DØ SOLENOID UPGRADE PROJECT

**Cold Mass Support System
for the DØ Solenoid**

D-ZERO ENGINEERING NOTE # 3823.111-EN-358

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INTRODUCTION

The support system is designed to support the gravitational, magnetic, and thermal contraction loads associated with the cold mass weighing 1.46 metric tons (3210 lbm). The loading constraints are listed in Table 1. The support system consists of axial members (axial supports) to provide longitudinal stiffness and nearly tangential members (radial supports) to provide radial stiffness. The members connect the outer support cylinder to the flat annular bulkheads of the vacuum vessel. See Figures 1 through 3 for additional details on the supports. Six axial compression-tension supports are located on the chimney end of the cryostat only. Six radial tension supports are located on each end. Both types of members are fabricated of Inconel 718 and have a design safety factor of 4 on the ultimate strength at 300 K. The axial supports are also designed for a buckling safety factor of 4 for the operating loads. Shipping stops will be installed to prevent the axial supports from going into compression during transportation. Axial and radial contraction of the coil support cylinder is accommodated by spherical bearings on both ends of each support member.

DISCUSSION

The support system is designed such that the radial supports cannot go into compression. The reason for this is that the radial support members are not designed to handle a significant load. To prevent any problems, the bearings on the end of the support member is designed to make the rod slide instead of compressing.

Because of the large axial contraction of the cold mass, axial supports are only placed on the chimney end of the cryostat. This effectively pins the supply tubing at the chimney end and makes designing the chimney easier. This arrangement of the axial supports requires the supports to handle compression as well as tensile loadings.

Radial space is quite limited in this solenoid design. The support cylinder is not thick enough to bolt in support brackets. As a result, the support brackets will be welded to the support cylinder and the bulkhead. The support cylinder and cryostat are constructed of 5083 aluminum in order to reduce the radiation and absorption thicknesses. This led to the selection of 5083 aluminum for the support bracket material.

The contact surface area within the spherical bearings is relatively small. To handle the design load of the support members, the material will need a high strength. Inconel 718 has been chosen for the bearing material in order to meet this criteria. The low thermal conductivity of the material will also reduce the heat load to the cold mass.

Calculations on the support system are given in the appendices. Appendix A shows the design calculations on the support members and the support brackets on each end of the support members. Appendix B gives the results of calculations performed with ANSYS by Bob Wands. Appendix C gives some additional detail on the cold position of the coil and the stiffness of the support system.

Table 2 is a summary of the design loads for the radial and axial support members. Comparing these values to the tables in Appendix B shows that the support system can handle the requirements of Table 1 with the exception of axial shipping loads.

In this case, axial shipping blocks will have to be installed in order to prevent the axial support members from going into compression.

Table 1. Loading constraints for the support system.

Condition	Radial Acceleration Loading	Axial Acceleration Loading
Shipping	4 g	6 g
Coil at 4.7 K	2 g	1 g

Table 2. Design loads of the support members.

	Tension (lbf)	Compression (lbf)
Radial Support	8836	---
Axial Support	3765	706

Appendix A

Support Design Loads

Radial Support Member

This support member is designed for tension only. The support is fabricated from Inconel 718 with a maximum allowable stress of 45 ksi at room temperature. The support member is 0.5 inches in diameter and a design load of 8,836 lbf (4 metric ton).

Axial Support Member

This support member is designed for tension and compression. The support is fabricated from Inconel 718. The support member is a 0.625 x 0.046 inch tube with a tension design of 3765 lbf (1.7 metric ton). The designed compression load is one forth the critical buckling load based on Euler's formula. Table A1 shows the calculation of the compression design loads and the equations used are as follows:

$$P_{cr} = n \cdot \pi^2 \cdot E \cdot I / L_p^2$$

$$I = A_w \cdot r^2$$

$$r = 0.5 \cdot \sqrt{R_o^2 + R_i^2} \quad (r \text{ is the Radius of Gyration for a cylinder})$$

$$\sigma = P_{cr} / A_w$$

$$A_w = \pi \cdot (R_o^2 - R_i^2)$$

$$D_o = 2 \cdot R_o$$

$$D_i = 2 \cdot R_i$$

$$P_d = P_{cr} / \text{Safety} \quad (\text{Design Load for Compression Loading})$$

Table A1. Solution of compression equations for the axial support member.

INPUT	VARIABLE	OUTPUT	UNITS	COMMENT
31000000	E		psi	Young's Modulus
1	n		---	End condition
	Ro	0.3125	in	Outer Radius of cylinder
	Ri	0.26642425	in	Inner radius of cylinder
	I	0.00353297	in ⁴	Moment of inertia
	r	0.20532787	in	Radius of Gyration
0.625	Do		in	Outer Diameter of cylinder
	Di	0.5328485	in	Inner Diameter of cylinder
19.562	Lp		in	Length Between Pivot Points
0.0838	Aw		in ²	Cross Sectional Area for the Warm End
	Pcr	2824.7157	lbf	Critical Load from Euler's Formula
	Sigma	33707.824	psi	Critical Stress
	Pd	706.17892	lbf	Buckling Design Load
4	Safety		---	Safety Factor on Pd
	Gb	1.153019	---	G Loading for Buckling [# g's]

Table A2. Solution of seismic equations for the axial support member.

INPUT	VARIABLE	OUTPUT	UNITS	COMMENT
3218.749	m		lbm	Mass of Cold Mass
0.1875	Z		---	Seismic Zone Coefficient
1.5	Is		---	Occupancy Importance Factor
2	K		---	Horizontal Force Factor
0.14	CS		---	Numerical Coefficient & Soil Factor
	G	0.07875	---	Seismic Loading G Factor
456	Pc		lbf	Loading on support due to cool down
	W	3674.7647	lbf	Dead Load
	V	289.38772	lbf	Load that support system must handle
	V%6	48.231286	lbf	Load that each support must handle

The D0 detector is in Zone 0 for earthquake design. Table A2 shows what a zone 1 earthquake design would require and the equations are as follows:

Buckling Criteria for Seismic Loadings
from "Minimum Design Loads for Buildings and Other Structures"
ASCE Standard ASCE 7-88 (Formerly ANSI A58.1) approved Dec-88
 $G_b = 6 * P_d / (m + P_c)$
 $G = Z * I_s * K * C_S$
 $W = m + P_c$
 $V \% 6 = V / 6$
 $V = G * W$

Support Block Design

The support blocks that attach the support members to the support cylinder and the bulkhead are designed to handle the maximum design load of the support members. The following pages detail the calculations performed to design the blocks. The axial support attachment at the bulkhead has not been analyzed at the time this note was written.

SUBJECT

Axial Support Bracket on Coil

NAME

B. Squires

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St	Input	Name	Output	Unit	Comment
	3770	W		lbf	Load in direction of H
	.625	d		in	Distance from W to base for weld
	.1875	h		in	Weld leg length
	2.125	H		in	Length of bracket in direction of W
	1.75	B		in	Width of bracket perpendicular to W
		tau	6148.1342	psi	Weld Shear Stress
		S	3200.9517	psi	Weld Bending Stress
		taumax	6353.0368	psi	Maximum Shear Stress
		Smax	7953.5127	psi	Maximum Bending Stress

Max. Allowable stress of
5083 Aluminum welded is 8ksi

S Rule

"from Practical Stress Analysis in Engineering Design by Alexander Blake
" (available in RD/MSD Library) page 464 - Theory of Weld Stresses

$$S = 3 \cdot \sqrt{2} \cdot W \cdot d / (h \cdot (H^2 + 3 \cdot B \cdot (H + h)))$$

$$\tau = \sqrt{2} \cdot W / 2 / h / (H + h)$$

$$\tau_{\max} = \sqrt{(S/2)^2 + \tau^2}$$

$$S_{\max} = S/2 + \tau_{\max}$$

SUBJECT

Study for Radial Support Brackets

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By looking at the "Design of Weldments" book, it is clear that the bending stresses on the welds is by using the section modulus of the welds based on the throat of the fillet weld and its length about a centroid of the welds as a whole.

The Lines are the Weld Areas

SUBJECT

Study for Radial Support Brackets

NAME

B. Squires

DATE
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Common Fillet Weld Size = t Areas

$$A_i = L_i \cdot t / \sqrt{2}$$

Moments of Inertiafor $i = 1$ through 4

$$I_i = L_i \cdot t^3 / (24 \cdot \sqrt{2})$$

for $i = 5$ through 8

$$I_i = t \cdot L_i^3 / (12 \cdot \sqrt{2})$$

Centroid Location Calculation

Line C is the Centroid. To determine its location with respect to line A, the following Calculation is performed:

$$C = \sum (A_i \cdot Y_i) / \sum (A_i)$$

where Y_i is the distance from the weld area centroid to line A

Section Modulus Calculation

$$S = \sum (I_i + A_i \cdot X_i^2) / C$$

where X_i is the distance from the area's centroid to Line C

Bending Stress Calculation

The bending stress is determined by the following equation:

$$\sigma = M / S$$

where M is the bending moment

$$M = T \cdot h$$

with T = Load

h = height from base of weld

Shear Stress Calculation

The shear stress is

$$\tau = T / \sum (A_i)$$

Maximum Stresses

$$\tau_{\max} = \sqrt{(\sigma/2)^2 + \tau^2}$$

$$\sigma_{\max} = \sigma/2 + \tau_{\max}$$

SUBJECT

Equations for Support Block Calculations using
TK Solver Plus

NAME

B. Squires

DATE

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Main
S Rule
A=Area()
call Moment()
C=Centroid()
S=SectionMod()
call Stress(T,h,S;M,sigma,tau,sigmax,taumax)
More='Inputs
Cy=YCentroid()

Routine: Area

Comment: Calculates the sum of the areas

Parameter Variables: t

Input Variables:

Output Variables: Area

S Statement

```
call blank('A)
k=member(0,'L)
j=length('L)
for i=1 to j
'A[i]='L[i]*t/sqrt(2)
next i
Area=sum('L)
```

Routine: Moment

Comment: Calculates the moments of the areas

Parameter Variables: t

Input Variables:

Output Variables:

S Statement

```
call blank('I)
k=member(0,'L)
j=length('L)
for i=1 to k-1
'I[i]='L[i]*t^3/24/sqrt(2)
next i
for i=k+1 to j
'I[i]=t*'L[i]^3/12/sqrt(2)
next i
'I[k]=0
```

SUBJECT

Equations ...

NAME

B. Squires

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Routine: Centroid

Comment: Calculates the Centroid of the areas

Parameter Variables:

Input Variables:

Output Variables: Centroid

S Statement

```
j=length('L')
for i=1 to j
  'AY[i]='A[i]*'Y[i]
next i
Centroid=sum('AY)/sum('A)
call delete('AY)
```

Routine: SectionMod

Comment: Calculates the Section Modulus of the whole area

Parameter Variables: C

Input Variables:

Output Variables: S

S Statement

```
j=length('L')
for i=1 to j
  '@SM[i]='I[i]+'A[i]*abs('Y[i]-C)^2
next i
S=sum('@SM)/C
call delete('@SM)
```

Routine: Stress

Comment: Calculates Bending and Shear Stresses w/ maximums

Parameter Variables:

Input Variables: T, h, S

Output Variables: M, sigma, tau, sigmax, taumax

S Statement

```
"INPUTS
" T = Applied Load [lbf]
" h = height from base for load [in]
" S = Section Modulus [in3]

"OUTPUTS
" M = Moment of applied load [in-lbf]
" sigma = bending stress [psi]
" tau = shear stress [psi]
" sigmax = maximum bending stress [psi]
" taumax = maximum shear stress [psi]
```

```
M=T*h
sigma=M/S
tau=T/sum('A)
taumax=sqrt((sigma/2)^2+tau^2)
sigmax=sigma/2+taumax
```

SUBJECT

Equations . . .

NAME

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Routine: YCentroid

Comment: Calculates the Y-axis Centroid of the areas

Parameter Variables:

Input Variables:

Output Variables: Centroid

S Statement

j=length('L')

for i=1 to j

'AX[i]='A[i]*'X[i]

next i

Centroid=sum('AX)/sum('A)

call delete('AX)

SUBJECT

Radial Support Bracket Design (on Coil)

NAME

B. Squires

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Radial Support Calculation - See next page for sketch of support

St	Input	Name	Output	Unit	Comment
		10207 T		lbf	Load on bracket
		0.75 h		in	Height of Load from weld
		0.1875 t		in	Fillet Weld Size
		More	'Inputs	in Lists	L, Y, and X
		A	12.1	in ²	Total Weld Area
		C	0.85103306	in	Centroid Location
		S	3.0156624	in ³	Section Modulus
		M	7655.5893	in-lbf	Moment on weld
		tau	6362.7626	psi	Shear Stress
		sigma	2538.6095	psi	Bending Stress
		taumax	6488.1339	psi	Maximum Shear Stress
		sigmama	7757.4387	psi	Maximum Bending Stress
		Cy	0.62603306		Should be 0.625

Element	L	Y	X	Comment
1	1.25	0	0.625	'Horizontal_lines
2	1.25	0.75	0.875	
3	0.25	-1.3	1.375	
4	0.25	3.25	0.125	
5	0	0	0	
6	3.25	1.625	0	'Vertical_lines
7	2.05	-0.275	1.5	
8	2.5	2	0.25	
9	1.3	-0.65	1.25	

← All dimensions in inches

SUBJECT

Radial Support Bracket on Bulkhead

NAME

B. Squires

DATE

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St Input	Name	Output	Unit	Comment
	I	1.0997855	in ⁴	Moment of Inertia = $1/12 b \cdot h^3$
10207	P		lbf	Load at L
.75	L		in	Distance from base
10400000	E		psi	Modulus of Elasticity
	del	.00012549	in	deflection at L
	delm	.00318752	mm	deflection at L
	C	1.0732143	in	Centroid Location from top surface
	S	1.0247585	in ³	Section Modulus
	Cy	.75	in	Y centroid location
	b		in	
	h		in	
	M	7655.25	in-lbf	
	{ sigma	7470.2964	psi	bending stress
	{ tau	6598.8013	psi	shear stress
	{ sigmamax	11317.728	psi	maximum principle stress theory
	{ taumax	7582.5794	psi	maximum shear stress
	{ vonM	13654.225	psi	energy of distortion theory (vonMises)

Bob Wards suggests only looking at these values
 Because they do not occur in the same location
 Allowable stress is 8Ksi $\therefore$ design is acceptable

Input Lists

Title: (all dimensions in inches)

Element	L	t	X	Y	Comment
1	1.5	.75	.375	.75	'Horizontal_areas
2	0	0	0	0	
3	2.125	.25	1.8125	.125	'Vertical_areas
4	2.125	.25	1.8125	1.375

use 5083 Aluminum
 Full Penetration weld
 weld Allowable 8Ksi

SUBJECT

Radial Support Bracket on Bulkhead

NAME

B. Squires

DATE

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Main

S Rule

* $I = b \cdot h^3 / 12$ $\delta = P \cdot L^3 / 3 \cdot E / I$ $\delta_{lm} = \delta \cdot 25.4$

call Area()

call Moment()

S=SectionMod()

I=S*C

C=Centroid()

Cy=YCentroid()

call Stress(P, L, S; M, sigma, tau, sigmax, tau_max)

 $\text{vonM} = 1 / \sqrt{2} \cdot \sqrt{(\text{sigma} / 2 + \text{tau}_{\text{max}})^2 + (\text{sigma} / 2 - \text{tau}_{\text{max}})^2 + (2 \cdot \text{tau}_{\text{max}})^2}$

Routines are the same as those on pages A6 through A8

SUBJECT

Quick Calculation on Web Buckling

NAME

B. Squires

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From "Practical Stress Analysis in Engng Design" by Alexander Blake
in MSD Library

P. 469

$$S_{cr} = K_b E \left(\frac{T}{H} \right)^2$$

 S_{cr} = Critical Compressive Stress K_b = Buckling Coeff. E = Modulus of Elasticity T = Thickness of Plate H = Maximum depth of plate L = Length of rib of constant dept

From fig. 33.33

Case 3

$$\frac{H}{L} = \frac{1\frac{3}{8}}{2.5} = 0.55$$

$$K_b \Rightarrow \sim 5$$

$$S_{cr} = 5 (10.4 \times 10^6 \text{ psi}) \left(\frac{0.25}{1\frac{3}{8}} \right)^2 = 1.7 \times 10^6 \text{ psi}$$

No problem

Appendix B

Results of ANSYS Analysis of Support System

Tables B1 through B3 are a summary of loads on the support members when the solenoid is subjected to various loadings. These values were determined by a model written on ANSYS by Bob Wands. For a description of the ANSYS model, see the internal paper of the Engineering Analysis Group of RD/MSD entitled "Finite Element Analysis of the D0 Solenoid" (EAR - 86) by Bob Wands.

Table B1. Shipping accelerational loadings (warm).

Acceleration: 4 g's lateral			
Radials	Load (lbf)	Axial	Load (lbf)
1	3477.81	1	12.3156
2	-1.91E-12	2	-11.1158
3	3497.18	3	19.4446
4	-3.07E-11	4	-1.86585
5	5.56055	5	27.4606
6	-2.37E-12	6	-46.3253
7	3493.04		
8	8.78E-12		
9	3480.91		
10	-2.29E-11		
11	1.97831		
12	5.99E-12		
Acceleration: 4 g's upward			
Radials	Load (lbf)	Axial	Load (lbf)
1	-7.70E-13	1	-17.5945
2	2850.36	2	27.2107
3	973.882	3	-9.79707
4	-2.64E-12	4	-17.2278
5	2850.4	5	27.5785
6	974.036	6	-9.82444
7	9.07E-13		
8	2854.13		
9	973.197		
10	-4.72E-12		
11	2854.05		
12	973.069		

Table B2. Cool down and magnetic pressure loads.

Cool Down Only			
Radials	Load (lbf)	Axials	Load (lbf)
1	491.29414	1	-90.337363
2	2.86E-13	2	14.571147
3	141.59537	3	455.99154
4	491.3903	4	-91.031591
5	-1.87E-13	5	15.219198
6	141.57144	6	455.98178
7	3196.2686		
8	709.40448		
9	1737.7112		
10	3196.2396		
11	709.57235		
12	1737.6362		
Magnetic Pressure Only			
Radials	Load (lbf)	Axials	Load (lbf)
1	268.15918	1	-3.0919566
2	44.832289	2	0.68157851
3	147.58913	3	7.2294247
4	268.15842	4	-3.0522989
5	44.832515	5	0.65165675
6	147.58698	6	7.2297825
7	320.42402		
8	59.401037		
9	175.79138		
10	320.42435		
11	59.400002		
12	175.79393		
Magnetic Pressure and Cool Down			
Radials	Load (lbf)	Axials	Load (lbf)
1	706.70157	1	-108.73645
2	-9.27E-13	2	39.535507
3	319.01299	3	494.4148
4	706.83221	4	-109.68758
5	6.99E-14	5	40.412715
6	318.97492	6	494.40532
7	3626.4681		
8	791.61392		
9	1999.3974		
10	3626.4267		
11	791.8442		
12	1999.2984		

Table B3. Accelerational loadings with coil at 4.7 K and energized to 2 T.

Acceleration: 2 g's lateral			
Radials	Load (lbf)	Axials	Load (lbf)
1	1941.9367	1	8.8902577
2	-5.63E-12	2	-37.689545
3	1532.6212	3	292.65525
4	46.360768	4	27.979648
5	-1.62E-12	5	115.17328
6	7.66E-12	6	370.36192
7	4356.7781		
8	505.76082		
9	3122.6055		
10	2968.6599		
11	967.43376		
12	910.58289		
Acceleration: 2 g's upward			
Radials	Load (lbf)	Axials	Load (lbf)
1	244.31508	1	-122.06652
2	1238.3285	2	61.545753
3	831.28525	3	519.13953
4	245.49874	4	-121.23939
5	1240.5587	5	61.442865
6	829.89441	6	519.2317
7	3211.937		
8	2077.0952		
9	2450.9854		
10	3212.0108		
11	2077.7882		
12	2450.7051		
Acceleration: 2 g's downward			
Radials	Load (lbf)	Axials	Load (lbf)
1	3710.1399	1	563.02506
2	-2.52E-11	2	41.491649
3	9.22E-12	3	-368.23788
4	3711.5566	4	559.53149
5	-1.08E-11	5	47.736642
6	-8.04E-13	6	-368.6266
7	5151.4235		
8	3.09E-12		
9	559.74396		
10	5150.1512		
11	8.45E-12		
12	559.831		

Table B3. cont'd

Acceleration: 1 g axial (backward)			
Radials	Load (lbf)	Axials	Load (lbf)
1	633.80152	1	-624.17149
2	1.39E-12	2	-478.73532
3	260.41884	3	-55.472422
4	633.79762	4	-624.71209
5	1.09E-12	5	-478.26326
6	260.47551	6	-55.486337
7	3720.6887		
8	803.1444		
9	2047.2778		
10	3720.7109		
11	803.18847		
12	2047.1956		
Acceleration: 1 g axial (forward)			
Radials	Load (lbf)	Axials	Load (lbf)
1	780.45537	1	406.97769
2	-2.68E-13	2	557.03381
3	378.90181	3	1044.2878
4	780.71912	4	405.62031
5	5.77E-14	5	558.3127
6	378.75895	6	1044.2775
7	3528.8983		
8	779.75944		
9	1948.969		
10	3528.786		
11	780.17675		
12	1948.8603		

Appendix C

Cold Position and Stiffness

The position of the coil when it is cold and operational must be known and the stiffness of the support system must be such that the coil has negligible deflection due to external forces. ANSYS was used to determine these characteristics of the solenoid.

The coil is centered in the cryostat when it is at room temperature. when cooled, the center of the coil will have shifted by the following amounts:

Axially	0.197 inches toward the chimney end
Upward	0.0127 inches
Laterally	~ 0 inches

These values are believed to be with about 0.1 inches of the true position¹. Rich Smith has determined that the position of the coil must be known within no more than 0.197 in (5 mm). Based on this criteria, it appears that the coil position will be within the desired tolerance.

The stiffness of the support system was also determined with ANSYS. The results of this analysis are as follows:

X-direction	3.93×10^5 lbf/in
+Y-direction	2.74×10^6 lbf/in
-Y-direction	2.84×10^5 lbf/in
+Z-direction	8.52×10^4 lbf/in
-Z-direction	6.21×10^4 lbf/in

The de centering forces of the coil with respect to the WAMUS and SAMUS iron is 63 and 38 lbf/in. This shows that the support system is stiff enough to handle forces due to magnetic de centering. Other forces on the coil would be caused by shipping and earthquakes. Appendix B shows that the support system can handle high shipping loads. Earthquakes are not expected to be a major concern for the solenoid, however, a zone 1 earthquake analysis shows that the loads are less than 0.1 g and Appendix B also shows that the support system can handle this load when the solenoid is cold and operational.