CYGNA

Calculation Cover Sheet

Project: Pilgrim Nuclear Power Station

Job No: 90089

File No: 1/F

Client: Boston Edison Company

Calc Set No: A

No. of Sheets: 23

Subject:

Salt Service Water Pump P208A.
Casing stresses due to Accidental Drop

Statement of Problem:

Estimate the bending stresses in the service water pump casing due to a drop of 6 to 12 inches of the impeller end of the pump onto a 6" inch concrete slab on grade.

Sources of Data:

See Calculation, Section 4.0.

Sources of Formulae & References:

See Calculation, Section 4.0.

Summary:

Revised sheets 4,7,14, 20. Replaced sheet 5. Added sheets 21 - 23

Originators	Checkers	Distribution	Revision No 1
R. Howard	W. Gallagher		Supersedes Calculation Set No 0
			Approved By: Date: 1-19-90

CYGNA

Calculation Sheet

Project: Boston Edison Co.
Subject: Pump Impact Analysis
System: —
Analysis No: A Rev No: 0

Prepared By: M. Engelman
Date: 1/19/90
Checked By:
Date: 1/15/90
Job No: 90089
File No: 1/F
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1.0 Background and Problem Statement

On January 11, 1990, Salt Service Water Pump P208A was being transported from the maintenance shop (on the first floor of the New Administration Building) enroute to the Intake Structure Building. The pump, without the motor attached, was being carried in a horizontal orientation, supported by slings from forklift trucks at either end. The pump assembly is shown on BECo Drawing M8-4, Rev. E4, and has an overall length in excess of 42' from its discharge head baseplate to the tip of the suction bell.

The pump discharge head was leading and the bowl/impeller end was following. The lead end was passing through the overhead door, on the north side of the maintence shop, and was just beginning to make a turn. The rear forklift and bowl/impeller portion of the pump was still within the building line of the maintenance shop.

Just prior to the turn of the lead forklift, the individual who was directing the handling operation had walked toward that operator, and had his back to the rear forklift. As the lead forklift operator began to execute a turn, the bowl/impeller end fell to the floor. None of the people present actually saw the bowl/impeller end as it was falling.

Immediately after the bowl/impeller end fell, it was observed that one of the five column sections had a 360 degree through-wall fracture. The fracture occurred in the second 80" column section up from the bowl/impeller end, approximately 3" from the flange away from the bowl/impeller end. The pump discharge head was still suspended in the sling from the lead end forklift. The column sections from the fracture back to the bowl/impeller end were resting flat on the ground. The impeller/bowl with its sling was laying on the concrete surface just inside the overhead door. The two abutting column sections were laying on the pavement just outside the building. The impeller shaft was intact preventing significant axial or lateral separation at the fracture. Subsequent examination showed it did not experience any permanent deformation. The position of the impeller/bowl end was such that the forks of the forklift were no longer directly over the sling point, as if the sling had been pulled off the forks.

The impeller/bowl end was estimated to be somewhere between 4" and 12" above the maintenance shop floor when the accident occurred. The pump end, suspended in its sling, was estimated to be approximately 12" to 24" off the ground. The most likely accident scenario is that the forklift movements were not fully coordinated resulting in the slings of the rear forklift slipping off the forks. A less likely scenario is that the column section fractured suddenly under its own weight, and then slipped off the forks of the rear forklift. The evidence supporting the former is as follows:

- The pump had been lifted and moved some distance before the accident. Thus it was successfully "proof tested", and had sustained its own dead weight.

- The front slings were restrained from coming off the forks by an "A" frame assembly while the rear slings were not. The rear slings depended on friction to remain on the forks if the pump were to move away from the forklift.

- The position of the rear forklift and the impeller/bowl immediately after the accident suggests relative movement occurred in a direction which would pull the slings off the forks.

The purpose of this calculation is to estimate the bending stresses in the pump casing resulting from a drop of 6 to 12 inches of the impeller end of the pump onto a six inch concrete slab on grade.

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Project Boston Edison Co.
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Prepared By M. Engelman Date 1/14/90
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2.0 Method of Analysis

The pump casing is modeled as a beam with lumped masses. An energy balance approach is used to estimate the stresses in the beam after impact with the concrete slab. The work associated with the gravity forces acting over the displacements due to angular rotation of the pump just prior to impact is calculated. The work is then equated to the strain energy of deformation of the beam after impact. Additional work done by the forces acting over the beam displacements are neglected for the strain energy calculations. This is conservative. The strain energy is calculated by replacing the beam by a series of springs representing the stiffness of the beam at the mass points. Each spring exactly represents the resistance of the beam to the kinetic energy of the mass. The spring forces are then calculated by conservation of energy. These forces represent the dynamic loads imparted on the structure from the masses. The forces are used to calculate beam shears, moments and bending stresses. Due to the stiffness of the concrete/soil spring, the frequency of response near the contact point will be much greater than the natural frequency of the pump casing (approximately 0.6 Hz, Reference 4.1.3), therefore high frequency contact forces will not significantly alter the stresses near the break location. The concrete soil spring is assumed rigid and acts as a support point after the initial impact. Local forces near the contact point were not investigated.

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1/19/9

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3.0 Summary of Results

The highest bending stresses occur at about 17 feet from the impeller end of the pump. The actual break occurred at or very near the predicted point of highest stress. The maximum stress ranged from about 29.6ksi for a drop of 6 inches, to 41.9 ksi for a 12 inch drop. These represent lower bound values due to conservative estimates of the pump flange and bearing weights, and neglect of additional work energy associated with the beam deflections.

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Project Boston Edison Co. Subject Pump Impact Analysis System Analysis No A Rev No 0	Checked By	Date 1/15/90
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	Sheet No 6	

4.0 References and Drawing List

4.1 References

4.1.1 Dynamics, by J.L. Meriam, 2nd Edition, John Wiley and Sons, 1971.

4.1.2 Ladish Catalog No. 55, "Forged and Stainless Welding Pipe Fittings".

4.1.3 Seismic Stress Analysis of Vertical Pumps, Model VIT-X-SD size 16 DHLC 1, McDonald Engineering Analysis Company.

4.1.4 Vibrations of Soils and Foundations, by F.E. Richart, Jr. et al, Prentice-Hall, 1970.

4.2 Drawing List

4.2.1 Boston Edison Company, Drawing No. M8-4, Rev. E4, "Service Water Pump Assembly Drawing".

4.2.2 Boston Edison Company, Drawing No. 1065, Rev. E0, "Administration Building Foundation Plan".

other References as noted in Calculation

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Project: Boston Edison Co.
Subject: Pump Impact Analysis
System: —
Analysis No: A
Rev No: 0

Prepared By: M. Engelman
Date: 1/10/90
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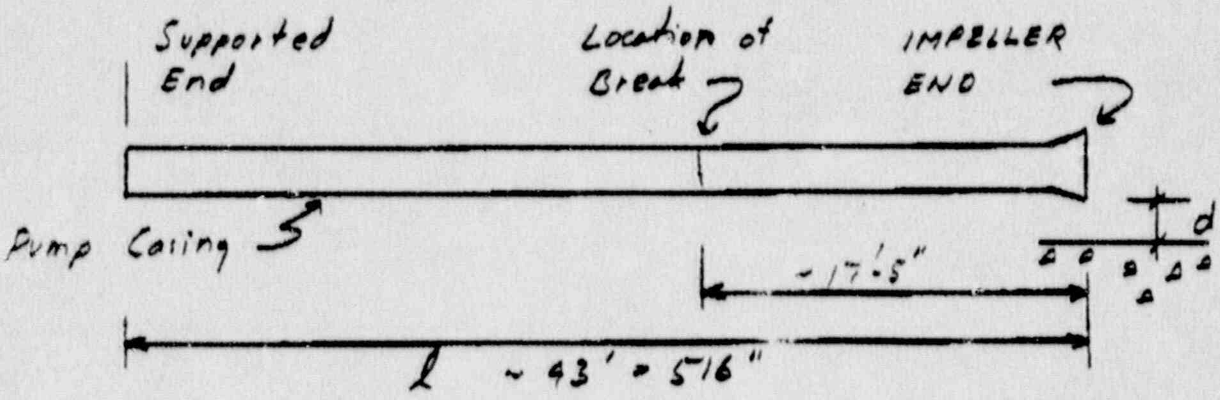
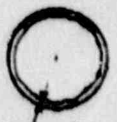
5.0 Calculations

For dimensions, see Ref. 4.2.1
4.1.3





$d = 6''$ to $12''$, Use $6''$ for initial calcs

t = 0.375
Ref. 4.1.3

$R = 6''$ O.D. $= 12.75''$ I.D. $= 12''$

$A = 2\pi R t = 14.6$ in^2

$I = 279$ in^4 Note, impeller end slightly higher I for last 3' - ignore

$S = 43.8$ in^3

Shaft Diameter $= 2.93''$ $\therefore w = 15.88$ #/ft

Casing, $w = 49.56$ #/ft Ref. AISCPI-89

Bearings, Flanges & Misc, $w = 15$ #/ft {Note: Actual min $w = 18.3$ #/ft Ref. 4.1.2

$w = 49.56 + 15.88 + 15 = 80.44$, say 80 #/ft

$W = wl = 80 \times 43 = 3440$ lb

Note: Material Density for Aluminum Bronze C95200 ~ 490 lb/ft^3
(see sheet 21)

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CKD [illegible]

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Calculation Sheet

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Checked By W. [illegible] Date 1/15/90
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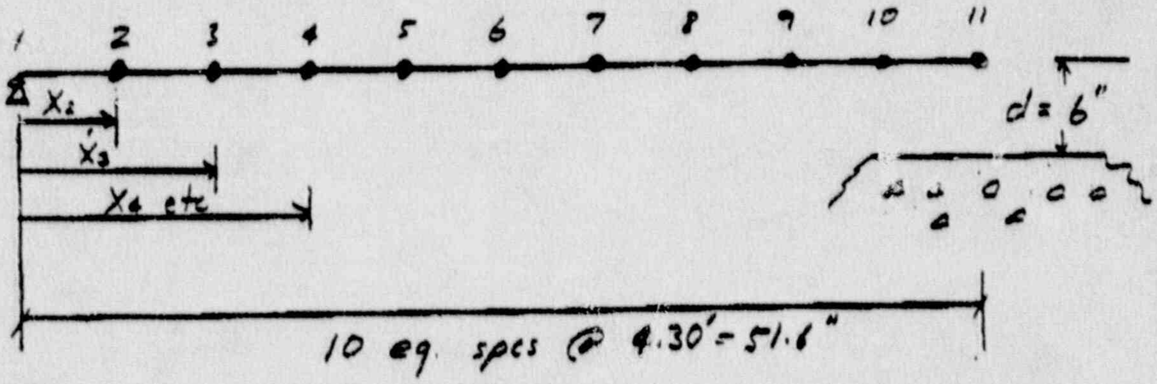
The free fall distance is small and the casing was essentially horizontal.

Use the following model to approximate the dynamic behavior of the pump casing. The numbers refer to the location of lumped masses

INITIAL - STAGE 1



$$m_{1,11} = \frac{W/g}{20} = \frac{3440/386.4}{20} = .445 \text{ IN-lb/sec}^2$$

$$m_{2-10} = \frac{W/g}{10} = \frac{3440/386.4}{10} = .890 \text{ IN-lb/sec}^2$$

After release of the impeller end, the pump casing rotates about point 1.

At the instance before impact, the model is represented as shown following

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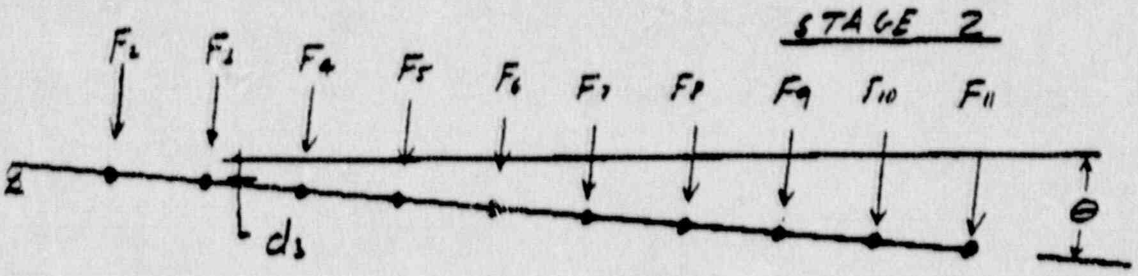

F_i = Tangential forces on masses m_i due to angular acceleration α

Equations of motion for fixed rotation:

$$\Sigma F_i = m\bar{r}\alpha$$ Ref. Dynamics eq. 116 Ref 4.1.1

$$\Sigma M_0 = I_0 \alpha$$ (0 represents pt. 1)

$$M_0 = W \times l/2 = mgl/2$$

$$I_0 = m\left(\frac{l^2}{12} + r^2\right) = m\left(\frac{l^2}{12} + \left(\frac{l}{2}\right)^2\right) = \frac{ml^2}{3}$$ Ref. 4.1.1

$$\alpha = \Sigma M_0 / I_0 = \frac{mgl/2}{ml^2/3} = \frac{3g}{2l} \text{ rad/sec}^2$$

$$\Sigma F_i = m\bar{r}\alpha = \frac{ml}{2} \times \frac{3g}{2l} = \frac{3}{4} W$$

@ any point i :

$$F_i = m_i \times X_i \times \frac{3g}{2l} \quad , X_i = .1l, .2l \text{ etc}$$

$$F_i = \frac{3}{2} W_i \frac{X_i}{l}$$

The work done by gravity just before impact is :

$We = ke = \Sigma F_i d_i$ where d_i = displacement @ node i just before impact

$d_i = \frac{X_i}{l} \times d$

Calculate the work or kinetic energy, ke for each mass location :

$Ke_i = F_i \times d_i = \frac{3}{2} w_i \left(\frac{X_i}{l}\right)^2 \times d$

$\Sigma ke_i = \frac{3d}{2l^2} \Sigma w_i x_i^2$

Now equate the total work done just before impact to the internal strain energy in the beam at the time of maximum deflection from the dynamic loads. The following assumptions are made :

1) The strain energy in the beam can be represented by springs at the mass point locations

2) The springs have a stiffness represented by the inverse of the deflection at point

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Project Boston Edison Co.		Prepared By M. Ezzahmn	Date 1/10/90
Subject Pump Impact Analysis		Checked By W. Hal	Date 1/15/90
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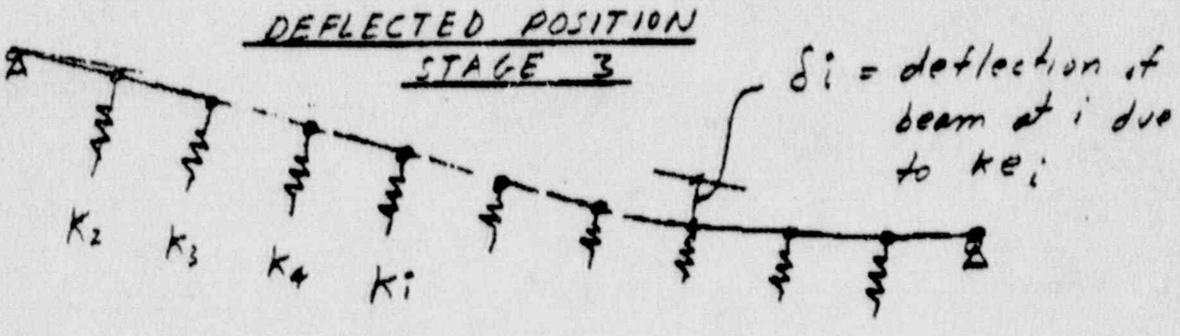
Analysis No A	Rev No 0	Sheet No 11	

i due to a unit load at i.

3) The maximum deflection of the springs occurs simultaneously. This should be reasonable for all nodes except those very near the point of contact. This is because the frequency of the pump casing is extremely low (~ .6 Hz) relative to the contact response frequency of the casing impacting slab on grade concrete. Any high frequency response near the impact point will be highly localized and will not significantly affect the response at the points of interest near midspan — Ref. 9.1.3

The model at the maximum deflection is :



The Strain Energy , Se for each spring is $Se = \frac{1}{2} k_i \delta_i^2$ at max. deflection

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Therefore, for each spring, equating work with strain energy:

$$ke_i = Se_i - \cancel{F(t) \times} \delta i = \frac{1}{2} k_i \delta_i^2$$

$$\delta_i = (2 ke_i / k_i)^{1/2}$$

Note: Additional work done by gravity forces over δ_i are small - neglect, conservative.

The spring force, $Fs_i = k_i \delta_i$ or

$$Fs_i = (2 ke_i \times k_i)^{1/2}$$

This represents the equivalent force on the beam at location i required to deflect the beam δ_i

From the equivalent forces acting on the beam, the reactions, shears, moments & stresses can be determined. These calculations and results follow:

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Calculation Sheet

Prepared By: M. Engelman	Date: 11/14/90
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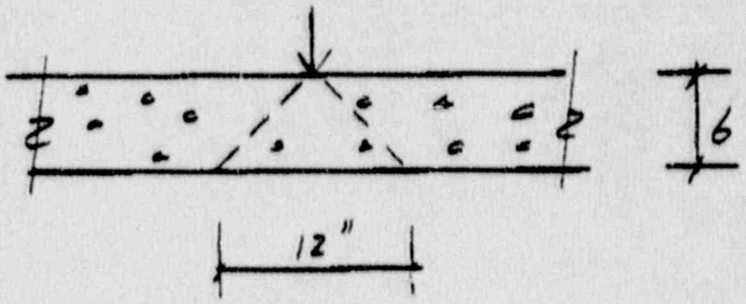
Calculate Soil Spring :
@ Contact Pt

SLAB ON
GRADE
Ref. 4.2.2



$$K = \frac{4GR_0}{1-\nu}$$ soil stiffness Ref 4.1.4 pg 205

G = Soil Shear Modulus

R_0 = Radius of Contact Area = 6"

ν = Poissons Ratio = 0.33

G is estimated as 3000 psi for a lower bound for compacted backfill. It is much higher in reality based on the chart on pg 205, Ref. 4.1.4 for granular material.

K = 4×3000×6 / 1−.33 = 107,463 lb/in >> Beam Stiffness

∴ Assume support is rigid for this analysis
Will have negligible effect on stresses.

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Calculation Sheet

Project *Boston Edison Co.*	Prepared By *M. Evgehman*		Date *1/14/90*
Subject *Pump Impact Analysis*	Checked By *[illegible]*		Date *1/15/90*
System —	Job No *90089*	File No *11F*	
Analysis No *A* Rev No *0*	Sheet No *14*		

$E := 29000000$ Modulus of Elasticity *Ref. 4.1.3* (See SHT 21)

$l := 516$ Length in inches

$I := 279.0$ Moment of Inertia

$S := 43.8$ Section Modulus

△ By [illegible] 1-19-90 CKD [illegible] 1/19/90

$i := 2\,..10$ Perform operations for points 2 to 10

$$x_i := \frac{i-1}{10}\cdot l$$ Distance to location i

$$k_i := 3\cdot E\cdot I\cdot l\cdot\frac{1}{x_i^2}\cdot\frac{1}{\left[l-x_i\right]^2}$$ Spring stiffness of beam at location i *Ref. AISC Manual 8th Ed. Case 8, pg 2-116*

i	x_i	k_i
2	51.6	21811.7
3	103.2	6901.4
4	154.8	4006.2
5	206.4	3067.3
6	258	2826.8
7	309.6	3067.3
8	361.2	4006.2
9	412.8	6901.4
10	464.4	21811.7

$d := 6$ inches Assumed free fall distance of impeller end of the pump casing

$w := 6.67$ lbs per in (80 lbs per foot) (See SHT 21 -23) △ By EHH 1-19-90 CKD [illegible] 1/19

$g := 386.4$ in/sec2

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Calculation Sheet

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$W := w \cdot l$ total weight

$m := \dfrac{W}{g}$ total mass

$w_i := \dfrac{W}{10}$ weight at location i, i= 2 to 10

$w_{11} := \dfrac{W}{20}$

$F_i := \dfrac{3}{2} \cdot w_i \cdot \left[\dfrac{x_i}{l}\right]$ Force at location i due to gravity

$Ke_i := F_i \cdot \left[\dfrac{x_i}{l}\right] \cdot d$ kinetic energy at each spring.

$\delta_i := \left[2 \cdot \dfrac{Ke_i}{k_i}\right]^{.5}$ deflection of the beam at location i

Note - This deflection is ***not*** *the total deflection of the beam*

$Fs_i := \delta_i \cdot k_i$ restoring force at location i

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Calculation Sheet

M. Engelman 1/14/90
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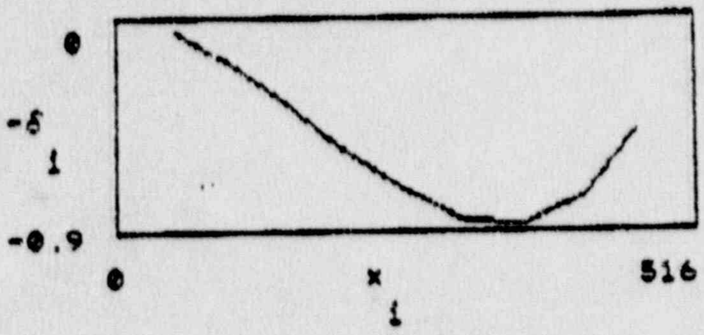
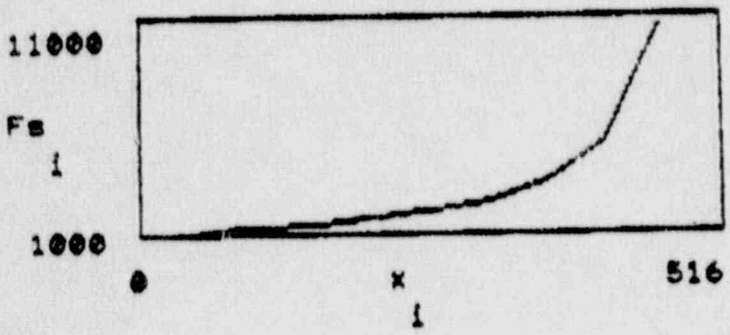
i	w_i	$\frac{x_i}{l}$	F_i	Ke_i	δ_i	Fs_i
2	344.2	0.1	51.6	31	0.1	1162.4
3	344.2	0.2	103.3	123.9	0.2	1307.7
4	344.2	0.3	154.9	278.8	0.4	1494.6
5	344.2	0.4	206.5	495.6	0.6	1743.7
6	344.2	0.5	258.1	774.4	0.7	2092.4
7	344.2	0.6	309.8	1115.1	0.9	2615.5
8	344.2	0.7	361.4	1517.8	0.9	3487.3
9	344.2	0.8	413	1982.4	0.8	5231
10	344.2	0.9	464.6	2509	[illegible].5	10461.9



Deflection

Note: Not total deflection. Only due to ke_i at point i.



Restoring Force

$$M_i := Fs_i \left[l - x_i \right]$$

Moment induced about point 11 due to dynamic loads at point i.

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$$\sum_i M_i = 4858513.4 \qquad R_1 := 4.86 \cdot \frac{10^6}{l} \qquad R_1 = 9418.6$$

Reaction at location 1

$$V_1 := R_1 \qquad V_i := V_{i-1} - Fs_i$$

Shear force from location i to i+1

$$M_1 := 0 \qquad M_i := M_{i-1} + V_{i-1} \cdot \frac{l}{10}$$

Moment at location i

$$M_{11} := 0$$

$$fb_i := \frac{M_i}{S} \qquad fb_{11} := 0$$

Bending Stress at location i

$i := 1 \,..10$

i	x_i	V_i	M_i	fb_i
1	0	9418.6	0	0
2	51.6	8256.2	486000	11095.9
3	103.2	6948.4	912018.4	20822.3
4	154.8	5453.9	1270557.4	29008.2
5	206.4	3710.2	1551977.1	35433.3
6	258	1617.8	1743424.4	39804.2
7	309.6	-997.6	1826904.7	41710.2
8	361.2	-4484.9	1775426.3	40534.8
9	412.8	-9715.9	1544002.9	35251.7
10	464.4	-20177.8	1042662.2	23805.1

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M. Ezahun 1/10/90

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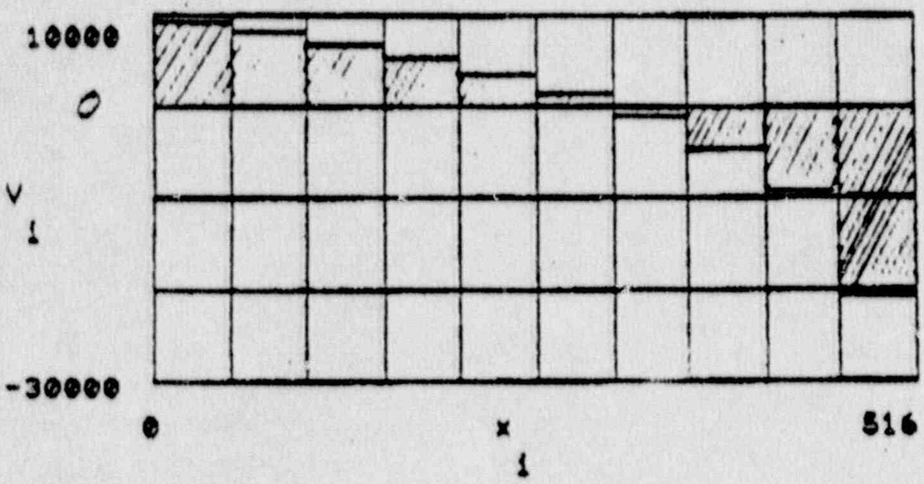
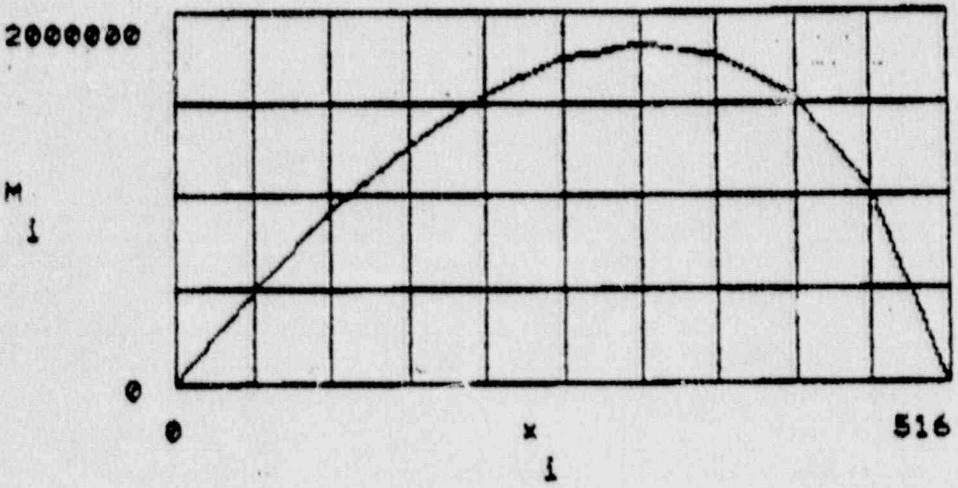


Shear Diagram
lbs

$i := 1 \,..11$

$x_{11} := 516$



Moment Diagram
inch-lbs

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Calculation Sheet

Prepared By M. Engelman
Date 11/16/90
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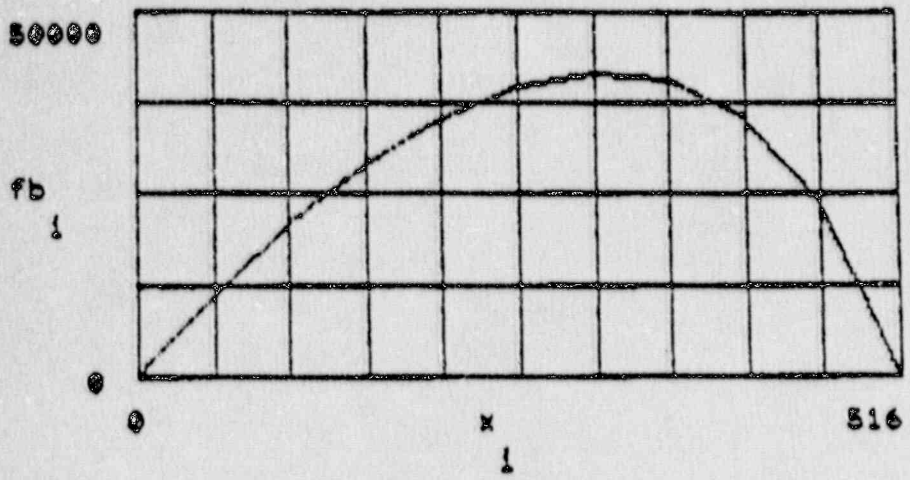

Per the above graphs and tables, the maximum predicted stress is at location 7, corresponding to 0.4 x 516 inches, or 17.2 feet from the impeller end of the casing. Actual failure occurred at approximately 17.4 feet from the end. Agreement is excellent with the predicted results.

Since Fs, the restoring force, is a function of the square root of Ks, then Fs, V (Shear), M, (Moment) and fb (Bending Stress) are also a function of Ks. Ks is proportional to d, therefore the above parameters are a function of the square root of d, the distance the impeller end of the pump shaft casing fell before striking the ground.

The predicted bending stresses for free fall distances greater than 6 inches are as follows:"

$j := 6 \, ..12$

$d_j := j$

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$$f_j := \left[\frac{d_j}{6}\right]^{.5} \qquad fb_j := f_j \cdot 41710$$

Distance to Impact (d), inches d_j
6
7
8
9
10
11
12

Maximum Bending Stress at location 7 fb_j
41710
45051.9
48162.6
51084.1
53847.4
56475.6
58986.8

See SHEET 21-23

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PAGE 14 OF THIS CALCULATION SHOWES A MODULUS OF ELASTICITY OF $E = 29 \times 10^6$ FOR THIS MATERIAL IT SHOULD BE $E = 15 \times 10^6$ ALSO THE DENSITY CHANGES FROM $W = 0.283$ #/IN³ TO 0.276 #/IN³ (REF. METALS HANDBOOK NINTH EDITION, MAT. C95200 88CU-3FE-9AL). A RATIO WILL BE DETERMINED USING THESE NEW VALUES TO AQUIRE NEW STRESSES

$$F_b \propto \left[\frac{F_i}{K_i}\right]^{1/2} K_i$$

$$F_b \propto \left[\frac{W_N/W_O}{K_i}\right]^{1/2} K_i$$

$$F_b \propto \left[\frac{W_N/W_O}{E_N/E_O}\right]^{1/2} \frac{E_N}{E_O}$$

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Calculation Sheet

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Date: 1-19-90
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$E_N = 15 \times 10^6$ $\quad$ $E_O = 29 \times 10^6$

$W_N = 0.276 \ \#/in^3$ $\quad$ $W_O = 0.283 \ \#/in^3$

$$F_b \propto \left[\frac{.276/.283}{15\times10^6/29\times10^6} \right]^{1/2} \frac{15\times10^6}{29\times10^6}$$

$$F_b \propto \left[\frac{.975}{.517} \right]^{1/2} .517$$

$$F_b = 0.7100$$

THEREFORE THE STRESSES LISTED ON PAGE 20 CAN BE MULTIPLIED BY THIS ADJUSTED FACTOR

CYGNA

Calculation Sheet

Prepared By R. Hood
Date 1-19-90
Checked By
Date 1-19-90
Project BOSTON EDISON CO
Subject PUMP IMPACT ANALYSIS
System
Job No 90089
File No 1/F
Analysis No B
Rev No 1
Sheet No 23

DISTANCE TO IMPACT (d), INCHES d_j	MAXIMUM BENDING STRESS AT LOCATION 7 Fb_j
6	29614
7	31982
8	34195
9	36270
10	38232
11	40098
12	41881

NUCLEAR ORGANIZATION RTYPE A2.20

CONTROLLED DOCUMENT CHANGE NOTICE (CDCN)

CDCN Log No. ______

~~MANUAL TITLE~~: ______

DOCUMENT TITLE: Operability Evaluation of SSW Pump Columns

DOCUMENT NO.: FS&YC Calc M-410

☒ NEW DOCUMENT ☐ RETIRE ☐ REVISION

SECTION(S)/PROCEDURE(S) AFFECTED

FSAR Sect 12, A&C

REV. NO./DATE AFTER CHANGE: Rev. 0 / 1/19/90

NO. OF PAGES ATTACHED: 11

OTHER KNOWN DOCUMENTS AFFECTED SUDDS/RF 89-75, F&MR 90-8/NCR 90-3&4

GENERAL REASON FOR CHANGE

☐ Change in Work Process ☒ Change in Related Document or Procedure

☐ Error in Previous Revision ☐ Editorial Change Only

☒ Other: Support JCO NED 90-041

SPECIFIC PURPOSE AND SUMMARY OF CHANGES

Determine operability of SSW Pumps in degraded condition as a result of transportation drop on 1/11/90. Pump Col found cracked + material (Al-Bz) physical prop. degraded. Determine whether remaining pump columns in service are operable assuming worst case mat'l prop. (Ref Enclosure)

Signature of Initiator: ______ Dept. Mgr: ______

Approvals to retire NUORG Procedures: ______
DNE SD SVPN

Approval to retire Nuclear Operations Procedures: ______ / ______
SD /date

Date Issued by Document Control ______