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COOLANT WATER TRANSIENT IN K REACTOR FOLLOWING LINE RUPTURE

by

J. A. Roberson and S. S. Jones

August 27, 1958

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COOLANT WATER TRANSIENTS IN K REACTOR FOLLOWING LINE RUPTURE

INTRODUCTION

This investigation is the second study of short period flow decay in the Hanford reactors. The first study was made on the D-Reactor.⁽¹⁾ As in the analysis for D-Reactor quantitative analyses were made for ruptures that might result from sabotage. A visual inspection of the entire process water piping system was also made to check for any glaring deficiencies with respect to earthquake resistance. A brief discussion of the earthquake resistance of the system is also included in this report.

SUMMARY AND CONCLUSIONS

Cursory analyses and observations reveal that the process water piping should be checked in more detail by specialists in the field of vibrations to determine the resistance of the piping to possible earthquake vibrations. Some of the K-Reactor piping is quite flexibly supported so that frequencies resonant with probable earthquake frequencies appear to be a possibility.

Rather detailed analyses were made to determine flow decay curves resulting from various assumed ruptures of the piping system. The location of ruptures were chosen according to the susceptibility of the system to sabotage. Figure 1 is a summary of the flow decay curves obtained from the analyses. It may be noted that with only two pipes ruptured (curves 3 and 4) the flow is maintained at a much higher rate than if four pipes are ruptured (curves 1 and 2). It was observed that the possibility of sabotage could be materially reduced if the coolant water system were physically separated more completely than now exists. This could be accomplished by constructing a reinforced concrete wall between each half of the system from the reactor face through the 165 Building. Further security could be accomplished if the 165 Building pipe gallery, pipe tunnels, and 105 Building pipe gallery which are critical areas could be kept locked and controlled by an adequate key system.

It is also noted (curve 3 vs. curve 4) that the FB-5 valve creates considerable loss of integrity in the piping system when it is open or when it is considered as a point of sabotage. As an integral part of the piping isolation this valve and line would be considerably reduced in size.

DISCUSSION

1. Earthquake Study

A visual inspection of the process water piping system between the main pump house and the reactor face revealed that the piping is supported in a more flexible manner than for the D-Reactor. In the K-Reactor the piping over most of the distance is supported either by suspension from

(1) "Coolant Water Transients In D-Reactor Following Line Rupture," HW-57298, J. A. Roberson and S. S. Jones, dated August 27, 1958. ()

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SUMMARY OF FLOW DECAY CURVES AT K REACTOR (INITIAL FLOW = 160,000 GPM)

vertical rods or by bearing on pedestal type supports. The only longitudinal restraint occurs at the main pumps and near the reactor face except for frictional resistance at the pedestal supports. A cursory analysis revealed that resonance vibration might be possible for the 24" diameter piping in the 165-K Building. In view of these observations it is suggested that specialists in the field of vibrations be assigned to study this problem. Driving frequencies to be used in a study such as this may be found in a report by Neuman.⁽²⁾

It should be noted that even if the piping is found to be susceptible to earthquake rupture it is improbable that ruptures would occur before the safety rods are dropped since several seconds of forced vibration would probably be needed to cause a failure in the piping. Furthermore, it is felt that if ruptures did occur they would only be partial ruptures and would not cause complete loss of pressure, therefore, it appears that an earthquake of the intensity that might be expected in the Richland area would probably not produce disastrous effects so far as direct rupture of the piping is concerned. As in the study of D-Reactor it is felt that the high stacks should be checked to determine their susceptibility to earthquakes. Again, it may be noted that the safety rods would probably be tripped before a falling structure, such as the stack, would hit any part of the coolant system.

2. Sabotage Considerations

The vulnerable locations for sabotage were assumed to be, (1) 36" pipe in the tunnel between 165-K Building and 105-K Building and, (2) the 24" high pressure cross-tie near the point where it joins the 36" pipes. These locations are shown in Figure 2. Discussions associated with each location are given below under separate headings.

A. Failure of Four 36-Inch Pipes in the Tunnel Between 165-K and 105-K Buildings

This was chosen as a critical location for the following reasons:

- (1) The pipes are fairly concentrated in the tunnels and probably only two explosions would be required to rupture the four pipes. Although there are two tunnels (one for two pipes), they are adjacent to each other and there is easy access from one tunnel to the other at several points.
- (2) Ruptures of all four lines would cause the flow to cease in the reactor until the V-73 valve in the high pressure cross-tie line is opened.
- (3) The tunnel area is normally void of personnel.

(2) GEH-18,039, "The Earthquake Problem in the Richland, Washington Area," by F. Neuman, January, 1951 ().

FIGURE 2

LOCATION OF VULNERABLE AREAS FOR SABOTAGE OF THE COOLANT WATER SUPPLY

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The sequence of events following rupture and the assumptions associated with the analysis are given below:

- (1) It is assumed that all four pipes are ruptured by explosive means and that the pressure instantaneously drops to 0 psig at the point of rupture.
- (2) The assisting reactor will start to feed the near reactor in about ten seconds (time allowed for operation of V-73 valve).
- (3) Phase change (from water to steam) in the reactor was not considered. In other words zero temperature change of water with time is assumed. This is also assumed for all other analyses. Because of the uncertainty of the flow decay curves under boiling conditions the regions of probable boiling have been shown (Figs. 1 & 3) by a cross-hatched area to point out the uncertainty.

Analysis

The following general equation must be solved to determine the flow decay curve:

$$\Delta p - \sum k p Q^n = \frac{\Delta Q}{\Delta t} \sum \frac{L}{A} \quad (2)$$

The derivation of this equation is included in the report for D-Reactor. (3)
The solution for the case of ruptures in four 36" line results in the curve 1 shown in Figure 3.

The next analysis was made for the conditions stated above except that the area of rupture was reduced. The area of rupture was taken as that area which would produce a zero pressure differential between the front face and rear face of the reactor when steady flow conditions prevail after rupture. This was found to be 32% of total cross sectional area of 36" pipe. The solution of the unsteady flow equations for these conditions resulted in curve 2 of Figure 3. It may be noted that the times of curve 2 will actually be slightly shorter than those shown especially for the first part of the period because at this time the reactor will be demanding more flow and the rupture will be discharging less flow thereby producing less pressure at the ruptured section until steady flow conditions prevail. As may be noted by the similarity of the two curves in the small time region the approximation is undoubtedly good.

B. Failure of Two 36-Inch Pipes in the Tunnel Between 165-K and 105-K Buildings

The assumptions for this case were the same as for the rupture of four pipes with the exception that the analysis was run with the FB-5 valve closed in the flow balance line. For the unsteady case with the FB-5 valve open there were more than twenty equations to solve simultaneously. Due to this complication, the decay curve was only estimated; however,

(3) Op. cit. reference 1.

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it is felt that the estimate is good since this curve would fall between the curve for rupture of four pipes and the curve for rupture of two pipes FB-5 valve closed. The sequence of events associated with the analysis with FB-5 valve closed is described below:

Sequence of Events

- (1) Rupture occurs and pressure drops to zero at the rupture.
- (2) Flow in the reactor and ruptured line will decelerate while the flow in the intake lines will accelerate.

Figure 4 is a sketch of the piping system showing definition of the symbols to be used in the analysis.

FIGURE 4

The solution of the case with FB-5 valve closed is shown by curve 1 in Figure 5. The estimated curve with the FB-5 valve open is given by curve 2 of Figure 5.

C. Effect of High Pressure Cross-Tie

The cases above have considered the flow through the near reactor without assistance from the far reactor through the 24-inch high pressure cross-tie pipe. The valving mechanism on the cross-tie operates automatically so that assisting flow will begin several seconds after pressure is lost in the near riser. The valves should be completely open, and equilibrium conditions, with respect to flow

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in the cross-tie should prevail after a period of about ten seconds. The dotted curves from $t = 1.0$ second to $t = 10$ seconds in Figures 3 and 5 show the effect of the assisting flow. It may be noted that the steady state flow at $t = 10$ seconds is based upon calculation whereas the transition curve is only "sketched in." The computations for steady-state conditions through the cross-tie show that with ruptures in all four supply lines of near reactor the cross-tie will supply a flow of 41,300 gpm, or 26% of the initial flow. When considering the assist from the far reactor with ruptures in two 36" pipes of the near reactor and FB-5 valve closed the final flow in the near reactor was found to be 121,000 gpm or 76% of the initial flow. With the FB-5 valve open the final flow was found to be equal to 100,000 gpm or 62.5% of initial flow.

D. Failure of 24-Inch Cross-Tie Near Point Where Cross-Tie Joins Piping of Near Reactor

In working out the solution for this case it was assumed that the rupture area was 50% of the cross sectional area of the pipe. The result of the solution is shown in graphical form in Figure 6.

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APPENDIX I

1. Nomenclature

- A - Cross sectional area of flow passage in ft.^2
- a - Acceleration in ft/sec^2
- D - Diameter in ft.
- F - Force in lbs.
- f - Dimensionless friction factor
- h_p - Dynamic head of pump in ft. of water
- L - Length in ft.
- p - Pressure in $\text{lbs}/\text{in.}^2$ or $\text{lbs}/\text{ft.}^2$
- p_p - Pressure downstream of pump
- Δp_f - Change in pressure due to friction
- Q - Flow discharge in $\text{ft}^3/\text{sec.}$
- Δt - Increment of time in seconds
- Torp - Top of riser pressure - psig
- V - Velocity in $\text{ft}/\text{sec.}$
- Z - Elevation in ft.
- γ - Specific weight of fluid in $\text{lbs}/\text{ft.}^3$
- ρ - Mass density = $\frac{\gamma}{g}$ in $\frac{\text{lb}/\text{sec}^2}{\text{ft}^4}$
- G - Flow in gals. minute

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2. Detailed Flow Analyses

A. Flow Computations for Failure (100%) of Four 36-Inch Pipes in the Tunnel Between 165-K and 105-K Buildings

The following general equation must be solved to determine the flow decay curve:

$$\Delta p - \sum K \rho Q^n = \rho \frac{\Delta Q}{\Delta t} \sum \frac{L}{A}$$

For this case of failure of the four 36-inch pipes Δp is approximately equal to -4180 psi due to the back pressure from the rear face. The friction loss in the pipes leading to the reactor was found to be negligible so the friction loss term, friction loss through process tubes, is given by

$$\sum K \rho Q^n = 1.43 Q^{1.8}$$

where Q = discharge in cfs

$\sum K \rho Q^n$ = pressure loss due to friction in psf

The above pressure loss equation was obtained from Hess. ⁽⁴⁾

The $\sum \frac{L}{A}$ term is evaluated in Table 1 where the areas are associated with the total flow through the reactor.

(4) HW-49651, "Reactor Flow Capabilities," K. W. Hess, April 17, 1957.

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TABLE 1

Evaluation of $\Sigma \frac{L}{A}$

<u>Description of Conduit</u>	<u>D ft.</u>	<u>A sq. ft.</u>	<u>No.</u>	<u>Total A</u>	<u>L</u>	<u>L/A</u>
36" pipe from rupture to crossheader - assume rupture is at opening between tunnels	2.8	6.15	4	24.6	170	6.92
Piping from crossheader to pigtail						
5" pipe	0.400	.125	118	14.76	25	1.70
4" pipe	0.335	.0088	118	10.40	10	0.96
Front Pigtail	0.073	.00415	2960	12.3	1.7	0.14
Process Tube:						
Active		.00371	2960	11.0	28.2	2.56
Dummies		.0091	2960	26.9	8.8	0.33
Rear Pigtail		.00415	2960	12.3	1.7	0.14
Pigtail to Riser						
4"		.088	118	10.40	13'	1.25
5"		.125	118	14.76	4'	<u>0.27</u>
						$\Sigma \frac{L}{A} = 14.27$

Using the terms evaluated above, the following equation results:

$$-4180 - 1.43Q^{1.80} = 27.5 \frac{\Delta Q}{\Delta t}$$

Realizing that ΔQ will be negative the above may be rearranged to give:

$$\Delta t = \frac{19.2 \Delta Q}{2920 + Q^{1.80}} \quad (1)$$

Equation 1 was solved by a step method and the results are shown graphically by curve 1 in Figure 3 in the body of this report.

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B. Flow Computations for Failure of Four 36-Inch Pipes in the Tunnel Between 165-K and 105-K Buildings with Reduced Area of Rupture Such That Zero Pressure Differential Exists Between the Front Face and Rear Face of the Reactor When Steady Flow Conditions Prevail After the Rupture

With this qualification on size of rupture the pressure at the bottom of the front face of the reactor and also upstream from the rupture would be approximately 29 psig. Then the discharge from the ruptured section would be given by:

$$Q = C_D A \sqrt{\frac{2 \Delta P}{\rho}}$$

where Q = flow from ruptures in cfs = 435 cfs.

C_D = coefficient of discharge - assume $C_D = 0.85$

A = rupture areas in sq. ft.

p = pressure difference across rupture in psf.

ρ = mass density = 1.94 slugs/cu. ft.

$$\text{then } 435 = 0.85 \times A \sqrt{\frac{2}{1.94} \times 29 \times 144}$$

Solving the above it was found that the area of rupture cross section is 32% of the total cross sectional area of the 36" pipes. Now Equation 1 will have the following form:

$$\Delta t = - \frac{19.2 \Delta Q}{Q^{1.80}}$$

or in differential form

$$dt = -19.2 Q^{-1.8} dQ$$

Then
$$t = - \int_{Q_0}^Q 19.2 Q^{-1.8} dQ$$

$$t = \left[\frac{24}{Q^{0.8}} \right]_{Q_0}^Q$$

$$t = 24 \left(\frac{1}{Q^{0.8}} - \frac{1}{Q_0^{0.8}} \right)$$

When $Q_o = 356$ cfs

$$t = \frac{24}{Q^{0.8}} - \frac{24}{110}$$

$$t = \frac{24}{Q^{0.8}} - 0.219$$

The solution of equation 2 is curve 2 of Figure 3.

C. Flow Analysis With Failure of Two 36-Inch Pipes in the Tunnel Between 165-K and 105-K Buildings (FB-5 valve closed)

By referring to Figure 4 in the body of this report it may be seen that the following general equations must be solved simultaneously.

$$P_F - P_o + K' \rho Q'^n = \rho \frac{\Delta Q'}{\Delta t} \Sigma \frac{L}{A} \quad (3)$$

$$P_{L_4} - P_F - KQ Q_{L_4}^n = \rho \frac{\Delta (Q_{L_4})}{\Delta t} \Sigma \frac{L}{A} \quad (4)$$

$$P_R - P_F + KQ Q_T^n = \rho \frac{\Delta Q_T}{\Delta t} \Sigma \frac{L}{A} \quad (5)$$

$$Q_T = Q' + Q_{L_4} + Q_5 + Q_6 \quad (6)$$

$$= Q' + 3Q_{L_4} \text{ since } Q_{L_4} = Q_5 = Q_6$$

$$\frac{dQ_T}{dt} = \frac{dQ'}{dt} + \frac{d(3Q_{L_4})}{dt} \quad (7)$$

Evaluation of the various constants for the above equations is made below.

In equation 3 it is assumed that p_o is equal to 0 psig. The pressure loss term is evaluated more precisely than was done for the case of four pipe ruptures. The pressure loss coefficient was evaluated analytically using "f" (Darcy-Weisbach friction factor) values of .012 for 36" pipe, .018 for 4 inch and 5 inch pipe. A loss coefficient of 0.15 was used for the elbows in the system. Then

$$\Delta P_f = \Sigma KQ \frac{V^2}{2} \quad \text{where } K (\text{pipes}) = \frac{fL}{D}$$

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$$\Delta p_f = \rho \frac{.012 \times 170 Q^2}{2 \times 2.8 \times (12.3)^2} + \rho \frac{3 \times .15}{(12.3)^2} Q^2 + \rho \frac{.018 \times 25 Q^2}{2 \times 0.4 \times (7.38)^2} + \rho \frac{.018 \times 10 Q^2}{2 \times .335 \times (5.2)^2} + \frac{6 \times .15 \rho Q^2}{2 \times (7.38)^2}$$

$$\Delta p_f = 1.94 \times .1088 Q^2$$

$$\Delta p_f = 0.211 Q^2$$

The $\Sigma \frac{L}{A}$ term is evaluated as $\Sigma \frac{L}{A} = \frac{170}{12.3} + \frac{25}{7.38} + \frac{10}{5.2} = 19.1$

$$\text{Then } p_f + 0.211 Q^2 = 37 \frac{\Delta Q}{\Delta t} \quad (8)$$

In considering evaluation for equation (4) attention is first directed to P_4 . This is the dynamic pressure at the main pump and is determined from the characteristic curve for the pumps as given in Figure 7. The pressure loss term was obtained from experimental data supplied by S. S. Jones. With a total flow of 356 cfs or single pump flow of 59.3 cfs the pressure loss was approximately 17 psi. Then,

$$17 \times 144 = K_Q Q_4^{1.8}$$

$$K_Q = \frac{17 \times 144}{(59.3)^{1.8}} = 1.63 \quad (9)$$

The $\Sigma \frac{L}{A}$ term is given in Table 2 below with all areas apportioned with respect to flow from one pump.

TABLE 2

Description of Pipe	<u>D</u>	<u>A</u>	<u>A_{eff}</u>	<u>L</u>	<u>L/A</u>
30"	2.44	4.07	4.07	116	28.5
24"	1.87	2.76	2.76	216	78.5
36"	2.80	6.15	4.12	355	86.0
5"	0.4	.125	2.46	25	10.2
4"	0.33	.088	1.73	10	<u>5.8</u>
					209.0

FIGURE 7
K REACTOR PUMP CHARACTERISTIC CURVE

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Then $P_h - P_F - 1.63 Q_h^{1.8} = 405 \frac{\Delta Q}{\Delta t}$ (10)

In equation (5) P_R is the pressure at the bottom of the rear face of the reactor and is equal to 3500 psf approximately. The pressure loss through the reactor is taken from a previous calculation and is equal to

$$\Delta P_F = 1.43 Q^{1.8}$$

The $\Sigma \frac{L}{A}$ term is equal to 4.90 ft^{-1} as determined from Table 1. Then

$$3500 + P_F + 1.43 Q_T^{1.8} = 9.50 \frac{\Delta Q_T}{\Delta t} \quad (11)$$

In summary, the following equations must be solved simultaneously:

$$P_F + 0.211 Q^2 = 37 \frac{\Delta Q}{\Delta t}$$

$$P_h - P_F - 1.63 Q_h^{1.8} = 405 \frac{\Delta Q}{\Delta t}$$

$$3500 - P_F + 1.43 Q_T^{1.8} = 9.50 \frac{\Delta Q}{\Delta t}$$

$$Q_T = Q' + 3 Q_h$$

$$\frac{dQ_T}{dt} = \frac{dQ'}{dt} + \frac{3dQ_h}{dt}$$

The solution of these equations results in the flow decay curve shown in Figure 5, curve 1.

D. Failure of 24-Inch Cross-Tie Near Point Where Cross-Tie Joins Piping of Near Reactor

The solution is similar to the case with ruptures in two pipes as computed previously. The necessary equations to solve are as given below:

$$P_h - P_F - 1.63 Q_h^{1.8} = 405 \frac{\Delta Q_h}{\Delta t}$$

$$P_F - 3500 - 1.43 Q_T^{1.8} = 9.50 \frac{\Delta Q_T}{\Delta t}$$

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$$Q_T = Q' - 3 Q_4$$

$$\frac{dQ_T}{dt} = \frac{dQ'}{dt} - \frac{3dQ_4}{dt}$$

$$Q_1 + Q_2 + Q_3 = Q_0 + Q'$$

$$P_F - P_0 + KQ'^2 = \rho \Sigma \frac{L}{A} \frac{\Delta Q'}{\Delta t}$$

The constants for the last equation are evaluated below. The pressure term p_0 is the pressure just upstream from the ruptured section and is related to Q_0 and the size of rupture. The general relationship is given as

$$Q_0 = C_D A_0 \sqrt{\frac{2 P_0}{\rho}}$$

where Q_0 = flow out of rupture in cfs

$$C_D = 0.85 \text{ (assumed)}$$

$$A_0 = 1.37 \text{ sq. ft. - 50\% area of cross-section}$$

$$\text{Then } Q_0 = 0.85 \times 1.37 \times 1.01 \sqrt{P_0}$$

$$P_0 = 0.85 Q_0^2$$

The friction loss term KQ'^2 is negligible so that is not evaluated. Data for $\Sigma \frac{L}{A}$ is picked from Table 1 and design drawings, $\Sigma \frac{L}{A}$ is equal to the following.

$$\Sigma \frac{L}{A} = \frac{50}{12.3} + \frac{25}{7.38} + \frac{10}{5.2} = 9.4$$

$$\text{Then } P_F - 0.85 Q_0^2 = 1.94 \times 9.4 \frac{\Delta Q}{\Delta t}$$

$$\text{but } Q_0 = Q_1 + Q_2 + Q_3 - Q'$$

In this case for a simplifying assumption it may be assumed that

$$Q_1 + Q_2 + Q_3 = 218 \text{ cfs}$$

$$\text{Then } P_F - 0.85 (218 - Q')^2 = 18.2 \frac{\Delta Q'}{\Delta t}$$

Solution of the above equations resulted in the curve shown in Figure 6.

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