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ANALYSIS OF PRIMARY SYSTEM BLOWDOWN BY RUPTURE DISC FAILURE

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The purpose of this analysis was to determine the time required for blowdown of the primary system when the rupture disc fails, and the effect of blowdown on the control rods during scram. The rupture disc is located in a tee at the first bend of the 4" pipe leading from the 12" primary circulating pipe to the pressurizer. This 4" line is connected to the primary loop on the discharge side of the reactor core vessel. The rupture "disc" will actually be either

A) A welded thick disc with a machined groove just inside the periphery of the 4" schedule 80 pipe which is designed to fail in direct shear at 2000 psia or

B) A capped stub of 4" schedule 80 pipe with a turned groove on the outside, reducing the thickness locally to a value designed to fail at 2000 psia.

The 2000 psia primary pressure is postulated to occur as a result of malfunctioning of the control rod electrical control system, causing the average temperature of the primary coolant throughout the loop to build up from a normal full load value of 440° to 490°F. In doing so the water expands and rises up into the pressurizer, and the pressure rise is the result of gaseous compression of the steam in the top of the pressurizer. Of course, to reach the 2000 psia setting of the rupture disc, from the normal operating pressure of 1200 psia, would require failure of the automatic scram signals on primary pressure and temperature, as well as failure of the primary pressure relief valve to open.

The steam thus trapped in the pressurizer undergoes an adiabatic isentropic compression and therefore becomes superheated steam, with 52°F of superheat. The compression of the steam follows the law PV^k = constant, where "k" is the isentropic expansion exponent, having an average value of 1.248 in this case. When the rupture disc fails, the superheated steam in the pressurizer will expand adiabatically and isentropically from 2900 psia down to 1200 psia. The volume by which the steam re-expands in this step equals the original volumetric expansion of the primary coolant, and this is the volume of 490°F water which must be discharged through the rupture disc during this step. This process takes 190 milliseconds.

The entire primary system can now be conveniently divided into three parts: (1) The entire primary loop of 490°F water with a volume of 164.5 ft^3 plus 1.23 ft^3 in the pressurizer leg. (2) The volume of 9.5 ft^3 of water in the pressurizer leg at 567°F, and (3) The volume of 22.9 ft^3 of steam at 567°F, saturation temperature at 1200 psia. The 9.5 ft^3 of water is normally maintained at a higher temperature than the remainder of the primary circuit by the action of the heaters located in the pressurizer inlet pipe. The elapsed time for the event under analysis is so short that no appreciable heat transfer will take place between the two quantities of water.

Upon a discharge of water from the system, with a corresponding pressure drop, the saturated steam in the pressurizer will undergo further isentropic expansion. An inspection of a temperature-entropy diagram or a Mollier chart will indicate that a portion of the steam upon expansion will become wet and momentarily condense out of the steam as saturated liquid. However, the above conditions are based on the assumption that the steam in the pressurizer and the liquid adjacent to it in the pressurizer leg are exactly at the same pressure and temperature at all times. The steam at the end of each increment of pressure drop is wet and can be considered to be composed of X pounds of steam and (1-X) pounds of saturated liquid. As this process continues, the slug of 9.5 ft^3 of saturated liquid at 567°F is flashing over into steam due to pressure drop. The basic assumption of this analysis is that the flashed steam is always entrained in the liquid resulting in a homogeneous mixture of vapor bubbles and liquid, the time required being too short to allow gravitational separation. It can therefore be concluded that in the pressure range of 1200 psia down to 620 psia, which is the saturation pressure of 490°F water, the isentropic expansion of the steam in the pressurizer will govern the volume discharge through the rupture disc. The volume expelled in this pressure range is composed of water and entrained vapor, both at the same pressure and temperature. The 490°F water in the primary loop will experience a volumetric change due to the change in specific volume of compressed sub-cooled liquid, but this change is so small it can be neglected. It is of interest to note that before the pressure gets down to 620 psia, all the water in the pressurizer leg will have either been discharged out of the rupture disc or flashed over into steam. This point occurs at 820 psia; therefore in the pressure range between 820 and 620 psia, the remaining volume of steam will expand and be discharged from the rupture disc in a relatively short period of time. The method of calculating blowdown involved in this analysis is recorded in the appendix. The total cumulative time for blowdown from 2000 psia to 620 psia is only 0.572 seconds.

At this point in the analysis, the entire remaining volume of 164.5 ft^3 in the primary loop at 490°F is at its saturation pressure (620 psia), and the discharge from the rupture disc will now be governed by the pressure drop and the rate of flashed vapor generated throughout the system. The trapped volume of steam in the pressurizer circuit will have very little effect on the performance of discharge from the primary blowdown as its pressure will simply follow the pressure dictated by the primary blowdown. The same method of analysis is used in this pressure range as previously referred to, outlined in the appendix. The blowdown of the primary loop was calculated from 620 psia to 280 psia and at this point there remained, according to calculations, 468 pounds of water and 101 pounds of steam. In the range of 280 psia, thermodynamic relations become so involved that to make any further calculations would give unreliable results, without a more rigorous method of analysis than used here, in order to take full account of the recondensation of the growing body of steam. The curve of Figure I shows pressure and weight-discharge versus time for the blowdown. The curve of pressure versus time may be extrapolated to account for blowdown from 280 psia to atmospheric pressure and the extrapolated curve indicates a total cumulative blowdown time of approximately 11.0 seconds.

From the standpoint of total time of blowdown, it can be concluded that a 4" rupture disc is sufficiently large to permit complete blowdown in an acceptable time interval.

Since the rupture disc is located in the discharge pipe from the reactor, it is necessary to determine the upward force which might be applied hydraulically to the control rods, during a scram following a rupture disc failure, and its effect on their position or motion. On page 103 of the Hazards Summary Report, APAE No. 2 Figure VII - 5 shows the reactor behavior following a main circulating pipe rupture, as postulated for the Maximum Credible Accident. A 10% reduction of the effective multiplication factor, due to density reduction of the moderator, as water is expelled out the rupture disc opening and steam generated throughout the system, would be more than sufficient to drive the reactor subcritical. This corresponds to 0.042 seconds after rupture on Figure VII-5, for the maximum credible accident. On page 238 of the same report, Figure F-1, the progress of variables affecting reactivity is plotted and it shows that after a time lapse of 0.042 seconds the density reduction on which Figure VII-5 was based amounted to 14%. This reduction in density corresponds to 8140 x 0.14 = 1140 pounds discharged from the primary loop for the present case, which begins at the time the primary system is at 620 psia. According to Figure I this weight discharge would correspond to only a 10 psi pressure drop in the entire primary loop: from 620 psia down to 610 psia. The corresponding time interval would be about 1.0 second. On the basis of previous calculations by W.M.S.Richards, a pressure difference across the reactor core of 10 psi would not cause expulsion of the control rods but rather would permit essentially unhindered acceleration downward by gravity toward scram. Thus the effect of pressure difference on the projected area of the control rod is negligible.

On the basis of the analysis contained in this memo, a 4" rupture disc, located in the position stated earlier, is acceptable for the following reasons: (1) The total time for blowdown is small, (2) the time required to scram the reactor by density reduction of the moderator is sufficiently short, and (3) the expulsion effect on the control rods is negligible during entire blowdown.

APPENDIX

CALCULATION OF BLOWDOWN TIME

Nomenclature

The following nomenclature is used in the formulas:

P = Pressure, psia or lb/$_{ft}{}^2$, as required for dimensional balance

M = Mass, lbs.

$M_{f_g 1}$ = Mass of liquid after vapor expansion, lbs.

v_s = Specific volume, ft^3/lb

V = Volume, ft^3

u = Internal energy, btu/lb.

x = Quality, %

Y = Lbs flashed vapor

W = Flow work, btu

J = Mechanical equivalent of heat, 778 $\frac{\text{ft-lb}}{\text{btu}}$

k = Isentropic exponent

g = Acceleration of gravity, 32.2 ft/sec^2

ΔP = Pressure drop, psi

ΔV = Total volume change, ft^3

ΔV_1 = Volume change from isentropic expansion of steam, ft^3

ΔV_2 = Volume change due to flashing, ft^3

ΔV_3 = Volume of vapor entrained in liquid, ft^3

V_4 = Volume of liquid and entrained vapor, ft^3
R = Volume ratio
A = Vapor discharged, lbs.
B = Liquid discharged, lbs.
C = Total discharge, lbs.
M_{f_3} - Water remaining, lbs.
M_{g_3} = Vapor remaining, lbs.
$v_{s_{mix}}$ = Special volume of discharge mixture, ft^3/lb.
H = Height of equivalent head, ft
Vel. = Velocity, ft/sec
A_d = Area of discharge, ft^2
t = Time, seconds

Subscripts

1 = Initial condition
2 - Final condition
g = Steam or vapor
f - Water or liquid
f_g - From liquid to vapor
avg = Mean value in increment

Solution

1. Assume a pressure drop 100 30

2. At initial pressure P_1 determine the following:

   M_{g_1} , $V_{s_{g_1}}$, V_{g_1} , U_{g_1}

   M_{f_1} , $V_{s_{f_1}}$, V_{f_1} , U_{f_1}

3. At final pressure P_2 determine the following:

   $P_2 = P_1 - \Delta P$

   x_2 , u_{g_2} , u_{f_2}

   $M_{g2} = X_2 \ (M_{g1})$

   $M_{f_2}{}^1 = (1-x) M_{g_1}$

   $M_{f_2} = M_{f_2}{}^1 + M_{f_1}$

4. Setup an energy balance on the basis of internal energy to determine amount of flashed vapor

$$M_{g_1} (u_{g1}) + M_{f1} (u_{f_1}) = M_{g_2} (u_{g2}) + (M_{f_2} - y) U_{f_2} + (y) + W$$

where $$W = \frac{M_{g_1} \times P_{avg} \left(v_{s_{g1}} - v_{s_{g_2}} \right)}{J \ (1 - k)}$$

Solve for Y

5. Compute isentropic expansion of steam

$$P_1 V_1^{k} = \text{constant} = P_2 V_2^{k}$$

$$V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{k}}$$

$$\Delta V_1 = V_2 - V_1$$

6. Determine the change in volume due to flashing

$$\Delta V_2 = Y \cdot v_{s_{fg,\ \text{mean}}}$$

7. Find total volume change

$$\Delta V = \Delta V_1 \not- \Delta V_2$$

8. Find volume of vapor entrained in liquid

$$V_3 = \Delta V \not- V_1$$

9. Find volume of liquid and entrained vapor

$$V_4 = (M_{f_2} - Y)\ v_{s_{f_2}} \not- V_3$$

10. Find ratio of volume of vapor entrained to volume of liquid and entrained vapor.

$R_2 = \frac{V_3}{V_4}$ R_1 was determined from preceding increment

11. Find the average ratio of volume ratios.

$$R_{avg.} = \frac{R_1 \not- R_2}{2}$$

12. Find the total weight discharge

$$\Delta V \frac{R_{avg}}{v_{s_{g_2}}} \not- \frac{1- R_{avg.}}{v_{s_{f_2}}} = \text{Total lbs. discharge}$$

Let A lbs. vapor $\not-$ B lbs liquid = C lbs total discharge

13. Calculate remaining weights of vapor and liquid

$M_{f_3} = M_{f_1} - B - Y =$ lbs water

$M_{g_3} = M_{g_2} + Y - A =$ lbs vapor

14. Determine time of blowdown in increment

$$P_{avg} = \frac{P_1 + P_2}{2}$$

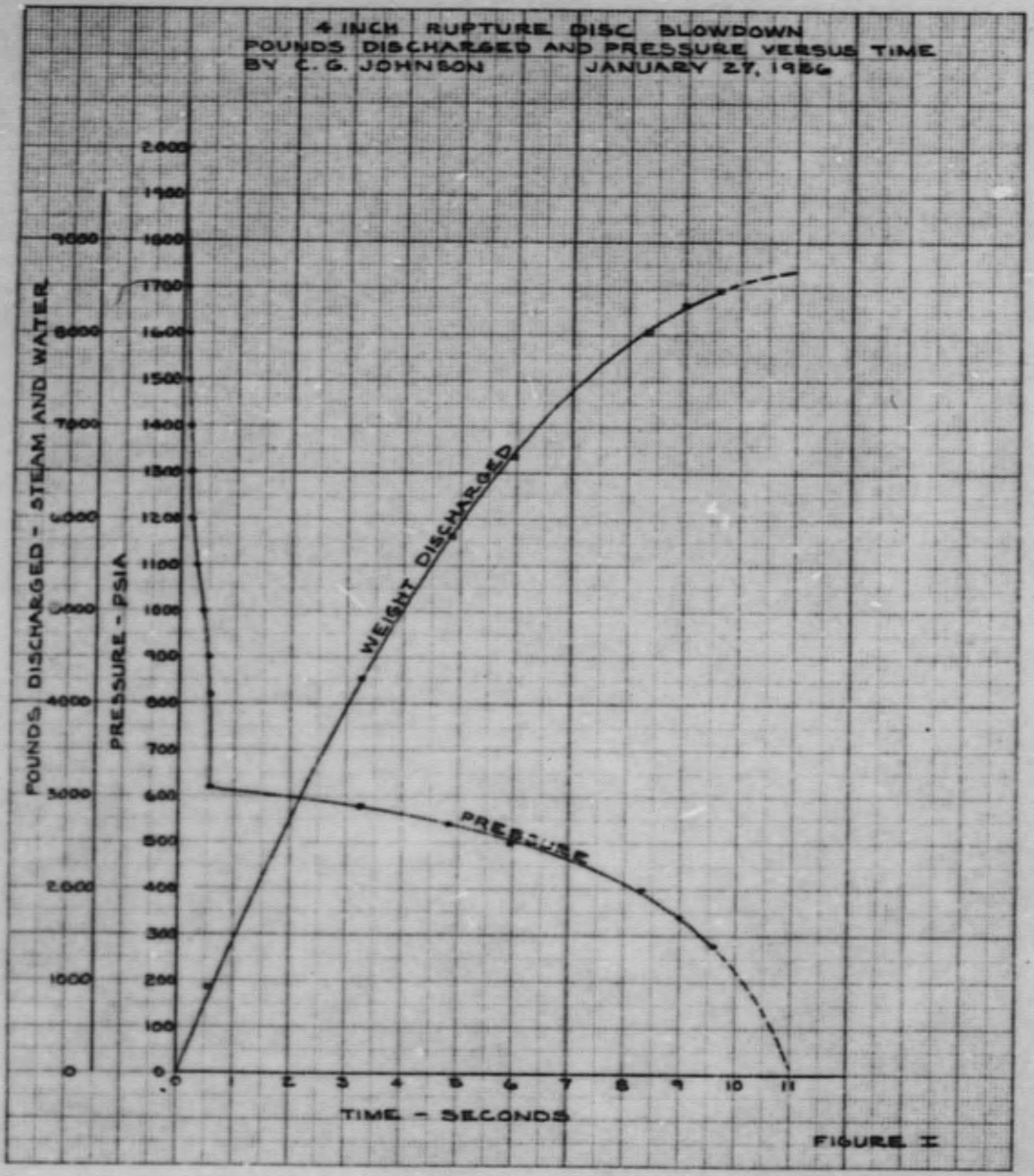
$$v_{s\,mix} = \frac{\Delta V}{C}$$

$$H = P_{avg.} (v_{s_{mix}})$$

$$\text{Vel.} = (2\, g\, H)^{\frac{1}{2}}$$

Ad = Discharge area

$$t = \frac{\Delta V}{A_d \times \text{Vel.}}$$



4 INCH RUPTURE DISC BLOWDOWN
POUNDS DISCHARGED AND PRESSURE VERSUS TIME
BY C. G. JOHNSON JANUARY 27, 1956

FIGURE I

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END