Engineering Services

Babcock & Wilcox
a McDermott company

REACTOR VESSEL HEAD COOLDOWN
DURING NATURAL CIRCULATION COOLDOWN TRANSIENTS

Prepared for

ANO-1

Prepared by: Bret L. Boman
B. L. Boman

Reviewed by: CW Talley 2/3/83
C. W. Talley

BABCOCK & WILCOX
UTILITY POWER GENERATION DIVISION
P.O. BOX 1260
LYNCHBURG, VA 24505

86-1140819-00

CONTENTS

1.0 INTRODUCTION

1.1 Scope of Work

This document provides the minimum time required to reach the decay heat removal system cut-in point during a natural circulation cooldown without flashing in the reactor vessel head. The decay heat removal system (DHR) cut-in point was assumed to be 291 psig and 280°F (Ref. 1).

1.2 Background

During natural circulation, the fluid in the upper reactor vessel head (above the plenum cover) is essentially stagnant and does not thermally communicate with the rest of the reactor coolant system. The cooldown rate of the head metal and fluid is very slow and is controlled by heat transfer to the reactor building and to the small amount of coolant that flows over the plenum cover. Hence, if the RCS is depressurized and cooled rapidly, flashing of the head fluid and uneven thermal stresses may result. Therefore, the head cooldown controls the amount of time required to reach the DHR cut-in point.

1.3 Summary

Figure 5 shows the maximum RV head fluid temperature as a function of time, and Figure 6 plots the corresponding saturation pressure. In order to start the decay heat removal system at 291 psig, the head fluid temperature must be below 419.1°F (T_{sat} at 291 psig). This also assumes the rest of the RCS is at or below 280°F. Thus, it takes about 135 hours to cool the head to this temperature.

2.0 ANALYSIS

2.1 Analytical Methods

The cooldown rate of the RV upper head under natural circulation conditions was determined using a finite difference heat transfer model. The model consisted of nodes representing the coolant, plenum cover, vessel wall, insulation, and the air trapped between the insulation and metal (see Figure 1). Heat transfer mechanisms considered were conduction, convection, and radiation. Figure 2 shows the heat transfer paths and mechanisms.

The flow through the upper head region was derived from previous hydraulics calculations, and Figure 3 shows these flow paths. The RV head temperature was assumed to be 604°F. This is approximately the hot leg temperature for 100 percent power. The head fluid temperature was initially set to 585°F (assuming the pumps continue to run for a short period after the reactor trips). However, as shown in the results, the fluid temperature quickly increases to the metal temperature. The RCS loops, including the hot leg, were assumed to cool down at 100°F/hr from 585°F to 310°F.

Other important assumptions used in this analysis are listed below:

1. Convective heat losses from the control rod drive (CRD) were effectively modeled as conductive heat losses. Instead of a $Q = hA \Delta T$ equation, a $Q = -kA\, dT/dx$ equation was used with the CRD temperature set at 120°F three feet above the RV head.

2. The flow rate for natural circulation was 3 percent of full flow.

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

4. Radiative heat transfer was used for the reflective insulation heat losses to the containment atmosphere. An emissivity value of 1.0 was used.

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

Typical RV head mirror insulation transference values were used at insulation/air interfaces. The upper portion of the RV and internals was divided into a multinode representation as shown in Figure 1. A mass transfer model was superimposed on this multinode model as indicated 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. Figure 1 shows that mixing is assumed only in the first layer of nodes in the RV upper head. This assumption is critical to the results of the analyses and, as discussed above, is conservative.

As shown on Figure 1, 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 20-second time step was chosen based on conventional stability criteria. Future node temperatures were calculated based on 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 = $-kA \times \Delta T/\Delta X$,

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

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

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

ρ = density of node material,

C_p = specific heat of node material,

V = volume of node,

k = thermal conductivity of node material

ΔT = temperature difference across interface,

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

h = convection coefficient,

B = Stefan-Boltzman constant,

T_{adj} = temperature of adjacent node

(both $T_{present}$ and T_{adj} in Q_r equation are absolute),

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

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

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

T_{in} = weighted mass average incoming temperature,

$T_{present}$ = present node temperature

Conductive heat transfer was considered at the 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). Finally, radiative heat transfer was considered for insulation-ambient air conditions.

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

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

where:

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

The additional Q term above 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 new node temperature. The process was carried out for all nodes before continuing on to the next time step.

2.1 Analytical Results

The results of the reactor vessel head cooldown analysis are shown in Figure 4. The temperatures of the hottest RV head coolant node and the hot leg coolant are shown as a function of time. The maximum coolant cooldown rate in the RV head is 1.70°F/hr while the primary coolant cooldown rate is 100°F/hr (Ref. 2). The analysis assumed the following:

- Initial coolant temperature of 585°F
- Initial shell temperature of 604°F
- Ambient temperature of 120°F
- Natural circulation flow of about 3 percent normal flow

The analysis assumed that flow up through the plenum cover affected only the first layer of nodes above the cover. These nodes cooldown at the same rate as the circulating coolant (100°F/hr). Hence, if flow were to extend farther above the plenum cover, the cooldown rate would increase.

However, there is no data or evidence to suggest that additional penetration would occur during natural circulation. 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 500 $ft.^3$, with a plenum cover to dome top distance of about 5½ feet. Even if twice the penetration had been assumed, the results would not change dramatically.

The model's results were compared with simple independent hand calculations which determined the initial cooldown rate with the head at 585°F. The agreement was good, confirming the model's general accuracy.

These results cannot be directly supported nor refuted by field data. No B&W plant has ever performed a natural circulation cooldown. In addition, the necessary instrumentation to measure the RV head cooldown rate is not presently installed at any site.

As shown in Figure 4, the model only simulated about eight hours of cooldown. Since the head fluid temperature is about 586°F at eight hours, the results need to be extrapolated to reach the decay heat removal system cut-in point. Since the cooldown rate is dependent upon the head fluid/ambient temperature differential, the cooldown rate will decrease as this differential decreases. The long-term cooldown is expected to be governed by the following equation:

$$\frac{T_{RVH}(t) - T_A}{T_{RVH}(t=0) - T_A} = e^{-t/\tau} \qquad \text{(Equation 1)}$$

where:

$T_{RVH}(t)$ = temperature of the RV head fluid

$T_{RVH}(t=0)$ = approximately 600°F

T_A = ambient temperature, 120°F

τ = time constant, hr^{-1}

The time constant was evaluated using data from the eight hours of simulation.

From Ref. 2, the peak RV head fluid temperature is 599.2°F at .17 hours, and the fluid temperature is 586.2°F, 7.7 hours after the peak.

Therefore:

$$\tau = \frac{-t}{\ln \frac{T_{RVH}(t) - T_A}{T_{RVH(t=0)} - T_A}} = \frac{-7.7}{\ln \frac{(586.2 - 120)}{(599.2 - 120)}} \sim 280 \text{ hr}^{-1}$$

Figure 5 has been constructed to extend the head fluid temperature vs. time plot using Equation 1. Note that it requires about 135 hours to cool down to 419.1°F (T_{sat} at 291 psig).

Figure 6 plots the saturation pressure corresponding to the head temperature as a function of time. This gives the minimum RCS pressure vs. time to avoid flashing during a natural circulation cooldown. Figure 7 shows head fluid temperature vs. saturation pressure superimposed with the NDT limits (Ref. 3). A subcooling margin line for the head saturation line has been developed by adding 25 psi and 10°F for instrument errors. Information has also been added to Figure 7 regarding the cooldown of the rest of the RCS. Assuming the hot leg conditions at full power are approximately 604°F and 2170 psia, the RCS could be depressurized and cooled to 350°F and 1500 psia in less than three hours (100°F/hr) without flashing in the head or violating NDT limits. Then as the system is slowly depressurized and the head fluid slowly cools over the next 130 plus hours, the RCS should be cooled to at least 280°F.

In summary, to prevent flashing in the head, the head fluid conditions must lie above and to the left of the head subcooling line.

As previously mentioned, it is possible to cool the rest of the RCS down at 100°F/hr from 604°F to 350°F if the head subcooling line and NDT limits are not violated. However, the resulting thermal stresses from having the head at 600°F and the rest of the RCS at 350°F may be significant and have not been evaluated.

3.0 CONCLUSIONS

Important conclusions of this document are:

- In order to prevent flashing in the head during a natural circulation, at least 135 hours are required to reach the decay heat removal system cut-in point. This may also require large amounts of AFW to remove decay heat for such an extended time period.

- Once the decay heat removal system cuts in, the RCS depressurization must still be slow since the RV head fluid will still be stagnant and cooldown very slowly.

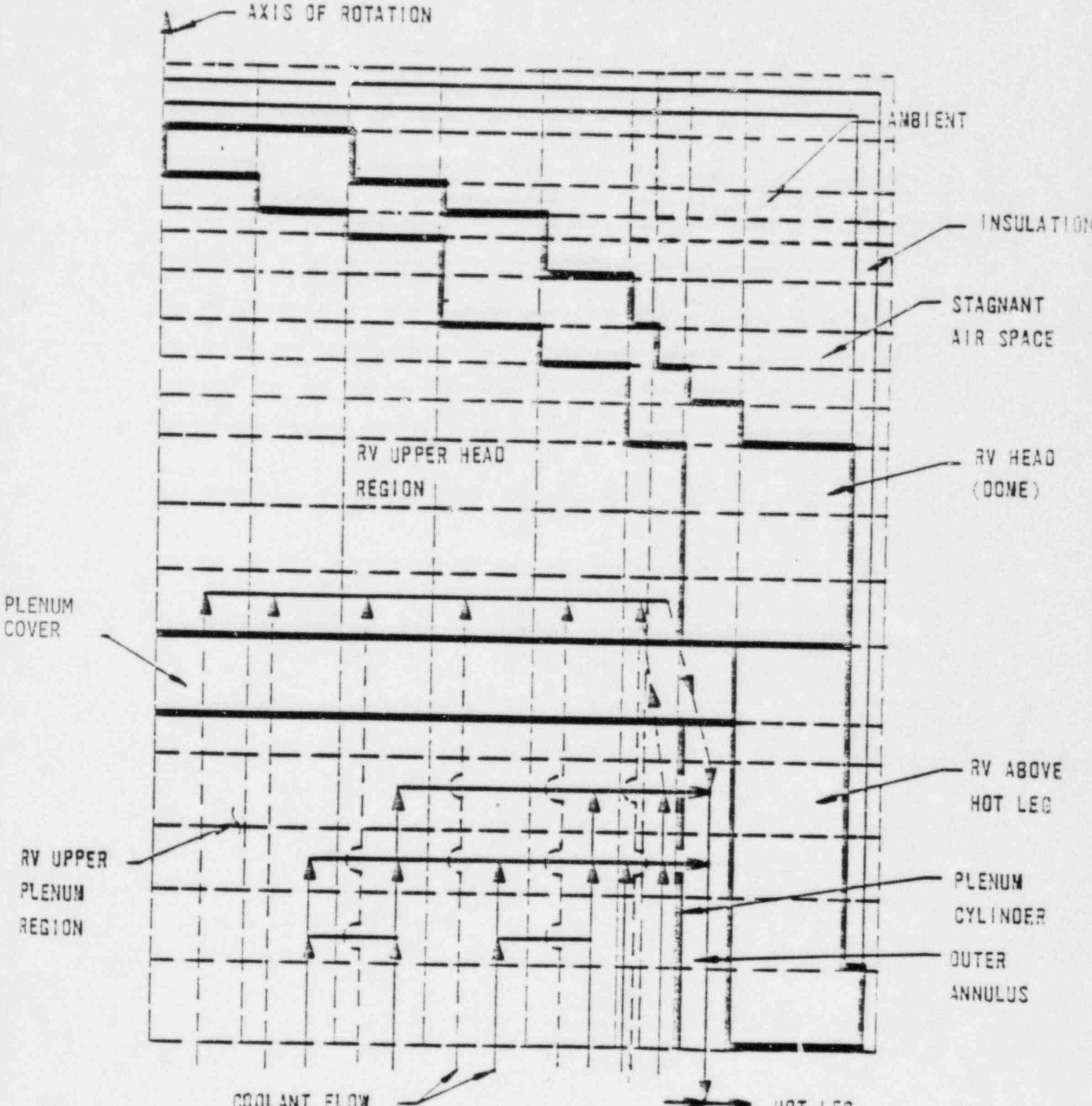
4.0 REFERENCES

1. "Plant Limits and Precautions for ANO-1," B&W Doc. No. DP 1101, Rev. 1.

2. "177 FA Natural Circulation Cooldown Rate," B&W Doc. No. 32-1132883-00, August 16, 1982.

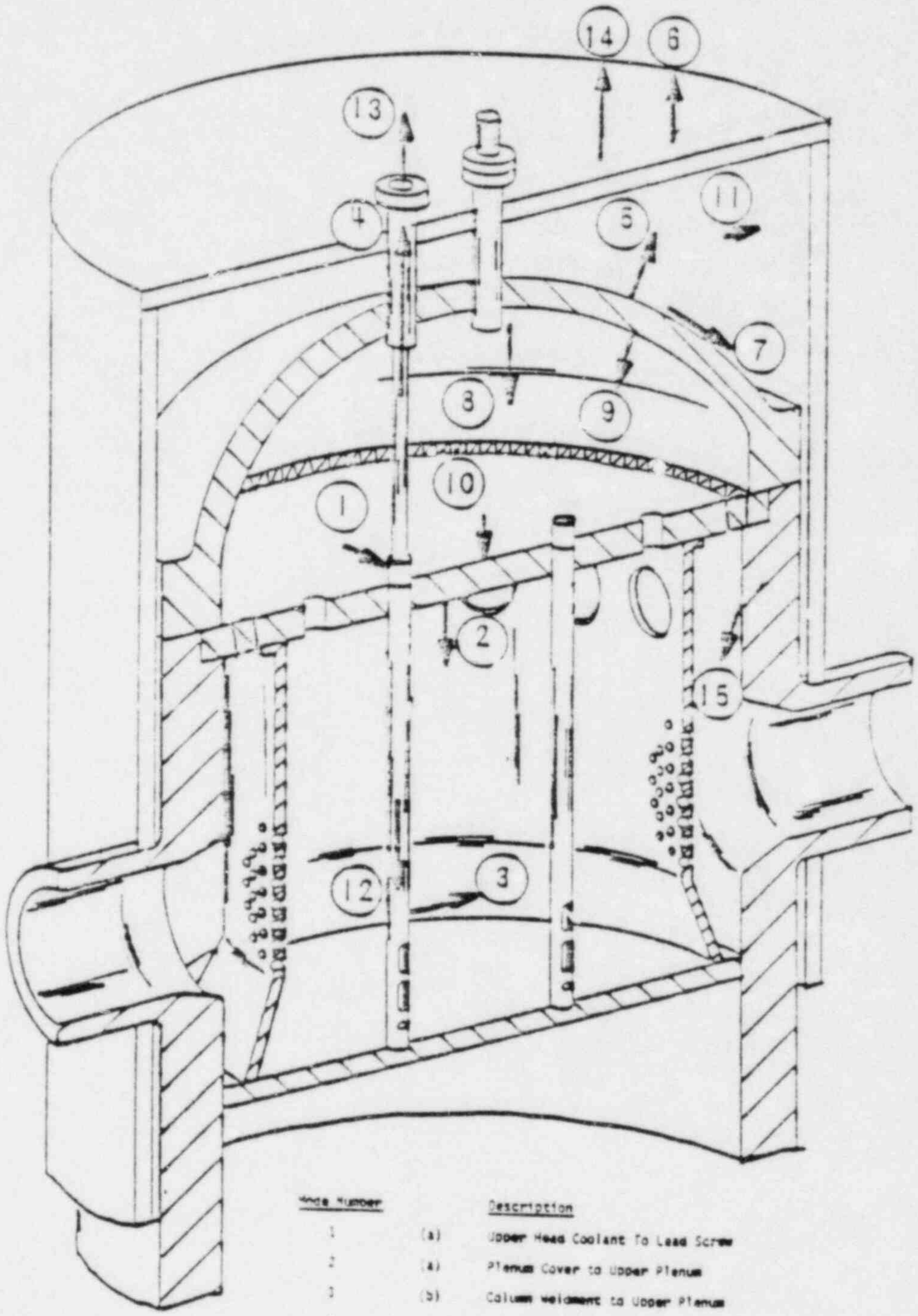
3. "Arkansas Nuclear One Unit 1 Technical Specifications," B&W Doc. No. 05-0003-06.

Figure 1
NODING DIAGRAM
(NO BLEED CASE)



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 S VERTICAL AXIS SO THAT THE RV AND INTERNALS ARE MODELED IN THREE DIMENSIONS. EAC NODE THUS BECOMES A RING.

FIGURE 2: HEAT TRANSFER MODEL



Node 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

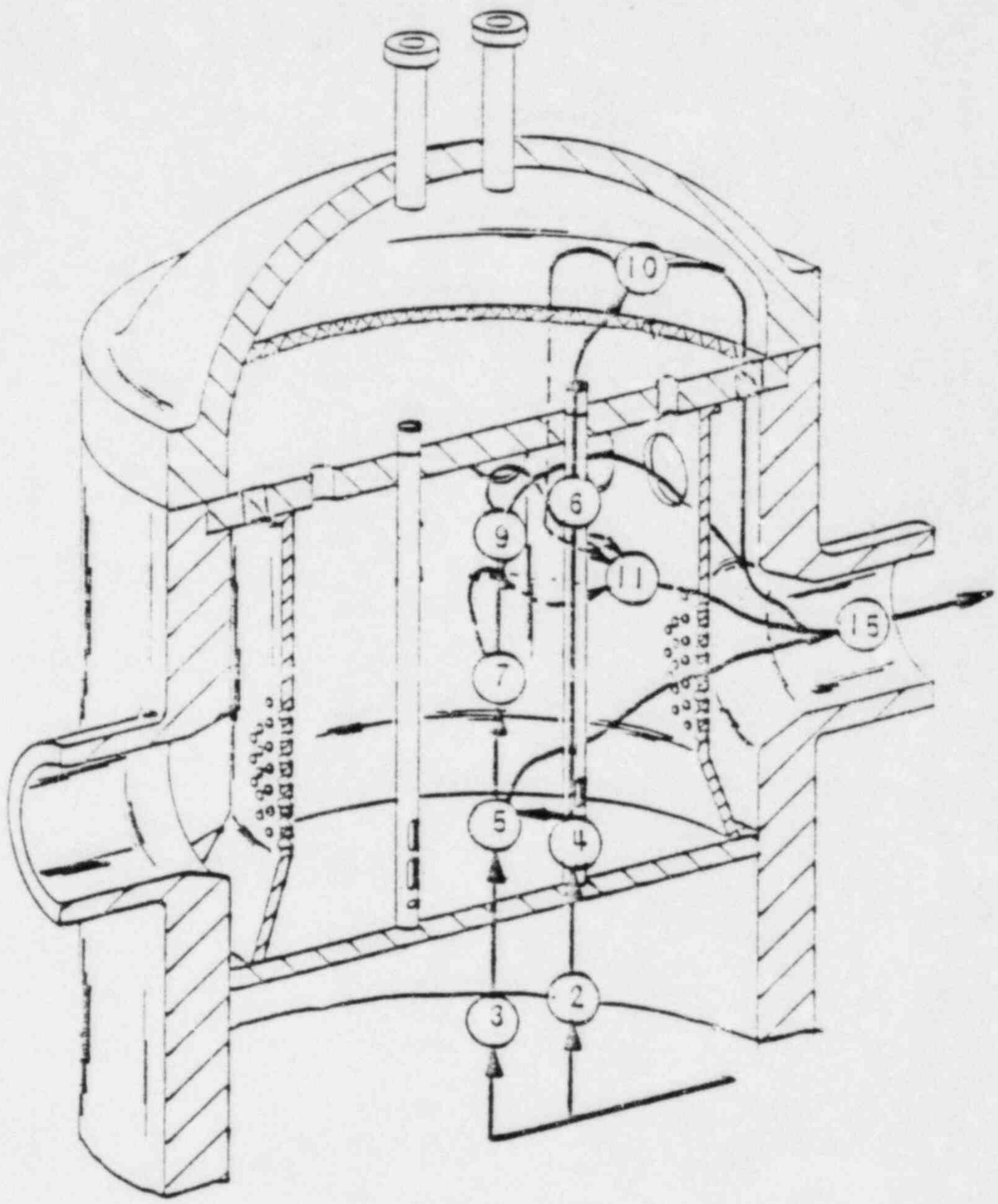
(b) Conduction

(c) Radiation

* CRD Nozzle was assumed to be 120F at 3 feet above RV head.

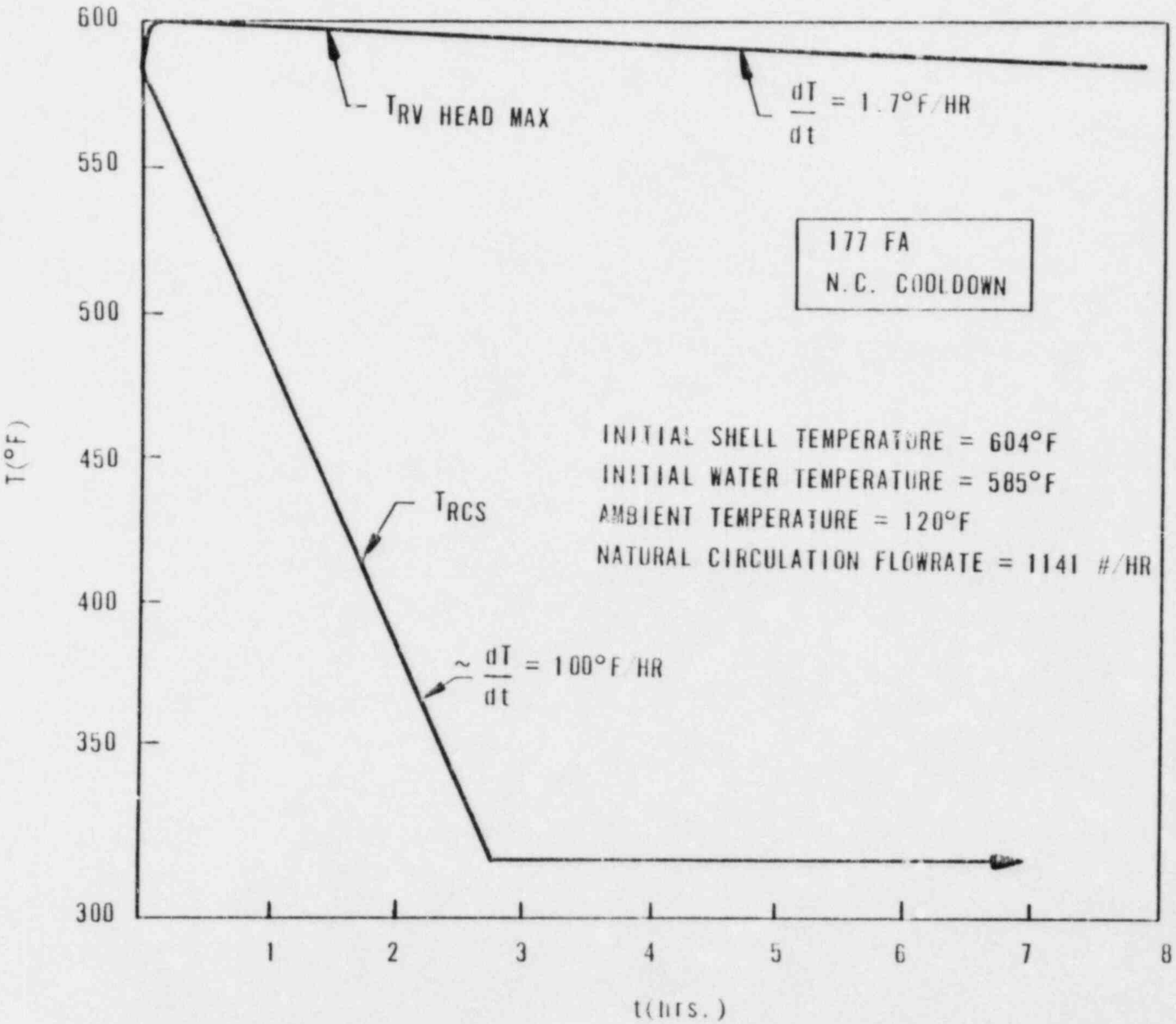
36-1140819-00

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 22- and 14-inch holes in plenum cyl. to plenum cyl. outer annulus
9	11	Thru 14-inch holes in plenum cyl. to plenum cyl. outer annulus
9	15	Thru 14-inch holes in plenum cyl. to outlet nozzle
6	10	Thru CW top caps to upper head
10	11	Thru plenum cover annulus to plenum cyl. outer
10	15	Thru plenum cover annulus to outlet nozzle
11	15	Plenum cyl. outer annulus to outlet nozzle

Figure 4: REACTOR VESSEL HEAD COOLDOWN



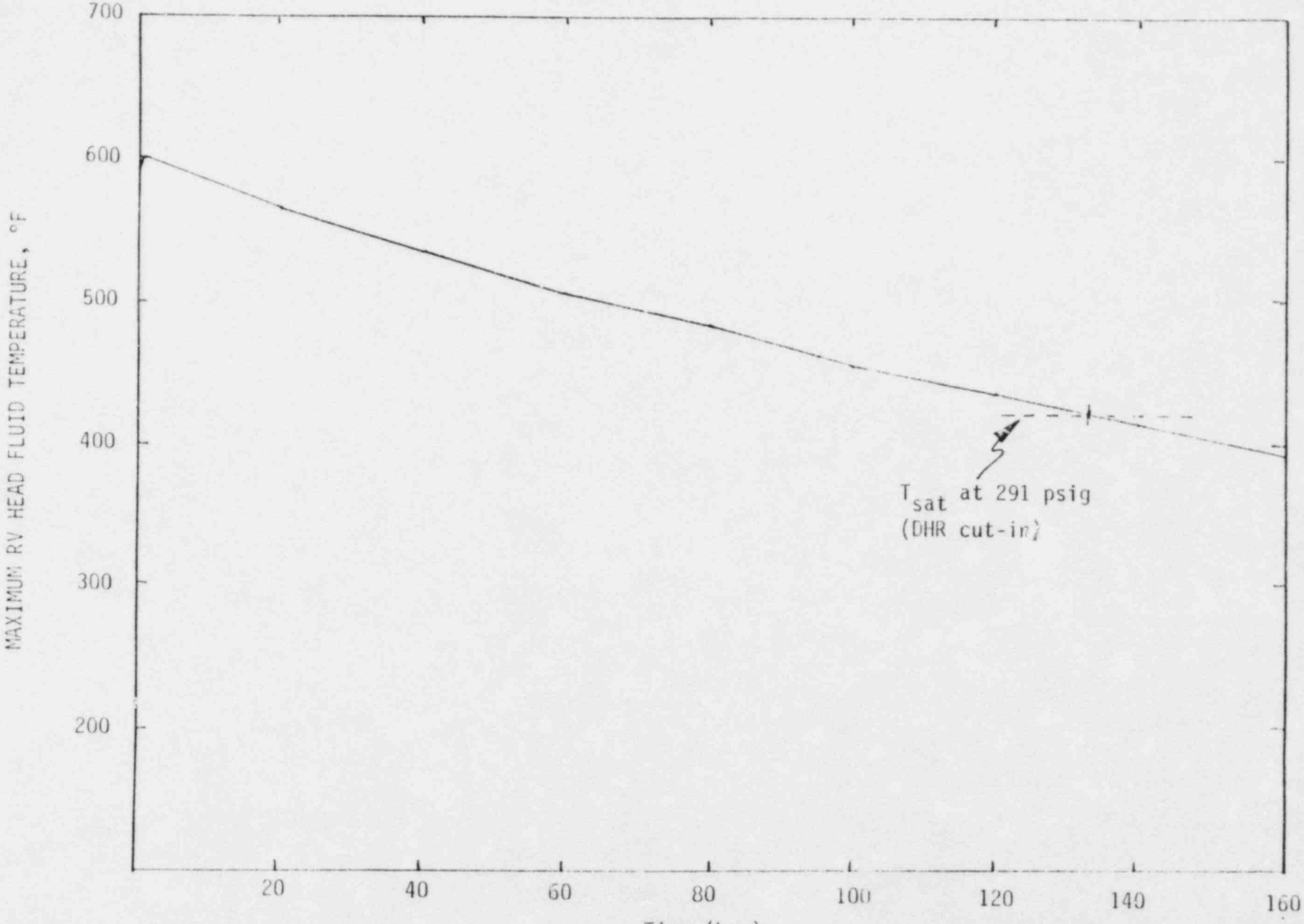


FIGURE 5: MAXIMUM RV HEAD FLUID TEMPERATURE VS TIME

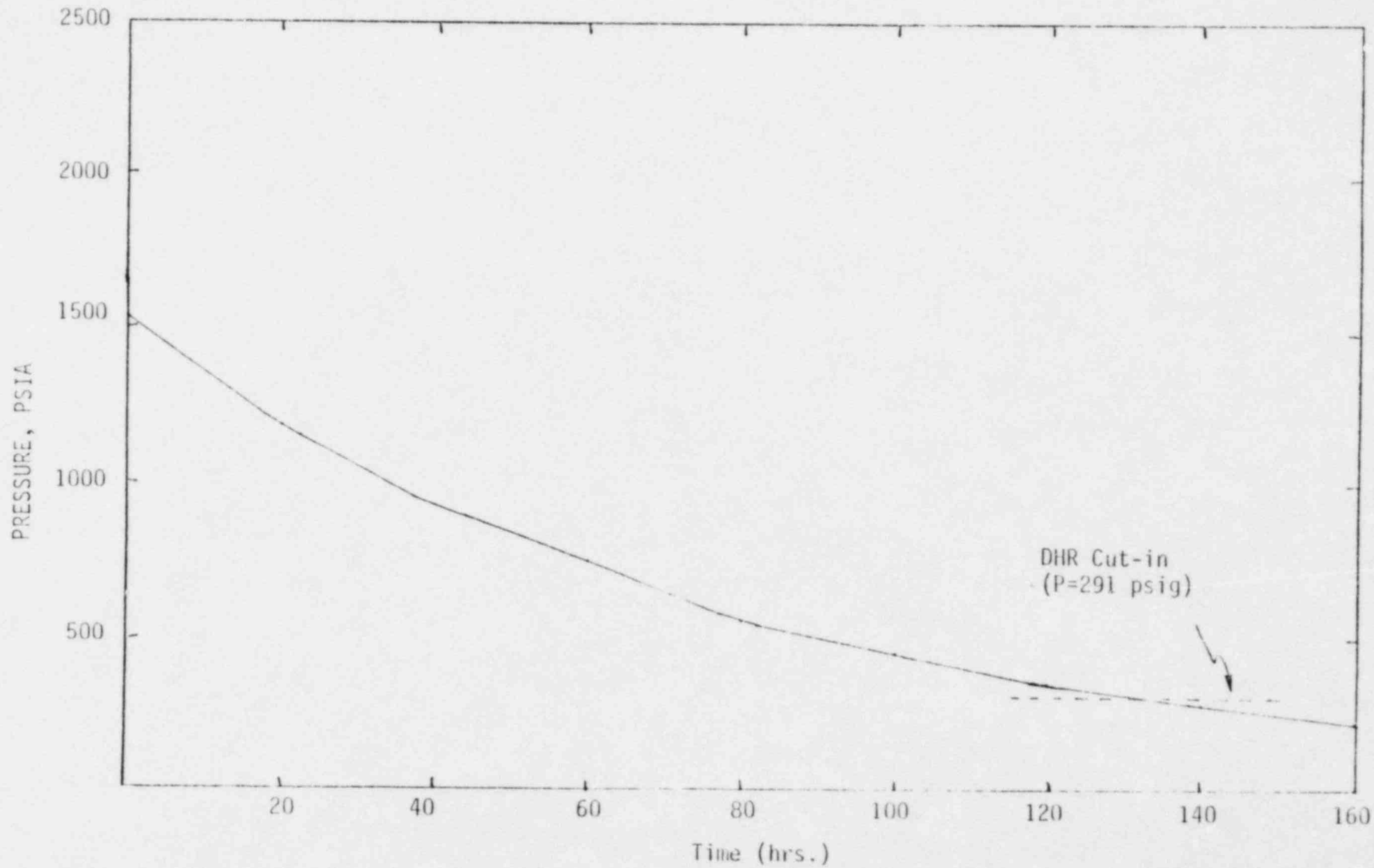


FIGURE 6: HEAD SATURATION PRESSURE VS TIME

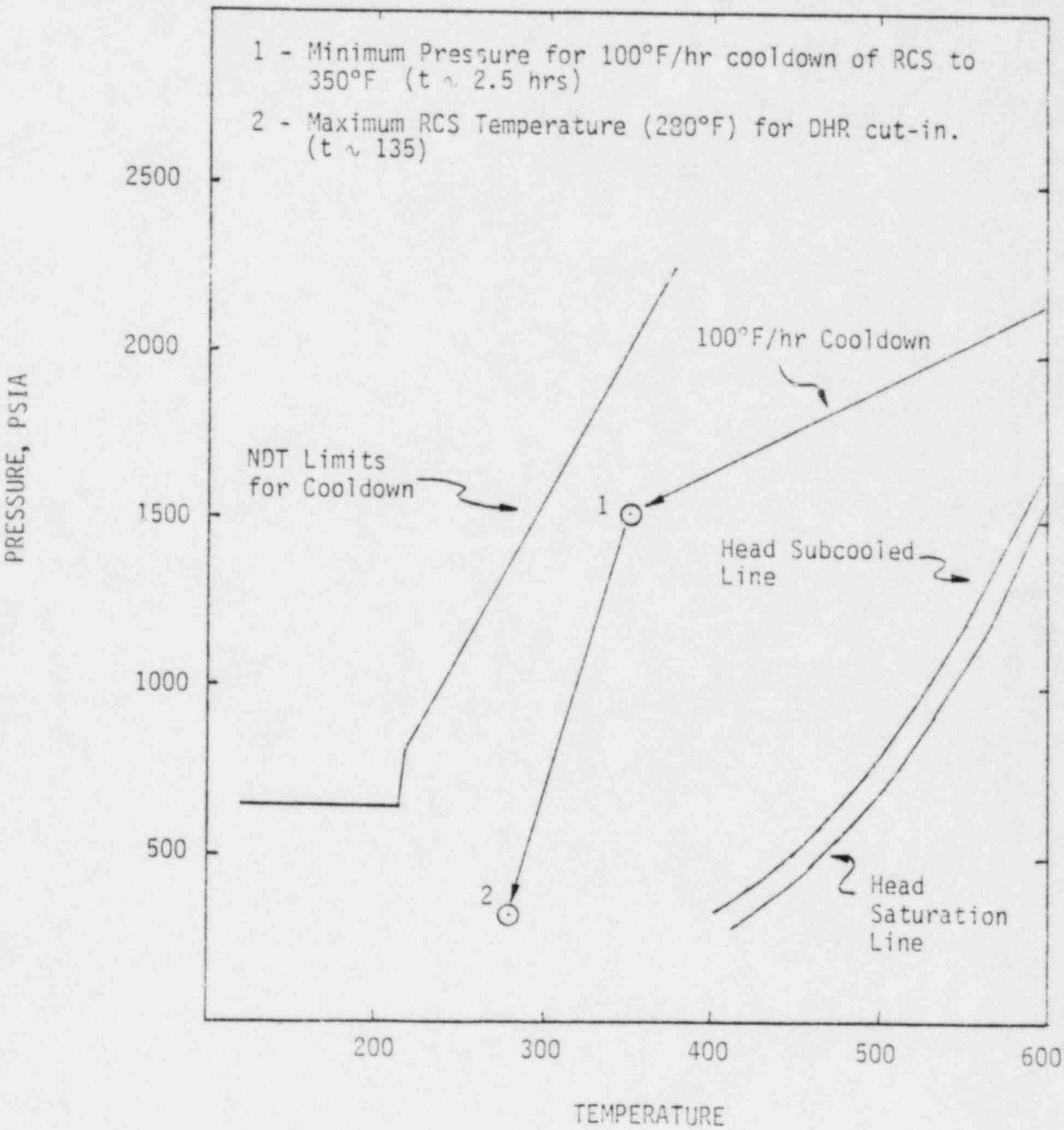


FIGURE 7: PRESSURE - TEMPERATURE DIAGRAM FOR NATURAL CIRCULATION COOLDOWN