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LOFT TECHNICAL REPORT LTR 1118-7

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LOFT CRDM VENT ORIFICES

S. W. Hills

THIS REVISION COMPLETELY SUPERSEDES ALL PREVIOUS ISSUES OF LTR 1118-7

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

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REMARKS: The orifice size specified and installed by drawing 208608, SWR's 51162 and 51163, and FCF-L-8306 is .088/.098 inch diameter.

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THERMAL ANALYSIS

LOFT CRDM VENT ORIFICES

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S. W. Hills

AUTHOR

S. W. Hills

CHECKED BY:

S. A. Atkinson

APPROVED BY:

R. P. Wallcut

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DISPOSITION OF RECOMMENDATIONS

The orifice size specified and installed by drawing 208608, SWR's 51162 and 51163, and FCF-L-8306 is .088/.098 inch diameter.

THIS REVISION COMPLETELY SUPERSEDES ALL PREVIOUS ISSUES OF LTR 1118-7.

SUMMARY

The original LTR 1118-7 presents an outline of the preliminary analysis which was performed in order to determine the size of the orifice needed to ensure that the CRA would not be ejected by a large pressure difference in the case of a vent line failure. This revision of the analysis includes any updates of the analysis plus more details of the analysis.

The results of the analysis remain the same. It is recommended that the orifice diameter be 3/32 inch. With this size orifice the air venting rate will be approximately 2 cubic feet per minute from each CRDM at 200 psig and 130°F.

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I. INTRODUCTION

The failure of a vent line on the LOFT control rod drive mechanism (CRDM) would result in the quick blowdown of the top of the CRDM with high pressure in the lower region. This large pressure drop across the lead screw could possibly eject the control rod assembly (CRA) from the reactor core. The rod ejection accident has been analyzed for the LOFT core but in this case a common mode failure may cause the loss of all four vent lines. Therefore, orifices must be installed in each CRDM pressure cap in order to ensure that the simultaneous failure of all four vent lines will not cause a quick pressure loss in the top of the CRDM's and subsequent ejection of all four CRA's.

II. METHOD OF ANALYSIS

1. FLOW THROUGH LEAD SCREW

In order to size the orifice for the CRDM vent opening, the flow through the CRDM must be calculated. Then the orifice can be sized such that the flow out the vent is less than or equal to the flow through the CRDM. In this manner, the pressure will be maintained in the top of the CRDM, causing a small enough pressure drop across the lead screw such that the CRA cannot be ejected.

Figure 1 shows a simplified diagram of the CRDM system. The lead screw can move up and down along its axis within the two bushings. The CRA is attached to the lower end of the lead screw (not shown in Figure 1) and rotation of the lead screw is prohibited by the spline shaft which slides in the top of the lead screw. As the lead screw is driven in or out to move the CRA, the water volume of the CRDM changes, necessitating water exchange between the CRDM and the reactor vessel. Therefore, flow paths are provided within the lead screw and through the bushings around the lead screw. A ball check valve is placed within the lead screw to prevent natural circulation from heating the upper CRDM during reactor operation.

The cross sectional area of the lead screw is 1.88 in^2 and the weight of the CRA is 200 pounds, therefore the pressure difference needed across the lead screw to lift the CRA is 106.5 psi. Because of the complicated flow geometry in this system, the following analysis can only be an approximation. Therefore, conservatism will be applied liberally and the allowable pressure drop across the lead screw will

be set to 50 psi. It is assumed that the maximum flow through the CRDM will be through the lead screw rather than through the bushings. If this assumption is incorrect, the following analysis will be conservative since the flow through the CRDM would then be greater than what is calculated. This would allow the pressure at the top of the CRDM to be higher resulting in a lower pressure drop across the lead screw.

The highest temperature and lowest pressure in the upper plenum during reactor operation can be no greater than 628°F or less than 2076 psia⁽¹⁾. With the maximum ΔP across the lead screw being 50 psia, the lowest possible pressure in the CRDM would be 2026 psia. It has been assumed, and agreed upon by engineers knowledgeable with the LOFT system, that the mass inventory and makeup system of the primary coolant system are adequate to maintain the system pressure in the case of a vent line leak. Therefore, there will be no two phase flow since the minimum pressure, 2026 psia, is considerably higher than the saturation pressure, 1892 psia.

The maximum flow through the orifice must not be greater than the flow through the lead screw that causes a ΔP of 50 psi across the lead screw. The diagram of Figure 1 shows the three pressure drops which were considered in calculating the flow through the lead screw. The pressure drop through the slots at the bottom of the lead screw was not considered because the flow area of the slots is significantly larger than the other flow areas in the lead screw. The flow area through the check valve seat is the smallest and this flow restriction was treated as if it was a square edged orifice. The flow restriction around the ball and weight was treated as a venturi since the inlet and outlet

would be well rounded. The pressure drop through the lead screw from the check valve to the end of the spline shaft was neglected because the velocity of the water through this large of a flow area would be quite small. The last flow restriction would be through the clearances and flow channels between the spline shaft and the spline bushing. This flow resistance was treated like an ordinary pipe flow with inlet and outlet losses.

The equations for the pressure drops described above are⁽²⁾:

$$Q = C_0 A_0 \sqrt{\frac{2g_c}{\rho} \left[\frac{P_1 - P_2}{1 - (A_0/A_1)^2} \right]} \quad (\text{square edged orifice}),$$

$$Q = C_v A_2 \sqrt{\frac{2g_c}{\rho} \left[\frac{P_2 - P_3}{1 - (A_2/A_1)^2} \right]} \quad (\text{venturi}),$$

$$P_3 - P_4 = \frac{\rho V_{OUT}^2}{2g_c} \left[\frac{fL}{D_h} + K_{IN} + K_{OUT} \right] \quad (\text{pipe flow and inlet, outlet losses), and}$$

$$V_{OUT} = \frac{Q}{A_{OUT}} \quad (\text{relationship of volumetric flow rate to velocity}).$$

P_1 is the reactor pressure and $P_1 - P_4$ is the pressure difference across the lead screw. The flow through the lead screw depends on the pressure difference, $P_1 - P_4$, rather than the absolute pressure of P_1 . However, the flow through the vent orifice will be a function of P_1 since it is venting to the atmosphere. Therefore, P_1 will be set to the high reactor pressure of 2440 psia in order to have a conservative calculation for the orifice diameter. Since the pressure difference across the lead screw is limited to 50 psi, $P_1 - P_4 = 50$, which results in $P_4 = 2390$ psia.

The above equations will be solved with an HP-25 programmable calculator by iterating on the value of Q. A more useful form of the equations is:

$$P_3 = \frac{\rho Q^2}{2g_c A_{OUT}^2} \left[\frac{fL}{D_h} + K_{IN} + K_{OUT} \right] + P_4,$$

$$P_2 = \frac{\rho Q^2}{2g_c A_2^2 C_v^2} \left[1 - \left(\frac{A_2}{A_1} \right)^2 \right] + P_3, \text{ and}$$

$$Q = C_0 A_0 \sqrt{\frac{2g_c}{\rho} \left[\frac{P_1 - P_2}{1 - (A_0/A_1)^2} \right]},$$

with the unknown parameters being P_2 , P_3 , and Q. The preliminary analysis⁽³⁾ showed that the orifice size was not affected by the value of density which was assumed for the analysis. Therefore, the density of water at 150°F and 2200 psia will be held constant for this analysis, $\rho = 61.61 \text{ lbm/ft}^3$. Assuming that the Reynolds number is $Re = 5 \times 10^5$;

the orifice loss coefficient is $C_0 = 0.607$,

the venturi loss coefficient is $C_v = 0.962$, and

the friction factor is $f = .019$ for $e/D_h = 0.0007$.

All the areas used in the equations are given by Figure 1. The hydraulic diameter of the spline shaft flow channel is

$$D_h = \frac{4A}{P} = \frac{4(.377) \text{ in}^2}{8.19 \text{ in}} = .184 \text{ in}$$

and the length of the spline bushing is $L = 2.31 \text{ in}$. For a well rounded inlet, the loss coefficient is $K_{IN} = .05$. The outlet loss coefficient is given by

$$K_{OUT} = \left[1 - \frac{A_{OUT}}{A_4} \right]^2 = \left(1 - \frac{.377}{2.62} \right)^2 = .73$$

Substituting all these values into the equations gives:

$$P_3 = \frac{61.61 \left[\frac{\text{lbm}}{\text{ft}^3} \right] Q^2 \left[\frac{\text{ft}^3}{\text{sec}} \right]^2 144 \left[\frac{\text{in}^2}{\text{ft}^2} \right]}{64.6 \left[\frac{\text{lbm ft}}{\text{lb f sec}^2} \right] .377^2 \left[\text{in}^2 \right]^2} \left[\frac{.019 \times 2.31}{.184} + .05 + .73 \right] + 2390 \left[\frac{\text{lb f}}{\text{in}^2} \right],$$

$$P_2 = \frac{61.61 \left[\frac{\text{lbm}}{\text{ft}^3} \right] Q^2 \left[\frac{\text{ft}^3}{\text{sec}} \right]^2 144 \left[\frac{\text{in}^2}{\text{ft}^2} \right]}{64.4 \left[\frac{\text{lbm ft}}{\text{lb f sec}^2} \right] .230^2 \left[\text{in}^2 \right]^2 .962^2} \left[1 - \left(\frac{.230}{.690} \right)^2 \right] + P_3, \text{ and}$$

$$Q = \frac{.607 \times .196 \left[\text{in}^2 \right]}{12 \left[\frac{\text{in}}{\text{ft}} \right]} \sqrt{\frac{64.4 \left[\frac{\text{lbm ft}}{\text{lb f sec}^2} \right] (2440 - P_2) \left[\frac{\text{lb f}}{\text{in}^2} \right]}{61.61 \left[\frac{\text{lbm}}{\text{ft}^3} \right] 1 - \left(\frac{.196}{.690} \right)^2}}$$

The solution of these equations gives:

$$P_1 = 2440 \text{ psia},$$

$$P_2 = 2404 \text{ psia},$$

$$P_3 = 2394 \text{ psia},$$

$$P_4 = 2390 \text{ psia, and}$$

$$Q = .0634 \text{ ft}^3/\text{sec or } 28.5 \text{ gpm.}$$

Now the Reynolds number must be calculated to check the initial assumption of $Re = 5 \times 10^5$.

$$Re = \frac{\rho V D}{\mu} = \frac{61.61 \left[\frac{\text{lbm}}{\text{ft}^3} \right] .0634 \left[\frac{\text{ft}^3}{\text{sec}} \right] .5 \left[\text{in} \right] 12 \left[\frac{\text{in}}{\text{ft}} \right]}{.196 \left[\text{in}^2 \right] 90 \times 10^{-7} \left[\frac{\text{lb f sec}}{\text{ft}^2} \right] 32.2 \left[\frac{\text{lbm ft}}{\text{lb f sec}^2} \right]} = 4.1 \times 10^5$$

This Reynolds number is close to what was assumed so the loss coefficients which were used should be correct.

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2. ORIFICE DIAMETER

The vent orifice is to be a one half inch long hole in a plug which will be inserted in the pressure cap of each CRDM. The approximate dimensions are shown in Figure 2. The pressure drop across the orifice can be calculated as a pipe with entrance and exit losses. This would be expressed as:

$$\Delta P = \frac{\rho V^2}{2g_c} \left[\frac{fL}{D} + K_1 + K_2 \right]$$

where V is the velocity through the orifice, f is the friction factor of the orifice wall, L and D are the dimensions of the hole, K_1 is the inlet loss coefficient and K_2 is the outlet loss coefficient.

The flow through the orifice is assumed to remain single phase since that would allow the highest flow rate which would give the most conservative calculation for the orifice diameter. In order to maintain the pressure above the lead screw, the flow rate through the orifice must be no more than the flow rate which was calculated for the lead screw in Section 1. The maximum pressure difference across the orifice would be the difference of 2390 psia and atmospheric pressure, which is assumed to be 12 psia for this analysis. Therefore $\Delta P = 2378$ psi. The velocity through the hole depends on the flow rate and the hole diameter. The relationship is:

$$V = \frac{Q \left[\frac{\text{ft}^3}{\text{sec}} \right] 144 \left[\frac{\text{in}^2}{\text{ft}^2} \right]}{\frac{\pi}{4} D^2 \left[\text{in}^2 \right]} = 183.3 \frac{Q}{D^2} \left[\frac{\text{ft}}{\text{sec}} \right] \quad \text{where } Q \text{ is in cubic feet}$$

per second and D is in inches. Substituting the above expression for V into the flow equation and solving for D yields:

$$D = \sqrt[4]{\frac{\rho}{2gc \Delta P} \left[183.3 Q \frac{\text{ft}}{\text{sec}} \right]^2 (K_1 + K_2 + \frac{fL}{D})}$$

This equation will be solved by trial and error by iterating on the value of D with an HP-25 programmable calculator.

Again assuming that $Re = 5 \times 10^5$, $f = .019$ for $\epsilon/D = .0007$. From the preliminary analysis⁽³⁾, it is assumed that the diameter of the hole will be in the range of .17 inch. The inlet area ratio is then

$\frac{A_2}{A_1} = \frac{.17^2}{.5^2} = .116$. For a square edged inlet the loss coefficient⁽⁴⁾ would then be $K_1 = .46$. However, if the edge is rounded at all the loss coefficient decreases rapidly. Therefore K_1 will be decreased by 50% to be conservative: $K_1 = .23$. The outlet loss coefficient is given by

$$K_2 = \left(1 - \frac{A_1}{A_2}\right)^2 = \left(1 - \frac{.17^2}{.8^2}\right)^2 = .91.$$

Substituting these values into the equation for D:

$$D = \frac{61.61 \left[\frac{\text{lbm}}{\text{ft}^3} \right] (183.3 \cdot .0634)^2 \left[\frac{\text{ft}^2}{\text{sec}^2} \right]}{64.4 \left[\frac{\text{lbm ft}}{\text{lb f sec}^2} \right] 2378 \left[\frac{\text{lb f}}{\text{in}^2} \right] 144 \left[\frac{\text{in}^2}{\text{ft}^2} \right]} \left(.23 + .91 + \frac{.019 \cdot .5}{D} \right)$$

where D must be in inches. Solving the equation gives $D = .146$ inch.

FIGURE 2
Approximate Dimensions of Orifice Plug

3. AIR FLOW THROUGH 3/32 INCH NOZZLE

The CRDM vents are used to let the air escape after the head is placed on the reactor vessel. The following analysis will determine what the air flow rate will be with the orifices in the vent openings. It is assumed that typical air conditions during the venting operation are 200 psig and 130°F. Simplifying the system to be a 3/32 inch converging nozzle, the ratio of the back pressure to the reservoir pressure is

$$\frac{P_b}{P_r} = \frac{12}{212} = .057.$$

For air, the critical ratio is .528, therefore the flow will be choked through the nozzle. For choked flow, the flow rate is calculated by⁽²⁾

$$\dot{m} = \frac{P_e}{R T_e} A_e \sqrt{\alpha g_c R T_e}$$

For a choked nozzle, the exit pressure is

$$P_e = .528 P_r = .528 \times 212 = 111.9 \text{ psia and the exit temperature is}$$

$$T_e = .883 T_t = .883(130+460) = 491.5^\circ\text{R}.$$

Therefore,

$$\dot{m} = \frac{111.9 \left[\frac{\text{lb}_f}{\text{in}^2} \right] \frac{\pi}{4} \left(\frac{3}{32} \right)^2 \left[\text{in}^2 \right]}{53.36 \left[\frac{\text{ft} \cdot \text{lb}_f}{\text{lbm} \cdot ^\circ\text{R}} \right] 491.5 [^\circ\text{R}]} \cdot 1.4 \times 32.2 \left[\frac{\text{lbm} \cdot \text{ft}}{\text{lb}_f \cdot \text{sec}^2} \right] 53.36 \left[\frac{\text{ft} \cdot \text{lb}_f}{\text{lbm} \cdot ^\circ\text{R}} \right] 491.5 [^\circ\text{R}]$$

$$\dot{m} = .0320 \text{ lbm/sec.}$$

The density of air at these conditions is

$$\rho = \frac{P}{RT} = \frac{212 \left[\frac{\text{lbf}}{\text{in}^2} \right] 144 \left[\frac{\text{in}^2}{\text{ft}^2} \right]}{53.36 \left[\frac{\text{ft lbf}}{\text{lbm } ^\circ\text{R}} \right] 590 [^\circ\text{R}]} = .970 \left[\frac{\text{lbm}}{\text{ft}^3} \right]$$

The flow rate through the nozzle would be

$$Q = \frac{.0320 \left[\frac{\text{lbm}}{\text{sec}} \right] 60 \left[\frac{\text{sec}}{\text{min}} \right]}{.970 \left[\frac{\text{lbm}}{\text{ft}^3} \right]} = 1.98 \text{ cfm .}$$

III. RESULTS

The main result of this analysis is that the pressure drop across the lead screw can be limited to 50 psi or less by installing an orifice plug as shown in Figure 2 with a hole diameter of .146 inch in the pressure cap of each CRDM. It should be remembered, however, that this analysis contains several approximations and assumptions.

The second result is that the air flow through a 3/32 inch orifice would be 1.98 cfm with the reactor at 200 psig for 130°F air. The total flow rate would then be 7.9 cfm for the simultaneous venting of all four CRDM's.

IV. CONCLUSIONS AND RECOMMENDATIONS

Since the analysis is based on several approximations and assumptions it is recommended that the orifice diameter be made smaller than the calculated value of .146 inch. By reducing this value to 3/32 inch, the orifice should be conservatively small enough to maintain the pressure above the lead screw.

The air venting rate of 7.9 cfm should not hinder reactor operation significantly.

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