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ADENSAM,E. Licensing Branch 4

SUBJECT: Forwards response to Items 2.1 & 2.2 of Generic Ltr 81-21, "Natural Circulation Cooldown." Natural circulation cooldown can be accomplished w/o violating other pressure-temp limits.Response to Item 2.3 will be submitted on 850301.

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TENNESSEE VALLEY AUTHORITY
CHATTANOOGA, TENNESSEE 37401
400 Chestnut Street Tower II

February 3, 1984

Director of Nuclear Reactor Regulation
Attention: Ms. E. Adensam, Chief
Licensing Branch No. 4
Division of Licensing
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Ms. Adensam:

In the Matter of the Application of) Docket Nos. 50-438
Tennessee Valley Authority) 50-439

This letter is in reply to Generic Letter No. 81-21, concerning natural circulation cooldown at the Bellefonte Nuclear Plant. Enclosed is our response to items 2.1 and 2.2 of the generic letter. The enclosed response was prepared for TVA by Babcock & Wilcox (NSSS supplier for Bellefonte). A response to item 2.3 will be submitted on March 1, 1985.

If you have any questions concerning this matter, please get in touch with Bill Watters at FTS 858-2691.

Very truly yours,

TENNESSEE VALLEY AUTHORITY

L. M. Mills

L. M. Mills, Manager
Nuclear Licensing

Sworn to and subscribed before me
this 3rd day of February 1984
Paulette H. White
Notary Public
My Commission Expires 9-5-84

Enclosure (20)
cc: (Enclosure):
U.S. Nuclear Regulatory Commission
Region II
Attn: Mr. James P. O'Reilly Administrator
101 Marietta Street, NW, Suite 2900
Atlanta, Georgia 30303

Babcock & Wilcox Company
P.O. Box 1260
Lynchburg, Virginia 24505
Attention: Mr. H. B. Barkley

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ENCLOSURE

ANALYSES

Introduction

These analyses were directed toward (1) avoiding a steam bubble in the RV upper head during a NC cooldown/depressurization and (2) mitigating the bubble if it occurs. (The upper head region design is shown in Figures 1 and 2.)

Bubble Avoidance

Several mechanisms can have a significant effect on the formation of a void (bubble) in the B&W designed reactor vessel upper head region during NC cooldown/depressurization transients:

Cooldown/Depressurization Rate - Voids will not form in the RV upper head until the coolant in the upper head reaches saturation conditions.

Natural Circulation Flow - NC flow is from the upper plenum to the top of the plenum cover and back down to the outer annulus. The flow from the upper plenum is at the temperature of the hot leg (core outlet). During a NC plant cooldown, the coolant temperature in the upper head region of the reactor vessel will not follow the loop coolant because the flow rate through this region is small (or stagnant in the uppermost part) without forced flow in the RCS.

Heat Transfer - The heat transfer is from the upper head fluid and metal to the cooler fluid at the top of the plenum cover, the control rod drive (CRD) nozzles, the column weldments and other cooler surroundings.

Forced RCP Flow Prior to Cooldown - The RV upper head region temperature is about equal to the hot leg temperature during forced flow conditions in the RCS. Operating RCPs after a reactor trip will reduce the RV upper head temperature from the full-power hot leg temperature down toward the lower post-trip hot leg temperature. The amount of upper head temperature reduction will be dependent upon the length of RCP operation assumed after the reactor trip and the post-trip decrease in hot leg temperature.

RV Head Bleed - Bleeding through the RV head vent replaces the stagnant upper head fluid with cooler, subcooled RC hot leg fluid. This minimizes the temperature lag, allows continued cooldown without flashing and cools the RV upper head metal, which is a heat source for the RV upper head fluid. Hence, these flows directly affect the temperatures in the upper head region.

Analyses were performed to determine the maximum allowable cooldown/depressurization rate of the coolant in the RV upper head during an NC cooldown following 100% power operation without forming a steam bubble. All the mechanisms above were considered in this analysis. RV head bleed was found to be the most effective upper head cooling mechanism. The upper head cooldown rate from these analyses was used to determine the time at which the decay heat removal system (DHRS) could be cut in without flashing in the RV upper head. Two cases of RV head bleed (rate) were analyzed; bleed at average rates of 50 and 200 gpm.

Bubble Mitigation

Several mechanisms can mitigate a steam bubble in the RV upper head, should it occur:

Heat Transfer - The bubble will eventually cool and condense due to heat transfer to the cooler surroundings. This is a very slow process because of the insulation around the RV upper head and the low heat transfer coefficients of steam.

Mixing - The bubble can be condensed by mixing with subcooled coolant. This mixing is very small under NC conditions.

RV Head Vent - The bubble may be displaced from the RV head by venting through the head vent.

Collapsing - It is very difficult to completely collapse a steam bubble in the RV upper head by simply raising the RCS pressure. In fact, in an ideal adiabatic system no condensation, as a result of this compression, will occur. The RV upper head, because of the low heat losses without mixing, approximates an adiabatic system.

Analyses were performed to evaluate the mitigation of a steam bubble in the RV upper head in the event that one is formed during an NC cooldown. The primary mechanism considered in the analyses was venting the bubble through the RV head vent. Because of the relatively short times required for venting, these other mechanisms were of minor importance. The venting was analyzed at two different pressures (1020 and 2500 psig) for comparison.

Analytical Method

RV Upper Head Cooldown

The cooldown of the RV upper head under NC conditions is a result of both heat and mass transfer (flow) from the upper head. The flow paths are shown in Figure 3 and the heat transfer model for the analyses is shown in Figure 4. Mass transfer from the upper head is through the plenum cover drain holes and the RV head vent. Heat transfer from the RV upper head is by a combination of conduction, convection and and a very small amount of radiation. The model for heat losses through the metallic insulation yielded heat transfer values very similar to those measured in the field, however this mode of heat loss was very minor compared to the heat transfer due to RV head bleed. The coolant rising from the fuel assembly upper end fitting into the upper plenum and column weldments is assumed to be the same temperature as the RCS hot leg since the bulk of this coolant goes directly to the hot leg. Initially, the upper head water temperature was assumed to be 590F, based on an assumed RCP trip concurrent with reactor trip and subsequent RCP coastdown. The RV head metal temperature was assumed to be 626F. This is approximately the hot leg temperature for 100% power. The RCS loops, including the hot leg, were assumed to cooldown at 50F/hr.

Some of the other assumptions used in this analysis are listed below:

1. Convective heat losses from the CRDs were modeled as conductive heat losses. This is a standard analytical method for modeling fins.[1]

2. The flow rate for natural circulation was 3% of full flow. Based on operating experience and the NATURAL code,[2] this flowrate is considered to be conservatively low.

3. Where conductive heat transfer exists between adjacent nodes of different materials with different thermal conductivities, the lesser value or limiting value was used.

4. Vendor supplied transference values were used at insulation/air interfaces.

5. The ambient (reactor building) temperature was assumed constant at 120F.

For the analyses, the upper portion of the reactor vessel and internals was divided into a multinode representation as shown in Figure 5. The mass transfer model was superimposed on this multinode model as shown by the solid and dotted flow paths. A solid line from one node to another signifies mixing. A dotted line signifies no mixing, such as the case for coolant rising inside the column weldments from the upper plenum to the RV upper head. The distribution of the coolant flow in the RV upper head was based on realistic assumptions. Water enters the upper head region from the coolant circulating above the plenum cover. Fluid rises upward from the row of nodes until it reaches the dome. At this point, the flow path connects with the next radially inward path. This pattern continues until all flow has been directed to the center flow path, at which time it exits out the top water node through the RV head vent. Figure 5 shows that the upper head coolant which exits back through the plenum cover drain holes comes from only the first layer of nodes in the upper head. This assumption is believed to be somewhat conservative and was used since a more realistic flow pattern was not determined in the analyses. The dimensions of the nodes were chosen to accommodate the dimensions of the actual hardware as much as possible.

As explained on Figure 5, each node represents a three dimensional ring in the analysis. Finite difference equations were then written for each node volume. This set of finite difference equations was then solved simultaneously for each discrete time step. A 25 second time step was chosen based upon conventional stability criteria.[1] Future node temperatures were calculated based upon the current temperature plus the heat and mass transfer over the time step. The general form of the finite difference equations is:

$$T_{Future} = T_{Present} + \frac{\Delta t[Q_k + Q_h + Q_m + Q_r]}{\rho \times C_p \times V}$$

Where: Δt = time step

Q_k = conduction heat transfer = $-kA \ \Delta T/\Delta X$

Q_h = convection heat transfer = $hA \ \Delta T$

Q_m = heat transferred with mass = $\rho \times V \times Cp \times (T_{new} - T_{present})/\Delta t$

Q_r = radiation heat transfer = $B \times A \times \varepsilon \times [(T_{present})^4 - (T_{adj.})^4]$,

ρ = density of node material

C_p = specific heat of node material

ε = emmissivity of metalic insulation

V = volume of node

k = thermal conductivity of node material

A = horizontal cross sectional area

ΔT = temperature difference across interface

$\Delta T/\Delta X$ = temperature gradient across node

h = convection coefficient

B = Stefman-Boltzman Constant

T_{adj} = temperature of adjacent node (both $T_{present}$ and T_{adj} in Q_r equation are absolute temperatures)

T_{new} = new temperature of node due to mass transfer,

= $(T_{present} - T_{in}) \exp [(-\dot{m}/\rho \times V)\Delta t] + T_{in}$,

$\dot{m}$ = mass flow rate into node,

T_{in} = weighted mass average incoming temperature,

$T_{present}$ = present node temperature.

Conductive heat transfer was considered at boundaries of similar media (air-air, steel-steel, water-water, insulation-insulation). Convective heat losses were considered at other boundaries, (air-steel, air-insulation, steel-water). Radiative heat transfer was also considered at the surface of the insulation to the nearest gray body, but this heat transfer was very minor.

The CRD convective heat losses (to the service structure region) were modeled as conductive heat losses. Ambient conditions of 120F were assumed.

$$Q_k = -kA(dT/dx)$$

Q_k = Heat transferred by conduction
k = thermal conductivity of carbon steel
A = horizontal-cross sectional area
dT/dx = linear temperature gradient along CRD length.

This additional Q term was added to the finite difference equations for nodes in the RV head (dome) that contain CRD nozzles. The leadscrews and column weldments were modeled similarly. The masses and volumes of these components were distributed among the applicable node rings to take into account the cooling by these components.

All sources of heat -- both into and out of each node -- were summed and then divided by the mass and C_p of the node. This term was added to the present temperature to obtain the future node temperature. The process was carried out for all nodes before continuing on to the next time step.

RV Upper Head Void Mitigation

Analyses were performed to determine under what conditions a void, if it occurred, could be vented from the RV head vent.

KPRZ, a non-equilibrium digital pressurizer model, was utilized to analyze the reactor vessel upper head region as a pressurizer.[3] The reactor vessel high point vent valve was modeled as a pressurizer relief valve, and flow through the RV upper plenum cover was approximated by flow through a pressurizer surge line.

The pressurizer model of the RV upper head is shown in Figure 6. KPRZ evaluates three thermodynamic regions in the pressurizer -- one for steam, one for subcooled liquid, and one for two-phase mixture. Heat transfer to and from the vessel walls and heat and mass transfer at the steam-liquid interface were evaluated. Steam separation from the liquid regions, condensate rainout from the steam region, and mixing between the two liquid regions were modeled. The deletion and subsequent recreation of the steam, mixture, and buffer regions were analyzed. At initiation, only two regions were considered, corresponding to the steam and mixture regions. However, during surge transients, a third region (called the buffer liquid region) was employed to represent the accumulation of the cooler primary system fluid as it flows into the bottom of the pressurizer. Regions were deleted and created based on mass inventory criteria. The numerical solution consisted of converting the partial differential equations describing the system into sets of coupled ordinary differential equations. These equations were then integrated continuously in time. Additional details of the KPRZ model are documented in reference 3.

Some of the more important assumptions used in the RV upper head void mitigation analysis are as follows:

1. The geometry rearrangement necessary to model the reactor vessel upper head as a pressurizer does not affect the physical processes occurring during the venting operation. The pressurizer volume used in the KPRZ model was the actual volume of the upper head region (690.7 ft^3).

2. The plant operator has throttling control of HPI during the venting operation so as to maintain constant pressure in the RV. The RCS pressure during venting was assumed to be 1020 psig for case 1 and 2500 pisg for case 2. The case 1 pressure is arbitrary, but it is near the expected pressure at which voiding might occur were a cooldown to have occurred and drawn an RV upper head steam bubble. The case 2 pressure is the RCS system design pressure. The steam is assumed to be saturated before venting.

3. The venting process is assumed to be constant-volume. For each cubic foot of steam that is displaced through the high point vent nozzle, one cubic foot of subcooled liquid flows from the RV into the upper head region (through the upper plenum cover plate).

Results of Analyses

The results of these analyses show that the RV upper head coolant can be cooled down sufficiently during a 50F/hr cooldown of the core and RC loops with natural circulation to allow DHRS cut-in without flashing in the upper head. The cooldown of the RV upper head without flashing is achieved by bleeding at least 3000 gallons of coolant from the RV head vent for each 50F of RCS loop cooldown. This upper head cooldown is accomplished within the time required for an RCS loop cooldown at 50F/hr by bleeding 50 gpm from the RV head vent during the RCS loop cooldown.

These results also show that the supplies of auxiliary feedwater required will not be increased by the requirement to avoid a steam bubble in the upper head if a 50 gpm bleed rate is maintained from the RV head vent. The auxiliary feedwater requirements are shown in Figure 7.

In the event the reactor vessel upper head is completely voided (690 ft^3), venting calculations show that it would take only about 12 minutes for Bellefonte 1 to completely vent the upper head.

A natural circulation cooldown can also be accomplished without violating other pressure-temperature limits. More detailed results are reported in the following sections.

RV Upper Head Cooldown

The results are shown in Figure 8 for both the 50 and 200 gpm bleed cases. This shows both the temperature of the hottest upper head coolant node and the temperature of the circulating coolant nodes (hot leg temperature) as a function of time. Water temperatures adjacent to the RV dome wall initially rose to 614F from 590F for the 50 gpm bleed case (and to 600F for the 200 gpm bleed case). The circulating reactor coolant that flowed above the plenum cover weldment and down into the outer annulus cooled the node represented by the ring at the head base. As the ring cooled, it drew heat from the dome shell, thus cooling it and the water adjacent to it. After several hours, the main heat transfer paths became (1) heat transferred to water near the top of the RV upper head from the RV dome, (2) heat transferred down the dome to the RV metal above the hot legs, (3) heat transferred from metal to water in the RV upper head at the periphery of the plenum cover, and most importantly, (4) heat removed by the bleeding coolant.

This bleed is replaced by coolant at the hot leg temperature. In addition, this bleeding promotes mixing up through the entire upper head as shown in Figure 5. The cooldown rate of the upper head coolant is 38F/hr for 50 gpm continuous bleed and 45F/hr for 200 gpm continuous bleed. These results are both with an RCS loop cooldown of 50F/hr. Note that an increase in the total bleed of 400% increases the RV upper head cooldown rate less than 20%. Higher bleed rates are not that much more effective since the RV upper head cooldown would never quite match the RCS loop cooldown rate. Either of these cases cools the upper head coolant sufficiently within the time required for RCS loop cooldown at 50F/hr so that the DHRS can be cut in when the RCS hot leg is at 305F. The 50 gpm bleed rate may be effectively obtained by venting a rate of 200 gpm for 15 minutes for each hour of cooldown or 100 gpm for 30 minutes, etc. The bleed rate of 200 gal/min was chosen as being representative of the maximum design rate of Bellefonte Nuclear Plant units 1 and 2 at normal system operating pressure. The results indicate that a bleed rate less than 50 gpm may also provide acceptable RV upper head cooldown rates. The temperature of the RCS loop at DHRS cut-in was assumed to be 305F. The maximum RCS pressure at DHRS cut-in was assumed to be 420 psig to prevent lifting the DH system relief valves. To achieve DHRS cut-in without flashing in the RV upper head would then require that the RV upper head temperature be no higher than 449F.

The analysis assumed the only flow above the first layer of nodes over the plenum cover was the bleed flow which continued upward and out the RV head vent. This first layer of nodes over the plenum cover cooled at about the same rate (50F/hr) as the RC loops as a result of this mixing. Hence, if NC flow (in addition to the bleed) were to extend farther above the plenum cover, the upper head cooldown rate would be nearer to that of the RC loops. However, flow velocities into the upper head region from below the plenum cover are expected to be less than two feet per second and could not cause appreciable penetration up into the dome region. It should be pointed out that the dome region is a large volume, approximately 690 ft.^{3}, with a plenum cover to dome top distance of over 6 feet. Even if twice the penetration had been assumed, the results of the cooldown would not change dramatically.

Typical pressure-temperature limits are shown in Figure 9. This case is based on RCP trip concurrent with reactor trip.

RV Upper Head Void Mitigation

The tabulation below defines the time required to completely vent steam voids from the RV upper head and refill the region with subcooled liquid for various initial bubble sizes. These analyses, using the KPRZ code, assumed that makeup is throttled to keep the pressure in the reactor vessel upper head nearly constant during the venting process.

Case 1 - 1020 PSIG: Time Required to Clear Reactor Vessel Upper Head

Fraction of Upper Head Voided At Start of Venting process	Time Required to Vent, Minutes Bellefonte 1 & 2
One-Fourth	2.9
One-Half	5.7
Three-Fourths	8.5
Completely Voided	11.0

Another case was also evaluated for comparison. Case 2 (at 2500 psig) might be encountered if the plant operators attempted to raise the pressure before opening the high point vent valve. A completely voided RV upper head would not actually be encountered under these conditions due to compression of the steam bubble. The tabulation below summarizes the time required to vent the RV upper head region for these conditions.

Case 2 - 2500 PSIG: Time Required to Clear Reactor Vessel Upper Head

Fraction of Upper Head Voided After Pressurizing Bubble to 2500 psig	Time Required to Vent, Minutes Bellefonte 1 & 2
One-Half	6.7
Completely Voided	12.0

These results are relatively insensitive to the RCS pressure. Lower pressures will take slightly less time since less mass is required to be vented. Also, it will take about 50% of the time to vent the upper head if it is 50% voided, etc.

Figure 1. Reactor Vessel and Internals

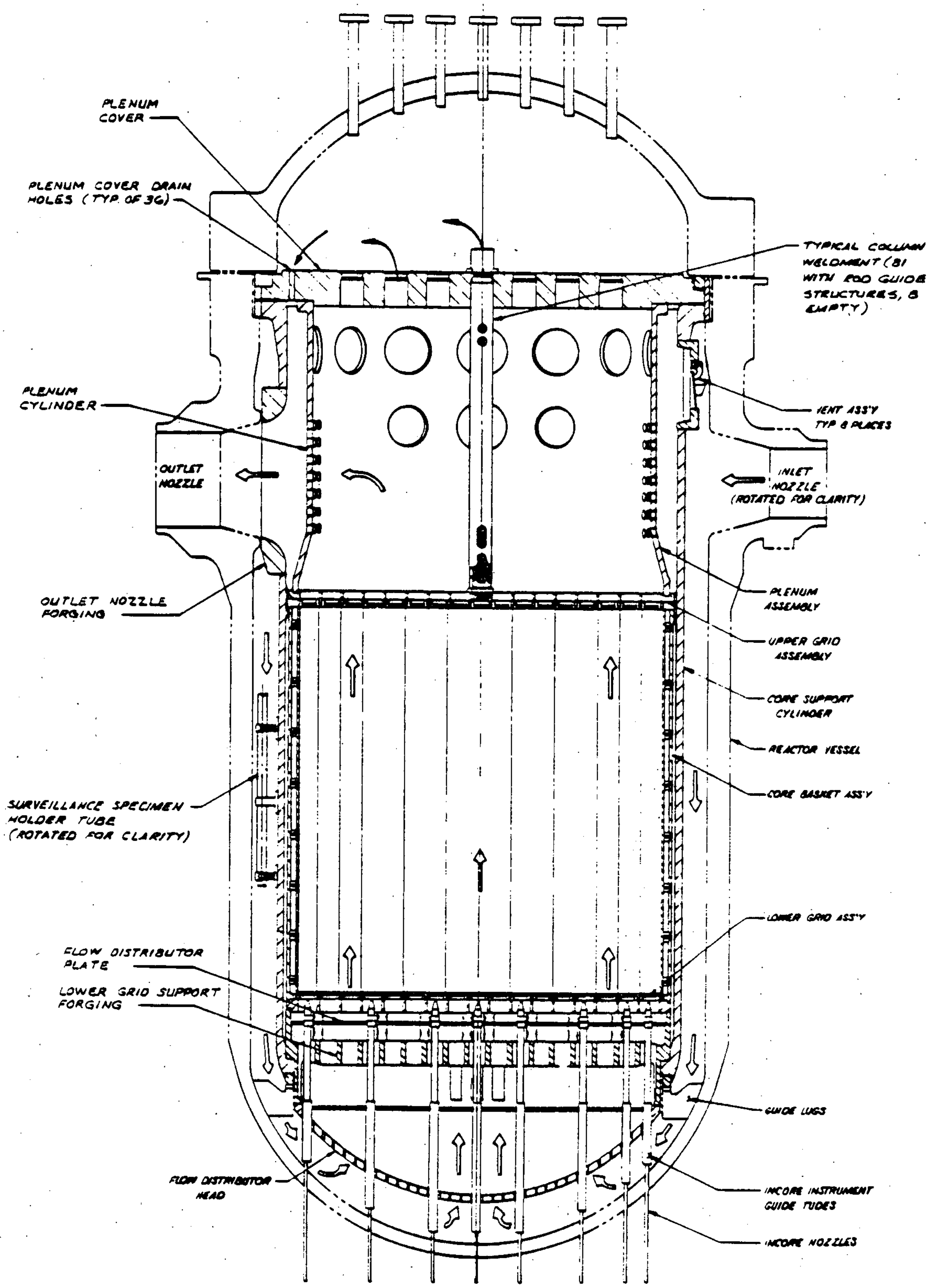


Figure 2. Schematic Diagram of Upper Portion of Reactor Vessel and Internals

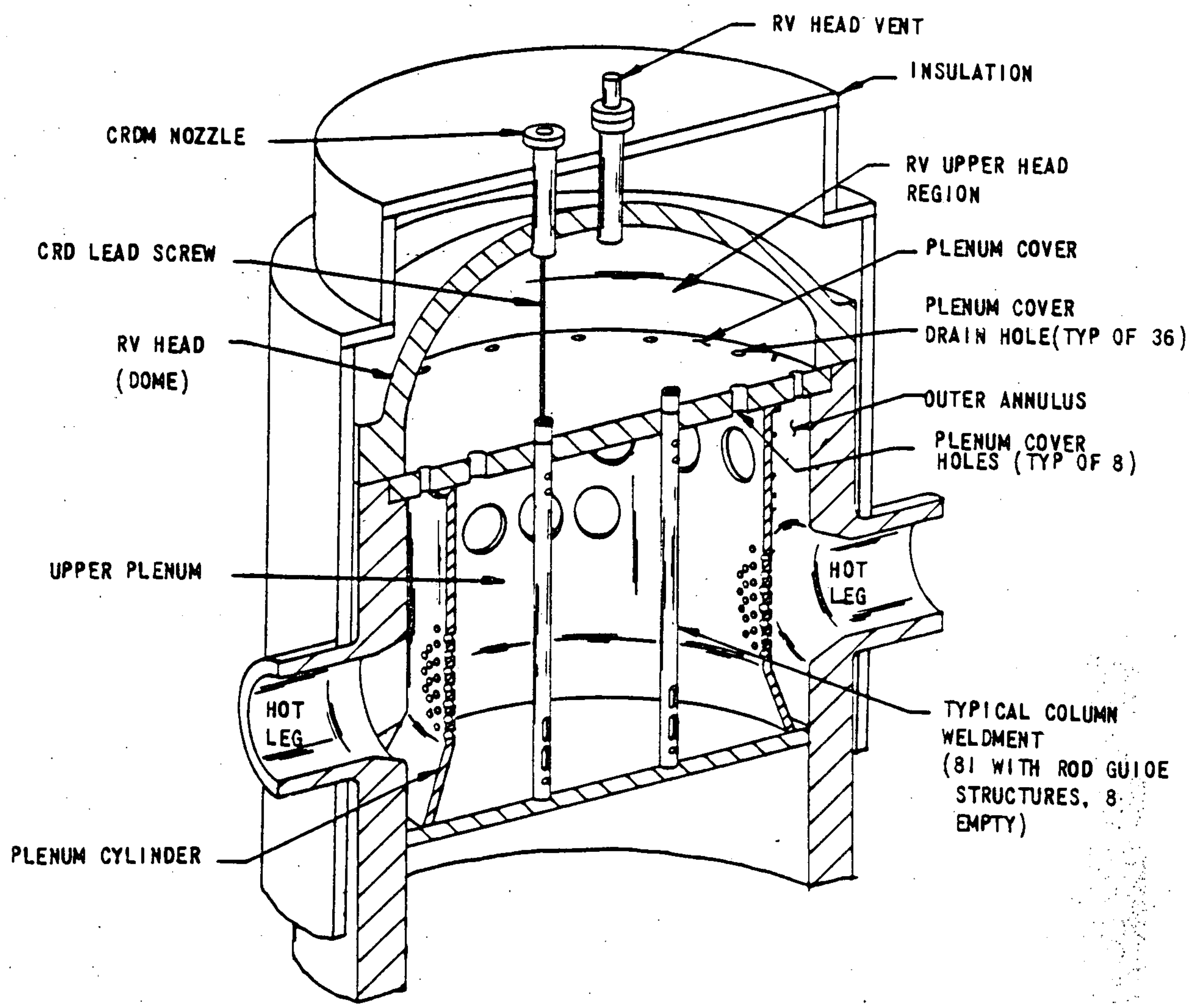
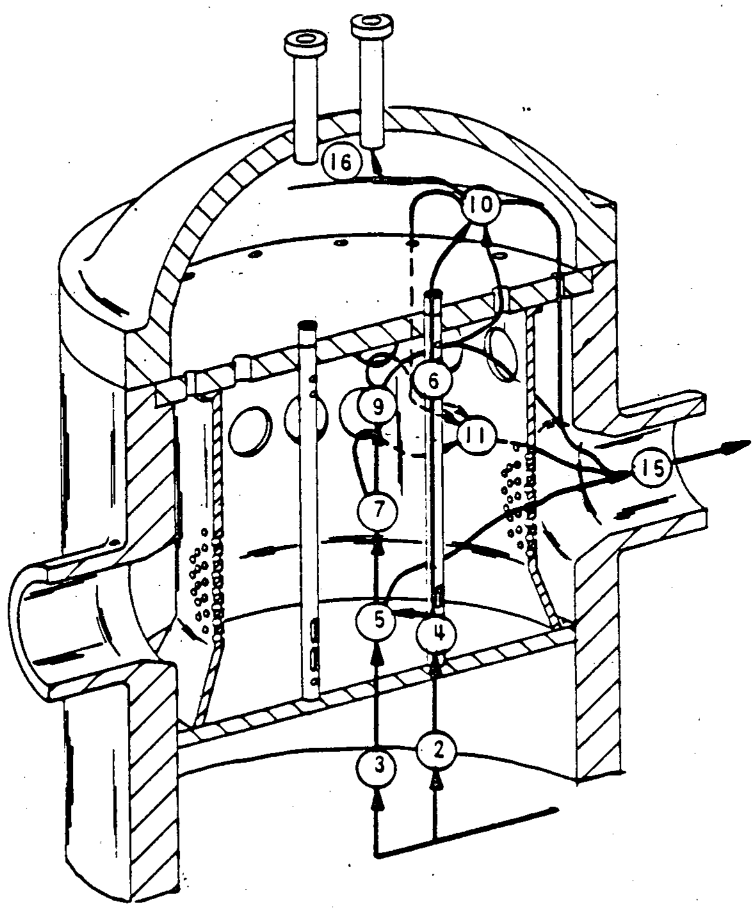
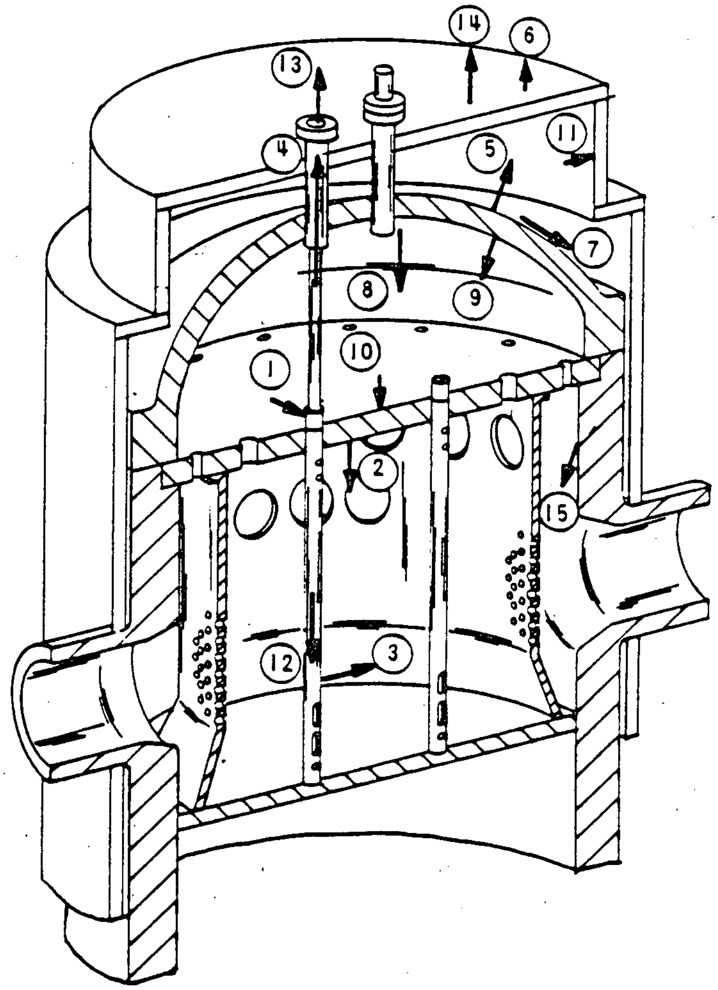


Figure 3 Upper Plenum and RV Upper Head Mass Transfer Model



From Node	To Node	Path Description
2	4	Thru Fuel Assembly upper end fitting (UEF) into column weldment (CW)
3	5	Thru Fuel Assembly UEF into plenum open area
4	5	From inside CW to plenum open area thru lower exit ports
4	6	Up full column weldment
5	7	Axial flow in plenum open area
5	15	Thru 3-inch holes in plenum cyl. to outlet nozzle
7	9	Axial flow in plenum open area
7	11	Thru 18- and 20-inch holes in plenum cyl. to plenum cyl. outer annulus
9	11	Thru 20-inch holes in plenum cyl. to plenum cyl. outer annulus
9	15	Thru 20-inch holes in plenum cyl. to outlet nozzle
6	10	Thru CW top caps to upper head
9	10	Thru empty CW's and 3¼-inch holes in plenum cover to outlet nozzle
10	11	Thru plenum cover drain holes to plenum cyl. outer annulus
10	15	Thru plenum cover drain holes to outlet nozzle
11	15	Plenum cyl. outer annulus to outlet nozzle
10	16	From upper head to RV head vent

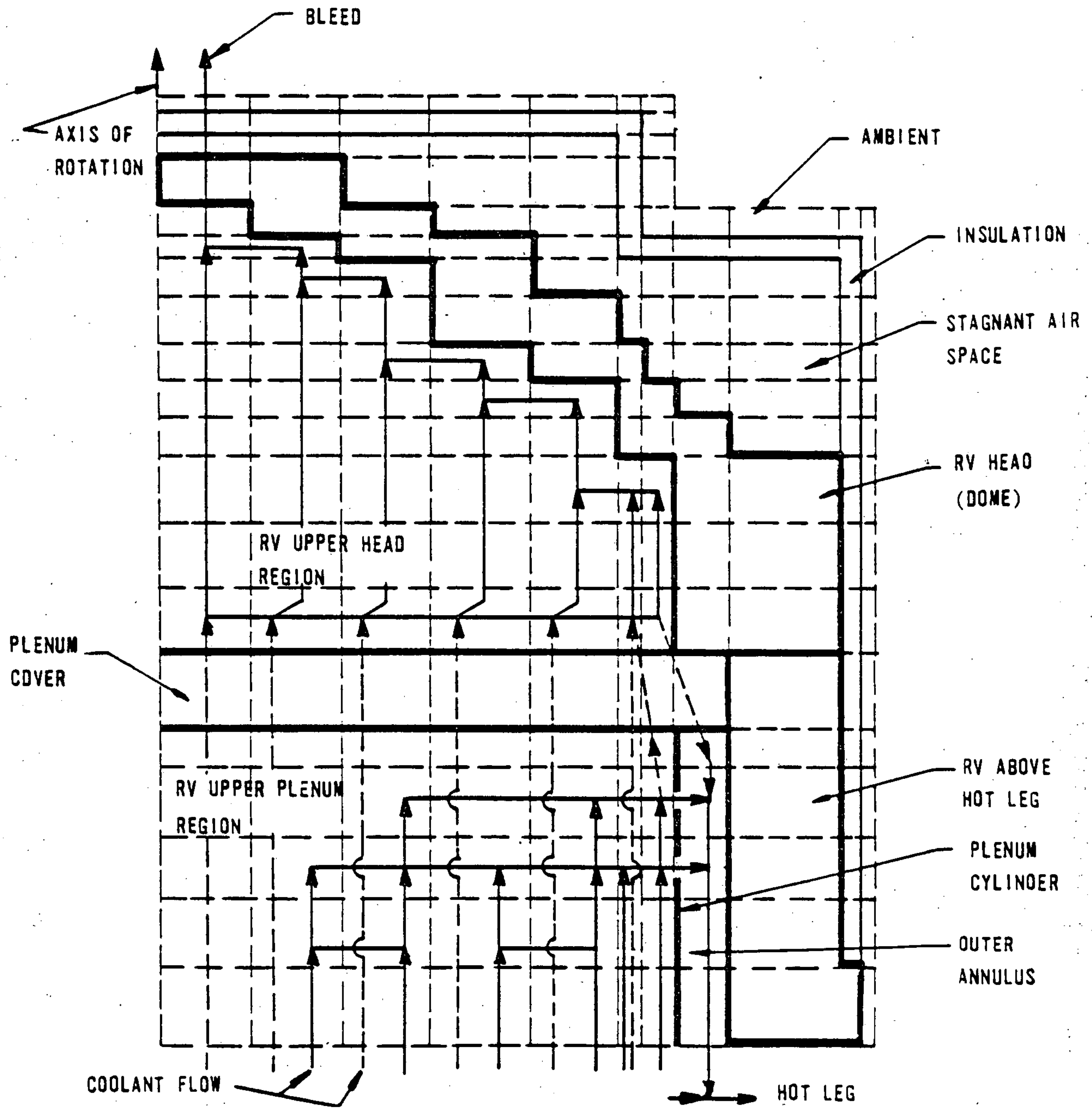
Figure 4. Heat Transfer Model



Mode Number		Description
1	(a)	Upper Head Coolant To Lead Screw
2	(a)	Plenum Cover to Upper Plenum
3	(b)	Column Weldment to Upper Plenum
4	(b)	Up CRD Nozzle
5	(a)	RV Head to Air Under Insulation
6	(c)	Insulation to Containment
7	(b)	RV Head to Plenum Cover
8	(b)	From Hotter to Cooler Coolant Nodes
9	(a)	RV Head to Coolant in Upper Head
10	(a)	Upper Head Coolant to Plenum Cover
11	(a)	Air Under Insulation to Insulation
12	(b)	From Hotter to Cooler Nodes of Column Weldment
13	*(b)	CRD Nozzle to Containment
14	(a)	Insulation to Containment
15	(a)	RV Wall to Upper Plenum Coolant

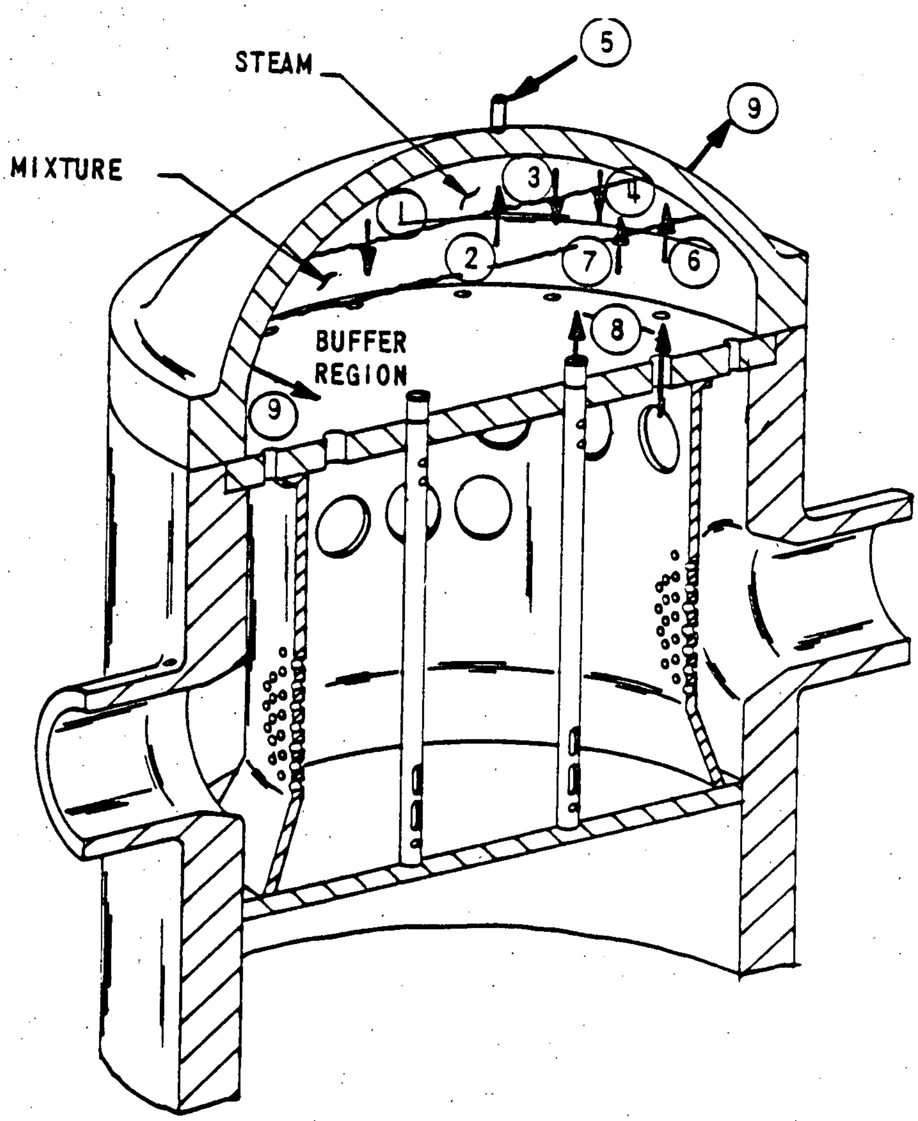
(a) Convection
(b) Conduction
(c) Radiation
* CRD nozzle was assumed to be 120F at 3 feet above RV head.

Figure 5 Noding Diagram



Note: This noding diagram is only a one-half cross section of the upper reactor vessel and internals. In the analysis, this noding diagram is rotated about the left side vertical axis so that the RV and internals are modeled in three dimensions. Each node thus becomes a ring.

Figure 6 Pressurizer Model of RV Upper Head



1. RAINOUT
2. BUBBLE RISE
3. MASS & ENERGY TRANSFER AT INTERFACE
4. CONDENSATION FROM DOME
5. PRESSURE RELIEF
6. BUBBLE RISE
7. MIXING
8. SURGE FLOW
9. HEAT TRANSFER BETWEEN RV HEAD (DOME) AND BUFFER MIXTURE AND STEAM, (3 REGIONS)

Figure 7. Required AFW Inventory Vs Time to DHRS Cut-In

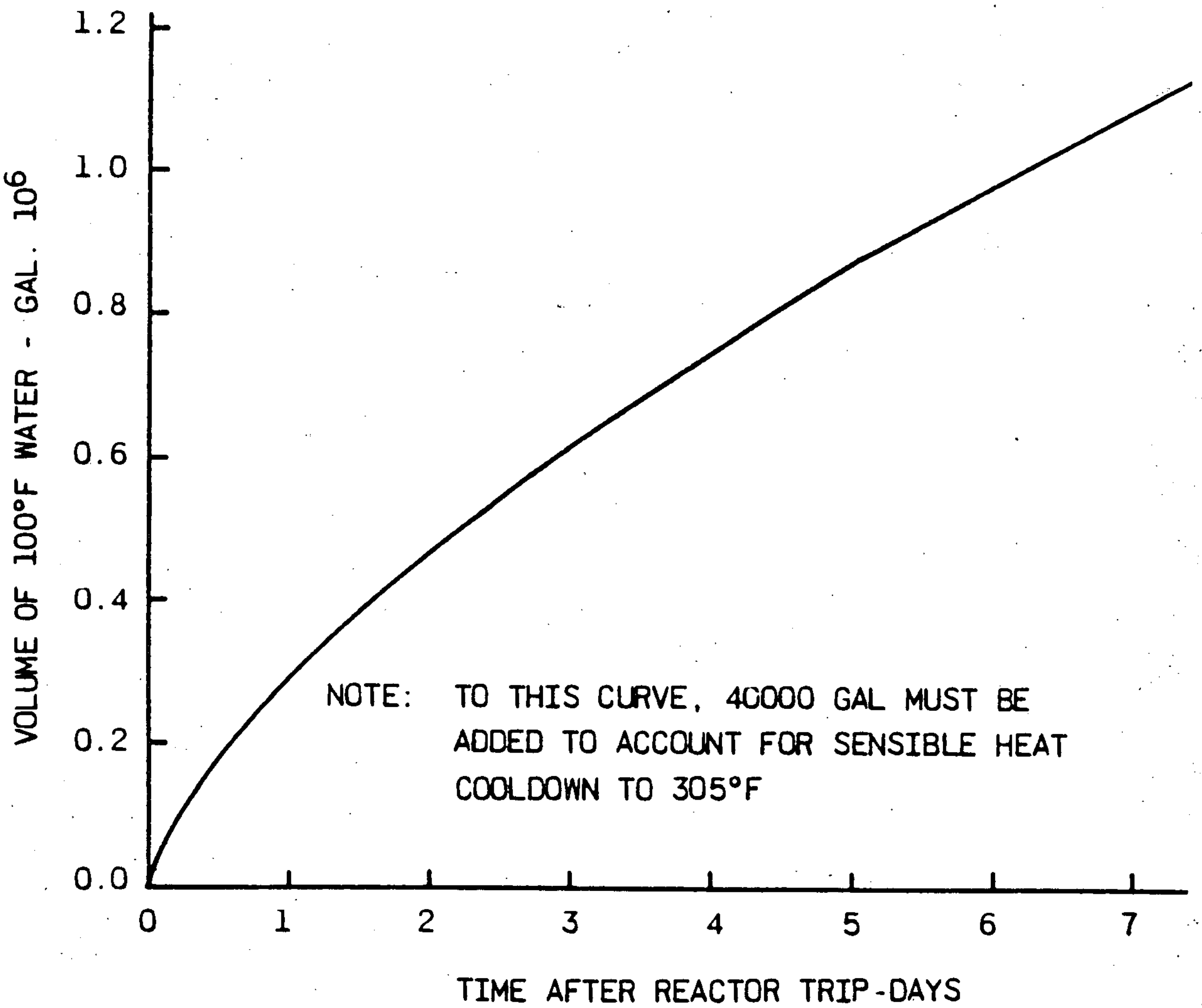


Figure 8 Natural Circulation Cooldown Temperature Vs Time

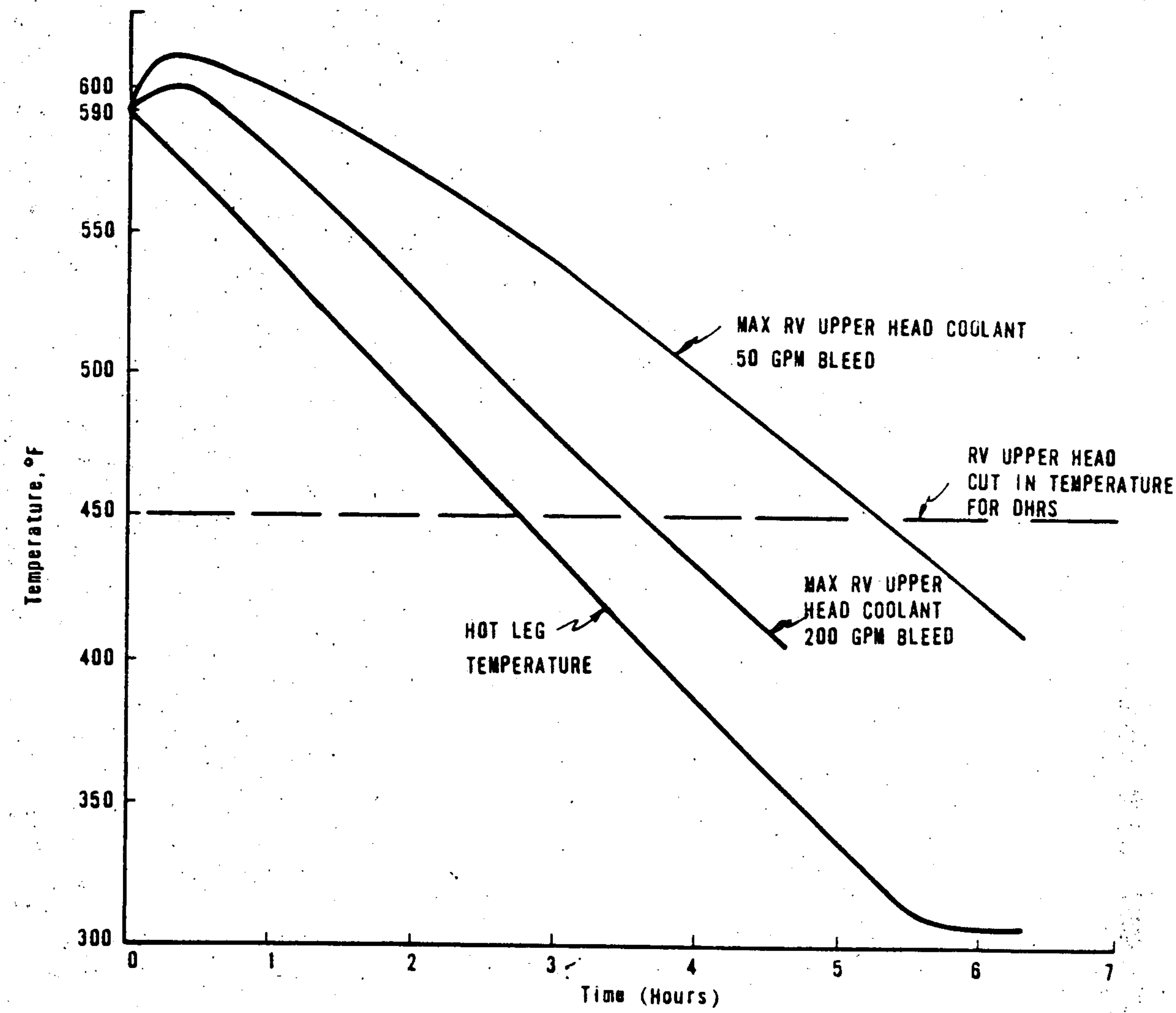
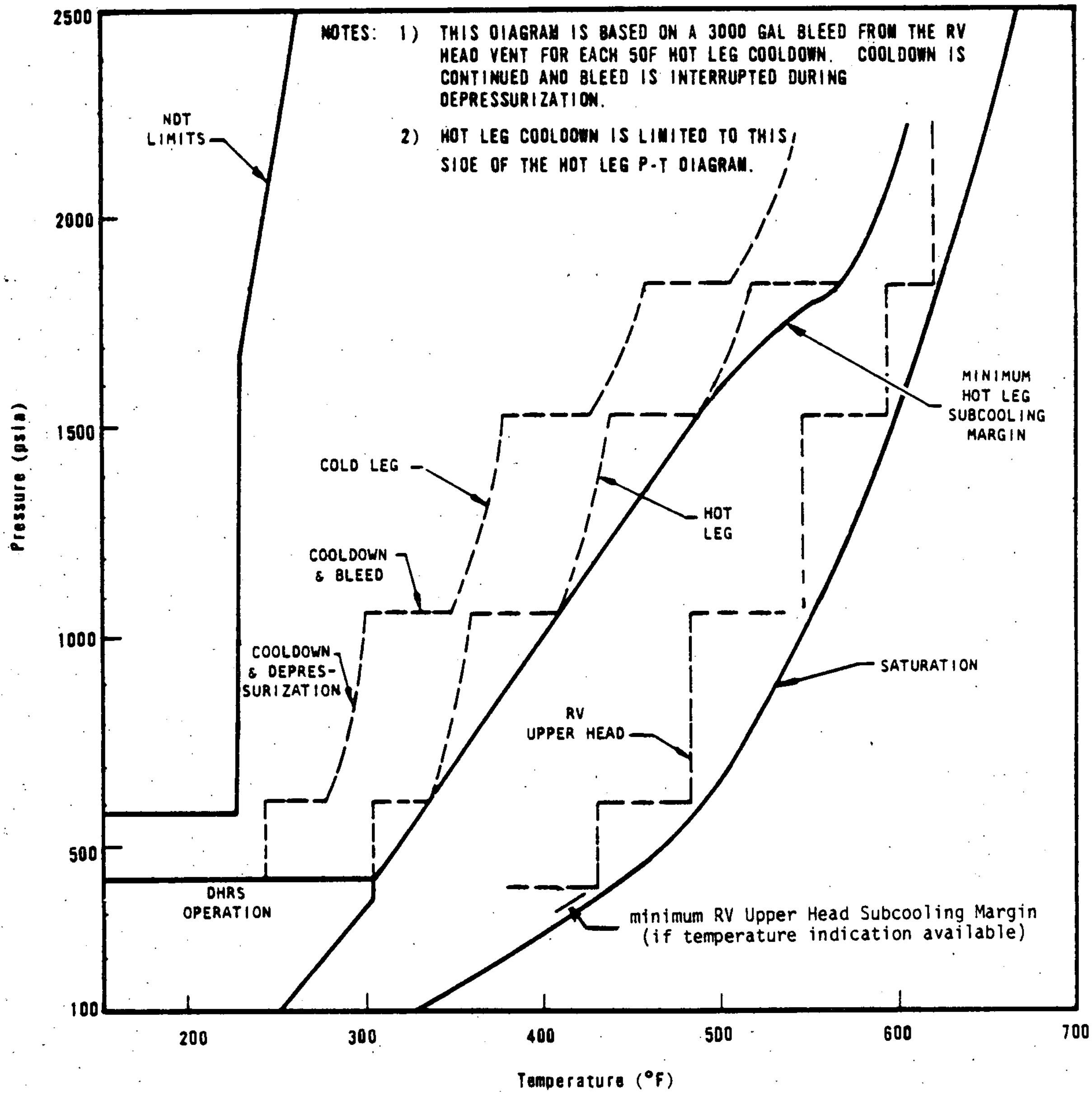


Figure 9 Typical Natural Circulation Cooldown — Pressure-Temperature Diagram



REFERENCES

1. J.P. Holman, "Heat Transfer", 4th Edition, 1976, New York, McGraw-Hill, section 4-6, Transient Numerical Method.

2. NPGD-TM-574, "NATURAL- Hybrid Natural Circulation Code".

3. NPGD-TM-568, "KPRZ, Digital Code for the Simulation of Transient Pressurizer Performance", March, 1982.