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1.

DELAY TIME PRIOR TO DUMPING THE HRT

Abstract:

Some refined calculations have been made, relative to a proposed delay prior to a dump, to determine the expected D_2 concentration in the vent stream from the pressurizer gas bleeds during a dump of the HRT. These calculations indicate that for vent valves having a Cv of 0.07 (venting time from 2000 psia to D_2 saturation pressure of approximately 12 minutes), a delay period is not required since the D_2 concentration is well below the lower explosive limit.

For vent valves having a Cv of 0.3 (venting time approximately 2.4 minutes), the calculations indicate that a delay before venting of approximately two minutes will be required. This is due entirely to the possibility of mass ebullition of the D_2 . Since the pressure drops so quickly, the reactor solution becomes saturated with D_2 before appreciable recombination can occur.

Introduction:

In a recent memo⁽¹⁾ it was estimated that the delay time required to reduce the D_2 explosion hazard in the HRT operating at 5 Mw and 20% letdown during a dump was approximately 3 to 5 minutes. Accordingly, such a delay time has been proposed for the HRT dumping operation. However, the recent dump tests at the HRT have indicated that with the existing pressurizer vent valves having a Cv of 0.07, approximately ten to fifteen minutes will be required to reduce the pressure prior to a controlled dump of the fuel solution^(6,7). Since such a vent time seems to be too long for the HRT, vent valves having a Cv of 0.3 have been proposed. Calculations were made to determine the time required to reduce

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the pressure in the pressurizers from 2000 psia to 933 psia. The method of calculation is given in Appendix III. These calculations show that with the vent valve in the half open position approximately 2-1/3 minutes are required to vent the pressurizer. In either case it is possible that no delay time would be required. To determine this the D_2 concentration in the pressurizer vapor space was estimated as a function of total pressure in the system, D_2 concentration in the reactor, and time after closure of steam removal valve in the steam generator.

The calculations show, as would be expected, that maximum D_2 concentration in the pressurizer is primarily dependent on the assumed rate at which the D_2 is stripped from the liquid to the gas phase. If it is assumed that the equilibrium between total gas and total liquid phases is reached instantaneously (as in CF 56-5-40) calculations indicate that the delay circuit is certainly required. If instead it is assumed that there is a rate at which D_2 is made accessible to the vapor phase calculations show that the delay circuit may not be required.

Some basic relations will be common to both methods of solution.

Power-Time Behavior:

The power-time behavior has been solved in CF 56-5-40 for a shut-down due to closure of the steam removal valve, and continued forced circulation of the fuel. This solution can be represented as:

$$\ln \frac{Q_T(o)}{Q_T(t)} = \frac{B WC_P}{C_b} t$$

where

$$B = \frac{\alpha (e^H - 1)}{1 + (\alpha - 1)e^H}$$

$$H = \frac{UA}{WC_P}$$

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The fission product energy curve was taken also from CF 56-5-40 where it had been approximated assuming a gradual reduction in fission power. These curves are reproduced in Figure 1.

D₂ Generation and Time Behavior

The D₂ generation rate in an aqueous reactor system may be represented by: (1)

$$v(t) = C E(t) G$$

$$\text{where: } C = 4.97 \times 10^{-7} \frac{\text{lb mols } D_2\text{-ev}}{16 \text{ mol sol-kw-molecule } D_2\text{-sec}} \quad (\text{for HRT system})$$

$$G = 1.67 \frac{\text{molecules } D_2}{100 \text{ ev abs.}} \quad (\text{for fission fragments})$$

$$= 0.45 \frac{\text{molecules } D_2}{100 \text{ ev abs.}} \quad (\text{for beta-gamma energies})$$

$$E(t) = Kw, \text{ energy absorption rate of } D_2O$$

$$v(t) = \frac{\text{lb mols } D_2}{\text{lb mol sol-sec}}$$

The total generation rate and that due only to fission product decay energies are shown also in Figure 1.

The HRT will use a copper catalyst which has been shown to recombine the D₂ in solution according to a first order rate equation. This can be represented as:

$$\frac{dy}{dt} = v(t) - k_{Cu} c y$$

$$y = \text{mol fraction } D_2 \text{ in sol. } \frac{\text{lb mol } D_2}{\text{lb mol sol.}}$$

$$v(t) = \text{generation rate } \frac{\text{lb mol } D_2}{\text{lb-mol-sol-sec}}$$

$$k_{Cu} = \text{reaction rate constant, } 5.8. \text{liters/gm mol } Cu^{++}\text{-sec at } 280^{\circ}C$$

$$= ae^{-\frac{b}{T}}$$

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Fig. 1. Reactor Power and D_2 Generator Rate vs. Time After Closure of Steam Removal Valve of Steam Generator

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$$a = 2.37 \times 10^{10}$$

$$b = 12,200$$

$$T = \text{Temp.}, ^\circ\text{K}$$

$$c = \text{Cu}^{++} \text{ concentration, } 0.0019 \text{ gm mols/liter}$$

The solution to this equation for a given temperature is then

$$y = \left[y_0 + \int_0^t v(t) e^{k_{\text{Cu}} ct} dt \right] e^{-k_{\text{Cu}} ct}$$

$y_0 = D_2$ concentration in fuel solution at time of shutdown

Pressure-Time Behavior

The data from the HRT dump tests show that the pressure drop during release of overpressure is essentially exponential. For the original vent valves ($C_v = 0.07$) the pressure has thus been assumed to drop exponentially from 2000 psia to 600 psia in twelve minutes. Thus:

$$P(t) = P_0 e^{-1.67 \times 10^{-3} t}$$

$$P_0 = 2000 \text{ psia}$$

$t = \text{time (sec.) after closure of steam valve}$

The replacement vent valves ($C_v = 0.3$) show a calculated vent curve (Figure 6) which is also exponential. This curve can be quite exactly represented by the equation:

$$P(t) = P_0 e^{-5.4404 \times 10^{-3} t}$$

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Case I. This case can best be described as one in which there is perfect equilibrium between the D_2 in the gas space and the D_2 in the entire reactor fuel solution at all times after closure of the steam valve. This case cannot represent a solution of the real reactor case since the stripping of the D_2 from the fuel solution will be governed by some rate equation. This case is of interest though in that it represents the worst situation. Some other assumptions are:

- (1) The temperature of the gas-liquid mixture in the high pressure system is uniform during the release of pressure.
- (2) No liquid leaves the system during the operation.
- (3) No heat is lost from the system except that of the gases being vented from the system.

With the use of these assumptions, the material and enthalpy balances, equilibrium relations of the system, a solution can be found for the problem. The method of calculation is given in Appendix I.

The results of this analysis are essentially the same as that in CF 56-5-40 for the case of no delay prior to the venting operation. This method gives a maximum concentration of approximately 14% D_2 in the venting gas stream (Figure 2). Thus if this were a valid analysis, a delay before venting certainly would be needed.

Case II. In the actual reactor case, the concentration of D_2 in the soup in the pressurizer leg will not be equal to the equilibrium concentration emerging from the reactor. More probably it will be a sum of the D_2 produced by fission fragment decay energy, fission fragments (by leakage neutrons) in the pressurizer leg, and a source plane

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of D_2 at the entrance to the pressurizer leg which will be attenuated through the pressurizer leg depending on the rate at which the D_2 would rise due to bouyancy and diffusion and the recombination rate of D_2 in the pressurizer leg.

Of these sources only that of fissions due to leakage neutrons may be neglected. The D_2 generation due to fission fragment decay can be estimated easily, as can the attenuation rate from the source plane if a velocity rise of D_2 in the pressurizer leg can be determined.

If we can assume that the D_2 in solution acts as a tiny bubble in its movement, then the D_2 velocity is a complex function of pressure, temperature, radius of bubble, viscosity, and density. As such it cannot be effectively measured for this case. However, it should be possible to give an over estimate of the rate of rise of a hypothetical bubble. In the previous case the bubble was assumed to rise through the pressure leg instantaneously and arrive at equilibrium in the vapor space at the moment the total pressure began to be dropped. This seems to be an extremely pessimistic viewpoint.

Some data has been published concerning the velocity of air bubbles rising in various liquids⁽³⁾. Data is presented of terminal velocity of the bubble vs bubble radius. This data shows (as would be expected) that until very large bubbles are formed the terminal velocity decreases as some function of the bubble radius if all other variables are kept constant.

Now the largest size bubble to be expected in our system would be the amount of gas formed if all the kinetic energy of the fission fragment were liberated as the decomposition energy to form a single gas

bubble. Calculations show that this bubble of D_2 and O_2 saturated with water at the operating conditions would have a radius no greater than 3.74×10^{-6} cm. If we take into account the accumulation of these bubbles, by assuming that no more than 100 such bubbles will coalesce, and the expected decrease of pressure and temperature during a vent we find that the bubble radius may be expected to increase approximately 50 times to a radius of 2.0×10^{-5} cm. Such radii are 1000 times smaller than those investigated⁽³⁾ and it seems reasonable to assume that such a bubble would have a correspondingly lower terminal velocity. Thus it should be quite a safe assumption to assume that the bubble under consideration should have a much lower velocity than the smallest bubbles which were investigated. This terminal velocity is approximately 2.0 cm/sec in water.

The pressurizer leg is made up of a 4.3 foot length of horizontal piping and approximately 20 inches of vertical piping filled with soup. It is assumed for the time required for the bubble to pass through this piping that the entire pressurizer leg length is vertical. For which case the time required is 90.9 seconds.

A further assumption necessary for the solution of this case is that the instantaneous gas-liquid equilibria is with the vapor space of the pressurizer and the liquid in the pressurizer leg only. The remaining reactor solution acts only as a source of D_2 at the entrance to the pressurizer leg. The validity of this assumption, while it seems reasonable, may be disputed.

Using these assumptions, the material and energy balances, equilibrium relations, and the appropriate rate relations of the system, the

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problem can be solved. The method of calculation is given in Appendix II.

This analysis, which was done for vent valves having a Cv of 0.07 and of 0.3, shows that the D_2 concentration during a vent is always less than the lower explosive limit of 2% in the steam, D_2 and O_2 mixture. This is shown in Figure 2.

These curves indicate that no delay is needed before initiating the vent. This is certainly true for the situation having the long venting time (valve Cv = 0.07). For the short venting time (valve Cv = 0.3), though the analysis yields very low D_2 concentration in the escaping vapor, the D_2 concentration in the reactor solution is still quite high when D_2O saturation pressures are approached. For this situation it seemed possible, due to the rapid decrease of total pressure and the relatively slower D_2 recombination rate, that the reactor solution could become saturated with D_2 . This could lead to a mass ebullition of D_2 from the system and possibly causing the D_2 concentration to rise suddenly above the lower explosive limit.

This situation was investigated by determining the saturation concentration of D_2 in the reactor solution as a function of pressure and time after initiating the vent. These results are shown in Figures (3) and (4).

It is seen that for the valve having the Cv of 0.07 the saturation concentration of D_2 is always much greater than the reactor concentration. Thus mass ebullition would not be a problem. For the valve having a Cv of 0.3 mass ebullition could be a problem since the saturation concentration of D_2 quickly drops below the expected reactor con-

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centration if no delay is used. If a two minute delay before venting is used the reactor concentration of D_2 has dropped sufficiently so that no danger of mass ebullition would exist.

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Fig. 2. % D_2 in Vent Gas Stream vs. Time After Closure of Steam Removal Valve in Steam Generator (No Delay)

Fig. 6. Pressurizer Pressure During Vent Period; Value $C_V = 0.3$; Value in One-Half Open Position

Fig. 4. Mol Fraction D_2 in Reactor vs. Time After Starting Vent
(Value $C_V = 0.3$)

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APPENDIX I

The concentration of D_2 in the gas phase is approximated by a trial and error procedure using the previously mentioned assumptions, enthalpy and mass balances, equilibrium relations, and the rate equations. The method used is similar to that given in CF 56-3-17⁽⁴⁾.

The calculation must be done in incremental steps of time, the smaller the increment the more accurate the calculation. As such let a subscript n refer to the n_{th} incremental step and $n + 1$ to the $(n + 1)_{th}$ incremental step.

Thus we find that the total heat content of the system at any time is given by

$$H_n = ML_{T_n} h_{L_n} + W_{s_n} h_{s_n} + N_{g_n} C_{P_n} (T_n - 492) \quad (1)$$

where H = Total heat content of system, Btu

L_T = lb mols liquid in high pressure system (Assumed D_2O)

M = molecular weight of liquid

W_s = weight of D_2O vapor in pressurizer, lbs.

N_g = total number of lb mols of gas present, liquid and gas phases

h_L = enthalpy of liquid, Btu/lb

h_s = enthalpy of vapor, Btu/lb

C_{P_n} = mean heat capacity of gases, Btu/lb mol $^{\circ}R$

T = temperature, $^{\circ}R$

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During any incremental step some D_2O liquid is flashed to vapor, this may be estimated by:

$$MS_n = \frac{H_n - M L_{T_n} h_{L_{n+1}} - W_{S_n} h_{S_{n+1}} - N_{G_n} C_{p_m} (T_{n+1} - 492)}{h_{fg_{n+1}}} \quad (2)$$

S_n = lb mol D_2O flashed

M = molecular weight of D_2O , 20 lb/lb mol

h_{fg} = heat of vaporization of D_2O , Btu/lb

For any incremental step mass balances for liquid and gas phases may be written:

Liquid Phase:

$$L_{T_{n+1}} y_{n+1} = L_{T_n} y_n (t) - X_n \quad (3)$$

y = mol fraction D_2 in liquid, lb mol D_2 /lb mol solution.

X_n = lb mols of D_2 stripped to gas phase in the increment.

Gas Phase:

$$Z'_{n+1} = Z_n + X_n \quad (4)$$

Z = lb mols D_2 in gas phase.

Now by Henry's law

$$P_{nD_2} = B_n y_n \quad (5)$$

P = partial pressure of D_2

B_n = Henry's law constant, psi/mol fraction⁽⁵⁾.

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the gas laws give then:

$$Z_n = \frac{B_n y_n V_{g_n}}{Z R T_n} \quad (6)$$

where V_g = Volume of gas space in the pressurizer, ft^3
 R = universal gas constant, $10.73 \text{ psi-ft}^3/\text{lb mol-}^\circ\text{R}$
 Z = non-ideality gas correction
 T = gas temperature, $^\circ\text{R}$.

The volume of the gas space in the pressurizer at any time is given by:

$$V_{g_n} = V_{g_o} + V_p \left(1 - \frac{L_{p_n}}{L_{p_o}}\right) \quad (7)$$

V_p = volume of pressurizer piping originally filled with soup, ft^3

L_p = lb mols of soup in pressurizer piping

Similarly

$$Z'_{n+1} = \frac{B_{n+1} y_{n+1} V'_{g_{n+1}}}{Z R T_{n+1}}$$

where

$$V'_{g_{n+1}} = \frac{P_n V_{g_n} T_{n+1} n_{n+1}}{n_n T_n P_{n+1}} \quad (8)$$

$$P = \text{total pressure in system} = 2000 e^{-1.67 \times 10^{-3} t} \quad (9)$$

n = total lb mols in gas phase

$$n_{n+1} = n_n + S_n + 1.59 X_n \quad (10)$$

$1.59 X_n$ = approximately the number of lb mols of D_2 and O_2 stripped in n -th increment

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Thus we see that the gas phase balance can be represented by:

$$\frac{B_{n+1} y_{n+1} V'_{g_{n+1}}}{Z R T_{n+1}} = \frac{B_n y_n V_{g_n}}{Z R T_n} + X_n \quad (11)$$

Now using the D_2 recombination rate equation we see that $y_n(t)$ may be represented by:

$$y_n(t) = \left[y_n + \int_0^{\Delta t_n} v(t) e^{k_{Cu} ct} dt \right] e^{-k_{Cu} c \Delta t_n} \quad (12)$$

where $\Delta t_n = n_{th}$ increment of time, sec

Since $v(t)$ cannot be represented analytically the equation must be graphically integrated for each increment of time.

Substituting equations (3), (8), and (10) into equation (11) and solving for X_n gives:

$$X_n = \frac{-C + \sqrt{C^2 + 4D}}{2} \quad (13)$$

$$C = \frac{1}{1.59} \left[n_n + S_n + \frac{L_{T_{n+1}} Z R T_n P_{n+1}}{B_{n+1} P_n V_{g_n}} - 1.59 L_{T_n} y_n(t) \right] \quad (14)$$

$$D = \left\{ \frac{L_{T_n} y_n(t) (n_n + S_n)}{1.59} - \left[\frac{B_n y_n V_{g_n}}{Z R T_n} \right] \frac{L_{T_{n+1}} Z R T_n P_{n+1}}{1.59 B_{n+1} P_n V_g} \right\} \quad (15)$$

$$D = \left[\frac{L_{T_n} y_n(t) (n_n + S_n)}{1.59} \right] \quad \text{for increment (1) only, since} \quad (15-A)$$

it is assumed that originally no D_2 is in the vapor space).

Thus using equations (1), (2), (12), (13), (14), (15) the system can be balanced for a given increment by:

(1) Calculating the total enthalpy of the system using equation (1) evaluated at the temperature of the system. (280°C initially).

(2) Choose a small increment of time and calculate P_{n+1} and $y_n(t)$ using equations (9) and (12).

(3) Evaluate S_n by assuming a partial pressure of D_2O for the first increment.

(4) Using this value of S_n , X_n may be evaluated using equations (13), (14), and (15).

(5) Check the assumed partial pressure of D_2O using the following equation:

$$\left[\frac{P_{nD_2O} V_{g_n}}{Z R T_n} + S_n \right] \left[\frac{P_{n+1}}{n_n + S_n + 1.59 X_n} \right] = P_{n+1D_2O} \quad (16)$$

If it does not check start again at (3) by assuming a better value for the partial pressure.

When a check is found calculate y_{n+1} , $V_{g_{n+1}}$, $V'_{g_{n+1}}$. Using these it is possible to calculate the quantities for the next increment since:

$$n_{n+1} = (n_n + S_n + 1.59 X_n) \frac{V_{g_{n+1}}}{V'_{g_{n+1}}}$$

$$Z_{n+1} = Z'_{n+1} \frac{V_{g_{n+1}}}{V'_{g_{n+1}}}$$

$$L_{T_{n+1}} = L_{T_n} - S_n$$

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APPENDIX II

For the solution of the second case the same general method is used, but some additional assumptions must be imposed. These will be stated as they are needed.

The total heat content of the system and the stripping equation are expressed as in the first case. Thus:

$$H_n = M L_{Tn} h_{L_n} + W_{Sn} h_{Sn} + N_{gn} C_{pm} (T_n - 492)$$

$$MS_n = \frac{H_n - M L_{Tn} h_{L_{n+1}} - W_{Sn} h_{Sn+1} - N_{gn} C_{pm} (t_{n+1} - 492)}{h_{fgn+1}}$$

The D_2 balance in the liquid now becomes:

$$L_{Rn+1} y_{Rn+1} + L_{pn+1} = L_{Rn} y_{Rn} + L_{pn} y_n(t) - X_n \quad (17)$$

L_R = lb mols liquid in core system, excluding pressurizer

L_p = lb mols liquid expected to be in connecting piping
between pressurizer and flowing system

y_R = mol fraction D_2 in flowing system

y = Avg mol fraction D_2 in pressurizer piping

X_n = mols D_2 stripped in increment

It must now be assumed that during each equilibrium step only D_2 in the pressurizer piping is affected, and that compressibility of the liquid is negligible.

$$\text{Thus: } L_{Rn+1} y_{Rn+1} = L_{Rn} y_{Rn} \quad (18)$$

and the D_2 balance in the liquid becomes:

$$L_{pn+1} y_{n+1} = L_{pn} y_n(t) - X_n \quad (19)$$

The D_2 balance in the gas phase is as before

$$Z_{n+1} = Z_n + X_n \quad (20)$$

All quantities are defined as in Case I with the single exception of $y_n(t)$. Thus the solution has the same form as before:

$$X_n = \frac{-C + \sqrt{C^2 + 4D}}{2} \quad (21)$$

$$C = \frac{1}{1.59} \left[n_n + S_n + \frac{L_{pn+1} Z R T_n n_n P_{n+1}}{B_{n+1} P_n V_{gn}} - 1.59 L_{pn} y_n(t) \right] \quad (22)$$

$$D = \frac{L_{pn} y_n(t) (n_n + S_n)}{1.59} - \left[\frac{B_n y_n V_{gn}}{Z R T_n} \right] \frac{L_{pn+1} Z R T_n P_{n+1}}{1.59 B_{n+1} P_n V_{gn}} \quad (23)$$

$$(D = \left[\frac{L_{pn} y_n(t) (n_n + S_n)}{1.59} \right] \text{ for increment (1) only since} \quad (23-A)$$

it is assumed that originally no D_2 is in the vapor space.)

To estimate $y_n(t)$ the following assumptions must be made:

- (1) D_2 concentration in the pressurizer leg is the sum of that due to fission product decay energy and that due to the source plane at the entrance to the pressurizer leg.
- (2) D_2 from the source plane rises at a rate of 2 cm/sec and is simultaneously attenuated by the internal recombination.
- (3) The pressurizer leg is assumed vertical with a total length equal to the sum of the horizontal and vertical sections as installed on the HRT. That portion which is assumed full of liquid is the entire horizontal section (approx. 4.3 ft) and 20 inches of the vertical section.

Thus:

$$y_n(t) = \overline{y_{f.p.n}(t)} + \overline{y_{Ln}(t)} \quad (24)$$

where

$y_{f.p.n}(t)$ = Avg. mol fraction D_2 generated by
fission product decay in pressurizer
leg

$\overline{y_{L_n}}(t) =$ Avg mol fraction D_2 in pressurizer leg due to reactor source

Since D_2 generation by fission product decay is essentially constant throughout pressurizer.

$$\overline{y_{f.p.n}}(t) = y_{f.p.n}(t) = \left[y_{f.p.n-1} + \int_0^{\Delta t_n} v(t) e^{k_{Cu} ct} dt \right] e^{-k_{Cu} c \Delta t_n}$$

for which assuming small increments of time $v(t) = \text{constant}$

$$\overline{y_{f.p.n}}(t) = \left[y_{f.p.n-1} + \frac{v(t)(e^{k_{Cu} c \Delta t_n} - 1)}{k_{Cu} c} \right] e^{-k_{Cu} c \Delta t_n} \quad (25)$$

Since $y_{L_n}(t)$ is attenuated as it goes up the pressurizer by the equation:

$$y_{L_n}(J) = y_{L_n}(0) e^{-k_{Cu} c \frac{J}{2}}$$

where $J = \text{height of soup filled pressurizer leg}$

it can be averaged over the pressurizer leg by

$$\overline{y_{L_n}}(t) = \frac{y_{L_n}(0)}{t_n} \int_0^{\Delta t} e^{-k_{Cu} ct} dt$$

$$\overline{y_{L_n}}(t) = \frac{y_{L_n}(0)}{t_n} \left(\frac{1 - e^{-k_{Cu} c \Delta t}}{k_{Cu} c} \right) \quad (26)$$

where $t_n =$ is the time in seconds required for the D_2 to move from the entrance to the pressurizer leg through the head of liquid above it.

$$t_n = \frac{90.9 L_{P_n}}{L_{P_o}} \quad (27)$$

Using these equations $y_n(t)$ can be evaluated and the problem solved for this case as outlined in Case I.

APPENDIX III

Venting Time Calculations of HRT Pressurizer Using Vent Valves with C_v of 0.3

The present vent valves on the HRT have a C_v of 0.07. Flow rates through these valves have been determined experimentally⁽⁸⁾, and flow rates through the proposed valves are assumed to be $0.3/0.07$ times those of the present valves. Figure 5 shows these values for the proposed vent valves at the full open and half open position.

The initial conditions in each pressurizer are as follows^(9,10):

Pressure	2000 psia
Steam volume	74.1 liters = 2.615 ft ³
Liquid volume	12.4 + 20.9 = 33.3 liters = 1.175 ft ³
Total volume	3.790 ft ³
Steam mass	$2.615/0.1878 = 13.92$ lb
Liquid mass	$1.175/0.0257 = 45.71$ lb
Total mass	59.63 lb
Steam enthalpy	$13.92 \times 1135.1 = 15,800$ Btu
Liquid enthalpy	$45.71 \times 671.7 = 30,700$ Btu
Total enthalpy	46,500 Btu

The pressurizer heaters are turned off during the venting period of the HRT dumping operation⁽⁷⁾. Heat losses are assumed to be constant at a rate 6.6 kw or 375.5 Btu/min.⁽⁹⁾

Equations can be written for determining the pressure in the pressurizers with respect to time. The presence of steam and water in the connecting piping are neglected for equations. These equations are:

Mass balance

$$m_L + m_S = 59.63 - m_V$$

where m_L = mass of liquid in pressurizer, lbs
 m_S = mass of steam in pressurizer, lbs.
 m_V = mass vented from pressurizer, lbs

Volume balance

$$m_L v_L + m_S v_S = 3.790$$

where v_L = specific volume of liquid in pressurizer, cu.ft/lb
 v_S = specific volume of steam in pressurizer, cu.ft/lb

Energy balance

$$m_L h_L + m_S h_S = 46,500 - H_V - Q_{loss}$$

where h_L = enthalpy of liquid in pressurizer, Btu/lb
 h_S = enthalpy of steam in pressurizer, Btu/lb
 H_V = total energy removed through vent valve, Btu
 Q_{loss} = heat loss from pressurizer, Btu

The valve is assumed to be at the 1/2 open position for these calculations. Total energy removed through the vent valve is determined by the sum of finite increments. Results of the solutions of these equations are shown in Figure 6. It can be seen that approximately 2-1/3 minutes are required to lower the pressure to the HRT saturation pressure, 933 psia.

Fig. 3. Mol Fraction D_2 in Reactor vs. Time After Starting Vent
(Value $C_V = 0.06$)

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Fig. 5. Flow Rate Through Vent Value with $C_v = 0.30$

NOMENCLATURE

- A = Heat transfer area of heat exchanger
 α = Constant relating inlet, exit, and mean core temperatures
 B = Henry's law constant, psia/mol fraction
 C = function defined by either equation (14) or equation (22).
 C_p = Specific heat of fuel solution, Btu/lb $^{\circ}\text{F}$
 C_b = Heat capacity of heat exchanger tubes and steam water system on shell side
 C_{pm} = Mean heat capacity of gases, Btu/lb mol $^{\circ}\text{R}$
 c = Cu^{++} concentration, gr mols/liter
 D = Function defined by any one of equations (15), (15-A), (23), or (23-A) depending on conditions
 $E(t)$ = Energy absorption rate, Kw
 G = Yield D_2 , molecules $\text{D}_2/100$ ev absorbed
 H = Total heat content of system, Btu
 H = Total energy removed through vent valve, Btu
 h = Enthalpy, Btu/lb, h_L = enthalpy of liquid, h_s = enthalpy of steam, h_{fg} = heat of vaporization
 J = Height of soup filled pressurizer leg, cm
 k_{Cu} = Reaction rate constant, liters/gr mol Cu^{++} -sec (5.8 at 280°C)
 L_T = lb mols liquid in primary core system, L_R = lb mols liquid in primary core system excluding pressurizer leg, L_p = lb mols liquid expected in pressurizer leg (Assumed D_2O) ($L_T = L_R + L_p$)
 M = Molecular weight of liquid, assumed D_2O
 m = Mass, lbs
 N_g = Total lb mols of gas present, liquid plus gas phases
 n = Total lb mols in gas phase

- p = Partial pressure, psia
 P = Total pressure, psia
 Q = Reactor power, Kw
 Q_{loss} = Heat loss from pressurizer, Btu
 R = Universal gas constant, $10.73 \text{ psi-ft}^3/\text{lb mol-}^\circ\text{R}$
 S_n = lb mol of D_2O flashed in increment n .
 T = Temperature, $^\circ\text{R}$
 t = time, in appropriate units
 U = Overall heat transfer coefficient in heat exchanger based on area A
 V = Volume, ft^3 ; V_g = Volumes of gas space in the pressurizer; V_p
 = Volume of pressurizer leg containing soup; V_g' = Assumed gas
 volume of pressurizer in free expansion from P_n to P_{n+1}
 v = Specific volume, ft^3/lb
 $v(t)$ = Generation rate of D_2 in fuel solution lb mol $\text{D}_2/\text{lb mol solution-sec}$
 W = Mass flow rate, lb/hr
 W_s = Weight of D_2O vapor in pressurizer, lb
 X = lb mol D_2 stripped to gas phase per equilibrium step
 y = Mol fraction D_2 in solution, lb mol $\text{D}_2/\text{lb mol solution}$
 Z_n = lb mol D_2 in gas phase, $Z_n' = \text{lb mol } \text{D}_2 \text{ in } V_{gn}'$
 Z = non ideality gas correction

Subscripts

- $f.p.$ = fission product
 L = core solution
 m or --- = mean or average value
 n = n -th increment of time

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22.

n+1 = (n+1) -th increment of time
O = initial value at time steam valve was closed
p = pressurizer
R = Primary system, excluding pressurizer
s = D₂O vapor
T = Entire primary core liquid system
v = vented material

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