Loads on BWR Pipe and Pipe Supports Due to Recirculation Pump Seizure

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ABSTRACT

A hypothetical recirculation pump instantaneous seizure and rotor stoppage within one-quarter revolution are postulated to occur as a consequence of an unexpected, unspecified event which is assumed to occur while the reactor is operating at power. The effect of the postulated event upon a typical Boiling Water Reactor (BWR) recirculation piping system was studied. It was shown that the piping and pipe supports maintain pressure integrity and functional capability respectively.

NOMENCLATURE

A = Area of cross-section of pipe (in^2)

B_1 & B_2 = ASME Code, Section III primary stress indices for the specific product under investigation

D = Outside diameter of pipe (in)

C = Sonic speed in saturated water 3300 ft/sec

F = Segment force (lbs)

g_c = Newton's Gravitational Constant LBm ft/L_{Bf} sec^2

K = Pump lock rotor pressure loss coefficient

L = Length of segment (in)

M = Calculated Moment (in-lbs)

P = Piping design pressure (psi)

P_{si} = Suction pressure - undisturbed (psi)

P_D = Pressure through the pump flow resistance (psi)

$P(x,t)$ = Pressure at a distance x and at time t

P_{Di} = Discharge pressure (undisturbed) - (psi)

P_L = Pressure at distance "L" (psi)

P_s = Suction pressure within the compression wave (psi)

Sm = Allowable design stress intensity value at (575°F) design temperature - (psi)

Sy = Yield strength at (575°F) design temperature - (psi)

t = Time for sound wave to travel segment length "L" - (sec)

t_n = Nominal thickness of pipe or fittings

V = Liquid velocity between the two traveling wave (ft/sec)

V_i = Undisturbed velocity of liquid (ft/sec)

Z = Section modulus (in^3)

ρ = Density of water at (575°F) design temperature and 1250 psi design pressure - (lb/ft^3)

α = Factor based on pipe components
= 1.5 for all components
= 2.0 branch connection and tee

τ = Time for recirculation pump to seizure (sec)

INTRODUCTION Nuclear power plant piping and piping support system are designed to meet the ASME Code, reference 1, allowable stress and load limits for normal events, operating transients and postulated accident conditions. The recirculation piping system is classified as an ASME Class I piping system. During normal plant operation, water flows from the suction side of the recirculation pump to the discharge side at a pressure differential. A hypothetical pump seizure is postulated to occur as a consequence of an unexpected, unspecified finite time stoppage of one recirculation loop pump shaft while the reactor is at power and operating under normal plant conditions. The postulated stoppage of the pump rotor would produce a rapid decrease of core coolant flow as a result of the large hydraulic resistance introduced by the stopped rotor. The rotor shaft is assumed to stop within one-quarter revolution. To assess the reality of a seizure or a fast coastdown, we must examine some events which might actually take place within the pump and motor.

BEARING FAILURE Torque created by simultaneous bearing failure would be insufficient to overcome motor torque. After a motor trip due to a failed bearing many revolutions would occur before seizure.

ROTOR-STATOR INTERFERENCE Worn bearings could result in contact between the rotor and stator. However, if the bearings are worn, they will allow the rotor to move away from the point of contact thus preventing seizure.

IMPELLER JAM DUE TO OBSTRUCTION Wedging of some foreign object or a fragment of an impeller blade between the impeller and the pump casing has often been proposed as a mechanism for instantaneous stoppage of the pump. Due to the pump geometry it is difficult to justify such an event. Analysis has been done, Reference [2] which shows that, if an object jams between the pump casing and the impeller blades, the impeller blades will yield before sufficient torque develops to cause a rapid pump seizure.

Recirculation pump seizure although highly unlikely could produce a very rapid decrease of coolant flow due to the intense hydraulic resistance of the seized pump. This would create transient loads on the recirculation piping and the piping support system. Force-time histories were developed assuming a pump seizure time of one-quarter revolution. To assure a conservative load evaluation, the safe shutdown earthquake (SSE) loads were used for evaluation.

EQUATION FORMULATION FOR INSTANTANEOUS SEIZURE During the steady state pump operation, the pressures in the suction and discharge lines are shown in Figure 1.

PUMP SEIZURE CONDITION It is assumed that the pump rotor stops instantaneously and creates an instantaneous flow resistance. The fluid's inertia will tend to maintain forward flow, and the locked rotor will create a pressure loss between the suction and discharge side of the pump. At sonic velocity, relative to the liquid (C), a compression wave will travel upstream and a decompression wave will travel downstream (Figure 2).

WATER HAMMER Pressure changes are determined from the water hammer equations:

$$(P_s - P_{si}) = \frac{\rho C}{g_c}(V_i - V) \qquad (1)$$

$$(P_{Di} - P_D) = \frac{\rho C}{g_c}(V_i - V) \qquad (2)$$

PRESSURE LOSS ACROSS PUMP

$$(P_S - P_D) = \frac{KV^2}{2g_c}\rho \qquad (3)$$

SOLUTION FOR PRESSURE AND VELOCITY Adding (1) and (2) and substituting in (3) for $(P_s - P_D)$, the velocity V is given by the following equation (provided the water pressure does not drop below its vapor pressure.)

$$V = \frac{2C}{K}\left(\left(1 + \frac{KV_i}{C} - \frac{Kg_c\,(P_{Di} - P_{si})}{2\rho C^2}\right)^{\frac{1}{2}} - 1\right) \qquad (4)$$

REACTION FORCES The reaction forces on pipe segments act in the same direction and are:

$$F = (P_s - P_{si})A = (P_{Di} - P_D)A \qquad (5)$$

EQUATION FORMULATION FOR FINITE TIME PUMP SEIZURE

The force equation is set up assuming that the pump seizure occurs over a finite time τ such that the fluid velocity drops linearly from V_i to V (Figure 3).

$$V = V_i - (V_i - V)t/\tau \qquad (6)$$

From equation (1) it follows that

$$(P_s - P_{si}) = \frac{\rho C}{g_c}(V_i - V)t/\tau \qquad (7)$$

Equation (1) is valid for any flow velocity and pressure. Since P(x,t) in the pipe can be expressed from a solution to the wave equation as

$$P(x,t) = f(x + Ct) + g(x - Ct)$$

where $f(x + Ct)$ = Left traveling wave and $g(x - Ct)$ = Right traveling wave

Choose x = o at the pump, we have for the left traveling wave

$$P(0,t) = P_s = \frac{\rho}{g_c}(V_i - V)\frac{Ct}{\tau} \text{ and } P(x,t) = \frac{\rho\,(V_i - V)}{g_c\,\tau}(X + Ct) \qquad (8)$$

For the suction line the force is determined as follows: (Figure 4)

$$F = (P_s - P_L)\,A$$

$$\tau > t = \frac{L}{C} \quad F = \frac{\rho CA}{g_c}(V_i - V)\frac{L}{C\tau} \qquad (9)$$

The above equation is true when $\tau > L/C$

If $\tau < L/C$, the full force occurs in the segment $F = \frac{\rho CA}{g_c}(V_i - V)$ (10)

EFFECT OF BRANCH CONNECTION The effect of the branch connection (Figure 5) is evaluated, in reference 3 with the resulting equation

$A_{II} = A_2 + A_3$ and assuming $\rho_I = \rho_{II}$ and $C_I = C_{II}$

$$\frac{P_i - P_\infty}{P_o - P_\infty} = \frac{2}{1 + \frac{A_2 + A_3}{A_I}} = \frac{2A_I}{A_I + A_2 + A_3} \quad (11)$$

where P_∞ = Initial pressure (psi)

$(P_o - P_\infty)$ = Pressure disturbance

P_i = Reflected pressure

C_I & C_{II} = Sonic Speed at area A_I, & A_2, A_3 respectively

ρ_I & ρ_{II} = Density at area A_I, & A_2, A_3 respectively

FUNCTIONAL CRITERIA LIMITS

- **LOAD AND LOAD COMBINATION**
- **LOADS**
  - Weight (W)
  - Design Pressure (P)
  - Safe Shutdown Earthquake (SSE)
  - Pump Seizure (PS)
  - Thermal Expansion (TE)
  - Primary Stress Indices (B_1 and B_2), references 1 and 5
- **LOAD COMBINATIONS**
  - **PIPING** (MOMENT)

    $P + W + (Ps^2 + SSE^2)^{1/2}$ (12)
  - **SNUBBERS** (FORCE)

    $(PS^2 + SSE^2)^{1/2}$ (13)
  - **STRUTS** (FORCE)

    $W + TE + (PS^2 + SSE^2)^{1/2}$ (14)
  - **VALVE ACCELERATION**

    $(PS^2 + SSE^2)^{1/2}$ (15)
  - **PIPING STRESS EVALUATION**

    $B_1 \frac{PD}{2t_n} + B_2 [W + (PS^2 + SSE^2)^{1/2}] \leq \alpha S_y$ (16)

The calculated loads for snubbers and struts should be less than or equal to the maximum load rating of these components. For piping components, the calculated stresses should be less than αS_y.

SEGMENT FORCE-TIME HISTORIES Considering the effect of the branch connection and using equation 9, force-time histories were calculated for different segments of a typical Boiling Water Reactor (BWR) recirculation piping system (Figures 6 and 7). These force-time histories were applied to the recirculation and RHR piping system segments and the piping response was calculated using the General Electric Company Proprietary Computer Program PISYS, (reference 6). Standard snubber and strut stiffnesses based on snubber and strut design load ratings were used in the PISYS model (Figure 8). Mass and stiffness proportional Rayleigh damping coefficients were calculated using three percent critical damping. The calculated values were:

α = Mass proportional damping = 2.6611

β = Stiffness proportional damping = 0.00014

The direct integration option for the time history analysis was used in the PISYS Computer Program using the calculated force-time histories. A .005 sec time increment was used with sufficient steps to pick up peak forces on snubbers and struts, maximum valve accelerations, and peak forces and moments on piping components. Stresses on piping components, snubbers and struts were calculated using the loads and load combinations given by equations (12) - (16). A summary of pipe properties, calculated stresses, snubber and strut loads and valve acceleration are given in Tables 1, 2, 3 and 4 respectively.

CONCLUSIONS

All snubber and strut loadings are within the snubber capability limits and strut service Level D ratings. The recirculation piping system will maintain functional capability and integrity of the primary pressure boundary, when subjected to loading due to a postulated one-quarter revolution pump seizure and stoppage.

ACKNOWLEDGEMENT

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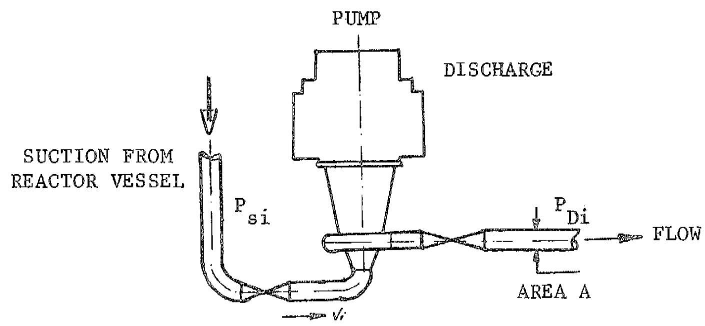


FIGURE 1

STEADY STATE FLOW CONDITION

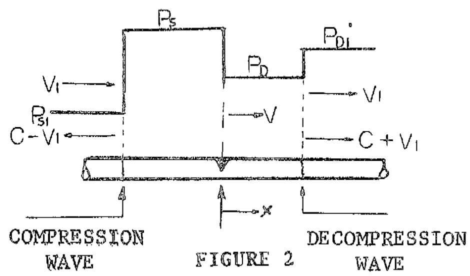


FIGURE 2

PUMP SEIZURE CONDITION

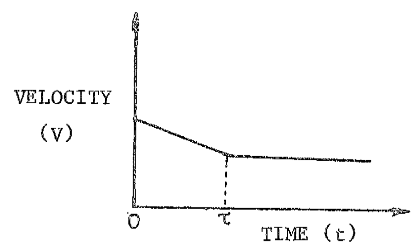


FIGURE 3

VELOCITY PROFILE

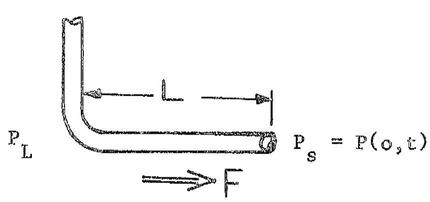


FIGURE 4

SEGMENT FORCE

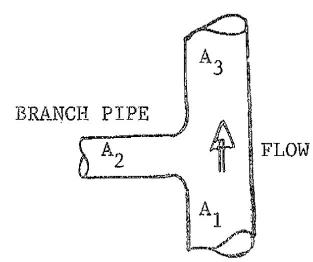


FIGURE 5
RECIRCULATION AND RHR PIPES

TABLE 1
PIPE PROPERTIES

	RECIRCULATION					RESIDUAL HEAT REMOVAL SYSTEM	
		RECIRULATION DISCHARGE					
	RECIRC-ULATION SUCTION	THROUGH VALVE	BEYOND VALVE	HEADER	RISER	TEE UPTO AND INCLUDING FIRST ELBOW	PAST FIRST ELBOW
NOM. PIPE SIZE (in)	24	24	24	16	12	20	20.0
NOM. PIPE OD (in)	23.704	24.256	24.542	16.351	12.78	19.780	20.0
NOM. PIPE ID (in)	21.78	21.70	21.70	14.359	11.38	18.030	17.938
NOM. WALL (in)	1.002	0.857	1.421	0.996	0.70	0.875	1.031
SCHEDULE	-	-	-	-	-	ROLLED WELDED	80
MATERIAL	SA 358 GR 304	SA 358 GR 304	SA 358 GR 304	SA 358 GR 304	SA 304 GR 304	SA 358, GR 304, C1I	SA 106,GrC
PIPE WEIGHT (lb/ft)	251.3	324.4	304.9	168.9	93.4	182.7	209
WATER WEIGHT (lb/ft)	159.8	159.8	159.8	70.0	43.9	110.3	109.4
INSULATION WEIGHT (lb/ft)	22.8	23.3	23.2	16.7	13.7	19.5	22.0
DESIGN TEMP. (^{o}F)	575	575	575	575	575	575	575
DESIGN PRESS. (psi)	1250	1550	1550	1550	150	1250	1250

TABLE 2
RECIRCULATION PIPE STRESS SUMMARY

STRUCTURAL NODE POINT	TYPE OF FITTING	STRESS INDICES B 1	STRESS INDICES B 2	CALCULATED STRESS (KSI)	ALLOWABLE STRESS (KSI)	STRESS RATION CALCULATED / ALLOWABLE
49	NOZZLE	0.5	1.0	15.06	27.75	.54
31	ELBOW	0.05	0.12	0.69	27.75	.03
42	TEE	0.5	2.81	16.25	37.00	.44
25	PUMP NOZZLE	0.5	1.0	10.66	27.75	.38
75	CROSS	1.0	1.0	18.00	27.75	.65
201	ELBOW	.04	0.14	0.79	27.75	.03
118	BRANCH CONNECTION	.67	2.70	16.38	37.00	.44

TABLE 3
SNUBBER AND STRUT LOAD SUMARY

SNUBBER(S) OR STRUT (ST) NUMBER	RATING (KIPS)	CALCULATED LOADS (KIPS)	ALLOW-ABLE LOADS (KIPS)	LOAD RATIO CALCULATED / ALLOWABLE	SNUBBER OR STRUT NUMBER	RATING (KIPS)	CALCULATED LOADS (KIPS)	ALLOW-ABLE LOADS (KIPS)	LOAD RATIO CALCULATED / ALLOWABLE
S301B	20	11.75	94	.12	S354B	20	9.13	94	.10
S302B	20	10.30	94	.11	S369B	100	17.05	927	.02
S303B	20	13.76	94	.15	S370B	50	5.80	231	.03
S304B	20	7.74	94	.08	S371B	100	16.48	927	.02
S305B	20	12.05	94	.13	S372B	50	18.40	231	.08
S306B	20	13.78	94	.15	S373B	50	13.59	231	.06
S356B	30	20.26	137	.15	S374B	50	13.79	231	.06
S357B	30	25.04	137	.18	S375B	50	11.77	231	.05
S358B	30	6.53	137	.05	S376B	50	42.05	231	.18
S359B	40	35.60	137	.26	ST301B	50	39.00	75*	.52
S360B	20	8.68	94	.09	ST302B	50	68.10	75*	.91
S361B	30	63.25	137	.46	S351B	20	17.25	94	.18
S362B	30	19.40	137	.14	S352B	20	8.94	94	.10
S363B	50	23.76	231	.10	S353B	20	17.02	94	.18

TABLE 4
VALVE ACCELERATION

VALVE NODE POINT	SSE ACCELERATION HORIZONTAL $(X^2+Z^2)^{1/2}$ (g)	SSE ACCELERATION VERTICAL Y (g)	PUMP SEIZURE ACCELERATION HORIZONTAL $(X^2+Y^2)^{1/2}$ (g)	PUMP SEIZURE ACCELERATION VERTICAL Y (g)	TOTAL ACCELERATION HORIZONTAL	TOTAL ACCELERATION VERTICAL
36	0.875	0.415	0.642	0.360	1.090	0.549
54	0.543	0.264	1.040	0.370	1.173	0.455

Horizontal 9 "g"

Vertical 6 "g"

FIGURE 6
FORCE-TIME HISTORIES FOR
874 REV. PUMP SEIZURE TIME

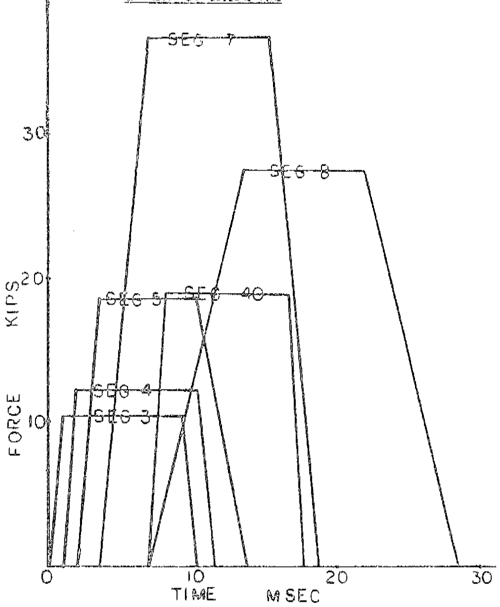
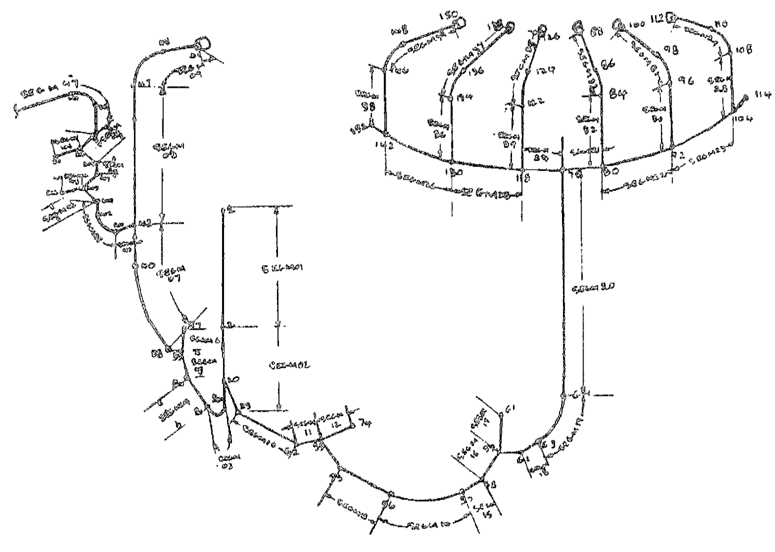


FIGURE 7
SEGMENTS MODELING
RECIRCULATION PIPING SYSTEM



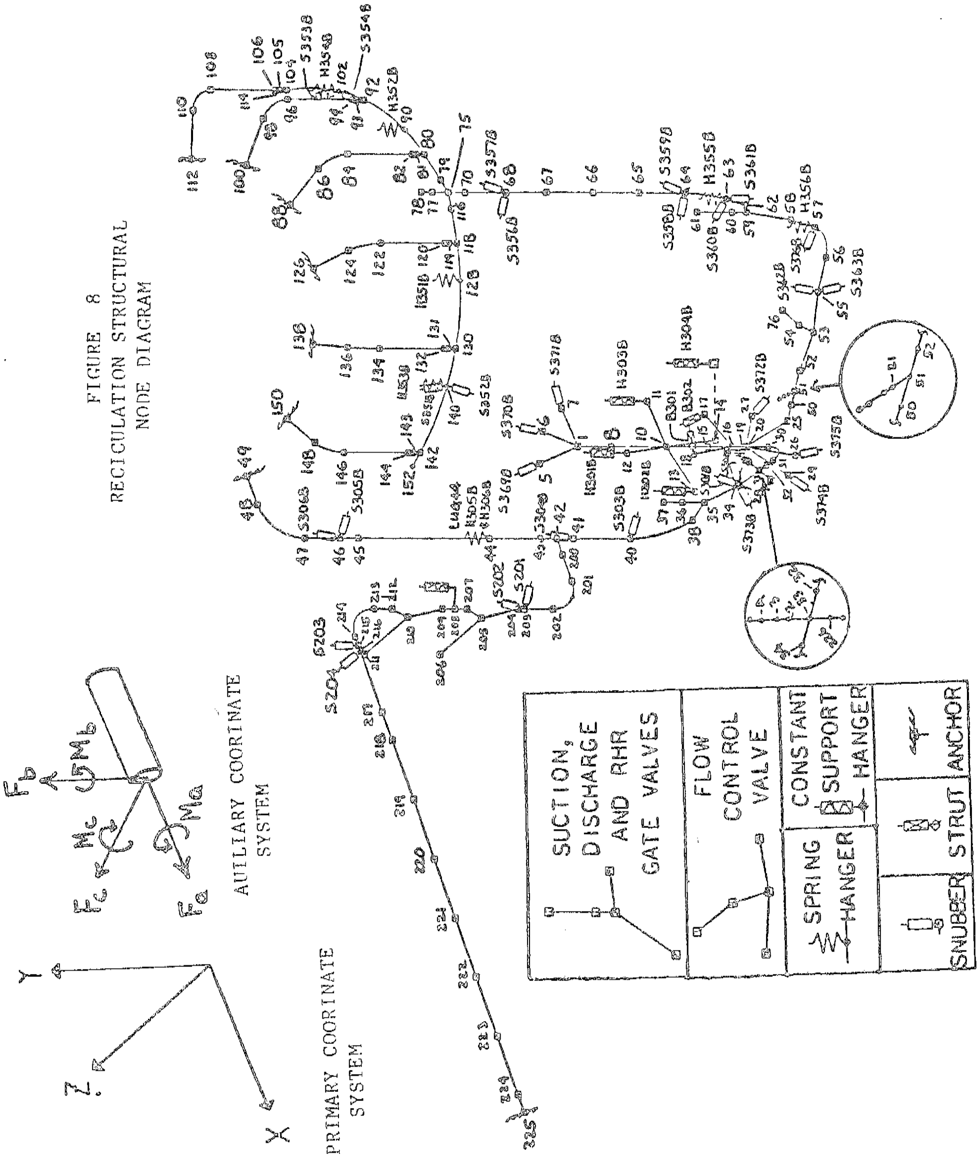


FIGURE 8
RECICULATION STRUCTURAL NODE DIAGRAM