New Folder Name Beam Tube Design

- INPUT VARIABLES

Tube outside diameter, Do =	49.004	in	
Beam Tube section length, L =	19.812	m =	65.000 ft
Beam Tube Span length, Lsp =	18.9484	m =	62.167 ft
Tube thickness, t =	0.127	in	
Insulation Density, Deni =	24	kg/m =	16.127 lbs/ft
Vacuum Stiffener thickness, ts =	0.1875	in	
Vacuum Stiffener width, ws =	1.75	in	
Vacuum Stiffener spacing, Ls =	29.84	in	
Support Stiffener thickness, tss =	0.375	in	
Support Stiffener width, wss =	4	in	
Mod. of Elast. @ ambient, Ea =	28,300	ksi	Table TM-1 @ 70
Mod. of Elast. @ 302 degrees, Eb =	27,000	ksi	Table TM-1, Page 664
Coefficient of expansion, e=	9E-06	in/in/F	Average from 70 to 300 degrees F
Anchor bolt spacing, Abs =	30	in	
C. line height of tube, H =	42.000	in	
Support Collar / Saddle width, b =	20.000	in	
Expansion Joint O.D., De =	53.75	in	
Expansion Joint I.D., Dei =	48.75	in	
E.J. Concentricity Error, CE =	0.1875	in	
Expansion joint axial spring rate, Kej =	9147.6	lbs/in	=8316 * 1.1
Spring rate variation, Eej =	10.0%		
Spring Rate, K =	10062	lbs/in = Kej * (1 + Eej)	

SUBJECT: LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	OFFICE: NOE-C		REVISION:	REFERENCE NO. 930212
	MADE BY: RJW	CHKD BY: WJC	MADE BY	CHKD BY
	DATE: 3/11/94	DATE: 4-4-94	DATE	DATE

- TUBE WEIGHT & PROPERTIES

Inside Diameter, Di =	48.75	in
Area, A =	19.501	in^2 = PI() * (Do^2 - Di^2) / 4
Section Modulus, S =	237.7	in^3 = PI() * (Do^4 - Di^4) / 32 / Do
Moment of inertia, I=	5823	in^4 = PI() * (Do^4 - Di^4) / 64
Radius of gyration, rg =	17.281	in = (I / A)^0.5
Theoretical # of vacuum stiffeners=	27	= Round(L/Ls*12)
Number of stiffeners used, Ns =	25	
True spacing =	31.200	in = L/(Ns)*12
Number of support stiffeners, Nss =	1.5	Per section
Shell weight per section =	4357	lbs = 495 * A/144 * L
Weight per vacuum stiffener =	14.987	lbs = PI() * ((Do+2*ws)^2-Do^2)/4 * Ts * 495 / 12^3
Weight per support stiffener =	71.550	lbs = PI() * ((Do+2*wss)^2-Do^2)/4 * Tss * 495 / 12^3
Stiffener weight per section =	482.01	lbs = Weight Vacuun * Ns + Weight support *Nss
Estimated Baffle wt / section =	27.5	lbs
Total metal weight, DL =	4867	lbs, or
wd =	74.87	lbs/ft
Insulation weight per section =	1048	lbs = Deni * L
DL + Insulation =	5915	lbs, or
wdi =	91.00	lbs/ft

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LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY RJW	CHKD BY WJC	MADE BY	CHKD BY	SHT 2 OF 29
	DATE 3/11/94	DATE 4.4.94	DATE	DATE	6.6

- ALLOWABLE STRESS PER ASME SECTION VIII DIV 1 UG 23(b)

- Allowable Stresses @ 300 Degrees F.

Yield Stress, Fy = 19,200 psi — Table Y1
Tensile Allowable, Sh = 13000 psi — Table 1A
Joint Efficiency, Et = 0.7
Compression Allowable — UG 23(b)

A = 0.000648 = 0.125 / (Ro/t)
B = 5900 psi per Figure HA 3, interpolate to 300 degrees F.
Where B = Fa = Fbx = Fby = Fbxy, local buckling stress
See below for column buckling

- Allowable Stresses @ Ambient (100 degrees F)

Yield Stress = 25,000 psi — Table Y1
Tensile Allowable, Sa = 16,300 psi — Table 1A
Compression Allowable — UG 23(b)

A = 0.000648 = 0.125 / (Ro/t)
B = 7800 psi per Figure HA 3, 100 degrees F.
Where B = Fa = Fbx = Fby = Fbxy

- Allowable Stress Increase for Wind and Seismic
Allowable increase for wind or seismic is 1.20

- Allowable Axial Stress, Column Buckling per AISC

k = 1
L = 746 in = Lsp * 12
r = 17.28069 in = rg

kL / r = 43.16958

Cc = 166.6081 = (2 * Pi()^2 * Eb * 1000 / Fy)^0.5

$$Fa = 10533 \text{ psi} = \frac{(1- (kL/r)^2 / 2 / Cc^2)*Fy}{(5/3 + 3*(kL/r)/8/Cc - (kL/r)^3/8/Cc^3)}$$

Fa > B, Thus use B = 5900 psi

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	DATE 3/11/94	DATE 4.4.94	DATE	DATE	

- CALCULATE WIND LOAD PER ASCE 7-88 (Livingston, LA)

F = Qz * Gh * Cf * Af			Table 4
Qz =	4.1472	= 0.00256*Kz * (I*V)^2	Eq 3
Kz =	0.80	, Assume exposure C	Table 6
I =	1.00		Table 5
V =	45	mph	Figure 1
Gh =	1.32		Table 8
Cf =	0.739	h / D = 0.0853	Table 12
		h = (Do / 2 +H)/12	
		D = L	
		D' / Do = ws / Do = 0.03571	
Af =	4.084	Sqft / ft = Do / 12	
F =	16.53	lbs / ft	
F =	1074	lbs / section	

- CALCULATE WIND LOAD PER ASCE 7-88 (Hanford, WA)

F = Qz * Gh * Cf * Af			Table 4
Qz =	4.1472	= 0.00256*Kz * (I*V)^2	Eq 3
Kz =	0.80	, Assume exposure C	Table 6
I =	1.00		Table 5
V =	45	mph	Figure 1
Gh =	1.32		Table 8
Cf =	0.739	h / D = 0.0853	Table 12
		h = (Do / 2 +H)/12	
		D = L	
		D' / Do = ws / Do = 0.03571	
Af =	4.083667	Sqft / ft = Do / 12	
F =	16.53	lbs / ft = ww	
F =	1074	lbs / section	

- CALCULATE SEISMIC LOAD PER UBC (Livingston, LA)

V = Z * I * C / Rw * W

Z =	0		
I =	1.0		
C =	2.75		
Rw =	3		
C/Rw =	0.916667	> 0.075 use:	0.91667
W =	91.00	lbs/ft = DL + Insulation	
V =	0.0500W	= 0.05W mimimum per ASCE 7-88, 9.11.2	
V =	4.55	Lbs/ft	
V =	295.8	Lbs per section	

- CALCULATE SEISMIC LOAD PER ASCE 7-88 (Hanford, WA)

V = Z * I * C / Rw * W

Z =	0.2		
I =	1.0		
C =	2.75		
Rw =	3		
C/Rw =	0.916667	> 0.075 use:	0.91667
W =	91.00	lbs/ft = DL + Insulation	
V =	0.1833W		
V =	16.68	Lbs/ft = wseis	
V =	1084.4	Lbs per section	

- CALCULATE SNOW LOAD PER ASCE 7-88 (Hanford, WA only)

Pf =	15.12	= 0.7 * Ce * Ct * I * Pg	Eq 5a
Ce =	0.9	Little shelter assumed	Table 18
Ct =	1.2	Unheated	Table 19
I =	1	Category 1	Table 20
Pg =	20	psf	Figure 6
Ps =	9.828	= Cs * Pf	
Cs =	0.65	Angle is 35 degrees, 90-(180-70)/2,	Figure 8b
Width =	46.049	in = Do * Sin 70	Per 7.4.3, slope > 70 no load
Snow Load per foot, wsn =	37.71	lbs/ft = Ps * Width	
Snow load per section =	2451	lbs	

- DETERMINE REACTIONS, STRESSES AND DEFLECTIONS FOR INDIVIDUAL LOAD CASES

  - Nomenclature

    Rfx1 = Reaction, fixed support, x direction (horizontal), case 1
    Rgy2 = Reaction, guided support, y direction (vertical), case 2
    Rfz1 = Reaction, fixed support, z direction (axial), case 1
    Mx1 = Moment about the horizontal axis due to vertical loads, Case 1.
    My2 = Moment about the vertical axis due to horizontal loads, Case 2.
    fa9c = Stress, axial, case 9, compression, (if tension t is used instead of c)

  - Reactions Based on RISA2D

    Fixed support = 7.029 kips, per RISA2D
    1/2 of guided support = 2.41 kips, per RISA2D
    Total, two spans = 11.849 kips, per RISA2D

    % Fixed support, Kf = 0.593215 (Percentage of 2 spans)
    % Guided support, Kg = 0.406785

  - Moments based on RISA2D

    Maximum Moment = 43480 lb-ft, at fixed support
    Based on, 91 lbs/ft, DL + Insulation, used in RISA2D

    True DL + Insulation = wdi = 91.00
    Estimated Moment = 43961 lb-ft = wdi * (Lsp ft)^2 / 8

    Moment correction factor, Km = 0.989 = RISA2D moment / Estimated moment

  - Deflections based on RISA2D

    Midspan Deflection = 0.079 in
    Based on, 91 lbs/ft, DL + Insulation, used in RISA2D

    True DL + Insulation = wdi = 91.00
    Estimated Deflection = 0.081 in = wdi * Lsp^4 / 185 / Eb / I * 12^3 / 1000

    Moment correction factor, Kd = 0.978 = RISA2D deflection / Estimated deflection

- CASE 1: Dead Load Reactions, Stresses and Deflections

FIXED SUPPORT

Rfx1 = 0
Rfy1 = 5774 lbs = Kf * 2 * L * wd
Rfz1 = 0

GUIDED SUPPORT

Rgx1 = 0
Rgy1 = 3959 lbs = Kg * 2 * L * wd

MOMENTS & BENDING STRESS

Mx1 = 35774 lb-ft = wd * (Lsp)^2 / 8 * Km
fbx1 = 1806 psi = Mx1 * 12 / S

My1 = 0
fby1 = 0 psi = My1 * 12 / S

MIDSPAN DEFLECTION

Dely1 (amb)= 0.062 in = wd * Lsp^4 / 185 / Ea / I * 12^3 / 1000 * Kd

- CASE 2: Dead Load plus Insulation Reaction, Stresses and Deflections

FIXED SUPPORT

Rfx2 = 0
Rfy2 = 7018 lbs = Kf * 2 * L * wdi
Rfz2 = 0

GUIDED SUPPORT

Rgx2 = 0
Rgy2 = 4812 lbs = Kg * 2 * L * wdi

MOMENTS & BENDING STRESS

Mx2 = 43480 lb-ft = wdi * (Lsp)^2 / 8 * Km
fbx2 = 2195 psi = Mx2 * 12 / S

My2 = 0
fby2 = 0 psi = My2 * 12 / S

MIDSPAN DEFLECTION

Dely2 (302)= 0.079 in = wdi * Lsp^4 / 185 / Eb / I * 12^3 / 1000 * Kd

- CASE 3: Snow Load Reaction, Stresses and Deflections (Hanford, WA)

FIXED SUPPORT

Rfx3 =	0	
Rfy3 =	2908	lbs = Kf * 2 * L * wsn
Rfz3 =	0	

GUIDED SUPPORT

Rgx3 =	0	
Rgy3 =	1994	lbs = Kg * 2 * L * wsn

MOMENTS & BENDING STRESS

Mx3 =	18020	lb-ft = wsn * (Lsp)^2 / 8 * Km
fbx3 =	910	psi = Mx3 * 12 / S
My3 =	0	
fby3 =	0	psi = My3 * 12 / S

MIDSPAN DEFLECTION

Dely3 (amb)= 0.031 in = wsn * Lsp^4 / 185 / Ea / I * 12^3 / 1000 * Kd

- CASE 4: Wind Load Reaction, Stresses and Deflections (Livingston, LA)

FIXED SUPPORT

Rfx4 =	1275	lbs = ww * 2 * L * Kf
Rfy4 =	0	
Rfz4 =	0	

GUIDED SUPPORT

Rgx4 =	874	lbs = ww * 2 * L * Kg
Rgy4 =	0	

MOMENTS & BENDING STRESS

Mx4 =	0	
fbx4 =	0	psi = Mx4 * 12 / S
My4 =	7896	lb-ft = ww * (Lsp)^2 / 8 * Km
fby4 =	399	psi = My4 * 12 / S

MIDSPAN DEFLECTION

Delx4 (amb)= 0.014 in = ww * Lsp^4 / 185 / Ea / I * 12^3 / 1000 * Kd

- CASE 5: Seismic Reaction, Stresses and Deflections (Hanford, WA), X Direction (Horizontal)

FIXED SUPPORT

Rfx5 =	1287	lbs = wseis * 2 * L * Kf
Rfy5 =	0	
Rfz5 =	0	

GUIDED SUPPORT

Rgx5 =	882	lbs = wseis * 2 * L * Kg
Rgy5 =	0	

MOMENTS & BENDING STRESS

Mx5 =	0	
fbx5 =	0	psi = Mx5 * 12 / S
My5 =	7971	lb-ft = wseis * (Lsp)^2 / 8 * Km
fby5 =	402	psi = My5 * 12 / S

MIDSPAN DEFLECTION

Delx5 (amb)= 0.014 in = wseis * Lsp^4 / 185 / Ea / I * 12^3 / 1000 * Kd

- CASE 6: Seismic Reaction, Stresses and Deflections (Hanford, WA), Z Direction (Axial)

FIXED SUPPORT

Rfx6 =	0	
Rfy6 =	0	
Rfz6 =	2169	lbs = wseis * 2 * L

GUIDED SUPPORT

Rgx6 =	0	
Rgy6 =	0	

MOMENTS & BENDING STRESS

Mx6 =	0	
fbx6 =	0	psi = Mx5 * 12 / S
My6 =	0	
fby6 =	0	psi = My6 * 12 / S

MIDSPAN DEFLECTION

Dely6 (amb)= 0.000 in

- CASE 7: Vacuum

Bellows effective area =	2062.9	sq in = PI()*((De+Dei)/2)^2/4
Tube pressure area =	1866.55	sq in = PI()*((Di))^2/4
Bellows pressure area =	196.35	sq in =Bellows effective - tube area
Axial force, Pzp =	2886	lbs = 14.7*Bellows pressure area, pos.=tension
Axial Stress due to vacuum, fav7 =	148.0	psi = Pzp / A, pos. = tension

FIXED SUPPORT

Rfx7 =	0	lbs
Rfy7 =	0	
Rfz7 =	0	

GUIDED SUPPORT

Rgx7 =	0	lbs
Rgy7 =	0	
fbx7 = fby7 =	0	
Dely7 =	0	

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LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WJC	MADE BY	CHKD BY	SHT 10 OF 29
	DATE: 3/11/94 / DATE: 4-4-94	DATE	DATE	6.14

- CASE 8: Differential Settlement of Fixed Support

  - Reactions Based on RISA2D with 1" differential settlement

Fixed support = -2.37 kips, per RISA2D
1/2 of guided support = 2.47 kips, per RISA2D
Based on, 1 lbs/ft, DL, used in RISA2D

FIXED SUPPORTS
Rfx8 = -2447 lbs = (RISA2D fixed) - DL * 2 * L * Kf
Rfy8 = -2447 lbs = (RISA2D fixed) - DL * 2 * L * Kf
GUIDED SUPPORTS
Rgx8 = 4887 lbs = 2 * (RISA2D guided) - DL * 2 * L * Kg
Rgy8 = 4887 lbs = 2 * (RISA2D guided) - DL * 2 * L * Kg

  - Moments based on RISA2D with 1" differential settlement

Maximum Moment = 71360 lb-ft, at fixed support
Based on, 1 lbs/ft, DL + Insulation, used in RISA2D

Mx8 = My8 = 70882 lb-ft = (RISA2D Moment) - DL * Lsp^2 / 8 * Km
fbx8 = fby8 = 3579 psi = Mx8 * 12 / S

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	DATE 3/11/94	DATE 4-4-94	DATE	DATE	6.15

- CASE 9: Expansion Joint Forces at 302 Degrees F.

Maximum Bellows spring rate, K =	10062	lbs/in = Kej * (1 + Eej)
Est. temp. change above 70, Tch =	232	degrees Fahrenheit
Thermal growth hot, x =	3.257	in = e * 2 * L * 12 * Tch
Longitudinal Comp. force, Pbc =	32776	lbs = K * x
fa9c =	-1681	psi = Pbc / A, stress on tube, neg is comp
FIXED SUPPORT		
Rfx9 =	0	lbs
Rfy9 =	0	
Rfz9 =	5959	lbs = 2 * Eej * Kej * x
GUIDED SUPPORT		
Rgx9 =	0	
Rgy9 =	167.8	lbs = Rfz9 * H / Lsp / 12 /2
fbx9 = fby9 =	0	
Delx9 = Dely9 =	0	

- CASE 10: Expansion Joint Forces at 100 Degrees F.

Maximum Bellows spring rate, K =	10062	lbs/in = Kej * (1 + Eej)
Est. temp. change above 70, Tch =	30	degrees Fahrenheit
Thermal growth hot, xw =	0.421	in = e * 2 * L * 12 * Tch
Longitudinal Comp. force, Pbc =	4238	lbs = K * xw
fa10c =	-217	psi = Pbc / A, stress on tube, neg is comp
FIXED SUPPORT		
Rfx10 =	0	lbs
Rfy10 =	0	
Rfz10 =	771	lbs = 2 * Eej * Kej * xw
GUIDED SUPPORT		
Rgx10 =	0	
Rgy10 =	21.7	lbs = Rfz10 * H / Lsp / 12 /2
fbx10 = fby10 =	0	
Delx10 = Dely10 =	0	

- CASE 11: Expansion Joint Forces at -16 Degrees F.

Maximum Bellows spring rate, K =	10062	lbs/in = Kej * (1 + Eej)
Est. temp. change below 70, Tchc =	86	degrees Fahrenheit
Thermal shrinkage, xs =	-1.207	in = e * 2 * L * 12 * Tchc
Longitudinal Tension force, Pbt =	12150	lbs = K * xs
fa11t =	623	psi = -Pbt / A Positive is tension

FIXED SUPPORT

Rfx11 =	0	lbs
Rfy11 =	0	
Rfz11 =	2209	lbs = -2 * Eej * Kej * xs

GUIDED SUPPORT

Rgx11 =	0	
Rgy11 =	62.2	lbs = Rfz11 * H / Lsp / 12 /2

fbx11 = fby11 =	0
Delx11 = Dely11 =	0

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	DATE 3/11/94	DATE 4.4.94	DATE	DATE	6.17

- LOAD COMBINATIONS FOR MAXIMUM REACTIONS, STRESS AND DEFLECTIONS

COMBINATION 1 - DL + Insulation + Vacuum + 302 F (Case 2 + 7 + 9)

FIXED SUPPORTS

Rx =	0 lbs	= Rfx2 + Rfx7 + Rfx9 (laterial)
Ry =	7018 lbs	= Rfy2 + Rfy7 + Rfy9 (Vertical)
Rz =	5959 lbs	= Rfz2 + Rfz7 + Rfz9 (axial)
Rmax per bolt =	3509 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3509 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx2 + Rgx7 + Rgx9
Ry =	4980 lbs	= Rgy2 + Rgy7 + Rgy9 (Vertical)
Rmax per bolt =	2490 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	2490 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= Delx2 + Delx7 + Delx9
Delta y (302) =	0.079 in	= Dely2 + Dely7 + Dely9
Max Delta =	0.079 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-1533 psi	fav7 + fa9c , neg = compression
fbx =	2195 psi	= fbx2 + fbx7 + fbx9
fby =	0 psi	= fby2 + fby7 + fby9
Md =	7966 in-lbs	= fac * A * (Max Delta + CE)
fd =	33.5 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00

Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3

fac / Fa =	0.260
fbx / Fbx =	0.372
fby / Fby =	0.000
fd / Fbxy =	0.006
SUM =	0.638 < 1.00

Tube is adequate

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	DATE 3/11/94	DATE 4.4.94	DATE	DATE	6.18

COMBINATION 2 - DL + Insulation + Settlement + Vacuum + 302 F (Case 2+7+8+9)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 0.579 = (x8^2 + y8^2)^0.5
Delta y, y8= 0.579 in

FIXED SUPPORTS

Rx =	0 lbs	= Rfx2 + Rfx7 +x8 * Rfx8 + Rfx9
Ry =	5601 lbs	= Rfy2 + Rfy7+ y8 * Rfy8 + Rfy9
Rz =	5959 lbs	= Rfz2 + Rfz7 + Rfz9
Rmax per bolt =	2800 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	2800 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx2 + Rgx7 + x8*Rgx8 + Rgx9
Ry =	7810 lbs	= Rgy2 + Rgy7 + y8*Rgy8 + Rgy9
Rmax per bolt =	3905 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3905 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= 0.5 * x8
Delta y (302) =	0.369 in	= Dely2 + 0.5 * y8
Max Delta =	0.369 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-1533 psi	fav7 + fa9c , neg = compression
fbx =	4267 psi	= fbx2 + fbx7 + y8 * fbx8 + fbx9
fby =	0 psi	= fby2 + fby7 + x8 * fby8 + fby9
Md =	22910 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	96.4 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3

fac / Fa =	0.260
fbx / Fbx =	0.723
fby / Fby =	0.000
fd / Fbxy =	0.016
SUM =	0.999 < 1.00

Tube is adequate

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	DATE: 3/11/94	DATE: 4.4.94	DATE	DATE	6.19

COMBINATION 3 - DL + Insul + Seis x + Dif settle + Vac + 302 F (Case 2+5+7+8+9)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 0.788 = (x8^2 + y8^2)^0.5

Delta y, y8= 0.788 in

FIXED SUPPORTS

Rx =	1287 lbs	= Rfx2 + Rfx5 + Rfx7 +x8 * Rfx8 + Rfx9
Ry =	5089 lbs	= Rfy2 + Rfy5 + Rfy7+ y8 * Rfy8 + Rfy9
Rz =	5959 lbs	= Rfz2 + Rfz5 + Rfz7 + Rfz9
Rmax per bolt =	4346 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	743 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	882 lbs	= Rgx2 + Rgx5 + Rgx7 + x8*Rgx8 + Rgx9
Ry =	8831 lbs	= Rgy2 + Rgy5 + Rgy7 + y8*Rgy8 + Rgy9
Rmax per bolt =	5651 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3180 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.014 in	= Delx5 + 0.5 * x8
Delta y (302) =	0.473 in	= Dely2 + 0.5 * y8
Max Delta =	0.473 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-1533 psi	fav7 + fa9c , neg = compression
fbx =	5015 psi	= fbx2 + fbx5 + fbx7 + y8 * fbx8 + fbx9
fby =	402 psi	= fby2 + fby5 + fby7 + x8 * fby8 + fby9
Md =	29157 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	122.7 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00

Where B=Fa=Fbx=Fby=Fbxy= 7080 psi = 1.2 * B from page 3

fac / Fa =	0.216
fbx / Fbx =	0.708
fby / Fby =	0.057
fd / Fbxy =	0.017
SUM =	0.999 < 1.00

Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY:	MADE BY	CHKD BY	SHT OF
	DATE: 3/11/94 / DATE:	DATE	DATE	

COMBINATION 4 - DL + Insul + Seis z + Dif settle + Vac + 302 F (Case 2+5+7+8+9)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 0.756 = (x8^2 + y8^2)^0.5
Delta y, y8= 0.756 in

FIXED SUPPORTS

Rx =	0 lbs	= Rfx2 + Rfx6 + Rfx7 +x8 * Rfx8 + Rfx9
Ry =	5168 lbs	= Rfy2 + Rfy6 + Rfy7+ y8 * Rfy8 + Rfy9
Rz =	8128 lbs	= Rfz2 + Rfz6 + Rfz7 + Rfz9
Rmax per bolt =	2584 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	2584 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx2 + Rgx6 + Rgx7 + x8*Rgx8 + Rgx9
Ry =	8675 lbs	= Rgy2 + Rgy6 + Rgy7 + y8*Rgy8 + Rgy9
Rmax per bolt =	4337 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	4337 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= 0.5 * x8
Delta y (302) =	0.457 in	= Dely27 + 0.5 * y8
Max Delta =	0.457 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-1644 psi	fav7 + fa9c - Rfz6 / A , neg = compression
fbx =	4901 psi	= fbx2 + fbx5 + fbx7 + y8 * fbx8 + fbx9
fby =	402 psi	= fby2 + fby5 + fby7 + x8 * fby8 + fby9
Md =	30247 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	127.3 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 7080 psi = 1.2 * B from page 3

fac / Fa =	0.232
fbx / Fbx =	0.692
fby / Fby =	0.057
fd / Fbxy =	0.018
SUM =	0.999 < 1.00

Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WJC	MADE BY	CHKD BY	SHT 17 OF 29
	DATE: 3/11/94 / DATE: 4.4.94	DATE	DATE	6.21

COMBINATION 5 - DL + Wind + Dif Set + 100 F (Case 1 + 4 + 8 + 10)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 0.965 = (x8^2 + y8^2)^0.5
Delta y, y8= 0.965 in

FIXED SUPPORTS

Rx =	1275 lbs	= Rfx1 + Rfx4 +x8 * Rfx8 + Rfx10
Ry =	3413 lbs	= Rfy1 + Rfy4+ y8 * Rfy8 + Rfy10
Rz =	771 lbs	= Rfz1 + Rfz4 + Rfz10
Rmax per bolt =	3491 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	-78 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	874 lbs	= Rgx1 + Rgx4 + x8*Rgx8 + Rgx10
Ry =	8697 lbs	= Rgy1 + Rgy4 + y8*Rgy8 + Rgy10
Rmax per bolt =	5572 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3125 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.014 in	= Delx4 + 0.5 * x8
Delta y (302) =	0.545 in	= Dely1 + 0.5 * y8
Max Delta =	0.545 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-217 psi	fav4 + fa10c , neg = compression
fbx =	5260 psi	= fbx1 + fbx4 + y8 * fbx8 + fbx10
fby =	399 psi	= fby1 + fby4 + x8 * fby8 + fby10
Md =	4885 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	20.6 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3

fac / Fa =	0.037
fbx / Fbx =	0.891
fby / Fby =	0.068
fd / Fbxy =	0.003
SUM =	0.999 < 1.00

Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WJC	MADE BY	CHKD BY	SHT 19 OF 29
	DATE: 3/11/94 / DATE: 4-4-94	DATE	DATE	6.22

COMBINATION 6 - DL + Insulation + Vacuum + 100 F (Case 2 + 7 + 10)

FIXED SUPPORTS

Rx =	0 lbs	= Rfx2 + Rfx7 + Rfx10 (laterial)
Ry =	7018 lbs	= Rfy2 + Rfy7 + Rfy10 (Vertical)
Rz =	771 lbs	= Rfz2 + Rfz7 + Rfz10 (axial)
Rmax per bolt =	3509 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3509 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx2 + Rgx7 + Rgx10
Ry =	4834 lbs	= Rgy2 + Rgy7 + Rgy10 (Vertical)
Rmax per bolt =	2417 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	2417 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= Delx2 + Delx7 + Delx10
Delta y (302) =	0.079 in	= Dely2 + Dely7 + Dely10
Max Delta =	0.079 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fac =	-69 psi	fav7 + fa10c , neg = compression
fbx =	2195 psi	= fbx2 + fbx7 + fbx10
fby =	0 psi	= fby2 + fby7 + fby10
Md =	360 in-lbs	= fac * A * (Max Delta + CE)
fd =	1.5 psi	= Md / S

COMBINED STRESS (compression)

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00

Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3

fac / Fa =	0.012
fbx / Fbx =	0.372
fby / Fby =	0.000
fd / Fbxy =	0.000
SUM =	0.384 < 1.00

Tube is adequate

SUBJECT	OFFICE: NOE-C		REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY RJW	CHKD BY WJC	MADE BY	CHKD BY	SHT 19 OF 29
	DATE 3/11/94	DATE 4.4.94	DATE	DATE	6.23

COMBINATION 10 - DL + snow + Dif Set + -16 F (Case 1 + 3 + 8 + 11)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 1.044 = (x8^2 + y8^2)^0.5
Delta y, y8= 1.044 in

FIXED SUPPORTS

Rx =	0 lbs	= Rfx1 + Rfx3 +x8 * Rfx8 + Rfx11
Ry =	6128 lbs	= Rfy1 + Rfy3+ y8 * Rfy8 + Rfy11
Rz =	2209 lbs	= Rfz1 + Rfz3 + Rfz11
Rmax per bolt =	3064 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	3064 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx1 + Rgx3 + x8*Rgx8 + Rgx11
Ry =	11118 lbs	= Rgy1 + Rgy3 + y8*Rgy8 + Rgy11
Rmax per bolt =	5559 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	5559 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= 0.5 * x8
Delta y (302) =	0.615 in	= Dely1 + Dely3 +0.5 * y8
Max Delta =	0.615 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fat =	623 psi,	fa11t , pos = tension
fbx =	6452 psi	= fbx1 + fbx3 + y8 * fbx8 + fbx11
fby =	0 psi	= fby1 + fby3 + x8 * fby8 + fby11
Md =	14962 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	63.0 psi	= Md / S

COMBINED STRESS

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3
Tension Allowable = 9100 psi = Sh * Et, for tension from page 3

	COMPRESSION	TENSION
fa(c or t) / Fa =	-0.106	0.068
fbx / Fbx =	1.094	0.709
fby / Fby =	0.000	0.000
fd / Fbxy =	0.011	0.007
SUM =	0.999 < 1.00	0.784 < 1.00 Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WJC	MADE BY	CHKD BY	SHT 23 OF 25
	DATE: 3/11/94 / DATE: 4-4-94	DATE	DATE	6.27

COMBINATION 12 - DL + Insulation + Settlement + Vacuum + 100 F (Case 2+7+8+11)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 1.224 = (x8^2 + y8^2)^0.5
Delta y, y8= 1.224 in

FIXED SUPPORTS

Rx =	0 lbs	= Rfx2 + Rfx7 +x8 * Rfx8 + Rfx11
Ry =	4023 lbs	= Rfy2 + Rfy7+ y8 * Rfy8 + Rfy11
Rz =	2209 lbs	= Rfz2 + Rfz7 + Rfz11
Rmax per bolt =	2011 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	2011 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	0 lbs	= Rgx2 + Rgx7 + x8*Rgx8 + Rgx11
Ry =	10856 lbs	= Rgy2 + Rgy7 + y8*Rgy8 + Rgy11
Rmax per bolt =	5428 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	5428 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.000 in	= 0.5 * x8
Delta y (302) =	0.691 in	= Dely2 + 0.5 * y8
Max Delta =	0.691 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fat =	771 psi	fav7 + fa11t , pos = tension
fbx =	6576 psi	= fbx2 + fbx7 + y8 * fbx8 + fbx11
fby =	0 psi	= fby2 + fby7 + x8 * fby8 + fby11
Md =	21223 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	89.3 psi	= Md / S

COMBINED STRESS

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 5900 psi for compression from page 3
Tension Allowable = 9100 psi = Sh * Et, for tension from page 3

	COMPRESSION	TENSION
fa(c or t) / Fa =	-0.131	0.085
fbx / Fbx =	1.115	0.723
fby / Fby =	0.000	0.000
fd / Fbxy =	0.015	0.010
SUM =	0.999 < 1.00	0.817 < 1.00 Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WC	MADE BY	CHKD BY	SHT 25 OF 29
	DATE: 3/11/94 / DATE: 4-4-94	DATE	DATE	6.29

COMBINATION 13 - DL + Insul + Seis x + Dif settle + Vac + -15 F (Case 2+5+7+8+11)

SETTLEMENT WITH COMBINATION

Delta x, x8 = 0 in Maxset = 1.438 = (x8^2 + y8^2)^0.5
Delta y, y8= 1.438 in

FIXED SUPPORTS

Rx =	1287 lbs	= Rfx2 + Rfx5 + Rfx7 +x8 * Rfx8 + Rfx11
Ry =	3499 lbs	= Rfy2 + Rfy5 + Rfy7+ y8 * Rfy8 + Rfy11
Rz =	2209 lbs	= Rfz2 + Rfz5 + Rfz7 + Rfz11
Rmax per bolt =	3551 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	-52 lbs	= Ry/2 - Rx * H / Abs

GUIDED SUPPORTS

Rx =	882 lbs	= Rgx2 + Rgx5 + Rgx7 + x8*Rgx8 + Rgx11
Ry =	11902 lbs	= Rgy2 + Rgy5 + Rgy7 + y8*Rgy8 + Rgy11
Rmax per bolt =	7186 lbs	= Ry/2 + Rx * H / Abs
Rmin per bolt =	4716 lbs	= Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION

Delta x (302) =	0.014 in	= Delx5 + 0.5 * x8
Delta y (302) =	0.798 in	= Dely2 + 0.5 * y8
Max Delta =	0.798 in	= (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES

fat =	771 psi	fav7 + fa11t , pos = tension
fbx =	7342 psi	= fbx2 + fbx5 + fbx7 + y8 * fbx8 + fbx11
fby =	402 psi	= fby2 + fby5 + fby7 + x8 * fby8 + fby11
Md =	24441 in-lbs	= fac * A * (Max(Max Delta or maxset) + CE)
fd =	102.8 psi	= Md / S

COMBINED STRESS

fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 7080 psi = 1.2 * B from page 3
Tension Allowable = 10920 psi = 1.2*Sh * Et, from page 3

	COMPRESSION	TENSION
fa(c or t) / Fa =	-0.109	0.071
fbx / Fbx =	1.037	0.672
fby / Fby =	0.057	0.037
fd / Fbxy =	0.015	0.009
SUM =	0.999 < 1.00	0.789 < 1.00 Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW / CHKD BY: WJC	MADE BY	CHKD BY	SHT 26 OF 29
	DATE: 3/11/94 / DATE: 4-4-94	DATE	DATE	v.30

COMBINATION 14 - DL + Insul + Seis z + Dif settle + Vac + -16 F (Case 2+5+7+8+11)

SETTLEMENT WITH COMBINATION
Delta x, x8 = 0 in Maxset = 1.411 = (x8^2 + y8^2)^0.5
Delta y, y8= 1.411 in

FIXED SUPPORTS
Rx = 0 lbs = Rfx2 + Rfx6 + Rfx7 +x8 * Rfx8 + Rfx11
Ry = 3565 lbs = Rfy2 + Rfy6 + Rfy7+ y8 * Rfy8 + Rfy11
Rz = 4378 lbs = Rfz2 + Rfz6 + Rfz7 + Rfz11
Rmax per bolt = 1782 lbs = Ry/2 + Rx * H / Abs
Rmin per bolt = 1782 lbs = Ry/2 - Rx * H / Abs

GUIDED SUPPORTS
Rx = 0 lbs = Rgx2 + Rgx6 + Rgx7 + x8*Rgx8 + Rgx11
Ry = 11770 lbs = Rgy2 + Rgy6 + Rgy7 + y8*Rgy8 + Rgy11
Rmax per bolt = 5885 lbs = Ry/2 + Rx * H / Abs
Rmin per bolt = 5885 lbs = Ry/2 - Rx * H / Abs

MIDSPAN DEFLECTION
Delta x (302) = 0.000 in = 0.5 * x8
Delta y (302) = 0.785 in = Dely27 + 0.5 * y8
Max Delta = 0.785 in = (Delta x ^2 + Delta y ^2)^0.5

TUBE STRESSES
fat = 660 psi, fav7 + fa11t - Rfz6 / A , pos = tension
fbx = 7245 psi = fbx2 + fbx5 + fbx7 + y8 * fbx8 + fbx11
fby = 402 psi = fby2 + fby5 + fby7 + x8 * fby8 + fby11

Md = 20568 in-lbs = fac * A * (Max(Max Delta or maxset) + CE)
fd = 86.5 psi = Md / S

COMBINED STRESS (compression)
fat/Fa + fbx/Fbx + fby/Fby +fd/Fbxy < = 1.00
Where B=Fa=Fbx=Fby=Fbxy= 7080 psi = 1.2 * B from page 3
Tension Allowable = 10920 psi = 1.2*Sh * Et, from page 3

	COMPRESSION	TENSION
fa(c or t) / Fa =	-0.093	0.060
fbx / Fbx =	1.023	0.663
fby / Fby =	0.057	0.037
fd / Fbxy =	0.012	0.008
SUM =	0.999 < 1.00	0.769 < 1.00

Tube is adequate

SUBJECT	OFFICE: NOE-C	REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY: RJW	CHKD BY: WJC	MADE BY	CHKD BY: SHT 27 OF 29
	DATE: 3/11/94	DATE: 4-4-94	DATE	DATE: 6.3.1

- CHECK RIM BENDING PER ROARK & YOUNG 4th Ed, TABLE XIII CASE 13

Mo = (p / 2 / landa^2) * (A / (A + t*c + 2 * t / landa)

p =	14.7	psi, internal pressure
Landa =	0.7277	= (3 * (1-0.3^2)/(((Do+t)/2)^2 * t^2))^0.25
A =	1.5	sq in = tss * wss
t =	0.127	in = t
c =	0.375	in = tss

Mo = 10.976 in lbs / in

Stress = 4083 psi = 6 * M / t^2 < 3 * S = 17700 psi

SUBJECT	OFFICE: NOE-C		REVISION:		REFERENCE NO. 930212
LIGO - BEAM TUBE DESIGN Configuration 3, K = 8316 + 20% Maximum Differential Settlements	MADE BY RJW	CHKD BY WJC	MADE BY	CHKD BY	SHT 28 OF 29
	DATE 3/11/94	DATE 4-4-94	DATE	DATE	

- SUMMARY - Vertical Differential Misalignment Only

Combination	Fixed supports (lbs)			Guided Support (lbs)		Settlement (in)		Unity	
	Rx	Ry	Rz	Rx	Ry	x	y	Comp	Tension
1	0	7018	5959	0	4980	0	0	0.638	
2	0	5601	5959	0	7810	0	0.579	0.999	
3	1287	5089	5959	882	8831	0	0.788	0.999	
4	0	5168	8128	0	8675	0	0.756	0.999	
5	1275	3413	771	874	8697	0	0.965	0.999	
6	0	7018	771	0	4834	0	0	0.384	
7	0	4541	771	0	9780	0	1.012	0.999	
8	1287	4010	771	882	10840	0	1.229	0.999	
9	0	4093	2939	0	10674	0	1.195	0.999	
10	0	6128	2209	0	11118	0	1.044	0.999	0.784
11	1275	2872	2209	874	9818	0	1.186	0.999	0.785
12	0	4023	2209	0	10856	0	1.224	0.999	0.817
13	1287	3499	2209	882	11902	0	1.438	0.999	0.789
14	0	3565	4378	0	11770	0	1.411	0.999	0.769

COMBINATIONS

1 - DL + Insulation + Vacuum + 302 F (Case 2 + 7 + 9)
2 - DL + Insulation + Settlement + Vacuum + 302 F (Case 2+7+8+9)
3 - DL + Insul + Seis x + Dif settle + Vac + 302 F (Case 2+5+7+8+9)
4 - DL + Insul + Seis z + Dif settle + Vac + 302 F (Case 2+5+7+8+9)

5 - DL + Wind + Dif Set + 100 F (Case 1 + 4 + 8 + 10)
6 - DL + Insulation + Vacuum + 100 F (Case 2 + 7 + 10)
7 - DL + Insulation + Settlement + Vacuum + 100 F (Case 2+7+8+10)
8 - DL + Insul + Seis x + Dif settle + Vac + 100 F (Case 2+5+7+8+10)
9 - DL + Insul + Seis z + Dif settle + Vac + 100 F (Case 2+5+7+8+10)

10 - DL + snow + Dif Set + -16 F (Case 1 + 3 + 8 + 11)
11 - DL + wind +Dif set -16 F (Case 1 + 4 + 8 + 11)
12 - DL + Insulation + Settlement + Vacuum + 100 F (Case 2+7+8+11)
13 - DL + Insul + Seis x + Dif settle + Vac + -15 F (Case 2+5+7+8+11)
14 - DL + Insul + Seis z + Dif settle + Vac + -16 F (Case 2+5+7+8+11)