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U.S. Nuclear Regulatory Commission
Washington, D. C., 20555

ATTENTION: T. R. QUAY

SUBJECT: POSITION PAPER IN SUPPORT OF THE ASSUMPTION OF COMPLETE MIXING OF AEROSOLS IN THE AP600 CONTAINMENT ATMOSPHERE FOLLOWING A LOSS OF COOLANT ACCIDENT

Reference: Westinghouse letter NSD-NRC-96-4787, August 5, 1996, "Position Paper on the Removal of Aerosols from the AP600 Containment Atmosphere following a Postulated LOCA with Core Melt Using Only Natural Removal Processes of Sedimentation and Deposition."

Dear Mr. Quay:

The NRC issued a request for information in a letter dated January 10, 1997 concerning information the NRC would like to address at the February 11 and 12, 1997 aerosol removal meeting. In preparation for the meeting, a telecon was held with the NRC on January 30, 1997 to discuss the January 10, 1997 letter. The aerosol removal coefficients calculated for the post-LOCA containment atmosphere (see Reference) were determined utilizing the assumption that the aerosols could be considered as well mixed in the containment atmosphere. During the telecon, Westinghouse agreed to provide documentation to justify the assumption. The enclosure to this letter describes the basis for this assumption.

This information is being provided is support of the planned meeting with NRC staff, February 11 & 12, 1997, at Polestar Applied Technology, Inc. in Los Altos, California.

Please contact me on (412) 374-4334 if you have any questions concerning this transmittal.

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Enclosure 130039

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Enclosure to Westinghouse
Letter NSD-NRC-97-4978

February 7, 1997

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Mixing of Aerosols in the AP600 Post-LOCA Containment Atmosphere

The AP600 design-basis analysis for aerosol removal coefficient (reference 1) assumes that the fission products released to containment following a postulated loss of coolant accident (LOCA) with core melt are well-mixed in the atmosphere within the open compartments in the containment that participate in natural circulation. The purpose of this discussion is to justify this assumption.

The justification provides:

- identification of the accident sequence assumptions and boundary conditions in the reactor coolant system and containment prior to the fission product release
- identification the limiting steam and fission product release location from the reactor coolant system to the containment
- discussion of containment natural circulation in quasi-steady conditions
- discussion of AP600 passive containment cooling system (PCS) large-scale test (LST) insights which support the well-mixed fission product assumption

1.0 Design Basis Sequence Assumptions

The design-basis source term (reference 2) is superimposed onto a design-basis sequence which defines the bounding thermal-hydraulic conditions for the evaluation of the fission product deposition. This AP600 design-basis sequence consists of a LOCA which drains the reactor coolant system (RCS) and core makeup tanks (CMTs) sufficiently to activate the automatic depressurization system (ADS). In this sequence, both trains of all four stages of ADS open sequentially. During the depressurization, the CMTs and accumulators inject fully into the reactor vessel downcomer. The final RCS pressure is essentially equal to the containment pressure which allows gravity injection of the IRWST water. Steam is produced in the core at the rate dictated by decay heat. Fission product release therefore occurs from a fully depressurized RCS. The aerosols are carried into the containment in a buoyancy-driven steam flow.

During such a sequence, the earliest time of fission product release is conservatively shown to be approximately 50 minutes after accident initiation (reference 3), well past the time of the blowdown. The containment conditions are considered to be quasi-steady-state. Internal heat sinks are conservatively assumed to be thermally saturated and the condensation rate of steam on the PCS dome and shell is equivalent to the decay heat steaming rate. Hydrogen is assumed to be mixed in the containment at a volume fraction of approximately 1% (see SSAR Figure 6.2.4-1)

1.1 Break Size and Release Location in Containment

This section discusses each of the postulated release locations from the RCS, the containment release points for each, the size limitations and the phenomena associated with the break locations. It is shown that it is conservative to assume that the steam and fission products are released from the RCS hot leg to the containment above the maximum water flood-up elevation and into the steam generator compartments atmosphere.

1.1.1 Releases from Depressurization System Lines

Any design-basis LOCA which can be postulated to produce a large core activity release to containment will actuate the four stages of the automatic depressurization system (ADS). The stage 1, 2 and 3 ADS lines, which relieve from the top of the pressurizer (see Figure 1), deliver flow to the containment through the in-containment refueling water storage tank (IRWST). This is not considered to be a major fission product release pathway because the IRWST is a cold, effectively closed system with no leakage pathway to the environment. The IRWST is full of water during the depressurization blowdown which would trap any postulated fission products released to the IRWST. At the time the water is drained below the spargers, the RCS is depressurized with stage 4 ADS open, and the IRWST vents, which are closed with flappers, are not expected be significantly opened by the small buoyancy-driven flows. Aerosols released from stages 1, 2 and 3, either before or after the draining of the IRWST, would essentially be trapped in the water or in the IRWST compartment. Therefore, this pathway is conservatively neglected as a release pathway from the RCS to maximize the activity entering the containment atmosphere.

Stage 4 ADS lines relieve RCS coolant, steam, and fission products from the hot legs (see Figure 1) to the steam generator compartments above the maximum water flood-up level. The stage 4 lines consist of four 12-inch diameter lines. Two lines are connected to each of the two hot legs. Each of these trains relieves at the 112-foot elevation to a steam generator compartment.

Of the postulated release locations in the RCS, openings in the hot-side piping, such as the stage 4 ADS, provide the lowest resistance pathway for fission product releases from the RCS because of the large flow area, high temperatures, short resident time in the RCS and low surface area for aerosol deposition. To reach openings in the cold side piping with stage 4 ADS valves open, the RCS low-pressure natural circulation must pass through the steam generator tubes (see Figure 1). At the superheated steam temperature of the gas which accompanies the fission product flow, significant heat transfer would take place in the steam generator tubes which are cooled on the secondary side by water. Aerosol deposition to the tubes would remove fission products from the release before the flow reached the containment. Therefore, releases from cold-side breaks are less severe than hot side breaks with the stage 4 ADS open.

1.1.2 Releases from Coolant Loop Breaks

Breaks in the RCS loop piping (hot legs or cold legs) relieve primary coolant [illegible] and fission products to the steam generator compartments. Assuming double-ended guillotine br[illegible] the hot-side break has a diameter of 31 inches (78.7 cm), the cold-side break has a diameter of 22 inches (55.9 cm). Breaks in the hot leg piping are more conservative than cold leg with respect to the fission product releases to the containment because of the larger break area, higher temperatures, shorter resident time and lower surface area for aerosol deposition in the RCS. Therefore, of the coolant loop breaks, hot-side breaks to the steam generator compartment provide the more conservative magnitude of fission product release to the containment and can be lumped with the stage 4 ADS releases.

1.1.3 Direct Vessel Injection Line Breaks

A break in one of the two direct vessel injection (DVI) lines can relieve steam and fission products outside the steam generator compartments to one of the two dead-ended accumulator rooms below the CMT Room. The DVI piping is 8-inch diameter schedule 160 piping (6.8-inch inner diameter), but an orifice at the reactor vessel wall limits the break size to a 4-inch diameter. The DVI nozzle connects to the reactor vessel in the downcomer (see Figure 1), so all DVI line breaks relieve from the cold-side of the RCS. The accumulator rooms have significant heat sink surfaces for aerosol deposition to trap fission products in the dead-ended compartment. Given the small break size, cold-side location of the break, and the compartment retention capacity, with the stage 4 ADS valves open very little fission product release is expected from the DVI line. The steam release to the accumulator room is negligible with respect to that from the stage 4 ADS.

1.1.4 CMT Balance Line Breaks

Breaks in the CMT balance lines can relieve steam and fission products to the CMT room. The balance line piping is 8-inch diameter schedule 160 piping (6.8-inch inner diameter). The balance line nozzle is attached to a cold leg (see Figure 1). Given the small break size and the cold-side location of the break, with the stage 4 ADS valves open very little fission product release is expected from the balance line. The steam release to the CMT room is negligible with respect to that from the stage 4 ADS.

1.1.5 CVS Line Breaks

A break in the chemical volume control system (CVS) line relieves to the dead-ended CVS vault below the CMT room. The CVS piping is 3-inch diameter schedule 160 piping (2.6-inch inner diameter). The inlet of the CVS draws from the cold leg and the outlet discharges to the reactor coolant pump suction, both on the cold-side of the RCS (see Figure 1). Given the small pipe size and the cold-side location of the break, with the stage 4 ADS valves open very little fission product release is expected from the CVS piping. The steam release to the CVS compartment is negligible with respect to that from the stage 4 ADS.

1.1.6 Release Location Conclusions

The fission product releases are expected to discharge from the stage-4 ADS lines, which relieve from the hot legs to the steam generator compartments. Stage 4 ADS is open in all design-basis LOCA sequences that can be postulated to produce large core activity releases to the containment. For a coolant loop break, the release would go to the steam generator compartments along with the releases from the stage-4 ADS lines. Fission products released to other postulated containment locations are expected to be negligible by comparison because the releases must be from the cold-side of the RCS through comparatively long and narrow piping pathways. Therefore, the bounding release pathway is a hot-side break into the steam generator compartments with fission product and steam releases through the break and stage 4 ADS.

1.2 Boundary Conditions

Based on the design-basis sequence, the following assumed boundary conditions apply in the containment:

- steam is released from the RCS into both steam generator compartments through stage 4 ADS, low in the containment (elevation 112 ft), at the rate of decay heat,
- the fission products are released with the steam flow as defined by reference 2, and occur over a period of 1.4 hours,
- the RCS is depressurized prior to the fission product release at 50 minutes, so the flow entering containment is buoyancy driven,
- the containment conditions are quasi-steady and the internal heat sinks are thermally-saturated, so the condensation rate on the PCS is equal to the steaming rate,
- the containment is flooded with IRWST water to the 107' 2" elevation,
- the volume of hydrogen present in the containment is consistent with design-basis analysis.

2.0 Containment Natural Circulation and Mixing

This section describes the natural circulation flow path and the mixing processes in the containment atmosphere. Figure 2 graphically depicts the containment natural circulation flow paths and the mixing processes.

The steam source low in the containment and the condensation on the PCS surface provide the driving forces for natural circulation in the containment. Based on the fission product release timing, the containment conditions at the time of the release are quasi-steady:

$$Q_{ST} \approx \text{constant}$$
$$Q_{COND} = Q_{ST}$$

where: Q_{ST} = steam volumetric flowrate
Q_{COND} = condensation volumetric flowrate.

Steam and fission products are released low in the containment at the 112-foot elevation as hot, buoyant plumes from the low pressure primary system into the steam generator compartments which act as chimneys. The fission products are released from the RCS with the steam plumes. The plumes rise through the steam generator compartments and are released into the upper compartment at the top of the steam generator doghouses (148-foot elevation). The plumes rise unconstrained for over 100 feet to the upper compartment dome. As they rise, the surrounding upper compartment gas mixture is entrained into the plumes. The steam, fission products and any non-condensible gases (e.g. hydrogen) in the plumes are mixed with a large volume of entrained mixture in the rising plume. Over the time period of interest, no mechanisms exist to separate the non-condensible gases (e.g. air and hydrogen) once they are mixed in the rising plumes. The molecular weight difference is so overwhelmed by the convection that it does not lead to gravitational separation. A simple calculation of the relative velocity of hydrogen in air gives a very low relative velocity. This mechanism is orders of magnitude less effective than convective mixing forces. Thus gravity effects are not expected lead to separation of hydrogen from the non-condensible mixture.

An estimate of the volume entrained into the plume is made based on Peterson's equations (reference 4):

$$Q_{ENT} = 0.15 * B^{1/3} * Z^{5/3}$$

where: Z = elevation
$B = g^*Q_{ST}^*(\rho_{AMB} - \rho_{ST})/\rho_{AMB}$
g = gravitational acceleration

At 1% decay heat, 19 MW, the source flow is approximately 400 ft^3/sec and $\Delta\rho/\rho$ is approximately 1/4. Thus, $B^{1/3}$ = 14.8 $ft^{4/3}$/sec. For a source release into the upper compartment where Z=100 ft, Q_{ENT}=4800 ft^3/sec. Therefore, for the AP600 height above the operating deck:

$$Q_{ENT-P} \approx 10\ Q_{ST}$$

where: Q_{ENT-P} = volumetric flowrate of entrained gas in the rising plume

The application of water to the external surface of the PCS maintains the containment shell at a cool temperature. The condensation of steam on the PCS creates a downward flowing layer at the wall. A review of literature on circulation within enclosures (reference 5) shows that as long as there is cooling on the inner surface of the PCS, downward flow of the wall layer will prevent stagnation under the dome. Fission products are carried along in the wall layer flow. As it flows downward along the wall, the wall layer also entrains surrounding mixture. Thus, the circulation flow rate in the above-deck volume is greater than ten times the break flow, generating significant mixing forces.

The mixing time constant for the AP600 LOCA can be estimated by $V/(10^*Q_{ST})$, where V is the containment volume above the operating deck, 40360 m^3 (1.4×10^6 ft^3). Therefore, the time constant is approximately 350 seconds. This is very short compared to the 1.3 hour release duration defined in reference 2. Therefore, the fission products are essentially mixed within the gas volume above the operating deck as soon they are released. There is no stagnant region in the upper compartment as the entire volume participates in the rising plume, entrainment flow and wall layer. Stratification exists in the form of a continuous vertical steam gradient as discussed in section 3.0.

As the downward boundary layer flow reaches the operating deck (135-foot elevation), it has been cooled and somewhat depleted of steam. The air and fission products remain well-mixed in the flow. Vents in the operating deck (135' elevation, see Figure 2) along the wall allow the denser gases to "drain" down into the CMT room and circulate through the doorways which empty to the tunnel between the steam generator compartments. Little condensation is expected below the operating deck in the quasi-steady condition as the metal heat sinks are thermally-saturated. The condensation on the concrete heat sinks below the operating deck is small compared to that on the PCS. In the steam generator compartment, the circulation flow is entrained within the initial steam source, and the circuit begins again.

The IRWST compartment, accumulator rooms, CVS room and reactor cavity, including the reactor coolant drain tank room, do not experience the natural circulation flow. The accumulator rooms and CVS rooms are dead-ended and cannot participate in the circulation. The IRWST compartment is essentially sealed at the vents by flappers after blowdown, and the reactor cavity is filled with water. These compartments should not be considered in the calculation of the aerosol deposition.

3.0 Insights from the PCS Large Scale Test and AP600 Stratification Studies

The AP600 PCS Large Scale Test (LST) provides insight into the circulation and mixing behavior in the AP600 containment. Since the LST did not include a flow path into the simulated steam generator compartment, the degree of mixing of injected light non-condensible gases with the existing air throughout the test vessel would be conservatively underestimated. This is because the extra flow path would allow density-driven circulation through the path into the compartment, introducing an additional mixing mechanism which exists in AP600.

In the LST rising plume, large amounts of surrounding air-steam mixture were entrained and mixed with the released gases. Estimates of entrainment over the 15 foot height above the deck in LST show that about one times the break volumetric flow may be entrained. In several LST tests, 217.1, 218.1, 219.1, and 221.1, in which helium (a hydrogen simulant) was released in an amount equal to 10-20 volume percent, non-condensible gas concentrations were measured (reference 6). It can be seen that the helium fraction reduced from 100% at the release point to 50% of the non-condensible gas in the dome during the initial period of injection. For design basis hydrogen releases, the hydrogen concentration as a fraction of the non-condensible gas in the dome would be much less.

The existence of circulation under the dome in the LST can be seen based on the further reduction of helium non-condensible fraction over time after the helium release stops. While the steam density gradient due to stratification of the dynamic fluid establishes itself in a few minutes in the LST, it was seen to take some time for the circulation to mix the injected non-condensible gases with the non-condensible gases throughout the vessel. In the LST, the time required for the helium non-condensible fraction at top and bottom of the vessel to equalize is 2-4 hours. Due to the additional height for entrainment in the AP600, circulation is about 10 times greater than in the LST based on plume entrainment alone. Wall layer entrainment and density driven circulation through the steam generator compartment (which acts as a chimney) would further increase the mixing in AP600. This indicates that in the AP600 circulation will have distributed the injected non-condensible gases with the air throughout the containment quickly compared to the duraion of the release.

The effect of external cooling on non-condensible gas distributions was studied in LST 219.1 which started out with a dry external shell, injected helium, and then initiated the external water cooling. Non-condensible gas data showed that the application of external cooling acts to accelerate the mixing of non-condensible gases, which is probably due to the higher wall layer entrainment rate from the higher condensation rate on the cooler shell.

As discussed above, the fluid dynamics of entrainment into a buoyant plume and wall boundary layers generate large amounts of circulation within the above deck region. Thus the region in AP600 is not a static, layered stratification, and there are no stagnant pockets of gases that do not participate in the circulation. The physics do however lead to a standing vertical steam density gradient, which will tend to be richer in steam at the top due to the lower density of the injected steam.

Based on the above, at quasi-steady conditions, the decay heat steaming and heat transfer to the PCS create natural circulation in the containment that mixes the aerosols quickly and uniformly throughout the circulating volume. The rising plume and the cooling of the shell create a vertical steam density gradient and a vertical temperature gradient in the upper compartment. The density and temperature gradients result from the forces which drive the natural circulation. Condensation and sensible heat transfer occur over the entire PCS shell, albeit at different rates over the height of the shell. Thermophoresis and diffusiophoresis are strong functions of this heat and mass transfer. Modeling the processes by uniformly mixing the aerosol mass throughout the circulating volume and averaging the steam condensation and sensible heat transfer over the entire upper shell provide a reasonable estimate of the aerosol deposition rates due to thermophoresis and diffusiophoresis.

4.0 Conclusions

Based on first principal arguments and insights from testing, the following conclusions are made with respect to mixing in the AP600 containment during quasi-steady conditions:

- As long as there is cooling on the inner surface of the PCS, downward flow will prevent stagnation under the dome

- no unmixed pockets develop as the doorways extend to the floor and vents are in the ceiling for the rooms participating in the natural circulation flow, the entire compartments' volumes participate in the circulation

- the rising plume, condensation of steam on the PCS dome, and downward flowing wall layer create vertical steam density and temperature gradients in the upper compartment

- aerosol fission products are quickly and uniformly mixed in the containment volumes participating in the natural circulation and are present at all sites of steam condensation and sensible heat transfer in the containment

- for the purpose of calculating long-term aerosol deposition, it is reasonable to assume that aerosols and non-condensible gases are well-mixed throughout the major compartments participating in the containment natural circulation: the steam generator compartments, upper compartment and CMT room.

5.0 References

1. Letter NSD-NRC-96-4787, 8/5/96, Subject: "Position Paper on the Removal of Aerosols from the AP600 Containment Atmosphere Following a Postulated LOCA with Core Melt Using Only Natural Removal Processes of Sedimentation and Deposition"

2. Letter NSD-NRC-96-4675, 4/1/96, Subject: "AP600 Loss of Coolant Accident Source Term Model"

3. Letter NTD-NRC-94-4335, 11/2/94, Subject: Position Paper on AP600-Specific Time Delay in the Physically Based Source Term"

4. Peterson, P., "Scaling and Analysis of Mixing in Large Stratified Volumes," International Journal of Heat and Mass Transfer, Vol. 37, Suppliment 1, pp 97-106, 1994.

5. Dzodzo, M.B., "Visualization of Laminar Natural Convection in Romb-Shaped Enclosures by Means of Liquid Crystals," Imaging in Transport Processes, Begell House, Inc. 1993.

6. WCAP-14135, Final Data Report for PCS Large Scale Test, Phase 2 and Phase 3, July 1995.

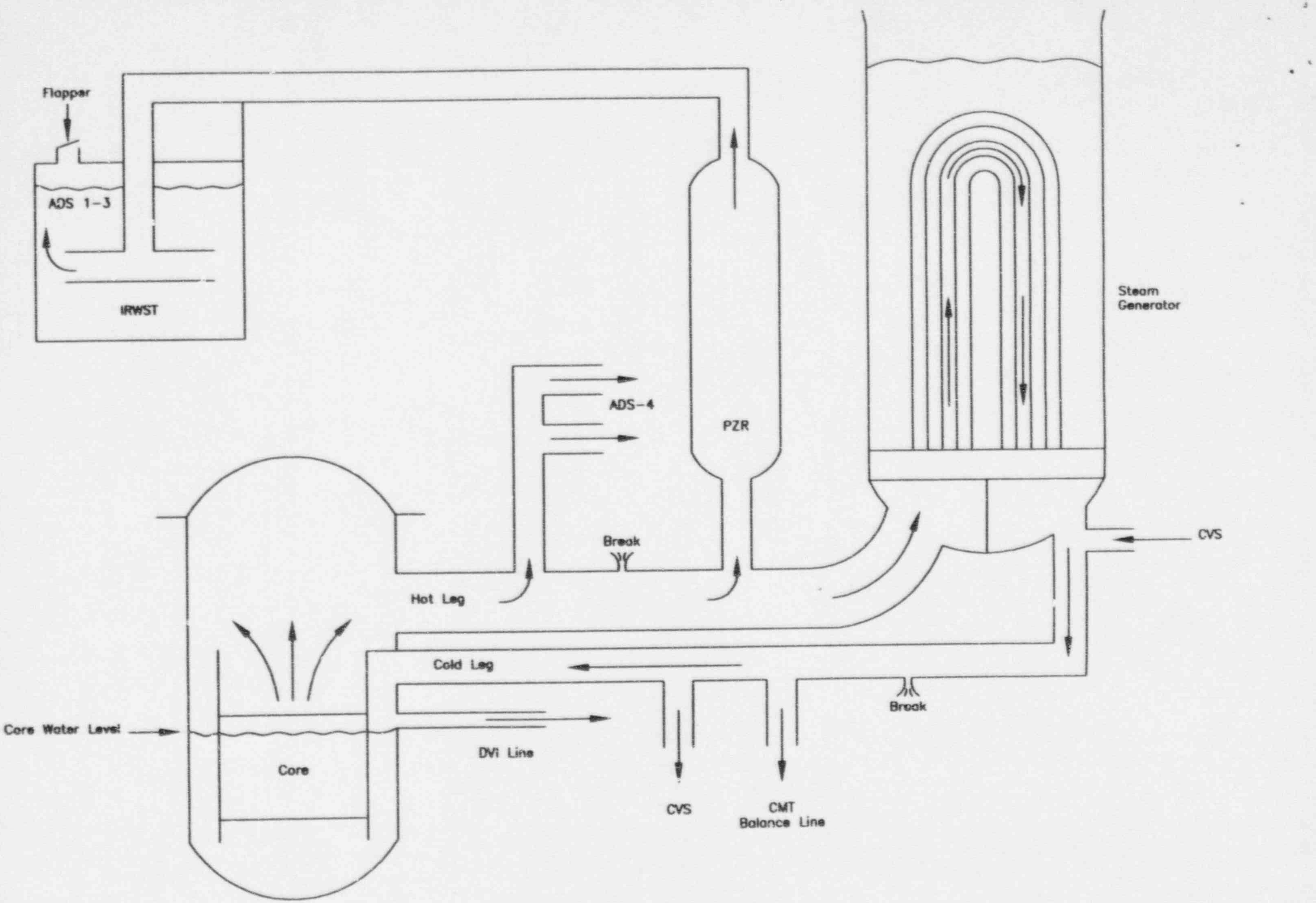

Figure 1 – RCS Release Locations

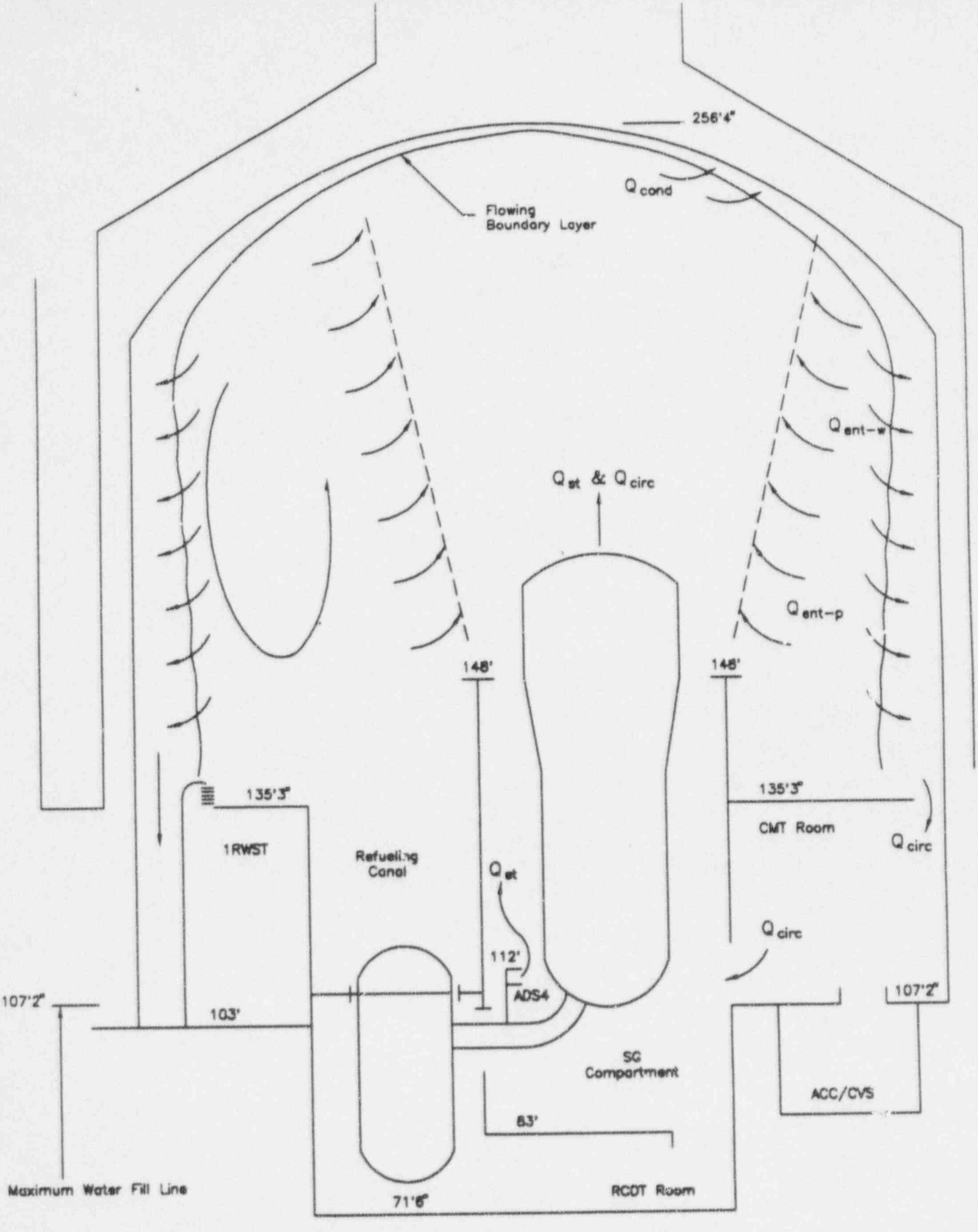

Figure 2 – Containment Natural Circulation

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