage ADS discharge area is approximately 10 times greater than that of the single operative first-stage ADS and, therefore, an observable increase in the rate of depressurization follows second-stage ADS actuation. The RCS pressure soon decreases to 4.83 MPa (700 psia), initiating coolant injection from the intact ACC (Fig. 8). The accumulator flow rate increases as the primary pressure continues to decrease. The increasing accumulator flow gradually terminates draining of the intact CMT attached to the same DVI line. A reverse flow through the intact CMT is predicted. Draining of the intact CMT does not resume until the ACC empties at the end of the third transient period. One train of the third-stage ADS starts to open at 362.7 s, a preset 120 s interval following ADS stage-2 actuation. One train of the third-stage ADS has one-half the discharge area of the two ADS stage-2 trains.

Throughout this period, the balance of inventory losses through the ADS and vessel-side break and inventory gains via CMT draining and accumulator injection vary. At the start of the period, the vessel-side break flow dominates the RCS inventory loss, being nearly an order of magnitude greater than the inventory gain via CMT draining. The first-stage ADS flow is a small contributor to inventory loss, approximately the same magnitude as the CMT draining flow. At the end of the period, the downcomer liquid level has drained below the level of the DVI nozzle, reducing the vessel-side break discharge to nearly zero. The second- and third-stage ADS flows are the dominant contributors to the continuing loss of RCS inventory. The maximum ADS mass flow through stages 1–3 is reached by 350 s as ADS stage 2 fully opens. The total ADS flow is rapidly decreasing at the end of the period. Throughout the period, the RCS coolant inventory decreases (Fig. 5). The intact accumulator flow, however, continues at an increasing flow rate (Fig. 8) , setting the stage for refilling the vessel early in the next period of the transient. The period of RCS depressurization via discharge through ADS stages 1–3 to the IRWST ends at 482.7 s, when fourth-stage ADS is activated following the reduction of the inventory of CMT-A to 20%, the volume fraction at which the fourth-stage actuation signal is generated.

Period 3 - Depressurization Via ADS Discharge to the Containment

The third period of this transient is characterized by *depressurization via ADS discharge to the containment.* Each of two fourth-stage ADS lines connect to the top of a separate hot leg and exhaust directly to the containment. The objective of the fourth-stage ADS is to complete the depressurization of the primary system by reducing the RCS pressure below a level at which the IRWST pool head is sufficient to induce injection. The period begins when the fourth-stage ADS is actuated at 482.7 s, and concludes when the IRWST injection begins at 631 s. About 80 s after fourth-stage ADS actuation, the RCS pressure approaches the containment pressure (Fig. 3), establishing the precondition for IRWST discharge into the intact DVI line once the ACC attached to the same line empties.

The fourth-stage ADS discharge area is approximately 62% of the total ADS system discharge area. At the time of fourth-stage ADS actuation, the hot-leg piping contains only a little liquid and, therefore, RCS depressurization continues with only a moderate additional loss of coolant inventory over a period of approximately three minutes (Fig. 9). After the discharge flow is established following opening of the ADS fourth stage, the rate of RCS inventory loss through fourth-stage ADS oscillates but generally decreases as the period progresses. Inventory discharges through ADS stages 1–3 continue to diminish throughout the period and are small at the end of the period. Eventually, the rate at which coolant is injected by the intact ACC exceeds the coolant loss through all stages of the ADS and the vessel-side break. This occurs at about 535 s and the core begins to refill (Fig. 5). The intact ACC empties at 623 s (Fig. 8). Draining of the intact CMT resumes shortly before the intact ACC empties. IRWST draining through the intact DVI line begins shortly after the intact ACC empties at 631 s, marking the end of the period.

Period 4 - Long-Term Cooling

The TRAC-PF1/MOD2 calculation does extend very far into the long-term cooling period. Thus, the descriptive information provided for the long-term cooling period is based upon other sources.[3-5] The long-term cooling period begins with IRWST actuation and continues indefinitely. IRWST injection begins at 631 s. Draining of the IRWST is expected to take several days, after which water from the sump is recirculated indefinitely. Water from the IRWST passes to the vessel downcomer through the DVI lines. The injected water is heated in the core, a portion evaporates establishing a two-phase liquid level in the core, and the steam generated in the core is discharged to the containment through the fourth-stage ADS. The passive containment cooling system plays an important role during the long-term cooling period. Steam released into the containment through either the break or fourth-stage ADS condenses on the inner surface of the steel containment shell, and drains downward either to gutters that return the condensed liquid to the IRWST or the sump. Heat transfer on the outside of the steel containment shell is by evaporation of water and buoyancy induced circulation of air until the PCCS water supply is exhausted. Thereafter, the buoyancy induced air flow is sufficient to remove the decay heat released into the containment.

IBLOCA ANALYSIS—OTHER RESULTS

Scaled DVI-Line IBLOCA in the ROSA Facility

The NRC has contracted with the Japan Atomic Energy Research Institute (JAERI) to perform AP600 confirmatory testing in the JAERI's ROSA facility. ROSA is not a perfect representation of the AP600 reactor, and numerous geometric distortions exist that must be considered when projecting the ROSA response to the AP600.[3] For example, AP600 has two cold legs per loop. AP600 has two cold-leg pressure balance lines, each connecting one CMT to one cold leg of the same loop. ROSA, however, has only a single cold leg per loop. Both the NRC and JAERI have concluded that while ROSA is not an exact scale model of the AP600, it is sufficiently similar to reproduce the most important thermal-hydraulic phenomena associated with AP600.

In October 1994, an IBLOCA experiment, AP-DV-01, was conducted in the ROSA facility.[3] This experiment simulated a DEGB in one of the AP600 DVI lines. Thus, one-half of the PSIS injection capability was disabled. Although a TRAC-PF1/MOD2 assessment of the test results is not planned, the test has been reviewed with the objective of highlighting areas of similarity and dissimilarity between the ROSA AP-DV-01 data and the TRAC-calculated results for the same postulated accident in AP600. ROSA experiment AP-DV-01 conditions differ in some respects from the TRAC counterpart model of a Westinghouse DVI-line LOCA.[1] For example, the ROSA break location is located ~6.8 m from the reactor vessel nozzle, which is equivalent to about 8.3 m from the reactor vessel nozzle in AP600. The break location for the TRAC DVI-line IBLOCA was at the reactor vessel nozzle. The ADS is fully functional in the ROSA test. One stage of the first- and third-stage ADS are assumed to fail in the TRAC calculation. A single heat exchanger and fluid train simulates the AP600 PRHRS in ROSA. Both AP600 PRHRS trains are simulated in the TRAC model. Other than the differences noted, the TRAC calculation is a reasonable counterpart to ROSA experiment AP-DV-01. A comparative assessment of the areas of similarity and dissimilarity between the TRAC calculation and ROSA experiment AP-DV-01 is briefly summarized as follows.

The following *similarities* between the ROSA test results and TRAC calculated results were identified. The sequence of events occurring during the ROSA experiment and in the AP600 calculation are similar. The pressurizer empties early due to flashing associated with the initial RCS depressurization. The pressurizer collapsed liquid level recovers following opening of the first-stage ADS. RCS depressurization stalls prior to ADS actuation when the hottest portions of the RCS saturate. The broken-line ACC discharges for an interval, terminates before ADS stage-1 initiation, and resumes after the RCS pressure once again decreases below the accumulator injection pressure. The broken-loop

CMT drains fairly rapidly into the broken DVI line and thence out the break. The intact-loop CMT has an initial period of recirculation, followed by a brief period of draining that is terminated following accumulator injection. CMT injection does not resume until the ACC is empty. CMT and IRWST injection proceed simultaneously after the ACC empties. Cladding temperatures follow saturation pressure. There is no core cladding heatup.

The following significant *dissimilarities* between the ROSA test results and TRAC calculated results were identified. The ROSA data show a shorter-duration primary pressure plateau following RCS saturation. The single ROSA PRHRS transfers sufficient energy from the RCS to the IRWST that RCS pressure begins to decrease before ADS stage-1 operation. The TRAC-calculated RCS pressure plateau persists until ADS stage 1 is actuated. TRAC models both of the PRHRS trains. In the TRAC AP600 calculation, asymmetries in the layouts of the two PRHRS trains result in different flows through the two heat exchangers, possibly reducing the total calculated heat removal through the PRHRS. Cladding temperatures follow RCS depressurization in both the ROSA data and the TRAC calculation, but the cooldown rate differs because a faster depressurization transient occurred in ROSA than that calculated by TRAC for AP600. In summary, the TRAC-calculated DVI-line IBLOCA is in general agreement with respect to the important systems, components, processes and phenomena occurring in ROSA test AP-DV-01. The primary area of disagreement relates to the system pressure response arising from PRHRS modeling and related processes and phenomena.

IBLOCA Analyses by Westinghouse Using COBRA/TRAC

In 1994, Westinghouse reported an analysis of a DVI-line IBLOCA.[1] The analysis was based upon a calculation performed with the NOTRUMP code. No core uncovery and cladding heatup is predicted to occur. This result is consistent with the TRAC-calculated result. In addition, the NOTRUMP-calculated and TRAC-calculated event times for reactor trip, S signal, start of RCP coastdown, ADS stage-1 actuation, start of intact-loop accumulator flow, ADS stage-2 actuation, ADS stage-3 actuation, and ADS stage-4 actuation are similar. Differences between the NOTRUMP and TRAC calculations were also observed. These included a shorter duration RCS pressure plateau, slower upper head draining, recovery of the downcomer mixture level after ADS actuation, and lower ADS flow rates predicted by NOTRUMP for the transient. Some of the differences may be related to the Appendix K methodology incorporated in the NOTRUMP model. Others, such as the the RCS pressure behavior following RCS saturation, may be related to different modeling approaches for the PRHRS.

When code-to-code comparisons are made, three potential causal areas must be explored. First, the same understanding of facility design and operation must be held by each team developing a code input model. Second, the input model must adequately represent the actual design and its operation. Third, code features or inadequacies may play a role. The areas of agreement between the NOTRUMP and TRAC results seem to indicate that the major features of both the codes and input models similarly represent AP600.

IBLOCA Analyses by the INEL

In 1995, Idaho National Engineering Laboratory (INEL) staff analyzed an AP600 DVI-line IBLOCA based on a RELAP5 calculation.[7] The objective of the effort was to provide a pretest AP600 counterpart calculation for ROSA DVI-line IBLOCA test AP-DV-01. Both baseline and sensitivity calculations were performed. A brief assessment of the similarities and dissimilarities of the RELAP5 pretest and TRAC calculations of the DVI-line IBLOCA follows.

There were some differences in the problem statements for the two calculations. These arise from differing objectives for the two AP600 DVI line LOCA. The objective of the TRAC calculation is to replicate the conditions of a Westinghouse analysis[1] as previously discussed. Thus, one train of the first-stage ADS is assumed to fail. One train of the third-stage ADS is also assumed to fail. All trains of the ADS are assumed to function in the ROSA counterpart calculation. Although the break location for each calculation is in the DVI line between the vessel and tee to the IRWST, the break location in the TRAC is closer to the vessel. In the INEL calculation, the containment is initially assumed to be at atmospheric pressure and is allowed to pressurize using a rudimentary containment model; in the TRAC calculation, a constant, 45-psia containment pressure was assumed. In addition, there are modeling differences related to the codes themselves. The baseline RELAP5 calculation modeled the downcomer as a single axial stack of fluid volumes. A sensitivity study was performed in which eight cross-connected axial stacks were used to simulate the multidimensional character of the downcomer.

There are significant areas of similarity between the TRAC and RELAP calculations. In general, the order and timing of events are similar. For example, the calculated times of IRWST injection are within 15 s. ADS actuation is predicted to occur about 45 s earlier in TRAC. RELAP5 calculated an interval during which draining of the broken CMT stalled when subcooled liquid from the downcomer entered the CMT and condensed vapor in the CMT. Because the ADS actuation signal is generated on CMT liquid level, all ADS actuations calculated by RELAP5 were delayed relative to the TRAC-calculated times. There are significant areas of similarity regarding processes and phenomena. Similarities are observed in the behavior of the ACC and CMT attached to the broken DVI line. The behaviors of the intact ECC trains are similar. The inventory trends of the downcomer and core calculated by the two codes are similar, with the exception discussed in the following paragraph. Both codes predict that the core remains cooled throughout the accident.

Several significant phenomenological differences were calculated by the two codes. First, RELAP5 calculated a significantly larger early reduction of core coolant inventory than TRAC. The collapsed liquid level decreased to 15% of the steady-state value early in the transient but rapidly recovered shortly thereafter. During the same interval, the TRAC-calculated core liquid fraction decreased to 70%. A RELAP5 sensitivity calculation was performed with RELAP5 with the eight-stack model. The collapsed liquid level again decreased to the bottom of the active fuel, but the duration of the core liquid level depression was reduced. The break flows calculated by the two codes immediately following the break are close. However, throughout the remainder of the period of *break dominated depressurization* , the average TRAC-calculated break flow is about 65% of the RELAP5-calculated break flow. Thus, the difference in early core collapsed liquid level calculated by the two codes is consistent with the differences in the calculated break flows. The different break locations used in the two calculations may be significant, but a sensitivity study has not yet been performed. Additional comparative reviews of the two calculations, and possibly sensitivity calculations for the two break locations, would provide the basis for understanding the root causes for the calculated differences. Second, following ADS actuation, RELAP5 calculates both more liquid in the pressurizer and a longer period during which the pressurizer retains liquid. The ADS failure specification in the TRAC calculation is a contributing factor, although it is not clear if this is the total explanation. Third, the pressurization plateau interval during the blowdown period is shorter in the RELAP5 calculation. Los Alamos attributes the longer period of the pressure plateau in the TRAC calculation to be associated with a reduced amount of heat rejection to the PRHRS. Sensitivity studies could provide insights into the adequacy of the TRAC two-train PRHRS model.

SUMMARY OBSERVATIONS

The summary observations that follow are based upon information from four sources. The TRAC-calculation-based insights are complemented by a scaled DVI-line IBLOCA experiment, test AP-DV-01, conducted in the ROSA facility.[3] They are further complement by counterpart analyses based upon DVI-line IBLOCA calculations performed with other codes. The TRAC calculation documented in this report is a direct counterpart of a calculation performed by Westinghouse using NOTRUMP.[1] The INEL has performed a direct AP600 counterpart calculation to ROSA test AP-DV-01 using RELAP5/MOD3.[6]

Although similar processes, phenomena, and outcomes have been either calculated or observed in each source, uncertainties remain. As with any scaled experimental facility, atypicalities exist. Work underway at the INEL should help to characterize these atypicalities. Activities to demonstrate code applicability for AP600 LOCA processes are either in progress or planned. However, the uncertainty associated with TRAC and RELAP5 calculations of IBLOCA processes and phenomena have not been quantified to date.

The key processes occurring in an AP600 during a IBLOCA are RCS depressurization, inventory depletion, inventory replacement via ECC injection, maintenance of continuous core cooling, and long-term decay heat rejection to the atmosphere.

RCS depressurization is successfully accomplished by the ADS. The primary outcomes of ADS depressurization are accumulator injection beginning at 4.83 MPa (700 psia), IRWST injection beginning when the RCS pressure equilibriates with the containment pressure, and the IRWST pool head is sufficient to inject coolant into the intact DVI line.

There are several sources of RCS inventory depletion. During the period of *Break Dominated Depressurization*, period 1, the vessel-side break is the only source of RCS inventory depletion. The vessel-side break is a significant contributor to inventory depletion for the first one-third of period 2, the period of *Depressurization Via ADS Discharge to the IRWST*. Discharges through the first three stages of the ADS are the dominant cause of RCS coolant loss during this period. This is particularly true after the vessel-side break flow diminishes when the downcomer liquid level drops below the downcomer connection to the broken DVI line. Some RCS coolant resides in the pressurizer following ADS stage-1 actuation, further reducing the circulating RCS coolant inventory. Following actuation of the fourth-stage ADS at the start of period 3, *Depressurization Via ADS Discharge to the Containment*, the fourth-stage ADS flow is the largest cause of RCS inventory reduction. However, the peak fourth-stage ADS flow is significantly lower than the peak flows through either the vessel-side break or ADS stages 1–3.

There are several sources of inventory replacement via ECC injection. Of course, the entire inventory of one ECC system train is lost as a direct result of the postulated DVI-line break. Thus, only the inventory of the intact ECC train is available for cooling the core. Intact-train accumulator injection begins following ADS actuation. Continuous draining of the intact-train CMT begins once the intact-train accumulator drains. IRWST injection into the intact DVI line begins following fourth-stage ADS actuation. Loss of RCS coolant inventory terminates once the ECC flow from the intact-train accumulator exceeds the RCS discharges through the vessel-side break, ADS stages 1-3, and ADS stage 4. This occurs at about 535 s, during period 3, depressurization via ADS discharge to the containment.

The core is continuously cooled. ECC coolant injection from the single intact train is sufficient to prevent core dryout.

Neither the calculations nor the ROSA test simulated that portion of the long-term cooling period when sump injection is active. In addition, the containment cooling system, which functions as an integral part of the long-term cooling process, was neither simulated in ROSA nor modeled in the calculations. Thus, the conclusion that the core is continuously cooled does not apply to the period of sump injection. The absence of this conclusion regarding the latter phase of the long-term cooling period does not imply that continuous core cooling is suspect. It only means that the needed analytical and/or experimental confirmation of cooling is unavailable at the present time.

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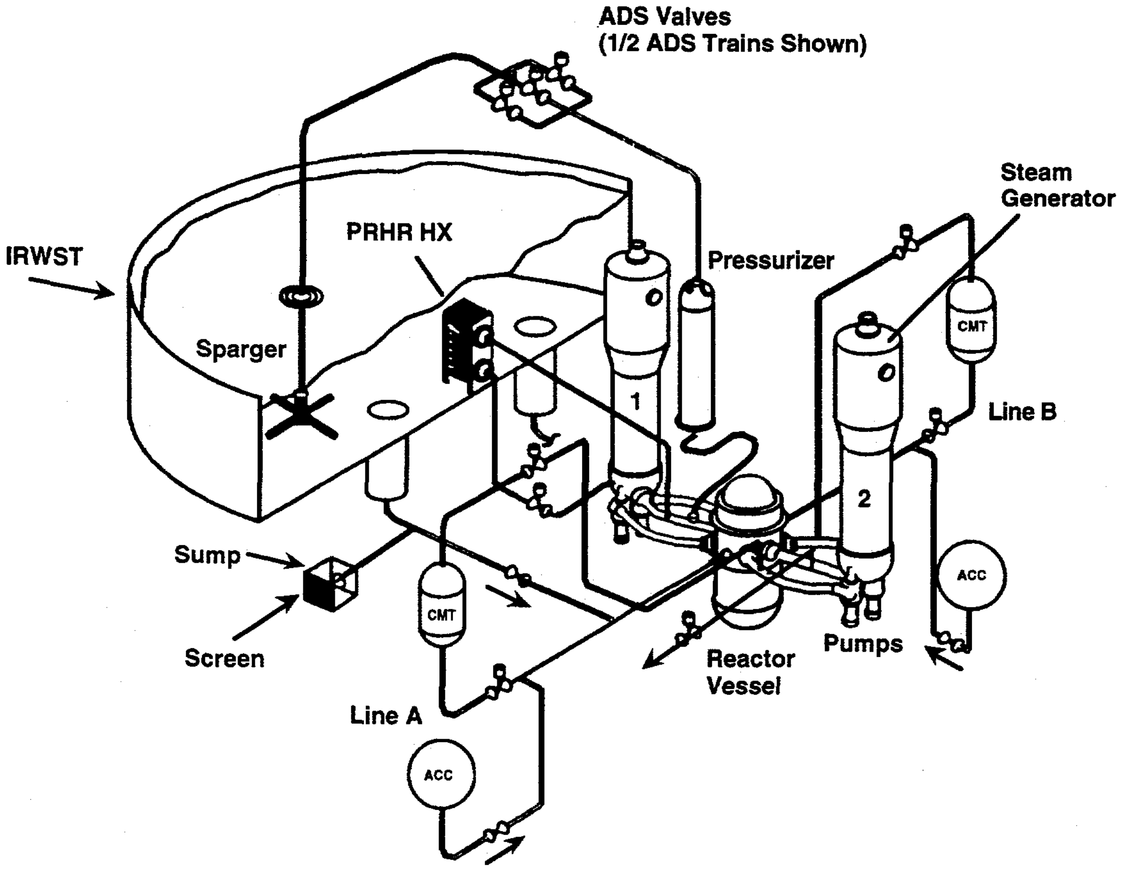

Fig. 1.
AP600 passive safety systems.

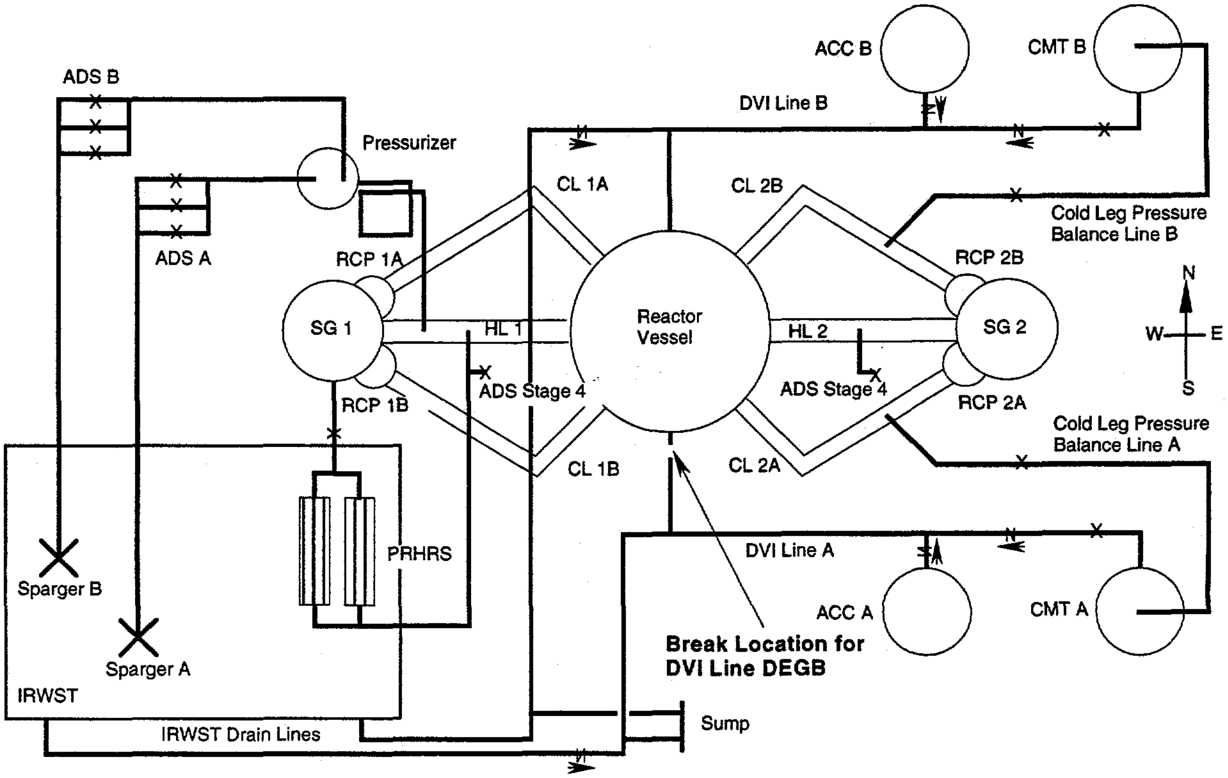

Fig. 2.
AP600 reactor coolant system and passive safety injection.

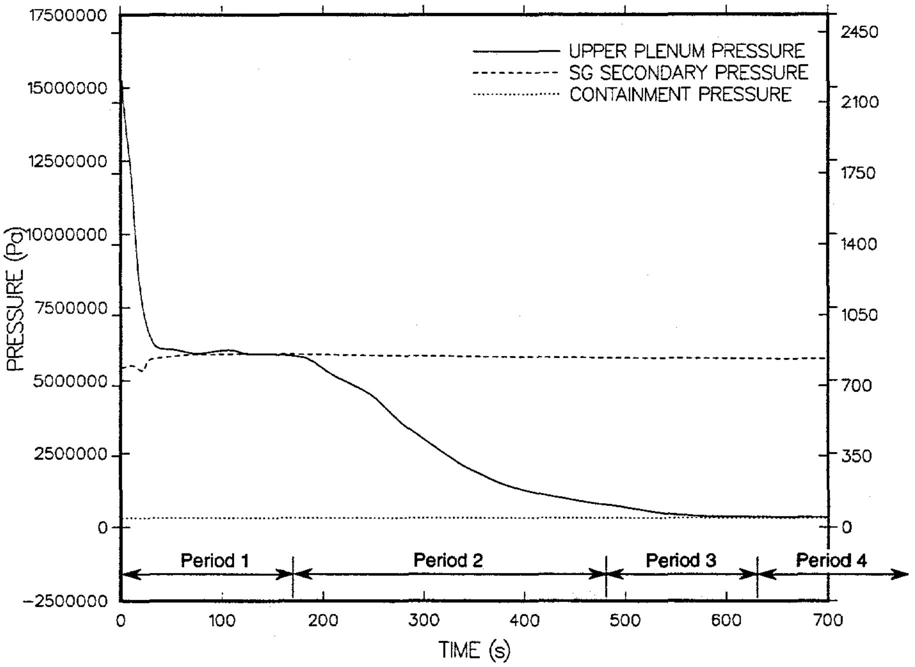

Fig. 3.
Primary and secondary pressures.

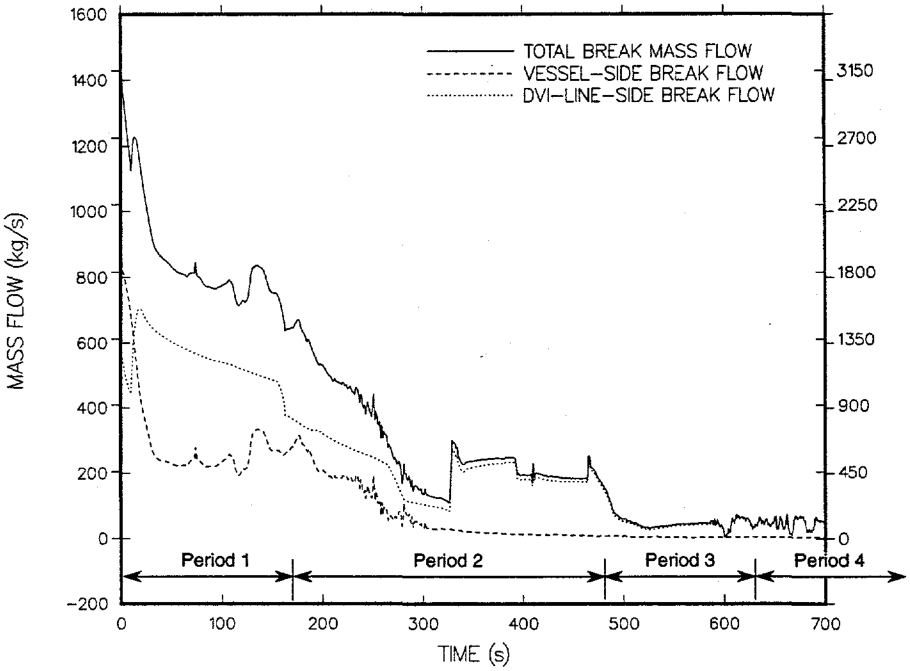

Fig. 4.
Break mass flows.

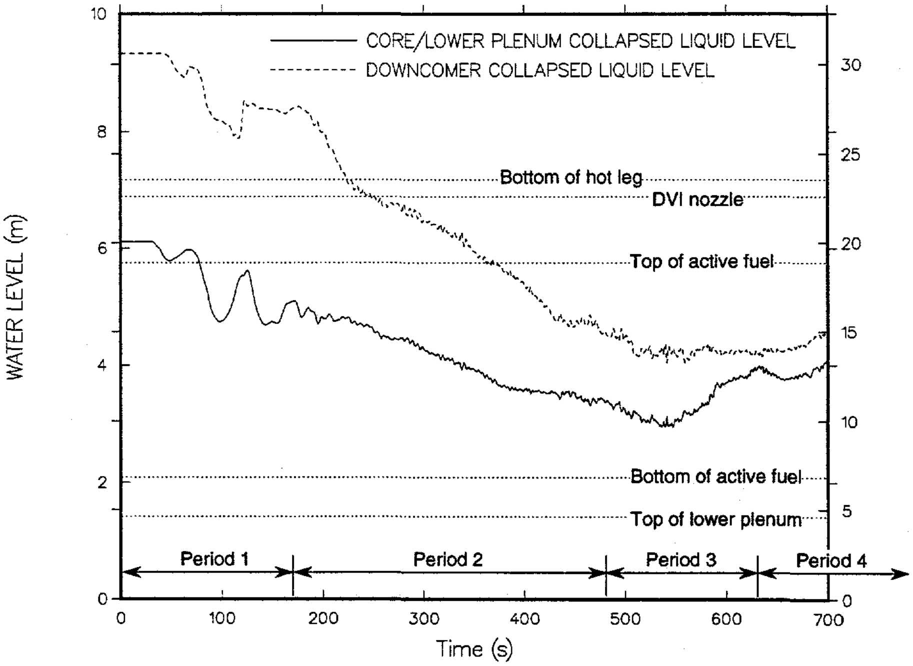

Fig. 5.
Downcomer and core collapsed liquid levels.

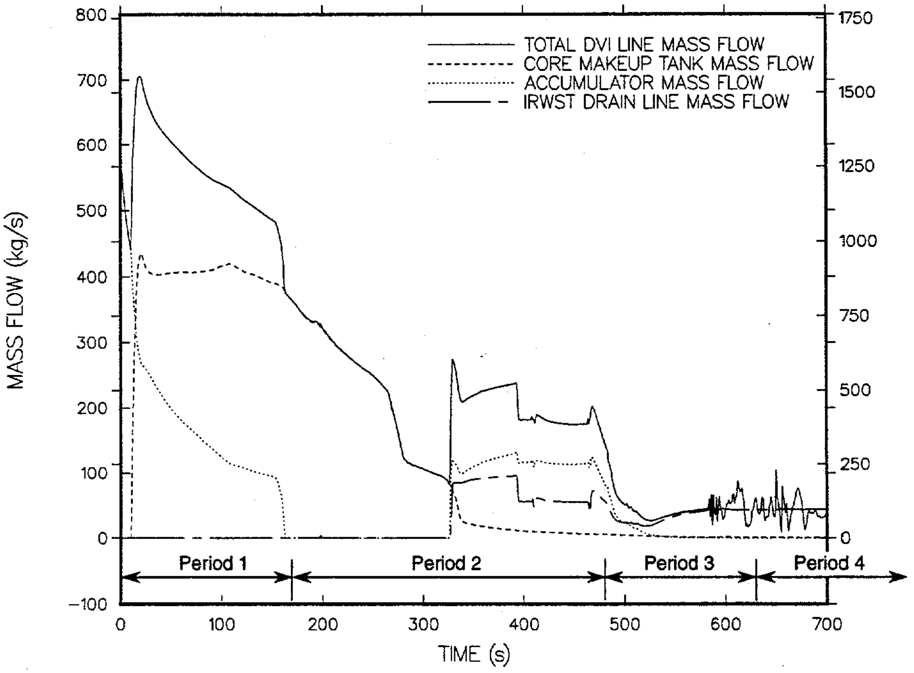

Fig.6.
Broken DVI line mass flow.

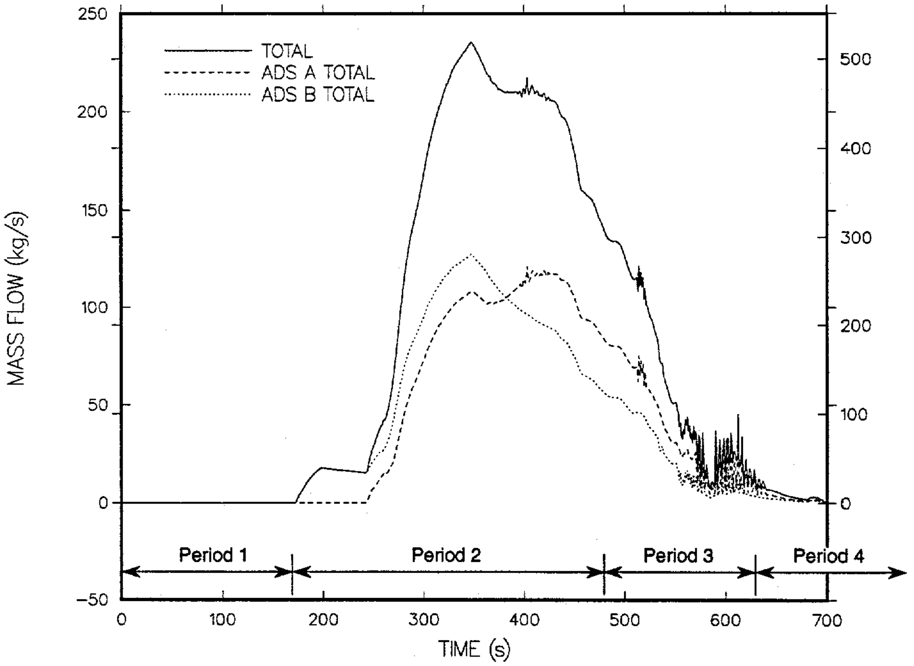

Fig. 7.
Total ADS stages 1-3 mass flow.

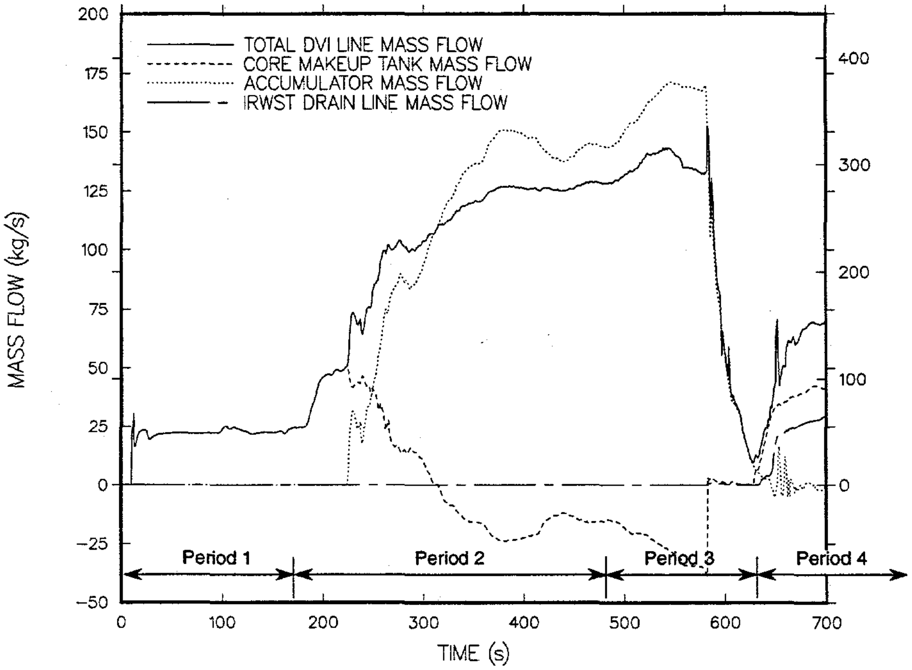

Fig. 8.
Intact DVI line mass flow.

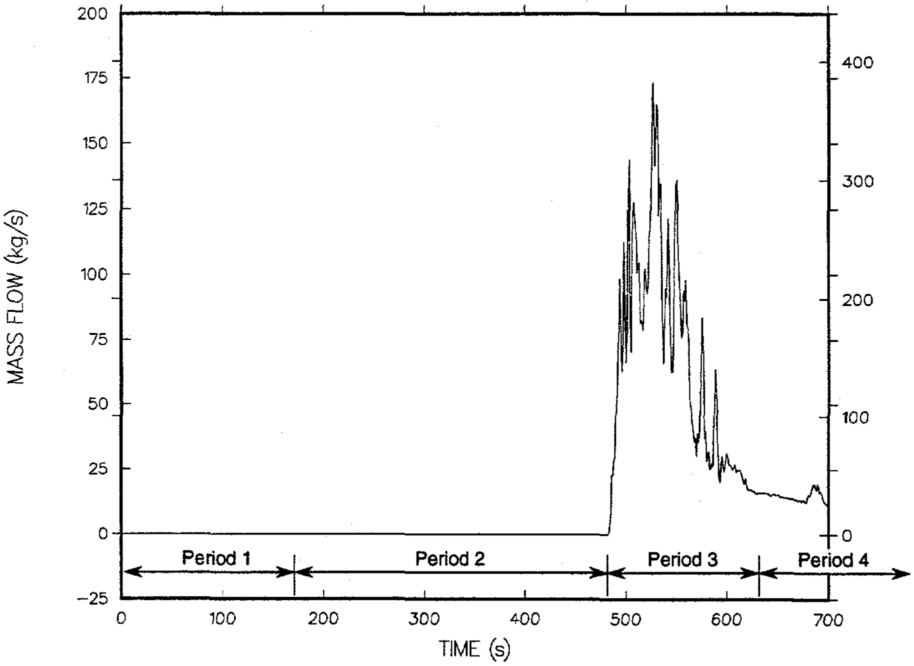

Fig. 9.
Total fourth-stage ADS mass flow.

TABLE I

IBLOCA SEQUENCE OF EVENTS

Time (s)	Event
0.0	Break occurs in DVI line A next to vessel.
8.3	Reactor trip on low pressurizer pressure.
9.2	"S" signal on low pressurizer pressure. Steam generator feedwater control valves starts to close.
10.4	PRHRS isolation valve starts to open. CMT isolation valves start to open.
18.9	Main steam line isolation valves start to close.
25.4	Reactor coolant pumps trip.
152.5	67% liquid volume fraction reached in CMT-A (broken DVI line).
172.6	ADS stage 1 control-valve trip signal. Stage 1 of ADS train B starts to open. Stage 1 of ADS train A assumed to be inoperative and does not open. Stage 1 valve opening time: 25 s.
242.7	ADS Stage 2 control-valve trip signal. Stage 2 valves of both ADS trains start to open. Stage 2 valve opening time: 105 s.
255.2	20% CMT level signal. This signal, plus a 120-s delay after Stage 3 valves open, allows actuation of ADS Stage 4 valves.
328	Flow through IRWST drain line-B (broken DVI line) begins.
337	CMT-A (broken DVI line) empties.
362.7	ADS Stage 3 control-valve trip signal. Stage 3 of ADS train A starts to open. Stage 3 of ADS train B assumed to be inoperative and does not open. Stage 3 valve opening time: 105 s.
482.7	ADS Stage 4a and 4c valves start to open. 85% valve area assumed. Valve opening time: 20 s.
512.7	ADS Stage 4b and 4d valves start to open. 85% valve area assumed. Valve opening time: 20 s.
516	Accumulator-A (broken DVI line) empties.
623	Accumulator-B (intact DVI line) empties.
631	Flow through IRWST drain line-A (intact DVI line) begins.