TMI-1

NUCLEAR GENERATING STATION

NATURAL CIRCULATION COOLDOWN ANALYSIS

WITHOUT REACTOR VESSEL UPPER HEAD VOID FORMATION

TOPICAL REPORT 017
REVISION 1

PROJECT NO: 5400 41274

D. C. Bucheit (Energy, Inc.)
A. A. Irani (GPU Nuclear)
P. W. Lynches (GPU Nuclear)

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[signature] 7/3/85
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DISCLAIMER OF RESPONSIBILITY

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SUMMARY

This report contains an analysis for TMI-1 which simulates a natural circulation cooldown without reactor vessel upper head void formation. A two-dimensional cylindrical model of the TMI-1 RV upper head was developed and used as the basis for the thermal analysis. Computer aided analyses were performed by means of HEATING6 (a multi-dimensional, generalized heat conduction code) to demonstrate the thermal response of the RV head to RCS cooldown rates of 10F°/hr and 50F°/hr. The results indicate that for an RCS cooldown of 10F°/hr to 204°F, it would require 22 hours to reduce the coolant temperature in the reactor vessel head to 429°F*. On the other hand, for an RCS cooldown of 50F°/hr to 204°F, the time required to cool the reactor vessel head to 429°F* is on the order of 7 hours.

The results of these analyses may be correlated into pressure versus temperature curves which can be incorporated into existing cooldown procedures.

* 429°F is the saturation temperature which corresponds to the decay heat removal system cut-in-point - 325 psig RCS pressure.

1.0 INTRODUCTION

1.1 BACKGROUND

On June 11, 1980, the St. Lucie reactor was shutdown due to a loss of component cooling water to the reactor coolant pump seals which also required shutdown of the reactor coolant pumps. The cooldown was accomplished by natural circulation. At approximately four hours into the event, charging flow, which was initially being divided between the cold legs and the auxiliary pressurizer spray, was diverted entirely to the auxiliary spray to enhance the depressurization and reduce the system pressure on the pump seals. At that time, abnormally rapid increases in pressurizer level were observed. Detailed evaluation and follow-up analyses have indicated that the increases in pressurizer level indication were the results of steam void formation in the upper head region of the reactor vessel. The steam void was produced at the instant the system pressure dropped below the saturation pressure corresponding to the upper head coolant temperature. Under conditions of natural circulation, coolant in the upper head is expected to be in poor thermal communication with coolant in the plenum. Consequently, the coolant temperatures in the RV head will tend to remain elevated above temperatures indicated by hot and cold leg instrumentation.

1.2 NRC Concerns and Requirements

Because of the unexpected occurrence the void during the St. Lucie event, and the failure of the operators to immediately recognize the void

formation and take corrective action, the question of whether such void formation is properly accounted for in safety analyses has been an area of concern to the NRC. These concerns relate to a) procedures and training to enable operators to avoid void formation (if possible), or recognize and properly react to reactor vessel head voiding during natural circulation cooldown and b) the possibility that significant head voiding increases the susceptibility of the plant to more serious accidents. In particular, these issues are contained in Reference 1 which requests the following information:

1. A detailed description of the natural circulation cooldown procedure and its basis (it should include guidance on possibility, prevention, and mitigation of upper head voiding and natural circulation interruption).

2. Demonstration by analysis or otherwise, that:
   a) Use of this procedure will not result in upper head voiding
   b) If voiding occurs, the procedure will prevent any voiding at the hot leg elevation

1.3 <u>TMI-1 Natural Circulation Cooling Procedure OP 1102-16</u>

Operating procedure 1102-16 addresses RCS natural circulation cooling for TMI-1 in which an RCS cooldown rate greater than 10F°/hr but less than or equal to 50F°/hr is prescribed as a means of preventing upper head voiding. Section A.2.6 and C.4.3 include guidance on possibility and mitigation of upper head voiding as quoted below:

Voids may occur in the Reactor Vessel head while depressurizing the RCS due to head water temperature being higher than RCS temperature. This condition may be evidenced by an increase in pressurizer level while reducing RCS pressure even though an adequate saturation margin is indicated between T_h (hot leg temperature) and RCS pressure. Reference IE Circular 80-15.

If void formation should occur in the RV head, the head bubble should be condensed before continuing the cooldown. If an RCP cannot be bumped, then RCS pressure should be held constant or slightly higher until the head bubble has condensed as indicated by the return of pressure control to the pressurizer.

In addition, the procedure will prevent any voiding at the hot leg elevation by Steps A.2.5 and B.2.5:

Steam voids at the top of the hot legs can interrupt natural circulation. This is prevented by establishing and maintaining at least a 25°F subcooled margin after Reactor Coolant Pump trip.

1.4 TMI-1 Natural Circulation Cooldown Analysis without Reactor Vessel Upper Head Void Formation

In order to formulate procedural requirements to prevent coolant flashing in the reactor vessel head, an analysis was performed to simulate a natural circulation cooldown at TMI-1. A two-dimensional cylindrical model of the RV upper head was used as the basis for the thermal analysis which utilized HEATING6 (a multi-dimensional, generalized heat conduction code).

Analyses were performed for RCS cooldown rates of 10F°/hr and 50F°/hr to determine the minimum time required to reach the decay heat removal system cut-in point (325 psig and RCS temperature of 300°F) based on the system design. In order to employ the decay heat removal system, the temperature of fluid in the vessel head must be less than the saturation temperature (429°F) which corresponds to 325 psig. In addition, the RCS temperature was allowed to decline to 204°F in both cases. The results of these analyses are presented in Section 4.0.

2.0 REACTOR VESSEL UPPER HEAD COOLDOWN PROCESSES

During natural circulation, the fluid in the RV upper head will remain relatively stagnant since the reactor coolant system loop flow rates will be significantly smaller than during forced circulation. The plenum cover and structural components (shown on Figure 2-1) tend to isolate the RV head fluid from coolant in the plenum. Coolant will enter the head region at low velocity through the CRD guide tubes which extend approximately 20 inches above the plenum cover. Consequently, little mixing is expected between entering coolant and the majority of fluid in the RV head dome. The head metal and water will cool slowly by means of the heat transfer processes delineated below and illustrated on Figure 2-2. Patterns of fluid circulation (which will likely result from the effects of natural convection cooling) are depicted on Figure 2-1.

The head cooling processes are:

- Heat transfer from the exterior surface of the mirror insulation to containment is considered to occur by means of free convection and radiation.

- Heat transfer across the three (3) inch thick mirror insulation is considered to occur by means of conduction.

- Heat transfer from the exterior surfaces of the vessel head through the air space to the inside surfaces of the mirror insulation is expected to occur by means of natural convection and radiation.

RV COMPONENTS

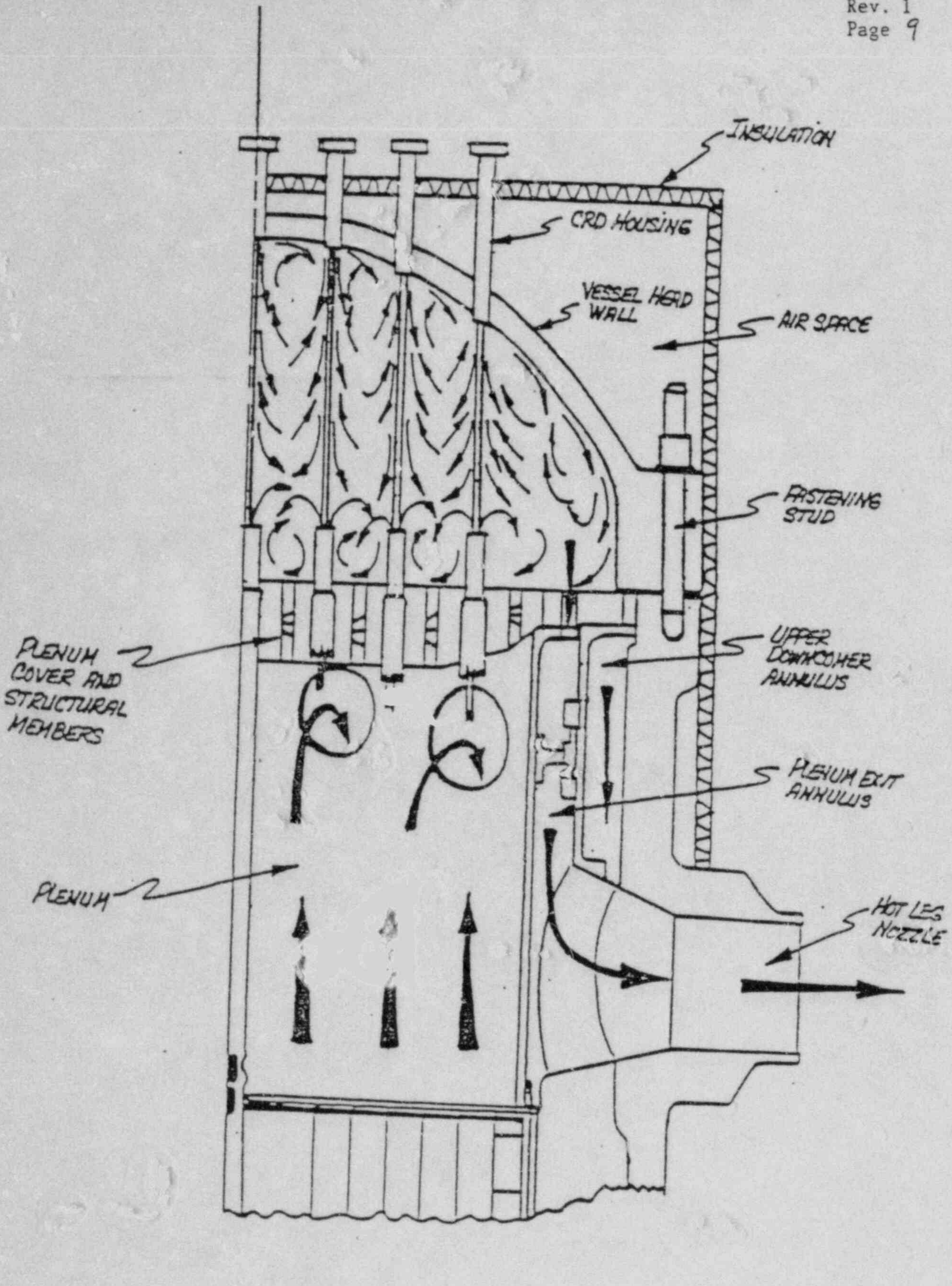


FIGURE 2-1

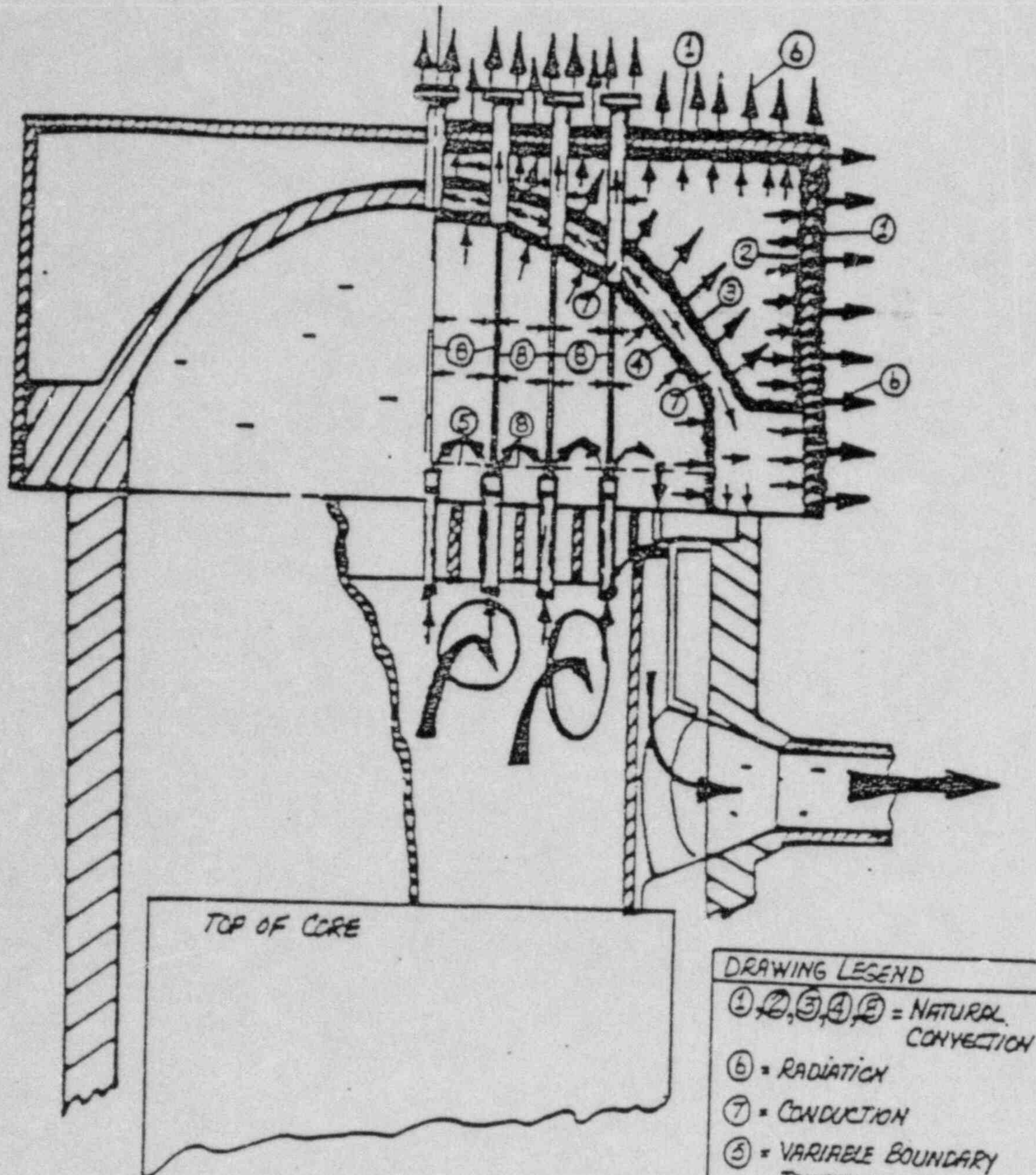

TOP OF CORE
DRAWING LEGEND
①,②,③,④,⑤ = NATURAL CONVECTION
⑥ = RADIATION
⑦ = CONDUCTION
⑧ = VARIABLE BOUNDARY TEMPERATURE

FIGURE 2-2

- Heat will be conducted along the metal walls toward the CRD housings located in the vessel head.

- Heat from the upper head wall will be conducted along the vessel steel toward the coolant inlet which is located in the annulus between the vessel walls and the core thermal shield. Heat will also be transferred from the vessel walls to the cold and hot leg nozzles.

- Heat will be transferred from the air space to the CRD housings by means of natural convection.

- During the cooldown of RV head metal, heat will be transferred from RV head coolant to the vessel walls by means of natural convection. In addition, heat will be removed from the upper head water by convective heat transfer between the coolant and the CRD lead screws.

- Heat transfer between layers of upper head water at different temperatures will include convective effects. The conditions under which convective heat transfer is expected are elaborated upon in Section 3.3

- In the short period of time following the 4 RCP trip, heat will be transferred from the plenum cover and its structural members to the plenum coolant by means of forced convection. Throughout the remainder of the cooldown period, coolant which enters the upper

head via CRD guide tubes is considered to mix with and displace the coolant in the vicinity of the CRD guide tubes. Mixing effects were restricted to the coolant volume defined by the 20.5 inch axial dimension (the guide tube height) above the plenum cover as shown on Figure 2-3.

- Energy transport will occur from the upper head by means of effluent coolant which will pass through the outlet annulus to the hot leg. Coolant which exits the upper head will be replaced by coolant flow from the CRD guide tubes.

- During the cooldown, the specific volume of coolant in the upper head will decline with temperature. Consequently, the RCS will provide over 5000 lbms of makeup coolant to the head until the decay heat system is employed.

RV ISOMETRIC

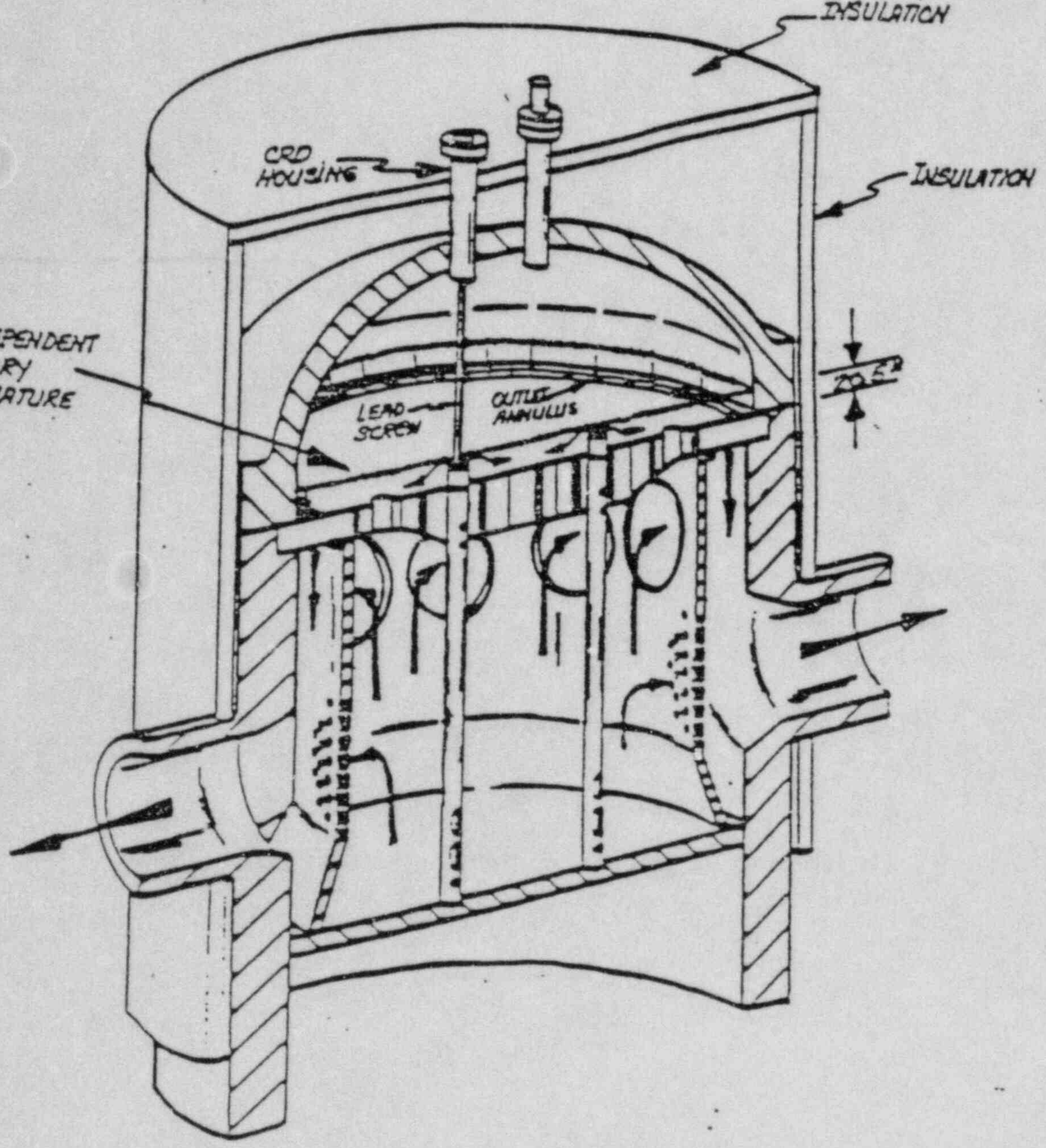


FIGURE 2-3

3.0 HEATING6 MODEL OF TMI-1 UPPER HEAD

3.1 HEATING6 Code

HEATING6 is a multi-dimensional, generalized heat conduction code which may be applied to problems which require steady state and/or transient solutions[2]. The thermophysical properties of various materials may be considered to be anisotropic, temperature or time dependent. Boundary conditions may be applied by means of the following:

- Coefficients for convective heat transfer
  - natural convection
  - forced convection
- Coefficients for radiative heat transfer
- Temperature
- Heat flux

User supplied subroutines allow flexibility in the manner in which the methods of solution may be developed. Both explicit and implicit finite difference numerical techniques are available to the user.

3.1.1 HEATING6 Limitations

Since HEATING6 is a nodal heat conduction computer code, it is limited by the following:

- The mesh applied over the geometry of interest is fixed in size. The mass which occupies each unit mesh is assumed to be concentrated at the geometric center.

- If each unit mesh is considered an elemental control volume, mass transport across control surfaces is non-existent.

- In HEATING6, the variation of material density as a function of temperature may inhibit or prolong the convergence of the iterative solution procedure. Consequently, the density of coolant in the upper head was assumed to be a constant (50.0 lbm/ft^3) throughout this analysis. This value tends to increase the thermal capacitance of nodes at high temperatures.

- In order to include convective effects between layers of coolant at different temperatures, an effective thermal conductivity for the coolant may be defined by means of the following:

$$K_{EFF} = h_{NC} \times L$$

where h_{NC} is the heat transfer coefficient for natural convection and L is a characteristic length of the nodal geometry.

3.2 Upper Head Model

The geometry of the reactor vessel upper head was approximated in a two dimensional cylindrical coordinate system. The 90° vessel symmetry about the vertical centerline was taken into consideration. During the development of the thermal analysis, care was taken to account for the heat transfer paths and processes discussed in Section 2.0. In addition, the following corrections were applied to various convective heat transfer coefficients used in this analysis in order to account for any differences in component surface area between the actual and model RV head geometry:

1. The interior surface area of the RV head;

2. The exterior surface area of the RV head;

3. CRD lead screws and housings.

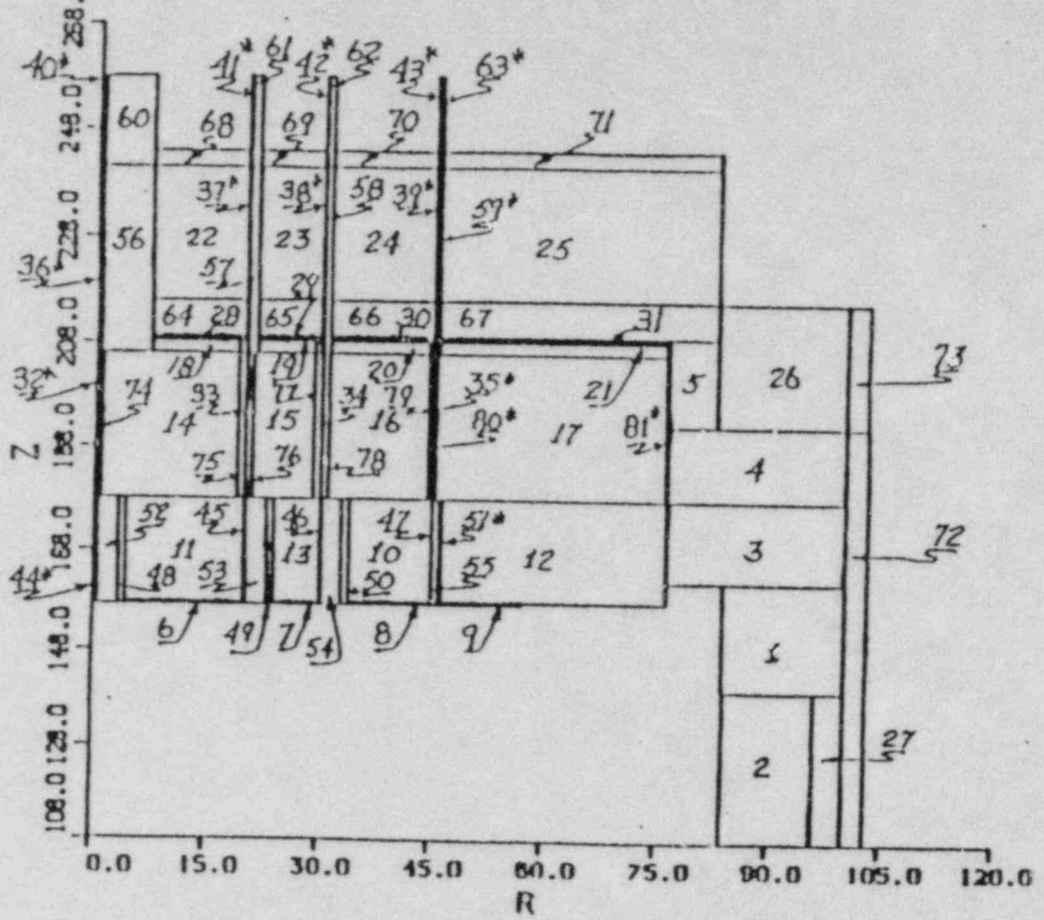
The primary components of the thermal model are: the plenum cover, the mass of upper head coolant, the vessel walls and mirror insulation. Model component dimensions were estimated from construction drawings or established by calculations. Geometric regions and nodes were further used to describe the head in detail. Figures 3-1 and 3-2 illustrate the regions and materials of the HEATING6 RV upper head model. They are discussed in detail below.

The carbon steel vessel walls were modeled from the mating surface down to a point just above the hot leg nozzle. Water from the cold leg which enters the vessel by means of the annulus downcomer was also included. The plenum cover and CRD guide tubes were also modeled. A variable boundary temperature (based upon an energy balance between coolant entering and leaving the upper head) was applied to the region defined from the top of the plenum cover to the top of the CRD guide tubes. Application of the boundary condition restricted the effects of coolant mixing to the first 20.5 inches above the plenum cover. Heat transfer to this region from the coolant directly above (adjacent nodes) is considered to occur by means of natural convection. Above the region of adjacent nodes, convective heat transfer effects were also included.

The CRD lead screws and housing were also modeled. The 69 CRD lead screws and housings were grouped into four separate concentric cylinders. The lead screw and housing cylinders were distributed radially and aligned on center with the CRD guide tubes.

ESTIMATE OF TMI-1 UPPER VESSEL HEAD GEOMETRY

Map of the Regions



NOTE:
* REGIONS NOT READILY DISCERNABLE AT THIS SCALE

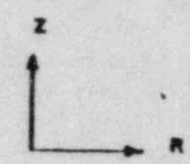


FIGURE 3-1

ESTIMATE OF THI-1 UPPER VESSEL HEAD GEOMETRY

MAP OF THE MATERIALS

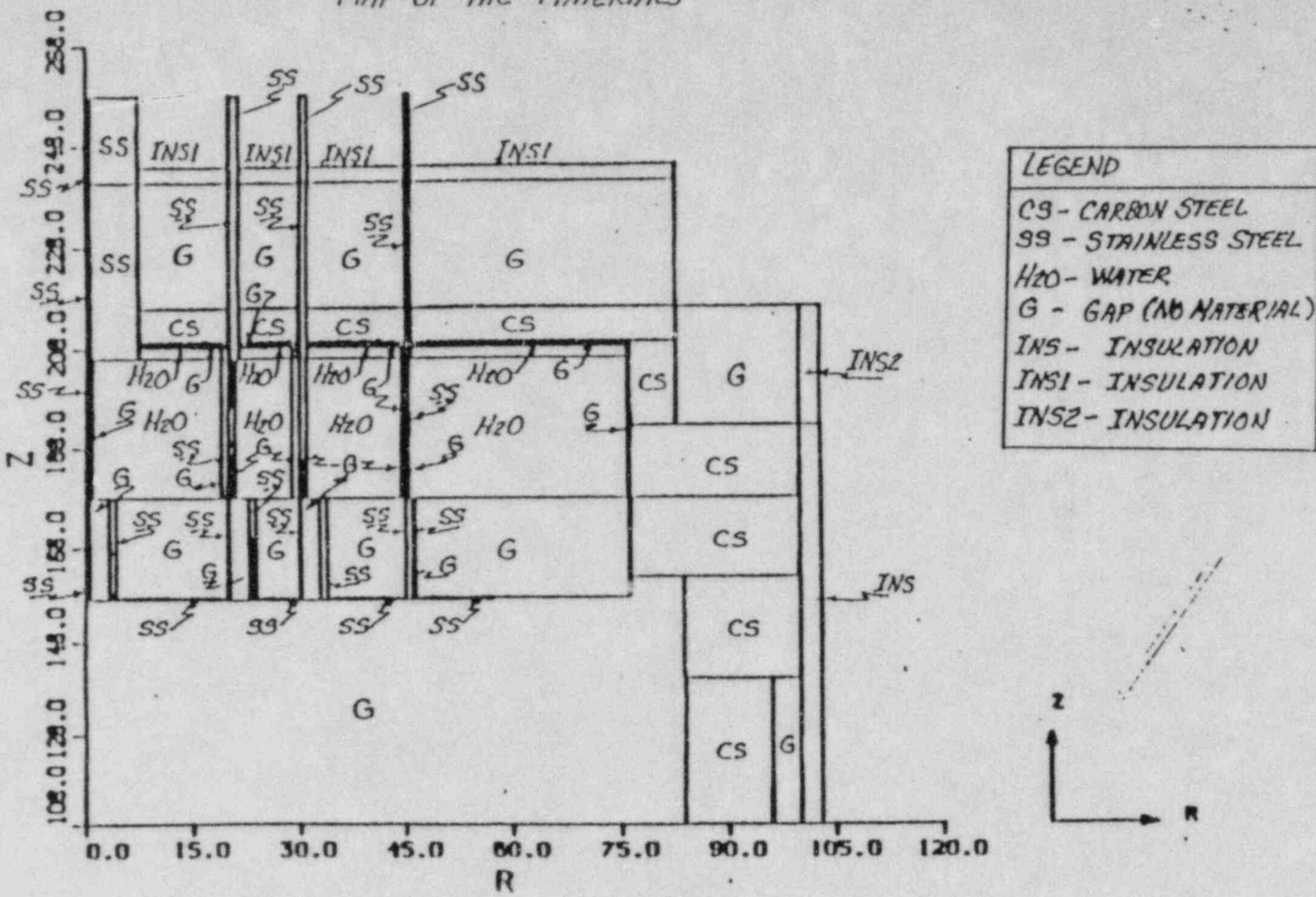


FIGURE 3-2

The reactor vessel head geometry was approximated by means of two cylindrical shells. The top of the head was modeled as a disk. Radial dimensions of various head components were fixed from construction drawings. The axial dimension of the head was established from a calculation which considered total coolant volume to be on the order of 522 cubic feet.

The vessel insulation was modeled as a cylindrical shell with an outer radius of 103 inches. The top of the insulation was modeled as a disk. Since the distance between the head and insulation actually varies with the head radius, a mathematical average distance was used to fix the position of the insulation.

3.3 Assumptions

The following modeling assumptions were used in the analysis:

1. The spherical head was approximated as a disk on top of two cylindrical shells.

2. The resistance to heat transfer offered by the 0.125" stainless steel cladding on the interior of the vessel was assumed to be negligible.

3. The effects of mixing between stagnant fluid in the upper head and coolant which exits the CRD guide tubes is assumed to occur in the first 20.50 inches above the plenum cover. An energy balance over that region was used to establish a time dependent temperature which

was applied as boundary condition at the top of the CRD guide tubes. The effects of coolant flow from the CRD guide tubes were considered limited to that region.

4. Heat transfer from the plenum cover to coolant in the plenum was based on a forced convection heat transfer coefficient for fluid flow over a flat plate.

5. Heat transfer from upper head coolant to the head metal was assumed to occur by means of natural convection.

6. Heat transfer from the CRD housings to the service structure region and containment were not included. A boundary temperature of 120°F was applied to the CRD housing 3 1/2 feet above the RV head. The temperature was based on a simplified heat transfer analysis performed on a CRD lead screw.

7. Heat transfer to/or from the CRD housings to the air located between the vessel head and insulation was neglected.

8. A short subprogram was used to include the effects of convective heat transfer in the axial and radial directions between nodes at different temperatures. Heat transfer between nodes in the radial direction is discussed in Item 9. For the axial direction, the relative position between a specified node and its neighbor were determined first. Convective effects were included if the following criteria were satisfied:

a) Neighboring node located above the specified node - temperature of the neighbor less than that of the specified node.

b) Specified node located above the neighbor - temperature of the specified node less than that of its neighbor.

Otherwise, the convective effects between nodes were considered to be limited to laminar natural convection.

9. A somewhat less conservative but realistic assumption is that some convective heat transfer is expected between adjacent nodes in the radial direction. Since cooler (denser) fluid will tend to fall in warmer surroundings, it is not unreasonable to expect fluid velocity components in the radial direction. Consequently, it appears realistic to carry over the influence of convective effects to the radial direction.

10. The thermophysical properties of the stainless steel mirror insulation were estimated from its thermal conductivity and knowledge of its construction.

11. Prior to the onset of the transient, the temperatures of upper head coolant and metal were initialized to 604°F. This temperature includes measurement uncertainty[3], and is the approximate temperature of coolant in the hot leg under conditions of 100% power.

12. Subsequent to the 4 RCP trip and flow coastdown, natural circulation flow was assumed to become stable and invariant at 3% of rated RCS flow at 100% power.

13. Coolant flow into the upper head from the CRD guide tubes was assumed to be 8% of the RCS flow at any given time.[4]
14. A four pump coastdown was assumed to occur following the reactor trip. The effects of the coastdown were included only in the energy balance described by Item 3, Section 3.3. Operation of the RCPs after a reactor trip will tend to substantially reduce the temperatures of upper head coolant and metal. Since the temperatures of coolant and metal in the RV head tend to follow the hot leg temperature during forced flow conditions, the amount of temperature reduction in the upper head will be dependent upon the duration of RCP operation assumed after the reactor trip and the post-trip cooldown rate of the RCS.
15. The ambient (reactor building) temperature was assumed constant at 120°F.
16. The insulation was considered to be completely sealed against air leakage.

3.4 Steady State Heat Transfer

The steady state heat transfer rate from the RV head was estimated from the manufacturer's specification for the heat flux associated with the insulation. Convective coefficients for the films which act at the exterior surfaces of the insulation and between the vessel head and the interior surfaces of the insulation were determined by means of an iterative procedure which included the following constraints:

1) Radiative heat transfer was assumed to take place between the exterior surfaces of mirror insulation and the containment surroundings. The insulation was assumed to be a gray body which transferred heat to black surroundings maintained at 120°F. An emissivity for #18-8 polished stainless steel (evaluated at 200°F) was assumed to be adequate.
2) The film resistances between the RV head metal and coolant were considered to be zero at steady state.
3) The RV head metal was considered to be at a temperature of 604°F.
4) The temperature change across the insulation (approximately 380F°) was determined from:
   a) Heat flux specified by the insulation manufacturer. The heat flux was assumed applicable for steady state conditions.
   b) Thermal conductivity of mirror insulation - assumed to be independent of temperature.
5) Containment air temperature was assumed to be invariant at 120°F.

The heat transfer coefficient applicable between the vessel and insulation was initially assumed and iterated upon until all constraints were satisfied.

3.5 Initial Conditions

Several of the initial conditions imposed on the thermal model at the onset of the reactor trip have already been outlined in Sections 3.3 and 3.4. Consequently, they will be summarized by the following:

- The plant was assumed to be operating at steady state conditions at 100% power.
- Insulation temperature was taken to be 408°F.
- Cold leg temperature was considered to be 555°F.

These are shown on Figure 3.3.

At time (t = 0+), the transient was initiated with the following events imposed:

- Reactor trip with insertion of control rods achieved.
- Following the reactor trip, 4 RCPs are tripped.
- Subsequent to the trip of the 4 RCPs, RCS flow was taken to decay with pump coastdown.

3.6 Boundary Conditions

Various boundary conditions were applied to components of the upper vessel head model. The types that were used are delineated below and illustrated on Figure 3-4.

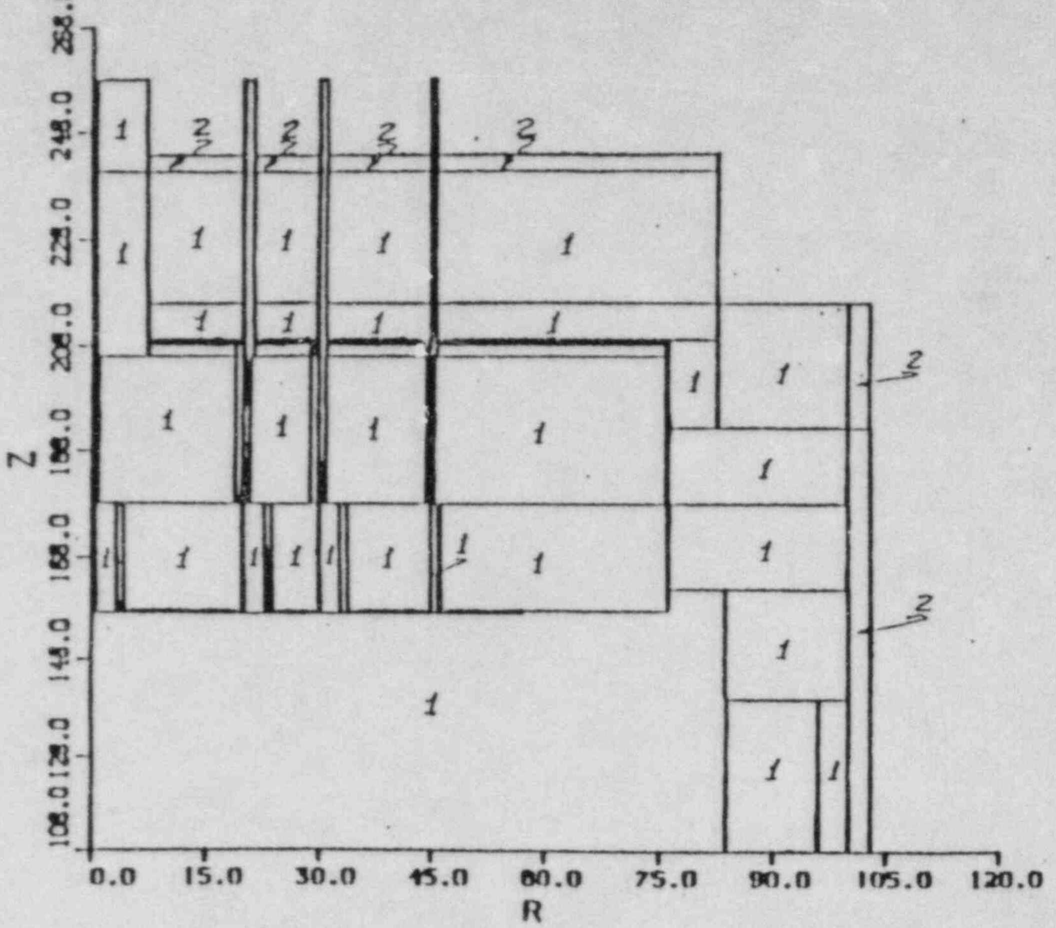
3.6.1 Specified Temperature

As explained in Section 3.3, a constant temperature (120°F) boundary condition was maintained at the top of the CRD lead screws and CRD housings (BC5). A time dependent temperature (which is a function of the RCS cooldown rate) was applied between coolant in plenum and hot leg metal (BC2).

A time dependent boundary temperature was defined at the top of the CRD guide tubes. The method used to establish boundary condition (BC6) is delineated in Section 3.3, Item 3.

ESTIMATE OF TMI-1 UPPER VESSEL HEAD GEOMETRY

MAP OF THE INITIAL CONDITIONS



LEGEND:
1 - 604°F
2 - 408°F

NOTE:
METAL, WATER, AND INSULATION TEMPERATURES SET TO 604°F, 604°F AND 408°F RESPECTIVELY. STEADY STATE TEMPERATURE DISTRIBUTION IS USED AS THE INITIAL CONDITION FOR THE TRANSIENT AT TIME = 0. SEE THE TEXT FOR DETAILS.

FIGURE 3-3

ESTIMATE OF TMI-1 UPPER VESSEL HEAD GEOMETRY

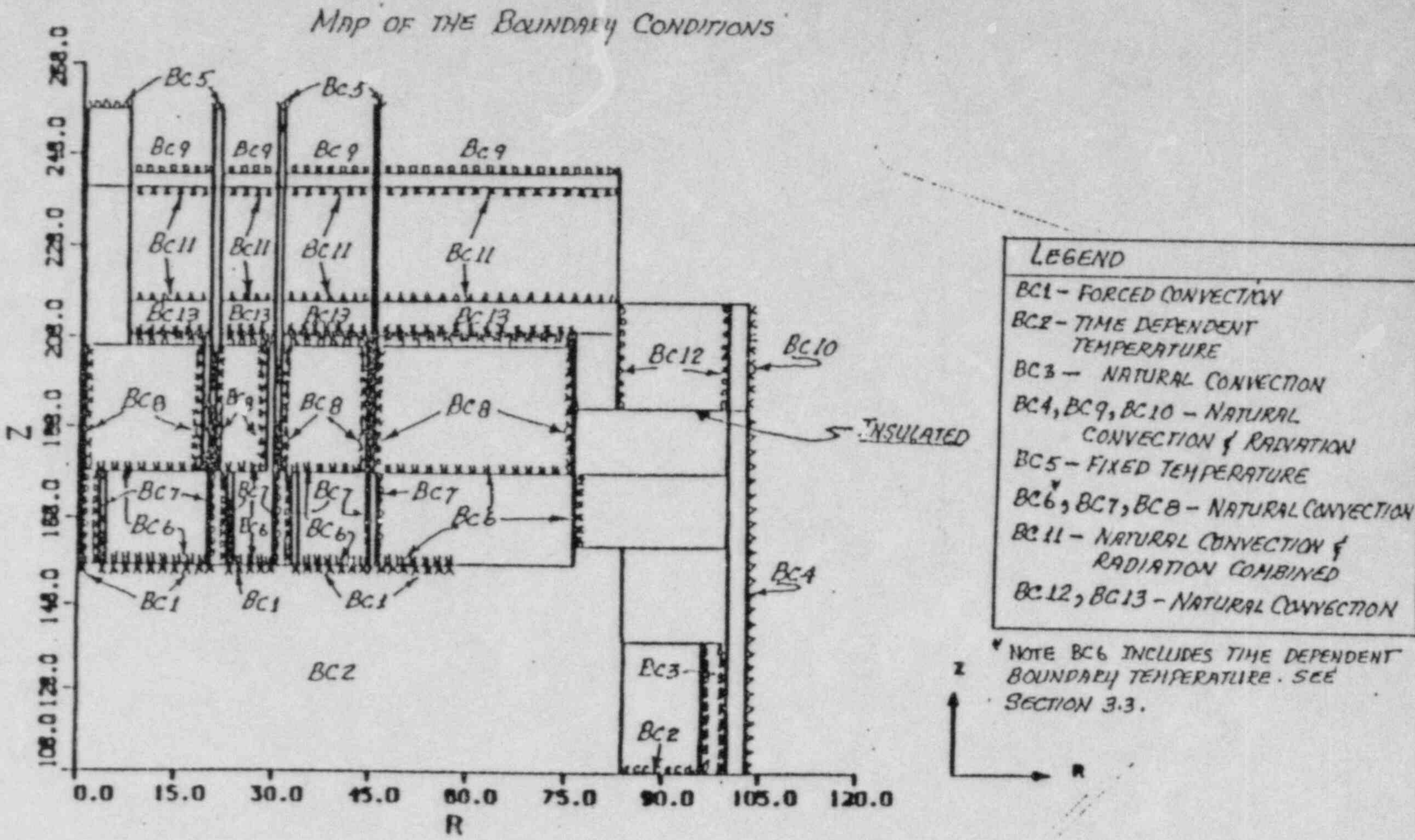


FIGURE 3-4

3.6.2 Convective Heat Transfer

A heat transfer coefficient for forced convection was applied as a boundary condition to the lower surface of the plenum cover (BC1).

Similarly, a natural convection heat transfer coefficient was applied in the annulus downcomer between the vessel wall and the core thermal shield.

In the upper head, natural convection heat transfer coefficients were applied at all metal-water surface interfaces.

Natural convection coefficients were also applied to the following model components:

- To the outside surfaces of the insulation
- To the air space between the vessel head and the inside surfaces of the insulation

As mentioned earlier, the convective coefficients were calculated by means of an iterative procedure performed on the conduction and convection heat transfer relationships. A known steady state heat flux across the insulation was used in the procedure to predict temperatures on the interior and exterior surfaces of the insulation. Subsequently, the temperatures were used to predict suitable convective coefficients. It should be noted that the convective coefficient used between the vessel and the inside

surface of the insulation is considered to include radiative heat transfer effects. Since it was difficult to determine an appropriate radiative heat transfer coefficient for the complex geometry of the air space, the lumped convective coefficient was adopted and the air space was modeled as an area devoid of material.

4.0 ANALYSIS RESULTS

Two analyses were carried out to demonstrate the thermal response of the RV head as a function of the cooldown rate in the RCS. The cooldown rates imposed on the RCS were 10F°/hr and 50F°/hr. The 10F°/ hr rate was imposed for a 40 hour period. The 50F°/hr rate was applied for an 8 hour period. Thereafter, the RCS temperature was held at 204°F for two hours. The results are shown on Figures 4-1 through 4-4 and are discussed in Sections 4.2 and 4.3.

The volume averaged coolant temperature in the top foot of the vessel head was used to represent the overall coolant temperature as explained in the following.

4.1 Volume Averaging of the Top Foot of the Vessel Head

Heat transfer by means of natural convection is a complex process which involves mass and energy transport at relatively low fluid velocities. Fluid circulation in natural convection is attributable to buoyant forces which arise from temperature variations in the fluid. Consequently, free convective flow is compressible flow. In this process, the convective heat transfer coefficient is characterized by the Rayleigh number which is a product of the Prandtl and Grashof numbers, the Grashof number being proportional to the ratio of buoyant to viscous forces.

During a natural circulation cooldown, convective cooling of upper head metal and coolant will result in buoyancy driven fluid circulation. With

continued cooling of fluid layers at different temperatures, coolant circulation is expected to develop as depicted on Figure 2.1.

During the cooldown, it is expected that buoyancy driven fluid circulation will propagate from the head walls and lead screws toward the centerline of the head. As mentioned previously, with the decline of coolant temperature in the RV head, it is expected that over 5000 lbms of coolant will be provided to the head by means of the RCS. Consequently, it appears to be unrealistic to treat the cooldown of the head strictly as a conduction problem.

Since convective effects are included in both coordinate directions, the use of a volume averaged coolant temperature in the top foot of the upper head appears to be a conservative representation of the coolant conditions in the RV head.

4.2 <u>RCS Cooldown at 10°F/HR</u>

Figure 4-1 demonstrates the rate of change of coolant temperature in the RV head in response to the 10F°/hr RCS cooldown rate. The results indicate that the coolant temperature decreases at the rate of 8.86 F°/hr over the 40 hour period. Figure 4-2 demonstrates the rate of change in the saturation pressure of head coolant throughout the cooldown. At this cooldown rate, it appears that it would take approximately 22 hours to cool the head to the DHR cut-in point without coolant flashing. The average change in coolant temperature over that time is on the order of 8.23F°/hr.

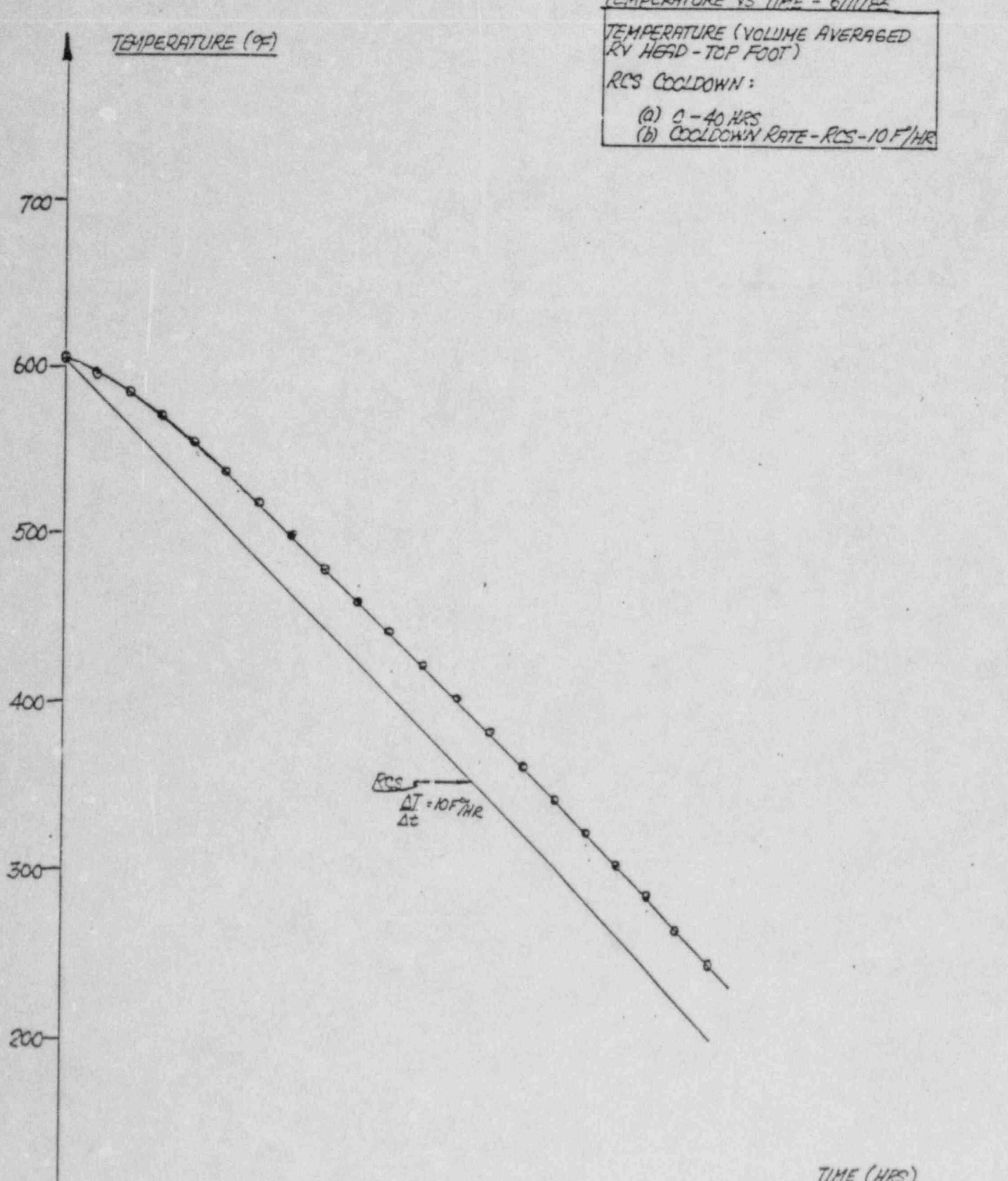

TEMPERATURE VS TIME - 6/11/85
TEMPERATURE (VOLUME AVERAGED RV HEAD - TOP FOOT)
RCS COOLDOWN:
(a) 0 - 40 HRS
(b) COOLDOWN RATE - RCS - 10 F°/HR
TEMPERATURE (°F)
700
600
500
400
300
200
100
RCS
ΔT/Δt = 10F°/HR
TIME (HRS)
0
10
20
30
40
50

FIGURE 4-1

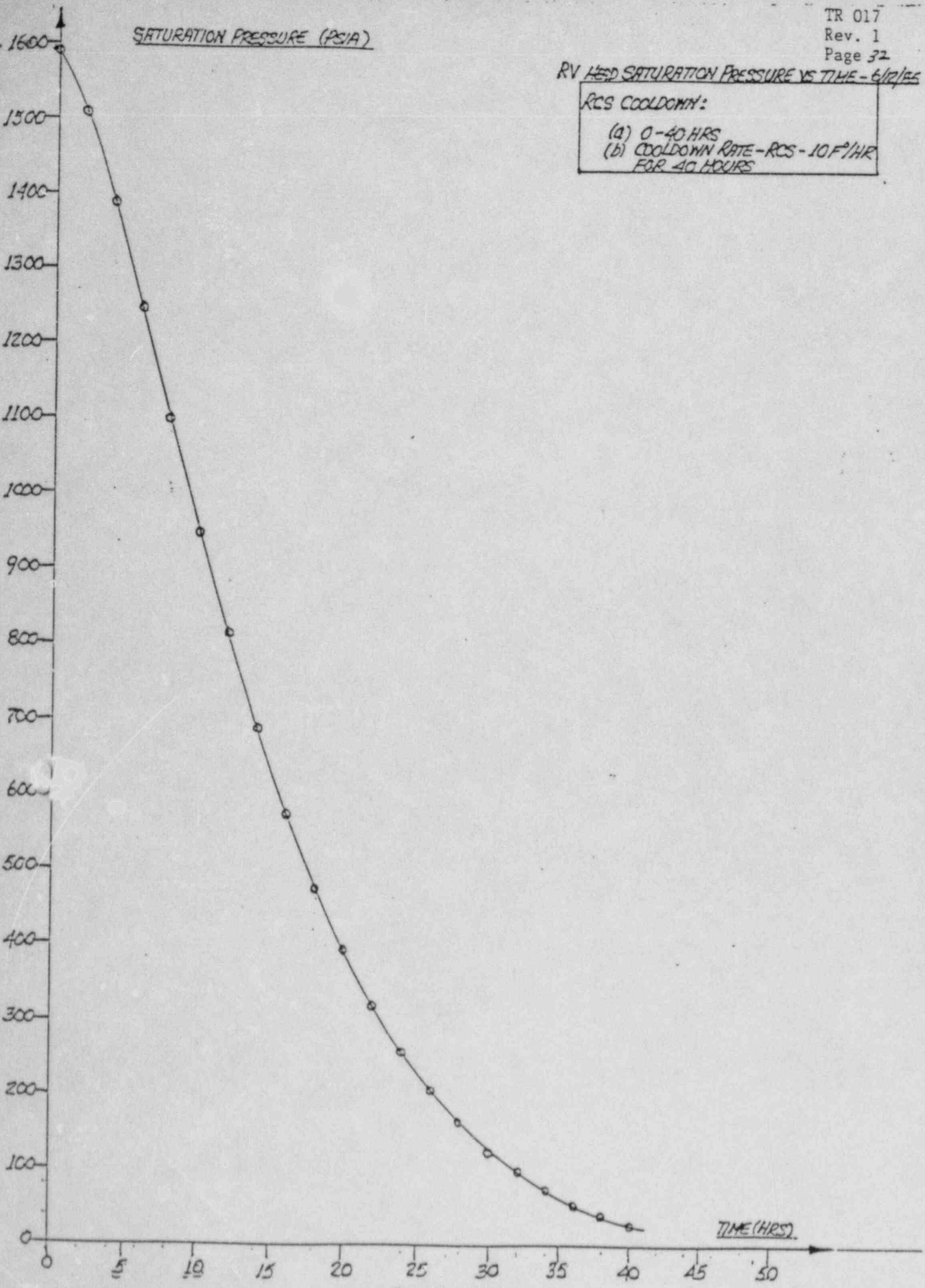

SATURATION PRESSURE (PSIA)
RV HEAD SATURATION PRESSURE VS TIME - 6/12/85
RCS COOLDOWN:
(a) 0-40 HRS
(b) COOLDOWN RATE - RCS - 10 F°/HR FOR 40 HOURS
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
TIME (HRS)
0
5
10
15
20
25
30
35
40
45
50

FIGURE 4-2

4.3 RCS Cooldown at 50F°/hr

Figure 4-3 demonstrates the thermal response of RV head coolant to the 50F°/hr rate of change imposed upon the RCS. As you will note, the RCS coolant temperature was held constant at 204°F after 8 hours. The results indicate that the average rate of decline in coolant temperature over the first 8 hours is approximately 31F°/hr. Thereafter (in the interim between hours 8-10), the rate of decline in coolant temperature shows the effects of the hold at 204°F.

Figure 4-4 demonstrates the rate of change of the saturation pressure of head coolant throughout the cooldown. At this cooldown rate, the results indicate that it would take approximately 7 hours to reach the DHR cut-in point.

At this point, it should be noted that the head coolant saturation pressure versus time data obtained for this cooldown rate were compared to RCS pressure data obtained during the natural circulation cooldown event at St. Lucie. The results of this analysis compare quite favorably to the St. Lucie data in predicting the time at which onset of coolant flashing was detected. The comparison is elaborated upon in Appendix A.

TEMPERATURE VS TIME - 6/7/85

TEMPERATURE (VOLUME AVERAGED RV HEAD - TOP FOOT)
RCS COOLDOWN:

(a) 0-10 HRS
(b) COOLDOWN RATE - RCS - -50F°/HR FOR 8 HOURS

T	t
604	0
599	1
565	2
557	3
526	4
488	5
446	6
403	7
358	8
319	9
294	10

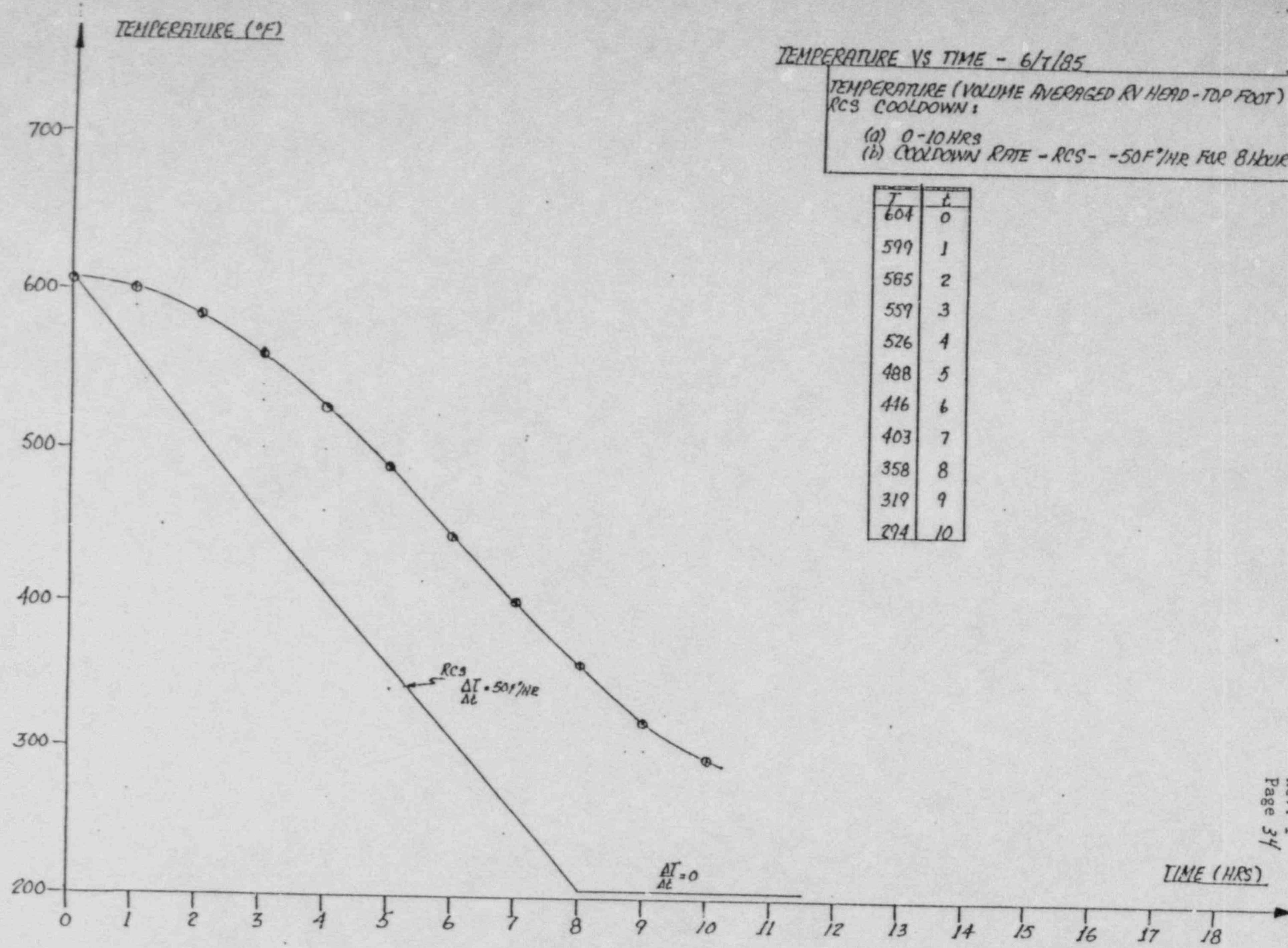


FIGURE 4-3

RV HEAD SATURATION PRESSURE VS TIME - 6/12/85

RCS COOLDOWN:

(a) 0-10 HRS
(b) COOLDOWN RATE - RCS - 50°F/HR FOR 8 HOURS

PSAT	t
1590	0
1532	1
1378	2
1124	3
856	4
610	5
406	6
256	7
149	8
88	9
61	10

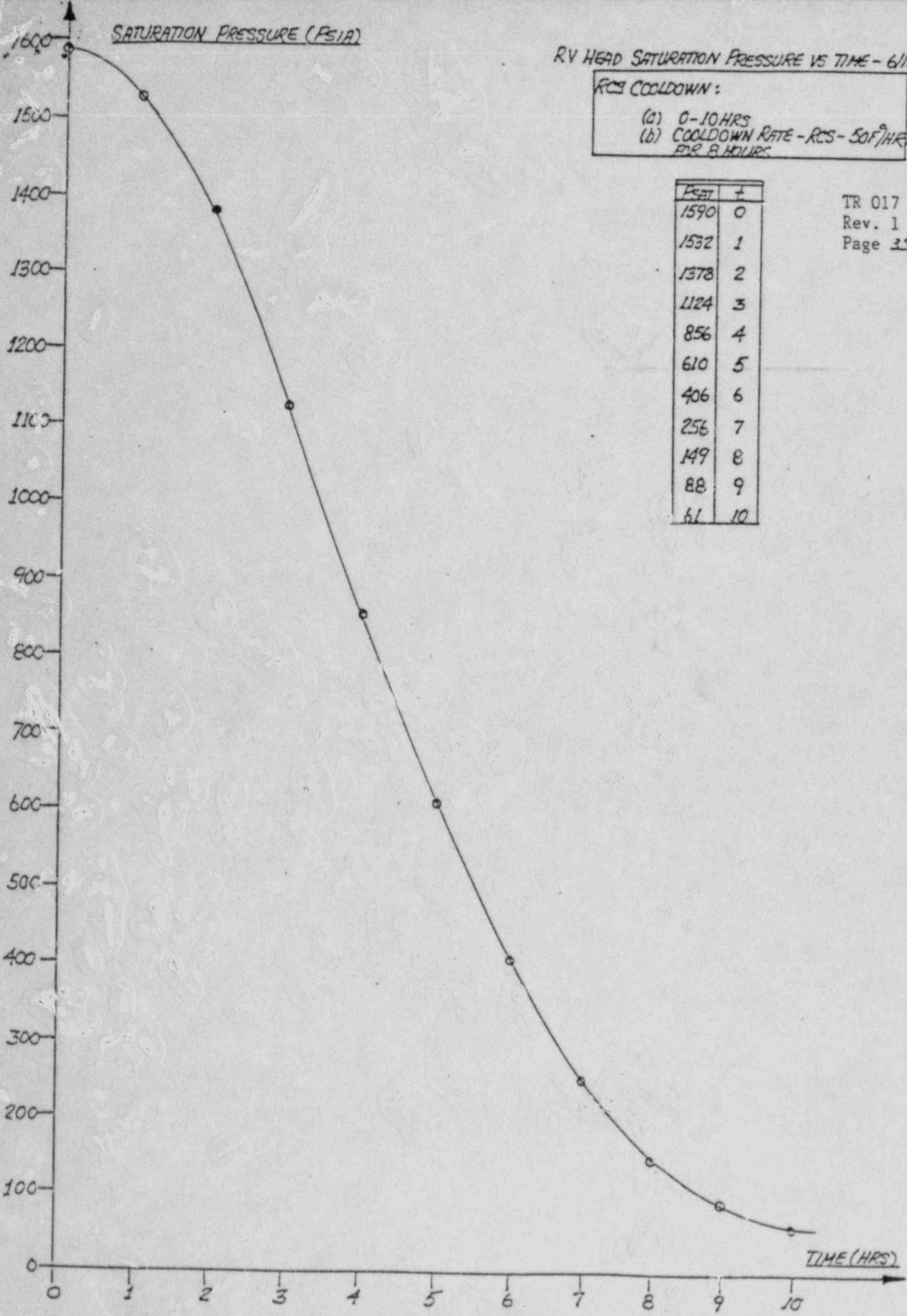


FIGURE 44

5.0 OPERATIONAL GUIDELINES

The methodology in previous sections of this report will provide the basis for operational guidelines to be developed for a natural circulation cooldown.

While it is desirable to avoid reactor vessel upper head voiding in non-emergency cooldown situations, the following should be noted to keep this phenomenon in perspective:

1. A natural circulation cooldown is an unlikely occurrence

   The two most likely reasons in which the RCPs will not be available are loss of power to the RCP motors and loss of services (cooling water and seal injection) to the RCPs. Experience has shown that both of these are unlikely for an extended time.

2. A steam bubble in the RV upper head is not a safety problem

   A steam bubble in the RV upper head is not in itself a safety problem, but a plant control problem for the operator. The expansion of the void into the hot leg to interrupt natural circulation is unlikely since the regions below the upper head are subcooled, and expansion of the void into these regions would result in condensation, thus restricting the void to the upper head region only.

3. Controlled transition to natural circulation or intermittent operation of RCPs

   In the highly likely event of a controlled transition to natural circulation, operation of the RCPs after a reactor trip will reduce

the RV upper head temperature. RCP operation for several minutes beyond the reactor trip will be an effective method in reducing the saturation pressure at which coolant flashing will occur. In addition, either intermittent operation or 'bumping' would be an equally effective alternative in reducing the potential for coolant flashing.

Figures 4-1 and 4-3 of the previous section demonstrated the thermal responses of the RV head to 10F°/hr and 50F°/hr cooldown rates in the RCS. The RCS could conceivably be cooled down at any rate up to 50F°/hr. Figures 5-1 and 5-2 represent the minimum (limiting) RCS pressures required to prevent coolant flashing in the RV head. These curves were developed by correlating the RCS temperature against the appropriate head coolant saturation pressure. For a given RCS temperature, as long as the RCS pressure is maintained above the saturation pressure line, coolant flashing in the RV head will be prevented.

Plotted on the saturation pressure versus RCS temperature coordinate system, the data obtained for the thermal response of the RV head to various RCS cooldown rates no longer appear explicitly in time. Consequently, Figures 5-1 and 5-2 are process diagrams. If the (P vs T) data for the 10F°/hr cooldown (Figure 5-1) were to be super-imposed onto Figure 5-2, it is apparent (for a given RCS temperature) that the 50F°/hr rate is more pressure limited. As you will note, the important parameter on the process diagram is the

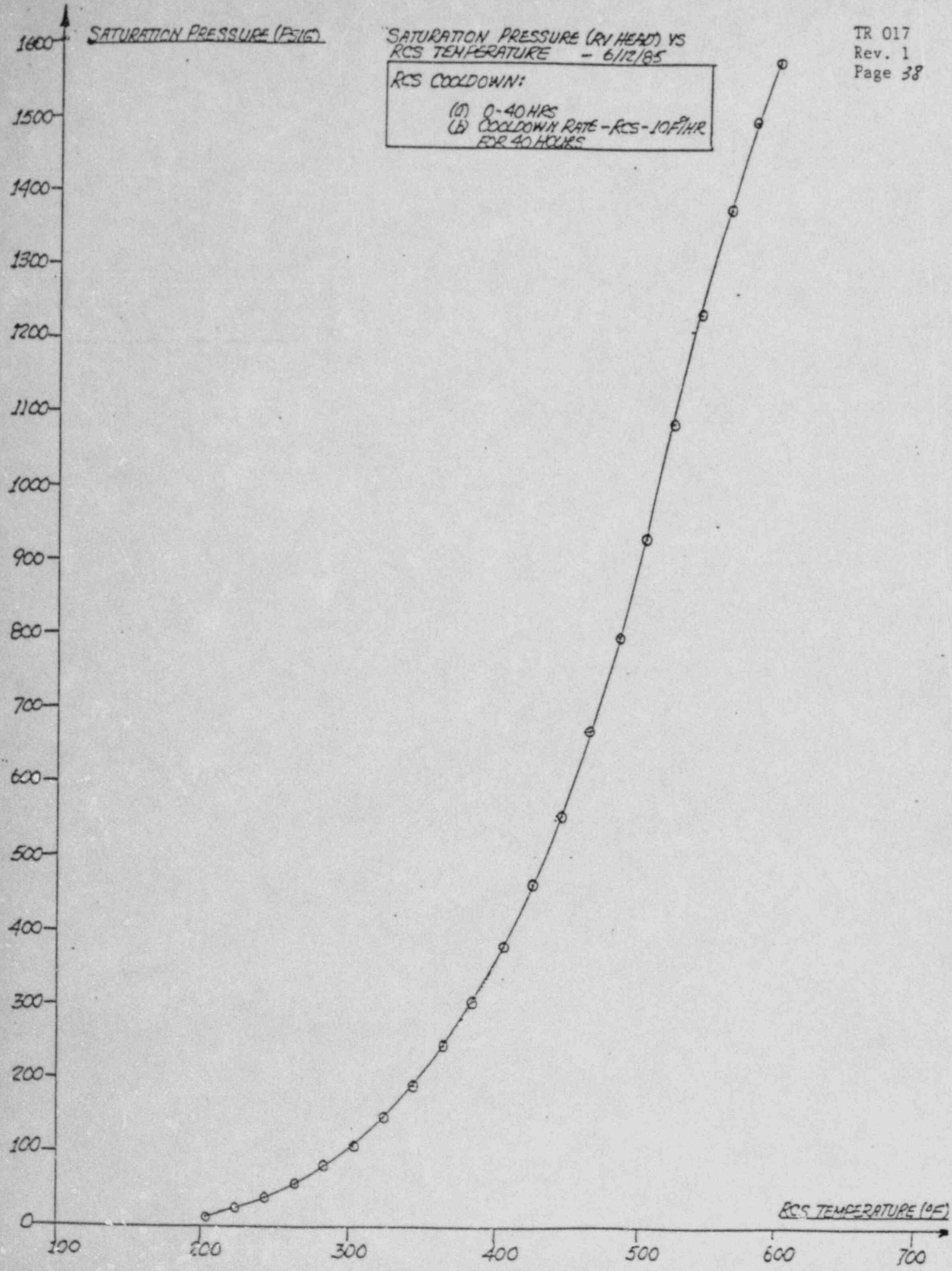
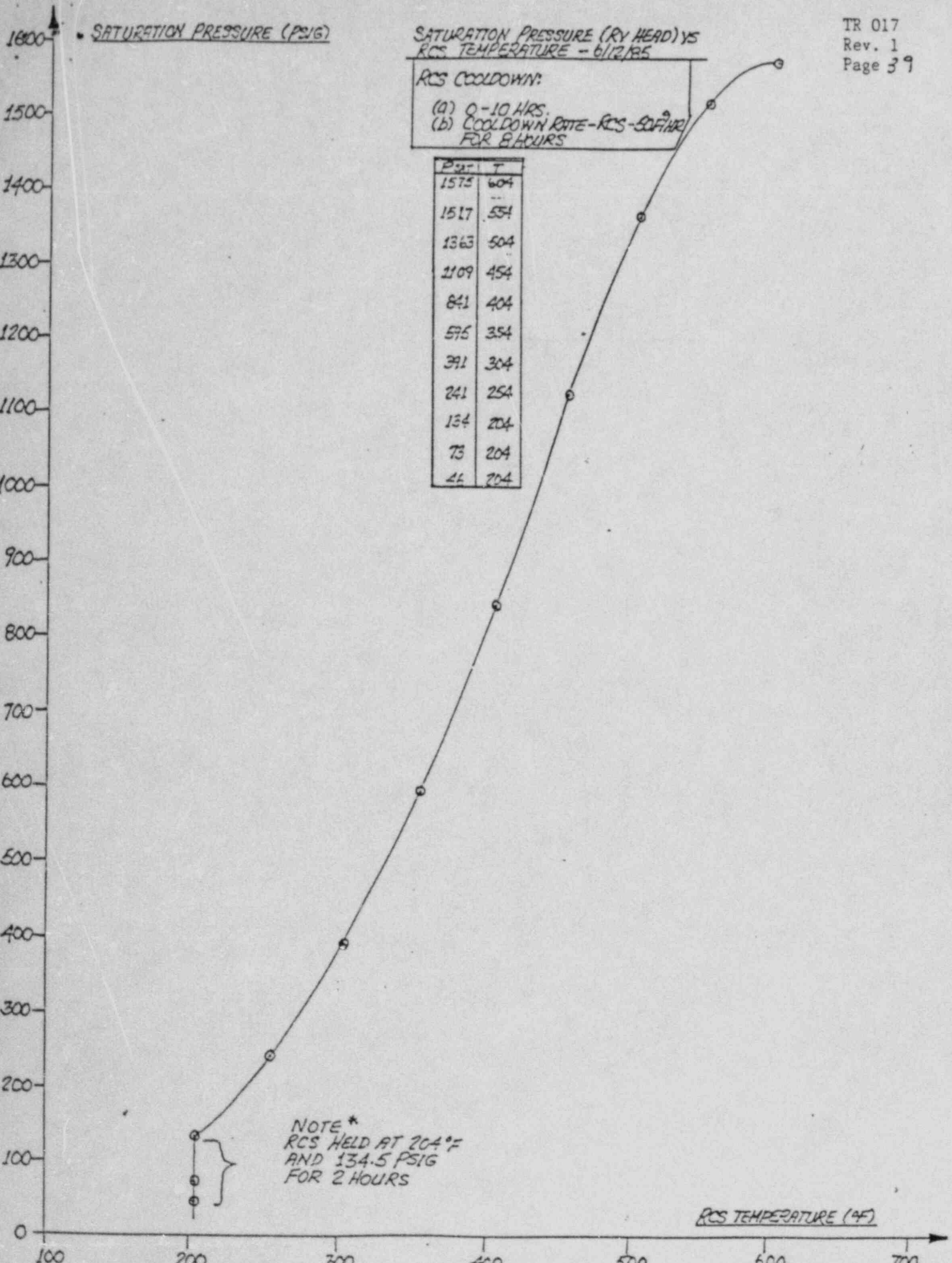

SATURATION PRESSURE (PSIG)
SATURATION PRESSURE (RV HEAD) VS
RCS TEMPERATURE - 6/12/85
RCS COOLDOWN:
(a) 0-40 HRS
(b) COOLDOWN RATE - RCS - 10°F/HR
FOR 40 HOURS
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
RCS TEMPERATURE (°F)
100
200
300
400
500
600
700

FIGURE 5-1



Psat	T
1575	604
1517	554
1363	504
1109	454
841	404
596	354
391	304
241	254
134	204
73	204
46	204

FIGURE 5-2

slope of the curve, i.e. the change in RV head saturation pressure with respect to the change in RCS temperature. With 604°F as one reference temperature, the slope of the 50F°/hr curve is obviously smaller than the slope of the 10F°/hr evaluated over the same conditions. As a result, system pressures at the 50F°/hr rate must be maintained substantially above those for the 10F°/hr case.

The data obtained from the 50F°/hr cooldown analysis will be included in the pressure/temperature limits for a natural circulation plant cooldown. Should there be a conflict between the 50F°/hr data and the fuel-pin-in-compression limits whereby the fuel-pin compression limits prove to be more limiting over a particular region of the process diagram, a composite diagram of the two will be developed as the limiting curve over that region.

6.0 CONCLUSIONS

Several important conclusions of this report are:

- In order to initiate the DHR system, the conditions in the RCS must be no greater than 325 psig and 300°F. To prevent coolant flashing in the RV head during RCS cooldowns at 10F°/hr and 50F°/hr, the head will be required to be cooled for at least 22 and 7 hours respectively.

- Provided the system pressure is maintained above the indicated minimums during the cooldown (saturation pressure shown on process diagrams 5-1 and 5-2), flashing of RV head coolant will be prevented.

- The results of 50F°/hr cooldown analysis (Figure 5-2) will be incorporated into the existing cooldown procedures. Should there be a potential conflict between this data and the fuel-pin-in-compression limits over any P-T region, the more limiting P-T data will be used over that region.

7.0 REFERENCES

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APPENDIX A

As mentioned in Section 4.3, the thermal response of the analytical model to the 50F°/hr RCS cooldown was compared to RCS pressure data obtained during the natural circulation cooldown at St. Lucie. The saturation pressure of RV head coolant (refer to Figure 4-4) was overlayed on to the RCS coolant pressure versus time history for the first 5 hours as shown on Figure A-1. You will note there appears to be reasonably close agreement in the time during which the onset of flashing of upper head coolant is thought to have occurred. Reference 15 indicates that the onset of RV head coolant flashing appears to have occurred at 6:15 AM. The authors have also noted that the RV head at St. Lucie appears to have cooled at a rate of 14F°/hr over the first 3 hours of the event. The RV head temperature versus time data for the first 3 hours (refer to Figure 4-3) predicts the RV head to be cooled at the rate of 15F°/hr. You will also note that the cross-hatched area (beyond the intersection of the two curves) on Figure A-1 demonstrates the presence of steam voids in the upper head. In addition, temperature data (cited in Reference 15) obtained from the core exit thermocouples throughout the event at St. Lucie, indicates the variation in RCS coolant temperature over time to be substantially reduced beyond the 3 hour mark into the event.

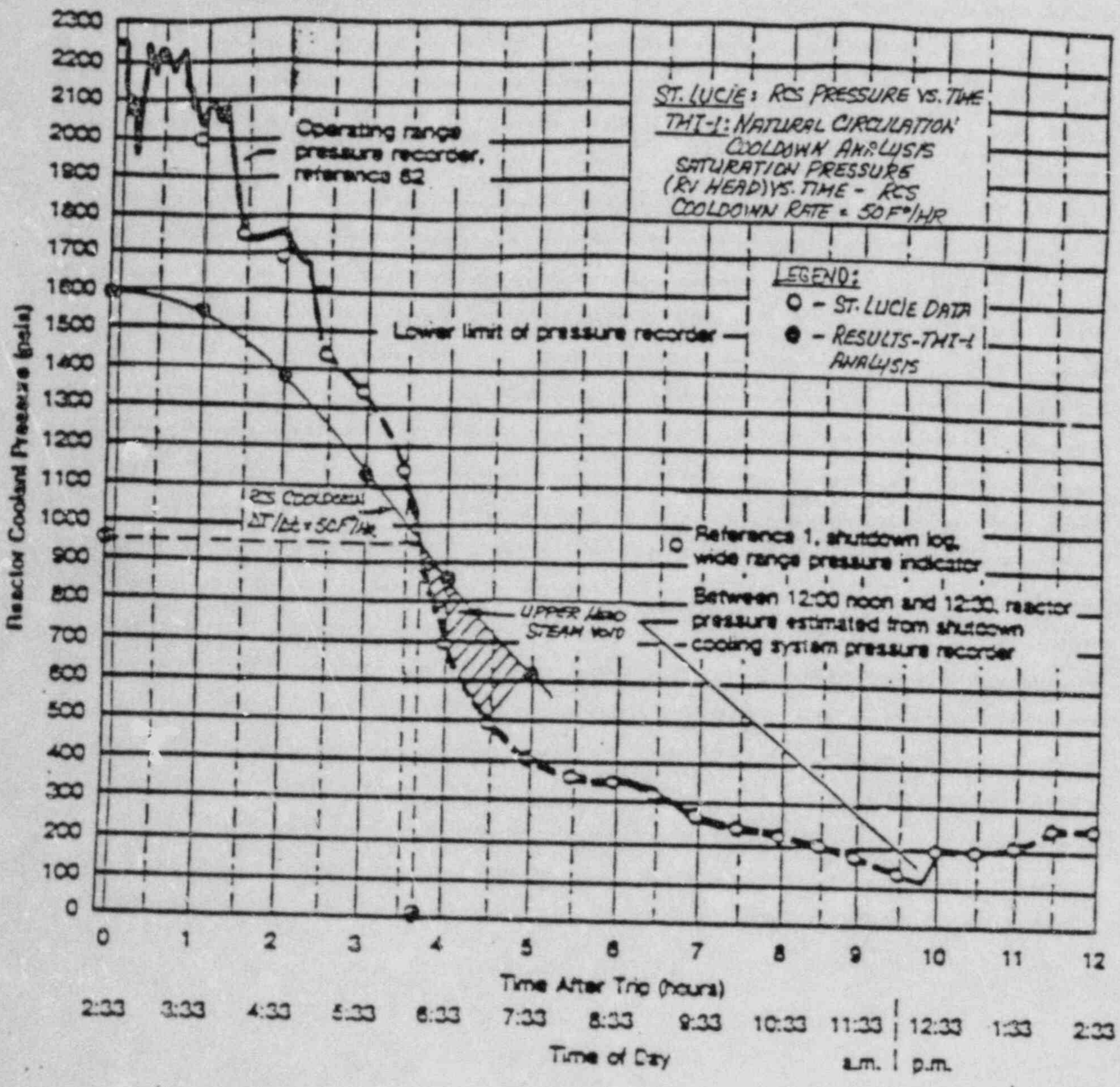
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Reactor Coolant Pressure (psia)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time After Trip (hours)
2:33
3:33
4:33
5:33
6:33
7:33
8:33
9:33
10:33
11:33
12:33
1:33
2:33
Time of Day
a.m.
p.m.
Operating range pressure recorder, reference 62
Lower limit of pressure recorder
ST. LUCIE: RCS PRESSURE VS. TIME
TMI-1: NATURAL CIRCULATION COOLDOWN ANALYSIS SATURATION PRESSURE (RV HEAD) VS. TIME - RCS COOLDOWN RATE = 50F°/HR
LEGEND:
O - ST. LUCIE DATA
● - RESULTS-TMI-1 ANALYSIS
RCS COOLDOWN ΔT/Δt = 50F°/HR
Reference 1, shutdown log, wide range pressure indicator
Between 12:00 noon and 12:30, reactor pressure estimated from shutdown cooling system pressure recorder
UPPER HEAD STEAM VOID

FIGURE A-1