MAY 6 1963

Eber- Study IV-303-2 ✓

EGCR

Revision 1

ACNP 63507

OAK RIDGE OPERATIONS OFFICE

ATOMIC ENERGY COMMISSION

MASTER

STUDY NO. IV-303-2

REVISION 1

LOSS-OF-PRESSURE ACCIDENT

HOT LEG PIPING FAILURE

QUICK-OPENING VALVES IN REACTOR BYPASS LINES

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Atomic Energy Division
Nuclear Power Department
Washington, D. C.

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LOSS-OF-PRESSURE ACCIDENT
HOT LEG PIPING FAILURE
QUICK-OPENING VALVES IN REACTOR BYPASS LINES

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SEE PREFACE NOTE

APPROVED

June 17, 1960

REVISION 1

December 20, 1962

2/27/63 *3/1/63*

NOTE :

Subsequent to the approved issue of this report, the volume of the attemperators was reduced. This resulted in a core pressure differential greater than that reported in this study. The analysis based on the revised attemperator volumes is reported in Study IV-303-4.

Additional design changes and analyses were made in accordance with the recommendations of this study. Quick-opening valves and bypass lines were precluded from further consideration.

LOSS-OF-PRESSURE ACCIDENT
HOT LEG PIPING FAILURE
QUICK-OPENING VALVES IN REACTOR BYPASS LINES

I. OBJECTIVE

The purpose of this study is to determine the differential pressure across the reactor core following a pipe rupture in the hot leg of the reactor coolant system. The effect of quick-opening valves in bypass lines around the reactor is evaluated.

II. CONCLUSIONS

1. In the event of the maximum sized hot-leg rupture, the maximum differential pressure across the reactor core is 24.8 psi which acts upward.

2. The graphite-to-core-plate gas seals at each fuel channel expose only a portion of the graphite column cross-sectional area to the pressure differential following a coolant system rupture. This reduction in effective area upon which the differential pressure can act reduces the net upward force on the core. The pressure differential required to lift a graphite column is 109 psi. The pressure differential required to lift the fuel assemblies and top grid structures and appendages is 32.4 psi.

3. Quick-opening valves in the reactor-coolant bypass lines will reduce the pressure differential produced across the core and consequently reduce the upward force on the reactor core and core support plate.

4. The differential pressure across the reactor-vessel temperature barrier and the temperature-barrier gas seal is slightly less than that across the reactor core. This differential also is reduced by the quick-opening valves.

5. The differential pressure resulting from a hot-leg rupture is affected by bypass-line size, valve opening time, and instrument delay time. The pressure differentials developed across the reactor core for various bypass-line sizes and valve and instrument times are summarized in Table I.

6. The pressure differentials across the steam generator and blower in the sound loop for various combinations of bypass size, valve acting time, and instrument delay time are summarized in Table II.

7. A pressure differential of 23.6 psi is required to overcome the weight of a fuel column. The incorporation of quick-opening valves in the reactor-coolant bypass lines will satisfactorily eliminate fuel-element levitation.

TABLE I

Bypass Line Size (in.)	Instrument Delay (msec)	Valve Opening Time (msec)	Pressure Differential (psi)
16	20	50	15.0
20	20	50	14.7
16	20	100	16.3
20	20	100	15.9
16	50	50	18.2
20	50	50	18.0
16	50	100	19.0
20	50	100	18.7

When bypass lines are not used, the differential pressure developed across the core following a hot-leg rupture is 24.8 psi.

TABLE II

Bypass Size (in.)	Instrument Delay (msec)	Valve Opening Time (msec)	Pressure Differential (psi)*					
			Blower**	Steam Generator				
				I	II	III	IV	Total
16	20	50	- 3.50	0.305	0.054	1.052	0.393	1.804
20	20	50	- 4.22	0.330	0.058	1.139	0.426	1.953
16	20	100	-10.8	0.723	0.128	2.494	0.932	4.277
20	20	100	-13.3	0.845	0.150	2.916	1.208	5.119
16	50	50	- 3.42	0.298	0.053	1.029	0.384	1.764
20	50	50	- 4.60	0.328	0.058	1.132	0.423	1.941
16	50	100	-10.3	0.764	0.130	2.637	0.986	4.517
20	50	100	-12.8	0.810	0.144	2.796	1.045	4.795
NO BYPASS LINES OR VALVES			20.6	0.269	0.048	0.927	0.346	1.590

-
- I Exit Loss
 - II Annular Shroud
 - III Differential across Tube Field
 - IV Inlet Loss

*In the sound loop only

**Negative values indicate reversal of normal flow direction

III. RECOMMENDATIONS

1. Quick-opening valves in the reactor bypass piping should be incorporated in the final reactor design unless it can be shown that the temperature barrier, the core support grid, and the blower in the sound loop can withstand the maximum pressure differentials developed due to any credible hot leg pipe rupture.
2. The core support plate should be secured to the bottom grid to prevent levitation of the entire core structure by excessive differential pressures across the support plate.
3. The temperature-barrier-to-core-plate seal should be designed to withstand the pressure differential developed across the reactor core during the accident.
4. The core support grid should be designed to withstand the load in the upward direction due to the pressure differential across the core.
5. The core-plate-to-fuel-channel seals should be designed to withstand the pressure differential developed across the core during the accident.
6. The temperature barrier should be designed to withstand the pressure differential developed across the core during the accident.
7. The blowers and steam generators should be designed to withstand the differential pressures given in Table II.

IV. GIVEN DATA

1. Reactor coolant-loop piping fluid-flow resistances are determined from the following pressure drops at 215,000 lb/hr (Reference 3):

a. Vessel outlet to and including isolation valve	0.48 psi
b. Valve to bypass connection	0.25
c. Bypass to attemperator	0.0
d. Attemperator	0.25
e. Attemperator to steam generator	0.35
f. Steam generator to blower	0.56
g. Blower to bypass connection	0.0
h. Bypass to isolation valve	0.59
i. Isolation valve (included) to vessel inlet	0.28

2. Bypass fluid flow resistances are determined from the following pressure drops at 215,000 lb/hr (Reference 3):

Bypass Size (in.)	Pressure Drop (psi)
20	1.15
16	2.68

3. Reactor-vessel volumes are as follows (Reference 4):

a. Top plenum	3200 cu ft
b. Between temperature barrier and reflector	2200 cu ft
c. Bottom plenum	2900 cu ft

4. The total pressure drop in the reactor plenums is 0.45 psi at 427,000 lb/hr (Reference 5).

5. The design core pressure drop is 10.25 psi.

6. The steam generator volumes are (Reference 6):

a. Outer shell	1100 cu ft
b. Tube field	220 cu ft
c. Inlet and distribution shroud	160 cu ft

7. The volume of the coolant-loop piping is as follows (Reference 3) for each loop:

a. Reactor vessel to attenuator	104.2 cu ft
b. Attenuator	196.0 cu ft
c. Bypass line	
20-in.	62.6 cu ft
16-in.	39.3 cu ft
d. Attenuator to steam generator	68.5 cu ft
e. Blower	51.7 cu ft
f. Steam generator to blower	125 cu ft
g. Blower to isolation valve	112 cu ft
h. Isolation valve to vessel inlet	56 cu ft

8. Steam-generator pressure drop at 215,000 lb/hr is 2.0 psi (Reference 6).

V. ASSUMPTIONS

1. Rupture occurs instantaneously in one hot leg on the steam-generator side of the attemperator. The piping configuration is such that the exhaust flow area is twice the cross-sectional area of the pipe and the exhaust flows do not oppose one another.
2. No flow is assumed through the blowers during the accident.
3. Reactor coolant undergoes adiabatic expansion and compression.
4. The reactor coolant system is idealized as several gas volumes and fluid-flow resistances. Idealized as gas volumes are:
 - a. Reactor-vessel top plenum
 - b. Reactor-vessel bottom plenum
 - c. Attemperators
 - d. Steam generator in the sound loop.

Idealized as fluid-flow resistances are:

- e. Reactor core
 - f. Coolant loop piping including the bypass lines and valves.
5. The steam generators are later considered as several alternate volumes and fluid-flow resistances to evaluate the pressure drop across component parts.
 6. Coolant escapes from the piping rupture with sonic velocity.

VI. DISCUSSION

The instantaneous rupture of the main coolant duct is assumed to occur immediately downstream of the attemperator; this is the closest possible approach to the reactor core for a failure of the assumed size and consequently produces the highest net upward force on the core.

The maximum differential pressure across the core is 24.8 psi and occurs when no bypass lines are used. Figure I shows the differential pressure, top-plenum pressure, and bottom-plenum pressure as a function of time after the rupture. Figures II and III show the differential pressures that will be developed across the reactor core when various combinations of bypass-line sizes, valve-opening times, and instrument delay times are used.

An examination of Figures II and III reveals that bypass-line size does not affect the pressure differential significantly, whereas instrument delay time in detecting the rupture and signaling valve action has the most significant effect.

Figures IV and V show the exhaust-mass flow and the pressure differential between the top plenum and the attenuator in the ruptured loop. This pressure differential may be used to provide a signal for initiating valve action and to identify the failed loop.

Due to lack of complete blower head characteristics, the assumption was made that there is no flow through both blowers during the accident. Although there actually will be some flow through the blowers, the error introduced will not be significant, i.e., less than 2 per cent (see Study IV-303-1).

The gas seals at each channel limit the area of the graphite column which is acted upon by inlet-plenum pressure. To limit this area, however, it is necessary that the following conditions occur:

1. The seal must not rupture or unseat during the accident.
2. Any gas outside the seal and under the column must depressurize rapidly and not be significantly higher than reactor outlet-plenum pressure.

The first condition is accomplished by designing the seal to withstand pressures in excess of the maximum possible pressure differential that would occur during a hot-leg rupture. Present seal design indicates that the internal bursting pressure will be approximately 700 psi. The bursting pressure will be verified by testing prototype seals to destruction. All seals will be tested at 75 psig internal pressure for five minutes to determine adequacy of seal convolution. After erection of the core, the seals will be compressed 0.140 inches. Since the seal spring constant is approximately 500 lb/in., an initial spring force of 70 lb will be exerted by the seal. In addition to the spring force, the internal pressure thrust will increase the seating pressure of the seal.

An examination of the core erection tolerances and thermal expansion effects of the top and bottom core support structures allows determination of fluid-flow resistances between the graphite columns. These fluid-flow resistances were used to determine the maximum pressure differential which could exist between the gas external to the fuel channel seal and the top plenum. A pressure differential of approximately 0.2 psi may be expected. This small differential will not substantially affect the upward force exerted on the columns or reduce the seal seating force.

VII. REFERENCES

1. EGCR Study No. 225 (Title I), Differential Pressure across the Core following a Reactor Coolant System Rupture.
2. EGCR Study IV-303-1, Loss of Pressure Accident, Hot Leg Piping Failure (Blower Behavior Considered), January 11, 1960.
3. KE Memorandum, Mr. L. E. Malm to Mr. P. A. Martin, March 11, 1960.
4. KE TWX No. 47, January 12, 1960.
5. KE Letter, Mr. P. D. Bush to Mr. W. F. Banks, March 15, 1960.
6. Process Computations for EGCR Steam Generators, C. F. Braun and Company, March 10, 1960.
7. Letter, Mr. Jackson to Mr. Bush, October 8, 1962.

REACTOR COOLANT SYSTEM DEPRESSURIZATION PRELIMINARY STUDY FOR BY-PASS LINES

A preliminary study for the transient state following a rupture in the hot leg can be done based on the previous analyses.
 The following sketch can be used for the reactor system

Note: Arrows indicate the directions for positive mass flow values

As before the system is idealized with capacitances (without fluid flow resistances): T, B, S, S', A and A' and fluid flow resistances (without capacitances): $N, N', H_1, H_2, H_2', L, L_1, L_1', L_2, L_2', C, V, V'$

No heat transfer was considered in this analysis and also for this preliminary study the blowers are assumed surging once the rupture occurs.

REACTOR COOLANT SYSTEM DEPRESSURIZATION
PRELIMINARY STUDY FOR BY-PASS.

Nov 1959

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EQUATIONS : The equations governing the process for the different parts of the reactor coolant system are as follows:

A. FLUID FLOW RESISTANCES.

Nozzle N: From previous analyses, the following expression can be written:

$$W_N = \frac{2A_N \sqrt{g \frac{R}{\mu}} \sqrt{\frac{\delta+1}{2}}}{4[A_N^2 \delta g 2k_N + 1 - \frac{\delta^2}{4}]} \left\{ -\delta + \sqrt{\delta^2 + 4[A_N^2 \delta g 2k_N + 1 - \frac{\delta^2}{4}]} \right\} \frac{p_A'}{\sqrt{T_A'}} = K_N \frac{p_A'}{\sqrt{T_A'}} \quad (I)$$

1200°F Piping:

Ruptured Loop

$$W_{N_1} = \sqrt{\frac{p_r^2 - p_A^2}{2k_{N_1} \frac{R}{\mu} T_r}} \quad (II)$$

Unruptured Loop

$$W_{N_2} = \sqrt{\frac{p_A^2 - p_r^2}{2k_{N_2} \frac{R}{\mu} T_A}} \quad \text{if } p_A > p_r \quad (III)$$

$$W_{N_2} = -\sqrt{\frac{p_r^2 - p_A^2}{2k_{N_2} \frac{R}{\mu} T_r}} \quad \text{if } p_r > p_A \quad (III')$$

By-Pass Line:

Ruptured Loop:

$$W_v = \sqrt{\frac{p_B^2 - p_A^2}{2(k_{v_1} + k_{v_2}) \frac{R}{\mu} T_B}} \quad (IV)$$

Unruptured Loop

$$W_v = \sqrt{\frac{p_B^2 - p_A^2}{2(k_{v_1} + k_{v_2}) \frac{R}{\mu} T_B}} \quad \text{if } p_B > p_A \quad (IV)$$

$$W_v = -\sqrt{\frac{p_A^2 - p_B^2}{2(k_{v_1} + k_{v_2}) \frac{R}{\mu} T_A}} \quad \text{if } p_A > p_B \quad (IV')$$

Reactor Core:

$$W_c = \sqrt{\frac{p_B^2 - p_r^2}{2k_c \frac{R}{\mu} T_B}} \quad (V)$$

1050°F Piping: Unruptured Loop

$$W_{N_1} = \sqrt{\frac{p_s^2 - p_A^2}{2k_{N_1} \frac{R}{\mu} T_s}} \quad \text{if } p_s > p_A \quad (VI)$$

$$W_{N_1} = -\sqrt{\frac{p_A^2 - p_s^2}{2k_{N_1} \frac{R}{\mu} T_A}} \quad \text{if } p_A > p_s \quad (VI')$$

B. CAPACITANCES:

Top Plenum: From $V_r = \text{const}$

$$\dot{v}_r = -\frac{V_r}{m_r} \dot{m}_r \quad (VII)$$

From mass conservation

$$\dot{m}_r = W_{N_2} + W_c - W_{N_1} \quad (IX)$$

REACTOR COOLANT SYSTEM DEPRESSURIZATION, PRELIMINARY STUDY FOR BY-PASS

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$$\text{From ideal gases} \quad \dot{T}_T = \frac{T_T}{P_T} \dot{P}_T + \frac{T_T}{V_T} \dot{V}_T \quad (X)$$

$$\text{From energy conservation} \quad \dot{P}_T = \frac{R\gamma}{\mu V_T} (W_C T_B + W_{H_2} T_A - W_{H_2} T_T) \quad \text{if } W_{H_2} > 0 \quad (XI)$$

$$- W_{H_2} T_T \quad \text{if } W_{H_2} < 0 \quad (XI')$$

Bottom Plenum:

$$\dot{V}_B = - \frac{V_B}{m_B^2} \dot{m}_B \quad (XII)$$

$$\dot{m}_B = -W_C - W_V - W_{V'} \quad (XIII)$$

$$\dot{T}_B = \frac{T_B}{P_B} \dot{P}_B + \frac{T_B}{V_B} \dot{V}_B \quad (XIV)$$

$$\dot{P}_B = - \frac{R\gamma}{\mu V_B} (W_C + W_V + W_{V'}) T_B \quad \text{if } W_V > 0 \quad (XV)$$

$$P_B = - \frac{R\gamma}{\mu V_B} (W_C T_B + W_V T_B - W_V T_A) \quad \text{if } W_V < 0 \quad (XV')$$

Steam Generator (Unruptured Loop) $\dot{V}_S = - \frac{V_S}{m_s^2} \dot{m}_s \quad (XVI)$

$$\dot{m}_s = -W_{H_1} \quad (XVII)$$

$$\dot{T}_S = \frac{T_S}{P_S} \dot{P}_S + \frac{T_S}{V_S} \dot{V}_S \quad (XVIII)$$

$$\dot{P}_S = - \frac{R\gamma}{\mu V_S} W_{H_1} T_S \quad \text{if } W_{H_1} > 0 \quad (XIX)$$

$$P_S = \frac{R\gamma}{\mu V_S} W_{H_1} T_A \quad \text{if } W_{H_1} < 0 \quad (XIX')$$

Attenuators:

Ruptured Loop:

$$\dot{V}_{A'} = - \frac{V_{A'}}{m_{A'}^2} \dot{m}_{A'} \quad (XX)$$

$$\dot{m}_{A'} = W_{V'} + W_{H_2'} - W_N \quad (XXI)$$

$$\dot{T}_{A'} = \frac{T_{A'}}{P_{A'}} \dot{P}_{A'} + \frac{T_{A'}}{V_{A'}} \dot{V}_{A'} \quad (XXII)$$

$$\dot{P}_{A'} = \frac{R\gamma}{\mu V_{A'}} (W_{V'} T_B + W_{H_2'} T_T - W_N T_{A'}) \quad (XXIII)$$

Unruptured Loop

$$\dot{V}_A = - \frac{V_A}{m_A^2} \dot{m}_A \quad (XXIV)$$

$$\dot{m}_A = W_V + W_{H_1} - W_{H_2} \quad (XXV)$$

$$\dot{T}_A = \frac{T_A}{P_A} \dot{P}_A + \frac{T_A}{V_A} \dot{V}_A \quad (XXVI)$$

$$\dot{P}_A = \frac{R\gamma}{\mu V_A} (W_V T_B + W_{H_1} T_S - W_{H_2} T_A) \quad \text{if } \begin{cases} W_V > 0 \\ W_{H_1} > 0 \\ W_{H_2} > 0 \end{cases} \quad (XXVII)$$

$$- W_V T_A \quad \text{if } W_V < 0$$

$$- W_{H_1} T_A \quad \text{if } W_{H_1} < 0$$

$$+ W_{H_2} T_T \quad \text{if } W_{H_2} < 0$$

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The number of equations for the capacitances can be reduced by elimination of variables as indicated in previous studies. The final set of equations for the capacitances is as follows:

Top Plenum: From Eq. (VIII), (IX) and (X):

$$\dot{T}_T = \frac{T_T}{P_T} \left[\dot{p}_T - \frac{RT_T}{\mu V_T} (W_C + W_{H_2} - W_{H_2}') \right] \quad (\text{VIII})$$

As before: $\dot{p}_T = \frac{R\gamma}{\mu V_T} (W_C T_B + W_{H_2} T_A - W_{H_2}' T_T) \quad \begin{matrix} \text{if } W_{H_2} > 0 \\ -W_{H_2} T_T \quad \text{if } W_{H_2} < 0 \end{matrix} \quad (\text{IX})$

Bottom Plenum

$$\dot{T}_B = \frac{T_B}{P_B} \left[\dot{p}_B + \frac{RT_B}{\mu V_B} (W_C + W_V + W_{V'}) \right] \quad (\text{X})$$

$$\dot{p}_B = -\frac{R\gamma}{\mu V_B} (W_C + W_V + W_{V'}) T_B \quad \text{if } W_V > 0 \quad (\text{XI})$$

$$\dot{p}_B = -\frac{R\gamma}{\mu V_B} [(W_C + W_{V'}) T_B - W_V T_A] \quad \text{if } W_V < 0$$

Steam Generator (Unruptured Loop)

$$\dot{T}_S = \frac{T_S}{P_S} \left[\dot{p}_S + \frac{RT_S}{\mu V_S} W_{H_1} \right] \quad (\text{XII})$$

$$\dot{p}_S = -\frac{R\gamma}{\mu V_S} W_{H_1} T_S \quad \text{if } W_{H_1} > 0 \quad (\text{XIII})$$

$$\dot{p}_S = \frac{R\gamma}{\mu V_S} W_{H_1} T_A \quad \text{if } W_{H_1} < 0$$

Attenuators:

Ruptured Loop: $\dot{T}_{A'} = \frac{T_{A'}}{P_{A'}} \left[\dot{p}_{A'} + \frac{RT_{A'}}{\mu V_{A'}} (W_N - W_{H_2}' - W_{V'}) \right] \quad (\text{XIV})$

$$\dot{p}_{A'} = \frac{R\gamma}{\mu V_{A'}} (W_V T_B + W_{H_2}' T_T - W_N T_A) \quad (\text{XV})$$

Unruptured Loop: $\dot{T}_A = \frac{T_A}{P_A} \left[\dot{p}_A + \frac{RT_A}{\mu V_A} (W_{H_2} - W_V - W_{H_1}) \right] \quad (\text{XVI})$

$$\dot{p}_A = \frac{R\gamma}{\mu V_A} (W_V T_B + W_{H_1} T_S - W_{H_2} T_A) \quad \text{if } \begin{cases} W_V > 0 \\ W_{H_1} > 0 \\ W_{H_2} > 0 \end{cases} \quad (\text{XVII})$$

$$\begin{matrix} -W_V T_A & \text{if } W_V < 0 \\ -W_{H_1} T_A & \text{if } W_{H_1} < 0 \\ +W_{H_2} T_T & \text{if } W_{H_2} < 0 \end{matrix}$$

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A

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NOMENCLATURE

A cross-sectional area, ft^2
 g gravity acceleration, ft/sec^2
 k constant, characteristic for pressure drop ($\Delta p = k W^2 v$), sec^2/ft^5
 m weight, lb
 p absolute pressure, lb/ft^2
 R universal gas constant, $\frac{lb \cdot ft}{mole \cdot ^\circ R}$
 T absolute temperature, $^\circ R$
 V volume, ft^3
 v specific volume, ft^3/lb
 W mass flow, lb/sec .

$\gamma = \frac{C_p}{C_v}$ ratio of specific heats, dimensionless.
 μ molecular weight, $lb/mole$.

Subscripts

A refers to Attenuator in the Unruptured Loop
 A' Ruptured Loop
 B Bottom Plenum
 C Reactor Core
 H_1 1050°F Piping of the Hot Leg in the Unruptured Loop.
 H_1' Ruptured Loop.
 H_2 1200°F Piping of the Hot Leg in the Unruptured Loop
 H_2' Ruptured Loop.
 L_1 Cold Leg Piping between Steam Generator and By-Pass (Unruptured Loop)
 L_1' (Ruptured Loop)
 L_2 Bottom Plenum and By-Pass (Unruptured Loop)
 L_2' (Ruptured Loop)
 N Nozzle in the Reactor Side.
 N' Steam Generator Side.
 P Blower in the Unruptured Loop
 P' Ruptured Loop
 S Steam Generator in the Unruptured Loop.

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B

C

S' refers to Steam Generator in the Ruptured Loop.

T Top Plenum

V By-Pass Line in the Unruptured Loop

V' Ruptured Loop.

**REACTOR COOLANT SYSTEM DEPRESSURIZATION
PRELIMINARY STUDY FOR BY-PASS.**

Nov 1959

SIMILAR TO

DR'N *J. A. LANDONI*

CH'D *R. O. WOLFF*

APP'D *ADA*

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ISSUE

ALLIS-CHALMERS MFG. CO. DEPT. *3761*

STUDY NO. 303-2

A

B

A-C MFG. CO., MILWAUKEE, WIS. FORM NO. 6833-3

Total Volume of Gas Enclosed by the Bellow Seal

$$V_1 = 0.183 \text{ in}^3$$

$$V_2 = 0.123 \text{ in}^3$$

$$V_3 = 0.140 \text{ in}^3$$

$$V_4 = 0.108 \text{ in}^3$$

$$\frac{1}{2} V_5 = 0.706 \text{ in}^3$$

$$V = 1.26 \text{ in}^3$$

Considering 4 bellow seals per graphite column: $4V \approx 5 \text{ in}^3$

Amount of Gas Enclosed:

$T = 970^\circ \text{R}$ (Bottom Plenum Temperature)

$p = 303.4 \text{ psia}$ (Top Plenum Absolute Pressure)

$$\text{He density: } \rho = \frac{0.37 \times 303.4}{970} = 0.116 \frac{\text{lb}}{\text{ft}^3}$$

$$\text{Mass of He: } M = 0.116 \frac{5}{12 \times 144} = 0.335 \times 10^{-3} \text{ lb}$$

ESTIMATE OF THE PRESSURE DROP ALONG THE COLD GAP

For isothermal flow between broad parallel plates (McAdams, Heat Transmission, p. 149)

$$\Delta p = 12 \frac{\mu G L}{g \rho z^3}$$

$$\text{where } G = \frac{W}{A}; \quad A = z S$$

Thus

$$\Delta p = 12 \frac{\mu W L}{g \rho S z^3} \therefore W = \Delta p \cdot z^3 \left(\frac{g \rho S}{12 \mu L} \right)$$

$$g = 32.2 \text{ ft/sec}^2$$

$$\mu = 0.0375 \text{ cp} = (0.0375) (0.000672) = 25.2 \times 10^{-6} \frac{\text{lb}}{\text{ft sec}}$$

$$L \approx 20 \text{ ft}$$

$$S = 16 \text{ in} = 1.33 \text{ ft}$$

$$\rho = 0.116 \frac{\text{lb}}{\text{ft}^3}$$

$$W = \left(\frac{32.2 \times 0.116 \times 1.33}{12 \times 25.2 \times 10^{-6} \times 20} \right) \Delta p \cdot z^3 = 0.00819 \times 10^6 \Delta p \cdot z^3 = 8.19 \times 10^2 \Delta p \cdot z^3$$

$$z = 0.020 \text{ in} = \frac{1}{50} \times 10^{-2} \text{ ft}$$

$$W = 8.19 \times 10^2 \frac{\Delta p \cdot 10^{-6}}{216} = 0.3791 \times 10^{-5} \Delta p$$

REACTOR COOLANT SYSTEM DEPRESSURIZATION

4/60

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Expressing Δp in psi the fluid flow resistance comes out to be:

$$R_f = \frac{1}{0.8791 \times 10^{-5} \times 144} = 1837 \frac{\text{psi}}{\text{lb}} \text{ sec}$$

The 5 in^3 gas volume of 4 bellow seals corresponds to one graphite column, and the fluid flow resistance evacuates the gas contained in 2.5 in^3 as indicated in the sketch.

Thus, referring to 5 in^3 :

$$R_f = 456 \frac{\text{psi}}{\text{lb}} \text{ sec}$$

As there are additional fluid flow resistances along the gap between the bottom plate and the tilted graphite column and by directional changes of the escaping flow, then

$$\text{say } R_f \approx 2 \times 10^3 \frac{\text{psi}}{\text{lb}} \text{ sec}$$

The rate of depressurization of the top plenum, using data from the hot leg double-ended rupture accident can be evaluated as follows:

Time (sec)	Pressure (psia)
0	303.4
0.1	273.7

$$\dot{p} = \frac{dp}{dt} \approx \frac{303.4 - 273.7}{0.1} = 297 \frac{\text{psi}}{\text{sec}} = 42.8 \times 10^3 \frac{\text{lb}}{\text{ft}^2 \text{ sec}}$$

The escaping mass flow required to follow such depressurization rate in the bellow seal gas is given by

$$\dot{p} = \frac{R}{\mu} \frac{\delta}{V} WT$$

where

$$\delta = 5/3$$

$$\frac{R}{\mu} = \frac{1545}{4} = 386.2 \frac{\text{ft}}{\text{R}}$$

$$V = 2.5 \text{ in}^3$$

$$T = 970^\circ \text{R}$$

$$W = \frac{(42.8 \times 10^3) (2.5)}{(386.2) \left(\frac{5}{3}\right) (1728) (970)} = 0.099 \times 10^{-3} \frac{\text{lb}}{\text{sec}}$$

REACTOR COOLANT SYSTEM DEPRESSURIZATION

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The differential pressure can be estimated

$$\Delta p \approx (2 \times 10^{-3}) (0.099 \times 10^{-2}) \approx 0.2 \text{ psi}$$

The volume of gas within the gas gap is

$$V = 16 \times 0.20 \times 20 \times 12 = 76.8 \text{ in}^3$$

Assuming this volume plus the gas under the column is concentrated at the bottom of the column

$$W = \frac{(42.8 \times 10^3)(79.3)}{356.25 \left(\frac{5}{3}\right)(1728)(970)} = 3.14 \times 10^{-3} \frac{\text{lb}}{\text{sec}}$$

$$\Delta p \approx (1 \times 10^3)(3.14 \times 10^{-3}) \approx 3.15 \text{ psi}$$

THE ^{MAXIMUM} OUTWARD FORCE AGAINST THE RESTRAINT IS

$$A = \frac{16}{0.707} (20)(12) = 5420 \text{ in}^2$$

$$F = 3.15 \text{ PSI} \times 5420 \text{ in}^2 = 17,100 \text{ lbs}$$

FROM STUDY II 240 THE RESTRAINT IS DESIGNED FOR 57,000 #
PER 3.75 COLUMNS OR

$$\frac{57,000}{3.75} = 15,200 \text{ #/column}$$

REACTOR COOLANT SYSTEM DEPRESSURIZATION

SIMILAR TO

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Study 303-2

LIFTING OF CORE COMPONENTS

1. FUEL CHANNEL CONTENTS

FUEL ASSEMBLY 47.56 lb
UPPER DUMMY 115.7
LOWER DUMMY 85

CROSS SECTIONAL AREA

FUEL CHANNEL DIA 5.00 IN
SLEEVE DIA 5.25 IN

AVERAGE DIA 5.12 IN

$$\Delta P = \frac{\text{TOTAL WEIGHT}}{\text{CROSS SECT AREA}} = \frac{(6)(47.56) + 115.7 + 85}{\frac{\pi (5.12)^2}{4}} = 23.6 \text{ PSI}$$

A PRESSURE DIFFERENTIAL GREATER THAN
23.6 psi WILL LIFT THE FUEL CHANNEL CONTENTS

2. GRAPHITE COLUMNS

DIMENSIONS

HEIGHT 19.33 ft

SIDES 16 in

FUEL CHANNELS 5.25 IN O.D.

$$\text{VOLUME} = \left[\left(\frac{16}{12} \right)^2 - 4 \frac{\pi}{4} \left(\frac{5.25}{12} \right)^2 \right] 19.33 = 22.7 \text{ FT}^3$$

$$\text{DENSITY} = 103 \text{ lb/ft}^3$$

$$\text{WEIGHT} = 22.7 (103) = 2344 \text{ lb}$$

AREA EXPOSED UNDER SEALS

SEAL OD 5.75 in

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$$\text{AREA : } 4 \frac{\pi}{4} (6.75^2 - 5.12^2) = 21.5 \text{ in}^2$$

$$\text{PRESSURE TO LIFT} > \frac{2.34 \times 10^3}{21.5} = 109 \text{ psi}$$

3 LIFTING PRESSURE ON COLUMN WITH ONE
FAILED SEAL OR MORE

EXPOSED AREA

$$16^2 - 4 \frac{\pi}{4} (5.12)^2 = 173 \text{ in}^2$$

$$\text{LIFTING PRESSURE} > \frac{2.34 \times 10^3}{1.73 \times 10^2} = 13.52 \text{ psi}$$

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1. ESTIMATE OF THE PRESSURE DROPS IN THE DIFFERENTS PARTS OF THE STEAM GENERATORS

Previously the system was idealized by pure capacitances and pure fluid flow resistances, but actually every steam generator has distributed capacitances and fluid flow resistances.

In order to have an estimate for the pressure drops during the transient state, the equivalent or fictitious length for the fluid flow resistances can be evaluated considering that the normal operating pressure drops are originated by the same mass flow; i. e.

Item	Pressure Drop	Average Specific Volume	Length
i	Δp_i	$\bar{v}_i \propto \frac{T_{i,NO}}{P_{i,NO}}$	$\Delta L_i \propto \frac{\Delta p_{i,NO}}{\bar{v}_i \cdot NO}$

The sketch shows the fluid flow resistance side of the different parts of the steam generator.

The capacitance side can be assumed proportional to the above calculated lengths, then the mass flow during the transient state grows as

$$\Delta W \propto \Delta V \propto L_i - L_{i-1} = \Delta L_i$$

As the differential pressure Δp is proportional to the product $W^2 v$, we can write for every item i of the steam generator:

$$\Delta p_i \propto \int W^2 v dL$$

being

$$W \approx W_{i-1} + \frac{W_i - W_{i-1}}{\Delta L_i} L$$

$$\text{Thus } \Delta p_i \propto \int \left[W_{i-1} + \frac{W_i - W_{i-1}}{\Delta L_i} L \right]^2 v dL \approx \bar{v}_i W_{i-1}^2 \Delta L_i + 2 \frac{\bar{v}_i}{\Delta L_i} W_{i-1} (W_i - W_{i-1}) \frac{\Delta L_i^2}{2} + \bar{v}_i \frac{(W_i - W_{i-1})^2}{\Delta L_i^2} \frac{\Delta L_i^3}{3}$$

$$\Delta p_i \propto \bar{v}_i W_{i-1} W_i \Delta L_i + \frac{\bar{v}_i}{3} (W_i^2 + W_{i-1}^2 - 2 W_i W_{i-1}) \Delta L_i$$

PRELIMINARY STUDY FOR HOT LEG RUPTURE

April 1960

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$$\Delta p_i \propto (W_i^2 + W_{i-1}^2 + W_i W_{i-1}) \bar{v}_i \Delta L_i$$

Consequently

$$\Delta p_i = \Delta p_s \cdot \frac{(W_i^2 + W_{i-1}^2 + W_i W_{i-1}) \bar{v}_i \Delta L_i}{\sum_j \bar{v}_j (W_j^2 + W_{j-1}^2 + W_j W_{j-1}) \Delta L_j} \approx \Delta p_s \frac{(L_i^2 + L_{i-1}^2 + L_i L_{i-1}) \Delta p_{i,NO}}{\sum_j (L_j^2 + L_{j-1}^2 + L_j L_{j-1}) \Delta p_{j,NO}}$$

$$\Delta p_i \approx \Delta p_s \frac{\Delta p_{i,NO} (L_i^2 + L_{i-1}^2 + L_i L_{i-1})}{\sum_j \Delta p_{j,NO} (L_j^2 + L_{j-1}^2 + L_j L_{j-1})}$$

2. ESTIMATE OF THE TOTAL PRESSURE DROP ACROSS THE STEAM GENERATOR

Going on with the dual representation of the steam generator, the differential pressure across it can be established on function of the differential pressure $p_s - p_A$ obtained by solving equations (I) to (XX).

In the sketch:

A refers to the characteristic point for the attenuator.

S steam generator.

S^x upper end of the steam generator (inlet during normal operation)

S^{xx} lower (exit)

In the mass flow diagram W is almost zero at S^{xx} because the blower is assumed blocking the cold leg.

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On the same basis as in 1., it is inferred that at any time t in the steam generator

$$\Delta p(L) = p(0) - p(L) \propto \int_0^L W^2 dL = \left(\frac{W_{H_1}}{L_s}\right)^2 \int_0^L L^2 dL = \left(\frac{W_{H_1}}{L_s}\right)^2 \frac{L^3}{3}$$

$$\Delta p(L) \propto \frac{1}{3} W_{H_1}^2 \left(\frac{L}{L_s}\right)^3 L_s \quad (1)$$

For the entire capacitance representing the steam generator, the coolant is considered at any time with the same physical properties, then

$$L_s \propto |\Delta p_{s no}| \quad (2)$$

Thus $\frac{p_{sxx} - p_s}{p_{sxx} - p_{sx}} = \frac{1}{2}$ during normal operating conditions because the mass flow keeps as constant.

and $\frac{p_{sxx} - p_s}{p_{sxx} - p_{sx}} = \left(\frac{1}{2}\right)^3 = \frac{1}{8}$ during transient state because $L = \frac{L_s}{2}$ at S .

During the transient state, the differential pressures can be written proportional to $W^2 L$, so

a. Steam Generator: By using (1) and (2)

$$p_{sxx} - p_s \propto \frac{1}{3} \cdot \frac{1}{2^3} |\Delta p_{s no}| W_{H_1}^2$$

$$p_{sxx} - p_{sx} \propto \frac{1}{3} |\Delta p_{s no}| W_{H_1}^2$$

$$p_s - p_{sx} \propto \frac{1}{3} \left(1 - \frac{1}{2^3}\right) |\Delta p_{s no}| W_{H_1}^2$$

b. Fluid flow resistance between S and A : Neglecting the variation in the mass flow along the attemperator's fluid flow resistance

$$p_s - p_A \propto \left\{ |p_A - p_s|_{no} - \frac{1}{2} |\Delta p_{s no}| \right\} W_{H_1}^2$$

$$p_s - p_A \propto \left\{ |p_A - p_s|_{no} - \frac{1}{2} |\Delta p_{s no}| \right\} W_{H_1}^2 + \frac{7}{24} |\Delta p_{s no}| W_{H_1}^2$$

$$\propto |p_A - p_s|_{no} W_{H_1}^2 - \frac{5}{24} |\Delta p_{s no}| W_{H_1}^2$$

Expressing the differential pressures $p_{sxx} - p_s$ and $p_{sxx} - p_{sx} = \Delta p_s$ on function of $p_s - p_A$ which is obtained from equations (1) to (XX), we get the following constant ratios:

$$\frac{p_{sxx} - p_s}{p_s - p_A} = \frac{\frac{1}{24} |\Delta p_{s no}|}{|p_A - p_s|_{no} - \frac{5}{24} |\Delta p_{s no}|} = f_0 \quad (XXI)$$

$$\frac{\Delta p_s}{p_s - p_A} = \frac{\frac{1}{3} |\Delta p_{s no}|}{|p_A - p_s|_{no} - \frac{5}{24} |\Delta p_{s no}|} = f_s$$

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April 1960

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By equation (XXI) the pressure on one side of the blower in the sound loop is evaluated. The pressure on the other side is given by backing down the fluid flow resistance in the by-pass line for the same loop; i. e. :

$$p_{s22} = p_s + f_o (p_s - p_A) \quad (XXI)$$

$$\Delta p_p = p_{s22} - \frac{k_{L2}}{k_v + \Delta k_v} (p_A - p_o) \quad (XXII)$$

where k_{L2} refers to the portion of cold leg duct between the by pass line and the bottom plenum.

The final equation in 1. together with the expression for p_s render the relationship wanted for determining the differential pressures across the different items of the steam generator, i.e.

$$\Delta p_i = f_s (p_s - p_A) \frac{\Delta p_{i no} (L_i^2 + L_{i-1}^2 + L_i L_{i-1})}{\sum_j \Delta p_{j no} (L_j^2 + L_{j-1}^2 + L_j L_{j-1})} \quad (XXIII)$$

PRELIMINARY STUDY FOR HOT LEG RUPTURE

April 1960

DR'N J.A. LANDONI

CH'D A.D. 967210

APP'D

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TRANSIENT STATE OF PRESSURES PRODUCED BY HOT LEG RUPTURE

STUDY IX 303-2 REV-1

FIG I

TRANSIENT STATE OF PRESSURES PRODUCED BY HOT LEG RUPTURE
16" & 20" BY-PASS LINES
BEGINNING OF VALVES OPENING : 50 msec.

STUDY 303-2 REV-1

Fig II

TRANSIENT STATE OF PRESSURES PRODUCED BY HOT LEG RUPTURE

16" & 20" BY-PASS LINES
 BEGINNING OF VALVES OPENING: 20 msec.

STUDY 303-2 REV-1

Fig III

EXHAUST MASS FLOW FROM THE ATTEMPERATOR SIDE OF THE RUPTURE

IV 303-2 Rev1

Fig IV

TRANSIENT STATE OF PRESSURES PRODUCED BY HOT LEG RUPTURE

DIFFERENTIAL PRESSURES
BETWEEN TOP PLENUM AND ATTENUATORS

Fig. II

Core Levitation Hazards Analysis⁽⁷⁾

Total Weight of fuel 234 channels	66,771 lb.
Weight of 234 top dummy assemblies @ 115.7# each	27,071 lb.
Weight of Top plate-grid structure	350 lb.
Weight of intermediate plate-grid structure	1,396 lb.
BSD piping	800 lb.
Fuel Channel extensions	4,444 lb.
Top grid and ring girder	25,830 lb.
Grid to temperature-barrier baffle	1,950 lb.
Weight of bottom dummies 234 @ 85# each	19,890 lb.
2 - 9-1/2" graphite plugs @ 1700# each	3,400 lb.
2 - 9" graphite plugs @ 1500# each	3,000 lb.
2 - 5-1/2" graphite plugs @ 600# each	1,200 lb.
Total Weight	156,102 lb.

Area for 232 fuel channels	= 4550 in ²
Area for 2 fuel channels	= 40 in ²
Area for 2 - 9-1/2" plugs	= 157 in ²
Area for 2 - 5-1/2" plugs	= 56.5 in ²
	4803.5 in ²

$$\frac{156,102 \text{ lb.}}{4803.5 \text{ in}^2} = 32.4 \text{ psi}$$

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