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Analysis of a Heatup and Pressurization During Dresden-3 Shutdown

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Keywords: Shutdown Cooling, Decay Heat, Pressurization, Heatup, Water Level

NOTICE

FOREWORD

An unintentional heatup and pressurization occurred at Dresden-3 on December 21, 1980 with the containment open. The reactor was in nominal cold shutdown conditions with recirculation pumps turned off and one loop of the shutdown cooling system in operation with throttled flow. This was a three day outage to make modifications and the reactor pressure vessel head and all vessel internals were in place. The reactor water level inadvertently was allowed to drift below the elevation that is needed to maintain shutdown cooling system flow through the core with only one shutdown cooling system loop in service. The existing procedures did not specify water level requirements. Core flow ceased and temperature stratification began at 8:00 p.m. of 12/20/80; pressurization began about two hours later and continued until 5:00 a.m. of the next morning when core flow was restored by starting a second loop of the shutdown cooling system. The maximum pressure and temperature were 180 psig and 380°F. The reactor was brought to atmospheric pressure in about two hours. There were no harmful effects to fuel or any part of the plant.

Dresden-3 is a General Electric Boiling Water Reactor rated at 2527 MWt and 794 MWe. It has been in commercial operation since November 1971.

ABSTRACT

An unintentional heatup and pressurization occurred at Dresden Unit 3 on December 21, 1980 when the reactor water level drifted below the level required for one shutdown cooling system (SCS) loop to maintain core flow. A post-event analysis was performed by the Nuclear Safety Analysis Center (NSAC) at the request of Commonwealth Edison Company, the owner. The analysis was based on reactor data supplied by Commonwealth Edison Co., and supplemented with first principles thermal hydraulics calculations. No computer analysis was made.

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Section 1

SUMMARY

Dresden 3 was shutdown about midnight of December 19, 1980 and was brought to atmospheric pressure and cold shutdown conditions with both recirculation pumps turned off. There were no plans to refuel or remove the reactor pressure vessel (RPV) head. On December 21, 1980 at about 5:00 a.m. while in a nominal cold shutdown condition with one loop of the shutdown cooling system (SCS) in operation but throttled, the control room operator observed that the reactor pressure was at ~150 psig and increasing. The situation was corrected by placing a second SCS loop in service and increasing flow in the first loop by opening the throttled valve. Commonwealth Edison Company (CECo) requested that NSAC examine this event in detail. This report is the NSAC response to that request.

It has been established that the initiating cause of the repressurization was that the reactor water level had drifted down and was below the separator turnaround level. This prevented circulation through the core when only one SCS loop was in operation with the flow throttled. The minimum required water level elevation for Dresden-3 is 547" for natural circulation or for one SCS loop in operation. This stopped the water recirculation flow through the core and caused the flow from the active jet pumps to bypass the core by flowing upward through the idle jet-pumps. The reactor water temperature distribution stratified and heat removal by the SCS from the RPV became less than the decay heat generation rate. The decay heat caused boiling in the core and the steam flowed through the separators into the upper part of the reactor vessel. The upper region of the RPV heated above 212°F and the system slowly pressurized to ~180 psig before it was depressurized when a second SCS pump was started.

The analysis shows that, if the water level is above a minimum value (the steam separator turnaround point), core flow will be sufficient to assure mixing regardless of the SCS flow rate. It can be shown similarly that, if two SCS pumps operate at full flow, core flow and mixing can be maintained when the reactor water level is a number of feet below the separator turnaround elevation.

Section 2

FINDINGS AND CONCLUSIONS

1. There is a minimum reactor water level below which natural circulation will stop and one throttled shutdown cooling system (SCS) loop cannot force water through the core. This minimum level is above the normal operating water level (20-30" on the narrow range recorder)* and at Dresden is approximately at the top of the narrow range recorder scale when in cold shutdown.

2. With the reactor water level above this minimum value there will always be adequate core flow for heat removal from the core and mixing of the water in the reactor pressure vessel (RPV); however, heat removal from the reactor vessel and thus core cooling is a function of SCS flow.

3. The minimum water level requirement under these conditions was not addressed in the SCS operating procedure (Reference 4).

4. If the shutdown conditions require that the reactor water level be maintained at a minimum value, the acceptable water level can be lowered by operating both SCS loops at full flow after cold shutdown has been achieved.

5. The SCS is automatically protected from high inlet water temperature by causing the pump suction valves to be closed whenever the inlet water is over 350°F. The SCS pumps are tripped on low suction pressure (<4 psig) and high temperature (>350°F) as a protective measure. There is no automatic protective action that results from increasing reactor pressure per se; thus, if the repressurization event had been allowed to continue (and assuming continued temperature stratification) it appears that the reactor pressure could have increased to the value of the reactor high pressure alarm (1030 psig).

*20-30" on the N. R. recorder is equivalent to water at elevation 518" to 525.5" under cold shutdown conditions.

Section 3

SYSTEM DESCRIPTION

The design objective of the shutdown cooling system (SCS) is to cool the reactor water when the steam pressure in the reactor vessel falls below the point at which the main condenser can be used as a heat sink. The SCS is capable of cooling reactor water from 350°F to 125°F within 24 hours after reactor shutdown and maintaining it at this temperature indefinitely by removing fission-product decay heat at the rate that it is produced.

Figure 3-1 shows schematically the principal flow paths through an SCS and the reactor when only one SCS loop is in use and low water level blocks the path through the steam separators. Figure 3-2 shows the steam separator internals; note that at Dresden-3, the lowest elevation for water to turn around and start flowing down is 547". When the water level is below this elevation the separator acts as a dam under natural circulation or single SCS loop operation. Figure 3-3, taken from the Dresden-3 FSAR, shows the shutdown cooling piping diagram. Note that the reactor building closed cooling water system (RBCCWS) flow cannot be throttled. The cooling rate during plant cooldown is controlled by throttling a valve in the path from the heat exchanger back to the reactor. The SCS consists of three partial-capacity cooling loops, each containing a 6750 gpm pump, a heat exchanger with 27 x 10^6 BTU/hr capacity, and the necessary valving and instrumentation. The shutdown heat exchangers are cooled by water from the RBCCWS. The SCS design pressure is 1250 psig, and the design temperature is 350°F.

It is typically necessary to throttle the SCS flow to the reactor to avoid cooling the reactor pressure vessel (RPV) too fast during the cooldown transient following shutdown (100°F/hr is the limit). The operating procedure (Reference 4) shows concern for over-cooling the RPV and for thermal shock to the heat exchangers. Step F.1.h calls for an initial pump discharge isolation valve position of "≈10% open". If a SCS loop is placed in service with reactor water at 350°F and RBCCW at 100-150°F, it will achieve or exceed the desired cooldown rate (≤100°F/hr) with ≈10% reactor water flow. Step F.1.k.1 (4) requires a single loop of SCS in preference to two loops. Thus, the typical configuration of the SCS in operation would be one loop in service with the shutdown cooling flow throttled to some extent. This is adequate with the water level above the minimum value which is the usual situation for a refueling and maintenance (R&M) outage.

The SCS flow feeds the corresponding jet pump nozzles. If one SCS loop is used, only one set (10) of jet pumps is "driven" and the other set is "idle" thus permitting reverse flow through the idle jet pumps. If flow through the core is blocked by low water level all of the flow from the driven pumps will be up through the idle pumps. If two SCS loops are used, both sets of jet pumps are driven. For a typical R&M outage the reactor water level is maintained high to aid in cooling the RPV; water level is eventually raised above the flange (693") to cool it and allow unbolting of the head. With water level above approximately 550" at Dresden 2 and 3, natural circulation of reactor water through the core will be a few million pounds/hr (see Section 4.1). When only one SCS loop is put into service, it will drive one set of jet pumps and increase the core flow. The actual core flow is dependent on the SCS loop flows and on reactor water level if the water level is less than ~550". With only one throttled SCS loop in service, the minimum required water level is very close to 550".

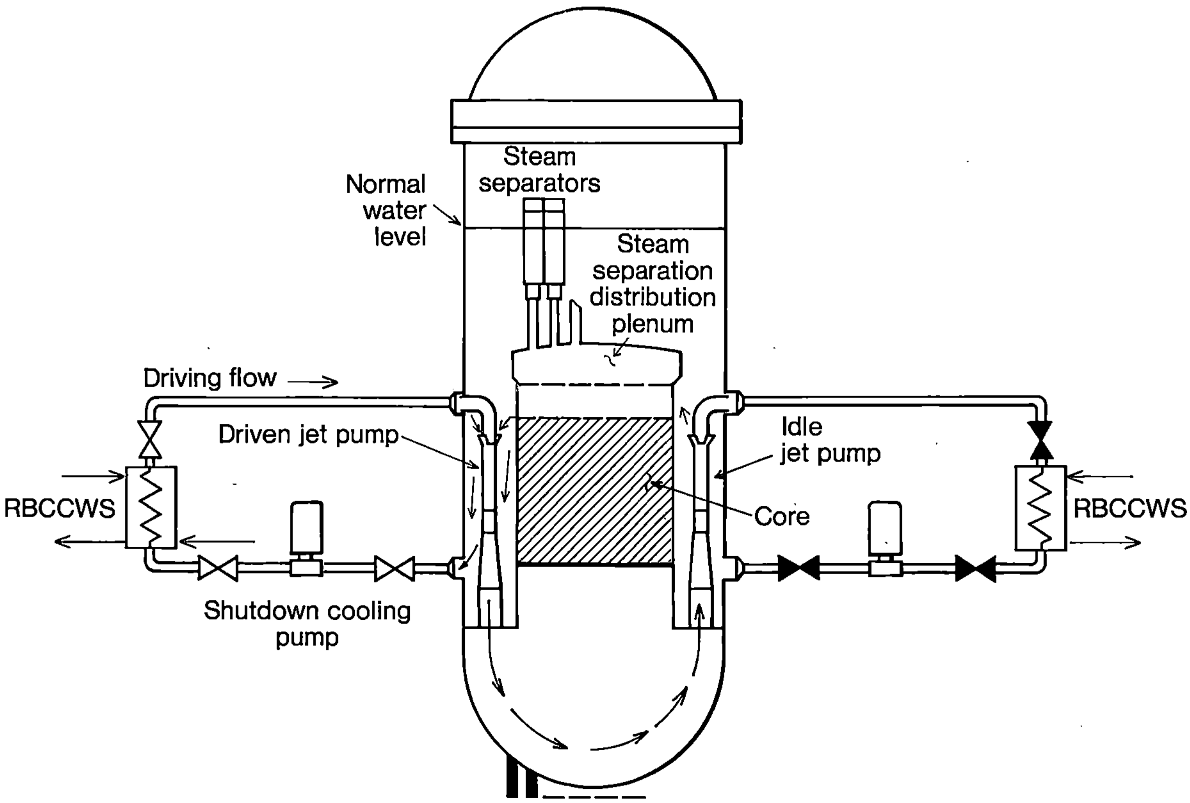


Figure 3-1. Reactor and shutdown cooling.

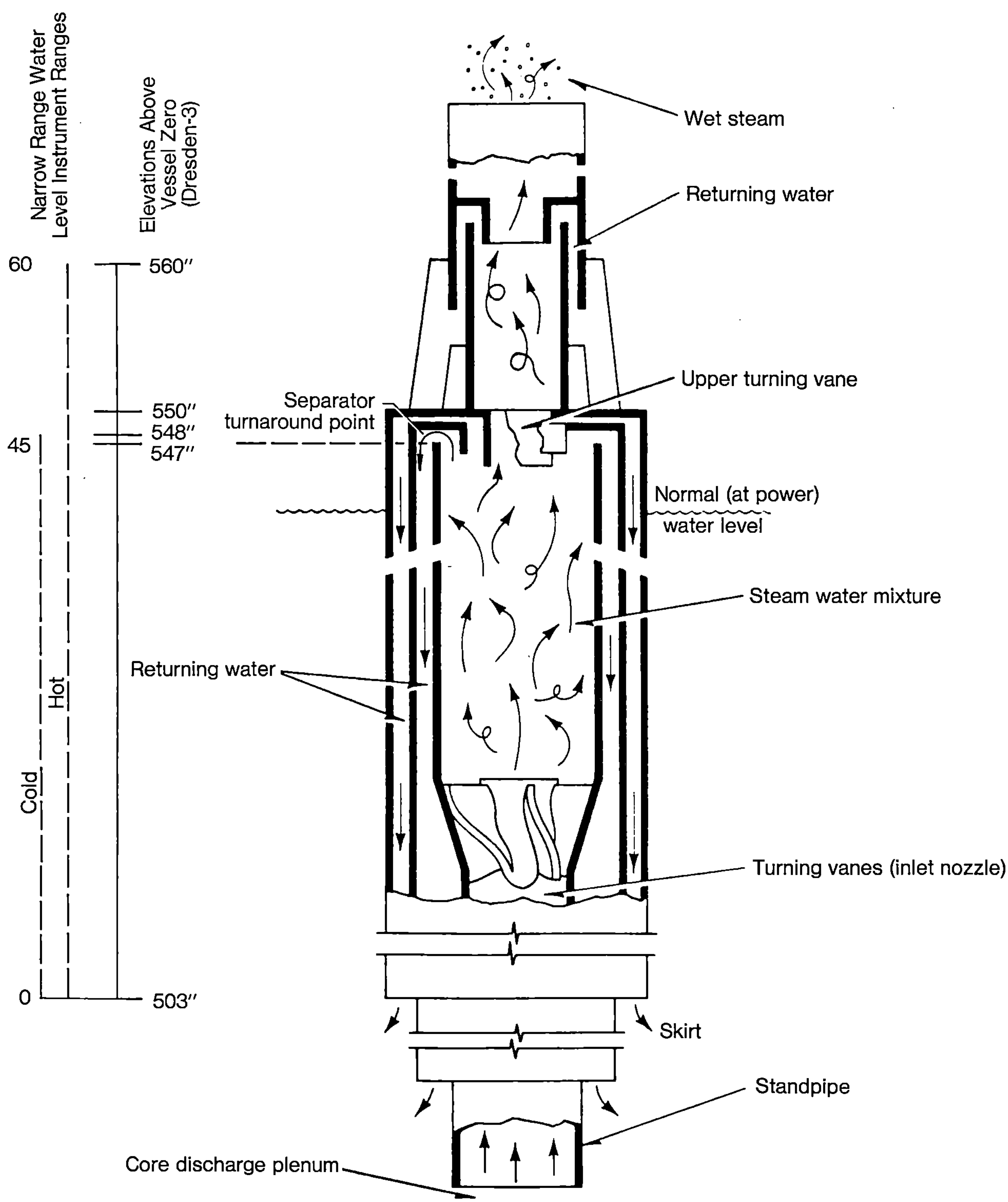


Figure 3-2. Steam separator flow paths.

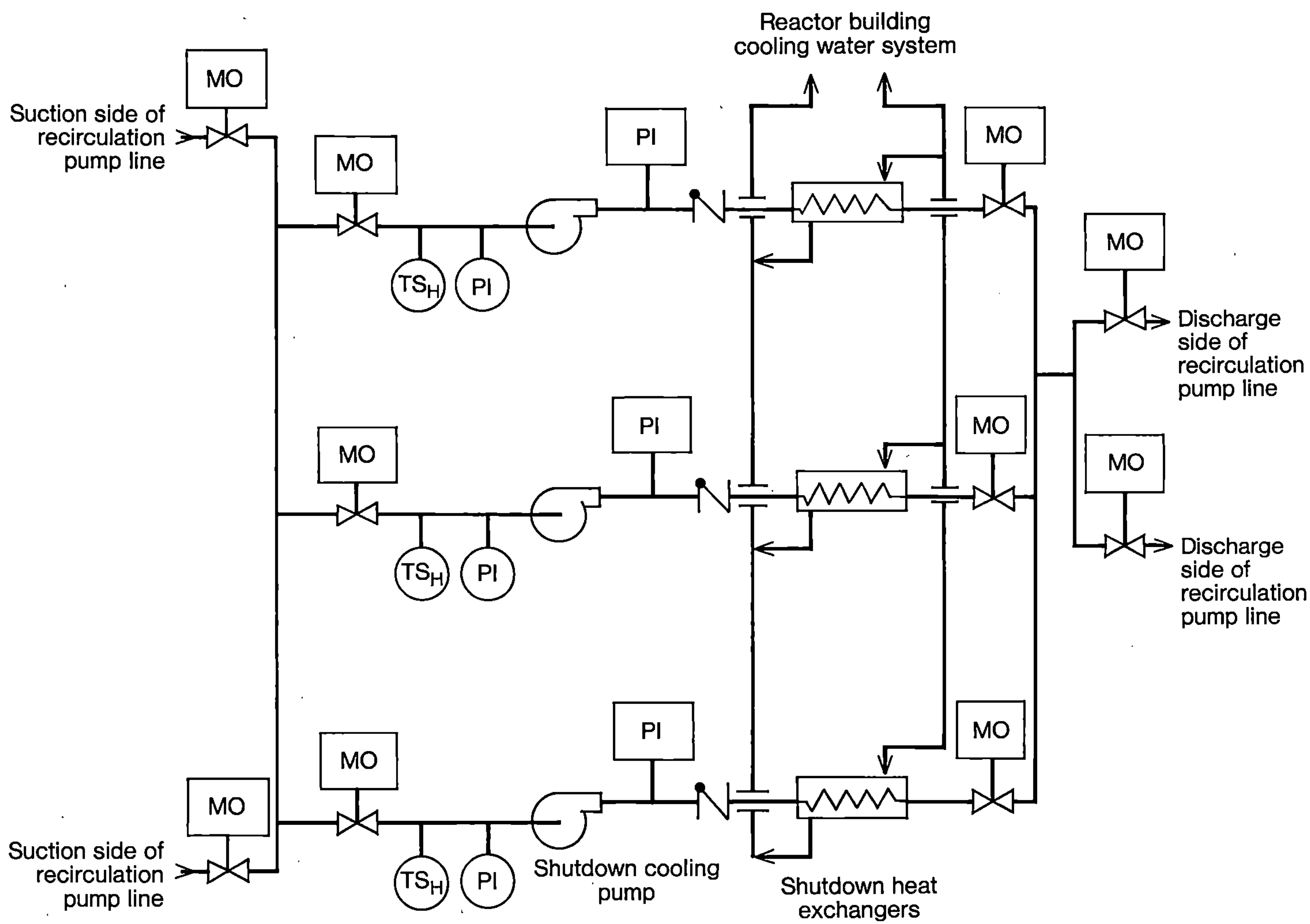


Figure 3-3. Shutdown cooling—piping diagram.

Section 4

ANALYSIS

This section describes the analytical methodology, calculations, input data, and results obtained from evaluation of the Dresden-3 plant pressurization of December 20-21, 1980. The results are compared with the results obtained from analyzing the actual plant data.

4.1 ANALYTICAL METHODOLOGY

The boiling water reactor (BWR) coolant system, in its simplest form, consists of a nuclear reactor core and a circulation loop (upper plenum, standpipes, steam separators, downcomer, jet pumps, and lower plenum) as shown in Figure 4-1. The driving head for recirculation at shutdown is provided by shutdown cooling system (SCS) pumps supplemented by natural circulation. The following describes the analytical techniques used in calculating natural circulation flow (i.e., no SCS pumps running), and forced circulation flow (i.e., two or one SCS pumps running) during shutdown.

4.1.1 Natural Circulation (Both SCS Pumps Turned Off)

The natural circulation analysis was performed using the system layout depicted in Figure 4-1. Figure 4-1 also shows the flow paths (1 through 6) around the circulation loop used in this calculation. Head losses due to the viscous forces in the flow path sections 1 through 6, i.e., upper plenum, standpipes, steam separators, downcomer, jet pumps, and lower plenum along with the viscous losses in the fuel channels are balanced by the buoyant forces developed in the channels.

The calculations were performed using the following input data:

Core Power	=	0.5% rated power (based on ANS decay heat curve @24 hours after shutdown)
Reactor Water Level	=	+47" (=550" elevation above vessel zero)
Number of Fuel Channels	=	724
Feedwater Flow	=	0
Pressure Drop Data for Various Flow Path Sections and Core	=	Reference 6

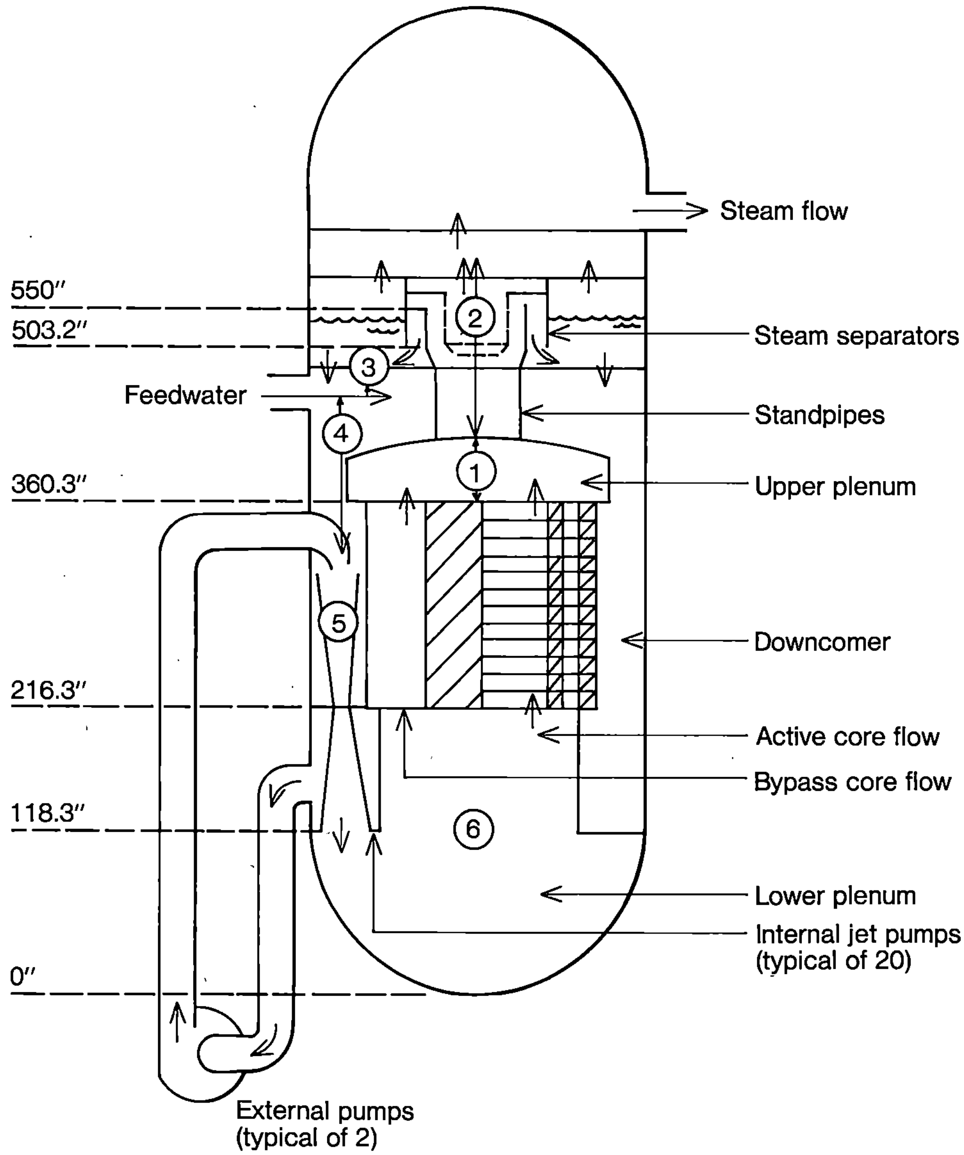


Figure 4-1. Thermal-hydraulic schematic for the boiling water reactor core and recirculation loop.

The calculations performed were done in the following sequence:

1. Compute core flow based on selected ΔT (core exit temperature - core inlet temperature) and power.

2. Determine viscous head loss and elevation head in the core based on $T_{in} + \Delta T/2$ and core flow.

3. Determine viscous head loss and elevation head for flow path sections 1 and 2 using $T_{in} + \Delta T$ and core flow.

4. Determine viscous head loss and elevation head for flow path sections 3 through 6 based on T_{in} and core flow.

5. Compute the total buoyant head based on elevation heads.

6. Compute total viscous head losses by adding viscous head losses in flow path sections 1 through 6 and the core.

7. If buoyant head is equal to total viscous head loss, Stop. If not, adjust ΔT, and return to 1.

The results obtained from this calculation are given in Figure 4-2. The above calculations were performed by selecting various ΔTs until the buoyancy forces were equal to the friction forces. The calculation shows that if the water level is above the separator turnaround point the flow at which the buoyancy and friction forces balance is approximately 4×10^6 pounds per hour. Thus the density difference between the downcomer and the heated length of core, upper plenum and separators is sufficient to drive enough flow through the core to prevent boiling and thus pressurization of the core. It should be noted that this is not a long term steady state operation as continued natural circulation will cause the downcomer temperature to rise to the point where boiling will occur in the core. The calculations also indicate that if the level drops more than ~1 inch below the separator turnaround point, a continuous circulation flow without boiling cannot be maintained with both shutdown cooling pumps tripped, and a core inlet temperature of 150°F.

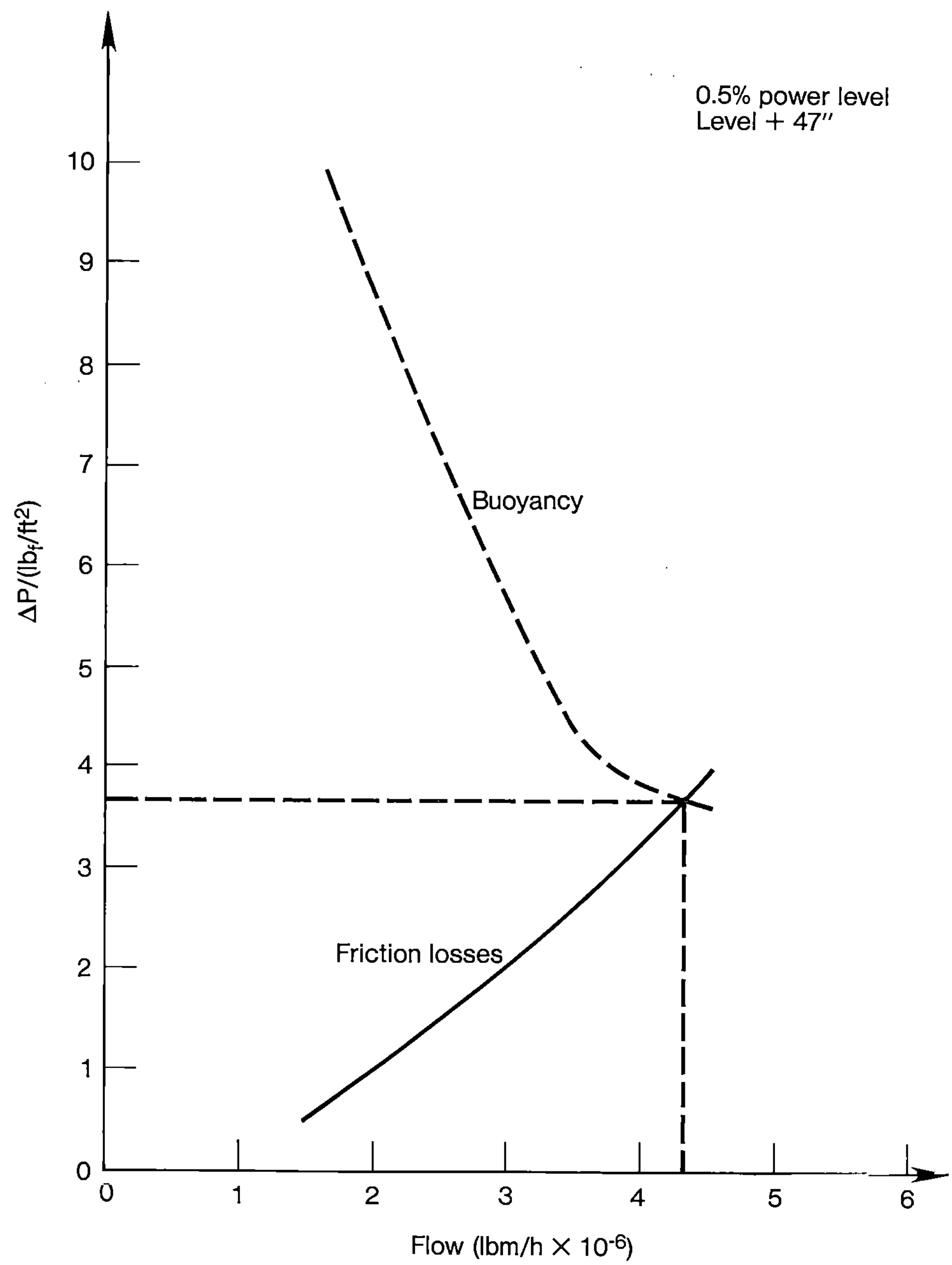


Figure 4-2. Pressure drop versus flow in natural circulation.

4.1.2 Forced Circulation (Both SCS Pumps Running)

The objective in performing this calculation was to determine the reactor vessel water level below which the forced circulation flow through the core will stop. This occurs as additional driving head is required in lifting water up to the steam separator turnaround point.

The analysis was performed by doing a momentum balance in the momentum exchange region of the jet pump. The jet pump mixing region pressure difference, ΔP was calculated for the following two cases:

Case 1: All flows (i.e., the suction flow M_{suc}, drive flow M_d, diffuser flow M_{diff}) in the forward direction

Case 2: drive flow forward, suction flow reversed and the diffuser flow is zero.

A momentum balance was performed within a small mixing region between planes A and B as shown in Figure 4-3. The region being small, it can be considered inertia free. The momentum balance for the inertia free momentum exchange region is given by:

$$\Sigma F = (M_{diff} V_{th} - M_d V_d - M_{suc} V_{suc})/g_c$$
$$= [P_{jet} (A_d + A_{suc}) - P_{diff} A_{th}] \, 144 \quad \text{. . . . .} \quad (1)$$

where

ΣF = Sum of external forces, lbf

M_{diff} = Mass flow entering the diffuser, lbm/sec

V_{th} = velocity at plane B, ft/sec

= $M_{diff}/\rho \, A_{th}$

ρ = Fluid density, lbm/ft^3

A_{th} = Throat area at plane B, ft^2

M_d = Drive mass flow rate, lbm/sec

V_d = Velocity at drive nozzle, ft/sec

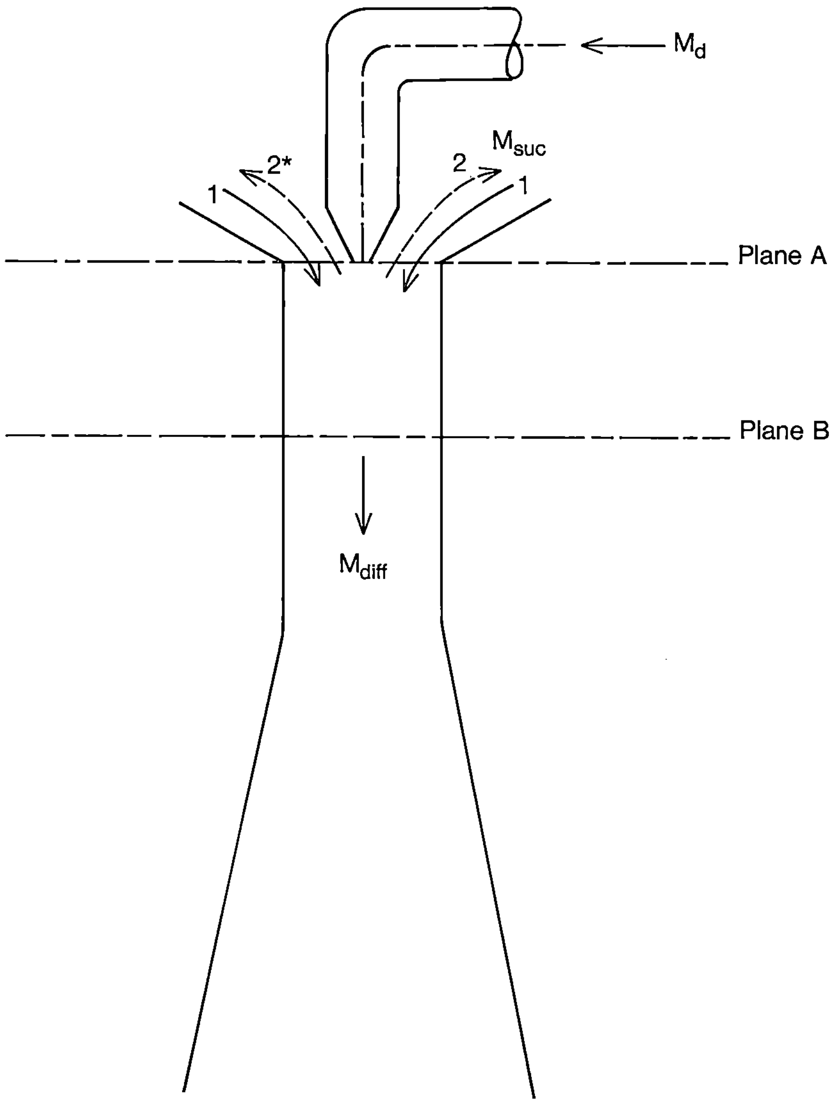
= $M_d/\rho \, A_d$

A_d = Exit area of the drive nozzle, ft^2

M_{suc} = Suction mass flow rate, lbm/sec.

V_{suc} = Suction flow velocity, ft/sec.

= $M_{suc}/\rho \, A_{suc}$



*Number represent case numbers.

Figure 4-3. Jet pump mixing region, momentum balance analysis.

A_{suc}	=	Suction flow area, ft^2
	=	$A_{th} - A_d$
g_c	=	Gravitational Constant, $\frac{lbm}{lbf} \frac{ft}{sec^2}$
	=	32.2
P_{jet}	=	Static pressure across the suction and drive flow area at the nozzle exit, psia
P_{diff}	=	Static pressure at plane B, psia

Replacing velocity terms with the mass flow rates in Eq. 1 yields:

$$\frac{1}{144\ g_c} \left[\frac{M_{diff}^2}{\rho\ A_{th}} - \frac{M_d^2}{\rho\ A_d} - \frac{M_{suc}^2}{\rho\ A_{suc}} \right] = P_{jet}\ (A_d + A_{suc}) - P_{diff}\ A_{th}$$

Substituting $A_d + A_{suc} = A_{th}$ and defining $\Delta P = P_{diff} - P_{jet}$ yields:

$$\Delta P = \frac{1}{144\ g_c\ A_{th}\ \rho} \left[\frac{M_d^2}{A_d} + \frac{M_{suc}^2}{A_{suc}} - \frac{M_{diff}^2}{A_{th}} \right] \quad \ldots\ldots\ldots \quad (2)$$

The above equation 2 is valid for all cases for geometry of Figure 6 such as:

(i) all flows forward
(ii) suction flow reversed
(iii) suction and diffuser flow reversed with forward drive flow
(iv) all flows reversed

Applying the above equation 2 for cases 1 and 2 with the following input data,

$$A_d = 0.0527 \text{ ft}^2$$
$$A_{th} = 0.2028 \text{ ft}^2$$
$$A_{suc} = 0.1501 \text{ ft}^2$$
$$\rho = 61.2 \text{ lbm/ft}^3$$

Case 1	Case 2
$M_d = 675$ gpm	$M_d = 675$ gpm
$= 92.05$ lbm/sec	$= 92.05$ lbm/sec
Assuming M Ratio, $\frac{\text{Suction Flow}}{\text{Drive Flow}} = 2$	
$M_{suc} = 2 \times M_d$	$M_{suc} = M_d = 92.05$ lbm/sec
$= 184.1$ lbm/sec	
$M_{diff} = 92.05 + 184.1$	$M_{diff} = 0$
$= 276.16$ lbm/sec	

yields the following ΔP values:

$$\Delta P_1 \text{ (Case 1)} = 0.2471 \text{ psi}$$
$$\Delta P_2 \text{ (Case 2)} = 5.1 \text{ psi}$$

From these, the height, h, above the reactor water vessel level to the separator turnaround point that will allow forced flow circulation with both SCS pumps running can be obtained by:

$$h = \frac{(\Delta P_2 - \Delta P_1)\,144}{\rho \;\; g/g_c}$$
$$\simeq 11 \text{ ft.}$$

It is our suggestion that although this margin is available it is not advisable to operate with water level below the narrow range operating level channel (0-60"). It is in fact recommended that the level should be kept above the separator turnaround point whenever possible since this would assure natural circulation if the SCS pumps were lost.

4.1.3 Forced Circulation (One SCS Pump Running)

The objective in performing this calculation was to determine what flow bypassing takes place in the ten non-operating jet pumps with only one operating shutdown cooling loop and with water levels above and below the separator turnaround point.

4.1.3.1 Level at or Above Separator Turnaround Point

The core flow and corresponding core pressure drop as well as the jet pump reverse flow and the corresponding jet pump pressure drop was taken from Reference 7 which yielded:

Core:	ΔP = 4.7 psi @ 52 x 10^6 lbm/hour
Jet Pumps: (Reverse Flow)	ΔP = 0.0275 psi @ 0.3 x 10^6 lbm/hour

The hydraulic network analysis performed using the above parameters yielded that 57% of the total flow goes through the core and 43% of the total flow by-passes through the ten non-operating jet pumps.

From this, it can be concluded that the plant can be operated in shutdown conditions with only one SCS pump running if the reactor water level is at or above the separator turnaround point.

4.3.1.2 Level Below Separator Turnaround Point.

This case determined the distance below the separator turnaround point at which all flow is bypassed through the non-operating jet pumps and the core is essentially in a boil-off mode. This, from calculation, based on the pressure drop through the non-operating jet pumps comes out to be ~1".

Therefore, with only one SCS pump running, and the reactor vessel water level more than ~1" below the separator turnaround point, there will be no shutdown core cooling as all forced flow will be bypassing the core via non-operating jet pumps.

The analysis performed above in Section 4.1.1 through 4.1.3.2 clearly demonstrates the importance of maintaining reactor vessel water level during various modes of shutdown cooling system operation. In addition, in determining that the reactor water level is up to the turnaround point in the steam separators the operator must correct his observed water level for temperature since the instrument is normally calibrated for hot conditions. The water level will actually be a few inches lower than the observed reading.

4.2 ANALYSIS OF REACTOR DATA

The Reference 1 data package contained a xerox copy of five partial-width control room charts arranged to match the times to a common reference. Selected data were read off these charts and replotted on Figure 4-4 together with data from the narrow range water level chart. Data were read at hourly intervals and connected with straight lines for interpolation. The water level fluctuated within the hourly intervals; the data point plotted is a visual average for the hour corrected to cold conditions (see Table 4.1).

The data show that at approximately 6:00 p.m. on December 20, 1980 the water level drifted down below the level which would allow return flow through the separators (this is the separator turnaround point referred to earlier and is ~547" as obtained from Reference 2). Prior to 4:00 p.m. the water level was off-scale (high) on this recorder and therefore above the separator turnaround or minimum level. After 5:00 p.m. on December 20, 1980 there is a steady drift downward to ~528" at 3:00 a.m. on December 21, 1980 where it remained through 7:00 a.m. It can be assumed that there was no core flow in the usual sense from ~6:00 p.m. (12/20/80) when the reactor water level fell below the separator turnaround point value until the second shutdown cooling system was started after 5:00 a.m. (12/21/80).

The data show that reactor pressure began to increase at ~10:00 p.m. (12/20/80) and continued upward to ~180 psig at 5:00 a.m. (12/21/80) when the second SCS pump was started. Starting the second pump effectively closed the low resistance path created by the idle jet pumps and increased the head sufficiently to force water flow through the core and over the 547" turnaround or minimum level in the separators. The saturation temperature for the corresponding pressure was plotted (Tsat) and is shown in Figure 4-4. Two reactor vessel metal temperatures from the data package were also plotted. Note that the downward trend in reactor vessel metal temperatures was reversed by 11:00 p.m., 12/20/80 and that they closely follow Tsat thereafter. This demonstrates that RPV thermocouples on the outer skin of the vessel below the surface of the reactor water will follow the reactor water temperature quite closely.

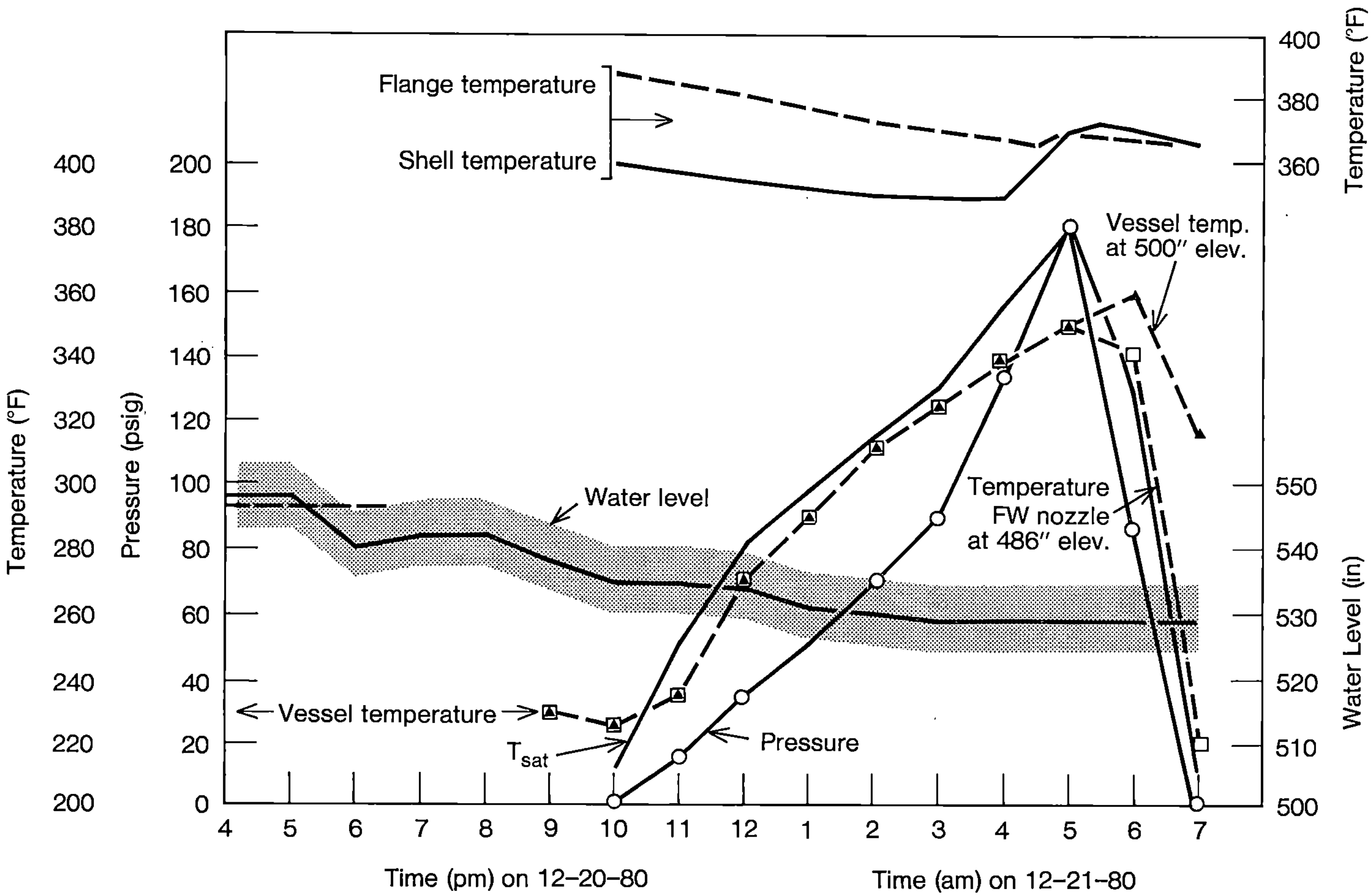


Figure 4-4. Reactor data.

Table 4-1

Water Level Data From Narrow Range Recorder

Time	Chart Reading On 0-200 Scale		Interpretation Hot (inches)		Interpretation Cold (inches)		RPV Elev. (inches)
4 p.m. 12/20/80	200 x 0.3	=	60 x 0.75	=	45 + 503	=	548
5	200		60		45		548
6	165		49.5		37		540
7	173		52		39		542
8	175		52.5		39		542
9	155		46.5		35		538
10	140		42		32		535
11	140		42		32		535
12 (Midnight)	136		41		31		534
1 a.m. 12/21/80	128		38		29		532
2	120		36		27		530
3	112		34		25		528
4	112		34		25		528
5	110		33		25		528
6	110		33		25		528
7	110		33		25		528

The reactor vessel flange and shell temperatures were also plotted (but on a different scale). These RPV thermocouples are above the water level and they continued to cool linearly until 2:00 a.m. on 12/21/80 when there was a noticeable slowing in the cooling rate as the steam temperature (Tsat) became >300°F. Both thermocouple readings began to increase as Tsat became greater than the flange and shell temperatures at 4:00 a.m. and 4:30 a.m. respectively. This demonstrates that the source of heat for the reactor water temperature stratification and pressurization was not the upper RPV metal but the reactor.

At the time of this heatup and pressurization, the decay heat was approximately 0.5% (~12 Mwt). If this heat were completely contained within the RPV, the system would have warmed at ~40°F/hr and passed from ~150°F to 212°F in ~1.5 hours. When the water level became too low to allow water flow through the separators the water in the core heated to boiling. There was some heat loss by conduction through the shroud and shroud head. The water circulation paths in the core area were upward through each fuel bundle and downward between the fuel bundles. The water volume in the shroud and shroud head would reach saturation in 20-30 minutes. The steam formed after that time would initially be condensed on the inner surface of the shroud head and in the separator standpipes; both surfaces would act as heat exchangers to heat all the water above ~400" elevation to saturation. The calculated time to reach saturation after core boiling began is 20-30 minutes assuming no heat transfer out of the heated volumes. The average rate of temperature change for the heated volumes would be ~72°F/hr, assuming no heat lost from the volumes. The observed heating rate (Tsat on Figure 4-4) was initially ~35°F/hr; therefore, approximately half of the decay heat was being removed by conduction through the shroud and by mixing at the interface between the hot water in the upper RPV and cold water in the lower RPV.

The above discussion assumes the reactor water level suddenly cut off the flow and the analysis implies that half of the decay heat stayed in the RPV and would have heated the upper part of the RPV to saturation in ~2 hours. Figure 4-4 shows that ~5 hours elapsed between the time the water level became less than 547" and pressurization began. The uncertainty in the water level is about ±4-5 inches after the temperature correction has been made. It is most probable that flow was not cut off cleanly at ~5:00 p.m. but that it was effectively stopped by ~8:00 p.m.

For the sake of completeness, the heatup and pressurization due to heat flow from the upper and uncooled portion of the reactor pressure vessel (RPV) was calculated from available data. The heat source was assumed to be the mass of metal in the RPV above elevation 550". The rate of cooling was estimated from the flange and shell temperature data on Figure 4-5.

The metal mass was estimated using Reference 2 and neglecting all nozzles and appurtenances. The value of 334 tons is conservatively high. The stored heat in this metal is approximately 8×10^4 Btu/°F. The rate of cooling of the shell and flange in the initial four hours is 2.5 - 3.5 °F/hr; thus, the heat flow rate was $20 - 28 \times 10^4$ Btu/hr or 59 - 82 kw. At this time the core decay heat was ~12 MWt; therefore, the contribution from RPV cooling towards heatup and pressurization was less than 1% of the reactor decay heat.

Section 5

OBSERVATIONS

1. Operating procedures should:

   (a) Include a minimum reactor water level requirement of above the separator turnaround point if the separators are in place.

   (b) Require operation of two shutdown cooling system (SCS) loops after cold shutdown has been achieved if circumstances require the water level to be held at or near the minimum.

   (c) Require periodic monitoring of selected reactor pressure vessel (RPV) metal temperature thermocouples if circumstances require the water level to be held at or near the minimum. (The data on Figure 4-4 came from the thermocouple at the 500" vessel level. This temperature should always be close to that at the inlet to the SCS heat exchanger.)

2. Operator Training and Retraining programs should include minimum water level requirements for SCS operation.

Section 6

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