ENGINEERING ANALYSES OF LARGE PRECISION CATHODE STRIP CHAMBERS FOR GEM

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October 21, 1993

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Abstract:

Structural analyses of large precision cathode strip chambers performed up to the date of this publication are documented. Mechanical property data for typical chamber materials are included. This information, originally intended to be an appendix to the "CSC Structural Design Bible," is presented as a guide for future designers of large chambers.

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1. Overview

The structural design of precision cathode strip chambers is an exercise in producing the lightest, thinnest, and stiffest functioning chamber out of the highest radiation length materials. An understanding of the structural function of each component allows the chamber designer to avoid unnecessary mass.

This paper contains material property data, design formulas, and selected analytical results. Sections are listed in the Table of Contents. Each section is preceded by a short index and summary. Illustrations of the chamber support structure draw upon the work of Draper Laboratories and Simpson Gumpertz and Heger Inc. GEM Technical Notes relating to chamber mechanical design are listed in the references section. GEM TN-93-350, *Gravity Sag of Sandwich Panel Assemblies as Applied to Precision Cathode Strip Chamber Structural Design*, provides an explanation the importance of shear coupling between sandwich panels in a chamber. Not cited in the references are numerous unpublished ideas informally proposed by the authors of this paper. Two examples, Gordeev's "discrete posts" and Polychronakos' "cast low density fillers", are analyzed in GEM TN-93-460, *Comparison of Gap Frame Designs and Materials for Precision Cathode Strip Chambers*.

Originally intended as an Appendix to a comprehensive "CSC Structural Design Bible", this collection of materials is a snapshot-in-time of the state of the structural design of the SSC/GEM precision cathode strip chambers as of October 21, 1993. It is recorded here for the benefit of future chamber designers.

Understanding Chamber Deformation Is Critical

Outer superlayer chamber gravity sag magnified 1,000 times

- Nonlinear orthotropic finite element model is used for 3-dimensional analyses
- Spreadsheet bending model is used for 2-dimensional analyses of sensitivity to geometric parameters and material properties
- Maximum gravity sag (A) is sum of long edge bending (B) and sandwich panel sag (C)
- CMM measurements of prototype panels and chambers will provide data on gravity sag, local heat source effects, internal pressure, and creep

2. Precision CSC Structural Design Concept

Contents:

System views of muon chambers (2 pages)

Cross section and plan views of cathode strip chamber conceptual design (2 pages)

Precision cathode etched copper pattern (1 page)

Sandwich panel and gap frame conceptual design (1 page)

CSC panel fabrication specifications (1 page)

Summary:

The conceptual design of the chambers is shown in the drawings by I.A. Golutvin and Y. Kiryushin.

The muon system uses chambers whose size closely matches the maximum size single sheet of copper plated G-10 that can be etched into the precision cathode pattern.

The overall chamber structure is designed to behave as a single beam with shear connections between individual sandwich panels.

1 OF 2

CHAMBERS ONLY

2 OF 2

CHAMBERS PLUS SUPPORT STRUCTURE

1 OF 2

SECTION A-A
(ALONG WIRES)

PRECISE STRIP READING

	OUTER LAYER	MIDDLE LAYER	INNER LAYER
h mm	5.0	4.0	2.5

H = 20 mm

CHAMBER CROSS SECTIONS

I. GOLUTVIN
Y. KIRYUSHIN
03/02/1993

2 OF 2

INNER SUPERLAYER
MIDDLE SUPERLAYER
OUTER SUPERLAYER

K mm	W mm	H mm	S mm
784	654	2.5	5.84
1063	933	4.0	8.33
1330	1200	5.0	10.7

CHAMBER PLAN VIEW

I. GOLUTVIN
Y. KIRYUSHIN
03/02/1993

TOP LEFT CORNER

precision cathode
copper pattern
7/19/93

1 OF 1

1 OF 1

CSC Panel Fabrication Specs

1 of 1

Panel Definition: A 19 mm (nominal) honeycomb NOMEX sheet sandwiched between two 20 mil (.5 mm) fiberglass (G-10 or FR-4; NEMA specs.) face sheets. The fiberglass face sheets are copper clad on the outward facing sides. The copper on one of the face sheets is etched to provide a precision cathode plane.

Specifications (prioritized)

1. Flatness
4 mil (100 μ m) over 1.2 m
2. Parallel to
4 mil over 1.2 m
3. Net thickness (incl. face sheets)
20 mm $\pm$ 10 mil (.25 mm)
4. Squareness
Diagonal measurements $\pm$ 10 mil of each other
5. Length and width dimensions
Not set at this time.

3. Sandwich Skin Materials

Contents:

Survey of sandwich skin material properties, ref. Hexcel TSB-124 (1 page)
Survey of sandwich skin material properties, ref. M.C. Gill (1 page)
Product data sheet for Gillfab 1045, fiberglass cloth/epoxy NEMA G-10 (2 pages)
Product data sheet for Gillfab 1024, fiberglass reinforced polyester, like G-10 (2 pages)
Product data sheet for GE Grade: 11635H, NEMA FR-4 (1 page)
Micrograph of plated and etched fiberglass cloth/epoxy laminate (1 page)
Analysis of generic G-10 woven fiberglass laminate (5 pages)
Analysis of generic fiberglass [0/+0/-0/90]sym "custom" (non-cloth) laminate (2 pages)
Analysis of generic fiberglass [0/+45/-45/90]sym "custom" (non-cloth) laminate (4 pages)

Summary:

The TDR Baseline sandwich panel skin material is Epoxy-Gillfab 1045 (equivalent to 1040 in all mechanical properties except maximum service temperature). It meets the NEMA G-10 electrical specifications.

Generic G-10 was selected as the TDR Baseline sandwich skin due to a long history of Cu plating and etching experience by industry, its electrical properties, the adequacy of its mechanical properties, and its low cost compared to "custom" laminate lay-ups.

Since NEMA G-10 is not a mechanical specification, G-10 from different vendors may have different mechanical properties. Its in-plane modulus varies from 3.0 to 3.3 MSI at 0-deg. and 90-deg. (angle measured in-plane) but may drop below 1.8 MSI at 45-deg.

"Custom" non-cloth fiberglass laminates made of unidirectional plies provide mechanical properties optimized for the application but at a premium price. In-plane properties become isotropic by going from a cloth [0/90]sym to a [0/-45/+45/90]sym or a [-60/0/+60]sym custom laminate.

FROM HEXCEL
Properties of Typical Sandwich Facing Material

1 OF 1

Facing Material	Yield Strength psi	Modulus of Elasticity E _f psi	λ_f 1 - μ^2	Weight per Mill Thickness lbs./ft. ²	Comments
Aluminum 1100 — H14	13,000C	10.0 x 10 ⁶	.99	.014	Moderate cost, workable, excellent chemical resistance, scars easily
3003 — H16	18,000C	10.0 x 10 ⁶	.99	.014	Fair strength, good weather resistant, moderate cost
6062 — H34	24,000C	10.1 x 10 ⁶	.99	.014	Better strength, good weather resistant, moderate cost
6061 — T6	35,000C.T	10.0 x 10 ⁶	.99	.014	Good strength, workable, only heat-treatable alloy easily welded
2024 — T3	42,000T	10.5 x 10 ⁶	.99	.014	Excellent strength, heat-treatable, soft stage for working, fair corrosion resistant
7075 — T6	68,000T	10.3 x 10 ⁶	.99	.014	High strength, fair corrosion resistant
Mild Carbon Steel	80,000	29 x 10 ⁶	.91	.040	Low cost, high weight, good availability
Stainless Steel: 304 annealed 316 annealed 17-7 ph	35,000 35,000 185,000	28 x 10 ⁶ 28 x 10 ⁶ 28 x 10 ⁶	.94 .94 .94	.040 .040 .040	High cost, corrosion resistant High strength, heat treatable
Woven Graphite/Epoxy 282-F185	85,000	8.1 x 10 ⁶	.99	.0080	High strength, high modulus
6" Tape Graphite/Epoxy TXI-145-F185	167,000	18.3 x 10 ⁶	.99	.0088	Low weight, high cost
Woven Glass/Epoxy 1851-F185	62,000	3.3 x 10 ⁶	.98	.0086	Low cost, good strength
6" Tape E-glass/Epoxy TZS-285-F185	120,000	6.0 x 10 ⁶	.98	.011	Moderate cost, good strength
6" Tape S2-glass/Epoxy TZS-180-F181	170,000	7.0 x 10 ⁶	.98	.011	High strength, moderate cost, good modulus
Woven Kevlar/Epoxy K49-285-F185	70,000T 32,000C	4.1 x 10 ⁶	1.00	.0073	Low weight, low compressive strength
6" Tape Kevlar/Epoxy	156,000T 33,000C	9.5 x 10 ⁶	1.00	.0072	Moderate cost
Fiberglass Material, Polyester Resin	14,000	0.92 x 10 ⁶	.98	.007	Very low cost
Woven Roving, Polyester Resin	28,000	1.85 x 10 ⁶	.98	.007	Very low cost
Exterior Fir Plywood	2,950	1.8 x 10 ⁶	.99	.003	For calculations involving plywood "Effective Thickness" should be used except for locating centroid.
Pine Plywood	3,000	1.8 x 10 ⁶	.99	.003	
Luan Plywood	2,250	1.8 x 10 ⁶	.99	.002	
Tempered Hardwood 70 Dcu R	3,800	0.95 x 10 ⁶	.98	.005	Good hardwood, low cost, smooth surface

FROM M.C. GILL
TABLE 1
MECHANICAL PROPERTIES
OF TYPICAL SANDWICH FACING MATERIALS

1 OF 1

Facing Material	Yield Strength f _y (psi x 10 ³)	Modulus of Elasticity E _f (psi x 10 ⁶)	Wt. per Mill Thickness (lb./ft. ²)	Comments
Aluminum-2024-T3	42	10	0.014	Good strength, moderate cost
Aluminum-3003-H16	20	10	0.014	Moderate strength, good weathering
Aluminum-6061-T6	21	10	0.014	Workable, corrosion resistant
Aluminum-7075-T6	60	10	0.014	High strength and dent resistant
Mild carbon steel	50	28	0.040	Low cost, high weight, hard to cut with hand tools
Stainless steel-316	60	29	0.040	Heavy, expensive, hard to bond and fabricate with hand tools
Titanium: Annealed Ti-75A	70	15	0.0235	Low corrosion, high cost, hard to bond
Fiberglass laminates				
Epoxy-Gillfab 1049	30	3.3	0.01	Std. epoxy, 180°F service temp.
Epoxy-Gillfab 1045	30	3.3	0.01	High strength, 250°F service temp.
Phenolic-Gillfab 1002	30	3.0	0.01	Good strength, 350°F service temp.
Polyester-Gillfab 1074	33	3.0	0.01	Good strength, most fire-resistant
Polyimide-Gillfab 1028	22	2.5	0.01	400°F service temp.
Polyester-mat-Gillfab 999	16	1.8	0.01	Low cost
Polyester-woven rovings-Gillfab 1027	25	2.0	0.01	Low cost
Kevlar-epoxy-Gillfab 1313	18	2.5	0.0068	Moderate strength, light weight
Kevlar-phenolic-Gillfab 5055	16	2.0	0.0068	Light weight, low smoke
Graphite-epoxy-Gillfab 1089	65	16.0	0.008	Watch for galvanic corrosion, high cost, strength, stiffness
Graphite-phenolic	60	15.0	0.008	Watch for galvanic corrosion, high cost, strength, stiffness
Douglas fir plywood	2.6	1.5	0.003	Low cost, poor weathering, heavy
Tempered hardboard	2.0	0.6	0.0045	Low cost, low strength, heavy

REF. THE M.C. GILL "DOORWAY"
VOL. 28 SPRING, 1991 - PART 2

PRODUCT DATA

M. C. GILL CORPORATION

4056 Easy Street, El Monte, CA 91731
Phone (818) 443-8094 • Telex 67-7467

GILLFAB 1045

APRIL 1986

TDR BASELINE
SANDWICH SKIN
MATERIAL

PROPERTIES OF GILLFAB 1045
Based on 0.060" Thick Laminates.
(Unless Noted)

DESCRIPTION: Gillfab 1045 is a fiberglass cloth-epoxy laminate.

APPLICATIONS: Used in structural applications requiring 300°F service temperature, especially in aircraft near heat sources. Also a standard NEMA G-10 or FRA electrical laminate.

FEATURES: Retains over 50% of its strength @ 300°F.
Fire resistant.
High flexural and other mechanical strengths.
Service temperature range: -65°F to 300°F.

SPECIFICATIONS: FAR 25.853 and 25.855. Fire resistance.
Douglas DMS 1668.
MIL-P-25421B, Ty 1, Class 1.
NEMA G-11.
NEMA FR 4.
MIL-P-22693, Ty 1.
LAL-C-9768, Ty GEE.

CONSTRUCTION: Resin: Epoxy.
Reinforcement: Fiberglass cloth. (WOVEN)
Surface: Matte.

AVAILABILITY: Thickness: From 0.01" in 0.01" multiples.
Length: Up to 168".
Width: Up to 72".
Color: Natural (off green).

STANDARD TOLERANCES: Thickness: $\pm 10\%$
Length and Width: $\pm 0.5"$, $-0"$

SIMILAR GILL PRODUCTS:

Product Number	Difference
1053	NEMA G-11, standard electrical laminate.
1024	Polyester MIL Spec. laminate - lower cost but 180°F service temperature.

PROPERTY

TEST METHOD

VALUE DMS (SI) (METRIC)

Mechanical properties

Tested in warp direction
at room temperature.

Flexural strength, ksi (MPa)	FTMS406-1031	85	(586)
Flexural modulus, msi (GPa)	FTMS406-1031	34	(23)
Tensile strength, ksi (MPa)	FTMS406-1011	55	(379)
Compressive strength, ksi (MPa)	FTMS406-1021	90	(615)
Bond strength, lbs (kg)	DMS 8-2	2000	(907)
After 2 hour boil			
Flexural strength, ksi (MPa)	FTMS406-1031	77	(531)
Flexural modulus, msi (GPa)	FTMS406-1031	3.3	(23)
Tensile strength, ksi (MPa)	FTMS406-1011	53	(365)

Physical properties

Weight, psf (kg/m ²) (0.125 laminate)		1.25	(6.11)
Specific gravity	FTMS406-5011	1.88	
Resin content, % avg.	FTMS406-7061	36	
Barcol hardness, min.	MODEL 934-1	65	
Water absorption, % max.	FTMS406-7031	0.20	
Flammability			
12 sec. vertical exposure	FAR 25.853b		Self Extinguishing
45 degree test	FAR 25.855		Pass
Izod impact strength min value in edge wise direction, ft-lb/in notch (N-m/25.4 mm notch)		7.0	(0.79)

Electrical properties

Dielectric strength, volts/mil	ASTM D-149	350 - 500
Arc resistance, seconds	ASTM D-495	180 min.
Dielectric constant, cps at 1 megacycle	FTMS406-4021	3.2
Standard conditions 24 hrs in water at 23°C		
Dissipation factor, cps at 1 mega cycle	FTMS406-4021	.003
Standard Conditions 24 hrs in water at 23°C		

PRODUCT DATA

M.C. GILL CORPORATION
4056 Easy Street, El Monte, CA 91731
Phone (818) 443-8084 - Telex 67-7467

GILLFAB 1024
APRIL 1986

1 of 2

2 of 2

PROPERTIES OF GILLFAB 1024
Based on 0.060" Thick Laminate
(Unless Noted)

DESCRIPTION: Gillfab 1024 is a fiberglass reinforced polyester laminate made to LP 383, Types I, II, III.

APPLICATIONS: Used in general purpose aircraft and military applications, where its high strength and radar transparency are necessary such as aircraft and missile parts, and radio and radar housings.

FEATURES: Good strength and corrosion resistance.
Type I - No electrical requirements.
Type II & III - Electrical requirements.
Service temperature range: Up to 180°F.

SPECIFICATIONS: LP 383, Type I, II, III (formerly MIL P 8013).
FAR 25.853 and 25.855. Fire resistance.

CONSTRUCTION: Resin: Fire resistant polyester to MIL R 7575.
Reinforcement: Fiberglass cloth per MIL C 9084.
Surface: Glossy or matte.

AVAILABILITY: Thickness: From 0.01" and up in 0.01" multiples.
Length: Up to 172" (up to 0.04" thickness, available in 50" x 125' rolls).
Color: Natural, greenish.

STANDARD TOLERANCES: Thickness: ±10%
Length and Width: +0.5", -0"
Warp, twist: ±1.5% of distance measured

SIMILAR GILL PRODUCTS:

Product Number	Differences
1004	Not fire retardant, otherwise the same.
1018B	Not to MIL Spec., but same properties.
1040	Higher strength using epoxy resin.

M.C. Gill Corporation gives no warranties, express, implied or otherwise, as to description, quality, strength, suitability or any other matter of this property described on data sheet. The values shown are minimum values and are not intended to be used as a basis for design. If additional testing of each lot is required to verify the values shown, the manufacturer's representative will be available to assist in the testing. The manufacturer's representative will be available to assist in the testing. The manufacturer's representative will be available to assist in the testing.

PROPERTY	TEST METHOD	VALUE
Mechanical properties		
Tested in warp direction at room temperature.		
Flexural strength, ksi (MPa)	FTMS406-1031	57 (393)
Flexural modulus, ksi (GPa)	FTMS406-1031	3.2 (22)
Tensile strength, ksi (MPa)	FTMS406-1011	48 (331)
Tensile modulus, ksi (GPa)	FTMS406-1011	3.0 (21)
Compressive strength, ksi (MPa)	FTMS406-1021	40 (276)
After 2 hour boil		
Flexural strength, ksi (MPa)	FTMS406-1031	54 (372)
Flexural modulus, ksi (GPa)	FTMS406-1031	3.0 (21)
Tensile strength, ksi (MPa)	FTMS406-1011	42 (290)
Tensile modulus, ksi (GPa)	FTMS406-1011	2.9 (20)
Compressive strength, ksi (MPa)	FTMS406-1021	35 (241)
After 1/2 hour @ 160°F		
Flexural strength, ksi (MPa)	FTMS406-1031	55 (379)
Flexural modulus, ksi (MPa)	FTMS406-1031	3.0 (21)
Physical properties		
Weight, psf (kg/m ²)	FTMS406-5011	0.60 (2.93)
Specific gravity	FTMS406-7061	1.87
Resin content, % avg.		38
Fiber volume, %		45
Barcol hardness, min.	MODEL 934-1	50
Water absorption, % max.	FTMS406-7031	0.5
Thermal expansion, 10E-5 in/°C	ASTM D-696	6.7-11.0
Flammability		1.2-2.0
12 sec. vertical exposure self-extinguishing time(sec)	FAR 25.853b	
burn length, inches		0
45 degree test	FAR 25.855	1
Electrical properties		
Dielectric constant, cps	FTMS406-4021	Pass
		4.2-4.6

$$12.0 \times 10^{-6} \frac{\text{PPH}}{\text{°C}} \left(\frac{100 \text{°C}}{1 \text{PPH}} \right) = 6.7 \frac{\text{PPH}}{\text{°C}}$$

$$20.0 \times 10^{-6} \frac{\text{PPH}}{\text{°C}} \left(\frac{100 \text{°C}}{1 \text{PPH}} \right) = 11.0 \frac{\text{PPH}}{\text{°C}}$$

generic E (0/90)

GENERIC G-10

Elastic Modulus of Generic (0/90)sym Fiberglass Laminate (E is NOT quasi-isotropic)

0 DEG

45 DEG
NOTE DROP IN MODULUS

90 DEG

GENERIC FIBERGLASS
[0/90]sym LAMINATE
1 of 5

generic CTE (0/90)

GENERIC G-10

CTE of Generic (0/90)sym Fiberglass Laminate (CTE is quasi-isotropic)

CTE AND CTE REMAIN CONSTANT

GENERIC FIBERGLASS
[0/90]sym LAMINATE
2 of 5

fiberglass+

[0/90] sym
3 of 5

	J	K	L	M	N	O	P	Q
1	INTACT PLY DATA MODULE				Temperature and moisture			
2	Scotch[Eng]				T opr	72	72	1.00
3	Rigid body rotation of the entire laminate, in				c,wet	0.005	0.005	1.00
4	Stiffness	Baseline	Modified	Mod/B	T cure	252	252	1.00
5	Ex	5.60	5.60	1.00	T glass	320	320	1.00
6	Ey	1.20	1.20	1.00	T*	1.00	1.00	1.00
7	nu/x	0.26	0.26	1.00	del T	-180	-180	1.00
8	Es	0.80	0.60	1.00				
9	ho,E-6	4925	4925	1.00	Thermal expansion,E-6/degree			
10	Micromechanics data				alph/x	4.78	4.78	1.00
11	vol/f	0.45	0.45	1.00	alph/y	12.28	12.28	1.00
12	Etx	12	12	1.00	Moisture expansion,c			
13	Em	0.49	0.49	1.00	beta/x	0.00	0.00	1.00
14	eta/y	0.52	0.52	1.00	beta/y	0.60	0.60	1.00
15	v'/y	0.63	0.63	1.00				
16	Efy	12.42	12.42	1.00	Ply & const strengths, MPa/ksi			
17	eta/s	0.32	0.32	1.00	X	154	154	1.00
18	v'/s	0.39	0.39	1.00	X'	89	89	1.00
19	Gtx	5.18	5.18	1.00	Y	4	4	1.00
20					Y'	17	17	1.00
21	Plane stress stiffness, GPa/mi				S	10	10	1.00
22	Qxx	5.68	5.68	1.00	Fxy*	-0.50	-0.50	1.00
23	Qyy	1.22	1.22	1.00	Xtx	343	343	1.00
24	Qxy	0.32	0.32	1.00	Xtm	4	4	1.00
25	Qss	0.60	0.60	1.00				
26	Linear combinations, GPa/mi				Strength parameters, E-6			
27	U1	2.97	2.97	1.00	Fxx	73.28	73.28	1.00
28	U2	2.23	2.23	1.00	Fyy	12977.81	12977.61	1.00
29	U3	0.48	0.48	1.00	Fxy	-487.60	-487.60	1.00
30	U4	0.80	0.80	1.00	Fss	9157.43	9157.43	1.00
31	U5=G*iso	1.08	1.08	1.00	Fx,E-3	-4.81	-4.81	1.00
32	Quasi-isotropic constants				Fy,E-3	163.87	163.87	1.00
33	E*iso	2.75	2.75	1.00	Gxx	1914	1914	1.00
34	nu*iso	0.27	0.27	1.00	Gyy	18882	18882	1.00
35					Gxy	1712	1712	1.00
36	Density	1.80	1.80	1.00	Gss	3306	3306	1.00
37	rho/m	1.20	1.20	1.00	Gx	25	25	1.00
38	rho/l	2.63	2.53	1.00	Gy	198	198	1.00
39								

PROPERTIES OF A SINGLE PLY

fiberglass+

[0/90] sym
4 of 5

	R	S	T	U	V	W	X	Y
1	INTACT LAMINATE MODULUS MODULE - elastic and hygrothermal constants							
2								
3	[Angle]	theta/1	theta/2	theta/3	theta/4			
4	[theta]	0.0	90.0	0.0	0.0	[REPT]+		
5	[#/grp]	2.0	2.0	0.0	0.0	5		
6	2X,rad	0E+00	3E+00	0E+00	0E+00	h+/r+,0		
7	4X,rad	0E+00	6E+00	0E+00	0E+00	4		
8								
9	Top z*	1.00	0.50	0.00	0.00			
10	Bot z*	0.50	0.00	0.00	0.00			
11	del(z*)	0.50	0.50	0.00	0.00	h+		
12						2E-01		
13							3.451	
14	Stiff	[Q]/1	[Q]/2	[Q]/3	[Q]/4	[A]	[A*]	
15	11	5.68	1.22	5.68	5.68	0.68	3.45	
16	22	1.22	5.68	1.22	1.22	0.68	3.45	
17	21=12	0.32	0.32	0.32	0.32	0.08	0.32	
18	66	0.60	0.60	0.60	0.60	0.12	0.60	
19	61=16	0.00	0.00	0.00	0.00	0.00	0.00	
20	62=26	0.00	0.00	0.00	0.00	0.00	0.00	
21					[A]	5E-02		
22	Compl	[e],m/GN		[a*]		Elo		
23	11	1.48		3E-01		3.42		
24	22	1.48		3E-01		3.42		
25	21=12	-0.14		-3E-02		0.09	0.09	
26	66	8.45		2E+00		0.60		
27	61=18	0.00		1E-18		0.00		
28	62=26	0.00		-6E-17		0.00		EGPa
29								XMPa
30	Nonmechanical stress(Pa) and strain					V*/IA		rho
31	V*/IA	0.500	-0.500	0.000	0.000	0.000		R=X/[sig]
32	V*/3A	0.000	0.000	0.000	0.000	0.000		rel rho
33		p*n /T	p*n /c	sig*n /T	sig*n /c	alpha o	beta o	eps/iso
34	1	2E-05	0.460	2E-05	0.460	6.305	0.122	rel stiff
35	2	7E-08	-0.270	2E-05	0.460	6.305	0.122	spec stiff
36	8	sig*n o	eps*n o	4E-22	-2E-17	0.000	0.000	spec R
37	1	-2E-03	-5E-04	e/x	-9E-04	0.000		nu/iso
38	2	-2E-03	-5E-04	e/y	8E-04	-0.001		ln(nu)
39	6	-2E-19	-2E-19	e/s	0E+00	0.000		

PROPERTIES OF A [0/90] sym LAMINATE
i.e. WOVEN CLOTH

3-8

fiberglass+

[0/90]5m
5 of 5

	A	B	C	D	E	F	G	H	I
1	MIC-MAC/IN-PLANE: [(theta/#)...]symm								
2	READ ME	Theta 1	Theta 2	Theta 3	Theta 4		Ply mat:	Scotch[Eng]	
3	[ply angle]	0.0	90.0	0.0	0.0	[repeat]	h, #	h, E-3	[Rotate]
4	[ply#]	2.0	2.0	0.0	0.0	5.0	40.0	197.0	0.00
5									
6	R/intact	18.38	3.41	#####	#####	R/FPF	3.41	safety	1.00
7	R/degrade	15.35	50.15	#####	#####	R/LPF	15.35	R/lim*	15.35
8	R/eps x (lr	18.55	118.12	#NUM!	#NUM!	R/ult	15.35	R/lim	3.41
9	[N], MN/m or k/in		[N]/lim	[N]/lim*	[N]/ult	[E*]/lim	E*u/E*lr	<alph>E-6	<beta>
10	1	1.00	3.41	15.35	15.35	3.4	0.83	6.31	0.12
11	2	0.00	0.00	0.00	0.00	3.4	0.83	6.31	0.12
12	6	0.00	0.00	0.00	0.00	0.6	0.04	0.00	0.00
13	eps/squad	1.21	2.32	#NUM!	#NUM!	#NUM!	#NUM!		
14		<sg>	<sg>lim	<sg>lim*	<sg>ult	<ep>E-3	<ep>lim	<ep>lim*	<ep>ult
15	1	5.	17.	78.	78.	1.5	5.1	27.6	27.6
16	2	0.	0.	0.	0.	-0.1	-0.5	0.0	0.0
17	6	0.	0.	0.	0.	0.0	0.0	0.0	0.0
18	Input:	0.04	Output 1	5.1	Output 2		Output 3		
19		T opr	c, moist	vol/	Em	Etx	Xm	Xtx	Em/Em*
20	Baseline	71.6	0.005	0.45	0.49	12	4.5	343	0.04
21	[Modified]	71.6	0.005	0.45	0.49	12	4.5	343	0.04
22	Mod/Base	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
23	Mod-Base	0.0	0.000	Hot/Wet	0.49	12	4.5	343	
24									
25									
26									
27	Ply data linked to Ply Data File:								
28	Scotch[En]	5.6023	1.2003	0.26	0.6009	0.4935	251.6	320	
29	154.136	88.534	4.4993	17.126	10.45	1.2	71.6	0.005	
30	-0.5	4925	0.45	1.8	0.518	0.5	0.2	0.9	
31	4.77778	12.278	0	0.6	0.316	0.01	0.01	3600	
32	2.75	14.2	0.775	1.76	0.04	0.04	0	0	
33									
34									
35									
36									
37									
38									
39									

RESULTING PROPERTY SUMMARY

generic Exx

Elastic Modulus of Generic Fiberglass Laminate (0/+theta/-theta/90)sym

GENERIC FIBERGLASS [0/+θ/-θ/90]sym
1 of 2

generic CTE

CTE of Generic Fiberglass Laminate (0/+theta/-theta/90)sym

[0/+θ/-θ/90]sym
2 of 2

generic E (0/+45/90)

Elastic Modulus of Generic (0/+45/-45/90)sym Fiberglass Laminate (quasi-isotropic)

GENERIC FIBERGLASS
[0/+45/-45/90]sym 1 of 4

fiberglass+

[0/+45/-45/90] sym

2 = 4

fiberglass+

[0/+45/-45/90] sym

3 = 4

	J	K	L	M	N	O	P	Q
1	INTACT PLY DATA MODULE				Temperature and moisture			
2	Scotch[Eng]				T opr	72	72	1.00
3	Rigid body rotation of the entire laminate, in				c,wei	0.005	0.005	1.00
4	Stiffness	Baseline	Modified	Mod/B	T cure	252	252	1.00
5	Ex	5.60	5.60	1.00	T glass	320	320	1.00
6	Ey	1.20	1.20	1.00	T*	1.00	1.00	1.00
7	nu/x	0.26	0.26	1.00	del T	-180	-180	1.00
8	Es	0.60	0.60	1.00				
9	ho,E-6	4925	4925	1.00	Thermal expansion,E-6/degree			
10	Micromechanics data				alph/x	4.78	4.78	1.00
11	vol/I	0.45	0.45	1.00	alph/y	12.28	12.28	1.00
12	Etx	12	12	1.00	Moisture expansion,c			
13	Em	0.49	0.49	1.00	beta/x	0.00	0.00	1.00
14	etay	0.52	0.52	1.00	beta/y	0.60	0.60	1.00
15	v*/y	0.63	0.63	1.00				
16	Efy	12.42	12.42	1.00	Ply & const strengths, MPa/ksi			
17	eta/s	0.32	0.32	1.00	X	154	154	1.00
18	v*/s	0.39	0.39	1.00	X*	89	89	1.00
19	Gtx	5.16	5.16	1.00	Y	4	4	1.00
20					Y*	17	17	1.00
21	Plane stress stiffness, GPa/msi				B	10	10	1.00
22	Oxx	5.68	5.68	1.00	Fxy*	-0.50	-0.50	1.00
23	Oyy	1.22	1.22	1.00	Xtx	343	343	1.00
24	Oxy	0.32	0.32	1.00	Xm	4	4	1.00
25	Oss	0.60	0.60	1.00				
26	Linear combinations, GPa/msi				Strength parameters, E-6			
27	U1	2.97	2.97	1.00	Fxx	73.28	73.28	1.00
28	U2	2.23	2.23	1.00	Fyy	12977.61	12977.61	1.00
29	U3	0.48	0.48	1.00	Fxy	-487.60	-487.60	1.00
30	U4	0.80	0.80	1.00	Fss	9157.43	9157.43	1.00
31	U5=G*iso	1.08	1.08	1.00	Fxx,E-3	-4.81	-4.81	1.00
32	Quasi-isotropic constants				Fy,E-3	163.87	163.87	1.00
33	E*iso	2.75	2.75	1.00	Gxx	1914	1914	1.00
34	nu*iso	0.27	0.27	1.00	Gyy	18882	18882	1.00
35					Gxy	1712	1712	1.00
36	Density	1.80	1.80	1.00	Gss	3306	3306	1.00
37	rho/m	1.20	1.20	1.00	Gx	25	25	1.00
38	rho/I	2.53	2.53	1.00	Gy	198	198	1.00
39								

	R	S	T	U	V	W	X	Y
1	INTACT LAMINATE MODULUS MODULE - elastic and hygrothermal constants							
2								
3	[Angle]	theta/1	theta/2	theta/3	theta/4			
4	[theta]	0.0	45.0	-45.0	90.0	[REPT]		
5	[#/grp]	2.0	2.0	2.0	2.0	5		
6	2X,rad	0E+00	2E+00	-2E+00	3E+00	h+/r+,#		
7	4X,rad	0E+00	3E+00	-3E+00	6E+00	8		
8								
9	Top z*	1.00	0.75	0.50	0.25			
10	Bot z*	0.75	0.50	0.25	0.00			
11	del(z*)	0.25	0.25	0.25	0.25	h+		
12						4E-01		
13							2.968	
14	Stiff	[Q]/1	[Q]/2	[Q]/3	[Q]/4	[A]	[A*]	
15	11	5.68	2.48	2.48	1.22	1.17	2.97	
16	22	1.22	2.48	2.48	5.68	1.17	2.97	
17	21=12	0.32	1.28	1.28	0.32	0.32	0.80	
18	66	0.60	1.57	1.57	0.60	0.43	1.08	
19	61=16	0.00	1.12	-1.12	0.00	0.00	0.00	
20	62=26	0.00	1.12	-1.12	0.00	0.00	0.00	
21					[A]	5E-01		
22	Compl	[e],m/GN		[a*]		Elo		
23	11	0.92		4E-01		2.75		
24	22	0.92		4E-01		2.75		
25	21=12	-0.25		-1E-01		0.27	0.27	
26	66	2.34		9E-01		1.08		
27	61=16	0.00		4E-18		0.00		
28	62=26	0.00		-2E-17		0.00		E/GPa
29								X/MPa
30	Nonmechanical stress(Pa) and strain						V*/IA	rho
31	V*/IA	0.250	0.000	0.000	-0.250	0.000		R=X/[sig]
32	V*/3A	0.000	0.250	-0.250	0.000	0.000		rel rho
33		p*n /T	p*n /c	sig*n /T	sig*n /c	alpha o	beta o	eps/iso
34	1	2E-05	0.460	2E-05	0.460	6.305	0.122	rel stiff
35	2	7E-06	-0.270	2E-05	0.460	6.305	0.122	spec stiff
36	6	sig*n o	eps*n o	2E-22	-8E-18	0.000	0.000	spec R
37	1	-2E-03	-5E-04	e/x	-9E-04	0.000		nu/iso
38	2	-2E-03	-5E-04	e/y	8E-04	-0.001		ln(nu)
39	6	-8E-20	-4E-20	e/s	0E+00	0.000		

fiberglass.

 $[0/+45/-45/90]_{2mm}$
 4 OF 4

	A	B	C	D	E	F	G	H	I
1	MIC-MAC/IN-PLANE: [(theta/#)...]symm								
2	README	Theta 1	Theta 2	Theta 3	Theta 4		Ply mat:	Scotch[Enr]	
3	[ply angle]	0.0	45.0	-45.0	90.0	[repeat]	h, #	h, E-3	[f'otale]
4	[ply#]	2.0	2.0	2.0	2.0	5.0	80.0	394.0	0.00
5									
6	R/Intact	20.30	0.50	0.50	5.50	R/FPF	5.50	safety	1.00
7	R/degrade	21.04	57.06	57.06	18.65	R/LPF	18.65	R/lim*	18.65
8	R/eps x (in	29.84	81.89	81.89	83.59	R/ult	18.65	R/lim	5.50
9	[N], MN/m or k/in	[N]/in	[N]/in*	[N]/in	[E*]/in	E*ul/E*in	[alpha>E-0	[beta>	
10	1	1.00	5.50	18.65	18.65	2.0	0.69	8.31	0.12
11	2	0.00	0.00	0.00	0.00	2.0	0.69	8.31	0.12
12	6	0.00	0.00	0.00	0.00	1.1	0.68	0.00	0.00
13	eps/quad	1.42	1.43	1.43	3.82	1.4178	29.837		
14	<sg*>	<sg*>lim	<sg*>lim*	<sg*>ult	<sg*>E-	<sg*>lim	<sg*>lim*	<sg*>ult	
15	1	3.	14.	42.	42.	0.0	5.1	22.2	22.2
16	2	0.	0.	0.	0.	-0.2	-1.4	-7.2	-7.2
17	6	0.	0.	0.	0.	0.0	0.0	0.0	0.0
18	Input:	0.04	Output 1	5.5	Output 2		Output 3		
19	T opr	c, moist	vol/f	Em	Etz	Xm	Xtz	Em/Em*	
20	Baseline	71.6	0.005	0.45	0.49	12	4.5	343	0.04
21	[Modified]	71.6	0.005	0.45	0.49	12	4.5	343	0.04
22	Mod/Base	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
23	Mod-Base	0.0	0.000	Hot/Wet	0.49	12	4.5	343	
24									
25									
26									
27	Ply data linked to Ply Data File:								
28	Scotch[Enr]	5.6023	1.2003	0.26	0.6009	0.4935	251.8	320	
29	154.136	88.534	4.4993	17.126	10.45	1.2	71.6	0.005	
30	-0.5	4925	0.45	1.8	0.518	0.5	0.2	0.9	
31	4.77778	12.278	0	0.6	0.316	0.01	0.01	3600	
32	2.75	14.2	0.775	1.76	0.04	0.04	0	0	

4. Sandwich Core Materials

Contents:

Survey of various core materials and their densities and mechanical properties (3 pages)

Data for HRH-10 aramid fiber/phenolic resin (Nomex) TDR Baseline core (4 pages)

Data for polymethacrylimide foam (Rohacell) core materials (4 pages)

Summary:

The TDR Baseline sandwich panel core material was aramid fiber/phenolic resin (Nomex) honeycomb. Hexcel corporation calls this line of Nomex honeycomb material HRH-10. The lowest density/shear modulus ratio HRH-10 material, HRH-10-1/8-1.8, was selected as the baseline. It has 1/8 inch cells and weighs 1.8 lb/ft³ (0.029 g/cm³).

Lower cost and better properties per unit mass were available with aluminum honeycomb materials but they were not chosen because an electrically insulating material was required to separate cathodes without introducing capacitance in the core.

Honeycomb materials have two different shear moduli due to their construction. HRH-10-1/8-1.8 has a shear modulus of 1.5 ksi in one direction and 3.8 in the other. For CSC's the highest shear modulus would be aligned to the long span of the chamber to better resist gravity sag.

An alternate core material is polymethacrylimide foam (Rohacell). The lowest density Rohacell available is 31-IG at 1.9 lb/ft³ (0.031 g/cm³). Its shear modulus is 1.99 ksi in all directions. Since it would be approximately half as stiff in shear in the long direction for essentially the same mass as HRH-10-1/8-1.8 it was not chosen as the TDR Baseline core material. Its virtue is its isotropic properties which allow it to better resist local loads such as would occur if the sandwich panel were used for a flooring sheet.

SANDWICH CORE MATERIALS —

SURVEY 1/3

Table I: Comparison of Typical Properties of Honeycomb Core Materials

Considerations	8052 8056 CR III	2024 CR III	ACG CR III	HRP	HFT	HFT-G	HRH 327	HRH 10	TPC
Cost	Med	High	Low	Med	Med	High	High	Med	High
Maximum Strength Temperature	300°F	420°F	350°F	350°F	350°F	350°F	500°F	350°F	350°F
Flammability	E	E	E	E	E	E	E	E	E
Impact Resistance	G	G	G	F	G	F	F	E	E
Moisture Resistance	G	G	G	E	E	E	E	G	E
Fatigue Strength	G	G	G	G	G	G	G	E	E
Heat Transfer	High	High	High	Low	Low	Med	Low	Low	Low
Corrosion Resistance	G	G	G	E	E	E	E	E	E

E = Excellent, G = Good, F = Fair, P = Poor

Table II: Example of Mechanical Property Tables from TSB 120

The following tables contain a sampling of mechanical properties of the various honeycomb core types for which Hexcel has developed data. See TSB 120 for more complete information.

5052 Alloy Hexagonal Aluminum Honeycomb — Specification Grade

Hexcel Honeycomb Designation Cell — Material — Gage	Nominal Density pcf	Compressive			Crush Strength psi	Plate Shear			
		Base		Stabilized		L Direction		W Direction	
		Strength psi	Strength psi	Mod ksi		Strength psi	Mod ksi	Strength psi	Mod ksi
1/16-5052-0007	8.5	typ	min	typ	min	typ	typ	typ	typ
1/16-5052-001	8.2	1500	1170	1550	1200	420	—	800	440
1/16-5052-0015	12.4	2430	1900	2950	2000	630	—	850	480
1/8-5052-0007	3.1	285	200	300	215	75	130	210	155
1/8-5052-001	4.5	850	375	570	405	190	280	340	285
1/8-5052-0015	6.1	880	850	1020	880	240	480	580	455
1/8-5052-002	8.1	1500	1000	1580	1100	350	750	800	670
3/16-5052-001	3.1	290	200	335	215	75	130	210	155
3/16-5052-0015	4.4	820	380	850	385	140	230	330	280
3/16-5052-002	5.7	820	580	880	600	220	380	480	410
1/4-5052-001	2.3	180	120	210	130	45	75	140	100
1/4-5052-0015	3.4	340	240	370	250	80	150	230	180
1/4-5052-002	4.3	500	350	540	370	140	230	320	285
1/4-5052-004	7.9	1420	870	1480	1050	340	725	700	650
3/8-5052-0007	1.9	58	20	55	20	10	25	45	32
3/8-5052-002	3.0	285	190	310	200	70	120	200	145

8056 Hexagonal Aluminum Honeycomb

1/8-8056-007	3.1	320	280	300	280	97	170	230	200	48.0	155	110	20.0
1/8-8056-001	4.5	630	475	680	500	185	320	440	350	70.0	255	205	28.0
3/16-8056-001	3.1	385	250	410	280	97	170	285	200	45.0	150	110	20.0
1/4-8056-001	2.3	240	145	285	155	58	100	180	130	32.0	100	62	15.0

SANDWICH CORE MATERIALS (CONTINUED)

SURVEY 2/3

2024 Hexagonal Aluminum Honeycomb

Hexcel Honeycomb Designation Cell — Material — Gage	Nominal Density pcf	Compressive			Crush Strength psi	Plate Shear			
		Base		Stabilized		L Direction		W Direction	
		Strength psi	Strength psi	Mod ksi		Strength psi	Mod ksi	Strength psi	Mod ksi
1/8-2024-0015	8.0	typ	min	typ	min	typ	typ	typ	typ
1/8-2024-003	8.5	810	525	840	620	200	425	800	480
3/16-2024-0015	3.5	400	280	500	280	88	280	1180	850
1/4-2024-0015	2.8	280	185	320	175	40	110	280	230

5052 Aluminum Flat-Core

5052-F40-0013	2.1	280	128	328	187	86	80	80	63	18.0	80	37	10.0
5052-F40-0018	3.1	370	238	480	280	125	185	170	128	32.0	100	75	13.0
5052-F80-0019	8.5	1280	780	1380	735	310	—	840	388	72.0	310	180	24.0
5052-F80-0025	8.0	1800	1100	1750	1120	400	—	880	434	88.0	470	280	31.0

Aluminum Commercial Grade — Aluminum Naval Grade Hexagonal Honeycomb

ACG-1/4	4.8	685	630	148	345	335	63	216	31
ACG-3/8	3.3	305	325	82	120	186	40	130	20
ACG-1/2	2.3	185	175	40	80	123	25	70	15
ACG-3/4	1.8	110	120	24	45	80	16	80	6
ACG-1	1.3	65	70	18p	25	50p	14p	40p	7p
ANG 2	4.2	600	620	135	—	300	85	180	28

HRP Glass Reinforced Phenolic Honeycomb

Hexcel Honeycomb Designation Material — Cell — Density		Compressive				Plate Shear			
		Base		Stabilized		L Direction		W Direction	
		Strength psi	Strength psi	Mod ksi		Strength psi	Mod ksi	Strength psi	Mod ksi
HRP-3/16-4.0		typ	min	typ	min	typ	typ	typ	typ
HRP-3/16-5.5		510	400	580	480	67	210	210	13.0
HRP-1/4-3.5		800	620	900	750	85	480	340	19.0
HRP-3/8-3.2		380	280	435	400	48	220	180	10.0
		350	280	380	350	38	205	180	12.0

SURVEY 2/3

SANDWICH CORE MATERIALS (CONTINUED)

HFT Glass Reinforced Phenolic Honeycomb

Honeycomb Designation Material - Cell - Density	Compressive			Plate Shear					
	Stabilized			L Direction		W Direction			
	Strength psi	Mod ksi		Strength psi	Mod ksi	Strength psi	Mod ksi		
HFT - 1/8 - 8.8	typ 880	min 840	typ 88	typ 480	min 380	typ 400	typ 230	min 180	typ 180
HFT - 3/16 - 4.0	typ 850	min 480	typ 44	typ 275	min 210	typ 230	typ 140	min 115	typ 140

HRH-327 Glass Reinforced Polyimide Honeycomb

HRH-327 - 3/16 - 4.5	820	400	46	320	220	33	150	110	11
HRH-327 - 3/16 - 8.0	1210	1000	128	700	480	95	420	300	22

WR II Shelter Core

Honeycomb Designation Material - Cell - Density	Compressive			Plate Shear					
	Bare		Stabilized	L Direction		W Direction			
	Strength psi	Strength psi	Mod ksi	Strength psi	Mod ksi	Strength psi	Mod ksi		
WR II - 3/8 - 2.5	typ 280	typ 340	typ 33	typ 170	typ 13	typ 100	typ 7		
WR II - 3/8 - 4.0	515	570	55	255	19	175	9		

HRH-10 Aramid Fiber Reinforced Honeycomb

Honeycomb Designation Material - Cell - Density	Compressive			Plate Shear					
	Bare		Stabilized	L Direction		W Direction			
	Strength psi	Strength psi	Mod ksi	Strength psi	Mod ksi	Strength psi	Mod ksi		
Hexagonal	typ	min	typ	typ	min	typ	typ	min	typ
HRH-10 - 1/8 - 1.8	105	85	115	80	75	130	50	40	1.5
HRH-10 - 1/8 - 8.0	1050	850	1125	385	330	130	200	170	6.5
HRH-10 - 3/16 - 3.0	300	235	325	175	140	6.5	100	85	3.4
HRH-10 - 3/8 - 2.0	140	115	155	90	72	3.7	55	36	2.4
Ox-Core									
HRH-10/OK - 3/16 - 3.0	320	290	350	115	95	3.0	135	110	8.0
Flex-Core									
HRH-10/F35 - 2.5	280	180	235	110	90	4.0	65	60	2.5
HRH-10/F50 - 3.5	380	300	400	170	130	7.5	100	75	4.0

BASELINE
CORE
MATERIAL

LOWEST DENSITY/SHEAR-MODULUS RATIO FOR NIMEX ARAMID H.C.
NOTE: ORIENT THE CORE WITH HIGHEST 'G' IN LONG DIRECTION.

Honeycomb

HRH[®]-10Aramid Fiber/Phenolic Resin Honeycomb
Data Sheet 4000

Features

High Strength at Low Densities
Small Cell Sizes at Low Densities
Damage Resistant Under Normal Shop Use
Formable
Fire-resistant (self extinguishing)
Water and Fungus Resistant
Excellent Dielectric Properties
Good Bonding Surfaces
Good Thermal and Electrical Insulator

Applications

HRH-10 has been widely accepted throughout the aerospace industry and several commercial areas as a very tough, environmentally resistant core material in sandwich panels. It has been designed and used in flat and contoured shapes, with a wide variety of facing materials and adhesives, and it has extensive service in both structural and non-structural parts. Most of the interior panels of commercial jets such as the 737, 747, MD 11, 757, 767, A310, A320, etc. are made with this core material primarily because of its resilience, small cell size — low density combination, and its fire-resistance. Exterior aircraft parts such as radomes, fairings, helicopter blades, flaps, etc. are designed with HRH-10 because of the features listed above. Surfboards and high performance boats are but two additional applications where this core has been used because of its toughness and resistance to corrosive attack. The "OX" configuration is a hexagonal honeycomb which has been over-expanded in the "W" direction, providing a rectangular cell shape which facilitates curving or forming in the "L" direction.

Description

HRH-10 is manufactured from Nomex[®] aramid fiber sheets. A thermosetting adhesive is used to bond these sheets at the nodes, and, after expanding to the hexagonal or OX-Core[®] configuration, the block is dipped in phenolic resin. After curing the resin, slices are cut to the desired thickness. For special applications, such as air directionalizing, the honeycomb can be provided without the phenolic resin. Using this process, a wide range of cell sizes, paper thicknesses and densities can be produced. The standard product line is shown in Table I.

Type Designation

HRH-10 honeycomb is designated as follows:

Material — Cell Size — Density

Example:

HRH-10 — 1/8 — 3.0

Where:

HRH-10 — designates honeycomb type
1/8 — is the cell size in inches
3.0 — is the nominal density in pounds per cubic foot

Dimensional Nomenclature

T = Thickness, or cell depth
L = Ribbon direction, or width
W = Long direction, or direction perpendicular to the ribbon

Availability

HRH-10 will be supplied F.O.B. Casa Grande, Arizona. Lead times will vary with particular core types selected.

Table I: Mechanical Properties of HRH-10 at Room Temperature

DS-4000 2 of 4

Hexcel Honeycomb Designation Material — Cell — Density	Compressive			Plate Shear (N/A) (UL V J)			
	Bare		Stabilized	L Direction		W Direction	
	Strength psi	Strength psi	Modulus ksi	Strength psi	Modulus ksi	Strength psi	Modulus ksi
Hexagonal	typ	min	typ	min	typ	min	typ
HRH-10-1/16-3.4	195	160	205	170	20	155	125
HRH-10-1/8-1.8	105	85	115	95	8	90	75
HRH-10-1/8-3.0	300	235	325	270	20	175	155
HRH-10-1/8-4.0	520	400	575	470	28	255	225
HRH-10-1/8-5.0	700	560	770	620	37	325	275
HRH-10-1/8-6.0	1050	850	1125	925	50	385	330
HRH-10-1/8-8.0	1675	1370	1830	1450	78	480	400
HRH-10-1/8-9.0	2000	1525	2100	1600	90	515	425
HRH-10-3/16-1.5	90	75	100	85	6	75	60
HRH-10-3/16-1.8	120	95	130	105	8	90	75
HRH-10-3/16-2.0	145	120	160	140	11	110	80
HRH-10-3/16-3.0	300	235	325	270	20	175	140
HRH-10-3/16-4.0	500	430	540	470	28	245	215
HRH-10-3/16-6.0	935	780	1020	865	40	420	370
HRH-10-1/4-1.5	80	65	90	75	6	70	55
HRH-10-1/4-2.0	140	115	155	125	11	105	85
HRH-10-1/4-3.1	285	240	310	265	21	185	160
HRH-10-1/4-4.0	440	360	480	390	28	250	205
HRH-10-3/8-1.5	95	75	105	80	6	70	55
HRH-10-3/8-2.0	140	115	155	125	11	80	72
HRH-10-3/8-3.0	290	240	320	270	17	185	160
HRH-10-3/4-1.5	70p	50p	80p	55p	7p	70p	55p
OX-Core							
HRH-10-OX-3/16-1.8	110	85	120	85	7	65	45
HRH-10-OX-3/16-3.0	320	280	350	285	17	115	95
HRH-10-OX-3/16-4.0	600	500	650	550	26	130	105
HRH-10-OX-1/4-3.0	350	280	385	310	17	110	90

Notes:

Test data obtained at 0.500 inch thickness.
p = Indicates limited testing has been performed

* TDR BASELINE CORE MATERIAL

Additional Properties

The following properties of HRH-10 were obtained on representative production materials.

Dielectric Constant

The dielectric constant of a few core types has been measured at a frequency of 9375 MHz. Polarization parallel to both the "L" and "W" direction was used.

Core Density	Polarization Parallel to L		Polarization Parallel to W	
	E Parallel L	E Parallel W	E Parallel L	E Parallel W
1.5	1.09	1.09	1.04	1.03
2.0	1.10	1.10	1.05	1.04
3.0	1.11	1.11	1.07	1.05
4.0	1.13	1.13	1.10	1.07
5.0	1.15	1.15	1.14	1.09
6.0	1.19	1.19	1.18	1.11

Special Configuration and Shapes

Honeycomb cores can be custom designed with non-standard mechanical property combinations to meet a variety of special applications. In addition to the hexagonal and over-expanded (OX) cell shapes HRH-10 is available in Flex-Core®, a very flexible core material (See Data Sheet 3700). HRH-10 can be provided machined or formed to your specific requirements, including flat pieces cut to size, simple tapers, edge chamfering, doubler reliefs, or machining to complex and compound curvatures. Hexcel has unique capabilities to machine parts to unusual contours and to shape honeycomb by a variety of heat forming techniques. Contact the nearest Hexcel Sales Office for addition information.

Standard Dimensions

HRH-10 honeycomb is available in the following standard sizes with the tolerances as indicated.

Products	L	W	T maximum	T minimum	Sq. Ft. Per Panel
HRH-10 Materials	44" ± 2"	96" ± 6"	36"	0.200"	29.3
	48" ± 2"	96" ± 6"	36"	0.200"	32.0
	52" ± 2"	110" ± 6"	36"	0.200"	39.7
HRH-10/OX Materials	38" ± 2"	96" ± 6"	36"	0.200"	25.3

Tolerances on cut thickness are as follows:

0.200" to 2.000" tolerance will be ± 0.006"

2.001" to 4.000" tolerance will be ± 0.010"

4.001" and over tolerance will be ± T/100

Special thickness tolerances as well as other "L", "W" and "T" dimensions are available upon special request. For large volume requirements it may be possible to supply panels to your specific size at little or no additional charge. Tolerances on "L" and "W" for pieces cut to size will depend on the core type and panel dimensions. Tight tolerances are not always possible because of the flexible nature of this core type.

Specifications

HRH-10 has been evaluated and approved for numerous corporate specifications and meets the requirements of SAE specifications AMS 3711B and MIL-C-81986, Amendment 1. In addition, HRH-10 meets the following parameters and properties.

Configuration — The cell size of hexagonal core will give the nominal cell dimensions in inches across the flats (nodes) of the cell. Cell size determination will be made by measuring the length of 10 consecutive cells in 6 random locations and averaging the results. Double laps will be permitted as long as the core blankets are within density tolerance. Unbonded nodes will be permitted to the extent that no opening larger than three times the nominal cell size is created and the minimum mechanical properties are obtainable.

Density — The tolerance on honeycomb density when measured on a minimum of 100 cubic inches of core will be ± 10%.

Flame Retardance — HRH-10 will meet the "self extinguishing" classification of FAA Air Crash Worthiness Rules and Regulations Section 25.853.

Water Migration — HRH-10 does not exceed 1 cell water migration in 24 hours when tested per MIL-STD-401B.

Mechanical Properties — Table I lists the HRH-10 product line and mechanical properties when tested per MIL-STD-401B using 0.500 inch core thickness. The "typical" values represent the mean average of a relatively large number of test values obtained from many blocks of honeycomb. The "preliminary" values marked with a "p" are results from a limited amount of testing. "Minimum" properties are guaranteed minimum individual values when tested at ambient conditions per MIL-STD-401B.

Thermal Conductivity

Several honeycomb cores have been tested for thermal conductivity. The figure below shows the results of this evaluation for HRH-10. The thermal conductivity constant varies with cell size and core thickness because the air convection affects inside the cells. Note the following values were obtained with the heat flow from top to bottom of the panel.

Properties at Elevated Temperatures

HRH-10 has been tested for shear and compressive strength at elevated temperatures and time exposures up to 500 hours. Because the Nomex softens between 450 to 500°F, the properties drop off rapidly at those temperatures; however, when returned to ambient conditions, almost all its original strength is regained.

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rohacell

P M I - R I G I D F O A M

Core material for new designs in composite construction

- High strength to weight
- Closed-cell
- Low density
- High stiffness
- Isotropic structure
- Excellent processing characteristics
- Range of densities (1.9 pcf to 18.7 pcf)
- Resistance to organic solvents
- Sheet form

rohacell IG

ROHACELL® IG is a lightweight, rigid, high-quality, polymethacrylimide foam. It is especially suited for use as a core material for composite construction.

Typical mechanical properties

Properties	Dimension	ROHACELL® IG					ROHACELL® PRESSED GRADES		ASTM Test Method
		31 IG	51 IG	71 IG	110 IG	P170	P190	P190	
Density	Lbs./cu. ft.	1.9 (pcf)	3.1 (pcf)	4.4 (pcf)	6.9 (pcf)	10.6 (pcf)	11.9 (pcf)	11.9 (pcf)	D1622
Tensile strength	PSI	142	270	398	498	1,070	1,210	1,210	D638
Compressive strength	PSI	57	128	213	427	824(398)	1,110(455)	1,110(455)	D1621
Flexural strength	PSI	114	228	356	640	1,490(1,420)	1,780(1,710)	1,780(1,710)	D790
Shear strength	PSI	57	114	185	341	640(427)	782(427)	782(427)	C273
Modulus of elasticity	PSI	5,120	9,950	13,100	22,700	45,500	54,000	54,000	D638
Shear modulus	PSI	1,990	2,990	4,270	8,250	17,000	26,300	26,300	D2236
Shear modulus	PSI	1,850	2,700	4,120	7,110	12,500	14,200	14,200	C273
Elongation at break	%	3.5	4	4.5	4.5	5	6	6	D638

Test conditions: 23°C (73°F) and 50% relative humidity

1) P170 and P190 are post-compressed non-structural grades. Values are based on the measured density of the foam.

Standard sheet sizes:	Sheet thickness
ROHACELL 31 IG	49.2 x 98.4 in. .12 in. to 2.6 in.
ROHACELL 51 IG	49.2 x 98.4 in. .04 in. to 2.2 in.
ROHACELL 71 IG	49.2 x 98.4 in. .12 in. to 2.0 in.
ROHACELL 110 IG	21.6 x 85 in. 1.9 in. only
ROHACELL P170	23.6 x 98.4 in. 1.1 in. only
ROHACELL P190	23.6 x 98.4 in. 0.9 in. only

Applications

ROHACELL IG has a variety of uses in composite construction as a core material e.g.

- Aircraft construction
- Radiation technology
- Electronics
- Construction of sporting goods: tennis rackets, canoe paddles, cross country and downhill skis, etc.
- Freight containers
- Marine construction such as hulls, decks, bulkheads and rudders
- Model building in industry and architecture
- Thermal expansion molding mandrels

Tensile strength (ASTM D638) as a function of temperature

Compressive strength (ASTM D1621) as a function of temperature

Shear modulus and mechanical damping (ASTM D2236) as a function of temperature

$\frac{P}{G} = \frac{31 IG}{1.9} = 0.016$

Materials less than 0.16 in. thick are only available 24.6 x 49.2 in.

$\frac{1.9}{3700} = 0.0005$

HALF AS STIFF IN SHEAR COMPARED TO TDR BASELINE CORE

5. Epoxy Filler Materials

Contents:

Data sheet, Fiberite 954-3 cyanate resin, 350F cure temperature (2 pages)
Data sheet, Hexcel F185 epoxy resin, 250F cure temperature (6 pages)
Data sheet, Fiber-Resin FR-337/338 carbon or aluminum fiber reinforced RT epoxy (2 pages)
Data sheet, Ciba-Geigy Epocast 1617 A/B syntactic RT epoxy (1 page)
Data sheet, Grace Eccofloat TG-24/24A low density syntactic (2 pages)
Mechanical data, Anocast low density syntactic (1 page)
Material comparison chart, Ref. GEM TN-93-460 (1 page)

Summary:

- *Alternative material choices show the most promise of achieving mass reductions without compromising chamber stiffness and without increasing design complexity. Materials having high stiffness-to-density ratios are needed only for load-bearing locations (under bolts, near support connections, etc.) thus requiring less material to carry a given load.*
 - *Castable epoxies with high-modulus fillers are optimal for all load-bearing components.*
 - *Ultra-low density materials are optimal for lightly loaded components.*
- *An optimal cathode strip chamber structural design simultaneously minimizes muon scattering (mass effects), shear deformations, gravity sag, stress levels, and complexity.*

A Data Sheet from

954-3 CYANATE RESIN

- Low microcracking, low moisture absorbing cyanate resin
- -200°F to 250°F (-128°C to 121°C) service temperature without post-cure. After post-cure, service temperature is 325°F/wet.
- Attractive electrical properties
- 350°F (177°C) cure
- Very low minimum viscosity
- Available in a broad range of fibers and forms including tape and fabric
- Autoclave or press-mold processable

Fiberite® 954-3 is a 350°F (177°C) curing cyanate resin with a -200°F to 250°F (-128°C to 121°C) service temperature. Fiberite 954-3 is formulated for autoclave or press molding. Standard cure is two hours at 350°F (177°C). Service temperatures are maximized by a post-cure of 428-450°F (220-232°C). Fiberite 954-3 can be impregnated via hot melt or solution techniques on all available fibers and fabrics. The recommended lay-up procedure for this material is L-7. The recommended cure procedure is C-9.

Typical applications for 954-3 include primary and secondary space structures and other applications where resistance to microcracking and moisture, together with light weight and excellent dielectric properties are required.

TYPICAL HEAT RESIN PROPERTIES

	RT	228°F (115°C)	328°F/Wet (165°C/Wet)
Tensile Strength, ksi	6.2		
Tensile Modulus, Msi	0.4		
Tensile Elong., %	2.4		
Tensile Strength, MPa	88.6		
Tensile Modulus, GPa	2.79		
Tensile Elong., %	2.4		
Flexural Strength, ksi	17.9	12.6	11.2
Flexural Modulus, Msi	0.43	0.33	0.30
Flexural Strength, MPa	119.27	86.89	77.21
Flexural Modulus, GPa	2.98	2.28	2.07
H ₂ O Uptake, Wt. %	0.88		
Tg (DMA-Tan δ), °C	208		
Density, g/cm ³	1.18		

Notes: (1) Post-cure 2 hours at 450°F
(2) Wet = 7 day immersion at 180°F.

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberte does not control the conditions under which its products are tested and used, ICI Fiberte cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

FIBERITE® 954-3 CYANATE RESIN

DIMENSIONAL STABILITY

	954-3	684
Hygrostrain, ppm	18.9	108.6
Water Absorption, %	0.18*	0.70*
CME, ppm/%	105	188

NOTES:

Hygrostrain divided by %M = CME

Pseudo-isotropic P75 laminate; 50% RC

*R. Brand and E. Derby, SPIE Conf., 1980, 308, April 1982 (Composites Optics, Inc.)

*C. Blair and J. Zakrzewski, SPIE Conf., 1980, 300, April 1982 (Lockheed MSC)

*55% RH/VEO

*50% RH/VEO

954-3 RESIN OUTGASSING

	954-3	ASTM LIMITS
Total Mass Loss	0.30%	1.0%
Volatile Condensable Materials	0.01%	0.1%
Water Vapor Recovered	0.04%	-

NOTES:

Tested per ASTM E 585

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberte does not control the conditions under which its products are tested and used, ICI Fiberte cannot guarantee that the properties listed will be obtained with other processes and equipment.

SANDWICH
ADHESIVE

1-6
F-185

Resin Systems for Advanced Composites

F185

A Structural Adhesive and Co-Curing Grade Epoxy Resin 250°F Cure

F185™ is an advanced epoxy formulation designed for autoclave curing to offer very high sandwich and metal bonding strengths with moderate laminate strengths. This system offers the highest available fracture toughness and strain to failure of the 250°F cure resins.

Features

Uncured:

- Single assembly sandwich layup procedure
- Controlled flow
- Excellent tack and drape properties

Cured:

- Excellent fracture toughness and strain to failure
- Self extinguishing
- Balanced tool and bagside peels on sandwich panels
- Very high sandwich and metal bonding strengths
- Good laminate properties
- Certified to MIL-A-25463 A, Type 1, Class 2, and MMM-A-132 A, Type 1, Class 2

Neat Resin Properties

Specific Gravity	1.286 g/cc
T _g Dry	171°F
Equilibrium Moisture Absorption	7.0%
Linear Coefficient of Thermal Expansion	4.75×10^{-5} in/in/°F
Tensile Strength	7.2 ksi
Tensile Modulus	0.42 msi
Tensile Strain	>9.5%
Fracture Toughness, K _{1C}	4.05 ksi $\sqrt{\text{in}}$
	3.69 MPa $\sqrt{\text{m}}$
Strain Energy Release Rate, G _{1C}	34.5 lb/in
	6.04 KJ/m ²
Gel Time @ 250°F	5-11 min.

F185
Gel Time vs. Temperature

Rheometrics Curve of F185
2 Deg./Min., 10 Rad/Sec,
RDS-7700, 50mm Plates

3-L
F-185

Availability

Form	Hercel Designation	Fiber	Fiber Area WT/gm ²	Weave	Count Warp x Fill	Standard Width	Widths Available
Glass Fabrics	120 36" F 185	450 1:2	115	Crowfoot ML C 9004 TYW	60 x 58	36"	44 50 60
	1581 36" F 185	150 1:2	300	8 Harness Salm ML C 9004 TYW	57 x 54	36"	44 50 60 72
	7781 36" F 185	75 1:0	300	8 Harness Salm ML C 9004 TYW	57 x 54	36"	44 50 60 72
Kevlar® Fabrics	K120 36" F 185	Max 49 185	61	Plain	34 x 34	36"	50 60
	K295 36" F 185	Max 49 1140	170	Crowfoot	17 x 17	36"	50 60
	K281 36" F 185	Max 49 1140	170	Plain	17 x 17	36"	50 60
Carbon Tapes	T_095 12" F 185	Various	85				
	T_145 12" F 185	Various	145				
	T_190 12" F 185	Various	190				

Note: Alternate glass and Kevlar® fabric weaving may be used with the F 185 Resin System. Also, F 185 Carbon Tapes may be produced with various carbon fiber types and low sizes. In designating carbon tapes, the second digit represents low size and the third digit represents fiber source. Consult your nearest Hercel representative for additional information.

© E I DuPont

Physical Properties

Property	Glass Fabrics		Kevlar® Fabric
Prepreg	Material Description	120	K285
	% Fiber @ 250°F 40 psi	24 34	24 34
	% Volatiles	4 12	4 12
	% Resin Content (Wt)	57 63	47 53
Laminate	Cured Thickness per Ply (in)	0.0049	0.0092
	% Fiber Volume	36 1	51 3

4-L
F-185

Mechanical Properties

Property	Temp	Glass Fabrics		Kevlar® Fabric
Laminate Properties Warp Tensile Strength, ksi Warp Tensile Modulus, msi Fill Tensile Strength, ksi Fill Tensile Modulus, msi Warp Compression Strength, ksi Warp Compression Modulus, msi Fill Compression Strength, ksi Fill Compression Modulus, msi Warp Short Beam Shear, ksi	°F	120	1581	7781
	75	44.7	55.0	63.8
	75			73.6
	75			3.40
	75			60.8
	75	41.0	50.0	3.81
	75			22.5
	75			2.79
	75			23.8
	75			2.00
Sandwich Panel Properties Drum Peel in./lb/in Drum Peel in./lb/in Drum Peel in./lb/in Flareless Tensile, psi Flareless Tensile, psi Long Beam Flex, lb	-65	15.0	23.3	28.0
	75	23.0	29.4	36.6
	180	20.5	31.2	35.0
	-65		1223	
	180		803	
Adhesive Properties Lap Shear, psi Lap Shear, psi Lap Shear, psi Tensile to Metal Peel, lb/in. Tensile to Metal Peel, lb/in.	75	4867	5378	4748
	75	5139	4808	4808
	180	3068	4123	2941
	-65	35.6	47.0	32.2
	180	48.7	73.0	76.4

All mechanical property values are based on the calculated fiber volume, based on the previous table.

Reported property values are averages to which no statistical assurance should be attached. While Hercel believes that the data contained herein is factual, the data is not to be taken as a warranty or representation for which Hercel assumes legal responsibility. They are offered solely for your consideration, interpretation, and verification.

Cure Cycle

S-6
F-185

Cure Procedure:

- Apply vacuum of 22 inches Hg minimum.
- Apply 85 + 15 - 0 PSIG pressure for laminates.
- Apply 45 + 15 - 0 PSIG pressure for sandwich.*
- Vent vacuum bag to atmosphere when pressure reaches 20 PSI.
- During cool down when the part temperature falls below 140°F, pressure can be relieved and the test panel removed from the autoclave and debagged.

*Typical for HRH 10-1/8-3.0 honeycomb.

Handling Safety

The Hexcel Corporation recommends that each of its customers observe established precautions for handling epoxy resins and fine fibrous materials. Operators working with this product should wear clean impervious gloves to reduce the possibility of skin contact, also to prevent contamination of the material.

Airborne graphite as a result of sawing, grinding, etc., can present electrical shorting hazards, refer to NASA Technical Memorandum 78652. For further information refer to the Material Safety Data Sheet.

Storage

F185 prepreg should be sealed in a polyethylene bag and refrigerated, preferably below 32°F (0°C). Following removal from refrigerated storage, allow the prepreg to reach room temperature before opening the polyethylene bag to avoid moisture condensation. Shelf life — 6 months at 0°F, 3 months at 40°F.

Shipping

Prepreg fabric and tape is generally shipped in a sealed polyethylene bag in an insulated container packed with dry ice.

Disposal of Scrap

Disposal of this material should be in a secure landfill in accordance with State and Federal regulations.

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VINYL-RESIN COAT

REF ID: A6358155 0000221 ?

FIBER-RESIN CORP.

STERN-RENNEN 1999
P.O. Box 442
10700 Piedmont Ave.
Berkeley, CA 94702
1-800-824-0077
Fax: 415-841-0000

STERN-RENNEN 1999
STERN-Museum
Strasse 48 49100
64289 Frankfurt
D 30 1-430-430-430
Tele. 069 177 347

PP-327, 328, PP-329-334

MAKES STRENGTH TWO PART EPOXY COMPOUNDS

५१

- LCN22-10290, Type I, Grade A: FR-337/In. #36 (Pourable)
- LCN22-10290, Type I, Grade B: FR-330-NA/In. #36 (Paste)
- LCN22-10290, Type 10, Grade A: FR-337/In. #37 (Pourable, Aluminum Filled)
- LCN22-10290, Type 10, Grade B: FR-330-NA/In. #37 (Paste, Aluminum Filled)

All combinations of FR-337 and FR-338-MA and Hardeners #37 and #38 are mixed at a ratio of 2 parts by weight of resin, to 1 part by weight of hardener.

The pot life of FR-337 with hardeners #37 or #38 is 35 - 45 minutes. The pot life of FR-338-NA with hardeners #37 or #38 is 20 - 30 minutes.

FR-337 and FR-338-NA set hard within 1 - 2 hours at room temperature. Full properties are met within 7 days at room temperature, or 1 hour at 280 - 350 F.

FR-227-NA/In. 937
FR-227-NA/In. 938

Viscosity, CPS	35,000 - 65,000	45 = $\frac{\text{Paga}}{0.95}$ + 23
Density, max., lbs/cu. in.	(0.95) - (0.945) (LH)	$\frac{0.95 - 0.945}{0.95}$
Machinability	(LH) Good	Good
Adhesive Strength, Flatwise, PSI		
Per MIL-A-2546)		
@ R. T.	> 3,500	> 3,500
@ 160 F.	> 2,000	> 2,000

0519 8-10

FIBER-RESIN COMPS

LOC 9 3548155 0000222 9 H-69-05-10

2 of 2

~~FD-327-Sub. #37~~ ~~FD-328-Sub. #37~~
~~FD-327-Sub. #38~~ ~~FD-328-Sub. #38~~

CYCLING PROPERTIES AT ELEVATED TEMPERATURES:

Physical Properties after 100 Cycles at 200	29C F.	423 F.
Strength, PSI	42,500	29,900
Modulus, PSI	3.3 x 10 ⁶	4.9 x 10 ⁶

	<u>299 P.</u>	<u>425 P.</u>
Strength, PSI	37,000	29,000
Modulus, PSI	<u>8.1×10^6</u>	<u>4.4×10^6</u>

As with all resin systems, liquid and vapor may cause irritation to some people. Avoid contact with skin and use adequate ventilation. Wash skin with soap and water. Flush eyes with water continuously and get medical attention.

6/89

CIBA-GEIGY

Product Data

Formulated
Systems Group**FURANE** Aerospace Products

1 of 1

6121 San Fernando Road West
Los Angeles, CA 90035-1071
Tel: 910-347-4210 Fax: 910-497-0187**EPOCAST® 1617-A/B****LOW DENSITY SYNTACTIC***

- Soft Paste
- One Hour Work Life
- Flame Resistant

DESCRIPTION

EpoCast 1617-A/B is a self-extinguishing epoxy syntactic compound developed as an edge sealant for honeycomb structures. Special features of high strength, low density, and ease of handling have been incorporated into this system. EpoCast 1617-A/B cures to an off-white color and is qualified to BMS 3-28, Type 17.

TYPICAL PROPERTIES AS RECEIVED

Property	1617-A	1617-B	1617-A/B	Test Method
Color	Off-white	Amber	Off-white	Visual
Specific gravity	0.65	1.05	0.70	ASTM-D-792
Viscosity, centipoise	Paste	50,000	Paste	ASTM-D-2393
Flash point, COC, °F	330	210	—	ASTM-D-92
Work life, 100 gms at 77°F, minutes	—	—	60-90	ASTM-D-1338
Shelf life at 77°F, unopened, months	6	6	—	FTM-204
Solids, %	—	—	100	ASTM-D-1644

MIX RATIO

To 100 parts by weight of EpoCast 1617-A, add 20 parts by weight of EpoCast 1617-B. Mix both components thoroughly for several minutes to assure complete blending. If EpoCast 1617-A separates during storage, stir thoroughly before adding EpoCast 1617-B.

CURE SCHEDULE: 24 hours at room temperature or 3 hours at 125°F.

TYPICAL CURED PROPERTIES (Not for specification purposes)

Test	Result	Test Method
Compressive strength, psi	5,500	ASTM-D-695
Compressive modulus, psi	3.5x10 ⁵	ASTM-D-695
Tensile lap shear, chromic acid etched aluminum, psi	1,800	ASTM-D-1002
Weight change, 24 hours immersion at 77°F, %		ASTM-D-570
MIL-S-3134, Type III test fluid	0.5	
MIL-B-5606 hydraulic fluid	1.5	
Skydrol 500A	2.0	
Distilled water	2.0	
Flammability	self extinguishing	

* Syntactic cellular polymer is produced by dispersing rigid, foamed microscopic particles in a fluid polymer and stabilizing the system. In other words, it is a polymer filled with microballoons.

5-7

GRACE Syntactics

TECHNICAL BULLETIN

ULTRA-LOW DENSITY
SYNTACTIC

$$\rho = 0.38 \text{ g/cc}$$

$$E = 0.18 \text{ Msi}$$

ECCOFLOAT® TG-24A

HIGH - PERFORMANCE, LOW - DENSITY SYNTACTIC FOAM

ECCOFLOAT TG-24A is a very high performance syntactic foam available in blocks. The basic ingredients are hydrospace-quality Glass Microballoons® and high-strength resin. The material is homogeneous in that pieces cut from a block will have the same properties as the original block, except for surface area-to-volume ratio effects.

FORMS AVAILABLE. The standard commercial form of ECCOFLOAT TG-24A is molded blocks one-half cubic foot (0.014 cu. m.) in volume, of dimensions 6" x 12" x 12" (15.2cm x 30.5cm x 30.5cm). Larger shapes can be made by adhesive bonding or mechanical attachment of these blocks. The material is readily sawed or machined with conventional tools, and the cut surfaces do not require any preparation before use. Hardware can be attached with bolts or adhesive.

RANGE OF APPLICATIONS: Although intended primarily for use as a buoyancy material for deepsea instruments and submersibles, ECCOFLOAT TG-24A can perform a variety of other functions. Its strength makes it useful for certain structural applications, and its acoustic behavior is good for devices requiring transparency to sound in sea water, such as sonar windows.

DETERMINATION OF LINE DEPTH.

All syntactic buoyancy materials absorb some water when subjected to hydrostatic pressure. The weight gain and corresponding buoyancy loss of ECCOFLOAT TG-24A is small, provided the material is not

Typical Properties	
Density, (MIL-S-24154A) Lbs./cu.ft. (g/cc)	24.2 (0.384) (0.3)
Crush Pressure, (MIL-S-24154A) psi	4,500
Crush Depth, (ASTM D2738) ft. (meters)	10,135 (3,089)
Service Pressure, psi	3,000 (207)
Service Depth, ft. (meters)	8,757
Water Absorption	<3% (24 Hours)
Ultimate Uniaxial Compressive Strength (ASTM D885) psi (kg/cm ²)	2,700 (190)
Uniaxial Compressive Elastic Modulus (ASTM D885) psi (kg/cm ²)	180,000 (12,967)
Bulk Modulus, (MIL-S-24154A) psi (kg/cm ²)	215,000 (15,130)
Speed of Sound ft./sec. (m/sec.)	8,510 (2,594)
Acoustic Impedance rays	940
Acoustic Loss Factor	0.01
Dielectric Constant @ 8.8 Ghz	1.585
Loss Tangent	.0029
Dielectric Strength (Average)	332 (Volts/mm)

used too close to its crush depth. The choice of use depth must be based upon the nature of the payload, time at depth, and the service life to be expected of the material.

This information, while believed to be completely reliable, is not to be taken as warranty for which we assume legal responsibility nor as permission or recommendation to practice any patented invention without license. It is offered for consideration, investigation, and verification.

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Canton, MA 02021
(617) 821-4250

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GRACE Syntactics

TECHNICAL BULLETIN

ULTRA-LOW DENSITY
SYNTACTIC

$$\rho = 0.384 \text{ g/cc}$$

$$E = 0.118 \text{ Msi}$$

ECCOFLOAT® RG-24

BULK BUOYANCY MODULES

ECCOFLOAT RG-24 is a plastic composite material with a high strength-to-weight ratio. It is low in density and exhibits excellent resistance to water penetration which makes it well suited for use as a RIBER Buoyancy material. In formulating this product particular emphasis was placed on achieving maximum uniaxial compressive strength enabling its use in 3,000 ft water depth and for extended periods of time. Higher density formulations of ECCOFLOAT RG have been successfully deployed to 4,800 ft. (1,722 m).

BASIC INGREDIENTS

The basic ingredients of ECCOFLOAT RG are specially prepared, hollow epoxy "microspheres" (average diameter 0.30" or .885 cm) and a surrounding matrix of syntactic foam, composed of epoxy resin and high-performance glass.

MICROBALLOONS® spheres (average diameter 80 microns). ECCOFLOAT Riber Buoyancy Modules are manufactured using a molding process which injects syntactic foam into a closed mold. Precise control of vacuum and pressure are essential to insure a void free module.

SURFACE PROTECTION

The surface of ECCOFLOAT Riber Buoyancy Modules is covered with a patented fiberglass reinforcement called **ECCORIDE®**. This ECCORIDE process integrally molds a tough FRP shell on all module exterior surfaces. While other coating concepts have been evaluated, ECCORIDE continues to be the most cost effective, lightweight protection available, resulting in a slight increase in overall module density.

ECCOFLOAT PERFORMANCE

ECCOFLOAT RG-24 Buoyancy Modules are solid constructions cast to achieve precise dimensions, size and shape are seldom a limitation. ECCOFLOAT Modules are designed to survive normal shipboard handling, and will not fail.

PERFORMANCE PROPERTIES	
Nominal Density, lbs./cu. ft. (g/cc)	24 (.384)
Buoyancy in Sea Water, lbs./cu. ft. (g/cc)	40 (.641)
Crush Pressure, psi (Kg/cm ²)	2200 (154.7)
Rated Service Depth, Ft. (Meters)	3000 (914)
Pressure at Service Depth, psi (Kg/cm ²)	1330 (93.5)

MECHANICAL PROPERTIES (Typical)	
Ultimate Tensile Strength, psi (Kg/cm ²)	520 (36.6)
Ultimate Uniaxial Compressive Strength, psi (Kg/cm ²)	2010 (141.3)
Shear Strength, psi (Kg/cm ²)	1080 (74.5)
Modulus of Elasticity in Compression, psi (Kg/cm ²)	118,000 (8,285)

catastrophically, even when accidentally damaged or punctured will beyond their service limit. The performance properties of ECCOFLOAT RG-24 are shown in the accompanying chart. It should be noted, that ECCOFLOAT RG-24 properties do not include the reinforcing effect of the ECCORIDE shell.

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MICROSPHERE-FILLED EPOXY : REF: VONME
POLYCHROMKOS
BAU

ANOCAST ANOCAD CORP., CHAGLEV FALLS, OHIO
LIGHTWEIGHT PC TARGET FRAME SYSTEMS FAX: 216-593-8995

PROPERTY	SYSTEM	
	1	2
System Formulation, wt%:		
Resin	53	64
Hardener	9	10
Black	1	2
Glass spheres	37	24
Flexure Strength, psi	1225	--
Flexural Modulus of Elasticity, psi (E_f)	139,500	--
Compressive Strength, psi	1755	3925
Young's Modulus, psi (E)	98,395	142,700
Density, lb/cu ft	26.2 (0.42)	34.6 (0.55)
Water Absorption, wt%		

ANOCAD REF.
(DAMIAN SMITH)
216-593-8995

"NOT NORMALLY
CAST BY USER,
BUT CAN BE
WITH PROPER
INSTRUCTION"

FOR, Young's Modulus = $E = 98,395$ psi

AND FLEXURAL MODULUS = $E_f = 139,500$ psi

THEN, $\nu = 0.317$

$$\text{WHERE } E_f = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

5-10

1 of 1

Edge Fillers (normalized to G10 woven laminate)										
material	rho density (g/cm3)	E modulus (ksi)	rl radiation length (cm)	n.rho normalized density	n.E normalized modulus	n.rl normalized radiation length	w width needed for equal sag	m1* (lower is better)	m2* (lower is better)	normalized rho/E
Fiber-Resin (FR-337)	1.66	5,000	34	0.86	1.52	1.75	0.66	0.38	0.32	0.57
G10 woven laminate	1.926	3,300	19.4	1.00	1.00	1.00	1.00	1.00	1.00	1.00
glass fiber filled epoxy	1.85	1800	21.2	0.96	0.48	1.09	2.06	1.89	1.81	1.98
Ciba-Geigy (1617) *	0.7	350	56	0.36	0.11	2.89	9.43	3.27	1.19	3.43
250F epoxy (954-3)	1.19	400	55	0.62	0.12	2.84	8.25	2.91	1.80	5.10
Anocast low-dens. *	0.42	100	91	0.22	0.03	4.69	33.00	7.04	1.53	7.20
(estimates below based on 25/75 ratio of SiO2/Epoxy)										
Ciba-Geigy (1617)	0.7	350	66	0.36	0.11	3.40	9.43	2.77	1.01	3.43
Anocast low-dens.	0.42	100	107	0.22	0.03	5.52	33.00	5.98	1.30	7.20

* (FIRST ESTIMATES BASED ON 50/50 RATIO OF SiO2/EPOXY)

Core Materials (normalized to Hexcel HRH-1-1/8/1.8)							
material	rho density (g/cm3)	G shear modulus (ksi)	rl radiation length (cm)	normalized density	normalized shear modulus	normalized radiation length	normalized rho/G
Rohacell 31 IG	0.0305	1.99	1,400	1.06	0.5686	1.00	1.86
Hexcel HRH-10-1/8-1.8	0.0289	3.50	1,400	1.00	1.0000	1.00	1.00

REF. GEM TN-93-460

6. Radiation Length

Contents:

Radiation length data for selected materials, ref. M. Marx, SUNY SB (1 page)

Routine for calculating rad. length of a compound, ref. T. Wenaus, LLNL (2 pages)

Radiation length estimates for typical CSC structural materials (1 page)

Summary:

Materials with high radiation lengths are most desirable for muon chambers.

RADIATION LENGTHS FOR SELECTED MATERIALS

REF. MIKE MARK
SUNY SB

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Material	Z	A	Nuclear total cross section σ_T (barn)	Nuclear inelastic cross section σ_I (barn)	Nuclear collision length λ_C (g/cm ²)	Nuclear interaction length λ_I (g/cm ²)	$\frac{dE}{dx}$ [MeV g/cm ²]	Radiation length X_0 (g/cm ²) (cm) () is for gas		Density ρ (g/cm ³) () is for gas (g/l)	Refractive index n () is (n-1) x 10 ⁶ for gas
H ₂	1	1.01	0.0387	0.033	43.3	80.8	4.12	61.28	885	0.0708(0.090)	1.112(140)
D ₂	1	2.01	0.073	0.061	45.7	84.7	2.07	122.6	787	0.162(0.177)	1.128
He	2	4.00	0.133	0.102	49.9	86.1	1.84	84.32	785	0.125(0.178)	1.024(35)
Li	3	6.94	0.211	0.157	54.6	73.4	1.58	82.78	185	0.534	—
Be	4	9.01	0.268	0.199	53.8	75.2	1.61	66.19	36.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.78	42.70	19.8	2.265 ¹	—
N ₂	7	14.01	0.379	0.265	61.4	87.8	1.82	37.59	47.0	0.806(1.23)	1.205(300)
O ₂	8	16.00	0.420	0.292	63.2	91.0	1.82	34.24	30.0	1.14(1.43)	1.22(266)
Ne	10	20.18	0.507	0.347	68.1	96.6	1.73	28.84	24.0	1.207(0.90)	1.002(57)
Al	13	26.98	0.634	0.421	70.6	106.4	1.82	24.01	2.70	—	—
Si	14	28.09	0.680	0.440	70.6	106.0	1.86	21.82	2.33	—	—
Ar	18	39.95	0.888	0.586	78.4	117.2	1.51	19.55	14.0	1.40(1.78)	1.233(283)
Ti	22	47.88	0.985	0.637	79.9	124.9	1.51	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.48	13.84	7.87	—	—
Cu	29	63.55	1.232	0.782	86.6	134.9	1.44	12.86	8.96	—	—
Ga	32	72.59	1.365	0.858	88.3	140.5	1.40	12.25	5.323	—	—
Sa	50	118.89	1.967	1.21	100.2	163	1.36	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	1.24	6.48	2.77	3.057(5.89)	(706)
W	74	183.85	2.767	1.65	110.3	185	1.16	6.78	0.35	19.3	—
Pb	78	195.06	2.461	1.708	113.3	189.7	1.15	6.34	0.305	21.45	—
Pb	82	207.19	2.060	1.77	116.2	194	1.13	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.09	6.00	19.32	18.95	—
Air, 20°C, 1 atm. (STP in paren.)											
H ₂ O			62.0	40.0	82.0	90.0	1.82	36.66	(30420)	0.001296(1.29)	1.000273(293)
Smoking concrete ^a			60.1	41.9	81.9	81.9	2.03	36.08	36.1	1.00	1.33
SiO ₂ (quartz)			67.4	49.0	87.0	87.0	1.70	26.7	10.2	2.6	—
H ₂ (bubble chamber 26°K)			43.3	50.8	41.2	61.28	1000	10.0	12.3	2.84	1.458
D ₂ (bubble chamber 31°K)			45.7	54.7	2.07	122.6	1000	10.0	10.0	0.063	1.100
H-Ne mixture (50 mole percent) ^d			65.0	44.5	1.84	29.70	73.0	10.0	10.0	0.407	1.002
Mixed emulsion G5											
NaI			82.0	134	1.44	11.0	2.89	3.815	—	—	—
BaF ₂			94.8	152	1.32	9.49	2.59	3.67	—	—	1.775
BCO (Bi ₄ Ge ₃ O ₁₂)			92.1	146	1.35	9.91	2.05	4.89	—	—	1.56
Polystyrene, scintillator (CH) ^e			97.4	156	1.27	7.98	1.12	7.1	—	—	2.15
Lucite, Plexiglas (C ₅ H ₈ O ₂)			58.4	62.0	1.86	43.8	42.4	1.032	—	—	1.581
Polyethylene (CH ₂)			89.2	83.6	1.95	40.55	34.4	1.16-1.20	—	—	1.49
Mylar (C ₅ H ₄ O ₂)			66.9	78.8	2.00	44.8	47.9	0.92-0.95	—	—	—
Borosilicate glass (Pyrex) ^f			80.2	85.7	1.86	39.95	28.7	1.39	—	—	—
CO ₂			66.2	97.6	1.72	28.3	12.7	2.23	—	—	1.474
Ethane C ₂ H ₆			62.4	90.5	1.82	36.2	(18310)	(1.977)	—	—	(410)
Methane CH ₄			55.73	75.71	2.25	45.66	(34035)	0.809(1.356) ^m	—	—	(1.038) ^m
Isobutane C ₄ H ₁₀			54.7	74.0	2.41	46.5	(64850)	0.423(0.717)	—	—	(444)
NaF			56.3	77.4	2.22	45.2	(18930)	(2.67)	—	—	(1270)
LiF			86.79	97.57	1.89	29.87	11.88	2.558	—	—	1.556
Proton 12 (CCl ₂ F ₂) gas, 26°C, 1 atm. ⁿ			62.00	88.24	1.86	39.25	14.91	2.632	—	—	1.592
Silica Aerogel ¹			70.6	108	1.82	23.7	4810	(4.93)	—	—	1.001080
NEMA G10 plate ^p			65.5	95.7	1.83	29.85	10.150	0.1-0.3	—	—	1.0-4.0.25p
EP6XY RESIN			62.6	90.2	1.87	33.0	19.4	1.7	—	—	—

50-60 +.14

REF. TORRE WENNAUS, LLNL
FORTRAN ROUTINE FOR COMPUTING RADIATION LENGTH

• Compute radiation lengths of compound materials.

```
parameter (rel2nav=.0478) ! Rel2nav**2*Navogadro
structure /element/
real z
real a
real x0
character*15 name
end structure
structure /compound/
integer natom
record /element/ el
real w
end structure
record /element/ C,H,O,N,Si
record /compound/ stuff(20)
```

```
parameter (n_rohacell=4)
record /compound/ rohacell(n_rohacell)
parameter (dens_rohacell=0.03)
```

ROHACELL ρ =

0.03 g/cm³

```
parameter (n_sio2=2)
record /compound/ sio2(n_sio2)
parameter (dens_sio2=2.64)
```

```
alpha=1./137.
C.Z=6.
C.A=12.
C.X0=42.7
C.name='Carbon'
H.Z=1.
H.A=1.
H.X0=61.28
H.name='Hydrogen'
O.Z=8.
O.A=16.
O.X0=34.24
O.name='Oxygen'
N.Z=7.
N.A=14.
N.X0=37.99
N.name='Nitrogen'
Si.Z=14.
Si.A=28.09
Si.X0=21.82
Si.name='Silicon'
```

```
rohacell(1).el=C
rohacell(1).natom=9
rohacell(2).el=H
rohacell(2).natom=13
rohacell(3).el=O
rohacell(3).natom=2
rohacell(4).el=N
rohacell(4).natom=1
```

ROHACELL
POLYMETHACRYLAMIDE
C₉H₁₃O₂N

```
sio2(1).el=Si
sio2(1).natom=1
sio2(2).el=O
sio2(2).natom=2
```

```
*** load stuff with desired compound
```

```
dens=dens_sio2
nel=n_sio2
do i=1,nel
  stuff(i)=sio2(i)
enddo
```

```
dens=dens_rohacell
nel=n_rohacell
do i=1,nel
  stuff(i)=rohacell(i)
enddo
```

```
amol=0.
zmol=0.
do i=1,nel
  amol=amol+stuff(i).el.a*stuff(i).natom
  zmol=zmol+stuff(i).el.z*stuff(i).natom
enddo
```

```
seff=0.
x0effinv=0.
do i=1,nel
  stuff(i).w=stuff(i).el.a*stuff(i).natom/amol
  seff=seff+stuff(i).el.a*stuff(i).w
  zeff=zeff+stuff(i).el.z*stuff(i).w
  x0effinv=x0effinv+stuff(i).w/stuff(i).el.x0
enddo
```

```
az=alpha*zeff
fc=az**2*(1./(1.+az**2)+.20206-.0369*az**2+.0083*az**4-.002*az**6)
xi=log(1440./zeff**.666)/(log(183/zeff**.333)-fc)
x0inv=4.*alpha*rel2nav/seff*zeff*(zeff+xi)*
+ (log(183/zeff**.333)-fc)
x0=1./x0inv/dens
x0eff=1./x0effinv/dens
print *, 'Material constituents:'
do i=1,nel
  print *, stuff(i).el.name, 'Natoms=', stuff(i).natom
enddo
print *, az, fc, xi, x0inv, amol
print *, 'X0 in cm. Formula: ', x0, ' Weighted mixture: ', x0eff
end
```

RADIATION LENGTH (ESTIMATES)

CHOPPED-GLASS FIBER FILLED EP

SiO₂
 $\chi = 12.3$ EP
 $\chi = 55$

$$\begin{aligned} \rho &= 1.85 = a(2.64) + (1-a)(1.19) \\ 1.85 &= a(2.64 - 1.19) + 1.19 \\ 1.85 &= (0.46)2.64 + (0.54)1.19 \\ \frac{1}{\chi} &= \frac{0.46}{12.3} + \frac{0.54}{55} \Rightarrow \chi = 21.2 \end{aligned}$$

CARBON-FIBER FILLED EPOXY

C
 $\chi = 18.8$ EP
 $\chi = 55$

$$\begin{aligned} \rho &= 1.53 = a(2.265) + (1-a)(1.19) \\ a &= (1.53 - 1.19) / (2.265 - 1.19) = 0.32 \\ 1.53 &= (0.32)(2.265) + (0.68)(1.19) \\ \frac{1}{\chi} &= \frac{0.32}{18.8} + \frac{0.68}{55} \Rightarrow \chi = 34.0 \end{aligned}$$

ALUMINUM-FIBER FILLED EPOXY

Al
 $\chi = 8.9$ EP
 $\chi = 55$

$$\begin{aligned} \rho &= 1.81 = a(2.70) + (1-a)(1.19) \\ a &= (1.81 - 1.19) / (2.70 - 1.19) = 0.41 \\ 1.81 &= (0.41)(2.70) + (0.59)(1.19) \\ \frac{1}{\chi} &= \frac{0.41}{8.9} + \frac{0.59}{55} \Rightarrow \chi = 17.6 \end{aligned}$$

CIBA-GEIGY 1617-A

SiO₂
 $\chi = 12.3$ EP
 $\chi = 55$

$$\begin{aligned} 50\% \text{ MIX } \rho &= 0.70 = a(2.64) + a(1.19) + (1-2a)(\phi) \\ a &= 0.18 \\ 0.70 &= (0.18)(2.64) + (0.18)(1.19) + (0.64)(\phi) \\ \frac{1}{\chi} &= \frac{0.18}{12.3} + \frac{0.18}{55} \Rightarrow \chi = 55.8 \\ 25\% \text{ MIX } \rho &= 0.70 = a(2.64) + 3a(1.19) + (1-4a)(\phi) \\ a &= 0.11 \\ 0.70 &= (0.11)(2.64) + (0.33)(1.19) + (0.55)(\phi) \\ \frac{1}{\chi} &= \frac{0.11}{12.3} + \frac{0.33}{55} \Rightarrow \chi = 66.1 \end{aligned}$$

MICROSPHERE-FILLED EPOXY (UNNYS)

SiO₂
 $\chi = 12.3$ EP
 $\chi = 55$

$$\begin{aligned} 50\% \text{ MIX } \rho &= 0.42 = a(2.64) + a(1.19) + (1-2a)(\phi) \\ a &= 0.11 \\ 0.42 &= (0.11)(2.64) + (0.11)(1.19) + (0.78)(\phi) \\ \frac{1}{\chi} &= \frac{0.11}{12.3} + \frac{0.11}{55} \Rightarrow \chi = 91.4 \\ 25\% \text{ MIX } \rho &= 0.42 = a(2.64) + 3a(1.19) + (1-4a)(\phi) \\ a &= 0.07 \\ 0.42 &= (0.07)(2.64) + (0.21)(1.19) + (0.73)(\phi) \\ \frac{1}{\chi} &= \frac{0.07}{12.3} + \frac{0.21}{55} \Rightarrow \chi = 107.2 \end{aligned}$$

7. Comparison of Gap Frame Designs and Materials

Contents:

Analyses and recommendations regarding chamber gap frame design (18 pages)

Summary:

An original design of a discrete post gap frame by Anatoly Gordeev is compared to the continuous gap frame design of the TDR Baseline chamber.

Ultra-low density castable materials suggested by Vinnie Polychronakos are compared to other syntactics and filled epoxies.

A method of determining the relative desirability of chamber materials in load-carrying and non load-carrying applications without detailed structural analysis is presented.

Based on comparative analyses, recommendations are made for the applicability of these suggestions in the context of maintaining adequate shear rigidity and minimum mass.

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1. Summary, and Conclusions

The following key points summarize this paper:

- The reductions in chamber mass achieved by incorporating small, discrete posts in the gap frame design evaporate when we restore the lost shear stiffness by appropriate sizing of the posts.
- Alternative material choices incorporated in a continuous gap frame design show the most promise of achieving mass reductions without compromising chamber stiffness and without increasing design complexity. Materials having high stiffness-to-density ratios are needed only for load-bearing locations (under bolts, near support connections, etc.) thus requiring less material to carry a given load.
 - Castable epoxies with high-modulus fillers are optimal for all load-bearing components of the gap frame region.
 - Ultra-low density materials are optimal for lightly loaded components.
- An optimal cathode strip chamber gap frame design simultaneously minimizes muon scattering (mass effects), shear deformations, gravity sag, stress levels, and complexity.

In addition, from the design perspective it is important to avoid close interdependence between electrical and structural component details along the perimeter of the chamber if there is no significant mass reduction.

- The development of an optimal design for structural and electrical systems is greatly complicated if both are expected to share the same real estate (discrete posts and electrical components in the same perimeter zone).
- Separate zones along the chamber perimeter for electrical components and structural details permits flexibility during the design process to accommodate the inevitable changes in electrical component sizes and layout.
- A design incorporating a perimeter bolting pattern outside of the gap seal is easier to seal with fewer parts. The discrete-post design requires that each bolt be sealed at both ends while maintaining a proper pre-load through the chamber assembly; a difficult design task that is more expensive to implement.

2. Background and Introduction

An un-optimized, "continuous" gap frame design (similar to Fig. 17) was prepared for the GEM P.A.C. Review held in May 1993. This design incorporated a continuous shear connection between sandwich panels. It used bolts along the perimeter of the chamber assembly to maintain the necessary shear connection.

An alternate design was subsequently proposed (Fig. 15) which incorporated discrete posts between panels in a chamber assembly. Bolts, which passed through the center of the posts from one panel to the next, established the shear connection in the assembly. The posts were located inside the perimeter gap frame seal and shared real estate with anode electrical components in a zone along the perimeter of the chamber. The dimensions of the perimeter region of the chamber were reduced thus reducing overall mass.

In GEM TN-93-350, *Gravity Sag of Sandwich Panel Assemblies as Applied to Precision Cathode Strip Chamber Structural Design*, July 12, 1993, we saw that high modulus/low density gap frames reduced gravity sag and that the honeycomb edge filler material appeared to contribute nothing to the structure (except around bolts). However, the beam bending theory used in that paper also predicted that the gravity sag of a stack of seven sandwich panels would be 39 times higher if slipping occurred between panels. In other words, disrupting the shear connection around the perimeter between panels could increase total gravity sag by as much as a factor of 39 (times the beam bending prediction of approximately 1mm).

In GEM TN-93-350, we also saw that shear "slipping" between sandwich panels in the gap region results in shear deflection as well as local distortions of chamber cross sections. In "pure bending" we assume the slabs shown in Fig. 1a. do not slide on each other. Shear "sliding" produces the increased gravity sag seen in Fig. 1b.

Figure 1: Shear Deflection Due To "Slipping"

The portion of this "worst-case factor of 39" that occurs depends on, among other things, chamber perimeter region design and material choices. The underlying assumption of beam theory is that all beam cross sections will remain flat during gravity sag, and that even the most narrow or soft gap frame will not permit slipping between sandwich panels.

Designs meant to reduce chamber mass may also increase shear deformation. One must maintain bending and shear structural rigidity to control gravity sag when lightening the chamber. Changing from a continuous gap frame to a discontinuous, discrete-post frame removes mass from the chamber perimeter while reducing chamber stiffness. Locating these discrete posts between electronic components is possible only if sufficient space is available. The removal of material from the perimeter region must be balanced with the added shear deformations that result. Fig. 2, taken from a finite element analysis of a structurally inadequate gap frame design, clearly illustrates the loss of cross-section flatness near a corner support point.

Figure 2: Loss of Cross Section Flatness Due To Shear

This paper is a follow-up to that earlier work. We evaluate the shear deflection component of gravity sag and use it to compare the structural adequacy of chamber perimeter designs and materials. We analyze ten combinations of two perimeter designs and six materials for their effectiveness in reducing mass without compromising chamber stiffness. Material removal, relocation, or substitution are the only mass-reduction techniques considered here. We evaluate the loss in structural rigidity that occurs for these ten chamber perimeter design and material combinations and make recommendations for further optimization. (Future work will include investigation of "external" stiffening techniques.)

3. How Chamber Structure Influences Gravity Sag

The "ideal" chamber design has negligible shear deformation. Inadequate gap frame shear rigidity causes sandwich panels to "slip" with respect to each other as explained in the previous section. Similarly, if the panel cores are not stiff enough in shear, the skins of each panel may "slip" with respect to each other. Sandwich panel skins carry most of the structural mass in a typical chamber design. Table 1 shows the dominance of the panel skins as a bending-load carrier. The application of beam bending theory to a barrel region outer superlayer chamber with a glass-fiber filled epoxy gap frame and an unfilled-epoxy core edge filler produced the results in Table 1.

The high-modulus components, if located appropriately, will carry a larger share of the total load. Table 1 shows the mass distribution and load sharing for a chamber in "pure bending" for the material choices listed.

Table 1. Effectiveness of Chamber Components in "Pure Bending"

component	% of total chamber mass added by component	% of total chamber mass carried by component	% of mass carried minus % of mass added
0.5mm G10 laminate panel skins	39	77	38
25mm unfilled epoxy core edge filler	18	7	-11
25mm glass-fiber / epoxy gap frame	12	9	-3
0.017mm copper cathode planes	4	7	3
19mm Nomex honeycomb core	11	0	-11
25kg hardware and utilities	16	0	-16

In an "ideal" chamber with negligible shear deflection, the panel skins carry about 77% of the load but add only 39% to the total mass. However, some results in Table 1 are deceptive. The gap frame does not seem to carry its own weight, and the Nomex honeycomb core appears to be dead

load. These components do not play a direct role in bending stiffness, but they are the *primary components of shear stiffness*.

The ultimate structural effectiveness of candidate gap frame materials can be estimated in advance of any detailed analyses by using a simple beam evaluation method as shown in the next section. The finite element analyses summarized later in this paper calculate changes in shear stiffness. We then explore how much material we can safely remove from a component, and the relative importance of a component's mechanical properties.

4. Evaluation of Materials

In this section, we observe the following:

- *High-modulus fiber-filled epoxies are superior to unfilled or ultra-low density epoxies for load-bearing applications.* G10 laminate is a less desirable frame material since it has the in-plane shear properties of unfilled epoxy, requires a 250°F cure, and is not castable.
- *Castable glass-fiber filled epoxy is the most promising of the room-temperature (R.T.) cured, electrically-insulating materials considered.*
- *Carbon-fiber filled epoxy is ideal as a honeycomb core edge filler where its electrical properties are acceptable*
- *Ultra-low density material is ideal for lightly loaded components.* The ultra-low density material evaluated here also has very low modulus. The amount of this material needed to carry a given load is larger, so the size (and mass) of higher-density components attached to it also increases.
- *High-modulus low-density fibers are the most desirable epoxy fillers.* Some examples are carbon, aluminum, glass, or kevlar fibers.

We know that a desirable chamber frame material has *low density, high modulus, and high radiation length*. However, no single parameter is meaningful in isolation. For instance, introducing bubbles into a bulk material not only reduces material density but also reduces modulus. Hence we must use more of that material to recover the lost stiffness.

The following analysis combines material density, modulus, and radiation length into m^* values that are proportional to the deleterious mass effects of that material on the moon system. Suppose we construct the rectangular cross-section beam shown in Fig. 3 from one of the candidate materials listed below.

1. carbon-fiber filled epoxy such as *Fiber-Resin FR-337* (castable, cure @ R.T.)
2. G10 woven-glass laminate such as *Epoxy-Gillfab 1040* (plies, cure @ 250 °F)
3. glass-fiber filled epoxy (castable, cure @ R.T.)
4. syntactic epoxy such as *Ciba-Geigy 1617-A* (castable, cure @ R.T.)
5. unfilled epoxy such as *Fiberite 954-3* (castable, cure @ 350 °F)
6. ultra-low density epoxy (precast blocks)

Figure 3: Beam Used For Material Comparisons

The beam carries an externally applied distributed load q plus its own distributed weight $\rho w h$. The beam sag at the center due to bending is:

$$\text{beam sag} = K \frac{(q + \rho w h)}{E w} = K1 \frac{q}{E w} + K2 \frac{\rho}{E}$$

where q is an external distributed load, ρ is the beam density, w is the beam width, h is beam height, and K , $K1$, and $K2$ are constants which account for beam length, height, and support conditions. Each of the two load sources, q and $\rho w h$, contributes to beam sag.

When the distributed load greatly exceeds the beam weight ($q \gg \rho w h$), then :

$$\text{beam sag} = K1 \frac{q}{E w}$$

and we reduce beam sag by minimizing $1/AE w$. The width of a beam (that produces the same gravity sag as the baseline for normalization) divided by the radiation length, l_r , produces the parameter $m1^*$ which is:

$$m1^* = \frac{w}{l_r} = \frac{E_b w_b}{E l_r}$$

where the subscript b denotes the properties used for the baseline for normalization. The parameter $m1^*$ (small for a beam with low width and high radiation length) is a valid indicator when the distributed load greatly exceeds the beam weight ($q \gg \rho w h$).

When the beam weight greatly exceeds the distributed load ($\rho w h \gg q$), then:

$$\text{beam sag} = K2 \frac{\rho}{E}$$

and we reduce beam sag by minimizing ρ/E . The ratio of ρ/E divided by the radiation length produces the parameter $m2^*$ which is:

$$m2^* = \frac{\rho}{E l_r}$$

where $m2^*$ (small for a beam with low density, high modulus, and high radiation length) is a valid indicator if the beam weight greatly exceeds the distributed load ($\rho w h \gg q$).

The results are summarized in Table 2 for the six materials. (Quantities normalized are with respect to G10 laminate.)

Table 2. Material Comparison

	carbon-fiber filled epoxy FR-337 cure @ R.T.	G10 laminate E-G 1040 cure @ 250F	chopped glass-fiber filled epoxy cure @ R.T.	synthetic epoxy 1617-A cure @ R.T.	unfilled epoxy F-954-3 cure @ 350F	ultra-low density epoxy precast blocks
ρ density g/cm ³	1.66	1.93	1.85	0.70	1.19	0.42
E modulus MPa [ksi]	34,900 [5,000]	22,760 [3,300]	11,030 [1,600]	2,410 [350]	2,760 [400]	680 [100]
l_g radiation length cm	34.0	19.4	21.2	56 - 66 (?)	35	91 - 107 (?)
normalized ρ / E	0.57	1.00	1.98	3.43	5.10	7.20
required width ($q \gg pwh$) $m1^*$	0.66	1.00	2.06	9.43	8.25	33.0
if q dominates ($q \gg pwh$) $m2^*$	0.38	1.00	1.89	2.77 - 3.27 (?)	2.91	5.98 - 7.04 (?)
if p dominates ($pwh \gg q$)	0.32	1.00	1.81	1.01 - 1.19 (?)	1.80	1.30 - 1.53 (?)

Table 2 notes:

"Smaller is better" for values in the last four rows of Table 2.

$m1^*$ and required width are VALID INDICATORS IF ($q \gg pwh$)

$m2^*$ is a VALID INDICATOR IF ($pwh \gg q$)

(?) denotes estimates based on 50/50 to 25/75 mass fractions of SiO₂/Epoxy

The last two rows indicate that a carbon-fiber filled epoxy is at least four (1.3M/0.32) times more desirable (using $m2^*$) than an ultra-low density epoxy. The advantage exceeds a factor of fifteen (5.98/0.38) for higher loads (using $m1^*$). Material mechanical properties and radiation lengths need additional verification.

The third row from the bottom indicates that, for load-carrying applications ($q \gg pwh$), low-modulus materials require larger widths to maintain stiffness. Therefore, choose high modulus materials for load-carriers such as the gap frame.

5. Comparison of Continuous and Discrete-Post Gap Frames

Finite element analyses predict total chamber deflection that includes the bending component and the shear component of gravity sag. We isolate and evaluate the shear component of gravity sag by subtracting the ideal zero-shear bending deflection from the total deflection. Fig. 4 illustrates the quarter-symmetric finite element model used in all analyses. Each corner of the chamber is a support location. The gravity vector is normal to the chamber face.

Figure 4: Quarter-Symmetric Finite Element Model

The finite element model assumes that gap frame parts are bonded such that "slipping" at part interfaces cannot occur. Movement is restricted to material distortion. The practical implementation of this assumption is achieved by bolts, friction, and/or adhesive at part interfaces.

In Table 3, case "A" has a continuous glass-fiber filled epoxy gap frame located outside the electronics zone and a carbon-fiber filled honeycomb edge filler. Fig. 5 shows case "A", the baseline for normalization and the most rigid design evaluated.

Figure 5: Displacements x 500 for Case "A" (Normalization Baseline)

Table 3 summarizes the results of finite element and beam bending gravity sag calculations.

Table 3. Comparison of Gap Frame Designs and Materials

case	(Note 1) gap frame	(Note 2) sandwich core edge filler	(Note 3) normalized total deflection of side frame	(Note 4) percent shear deflection of side frame	(Note 5) normalized total mass	(Note 6) % change in mass
A	continuous glass-fiber filled epoxy	continuous carbon-fiber filled epoxy	1.00	10	1.00	0
B	continuous glass-fiber filled epoxy	continuous glass-fiber filled epoxy	1.48	16	1.02	+ 2
C	continuous unfilled epoxy	continuous unfilled epoxy	1.73	24	0.92	- 8
D	continuous ultra-low density epoxy	continuous ultra-low density epoxy	1.86	37	0.81	- 19
E	continuous ultra-low density epoxy	continuous unfilled epoxy	1.82	30	0.89	- 11
F	continuous glass-fiber filled epoxy	continuous unfilled epoxy	1.67	21	0.95	- 5
G	continuous glass-fiber filled epoxy	no edge filler	2.21	47	0.83	- 17
H	15mm x 15mm discrete-post glass-fiber epoxy	inter-post ultra-low density epoxy	2.25	49	0.78	- 22
I	60mm x 15mm discrete-post glass-fiber epoxy	inter-post ultra-low density epoxy	2.13	45	0.80	- 20
J	60mm x 15mm discrete-post glass-fiber epoxy	inter-post carbon-fiber filled epoxy	1.04	18	0.93	- 7

Table 3 notes:

1. material properties are assumed "isotropic", having the same properties in all directions
2. "discrete posts" extend through the panel ("inter-post edge filler" is between posts)
3. total deflection from finite element analyses are normalized to case "A"
4. equals total deflection minus the bending component divided by the total deflection
5. includes 25kg for chamber utilities and added width for continuous gap frame cases
6. % change in the sum of sandwich panel, gap frame, honeycomb edge filler mass, and utilities (25kg for all cases)

A trend emerges as one inspects the normalized total side frame deflection and the percent change in mass for the discrete-post designs, cases "H", "I", and "J", at the end of Table 3. As the discrete-post design is stiffened to reduce shear deflection the mass reduction becomes small. Case "J", the stiffest discrete-post design evaluated, sagged 4% more than the baseline case "A" but reduced chamber mass by only 7%. Case "J" uses 60mm x 15mm glass-fiber filled epoxy discrete posts, the largest that could be accommodated in the space allowed between electronics. They extend through the entire thickness of the chamber as shown in Fig. 13, and have carbon-fiber filled epoxy honeycomb edge filler between them.

Comparing continuous gap frame cases "A" and "G" we see that removing the honeycomb edge filler material increases the total deflection by a factor of 121%. Since case "G" is 17% lighter than case "A", the increased sag is due to shear movement between faces of the sandwich panels. The percent-shear-deflection increases to 47% from the baseline of 10%. The sandwich honeycomb cores are experiencing the added shear deformation. This suggests that during optimization we evaluate alternate honeycomb materials that exhibit better density-to-shear-modulus ratios. Shear stresses in discrete posts go up disproportionately fast since stress concentration factors of about 3.0 exist at the fillets. Creep rate is a function of stress level, therefore these high discrete-post stresses demand additional evaluation.

Shear deformations or "slipping" between sandwich panels in the gap regions also result in a degradation in gap uniformity. This effect is visible (using a displacement scale factor of 500) in case "H" shown in Fig. 6.

Figure 6: Displacements x 500 for Case "H" Showing Loss of Gap Uniformity

Fig. 7 illustrates the forces and moments that cause these panel curvatures.

Figure 7: Moments and Shear Forces In End-Region Gap Frame

The ends of the panels near the supports must resist moments and shear forces. This warps the panels locally and degrades gap spacing. The degradation is not visible in case "B" in Fig. 8 that has a continuous glass-fiber filled epoxy gap frame and honeycomb edge filler.

Note: Numbers in parentheses are displacements normalized with respect to the deflection of the corresponding location in case "A". For example, the center of the chamber in case "B" deflects 38% more than the center for case "A".

Figure 8: Displacements x 500 for Case "B"

The degradation in gap spacing is visible on the right in Fig. 9 for case "J" with deflections magnified 500 times.

Note: Numbers in parentheses are displacements normalized with respect to the deflection of the corresponding location in case "A". For example, the center of the chamber in case "J" deflects 3% more than the center for case "A".

Figure 9: Displacements x 500 for Case "J"

The numbers in parentheses are the normalized deflections at those locations. For instance, in Fig. 9 the center of the long edge deflects 1.04 times more than that location in case "A". The discrete-post design in case "J" has acceptable total deflection, but contains high stresses as discussed later in section 8.

The magnitude of the gap-spacing error observed in Fig. 9 for case "J" exceeds 15 microns. This side effect of shear deformation is a potential problem and merits additional evaluation. Discrete-post designs such as cases "H", "I", and "J" require the highest modulus gap frame because there is less shear area available to carry the load. The local shear load on individual posts requires that a honeycomb edge filler be used between the discrete-post locations. Local stresses around posts will be subject to stress concentrations of 3.0 based on handbook estimates.

6. Continuous Gap Frame Details

The comparison analyses in this paper use a continuous gap frame 15mm wide along the chamber sides and ends. Fig. 10 shows an isometric view of a continuous gap frame.

Figure 10: Isometric View of Continuous Gap Frame

The widest allowable "discrete post" that can be accommodated due to electronics as configured in Fig. 14 is 15mm. We use a 15mm value for all gap frames in this analysis in order to provide a fair basis for stiffness comparison.

7. Discrete-Post Gap Frame Details

The sketch shown in Fig. 11 and the electronics layout in Fig. 14 define a discrete-post gap frame design incorporating 48 perimeter bolts per chamber.

Figure 11: Isometric View of Discrete-Post Gap Frame

The electronics layout dictates the allowable positions for the discrete posts. The resulting design is slightly shorter than a TDR outer superlayer barrel chamber.

Fig. 4 shows the bolt pattern and Fig. 12 shows a stack of panels in cross section.

Figure 12: Cross Section of Stack of Panels With Post

Fig. 13 shows how discrete posts are always assumed to be solid through the entire chamber thickness. In the context of the discrete-post gap frame designs listed in Table 3, edge filler refers to the perimeter zone between the posts.

Figure 13: Cross Section of a Discrete Post

The following discrete-post design constraints are derived from conversations between Coleman Johnson, Anasoly Cordcov, and the authors:

- Discrete posts along the perimeter of the chamber are:
 - Internal to the pressurized gas region;
 - Dimensioned such that they do not exceed 15mm in width (the distance between the "wire fixation bar" and the "scaling bar" in Fig. 15);
 - Collocated with electronics components in the 15mm-wide zone shown in Fig. 14; and
 - Limited in cross section by area not already occupied by electronics.
- There are eight evenly-spaced discrete posts along the short edges of the chamber. Provision for relocation based on chamber end region electronics exists.
- The resulting chamber design has eight wire readout connectors along the long edge, and a width that is consistent with the outer superlayer.

A plausible electronics layout for an outer superlayer barrel chamber is shown in Fig. 14. Four 15mm-by-60mm discrete posts are visible.

* Figure 14: Layout of Perimeter Electronics for Outer Superlayer CSC

Cross section "A-A" through an edge connector is shown in Fig. 15. The discrete post is seen in profile behind the capacitor.

* Figure 15: Cross Section "A-A" Through Edge Connector

The coexistence of gap frame material and electronic components in the same perimeter strip limits the possible size and location of the discrete posts. Assuming that the capacitors and wiring shown in Figs. 14 and 15 do not require more space than shown, 15mm x 60mm discrete posts are the

largest that can be accommodated. They are located on 200mm centers in the 4R-post design used here.

The electrical layout in Fig. 14 is for the outer superlayer only. Similar layouts would be required for all other different electronics arrangements in order to locate and dimension the discrete posts for those chambers.

8. Loads and Stresses

A beam with a uniformly distributed load has a shear force distribution as shown in Fig. 16.

Figure 16: Load and Shear Force Distribution

We estimate the maximum stress in a continuous gap frame by assuming that the chamber weight produces a shear stress that is distributed over the gap frame vertical shear area, and a normal stress that is due to chamber overall bending. Using a chamber weight of 180kg (400lb) and a continuous 15mm-wide gap frame the maximum shear stress is 0.15MPa (22psi) and the normal stress is 0.09MPa (13psi). The maximum combined stress of 0.18MPa (26psi) occurs near the chamber support points and diminishes to zero at the centroid of the chamber midway between the supports as seen in Fig. 16. The gravity vector is assumed to be normal to the panels for this calculation.

We estimate the maximum stress in a discrete-post gap frame by calculating the shear load carried by each post, applying this load to the post in the form of a shear force couple and moments (as shown in Fig. 7), calculating the combined stress at the post ends, and applying a stress concentration factor. Stress concentrations occur at the small-radius fillets at the ends of the discrete posts. Using a chamber mass of 180kg (400lb) and a stress concentration factor of 3.0 (estimate based on handbook values for similar geometries) the maximum combined stress (bending plus shear) in a 15mm x 60mm discrete post is 5.38MPa (780psi). This occurs at the fillets in the discrete posts near the chamber ends.

The discrete-post-gap-frame stress is 30-times higher than a comparable continuous-gap-frame stress because of three factors:

1. the reduced shear area
2. the creation of a large bending stress
3. the introduction of a stress concentration.

Chamber gap frames should at least be continuous in the vicinity of the chamber ends where support points are located and shear forces are highest.

9. Practical Considerations

A discrete-post design that has posts and electrical circuitry located in the same zone (collocated design) ties the hands of chamber structural and electrical designers. No allowance is made in the collocated discrete-post concept for larger capacitors, changes in circuit trace locations, or longer continuous gap frame segments. Also, the stiffest discrete-post design evaluated is not structurally adequate in the corners near support locations.

Locating the gap frame outside of the electrical circuitry zone adds 15mm to the perimeter of the chamber (each side). This material is made up of sandwich panel skins and honeycomb which accounts for about 2% to the chamber mass. This also possibly allows for a discontinuous gap-frame to be used where stresses are low. The size of discrete posts could then be optimized based on the local shear stress, and an optimization can proceed unconstrained by the electronics layout details. The mass savings may however be small and not worth the detail design effort.

Many ultra-low density epoxies are only available in pre-cast blocks that must be machined and pieced into larger assemblies. This introduces additional adhesive bond lines that may be undesirable and may increase fabrication labor requirements.

The finite element analyses in this report assume a non-slip linkage between all panels in the gap frame region. In terms of chamber frame design, this "bond" between panels must be achieved by some combination of the following methods:

- friction at part interfaces that is developed and maintained by bolt pre-loads
- direct shear into perimeter bolts (the "Leggo block" effect)
- adhesive

10. Design Recommendations

The chamber perimeter design recommended here is structurally efficient and lends itself to further mass reduction. An optimal chamber design is one which minimizes mass scattering (mass effects), shear deformations, gravity sag, stress levels, and complexity. In other words, each component is designed to perform its structural function using the least amount of the highest radiation-length materials.

Fig. 17 shows a cross section of the recommended chamber edge design. It possesses the following desirable characteristics:

- Edge bolts are located outside of the perimeter electronics pattern. This allows the number and spacing of bolts to be dictated by structural necessity only. (Locally discontinuous

gap-frame designs that reduce material in the low-stress regions can be considered in the future, independent of any electronics layout details.)

- *Edge bolts are located outside of the chamber gas seal.* This eliminates the need for gas seals on all of the bolt ends.
- *Edge bolts are threaded rods or tubes.* The length and diameter of threaded rods or tubes are chosen based on the minimum required to perform the clamping function. Washers at the ends reduce local compressive stress.
- *The gap frame is continuous.* This eliminates the secondary bending stresses, gap spacing degradation, and stress concentrations caused by discrete posts.
- *The gap frame material is glass-fiber filled epoxy.* This is a castable material that has isotropic mechanical properties and is an electrical insulator.
- *The core edge filler is continuous.* The width can be minimized in combination with future evaluations of higher shear-modulus core materials.
- *The core edge filler material is either carbon-fiber filled or glass-fiber filled epoxy.* Either choice provides low total chamber displacement.
- *Materials with high modulus-to-density ratios and high modulus values are used for load-carrying components.* This reduces the volume of material in a component and in all other components that must be attached to it.
- *Ultra-low density materials are used for lightly-loaded components.* The wire fixation bars and wire position bars are to be made from the lightest competent material.

Figure 17: Cross Section of Recommended Edge Design

11. Further Design and Analysis Tasks

The next paper in this series will illustrate a "generic" engineering design implementing the recommendations set forth here. This will be used for the next phase of chamber optimization.

Other recommended future tasks include the following:

- Produce a design for the chamber perimeter bolted connection that provides the non-slip bond assumed in analyses with the least added connector mass (considering threaded tubes and alternate patterns).
- Confirm radiation length and mechanical property values for all materials of interest.
- Consider higher shear-modulus panel core with the goal of further reducing the mass of the sandwich panels while maintaining stiffness.
- Evaluate a "discontinuous" gap frame in conjunction with the recommended design.
- Evaluate the effect of an external chamber stiffening techniques (metallic "cage") on chamber mass and stiffness.

8. Gravity Sag as a Function of Sandwich Core Material

Contents:

Summary of gravity sag results for three core materials (1 page)

Analysis of TDR Baseline HRH-10-1/8-1.8 "Nomex" core (7 pages)

Analysis of WR-II-3/8-2.5 "Shelter Core" (7 pages)

Analysis of WR-II-3/8-4.0 "Shelter Core" (7 pages)

Summary:

On the basis of gravity sag alone, the stiffer WR-II-3/8-2.5 "Shelter Core" is the best choice. However, since the density is 2.5 lb/ft³ as opposed to the 1.8 lb/ft³ for the TDR Baseline HRH-10-1/8-1.8 core material, the benefit of the slight added stiffness is erased.

The density of the sandwich core material heavily influences the performance of the muon system, hence higher density core materials must provide a much larger stiffness improvement in order to be considered.

CHAMBER DISPLACEMENT VS. CORE DENSITY FOR THREE CORE MATERIALS

* HRH-10-1/8-1.8 ARAMID FIBER REINFORCED H.C (NOMEX)

** WR II - 3/8 - 2.5 } WR II SHELTER CORE
" " - 4.0 } WATER RESISTANT

DIRECTORY .411762 / CSCBASE3 / SAGNOFIL

(NO EDGE FILER) USING HRH-10 - 1/8 - 1.8

@ 1.8 $\frac{G}{T}$

CSC outer base? (25mm epoxy frame)
Time = 0.10000E+01

$\lambda = 3402 \text{ mm}$
 $w = 1250 \text{ mm}$

CSC outer base? (25mm epoxy frame)
Time = 0.10000E+01

8-3

z
y

disp. scale factor = 0.100E+04

SAGNOFIL
1 OF 7

z
y

disp. scale factor = 0.100E+04

SAGNOFIL
2 OF 7

CSC outer base? (25mm epoxy frame)
 time = 0.10000E+01

CSC outer base? (25mm epoxy frame)
 time = 0.10000E+01

8-4

disp. scale factor = 0.100E+04

SAGNOFIL
 3 OF 7

disp. scale factor = 0.100E+04

SAGNOFIL
 4 OF 7

8-5

CSC outer bas (28mm epoxy frame)
 c file cno1113 baseline-2 (rev 1)
 c Revised kinematic mounts.
 c Revised for nodes on centerlines.
 c This file is used to generate NIKE3D input.

SAGNIFIL
 5 OF 7

Ingrid input for CSC outer superlayer chamber
 c 6 wire layers
 c l=3402mm w=1250mm h=200mm
 c edge frame w=25mm
 c end frame w=25mm

sandwich panels (7) t=20mm (18mm core + 0.6mm skins)
 c gaps (6) t=10mm

Procedure for UNICOS:
 c Ingrid i=infille
 c stp 0.1
 c continue
 c mv Ingrid outfile.1
 c vi outfile.1
 c card:field value comments
 c 0:1 8 only print last step to hsp
 c 0:1 80 percent of core
 c 0:3 3 buffer size
 c 0:4 1 storage option in core
 c 0:5 1 incompatible modes for bricks
 c 0:6 1 shell geometric stiffness flag
 c change boundary conditions
 c node 4 (code 7) x,y,z trans. fixed/all rot. free
 c node 10 (code 3) z trans. fixed/all rot. free
 c node 111 (code 5) y,z trans. fixed/all rot. free

box s48 horvath
 tv 1
 NIKE3D c generate NIKE3D input
 ANAL STAT c static analysis
 NSTEP 4 c number of time steps
 DELT 2.500e-01 c time step size

c six-step load curve
 LCD 1 0 0.0 0.0 0.2 0.05 0.4 0.1 0.6 0.2 0.8 0.4 1.0 1.0

GRAV c lg in z-direction (normal to panel)
 0.0 0.0 9.81458e+03

MAT 1 1 SHELL c Epoxy-Gillifab 1040 (0-10)
 E 2.2819e+10 c g-mm/sec2/mm2 (3.3e+08 psi)
 PR 0.26 c poisson's ratio
 RHO 1.9262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 THICK 0.5 c mm thickness

ENDMAT

MAT 2 1 c Epoxy-Gillifab 1040 (0-10)
 E 2.2819e+10 c g-mm/sec2/mm2 (3.3e+08 psi)
 PR 0.26 c poisson's ratio
 RHO 1.9262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)

ENDMAT

SAGNIFIL
 6 OF 7

MAT 3 2 c H. 10-1/8-1.8 (honeycomb)
 EC 5.5319e+07 c g-mm/sec2/mm2 (8.0e+03 lb/in2)
 EA 5.5319e+02 c g-mm/sec2/mm2 (e-06 softer)
 EB 5.5319e+02 c g-mm/sec2/mm2 (e-06 softer)
 GAB 1.0372e+02 c g-mm/sec2/mm2 (e-06 softer)
 GBC 1.0372e+07 c g-mm/sec2/mm2 (1.6e+03 lb/in2)
 GCA 2.6276e+07 c g-mm/sec2/mm2 (3.8e+03 lb/in2)
 PRBA 0.3 c Poisson-ba
 PRCA 0.3 c Poisson-ca
 PRCB 0.3 c Poisson-cb
 RHO 2.8894e-08 c g/mm3 (1.8 lb/ft3)
 AOPT 2.0 c globally anisotropic definition
 A1 1.0 c x for a-vector
 A2 0.0 c y for a-vector
 A3 0.0 c z for a-vector
 D1 0.0 c x for d-vector
 D2 1.0 c y for d-vector
 D3 0.0 c z for d-vector

ENDMAT

MAT 4 1 c epoxy MC filler
 E 2.7800e+09 c g-mm/sec2/mm2 or GPa (0.4e+08 psi)
 PR 0.26 c poisson's ratio
 RHO 1.1800e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)

ENDMAT

START c sandwich panel skins
 1 2 14 15 : 1 2 8 9 : -1 :
 -1701. -1676. 1676. 1701.
 -825. -800. 800. 825.
 0.0
 MATE 1 c Epoxy-Gillifab 1040 (0-10)
 LCT 14 : c repeat the part 14 times
 MZ -100. : MZ -80. :
 MZ -70. : MZ -60. : MZ -40. : MZ -20. : MZ -10. :
 MZ 10. : MZ 20. : MZ 40. : MZ 60. : MZ 70. :
 MZ 80. : MZ 100. :
 LREP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 : c use the 14 clones

END

START c sandwich panel frames
 1 2 14 15 : 1 2 8 9 : 1 2 :
 -1701. -1676. 1676. 1701.
 -825. -800. 800. 825.
 0.0 20.
 0 2 2 1 3 3 2 c remove the honeycomb region
 MATE 3 c H-10-1/8-1.8 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -60. : MZ -40. : MZ -20. : MZ 10. : MZ 20. : MZ 60. : MZ 80. :
 LREP 1 2 3 4 5 6 7 : c repeat the part 7 times

END

START c gap frames
 1 2 14 15 : 1 2 8 9 : 1 2 :
 -1701. -1676. 1676. 1701.
 -825. -800. 800. 825.
 0.0 10.
 0 2 2 1 3 3 2 c remove wire gap region
 MATE 2 c Epoxy-Gillifab 1040 (0-10)
 LCT 8 : MZ -80. : MZ -60. : MZ -40. : MZ -20. : MZ 10. : MZ 20. : MZ 60. : MZ 70. :
 LREP 1 2 3 4 5 6 : c repeat the part 6 times

SAGNIFIL
 7 OF 7

END

START c sandwich panel honeycomb
 1 13 : 1 7 : 1 2 :
 -1676. 1676.
 -800. 800.
 0.0 20.
 MATE 3 c H-10-1/8-1.8 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -60. : MZ -40. : MZ -20. : MZ 10. : MZ 20. : MZ 60. : MZ 80. :
 LREP 1 2 3 4 5 6 7 : c duplicate 7 times

END

END

DIRECTORY .411762/CSCBASE3/SAGNEWHL

(NO FIBER FILLER) . USING WRII - 3/8 - 2.5

@ 2.5 $\frac{lb}{ft^3}$

CSC outer base3 (new bc no fill)
time = 0.10000E+01

$l = 3402 \text{ mm}$
 $w = 1250 \text{ mm}$

CSC outer base3 (new bc no fill)
time = 0.10000E+01

8-6

disp. scale factor = 0.100E+04

SAGNEWHL
1 OF 7

disp. scale factor = 0.100E+04

SAGNEWHL
2 OF 7

CSC outer base? (new bc no fill)
time = 0.100000000

8-7

disp. scale factor = 0.100E+04

CSC outer base? (new bc no fill)
time = 0.100000000

SAGWENHC
3 of 7

disp. scale factor = 0.100E+04

SAGWENHC
4 of 7

8-8

CSC outer bas. (new hc/no fill)
 c file cnohcc3 baseline-2 (rev 1)
 c Revised kinematic mounts.
 c Revised for nodes on centerlines.
 c This file is used to generate NIKE3D input.

SAGNEW HC
 5 of 7

c Ingrid input for CSC outer superlayer chamber
 c 8 wire layers
 c l=3402mm u=1250mm h=200mm
 c edge frame u=25mm
 c end frame u=25mm
 c 44berglase-laminates-to-HH-10-1-10-1-0
 c honeycomb-to-EP019-0111ab-1040
 c sandwich panels (7) l=20mm (18mm core + 0.6mm skins)
 c gaps (6) l=10mm

a Procedure for UNICOS:
 a Ingrid i=infile run Ingrid
 a step 0.1 merge nodes
 a continue make NIKE3D input
 a mv Ingrida outfile.1 change name
 a vi outfile.1 edit cscb2.1

card	field	value	comments
0:1	8		only print last step to hep
0:1	90		percent of core
0:3	3		buffer size
0:4	1		storage option in core
0:5	1		incompatible nodes for bricks
0:9	1		shell geometric stiffness flag

c change boundary conditions
 c node 4 (code 7) x,y,z trans. fixed/all rot. free
 c node 18 (code 3) z trans. fixed/all rot. free
 c node 111 (code 8) y,z trans. fixed/all rot. free

box 948 herveith
 tv 1
 NIKE3D a generate NIKE3D input
 ANAL STAT a static analysis
 NSTEP 4 c number of time steps
 DELT 2.500e-01 c time step size

c six-step load curve
 LCD 1 8 0.0 0.0 0.2 0.05 0.4 0.1 0.6 0.2 0.6 0.4 1.0 1.0

GRAV a lg in z-direction (normal to panel)
 0.0 0.0 0.81455e+03

MAT 1 1 SHELL a Epoxy-Gillifab 1040 (0-10)
 E 2.2619e+10 c g-mm/sec2/mm2 (3.3e+06 psi)
 PR 0.26 c poisson's ratio
 RHO 1.6262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 THICK 0.6 c mm thickness
 ENDMAT

MAT 2 1 a Epoxy-Gillifab 1040 (0-10)
 E 2.2619e+10 c g-mm/sec2/mm2 (3.3e+06 psi)
 PR 0.26 c poisson's ratio
 RHO 1.6262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

SAGNEW HC
 6 of 7

MAT 3 2 c W 1-3/8-2.5 (honeycomb)
 EC 2.2619e+08 c g-mm/sec2/mm2 (33.0e+03 lb/in2)
 EA 2.2619e+03 c g-mm/sec2/mm2 (e-06 softer)
 EB 2.2619e+03 c g-mm/sec2/mm2 (e-06 softer)
 GAB 4.0403e+02 c g-mm/sec2/mm2 (e-06 softer)
 GSC 4.0403e+07 c g-mm/sec2/mm2 (7.0e+03 lb/in2)
 GCA 8.0992e+07 c g-mm/sec2/mm2 (13.0e+03 lb/in2)
 PRGA 0.3 c Poisson-ba
 PRCA 0.3 c Poisson-ca
 PRCB 0.3 c Poisson-cb
 RHO 4.0131e-06 c g/mm3 (2.6 lb/ft3)
 ADPT 2.0 c globally orthotropic definition
 A1 1.0 c x for a-vector
 A2 0.0 c y for a-vector
 A3 0.0 c z for a-vector
 D1 0.0 c x for d-vector
 D2 1.0 c y for d-vector
 D3 0.0 c z for d-vector
 ENDMAT

MAT 4 1 c epoxy MC filler
 E 2.7000e+08 c g-mm/sec2/mm2 or GPa (0.4e+06 psi)
 PR 0.26 c poisson's ratio
 RHO 1.8000e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

START a sandwich panel skins
 1 2 14 15 : 1 2 8 9 : -1 :
 -1701. -1676. 1676. 1701.
 -625. -600. 600. 625.
 0.0
 MATE 1 a Epoxy-Gillifab 1040 (0-10)
 LCT 14 : c repeat the part 14 times
 MZ -100. : MZ -80. :
 MZ -70. : MZ -60. : MZ -40. : MZ -20. : MZ -10. :
 MZ 10. : MZ 20. : MZ 40. : MZ 60. : MZ 70. :
 MZ 80. : MZ 100. :
 LREP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 : c use the 14 clones
 END

START a sandwich panel frames
 1 2 14 15 : 1 2 8 9 : 1 2 :
 -1701. -1676. 1676. 1701.
 -625. -600. 600. 625.
 0.0 20.
 D 2 2 1 3 3 2 c remove the honeycomb region
 MATE 3 c W 1-3/8-2.5 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 60. : MZ 80. :
 LREP 1 2 3 4 5 6 7 : c repeat the part 7 times
 END

START c gap frames
 1 2 14 15 : 1 2 8 9 : 1 2 :
 -1701. -1676. 1676. 1701.
 -625. -600. 600. 625.
 0.0 10.
 D 2 2 1 3 3 2 c remove wire gap region
 MATE 2 c Epoxy-Gillifab 1040 (0-10)
 LCT 6 : MZ -80. : MZ -60. : MZ -20. : MZ 10. : MZ 40. : MZ 70. :
 LREP 1 2 3 4 5 6 : c repeat the part 6 times

SAGNEW HC
 7 of 7

END

START c sandwich panel honeycomb
 1 13 : 1 7 : 1 2 :
 -1676. 1676.
 -600. 600.
 0.0 20.
 MATE 3 c W 1-3/8-2.5 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 60. : MZ 80. :
 LREP 1 2 3 4 5 6 7 : c duplicate 7 times
 END

DIRECTORY .411762 / CSCBASE3 / SAGNEWHL
 (NO EDGE FILLER) USING WR II - 3/8 - 4.0

@ 7.0 $\frac{1}{4}$ ft/s

CSC meter base? (new bc no fill)
 time = 0.1111111111

$L = 3402 \text{ mm}$
 $G = 1250 \text{ mm}$

CSC meter base? (new bc no fill)
 time = 0.1111111111

6-8

disp. scale factor = 0.100E+04

SAGNEWHL
 1 OF 7

disp. scale factor = 0.100E+04

SAGNEWHL
 2 OF 7

CSC outer base3 (new base (111))
 c file cns2h3c baseline-2 (rev 1)
 c Revised kinematic moments.
 c Revised for nodes on centerlines.
 c This file is used to generate NIKES3D input.

SAGNEWHL

5 OF 7

a Ingrid input for CSC outer superlayer chamber
 c 6 wire layers
 c 1=3402mm w=1200mm h=200mm
 c edge frame w=25mm
 c end frame w=25mm
 c sandwich panels (7) 1=20mm (10mm core + 0.5mm skins)
 c gaps (6) 1=10mm

c Procedure for UNICOB:
 c Ingrid inifile run Ingrid
 c stop 0.1 merge nodes
 c continue make NIKES3D input
 c mv Ingrid outfile.1 change name
 c vi outfile.1 edit cscb2 i
 c card:field value comments
 c 0:1 5 only print last stop to hsp
 c 0:1 00 percent of core
 c 0:2 3 Buffer size
 c 0:3 1 Storage option in core
 c 0:4 1 Incompatible nodes for bricks
 c 0:5 1 Shell geometric stiffness flag
 c 0:6 1
 c change boundary conditions
 c node 4 (code 7) x,y,z trans. fixed/all rot. free
 c node 10 (code 3) z trans. fixed/all rot. free
 c node 111 (code 5) y,z trans. fixed/all rot. free

bas sds harvath

to 1
 NIKES3D c generate NIKES3D input
 ANAL STAT c static analysis
 NSTEP 4 c number of time steps
 DELT 2.000e-01 c time step size

c six-step load curve
 LCD 1 0 0.0 0.0 0.2 0.00 0.4 0.1 0.0 0.2 0.0 0.4 1.0 1.0

GRAV c 1g in z-direction (normal to panel)
 0.0 0.0 0.01000e+03

MAT 1 1 SHELL c Epoxy-Giliteb 1040 (0-10)
 E 2.2010e+10 c g-mm/sec2/mm2 (3.3e+08 psi)
 PR 0.20 c poisson's ratio
 RHO 1.0202e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 THICK 0.5 c mm thickness
 ENDMAT

MAT 2 1 c Epoxy-Giliteb 1040 (0-10)
 E 2.2010e+10 c g-mm/sec2/mm2 (3.3e+08 psi)
 PR 0.20 c poisson's ratio
 RHO 1.0202e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

MAT 3 2 c BR 11-3/B-4.0 (honeycomb)
 EC 3.0032e+08 c g-mm/sec2/mm2 (55.0e+03 lb/in2)

SAGNEWHL

6 OF 7

EA 3.0032e+03 c g-mm/sec2/mm2 (e-05 better)
 EB 3.0032e+03 c g-mm/sec2/mm2 (e-05 better)
 GAB 0.2232e+02 c g-mm/sec2/mm2 (e-05 better)
 GBC 0.2232e+07 c g-mm/sec2/mm2 (5.0e+03 lb/in2)
 GCA 1.3130e+00 c g-mm/sec2/mm2 (10.0e+03 lb/in2)
 PRBA 0.3 c Poisson-ba
 PRCA 0.3 c Poisson-ca
 PRCB 0.3 c Poisson-cb
 RHO 0.4200e-08 c g/mm3 (4.0 lb/ft3)
 ADPT 2.0 c globally or tetragic definition
 A1 1.0 c 1 for a-vector
 A2 0.0 c y for a-vector
 A3 0.0 c z for a-vector
 D1 0.0 c x for d-vector
 D2 1.0 c y for d-vector
 D3 0.0 c z for d-vector
 ENDMAT

MAT 4 1 c epoxy MC filler
 E 2.7000e+08 c g-mm/sec2/mm2 or GPa (0.4e+08 psi)
 PR 0.20 c poisson's ratio
 RHO 1.0000e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

START c sandwich panel skins
 1 2 14 10 : 1 2 0 0 : -1 :
 -1701. -1070. 1070. 1701.
 -020. -000. 000. 020.
 0 0 20
 MATE 1 c Epoxy-Giliteb 1040 (0-10)
 LCT 14 : c repeat the part 14 times
 MZ -100. : MZ -00. : MZ -00. : MZ -00. : MZ -10. :
 MZ -70. : MZ -00. : MZ -00. : MZ -00. : MZ 70. :
 MZ 10. : MZ 20. : MZ 00. : MZ 00. : MZ 00. :
 MZ 00. : MZ 100. :
 LREP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 : c use the 14 clones
 END

START c sandwich panel frames
 1 2 14 10 : 1 2 0 0 : 1 2 :
 -1701. -1070. 1070. 1701.
 -020. -000. 000. 020.
 0 0 20
 D 2 2 1 3 3 2 c remove the honeycomb region
 MATE 3 c BR 11-3/B-4.0 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -00. : MZ -10. : MZ 20. : MZ 00. : MZ 00. :
 LREP 1 2 3 4 5 6 7 : c repeat the part 7 times
 END

START c gap frames
 1 2 14 10 : 1 2 0 0 : 1 2 :
 -1701. -1070. 1070. 1701.
 -020. -000. 000. 020.
 0 0 10
 D 2 2 1 3 3 2 c remove wire gap region
 MATE 2 c Epoxy-Giliteb 1040 (0-10)
 LCT 6 : MZ -00. : MZ -00. : MZ -20. : MZ 10. : MZ 00. : MZ 70. :
 LREP 1 2 3 4 5 6 : c repeat the part 6 times
 END

SAGNEWHL

7 OF 7

START c sandwich panel honeycomb
 1 13 : 1 7 : 1 2 :
 -1070. 1070.
 -000. 000.
 0 0 20
 MATE 3 c BR 11-3/B-4.0 (honeycomb)
 LCT 7 : MZ -100. : MZ -70. : MZ -00. : MZ -10. : MZ 20. : MZ 00. : MZ 00. :
 LREP 1 2 3 4 5 6 7 : c duplicate 7 times
 END
 END

9. Parametric Studies

Contents:

SL-3 CSC with and without 10mm thick x 25mm wide aluminum stiffeners (2 pages)

Gravity sag as a function of chamber design parameters (9 pages)

Summary:

10mm thick by 25mm wide aluminum stiffeners added to the top and bottom of the side frames in the long direction reduce SL-3 barrel chamber gravity sag by 40% while adding 9.5kg of mass.

The location of the support points away from the ends of the chamber has the greatest effect on the gravity sag (see the section on support locations).

Frame width has little effect on gravity sag since mass is added at non-optimum locations near the section neutral plane.

Sandwich panel overall thickness has a large effect on gravity sag since increasing core material has little effect on mass.

Increasing the central sandwich panel thickness has some beneficial effect with no change in mass.

Adding G-10 extensions has a moderate effect on gravity sag.

SL-3 barrel chamber (TDR Baseline)

shaded denotes input values

	metric	English (in, lb)
chamber w (mm)	1330	52.362
chamber length (mm)	3500	137.795
sandwich h (mm)	20	0.787
sandwich face (mm)	0.5	0.020
gap h (mm)	10	0.394
gap frame w (mm)	25	0.984
core frame w (mm)	25	0.984
extension w (mm)	0	0.000
extension h (mm)	0	0.000
Cu plating w (mm)	1200	47.244
precise cath. cvr. (%)	85.6	
coarse cath. cvr. (%)	100	
Cu plating t (mm)	0.017	0.001
prec.cath.substr. t (mm)	0.000	0.000
crs.cath.substr. t (mm)	0.000	0.000
hardware+utilities (g)	25000	55.0

(ref=0.017
0.005 w/mylar)

allowable material choices	E (psi)	E (MPa)	density (lb/in3)	density (g/cm3)
MAT1 G10 laminate	3,300,000	22,759	0.069	1.9264
MAT2 glass-fiber/epoxy	1,600,000	11,034	0.067	1.85
MAT3 C-fiber/epoxy (FR-337)	5,000,000	34,483	0.060	1.66
MAT4 aluminum	10,000,000	68,966	0.098	2.718
MAT5 copper	18,000,000	124,138	0.322	8.9317
MAT6 epoxy (F 954-3) 350F	400,000	2,759	0.043	1.19
MAT7 ultra-low density	100,000	690	0.015	0.42
MAT8 syntactic (CG 1617-A)	350,000	2,414	0.025	0.7
MAT9 mylar	550,000	3,793	0.050	1.3889
MAT10 nomex @ 1.8lb/ft3	0	0	0.001041673	0.026894

composition	component	% of total wt.	% of tot. carried	%carried-%wt.	mass (kg)
MAT2 glass-fiber/epoxy	gap frame	12.2	8.6	-3.6	19.43
MAT6 epoxy (F 954-3) 350F	core edge filler	17.4	6.6	-10.8	27.70
MAT4 aluminum	extensions	0.0	0.0	0.0	0.00
MAT1 G10 laminate	sandwich skins	39.4	77.5	38.1	62.77
MAT10 nomex @ 1.8lb/ft3	sandwich core	10.8	0.0	-10.8	17.22
MAT5 copper	cathode planes	4.5	7.3	2.8	7.10
MAT9 mylar	cath. substrate	0.0	0.0	0.0	0.00
	htrdr + util	15.7	0.0	-15.7	25.00

totals =	100.0	100.0	0.0	159.21
			weight (lb) =	350.3

chamber h (mm)	200.0
sandwich w (mm)	1330.0
core w (mm)	1280.0
core h (mm)	19.0

mode-1 freq. = 18.5 hertz

	sandwich skins	gap frame	core edge filler	extensions	sandwich core	cathode	cathode substrate	Totals	
sum Eln.a. =	7.829E+11	8.717E+10	6.659E+10	0.000E+00	0.000E+00	7.375E+10	0.000E+00	1.010E+12	(Mpa mm^4)
ln.a. =	3.440E+07	7.900E+06	2.414E+07	0.000E+00	0.000E+00	5.941E+05	0.000E+00	6.704E+07	(mm^4)
weight/l =	0.1755	0.0543	0.0774	0.0000	0.0481	0.0199	0.0000	0.3752	(N/mm)
mass/l =	17.9348	5.5500	7.9135	0.0000	4.9189	2.0291	0.0000	38.35	(g/mm)
length =	3,500	3,500	3,500	3,500	3,500	3,500	3,500	---	(mm)
E =	22,759	11,034	2,759	68,966	0	124,138	3,793	233,448	(MPa)
mass density =	0.001826	0.001850	0.001190	0.002718	0.000029	0.006932	0.001387	0.018032	(g/mm^3)
wt. density =	1.885E-05	1.810E-05	1.184E-05	2.660E-05	2.827E-07	8.740E-05	1.357E-05	1.765E-04	(N/mm^3)
displacement =	0.726	0.726	0.726	0.000	(dead load)	0.726	0.000	---	(mm)
sum Eln.a. =	2.727E+08	3.037E+07	2.320E+07	0.000E+00	0.000E+00	2.569E+07	0.000E+00	3.520E+08	(lb in^2)
ln.a. =	82.65	18.98	58.00	0.00	0.00	1.43	0.00	161.05	(in^4)
weight/l =	1.00	0.31	0.44	0.00	0.27	0.11	0.00	2.14	(lb/in)
mass/l =	2.594E-03	8.026E-04	1.144E-03	0.000E+00	7.114E-04	2.934E-04	0.000E+00	5.546E-03	(lb sec^2/in)
length =	137.80	137.80	137.80	137.80	137.80	137.80	137.80	---	(in)
E =	3,300,000	1,600,000	400,000	10,000,000	0	18,000,000	550,000	---	(lb/in^2)
mass density =	1.797E-04	1.728E-04	1.110E-04	2.536E-04	2.696E-06	8.333E-04	1.294E-04	1.682E-03	(lb sec^2/in^4)
wt. density =	0.069	0.067	0.043	0.098	0.001	0.322	0.050	0.650	(lb/in^3)
displacement =	28.58	28.58	28.58	0.00	(dead load)	28.58	0.00	---	(mils)
sum A =	9.3100E+03	3.0000E+03	6.6500E+03	0.0000E+00	1.7024E+05	2.2717E+02	0.0000E+00	1.894E+05	(mm^2)
sum Ay =	9.3100E+05	3.0000E+05	6.6500E+05	0.0000E+00	1.7024E+07	2.2717E+04	0.0000E+00	---	(mm^3)
Yna=sum AY/sum A =	1.0000E+02	1.0000E+02	1.0000E+02	0.0000E+00	1.0000E+02	1.0000E+02	0.0000E+00	---	(mm)
sum AY^2 =	1.2750E+08	3.7875E+07	9.0440E+07	0.0000E+00	2.3153E+09	2.8658E+06	0.0000E+00	2.574E+09	(mm^4)
Yna.*AY =	9.3100E+07	3.0000E+07	6.6500E+07	0.0000E+00	1.7024E+09	2.2717E+06	0.0000E+00	---	(mm^4)
sum Ioo =	1.9396E+02	2.5000E+04	2.0005E+05	0.0000E+00	5.1214E+06	5.4711E-03	0.0000E+00	5.347E+06	(mm^4)
AY^2-Yna.*AY =	3.4401E+07	7.8750E+06	2.3940E+07	0.0000E+00	6.1286E+08	5.9407E+05	0.0000E+00	---	(mm^4)
section Ioo =	3.4401E+07	7.9000E+06	2.4140E+07	0.0000E+00	6.1799E+08	5.9407E+05	0.0000E+00	6.850E+08	(mm^4)

"ideal chamber" v4.0

1 of 2
TDR
BASELINE
WITHOUT
ALUMINUM
EXTENSIONS

SL-3 barrel chamber (TDR Baseline) **EXTENSIONS ADDED**

"shaded" denotes input values

	metric	English (in, lb)
chamber w (mm)	1330	52.362
chamber length (mm)	3500	137.795
sandwich h (mm)	20	0.787
sandwich face (mm)	0.5	0.020
gap h (mm)	10	0.394
gap frame w (mm)	25	0.984
core frame w (mm)	25	0.984
extension w (mm)	25	0.984
extension h (mm)	10	0.394
Cu plating w (mm)	1200	47.244
precise cath. cvr. (%)	85.6	
coarse cath. cvr. (%)	100	
Cu plating t (mm)	0.017	0.001
prec.cath.substr. t (mm)	0.000	0.000
crs.cath.substr. t (mm)	0.000	0.000
hardware+utilities (g)	25000	55.0

(rel=0.017
0.005 w/mylar)

chamber h (mm)	220.0
sandwich w (mm)	1330.0
core w (mm)	1280.0
core h (mm)	19.0

mode-1 freq. = 23.9 hertz

allowable material choices	E (psi)	E (MPa)	density (lb/in3)	density (g/cm3)
MAT1 G10 laminate	3,300,000	22,759	0.069	1.9264
MAT2 glass-fiber/epoxy	1,600,000	11,034	0.067	1.85
MAT3 C-fiber/epoxy (FR-337)	5,000,000	34,483	0.060	1.66
MAT4 aluminum	10,000,000	68,966	0.098	2.718
MAT5 copper	18,000,000	124,138	0.322	8.9317
MAT6 epoxy (F 954-3) 350F	400,000	2,759	0.043	1.19
MAT7 ultra-low density	100,000	690	0.015	0.42
MAT8 syntactic (CG 1617-A)	350,000	2,414	0.025	0.7
MAT9 mylar	550,000	3,793	0.050	1.3869
MAT10 nomex @ 1.8lb/ft3	0	0	0.001041673	0.028894

composition	component	% of total wt.	% of tot. carried	%carried-%wt.	mass (kg)
MAT2 glass-fiber/epoxy	gap frame	11.5	4.8	-6.7	19.43
MAT6 epoxy (F 954-3) 350F	core edge filler	16.4	3.7	-12.7	27.70
MAT4 aluminum	extensions	5.6	44.1	38.5	9.51
MAT1 G10 laminate	sandwich skins	37.2	43.3	6.1	62.77
MAT10 nomex @ 1.8lb/ft3	sandwich core	10.2	0.0	-10.2	17.22
MAT5 copper	cathode planes	4.2	4.1	-0.1	7.10
MAT9 mylar	cath. substrate	0.0	0.0	0.0	0.00
	hddw + util	14.8	0.0	-14.8	25.00
	totals =	100.0	100.0	0.0	168.72

weight (lb) = 371.2

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ALUMINUM
EXTENSIONS
ADDED ALL 4 CORNERS
FULL LENGTH

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	sandwich skins	gap frame	core edge filler	extensions	sandwich core	cathode	cathode substrate	Totals	
sum Eln.a. =	7.829E+11	8.717E+10	6.659E+10	7.984E+11	0.000E+00	7.375E+10	0.000E+00	1.809E+12	(Mpa mm^4)
ln.a. =	3.440E+07	7.900E+06	2.414E+07	1.158E+07	0.000E+00	5.941E+05	0.000E+00	7.861E+07	(mm^4)
weight/l =	0.1755	0.0543	0.0774	0.0266	0.0481	0.0199	0.0000	0.4018	(N/mm)
mass/l =	17.9348	5.5500	7.9135	2.7180	4.9189	2.0291	0.0000	41.06	(g/mm)
length =	3,500	3,500	3,500	3,500	3,500	3,500	3,500	---	(mm)
E =	22,759	11,034	2,759	68,966	0	124,138	3,793	233,448	(MPa)
mass density =	0.001926	0.001850	0.001190	0.002718	0.000029	0.008932	0.001387	0.018032	(g/mm^3)
wt. density =	1.885E-05	1.810E-05	1.164E-05	2.660E-05	2.827E-07	8.740E-05	1.357E-05	1.765E-04	(N/mm^3)
displacement =	0.434	0.434	0.434	0.434	(dead load)	0.434	0.000	---	(mm)
sum Eln.a. =	2.727E+08	3.037E+07	2.320E+07	2.781E+08	0.000E+00	2.569E+07	0.000E+00	6.301E+08	(lb in^2)
ln.a. =	82.65	18.98	58.00	27.81	0.00	1.43	0.00	188.87	(in^4)
weight/l =	1.00	0.31	0.44	0.15	0.27	0.11	0.00	2.29	(lb/in)
mass/l =	2.594E-03	8.026E-04	1.144E-03	3.931E-04	7.114E-04	2.934E-04	0.000E+00	5.939E-03	(lb sec^2/in)
length =	137.80	137.80	137.80	137.80	137.80	137.80	137.80	---	(in)
E =	3,300,000	1,600,000	400,000	10,000,000	0	18,000,000	550,000	---	(lb/in^2)
mass density =	1.797E-04	1.726E-04	1.110E-04	2.536E-04	2.696E-06	8.333E-04	1.294E-04	1.682E-03	(lb sec^2/in^4)
wt. density =	0.069	0.067	0.043	0.098	0.001	0.322	0.050	0.650	(lb/in^3)
displacement =	17.09	17.09	17.09	17.09	(dead load)	17.09	0.00	---	(mils)
sum A =	9.3100E+03	3.0000E+03	6.6500E+03	1.0000E+03	1.7024E+05	2.2717E+02	0.0000E+00	1.904E+05	(mm^2)
sum Ay =	1.0241E+06	3.3000E+05	7.3150E+05	1.0750E+05	1.8726E+07	2.4989E+04	0.0000E+00	---	(mm^3)
Yna=sum AY/sum A =	1.1000E+02	1.1000E+02	1.1000E+02	1.0750E+02	1.1000E+02	1.1000E+02	0.0000E+00	---	(mm)
sum AY^2 =	1.4705E+08	4.4175E+07	1.0441E+08	2.3125E+07	2.6728E+09	3.3429E+06	0.0000E+00	2.995E+09	(mm^4)
Yna.*AY =	1.1265E+08	3.6300E+07	8.0465E+07	1.1556E+07	2.0589E+09	2.7488E+06	0.0000E+00	---	(mm^4)
sum Ioo =	1.9396E+02	2.5000E+04	2.0005E+05	8.3333E+03	5.1214E+06	5.4711E-03	0.0000E+00	5.355E+06	(mm^4)
AY^2-Yna.*AY =	3.4401E+07	7.8750E+06	2.3940E+07	1.1569E+07	6.1286E+08	5.9407E+05	0.0000E+00	---	(mm^4)
section Ioo =	3.4401E+07	7.9000E+06	2.4140E+07	1.1577E+07	6.1799E+08	5.9407E+05	0.0000E+00	6.966E+08	(mm^4)

"ideal chamber" v4.0

- outer CSC, 6 gas gaps @ 10mm, 3500mm x 1289mm, skin thickness = 0.5mm
- sandwich thickness varied from 10mm to 50mm (chamber thickness goes from 130mm to 410mm)
- frame width varied from 10mm to 60mm
- maximum deflection (0.060mm panel sag has been added to beam bending)

- outer CSC, 6 gas gaps @ 10mm, 3500mm x 1289mm, 25mm wide frame
- sandwich thickness varied from 20mm to 32mm (chamber thickness goes from 200mm to 284mm)
- skin thickness varied from 0.5mm to 5.0mm
- maximum deflection (0.060mm panel sag has been added to beam bending)

- inner CSC, 6 gas gaps @ 5mm, 3300mm x 700mm, 25mm wide frame
- sandwich thickness varied from 20mm to 32mm (chamber thickness goes from 170mm to 254mm)
- skin thickness varied from 0.5mm to 5.0mm
- maximum deflection (0.060mm panel sag has been added to beam bending)

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- outer CSC, 6 gas gaps @ 10mm, 3500mm x 1289mm, frame width = 25mm
- central sandwich thickness varied from 20mm to 80mm (chamber thickness held constant at 200mm)
- skin thickness varied from 0.5mm to 5.0mm
- maximum deflection (0.060mm panel sag has been added to beam bending)

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- outer CSC, 6 gas gaps @ 10mm, 1289mm wide, 25mm wide frame, skin thk. = 0.5mm
- chamber length varied from 3000mm to 3500mm
- sandwich thickness varied from 20mm to 30mm (chamber thickness goes from 200mm to 270mm)
- maximum deflection (0.060mm panel sag has been added to beam bending)

Outer CSC, 6 gas gaps, 7 panels @ 20mm, 3500mm x 1289mm x 200mm

deflection vs. skin thickness

- outer CSC, 6 gas gaps @ 10mm, 3500mm x 1289mm, skin thickness = 0.5mm, frame width = 25mm
- central sandwich thickness varied from 20mm to 80mm (chamber thickness goes from 200mm to 280mm)
- extension height varied from 0 to 60mm
- maximum deflection (0.060mm panel sag has been added to beam bending)

- outer CSC, 6 gas gaps @ 10mm, 3500mm x 1289mm, 25mm wide frame
- single frame extension varied from 10mm to 80mm (added to top and bottom)
- skin thickness varied from 0.5mm to 5.0mm (chamber thickness held constant at 200mm)
- maximum deflection (0.060mm panel sag has been added to beam bending)

- inner CSC, 6 gas gaps @ 5mm, 3300mm x 700mm, 25mm wide frame
- frame extension varied from 0 to 80mm (added to top and bottom)
- skin thickness varied from 0.5mm to 5.0mm (chamber thickness held constant at 170mm)
- maximum deflection (0.060mm panel sag has been added to beam bending)

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file: extvskin.in
jsh 2/18/93

10. Thermal Deformation

Contents:

Summary viewgraph (1 page)

Slab thermal deformation calculation (2 pages)

Summary:

Thermal deformation of a slab is proportional to the first power of temperature and CTE, the second power of length and width, and inversely proportional to the first power of slab thickness.

Thermal Deformation Levels Are Acceptable

- Thermal deflection of a homogeneous slab subjected to a linear temperature gradient through its thickness is

$$\delta_{\text{thermal}} = \delta_L + \delta_W = \frac{(L^2 + W^2) \alpha \Delta T}{8 h}$$

where, L = length
W = width
 α = coefficient of thermal expansion = $11.3 \times 10^{-6} / ^\circ\text{C}$
h = thickness
 $\Delta T = 2^\circ\text{C} / 9.0\text{m} \times \text{thickness}$

chamber	length (mm)	width (mm)	thickness (mm)	deflection (mm)
outer superlayer	3500	1300	200	0.004
middle superlayer	2600	1100	188	0.001
inner superlayer	3500	770	170	0.004

10-3

J. HORVATH

THERMAL DISTORTION

JIF2

2 OF 2

thermal deformation						
superlayer	length (mm)	width (mm)	thickness (mm)	alpha (10E-6/deg. C)	delta T (deg. C)	deflection (mm)
SL-1 (inner)	3500	1300	200	0.0000113	0.044	0.004
SL-2 (middle)	1100	1100	188	0.0000113	0.042	0.001
SL-3 (outer)	3500	770	170	0.0000113	0.038	0.004
delta T = (2 deg. C * thickness) / (9000 mm) deflection = (length^2 + width^2) alpha delta T / (8 thickness)						

RT. TRIANGLE: $(R + t - s)^2 + \left[\frac{L}{2}(1 + \alpha \Delta T)\right]^2 = (R + t)^2$
 $(R + t - s)(R + t - s) + \frac{L^2}{4}(1 + \alpha \Delta T)(1 + \alpha \Delta T) = (R + t)(R + t)$
 $\cancel{R^2} + \cancel{Rt} - Rs + \cancel{Rt} - \cancel{Rs} + \cancel{t^2} - \cancel{ts} - \cancel{ts} + \cancel{t^2} + \frac{L^2}{4}(1 + \alpha \Delta T) + \alpha \Delta T + (\alpha \Delta T)^2 = \cancel{R^2} + \cancel{Rt} + \cancel{t^2}$

$$-2Rs - 2ts + \frac{L^2}{4}(1 + 2\alpha \Delta T) = 0$$

$$-2s(R + t) = -\frac{L^2}{4}(1 + 2\alpha \Delta T)$$

BUT $R = \frac{t}{\alpha \Delta T}$

$$\therefore -2s\left(\frac{t}{\alpha \Delta T} + t\right) = -\frac{L^2}{4}(1 + 2\alpha \Delta T)$$

$$\frac{2st}{\alpha \Delta T}(1 + \alpha \Delta T) = \frac{L^2}{4}(1 + 2\alpha \Delta T)$$

$$s = \frac{L^2 \alpha \Delta T}{8t} \left[\frac{1 + 2\alpha \Delta T}{1 + \alpha \Delta T} \right]$$

$$\therefore s \approx \frac{L^2 \alpha \Delta T}{8t}$$

11. Support Point Location and Gravity Sag

Contents:

Analysis of gravity sag of TDR SL-3 barrel chamber vs. support point location (3 pages)

Calculation of shear, moment, curvature, and deflection functions (6 pages)

Beam deflection "special cases" chart, ref. Don Carter, LLNL (1 page)

Summary:

The optimum support points for a uniformly loaded beam are located $0.223L$ from the ends of the beam.

Support at the extreme ends results in a gravity sag 48.6 times higher than the optimum.

GRAVITY SAG IF RIGHT SUPPORT IS KEPT AT END AND
LEFT SUPPORT IS MOVED INWARD.

1 OF 3

GRAVITY SAG IF LEFT SUPPORT IS KEPT AT 0.3L
 AND RIGHT SUPPORT IS MOVED INWARD,

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11-3

outer superlayer 6-gap CSC			
length (mm) L =	3,500.00	length (in) =	137.80
(dist. to 1st supp't)/(length) =	0.00	(dist. to 1st supp't)/(length) =	0.00
(dist. to 2nd supp't)/(length) =	1.00	(dist. to 2nd supp't)/(length) =	0.04
dist. to 1st supp't (mm) A =	0.00	dist. to 1st supp't (in) =	0.00
dist. to 2nd supp't (mm) B =	3,500.00	dist. to 2nd supp't (in) =	137.80
distributed load (N/mm) W =	0.41	distributed load (lb/in) =	2.32
distributed load (g/mm) W =	41.44		
Modulus of Elasticity (MPa) E =	22,759	Modulus of Elasticity (psi) =	3,300,000
Moment of Inertia (mm ⁴) I =	42,301,228	Moment of Inertia (in ⁴) =	101.63
1st support reaction (g) F1 =	711.75	1st support reaction (lb) =	159.54
2nd support reaction (g) F2 =	711.75	2nd support reaction (lb) =	159.54
c1 =	0.000E+00	c1 =	0.000E+00
c2 =	-7.268E+08	c2 =	-2.524E+05
c3 =	0.000E+00	c3 =	0.000E+00
c4 =	0.000E+00	c4 =	0.000E+00
c5 =	-7.268E+08	c5 =	-2.524E+05
c6 =	0.000E+00	c6 =	0.000E+00
c7 =	-2.491E+06	c7 =	-2.198E+04
c8 =	3.833E+09	c8 =	1.262E+06
c9 =	-5.066E+12	c9 =	-6.957E+07
location (mm) x =	1750.00	location (in) x =	68.898
if (x<a) or (x=a)		if (x<a) or (x=a)	
deflection (mm) =	-1.486	deflection (in) =	-0.058
if (x>a) or (x<b)		if (x>a) or (x<b)	
deflection (mm) =	-0.825	deflection (in) =	-0.032
if (x=b) or (x>b)		if (x=b) or (x>b)	
deflection (mm) =	-1.486	deflection (in) =	-0.058
deflection at x (mm) =	-0.825	deflection at x (in) =	-0.03

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location x	deflection
-0.825	3500
0	0.000
100	-0.075
200	-0.150
300	-0.223
400	-0.294
500	-0.363
600	-0.428
700	-0.490
800	-0.548
900	-0.601
1000	-0.649
1100	-0.692
1200	-0.729
1300	-0.761
1400	-0.786
1500	-0.805
1600	-0.818
1700	-0.825
1800	-0.825
1900	-0.818
2000	-0.805
2100	-0.786
2200	-0.761
2300	-0.729
2400	-0.692
2500	-0.649
2600	-0.601
2700	-0.548
2800	-0.490
2900	-0.428
3000	-0.363
3100	-0.294
3200	-0.223
3300	-0.150
3400	-0.075
3500	0.000

ASSUMED SECTION PROPERTIES
AND DIMENSIONS
(APPROXIMATE TDR SL-3 BARREL CHAMBER)

SIMPLE
BEAMCSC SIMPLE BEAM MODEL: ASSUMPTIONS: UNIFORM CROSS-SECTION, LOAD, AND MATERIAL E = MODULUS OF ELASTICITY I = SECTION MOMENT OF INERTIA l = LENGTH w = DISTRIBUTED LOADCALCULATION OF SHEAR, MOMENT, CURVATURE,
AND DISPLACEMENT FUNCTIONS...SIMPLE
BEAM

w - distributed load
 a - dist to first support
 b - " " second "
 l - length
 E - Modulus
 I - Moment of inertia

$$\text{Total load } W = wL = F_1 + F_2 \Rightarrow F_1 = wL - F_2$$

$$\sum M_o = 0 = wL(\frac{l}{2}) - F_1 a - F_2 b$$

$$0 = wL\frac{l}{2} - (wL - F_2)a - F_2 b$$

$$0 = wL\frac{l}{2} - wLa + F_2 a - F_2 b$$

$$wLa - wL\frac{l}{2} = F_2 (a - b)$$

$$F_2 = \frac{wL(a - \frac{l}{2})}{a - b}$$

$$F_1 = wL - F_2 = wL - (wL(a - \frac{l}{2}) / (a - b))$$

$$F_1 = \frac{wL(a - b) - wL(a - \frac{l}{2})}{a - b}$$

$$F_1 = \frac{wL(a - b - a + \frac{l}{2})}{a - b}$$

$$F_1 = \frac{wL(\frac{l}{2} - b)}{a - b}$$

define V = shear
 M = moment
 Θ = slope
 y = deflection

for $0 \leq x \leq a$

$$V = -wX$$

$$M = -wX^2/2 + C_1$$

$$\Theta = \frac{1}{EI} \left[-w\frac{X^3}{6} + C_1 X + C_2 \right]$$

$$y = \frac{1}{EI} \left[-\frac{wX^4}{24} + C_1 \frac{X^2}{2} + C_2 X + C_3 \right]$$

SIMPLE
BEAM

5/6

using extra B.C. to check:

$$\text{from BC (i)} \quad -\frac{\omega b^3}{2} + F_1 b + C_7 = -\frac{\omega b^3}{2} + \omega l b + C_7$$

$$F_1(b-a) = \omega l(b-\frac{1}{2})$$

$$F_1 = \frac{\omega l(b-\frac{1}{2})}{b-a} \quad \text{— this checks out with free-body value.}$$

$$\text{from (i)} \quad C_1 = 0$$

$$\text{from (ii)} \quad C_7 = -\frac{\omega l^2}{2}$$

$$\text{from (iii)} \quad C_4 = -F_1 a$$

$$\text{from (3)} \quad C_2 = F_1 \frac{a^2}{2} + C_4 a + C_5 \Rightarrow C_2 = F_1 \frac{a^2}{2} - F_1 a^2 + C_5$$

$$C_2 = C_5 - \frac{F_1 a^2}{2}$$

$$\text{from (6)} \quad C_4 \frac{a^2}{2} + C_5 a + C_6 = \frac{\omega a^3}{24} - F_1 \frac{a^3}{6}$$

$$C_5 a + C_6 = \frac{F_1 a^3}{2} + \frac{\omega a^3}{24} - F_1 \frac{a^3}{6}$$

$$C_5 a + C_6 = \frac{\omega a^3}{24} + F_1 \frac{a^3}{3}$$

$$\text{from (1)} \quad C_4 \frac{b^2}{2} + C_5 b + C_6 = \frac{\omega b^3}{24} - F_1 \frac{b^3}{6}$$

$$C_5 b + C_6 = \frac{\omega b^3}{24} + F_1 \frac{ab^2}{2} - F_1 \frac{b^3}{6}$$

$$C_5 b + C_6 = \frac{\omega b^3}{24} + F_1 \left(\frac{ab^2}{2} - \frac{b^3}{6} \right)$$

$$\text{subtract (iv) from (v)} \quad C_5(b-a) = \frac{\omega}{24}(b^3-a^3) + F_1 \left(\frac{ab^2}{2} - \frac{b^3}{6} - \frac{a^3}{3} \right)$$

$$C_5 = \frac{\omega}{24} \frac{(b^3+a^3)(b+a)(\cancel{b-a})}{(b-a)} - \frac{F_1}{6} \frac{(b^3-3ab^2+2a^3)}{(b-a)}$$

$$C_5 = \frac{\omega(b^2+a^2)(b+a)}{24} - \frac{F_1(b^3-3ab^2+2a^3)}{6(b-a)}$$

$$\text{from (12)} \quad C_6 = \frac{\omega b^3}{24} + F_1 \left(\frac{ab^2}{2} - \frac{b^3}{6} \right) - C_5 b$$

SIMPLE
BEAM

5/6

$$\text{from (3)} \quad C_2 = C_5 - \frac{F_1 a^2}{2}$$

$$\text{from (5)} \quad C_3 = \frac{\omega a^3}{24} - C_2 a$$

$$\text{from (4)} \quad C_8 = C_4 b + C_5 + F_1 \frac{b^2}{2} - \frac{\omega l b^2}{2} - \frac{\omega l^2 b}{6}$$

$$\text{from (8)} \quad C_8 b + C_9 = \frac{\omega l^2 b^2}{4} - \frac{\omega l b^3}{6} + \frac{\omega b^3}{24}$$

$$C_9 = \frac{\omega l^2 b^2}{4} - \frac{\omega l b^3}{6} + \frac{\omega b^3}{24} - C_8 b$$

11-7

BEAM CALCULATIONS - SPECIAL CASES OF SYMMETRICAL OVERHANGING BEAMS WITH UNIFORM LOAD w = UNIT LOAD (e.g. lbs/ft)							
SPECIAL CASE	CASE#		DISTANCE FROM CENTER TO INFLECTION POINT (POINT OF ZERO MOMENT) $= \sqrt{\frac{l^2}{2} - c^2}$	MOMENT AT CENTER $= \frac{w(c^2 - \frac{l^2}{2})}{2}$	MOMENT AT SUPPORTS (MAX. MOMENT) $= -\frac{wl^2}{2}$ = MAX. MOMENT	DEFLECTION AT ENDS $= \frac{wl^3}{24EI} (3c^2(c+2l) - l^2)$ PLUS = DOWN MINUS = UP	DEFLECTION AT CENTER $= \frac{wl^3}{384EI} (5l^2 - 24c^2)$ PLUS = DOWN MINUS = UP
EQUAL MOMENTS AT SUPPORTS & CENTER	①		.207 L	.0214 wL^2	.0214 wL^2	-.00021 $\frac{wL^4}{EI}$	.00045 $\frac{wL^4}{EI}$
ZERO SLOPE AT ENDS	②		.196 L	.0192 wL^2	.0223 wL^2	-.000076 $\frac{wL^4}{EI}$	.000512 $\frac{wL^4}{EI}$
NO END DEFLECTION	③		.183 L	.0177 wL^2	.0230 wL^2	0	.000446 $\frac{wL^4}{EI}$
END & CENTER DEFLECTIONS EQUAL, MINIMUM OVERALL DEFLECTION	④		.164 L	.0135 wL^2	.0248 wL^2	.000268 $\frac{wL^4}{EI}$	.000248 $\frac{wL^4}{EI}$
ZERO SLOPE AT SUPPORTS	⑤		.159 L	.0126 wL^2	.0232 wL^2	.000317 $\frac{wL^4}{EI}$	.000237 $\frac{wL^4}{EI}$
NO CENTER DEFLECTION	⑥		.106 L	.0057 wL^2	.0284 wL^2	.000739 $\frac{wL^4}{EI}$	0
INFLECTION POINT AT CENTER MAX. DEFLECTION AT CENTER ZERO MOMENT AT CENTER	⑦		0	0	.0312 wL^2	.00113 $\frac{wL^4}{EI}$	-.000262 $\frac{wL^4}{EI}$

← OPTIMUM

10=1

REF. DON CARTER, LLNL

12. Bulge Due To Internal Pressure

Contents:

Summary viewgraphs (4 pages)

Chamber with external plenum, quarter-symmetry model and deflection results (10 pages)

TDR Baseline with 3 internal posts, quarter-sym. model and deflection results (8 pages)

Chamber without plenum or posts, quarter-sym. model and deflection results (7 pages)

Hand calculation of bulge using simply-supported edges for upper bound value (3 pages)

Spacer post design detail and comments (1 page)

Summary:

Panel bulge is proportional to the 4th. power of unsupported span, 2nd. power of outermost sandwich thickness, and 1st. power of outermost sandwich skin thickness. A hand calculation using simply-supported edges (no edge moments) provides an upper bound to the expected value (0.359mm for SL-3 TDR Baseline chamber). A finite element model provides the actual value and the deflected shape (0.064mm for SL-3 TDR Baseline chamber). The internal spacer posts carry high tensile loads to react the pressure load.

An external plenum, or bladder, eliminates the bulge on all cathode planes and transfers it to the external bladder itself. Spacer post tensile loads are reduced to the minimum amount needed to maintain contact for controlling the cathode-to-cathode spacing.

External Plenum Simplifies Spacer Posts

- External plenum eliminates bulge on all cathode plane sandwich panels
- Spacer post design is simplified since only small tension is needed to pull panel stack together (no internal honeycomb reinforcements are needed)
- Leak-tightness requirement is eliminated since spacer posts would terminate inside the plenum

GEM PAC Review, 26 May 1993

J.A. Horvath

Effect of Internal Pressure on Baseline Chamber

- A finite element model of an outer superlayer chamber with a 25mm epoxy honeycomb edge filler and a 25mm G10 gap spacer frame produces a 64 micron bulge for a 0.2 inch H2O positive internal pressure.
- A finite element model of an outer superlayer chamber without spacer posts predicts a 175 micron bulge for the same internal pressure. There is a sensitivity to panel edge moment restraint.

- Panel bulge is proportional to
 - 4th. power of unsupported width
 - 2nd. power of outermost sandwich thickness
 - 1st. power of outermost sandwich skin thickness
- Outside plenum or additional internal posts being evaluated

GEM PAC Review, 26 May 1993

J.A. Horvath

Spacer Posts Use Tension To Reduce Panel Bulge

- Outer superlayer chamber without spacer posts bulges 175 microns under 0.007 psi (0.2" H₂O) internal pressure
- Three spacer posts reduce the maximum bulge to 64 microns
- In both cases only the external sandwich panels bulge since pressure is equilibrated on both sides of the internal panels
- Chamber internal pressure produces tension in the spacer posts
- Spacer posts must be designed to restrain against overpressures without damage

GEM PAC Review, 26 May 1993

J.A. Horvath

Spacer Posts Limit Bulge Locally

- Internal spacer posts limit panel bulge by applying restraint at discrete points
- A plenum at the outer surfaces would uniformly restrain bulge without spacer posts

GEM PAC Review, 26 May 1993

J.A. Horvath

DIRECTORY: .411762/CSCPRESSURE/BLADDER/3POINT BASE 2

MODIFIED BASELINE 2 WITH BLADDERS ADDED (15 mm TOP & BOTTOM)

0.2" H₂O
0.007 psi
50 Pa

CSC outer - 0.2" H₂O WITH BLADDER (25mm epoxy fr
time = 0.10000E+01

EXTERNAL PLENUM

BLADDER

1 OF 10

(DISPLACEMENT MAGNIFICATION
FACTOR = 100)

disp. scale factor = 0.100E+03

CSC outer - 0.2" H₂O WITH BLADDER (25mm epoxy fr
time = 0.10000E+01

BLADDER

2 OF 10

(DISP. MAG. = 100)

disp. scale factor = 0.100E+03

CSC outer - 0.2" H2O WITH BLADDER (25mm epoxy fr
time = 0.10000E+01)

BLADDER
3 of 10

(DISP. MAG. = 100)

disp. scale factor = 0.100E+03

CSC outer - 0.2" H2O WITH BLADDER (25mm epoxy fr
time = 0.10000E+01)

BLADDER
4 of 10

(DISP. MAG. = 500)

disp. scale factor = 0.500E+03

CSC outer - 0.2' H2O WITH BLADDER (25mm epoxy fr
time = 0.10000E+01

BLADDER
5 OF 10

DISPLACEMENT SCALE FACTOR = 1.0
(NO MAGNIFICATION)

disp. scale factor = 0.100E+01 (default)

BLADDER 6 of 10

CSC outer - 1.2" H2O WITH BLADDER (26mm epoxy frame)
 c modified to simulate external bladders on a 4-gap chamber
 c file cepsrbl
 c Bladder ended top and bottom
 c Quarter-symmetry model
 c Baseline-2 with three spacer posts
 c This file is used to generate NIKE3D input.

c Ingrid input for CSC outer superlayer chamber
 c 6 wire layers
 c i=3402mm w=1200mm h=200mm
 c edge frame w=25mm
 c end frame w=25mm
 c sandwich panels (7) t=20mm (19mm core + 0.5mm skins)
 c gaps (6) t=10mm

c Procedure for UNICOS:
 c Ingrid i=infile run Ingrid
 c step 0.1 merge nodes
 c continue make NIKE3D input
 c sv Ingrid outfile.i change name
 c vi outfile.i edit cscb2.i

card	field	value	comments
0:1	5		only print last step to hap
0:1	50		percent of core
0:3	3		buffer size
0:4	1		storage option in core
0:5	1		incompatible modes for bricks
0:9	1		shell geometric stiffness flag

change boundary conditions
 c node 171 (code 8) x,z trans. fixed

box s48 horvath
 tv 1
 NK3D o generate NIKE3D input
 ANAL STAT o static analysis
 NSTEP 4 o number of time steps
 DELT 2.500e-01 o time step size

c six-step load curve
 LCD 1 6 0.0 0.0 0.2 0.06 0.4 0.1 0.8 0.2 0.8 0.4 1.0 1.0

c GRAV o 1g in z-direction (normal to panel)
 c 0.0 0.0 9.81488e+03

MAT 1 1 SHELL o Epoxy-Gillifab 1040 (G-10)
 E 2.2819e+10 o g-mm/sec2/mm2 (3.3e+06 psi)
 PR 0.28 o poisson's ratio
 RHO 1.9282e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 THICK 0.6 c mm thickness
 ENDMAT

MAT 2 1 o Epoxy-Gillifab 1040 (G-10)
 E 2.2819e+10 o g-mm/sec2/mm2 (3.3e+06 psi)
 PR 0.28 o poisson's ratio
 RHO 1.9282e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

MAT 3 2 c MRH-10-1/B-1.8 (honeycomb)
 EC 6.5319e+07 c g-mm/sec2/mm2 (8.0e+03 lb/in2)

BLADDER 7 of 10

EA 6.5319e+07 c g-mm/sec2/mm2 (e-06 softer)
 EB 6.5319e+02 c g-mm/sec2/mm2 (e-06 softer)
 GAB 1.0372e+02 c g-mm/sec2/mm2 (e-06 softer)
 GBC 1.0372e+07 c g-mm/sec2/mm2 (1.5e+03 lb/in2)
 GCA 2.6278e+07 c g-mm/sec2/mm2 (3.8e+03 lb/in2)
 PRBA 0.3 c Poisson-ba
 PRCA 0.3 c Poisson-ca
 PRCB 0.3 c Poisson-cb
 RHO 2.8894e-06 c g/mm3 (1.8 lb/ft3)
 AOPT 2.0 c globally orthotropic definition
 A1 1.0 c x for a-vector
 A2 0.0 c y for a-vector
 A3 0.0 c z for a-vector
 D1 0.0 c x for d-vector
 D2 1.0 c y for d-vector
 D3 0.0 c z for d-vector
 ENDMAT

MAT 4 1 c epoxy MC filler
 E 2.7800e+08 c g-mm/sec2/mm2 or GPa (0.4e+06 psi)
 PR 0.28 c poisson's ratio
 RHO 1.1800e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 ENDMAT

MAT 5 1 c epoxy center spacer qtr-posts
 BEAM o invokes collapsed thin shell formulation
 E 2.7800e+08 c g-mm/sec2/mm2 or GPa (0.4e+06 psi)
 PR 0.28 c poisson's ratio
 RHO 1.1800e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 sth 2.5 c outer dimension in s-direction/2 at ctr.n (mm)
 tth 2.5 c outer dimension in t-direction (mm)
 ENDMAT

MAT 6 1 c epoxy spacer half-posts
 BEAM o invokes collapsed thin shell formulation
 E 2.7800e+08 c g-mm/sec2/mm2 or GPa (0.4e+06 psi)
 PR 0.28 c poisson's ratio
 RHO 1.1800e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
 sth 2.5 c outer dimension in s-direction (mm)
 tth 5.0 c outer dimension in t-direction (mm)
 ENDMAT

START c sandwich panel skins (bladder external i.e. no pressure)
 1 13 15 : 1 13 15 : -1 ;
 0. 1878. 1701.
 0. 600. 626.
 0.0
 8 1 1 1 1 3 1 100011
 8 1 1 1 3 1 1 010101
 MATE 1 c Epoxy-Gillifab 1040 (G-10)
 LCT 2 : c repeat the part 2 times
 MZ -115. : MZ 115. :
 LREP 1 2 : c use the 2 clones
 END

START c sandwich panel skins (internal gap-top)
 1 13 15 : 1 13 15 : -1 ;
 0. 1878. 1701.
 0. 600. 626.
 0.0

BLADDER 8 OF 10

12-8

```

0 1 1 1 1 1 100011
0 1 1 1 3 1 010101
PR 1 1 1 2 2 1 1 49.878 0. 0. -1. c downward pressure (g/mm-sec2)
c 0.2in. M20

MATE 1 c Epoxy-Gillifab 1040 (G-10)
LCT 8 : c repeat the part 8 times
M2 -100. : M2 -80. :
M2 -80. : M2 -20. :
M2 10. : M2 40. : M2 70. : M2 100. :
LREP 1 2 3 4 5 6 7 8 : c use the 8 clones

END

START c sandwich panel skins (internal gap-bottom)
1 13 15 : 1 13 15 : -1 :
0. 1878. 1701.
0. 600. 825.
0. 0
0 1 1 1 1 3 1 100011
0 1 1 1 3 1 1 010101
PR 1 1 1 2 2 1 1 49.878 0. 0. 1. c upward pressure (g/mm-sec2)
c 0.2in. M20

MATE 1 c Epoxy-Gillifab 1040 (G-10)
LCT 8 : c repeat the part 8 times
M2 -100. : M2 -70. : M2 -40. : M2 -10. :
M2 20. : M2 80. :
M2 80. : M2 100. :
LREP 1 2 3 4 5 6 7 8 : c use the 8 clones

END

START c sandwich panel frames
1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0. 0 20.
0 1 1 1 2 2 2 c remove the honeycomb region
MATE 4 c epoxy MC filler
LCT 7 : M2 -100. : M2 -70. : M2 -40. : M2 -10. : M2 20. : M2 80. : M2 80. :
LREP 1 2 3 4 5 6 7 : c repeat the part 7 times

END

START c bladder sandwich panel frames
1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0. 0 10.
0 1 1 1 2 2 2 c remove the honeycomb region
MATE 4 c epoxy MC filler
LCT 2 : M2 -115. : M2 105. :
LREP 1 2 : c repeat the part 2 times

END

START c gap frames
1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0. 0 10.
0 1 1 1 2 2 2 c remove wire gap region
MATE 2 c Epoxy-Gillifab 1040 (G-10)
LCT 8 : M2 -80. : M2 -50. : M2 -20. : M2 10. : M2 40. : M2 70. :
LREP 1 2 3 4 5 6 : c repeat the part 6 times

```

END

BLADDER

9 OF 10

```

START c bladder gap frames
1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0. 0 5.
0 1 1 1 2 2 2 c remove wire gap region
MATE 2 c Epoxy-Gillifab 1040 (G-10)
LCT 2 : M2 -105. : M2 100. :
LREP 1 2 : c repeat the part 2 times

END

START c sandwich panel honeycomb
1 13 : 1 13 : 1 2 :
0. 1878.
0. 600.
0. 0 20.
MATE 3 c MMH-10-1/8-1.8 (honeycomb)
LCT 7 : M2 -100. : M2 -70. : M2 -40. : M2 -10. : M2 20. : M2 80. : M2 80. :
LREP 1 2 3 4 5 6 7 : c duplicate 7 times

END

START c bladder sandwich panel honeycomb
1 13 : 1 13 : 1 2 :
0. 1878.
0. 600.
0. 0 10.
MATE 3 c MMH-10-1/8-1.8 (honeycomb)
LCT 2 : M2 -115. : M2 105. :
LREP 1 2 : c duplicate 2 times

END

BEAM c spacer posts
rt 000000 0. 0. -100.
rt 000000 0. 0. -80.
rt 000000 0. 0. -70.
rt 000000 0. 0. -60.
rt 000000 0. 0. -40.
rt 000000 0. 0. -20.
rt 000000 0. 0. -10.
rt 000000 0. 0. 10.
rt 000000 0. 0. 20.
rt 000000 0. 0. 40.
rt 000000 0. 0. 60.
rt 000000 0. 0. 70.
rt 000000 0. 0. 80.
rt 000000 0. 0. 100.
rt 000000 838. 0. -100.
rt 000000 838. 0. -80.
rt 000000 838. 0. -70.
rt 000000 838. 0. -60.
rt 000000 838. 0. -40.
rt 000000 838. 0. -20.
rt 000000 838. 0. -10.
rt 000000 838. 0. 10.
rt 000000 838. 0. 20.
rt 000000 838. 0. 40.
rt 000000 838. 0. 60.
rt 000000 838. 0. 70.

rt 000000 838. 0. 80.
rt 000000 838. 0. 100.
0 c end of coordinate specification
1 2 1 5 1 20
2 3 1 5 1 20
3 4 1 5 1 20
4 5 1 5 1 20
5 6 1 5 1 20
6 7 1 5 1 20
7 8 1 5 1 20
8 9 1 5 1 20
9 10 1 5 1 20
10 11 1 5 1 20
11 12 1 5 1 20
12 13 1 5 1 20
13 14 1 5 1 20
14 15 1 5 1 1
15 16 1 5 1 1
16 17 1 5 1 1
17 18 1 5 1 1
18 19 1 5 1 1
19 20 1 5 1 1
20 21 1 5 1 1
21 22 1 5 1 1
22 23 1 5 1 1
23 24 1 5 1 1
24 25 1 5 1 1
25 26 1 5 1 1
26 27 1 5 1 1
27 28 1 5 1 1
0 c end of element generation

END

```

BLADDER

10 OF 10

END

DIRECTORY: .41762 / CSC PRESSURE / 3POST BASE 2

BASLINE 2 (WITH 3 SPACER POSTS)

0.2" H₂O
0.007 psi
SD P₄

CSC outer - 0.2" H₂O pressure (25mm epoxy frame),
time = 0.10000E+01

INTERNAL POSTS ONLY
NO PLENUM

3POST BASE 2

1 of 8

CSC outer - 0.2" H₂O pressure (25mm epoxy frame)
time = 0.10000E+01

3POST BASE 2
2 of 8

CSC outer - 0.2" H₂O pressure (25mm epoxy frame)
time = 0.10000E+01

3 POST BASE 2
3 of 8

(DISP. MAG. = 1,000)

disp. scale factor = 0.180E+04

CSC outer - 0.2" H₂O pressure (25mm epoxy frame)
time = 0.10000E+01

0.2" H₂O INTERNAL PRESSURE
(0.007213 psi)
(49.876 gmm/mm²/mm)
(49.876 Pa)

3 POST BASE 2
4 of 8

(DISP. MAG. = 5,000)

disp. scale factor = 0.580E+04

3 POST BASEZ 5 OF 8

```

CSC outer - 4.2" H2O pressure (25mm epoxy frame)
c file capprae
c Quarter-symmetry model
c Baseline-2 with three spacer posts
c This file is used to generate NIKE3D input.

c Ingrid input for CSC outer superlayer chamber
c 6 wire layers
c l=3402mm w=1250mm h=200mm
c edge frame w=25mm
c end frame w=25mm
c sandwich panels (7) t=20mm (10mm core + 0.5mm skins)
c gaps (6) t=10mm

c Procedure for UNICOB:
c Ingrid i=Infile          run Ingrid
c   slp 0.1                merge nodes
c   continue               make NIKE3D input
c   mv Ingrid outfile.1    change name
c   vi outfile.1           edit cscb2.1
c   card:field value comments
c   1:1 5 only print last step to hsp
c   2:1 90 percent of core
c   3:2 3 buffer size
c   4:4 1 storage option in core
c   5:0 1 incompatible modes for bricks
c   6:0 1 shell geometric stiffness flag
c   change boundary conditions
c   node 171 (code 0) x,z trans. fixed

Box 048 horvath
lv 1
NIKE3D          o generate NIKE3D input
ANAL STAT      o static analysis
NSTEP 4        o number of time steps
DELT 2.000e-01 o time step size

o six-step load curve
LCD 1 0 0.0 0.0 0.2 0.05 0.4 0.1 0.6 0.2 0.8 0.4 1.0 1.0

o GRAV          o 1g in z-direction (normal to panel)
c 0.0 0.0 9.81480e+03

MAT 1 1 SHELL o Epoxy-Billfab 1040 (0-10)
E 2.2010e+10 o g-mm/sec2/mm2 (3.3e+06 psi)
PR 0.20      o poisson's ratio
RHO 1.0202e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
THICK 0.5    o mm thickness
ENDMAT

MAT 2 1      o Epoxy-Billfab 1040 (0-10)
E 2.2010e+10 o g-mm/sec2/mm2 (3.3e+06 psi)
PR 0.20      o poisson's ratio
RHO 1.0202e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENDMAT

MAT 3 2 c MM-10-1/0-1.0 (honeycomb)
EC 5.6310e+07 o g-mm/sec2/mm2 (8.0e+03 lb/in2)
EA 5.6310e+02 o g-mm/sec2/mm2 (e-06 softer)
EB 5.6310e+02 o g-mm/sec2/mm2 (e-06 softer)

```

3 POST BASEZ 6 OF 8

```

DAB 1.0372e-02 o g-mm/sec2/mm2 (e-06 softer)
GBC 1.0372e+07 o g-mm/sec2/mm2 (1.0e+03 lb/in2)
GCA 2.8270e+07 o g-mm/sec2/mm2 (3.0e+03 lb/in2)
PRCA 0.3       o Poisson-rs
PRCB 0.3       o Poisson-rs
RHO 2.0004e-06 o g/mm3 (1.0 lb/ft3)
ADPT 2.0       o globally orthotropic definition
A1 1.0         o x for a-vector
A2 0.0         o y for a-vector
A3 0.0         o z for a-vector
D1 0.0         o x for d-vector
D2 1.0         o y for d-vector
D3 0.0         o z for d-vector
ENDMAT

MAT 4 1        o epoxy HC filler
E 2.7000e+09   o g-mm/sec2/mm2 or GPa (0.4e+06 psi)
PR 0.20       o poisson's ratio
RHO 1.1000e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENDMAT

MAT 5 1        o epoxy center spacer qtr-posts
BEAM           o invokes collapsed thin shell formulation
E 2.7000e+09   o g-mm/sec2/mm2 or GPa (0.4e+06 psi)
PR 0.20       o poisson's ratio
RHO 1.1000e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
sthi 2.5      o outer dimension in s-direction/2 at ctr.n (mm)
tthi 2.5      o outer dimension in t-direction (mm)
ENDMAT

MAT 6 1        o epoxy spacer half-posts
BEAM           o invokes collapsed thin shell formulation
E 2.7000e+09   o g-mm/sec2/mm2 or GPa (0.4e+06 psi)
PR 0.20       o poisson's ratio
RHO 1.1000e-03 o g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
sthi 2.5      o outer dimension in s-direction (mm)
tthi 5.0      o outer dimension in t-direction (mm)
ENDMAT

START c sandwich panel skins (external i.e. no pressure)
1 13 16 : 1 13 16 : -1 :
0. 1070. 1701.
0. 600. 620.
0.0
0 1 1 1 1 3 1 100011
0 1 1 1 3 1 1 010101
MATE 1 c Epoxy-Billfab 1040 (0-10)
LCT 2 : c repeat the part 2 times
M2 100. : M2 100. :
LREP 1 2 : c use the 2 clones
END

START c sandwich panel skins (internal gap-top)
1 13 16 : 1 13 16 : -1 :
0. 1070. 1701.
0. 600. 620.
0.0
0 1 1 1 1 3 1 100011
0 1 1 1 3 1 1 010101

```

12-11

3POST BASE2 7 OF 8

```

PR 1 1 1 1 1 1 49.078 0. 0. -1. c downward pressure (g/mm-sec2)
c 0.2in. H2O
MATE 1 c Epoxy-Gliffab 1040 (0-10)
LCY 0 : c repeat the part 0 times
MZ -50. : MZ -20. : MZ 70. :
MZ 10. : MZ 40. : MZ 70. :
LREP 1 2 3 4 5 6 : c use the 6 clones
END

START c sandwich panel skins (internal gap-bottom)
1 13 16 : 1 13 16 : -1 :
0. 1078. 1701.
0. 000. 025.
0. 0
0 1 1 1 1 3 1 100011
0 1 1 1 3 1 1 010101
PR 1 1 1 2 2 1 1 49.078 0. 0. 1. c upward pressure (g/mm-sec2)
c 0.2in. H2O
MATE 1 c Epoxy-Gliffab 1040 (0-10)
LCY 0 : c repeat the part 0 times
MZ -70. : MZ -40. : MZ -10. :
MZ 20. : MZ 50. :
MZ 80. :
LREP 1 2 3 4 5 6 : c use the 6 clones
END

START c sandwich panel frames
1 13 16 : 1 13 16 : 1 2 :
0. 1078. 1701.
0. 000. 025.
0. 0 20.
0 1 1 1 2 2 2 c remove the honeycomb region
MATE 4 c epoxy HC filler
LCY 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c repeat the part 7 times
END

START c gap frames
1 13 16 : 1 13 16 : 1 2 :
0. 1078. 1701.
0. 000. 025.
0. 0 10.
0 1 1 1 2 2 2 c remove extra gap region
MATE 2 c Epoxy-Gliffab 1040 (0-10)
LCY 0 : MZ -50. : MZ -20. : MZ -10. : MZ 10. : MZ 40. : MZ 70. :
LREP 1 2 3 4 5 6 : c repeat the part 6 times
END

START c sandwich panel honeycomb
1 13 : 1 13 : 1 2 :
0. 1078.
0. 000.
0. 0 20.
MATE 3 c MMH-10-170-1.0 (honeycomb)
LCY 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c duplicate 7 times
END

SEAM c spacer posts

```

3POST BASE2 8 OF 8

```

r1 000000 0. 0. -100.
r1 000000 0. 0. -80.
r1 000000 0. 0. -70.
r1 000000 0. 0. -60.
r1 000000 0. 0. -50.
r1 000000 0. 0. -40.
r1 000000 0. 0. -30.
r1 000000 0. 0. -20.
r1 000000 0. 0. -10.
r1 000000 0. 0. 0.
r1 000000 0. 0. 10.
r1 000000 0. 0. 20.
r1 000000 0. 0. 30.
r1 000000 0. 0. 40.
r1 000000 0. 0. 50.
r1 000000 0. 0. 60.
r1 000000 0. 0. 70.
r1 000000 0. 0. 80.
r1 000000 0. 0. 90.
r1 000000 0. 0. 100.
r1 000000 030. 0. -100.
r1 000000 030. 0. -80.
r1 000000 030. 0. -70.
r1 000000 030. 0. -60.
r1 000000 030. 0. -50.
r1 000000 030. 0. -40.
r1 000000 030. 0. -30.
r1 000000 030. 0. -20.
r1 000000 030. 0. -10.
r1 000000 030. 0. 0.
r1 000000 030. 0. 10.
r1 000000 030. 0. 20.
r1 000000 030. 0. 30.
r1 000000 030. 0. 40.
r1 000000 030. 0. 50.
r1 000000 030. 0. 60.
r1 000000 030. 0. 70.
r1 000000 030. 0. 80.
r1 000000 030. 0. 90.
r1 000000 030. 0. 100.
0 c end of coordinate specification
1 2 1 0 1 20
2 3 1 0 1 20
3 4 1 0 1 20
4 5 1 0 1 20
5 6 1 0 1 20
6 7 1 0 1 20
7 8 1 0 1 20
8 9 1 0 1 20
9 10 1 0 1 20
10 11 1 0 1 20
11 12 1 0 1 20
12 13 1 0 1 20
13 14 1 0 1 20
14 15 1 0 1 1
15 16 1 0 1 1
16 17 1 0 1 1
17 18 1 0 1 1
18 19 1 0 1 1
19 20 1 0 1 1
20 21 1 0 1 1
21 22 1 0 1 1
22 23 1 0 1 1
23 24 1 0 1 1
24 25 1 0 1 1
25 26 1 0 1 1
26 27 1 0 1 1
27 28 1 0 1 1
0 c end of element generation
END

```

12-12

DIRECTORY: 411762 / CSC PRESSURE / NO POST BASE 2

MODIFIED BASELINE 2 W/O SPARK POSTS

0.2" H₂O
0.007 psi
50 Pa

CSC outer - 0.2" H₂O pressure (25mm epoxy frame)
time = 0.10000E+01

NO INTERNAL POSTS
NO PLENUM

NOPOSTBASE2
1 OF 7

(DISPLACEMENT MAGNIFICATION
FACTOR = 1,000)

CSC outer - 0.2" H₂O pressure (25mm epoxy frame)
time = 0.10000E+01

NOPOSTBASE2
2 OF 7

(DISP. MAG. = 1,000)

CSC outer - 0.2' H₂O pressure (23mm epoxy frame)
time = 0.10000E+01

NO POSTBASE 2
3 of 7

(DISP. MAG. = 1,000)

disp. scale factor = 0.100E+04

12-15

NOPOSTBASE2 4 OF 7

```

CSC outer = 1.0" H2O pressure (25mm epoxy frame)
c file cepsrnp
c Quarter-symmetry model
c Baseline-2 with three spacer posts
c This file is used to generate NIKE3D input.

c Ingrid input for CSC outer superlayer chamber
c 6 wire layers
c l=3402mm w=1250mm h=200mm
c edge frame w=25mm
c end frame w=25mm
c sandwich panels (7) t=20mm (18mm core + 0.5mm skins)
c gaps (8) t=10mm

c Procedure for UNICOS:
c Ingrid i=infile          run Ingrid
c   stp 0.1                merge nodes
c   continue               make NIKE3D input
c   mv Ingrid.outfile.i    change name
c   vi outfile.i           edit cscb2.i
c   card:field value comments
c   5:1 5 only print last step to hsp
c   5:1 90 percent of core
c   5:3 3 buffer size
c   5:4 1 storage option in core
c   5:5 1 incompatible modes for bricks
c   5:6 1 shell geometric stiffness flag
c   change boundary conditions
c   node 171 (code 8) x,z trans. fixed

box s48 horvath
lv 1
MK3D          c generate NIKE3D input
ANAL STAT    c static analysis
NSTEP 4       c number of time steps
DELT 2.500e-01 c time step size

c six-step load curve
LCD 1 8 0.0 0.0 0.2 0.05 0.4 0.1 0.6 0.2 0.8 0.4 1.0 1.0
c GRAV          c 1g in z-direction (normal to panel)
c 0.0 0.0 9.81458e+03

MAT 1 1 SHELL    c Epoxy-Gilifab 1040 (G-10)
E 2.2819e+10    c g-mm/sec2/mm2 (3.3e+08 psi)
PR 0.28         c poisson's ratio
RHO 1.9282e-03  c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
THICK 0.5       c mm thickness
ENDMAT

MAT 2 1          c Epoxy-Gilifab 1040 (G-10)
E 2.2819e+10    c g-mm/sec2/mm2 (3.3e+08 psi)
PR 0.28         c poisson's ratio
RHO 1.9282e-03  c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENDMAT

MAT 3 2 c HRH-10-1/8-1.8 (honeycomb)
EC 8.6319e+07   c g-mm/sec2/mm2 (8.0e+03 lb/in2)
EA 8.6319e+02   c g-mm/sec2/mm2 (e-06 softer)
EB 8.6319e+02   c g-mm/sec2/mm2 (e-06 softer)

```

NOPOSTBASE2 5 OF 7

```

GAB 1.0372e-02 c g-mm/sec2/mm2 (e-06 softer)
GBC 1.0372e+07 c g-mm/sec2/mm2 (1.8e+03 lb/in2)
GCA 2.8276e+07 c g-mm/sec2/mm2 (3.8e+03 lb/in2)
PRBA 0.3        c Poisson-ba
PRCA 0.3        c Poisson-ca
PRCB 0.3        c Poisson-cb
RHO 2.8894e-05  c g/mm3 (1.8 lb/ft3)
ADPT 2.0        c globally orthotropic definition
A1 1.0          c x for a-vector
A2 0.0          c y for a-vector
A3 0.0          c z for a-vector
D1 0.0          c x for d-vector
D2 1.0          c y for d-vector
D3 0.0          c z for d-vector
ENDMAT

MAT 4 1          c epoxy HC filler
E 2.7800e+09    c g-mm/sec2/mm2 or GPa (0.4e+08 psi)
PR 0.28         c poisson's ratio
RHO 1.1800e-03  c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENMAT

MAT 5 1          c epoxy center spacer qtr-posts
c invokes collapsed thin shell formulation
E 2.7800e+09    c g-mm/sec2/mm2 or GPa (0.4e+08 psi)
PR 0.28         c poisson's ratio
RHO 1.1800e-03  c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
sthi 2.5        c outer dimension in s-direction/2 at ctr.n (mm)
tthi 2.5        c outer dimension in t-direction (mm)
ENDMAT

MAT 6 1          c epoxy spacer half-posts
c invokes collapsed thin shell formulation
E 2.7800e+09    c g-mm/sec2/mm2 or GPa (0.4e+08 psi)
PR 0.28         c poisson's ratio
RHO 1.1800e-03  c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
sthi 2.5        c outer dimension in s-direction (mm)
tthi 5.0        c outer dimension in t-direction (mm)
ENDMAT

START c sandwich panel skins (external i.e. no pressure)
1 13 15 : 1 13 15 : -1 ;
0. 1878. 1701.
0. 600. 625.
0.0
B 1 1 1 1 3 1 100011
B 1 1 1 3 1 1 010101
MATE 1 c Epoxy-Gilifab 1040 (G-10)
LCY 2 : c repeat the part 2 times
M2 -100. : M2 100. :
LREP 1 2 : c use the 2 clones
END

START c sandwich panel skins (internal gap-top)
1 13 15 : 1 13 15 : -1 ;
0. 1878. 1701.
0. 600. 625.
0.0
B 1 1 1 1 3 1 100011
B 1 1 1 3 1 1 010101

```

NOPOSTBASE2 6 OF 7

PR 1 1 1 1 1 1 49.878 0. 0. -1. c downward pressure (g/mm-sec2)
c 0.2in. H2O

MATE 1 c Epoxy-Gillifab 1040 (G-10)

LCT 6 : c repeat the part 6 times

MZ -80. :
MZ -60. : MZ -20. :
MZ 10. : MZ 40. : MZ 70. :
LREP 1 2 3 4 5 6 : c use the 6 clones

END

START c sandwich panel skins (internal gap-bottom)

1 13 15 : 1 13 15 : -1 :
0. 1878. 1701.
0. 600. 825.
0.0

8 1 1 1 1 3 1 100011
8 1 1 1 3 1 1 010101

PR 1 1 1 2 2 1 1 49.878 0. 0. 1. c upward pressure (g/mm-sec2)
c 0.2in. H2O

MATE 1 c Epoxy-Gillifab 1040 (G-10)

LCT 6 : c repeat the part 6 times

MZ -70. : MZ -40. : MZ -10. :
MZ 20. : MZ 50. :
MZ 80. :
LREP 1 2 3 4 5 6 : c use the 6 clones

END

START c sandwich panel frames

1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0.0 20.
D 1 1 1 2 2 2 c remove the honeycomb region

MATE 4 c epoxy MC filler

LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c repeat the part 7 times

END

START c gap frames

1 13 15 : 1 13 15 : 1 2 :
0. 1878. 1701.
0. 600. 825.
0.0 10.
D 1 1 1 2 2 2 c remove wire gap region

MATE 2 c Epoxy-Gillifab 1040 (G-10)

LCT 6 : MZ -80. : MZ -60. : MZ -20. : MZ 10. : MZ 40. : MZ 70. :
LREP 1 2 3 4 5 6 : c repeat the part 6 times

END

START c sandwich panel honeycomb

1 13 : 1 13 : 1 2 :
0. 1878.
0. 600.
0.0 20.
MATE 3 c HRH-10-1/8-1.8 (honeycomb)

LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c duplicate 7 times

END

[c do not include spacer posts

NOPOSTBASE2 7 OF 7

BEAM c spac. posts

rt 000000 0. 0. -100.
rt 000000 0. 0. -80.
rt 000000 0. 0. -70.
rt 000000 0. 0. -60.
rt 000000 0. 0. -40.
rt 000000 0. 0. -20.
rt 000000 0. 0. -10.
rt 000000 0. 0. 10.
rt 000000 0. 0. 20.
rt 000000 0. 0. 40.
rt 000000 0. 0. 60.
rt 000000 0. 0. 70.
rt 000000 0. 0. 80.
rt 000000 0. 0. 100.
rt 000000 838. 0. -100.
rt 000000 838. 0. -80.
rt 000000 838. 0. -70.
rt 000000 838. 0. -60.
rt 000000 838. 0. -40.
rt 000000 838. 0. -20.
rt 000000 838. 0. -10.
rt 000000 838. 0. 10.
rt 000000 838. 0. 20.
rt 000000 838. 0. 40.
rt 000000 838. 0. 60.
rt 000000 838. 0. 70.
rt 000000 838. 0. 80.
rt 000000 838. 0. 100.
0 c end of coordinate specification

1 2 1 5 1 28
2 3 1 5 1 28
3 4 1 5 1 28
4 5 1 5 1 28
5 6 1 5 1 28
6 7 1 5 1 28
7 8 1 5 1 28
8 9 1 5 1 28
9 10 1 5 1 28
10 11 1 5 1 28
11 12 1 5 1 28
12 13 1 5 1 28
13 14 1 5 1 28
15 16 1 5 1 1
16 17 1 5 1 1
17 18 1 5 1 1
18 19 1 5 1 1
19 20 1 5 1 1
20 21 1 5 1 1
21 22 1 5 1 1
22 23 1 5 1 1
23 24 1 5 1 1
24 25 1 5 1 1
25 26 1 5 1 1
26 27 1 5 1 1
27 28 1 5 1 1
0 c end of element generation

END

] c do not include spacer posts

END

12-16

ASSUMPTION:
SIMPLE SUPPORT ON
ALL 4 EDGES.

(PRESSURE
1/3)

SIMPLY SUPPORTED PLATE

UNIFORM PRESSURE LOAD

$$\text{DEFLECTION } \delta = \frac{2 K_1 p b^4 \lambda}{E_f t_f h^2}$$

WHERE, K_1 IS FROM FIG. 8
 p = PRESSURE
 b = WIDTH
 $\lambda = 1 - \mu^2$
 E_f = FILING MODULUS
 t_f = FILING THICKNESS
 h = CENTROID DIST.
 $R = G_b / G_a$
 G_b = SHEAR MOD b
 G_a = SHEAR MOD a
 $G_c = G_a$

TO READ K_1 FROM FIG. 8 CALCULATE b/a , R AND V ,

$$b = 137.8/4$$

$$b = 34.45$$

$$\frac{b}{a} = \frac{137.8/4}{51.2}$$

$$\frac{b}{a} = 0.673$$

(NOMEX)
 FOR HRH-10-1/8-1.8, $G_b = 3.8 \times 10^3 \text{ PSI}$
 $R = \frac{G_b}{G_a} = \frac{3.8 \times 10^3}{1.5 \times 10^3}$
 $R = 2.5$
 $G_a = 1.5 \times 10^3 \text{ PSI}$

$$V = \frac{\pi^2 E_f t_f h^2}{2 b^2 h G_c \lambda}$$

$$V = \frac{\pi^2 (3.3 \times 10^6) (0.0197) (0.384^2)}{2 (34.45^2) (0.384) (1.5 \times 10^3) (0.89)}$$

$$V = 0.078$$

FOR G10 FACING,
 $E_f = 3.3 \times 10^6 \text{ PSI}$
 $t_f = 0.0197 \text{ in}$
 $G_c = G_a = 1.5 \times 10^3 \text{ PSI}$
 $\lambda = (1 - \mu^2) = (1 - 0.33^2) = 0.89$
 $h = 0.384 \text{ in}$

FROM FIG. 8, $K_1 = 0.0075$

$$\delta = \frac{2 (0.0075) (p) (34.45^4) (0.89)}{(3.3 \times 10^6) (0.0197) (0.384^2)}$$

$$\delta = 1.9615 p$$

FOR $p = 0.2" \text{ H}_2\text{O} = (0.2) \left(\frac{0.036065 \text{ psi}}{\text{in H}_2\text{O}} \right)$
 $p = 0.0072 \text{ psi}$

$$\therefore \delta = 1.9615 (0.0072)$$

$$\delta = 0.01412" \quad (0.359 \text{ mm})$$

REF. HEXCEL TSB-124

MAX. DEFLECTION AT CENTER
 DUE TO PRESSURE

(ACTUAL WILL BE LESS DUE TO 3 FIXED EDGES!)

Sample Problems

B. Simply Supported Plate (from MIL HDBK-23)

SANDWICH PANEL BULGE (PRESSURE)
UNDER UNIFORM PRESSURE LOAD 2/3
(REF. HEXCEL TSB-124)

SAMPLE ASSUMES AD JOSE H.C. CORE

1. Determine Plate Coefficients:

$$\frac{b}{a} = \frac{48}{96} = 0.50$$

$$R = \frac{G_b}{G_a} = \frac{43,000}{21,200} = 2.03$$

USE $R = 2.5$ (see Figure 8)

$$V = \frac{\pi^2 E_f t_f h^2}{2b^2 h G_c \lambda}$$

$$V = \frac{\pi^2 (10.1 \times 10^6) (0.020) (1.020)^2}{2 (48)^2 (1.020) (21,200) (0.89)} = 0.023$$

FROM FIGURE 8 $K_1 = 0.0105$

FIGURE 9 $K_2 = 0.103$

FIGURE 10 $K_3 = 0.37$

2. Check Panel Deflection:

$$\Delta = \frac{2K_1 p b^4 \lambda}{E_f t_f h^2}$$

$$\Delta = \frac{2(0.0105)(0.139)(48)^4 (0.89)}{(10.1 \times 10^6) (0.020) (1.020)^2} = 0.066$$

3. Check Facing Stress:

$$\sigma_f = \frac{K_2 p b^2}{h t_f} = \frac{(0.103)(0.139)(48)^2}{(1.020)(0.020)} = 1,617 \text{ psi}$$

$$\text{F.S.} = \frac{24,000}{1,617} = 14.8$$

4. Check Core Shear Stress:

$$\tau_c^w = \frac{K_3 p b}{h} = \frac{(0.37)(0.139)(48)}{1.020} = 2.42 \text{ psi}$$

$$\text{F.S.} = \frac{85(0.93)^*}{2.42} = 32.7$$

*Correction Factor for 1" Thick Al. H/C, TSB 120

5. Check Facing Dimpling:

$$\sigma_{cr} = \frac{2E_f}{\lambda} \left[\frac{t_f}{s} \right]^2$$

$$\sigma_{cr} = \frac{2(10.1 \times 10^6)}{0.89} \left[\frac{0.020}{0.375} \right]^2 = 64,560 \text{ psi}$$

64,560 psi > 24,000 $\therefore$ NOT CRITICAL!

6. Check Facing Wrinkling:

$$\sigma_{cr} = 0.82 E_f \left[\frac{E_c t_f}{E_f t_c} \right]^{1/2}$$

$$\sigma_{cr} = 0.82 (10.1 \times 10^6) \left[\frac{(70,000)(0.020)}{(10.1 \times 10^6)(1.000)} \right]^{1/2} = 97,500 \text{ psi}$$

97,500 psi > 24,000 $\therefore$ NOT CRITICAL!

7. Check Factor-of-Safety:

MINIMUM F.S. (FACE YIELDING) = 14.8

12-18

(PRESSURE)
3/3

Figure 8 -- K_1 , for determining maximum deflection, Δ , of flat rectangular sandwich panels $a > b$

Figure 9 -- K_2 , for determining facing stress, σ_f , of flat rectangular sandwich panels $a > b$

Figure 10 -- K_3 , for determining core shear stress, τ_c , for flat rectangular sandwich panels $a > b$

JAH 5/20/93

TENSION ROD:

HIGH STRENGTH
NOT NEEDED
IF PLENUM
IS USED.

SPACER POSTS:

WOULD ONLY
BE USED TO
MAINTAIN
C-TO-C GAP.

SINCE NO
PRESSURE LOAD
WOULD BE CARRIED,
TENSILE LOAD
IS MINIMAL
AND CONSTANT.

SANDWICH PANEL

CATHODE

ANODE WIRES

SPACER POST

CATHODE

SANDWICH PANEL

TENSILE ROD
12-20

13. Chamber Mode Shapes and Natural Frequencies

Contents:

Summary of TDR chamber natural frequencies (1 page)

TDR chamber with G10 frame, outer superlayer, details of mode shapes (7 pages)

TDR chamber with G10 frame, middle superlayer, details of mode shapes (7 pages)

TDR chamber with G10 frame, inner superlayer, details of mode shapes (7 pages)

TDR chamber with epoxy frame, outer superlayer, details of mode shapes (6 pages)

Summary:

Natural frequencies of 3.5m long chambers tend to be low due to their length and limited thickness (limited by overlap of chambers and maximum muon track lever arm). The limited thickness produces a low stiffness. Adding mass to increase stiffness also produces particle scattering and thus should be avoided.

Changing the "frame" material from relatively "stiff" G10 to "soft" epoxy reduces the lowest natural frequency by 25% due to loss of shear stiffness in the chamber. This linkage between frame design and chamber stiffness is documented in GEM TN-93-460, *Comparison of Gap Frame Designs and Materials for Precision Cathode Strip Chambers*.

Bare Panel^{*} Natural Frequencies Begin At 19 hz

^{*} NO ADDED MASS FOR ELECTRONICS AND UTILITIES (VALUES WOULD DROP SLIGHTLY)

mode #	frequency (hz) for first six modes					
	1	2	3	4	5	6
outer superlayer	20.6	22.4	30.0	57.4	61.3	63.8
middle superlayer	28.9	38.9	45.6	90.3	90.6	92.0
inner superlayer	19.7	32.0	66.8	77.6	83.4	113.7

- Bare panels are sandwich panels, edge fillers, and gap frames.
(Not included are detector wires, copper plating, circuit boards, gas pipe, heat sinks, bolts, cables, or connectors.)
- Bare panel frequencies are within 5% of loaded panel values.
The effect of added mass is estimated using the expression for a spring/mass system.

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{M}}$$

An increase in chamber mass of 10% will decrease the natural frequency by 5%.

Outer Superlayer Chamber: First Six Modes

{ DIRECTORY .411762/CSCBASE2/KINEMODE/OUTEREND
KINEMATIC SUPPORT AT ENDS
12.5mm SOLID G10 FRAME ASSUMED

CSC outer superlayer (12.5mm frame)
time = 0.12917E+03

20.6 hz

disp. scale factor = 0.500E+01 (default)

CSC outer superlayer (12.5mm frame)
time = 0.14059E+03

22.4 hz

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer (12.5mm frame)
time = 0.16079E+03

30.0 hz

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer (12.5mm frame)
time = 0.26042E+03

57.4 hz

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer (12.5mm frame)
time = 0.30030E+03

61.3 hz

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer (12.5mm frame)
time = 0.40081E+03

63.8 hz

disp. scale factor = 0.100E+01 (default)

13-3

outer 10F7

DIRS: 2Y
 .911762/CSCBASE2
 /KINEMODE/OUTEREND

(KINEMATIC
 SUPPORT)

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

CSC Outer Support Layer 112 Run Frame
 Time = 0.147917E+00

Stop: Mesh Factor = 0.000000E+00

OUTER 2 of 7

SL-3
 MODE 1

20.6 kg

OUTER 3 of 7

SL-3
 MODE 2

22.4 kg

13-4

Q32 outer super layer 112.5m frame
 1km = 0.00000145

Q32 outer super layer 112.5m frame
 1km = 0.00000145

Q32 outer super layer 112.5m frame
 1km = 0.00000145

Q32 outer super layer 112.5m frame
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Q32 outer super layer 112.5m frame
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Q32 outer super layer 112.5m frame
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Q32 outer super layer 112.5m frame
 1km = 0.00000145

Q32 outer super layer 112.5m frame
 1km = 0.00000145

OUTER

SL-3 6.57
 MODE 5
 61.3 kg

OUTER 7.07

SL-3
 MODE 6
 63.8 kg

13-6

Middle Superlayer Chamber: First Six Modes

{ DIRECTORY .41762 / CSCBASEZ / KINEMODE / MIDDLEND
KINEMATIC SUPPORT AT ENDS
12.5mm SOLID G10 FRAME ASSUMED

CSC middle superlayer (12.5mm frame)
time = 0.10162E+00

28.9 hz

disp. scale factor = 0.100E+01 (default)

13-7

CSC middle superlayer (12.5mm frame)
time = 0.20462E+00

38.9 hz

disp. scale factor = 0.100E+01 (default)

CSC middle superlayer (12.5mm frame)
time = 0.20627E+00

45.6 hz

disp. scale factor = 0.100E+01 (default)

CSC middle superlayer (12.5mm frame)
time = 0.90766E+00

90.3 hz

disp. scale factor = 0.100E+01 (default)

CSC middle superlayer (12.5mm frame)
time = 0.90906E+00

90.6 hz

disp. scale factor = 0.100E+01 (default)

CSC middle superlayer (12.5mm frame)
time = 0.92776E+00

92.0 hz

disp. scale factor = 0.100E+01 (default)

MIDDLE 1057

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

SL-2
MODE 3

MIDDLE 4 of 7

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

CMC middle super layer (12.5mm frame)
time = 0.00000000

Stop scale factor = 0.000000000000000000

SL-2
MODE 4

MIDDLE 5 of 7

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

SL-2
MODE 5

MIDDLE 6 of 7

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

CEC middle super layer 132.0km frame!
time = 0.00000000

stop scale factor = 0.000000000000000000

SL-2
MODE 6

MIDDLE 7 of 7

Inner Superlayer Chamber: First Six Modes

DIRECTORY .411762 / CSCBASE2 / KINEMODE / INNEREND
 { KINEMATIC MOUNTS AT ENDS
 12.5mm SOLID G10 FRAME ASSUMED

CSC inner superlayer 112.5mm frame!
 time = 0.12400E+00

19.7 hz

disp. scale factor = 0.100E+01 (default)

CSC inner superlayer 112.5mm frame!
 time = 0.20000E+00

32.0 hz

disp. scale factor = 0.100E+01 (default)

CSC inner superlayer 112.5mm frame!
 time = 0.41974E+00

66.8 hz

disp. scale factor = 0.100E+01 (default)

CSC inner superlayer 112.5mm frame!
 time = 0.48726E+00

77.6 hz

disp. scale factor = 0.100E+01 (default)

CSC inner superlayer 112.5mm frame!
 time = 0.52000E+00

83.4 hz

disp. scale factor = 0.100E+01 (default)

CSC inner superlayer 112.5mm frame!
 time = 0.71110E+00

113.7 hz

disp. scale factor = 0.100E+01 (default)

INNER
 (G10 FRAME)
 1 OF 7

END Inner super layer 112.5m frame!
Time = 0.124000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.124000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.124000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.124000e+00

stop scale factor = 0.000001e+00

SL-1
MODE 1

INNER 2 of 7
(410 FRAME)

END Inner super layer 112.5m frame!
Time = 0.000000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.000000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.000000e+00

stop scale factor = 0.000001e+00

END Inner super layer 112.5m frame!
Time = 0.000000e+00

stop scale factor = 0.000001e+00

SL-1
MODE 2

INNER 3 of 7
(410 FRAME)

13-12

CSC Inner Super Layer 110.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

INNER 4 of 7
(GID FRAME)

SL-1
MODE 3

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

CSC Inner Super Layer 112.0m Frame
Time = 0.01974E+00

Stop scale factor = 0.100E+01 (default)

INNER 5 of 7
(GID FRAME)

SL-1
MODE 4

13-13

 

MODE 6
SL-1

ALL INFORMATION CONTAINED
HEREIN IS UNCLASSIFIED
DATE 01-10-2011 BY 60322

100-361014-0 - 0091
100-361014-0 - 0091

1944 - 1945
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2616 - 2617
2618 - 2619
2620 - 2621
2622 - 2623
2624 - 2625
26

100-251014-0 - 100-1
100-251014-0 - 100-1

SL-1
MODE 5

1. The first step is to identify the problem or question that needs to be answered. This involves understanding the context and the specific information required.

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DATE 08-11-2010 BY 60322 UCBAW

100-388619-0 - 0011
100-388619-0 - 0011

 

DIRECTORY: 411762/CSC BASE3/MODNOFIL
(SOFT EDGE FILLER IN H.C.)
i.e. EPOXY FRAME

CSC outer superlayer base3 (25mm frame)
time = 0.97019E+02

1
15.6 kg

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer base3 (25mm frame)
time = 0.11295E+03

2
17.9 kg

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer base3 (25mm frame)
time = 0.22544E+03

3
35.9 kg

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer base3 (25mm frame)
time = 0.23219E+03

4
37.0 kg

disp. scale factor = 0.100E+01 (default)

CSC outer superlayer base3 (25mm frame)
time = 0.23226E+03

5
37.0 kg

disp. scale factor = 0.100E+01 (default)

 

CHI outer super layer covered (2000 ft deep)
1000 - 2000 ft deep

100-443887-100

EPOXY
FRAME

SL-3

MODE 1

EXPOS FRAME 2 OF 6

 

[illegible]

 

also scale factor = 0 (see 4b) (unusable)

U.S. GOVERNMENT PRINTING OFFICE: 1969 O 344-000

١٤٤٥

EPoxy
FRAME

SL-3

MODE 2

EXPIRY FRAME 3 of 6

13-16

THE author gratefully thanks (Name of person)
(last + 0. 2070-02-100)

1. dispute factor : 0 TIME @ 1000000

Call center support hours: 8am - 6pm
Mon - Fri 9am - 4pm

step. could feature a 5.5mm x 10mm

THE above paper layer must be (2)mm to mm
(max = 0.25mm)

١٤٠٠

Cite order: 1000-1000 (1000-1000)
 (1000 - 1000)

stop scale factor = 0.000001 default

EPOXY
FRAME

SL-3
MODE 3

EXPER FRAME 4 of 6

SEE WATER SUPPLY MAP SHEET 17000 11-000
11-000 = 0.225141-000

Stop waste paper • © 1988 All rights reserved

FBI Denver Supply Center based 1/2 hour from
 home - 8.820101-00

L.

Drop table factor = 8-1000000000000000

THE UNITED STATES DEPARTMENT OF JUSTICE
WASHINGTON, D. C. 20535

1 pencil in
unison

1

FOR OFFICIAL USE ONLY (When Filled)
FORM NO. 10-10-10-10-10

100-443887-100

EPOXY
FRAME

9L-3
MODE 4

EPoxy FRAME 5076

001 meter super layer based 100m frame
time = 0.00000000

stop state factor = 0.00000000

001 meter super layer based 100m frame
time = 0.00000000

stop state factor = 0.00000000

001 meter super layer based 100m frame
time = 0.00000000

stop state factor = 0.00000000

1 meter aperture
(pic is small
element)

001 meter super layer based 100m frame
time = 0.00000000

stop state factor = 0.00000000

EPOXY
FRAME

SL-3

MODE 5

EPOXY FRAME OF 6

14. Chamber Twist

Contents:

- Summary of results and requirements for TDR Baseline (3 pages)
- Analysis of chamber twist due to an applied force-couple (3 pages)
- Calculation of chamber torsional rigidity from applied torque and observed twist (4 pages)
- Description of finite element analysis model (4 pages)
- Edge straightness for 4-corner support with imposed 1mm corner displacement (2 pages)

Summary:

An applied torque produces a twist value. This information produces torsional rigidity values for each superlayer chamber which can be used to predict chamber twist for various mounting orientations and offsets of the center of gravity.

TDR Baseline chambers were extremely stiff in torsion due to their continuous side frame which formed a closed section beam.

When all four corners are supported in z (quasi-kinematic) and a 1mm displacement is imposed on one corner, the long edges remain straight to within 2 microns.

From: John Horvath (6/10/93)
To: Curt Belser

CHAMBER
TWIST

Subject: chamber twist summary Time: 7:43 AM
Date: 6/10/93
OFFICE MEMO
Curt. Here are individual chamber twist values (one row of 3 fids w/t the opposite row of 3 fids on a chamber) and torsional stiffness values (the "EJ" term in $\alpha = TL / (EJ)$) for the 3 o'clock position in the barrel:

position	EJ (kg m ² /sec ²)	alpha (mradians)
outer (SL-3)	1.104e+09	0.69
middle (SL-2)	0.871e+09	0.50
inner (SL-1)	0.497e+09	0.79

Here are the relative twist values w/t (SL-1) compared to the allowables as set out in Mitselmakher & Ostapchuk's GEN TN-93-333 ("Alignment Requirements for the GEN Nuon System"):

location	predicted R _z	allowable R _z
(SL-3) w/t (SL-1)	1.29 mrad	± 3 mrad
(SL-2) w/t (SL-1)	1.48 mrad	± 5 mrad

Chamber twist can be reduced by several methods:

1. reduce chamber mass (I am assuming conservatively high values of 500lb/415lb/300lb for SL-1, 2, & 3 respectively).
2. bring chamber cg closer to bracket connection face (i.e. put electronics and utilities on bracket support side of chamber.)
3. increase chamber torsional rigidity (already very good).

2 of 3

SUMMARY:

	EJ ($\frac{\text{kg m}^2}{\text{sec}^2}$)	α (m RAD)	
OUTER	1.104×10^9	0.69	SL-3
MIDDLE	0.87144×10^9	0.50	SL-2
INNER	0.4977×10^9	0.79	SL-1

INNER TOWER

$$\text{REL } R_z(\text{SL-2}) = R_z(\text{SL-2}) + R_z(\text{SL-1}) = 0.50 + 0.79 = 1.29 \text{ mrad}$$

$$\text{TOTAL } R_z(\text{SL-3}) = R_z(\text{SL-3}) + R_z(\text{SL-1}) = 0.69 + 0.79 = 1.48 \text{ mrad}$$

OUTER TOWER

$$\text{REL } R_z(\text{SL-2}) = R_z(\text{SL-2}) - R_z(\text{SL-1}) = 0.50 - 0.79 = -0.29 \text{ mrad}$$

$$\text{TOTAL } R_z(\text{SL-3}) = R_z(\text{SL-3}) + R_z(\text{SL-1}) = 0.69 + 0.79 = 1.48 \text{ mrad}$$

	(R _z)	
	PREDICTED	ALLOWABLE
SL-2	1.29 mRAD	± 3 mRAD
SL-3	1.48 mRAD	± 5 mRAD

Alignment Requirements for the GEM Muon System

REF. GEM TN-93-333Table 2: The local alignment requirements ($\sigma_z^{out} = 30mm$)

Factor	Parameter	Requirement	σ_{align}^i	
Monitor resolution and	σ_{mon}	25μ		
Monitor positioning	$\sigma_{\phi}^{inn,out}$	20μ		
	σ_{ϕ}^{mid}	10μ		
Monitor defocusing	$Dist_x^{IP}$	$30mm$		
	$Dist_y^{IP}$	$30mm$	10μ	
	$Dist_z^{IP}$	$30mm$		
Superlayers positioning	D_x^{mid}	$\pm 1.5mm$		
	D_y^{mid}	$\pm 1.5mm$		
	D_z^{mid}	$\pm 1.5mm$		
	R_x^{mid}	$\pm 1mrad$		
	R_y^{mid}	$\pm 1mrad$		
	R_z^{mid}	$\pm 3mrad$	12μ	
	D_x^{out}	$\pm 3mm$		
	D_y^{out}	$\pm 3mm$		
	D_z^{out}	$\pm 3mm$		
	R_x^{out}	$\pm 1.5mrad$		
Chamber non-flatness	R_y^{out}	$\pm 1.5mrad$		
	R_z^{out}	$\pm 5mrad$		
Total	σ_{flat}	100μ	10μ	
	Sag_{max}	200μ		
Total	σ_{align}^{tot}	25μ	21μ	

} w/ft base

DIRECTORY:

.411762 / C/SCTWIST / TOUTPIL

SL-3

1 OF 3

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

$$\lambda = \frac{.00236 + .00223}{2} = .00230 \text{ mm}$$

(FOR 10³ Kg COUPLE)

DIRECTORY:

.411762 / C/SCTWIST / TMIDDLE

SL-2

2 OF 3

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

$$\lambda = \frac{0.00163 + 0.00171}{2} = 0.00167 \text{ mm}$$

FOR 10³ Kg COUPLE

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

CSE motor based (175mm spring frame)
Time = 0.100000 (s)

L

Step scale factor = 0.100000

DIRECTORY

41762 / CSC TWIST / T100RR
SL-1

3 OF 3

100RR
CSC TWIST TWIST (100mm square frame)
Time = 0.00000001

CSC TWIST TWIST (100mm square frame)
Time = 0.00000001

L
Step scale factor = 0.00000001

L
Step scale factor = 0.00000001

$$d = \frac{0.00234 + 0.00184}{2}$$

$$= 0.00209 \text{ mm}$$

CSC TWIST TWIST (100mm square frame)
Time = 0.00000001

CSC TWIST TWIST (100mm square frame)
Time = 0.00000001

FOR 10³ Kg COUPLE

L
Step scale factor = 0.00000001

L
Step scale factor = 0.00000001

RESULTS OF
 $\lambda = \frac{0.00136 \pm 0.00233}{2}$
 $\lambda = 0.00230$

DIR: 41762 / CSC TWIST / TOUTER

$\alpha = \tan^{-1} \left(\frac{0.00230}{1.225} \right) = 3.747 \times 10^{-5} \text{ RAD}$
 TORQUE = $(1.0 \times 10^{-6} \frac{\text{mm}}{\text{sec}}) (1.225 \text{ mm})$
 $= 1.225 \times 10^{-9} \frac{\text{mm}^2}{\text{sec}}$

ANGLE OF TWIST = $\alpha = \frac{TL}{EJ}$ WHERE $E = \text{MODULUS OF ELASTICITY}$
 $J = \text{TOP. MOM. OF INERTIA}$

LET $EJ = \text{TORSIONAL RESISTANCE}$

$(EJ)_{\text{outer}} = \frac{TL}{\alpha}$

$(EJ)_{\text{outer}} = \frac{(1.225 \times 10^{-9} \frac{\text{mm}^2}{\text{sec}}) (3.747 \text{ mm})}{3.747 \times 10^{-5} \text{ RAD}}$

$(EJ)_{\text{outer}} = 1.104 \times 10^{-18} \frac{\text{mm}^3}{\text{sec}^2}$

$\therefore \alpha_{\text{outer}} = \frac{TL}{1.104 \times 10^{-18} \text{ RAD}}$

OUTER CSC TWIST -

BOUNDARY FORCE
 $F = 500 \text{ LB (230 Kg)}$
 (ASSUMED CSC WT.)

$\alpha_{\text{outer}} = \frac{TL}{1.104 \times 10^{-18} \text{ RAD}}$
 $\alpha_{\text{outer}} = \frac{(230 \times 10^3 \text{ N}) (9.81456 \times 10^{-3} \text{ m}) (100 \text{ mm}) (3.747 \text{ mm})}{1.104 \times 10^{-18}}$

$\alpha_{\text{outer}} = 0.00069 \text{ RAD}$

$\alpha_{\text{outer}} = 0.69 \text{ m RAD}$

OUTER CHAMBER TWIST (UNPAID)

MIDDLE CSC TORSIONAL RIGIDITY

FROM FEM MODEL (DIR: 411762/CSC TWT/TMIDDLE)

$$J = \frac{0.00163 + 0.00171}{2}$$

$$J = 0.00167$$

$$\alpha = \tan^{-1} \left(\frac{0.00167}{1079/2} \right)$$

$$\alpha = 3.09546 \times 10^{-5} \text{ RAD}$$

$$= 0.00018 \text{ DEG}$$

$$\text{TORQUE} = (1.0 \times 10^3 \frac{\text{mm}^2}{\text{mm}}) \left(\frac{1079}{\text{mm}} \right)$$

$$T = 1.079 \times 10^3 \frac{\text{mm}^2}{\text{mm}}$$

$$\text{ANGLE OF TWIST } \alpha = \frac{(EJ)_{\text{MIDDLE}}}{TL}$$

$$\frac{\alpha}{TL} = (EJ)_{\text{MIDDLE}}$$

$$(EJ)_{\text{MIDDLE}} = \frac{3.09546 \times 10^{-5} \text{ RAD}}{(1.079 \times 10^3 \frac{\text{mm}^2}{\text{mm}})} \left(\frac{2560}{\text{mm}} \right)$$

$$(EJ)_{\text{MIDDLE}} = 8.71438 \times 10^{17} \frac{\text{mm}^2}{\text{mm}}$$

$$\therefore \alpha_{\text{MIDDLE}} = \frac{TL}{8.71438 \times 10^{17} \text{ RADIAN}}$$

$$\alpha_{\text{MIDDLE}} = 0.00050 \text{ RADIAN}$$

$$= 0.50 \text{ m RAD}$$

3 OF 4

INNER CSC TORSIONAL RIGIDITY

FROM FEM MODEL (DIR: 411762/CSC TWT/TINNER)

$$J = \frac{0.00234 + 0.00184}{2}$$

$$J = 0.00209$$

$$\alpha = \text{ANGLE OF TWIST} = \tan^{-1} \left(\frac{0.00209}{711/2} \right)$$

$$\alpha = 5.4215 \times 10^{-5} \text{ RAD}$$

$$= 0.00031 \text{ DEG}$$

$$\text{TORQUE} = (1.0 \times 10^3 \frac{\text{mm}^2}{\text{mm}}) \left(\frac{711}{\text{mm}} \right)$$

$$= 0.711 \times 10^3 \frac{\text{mm}^2}{\text{mm}}$$

$$\text{ANGLE OF TWIST } \alpha = \frac{(EJ)_{\text{INNER}}}{TL}$$

$$\frac{\alpha}{TL} = (EJ)_{\text{INNER}}$$

$$(EJ)_{\text{INNER}} = \frac{5.4215 \times 10^{-5} \text{ RAD}}{(0.711 \times 10^3 \frac{\text{mm}^2}{\text{mm}})} \left(\frac{3500}{\text{mm}} \right)$$

$$(EJ)_{\text{INNER}} = 4.9774 \times 10^{17} \frac{\text{mm}^2}{\text{mm}}$$

$$\therefore \alpha_{\text{INNER}} = \frac{TL}{4.9774 \times 10^{17} \text{ RADIAN}}$$

$$\alpha_{\text{INNER}} = 0.00079 \text{ RAD}$$

$$= 0.79 \text{ m RAD}$$

4 OF 4

CSC BASE 3

REV. 1

ANALYSIS MODEL
DESCRIPTION

1 OF 4

TORONTER

CSC outer superlayer base3 (12.5mm frame)
INGRID nodes

1	3	19	21	23	25	27	29	31	33	35	37	39	41	127
2	4	20	22	24	26	28	30	32	34	36	38	40	42	128
5		11	43	49	55	61	67	73	79	85	91	97	103	109 129
6		12	44	50	56	62	68	74	80	86	92	98	104	110 130
7		13	45	51	57	63	69	75	81	87	93	99	105	111 131
8		14	46	52	58	64	70	76	82	88	94	100	106	112 132
9		15	47	53	59	65	71	77	83	89	95	101	107	113 133
10		16	48	54	60	66	72	78	84	90	96	102	108	114 134
17	18		115	116	117	118	119	120	121	122	123	124	125	126 135

TOROUTER 2 OF 4

```

CSC outer be: (25mm epoxy frame)
c file torouter baseline-2 (rev 1)
c Revised kinematic mounts.
c Revised for nodes on centerlines.
c This file is used to generate NIKE3D input.

c Ingrid input for CSC outer superlayer chamber
c 8 wire layers
c l=3402mm w=1250mm h=200mm
c edge frame w=25mm
c end frame w=25mm
c sandwich panels (7) t=20mm (19mm core + 0.5mm skins)
c gaps (6) t=10mm

c Procedure for UNICOS:
c   Ingrid i=infile          run Ingrid
c   stp 0.1                  merge nodes
c   continue                  make NIKE3D input
c   mv ingrid.o outfile.1    change name
c   vi outfile.1              edit cscb2.1
c   card:field value comments
c   4:3 2 concentrated nodal loads NMACL
c   4:1 5 only print last step to hsp
c   4:3 30 percent of core
c   4:4 3 buffer size
c   4:5 1 storage option in core
c   4:6 1 incompatible nodes for bricks
c   4:8 1 shell geometric stiffness flag
c   change boundary conditions
c   node 4 (code 7) x,y,z trans. fixed/all rot. free
c   node 18 (code 7) x,y,z trans. fixed/all rot. free
c   add point loads
c .....12345678901234567890123456
c   42 3 1.000e+08 } CoAs
c   114 3 1-1.000e+08

box s48 horvath
iv 1
NIKE3D
ANAL STAT c generate NIKE3D input
NSTEP 4 c static analysis
DELT 2.600e-01 c number of time steps
c time step size

c six-step load curve
LCD 1 6 0.0 0.0 0.2 0.05 0.4 0.1 0.6 0.2 0.8 0.4 1.0 1.0

c turn off gravity (OFF)
c GRAV c 1g in z-direction (normal to panel)
c 0.0 0.0 9.81450e+03

MAT 1 1 SHELL c Epoxy-Gilifab 1040 (G-10)
E 2.2819e+10 c g-mm/sec2/mm2 (3.3e+06 psi)
PR 0.26 c poisson's ratio
RH0 1.8262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
THICK 0.5 c mm thickness
ENDMAT

MAT 2 1 c Epoxy-Gilifab 1040 (G-10)
E 2.2819e+10 c g-mm/sec2/mm2 (3.3e+06 psi)
PR 0.26 c poisson's ratio

```

TOROUTER 3 OF 4

```

RH0 1.8262e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENDMAT

MAT 3 2 c HRH-10-1/8-1.8 (honeycomb)
EC 5.8319e+02 c g-mm/sec2/mm2 (8.0e+03 lb/in2)
EA 5.8319e+02 c g-mm/sec2/mm2 (n-95 softer)
EB 5.8319e+02 c g-mm/sec2/mm2 (n-95 softer)
GAB 1.0372e+02 c g-mm/sec2/mm2 (n-95 softer)
GBC 1.0372e+07 c g-mm/sec2/mm2 (1.5e+03 lb/in2)
GCA 2.6276e+07 c g-mm/sec2/mm2 (3.8e+03 lb/in2)
PRBA 0.3 c Poisson-ba
PRCA 0.3 c Poisson-ca
PRCB 0.3 c Poisson-cb
RH0 2.8894e-06 c g/mm3 (1.8 lb/ft3)
ADPT 2.0 c globally orthotropic definition
A1 1.0 c x for a-vector
A2 0.0 c y for a-vector
A3 0.0 c z for a-vector
D1 0.0 c x for d-vector
D2 1.0 c y for d-vector
D3 0.0 c z for d-vector
ENDMAT

```

```

MAT 4 1 c epoxy HC filler
E 2.7800e+06 c g-mm/sec2/mm2 or GPa (0.4e+06 psi)
PR 0.26 c poisson's ratio
RH0 1.8800e-03 c g/mm3 (120 lb/ft3 = 0.01 lb/ft2/MIL)
ENDMAT

```

```

START c sandwich panel skins
1 2 14 15 : 1 2 8 9 : -1 :
-1701. -1678. 1678. 1701.
-825. -800. 800. 825.
0.0
MATE 1 c Epoxy-Gilifab 1040 (G-10)
LCT 14 : c repeat the part 14 times
MZ -100. : MZ -80. :
MZ -70. : MZ -60. : MZ -50. : MZ -40. : MZ -30. : MZ -20. : MZ -10. :
MZ 10. : MZ 20. : MZ 30. : MZ 40. : MZ 50. : MZ 60. : MZ 70. :
MZ 80. : MZ 100. :
LREP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 : c use the 14 clones
END

```

```

START c sandwich panel frames
1 2 14 15 : 1 2 8 9 : 1 2 :
-1701. -1678. 1678. 1701.
-825. -800. 800. 825.
0.0 20.
0 2 2 1 3 3 2 c remove the honeycomb region
MATE 4 c epoxy HC filler
LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c repeat the part 7 times
END

```

```

START c gap frames
1 2 14 15 : 1 2 8 9 : 1 2 :
-1701. -1678. 1678. 1701.
-825. -800. 800. 825.
0.0 10.
0 2 2 1 3 3 2 c remove wire gap region

```

TOROUTER 4 OF 4

```

MATE 2 c Epoxy-Gilifab 1040 (G-10)
LCT 6 : MZ -80. : MZ -60. : MZ -40. : MZ -20. : MZ 10. : MZ 40. : MZ 70. :
LREP 1 2 3 4 5 6 : c repeat the part 6 times
END

START c sandwich panel honeycomb
1 13 : 1 7 : 1 2 :
-1678. 1678.
-800. 800.
0.0 20.
MATE 3 c HRH-10-1/8-1.8 (honeycomb)
LCT 7 : MZ -100. : MZ -70. : MZ -40. : MZ -10. : MZ 20. : MZ 50. : MZ 80. :
LREP 1 2 3 4 5 6 7 : c duplicate 7 times
END

```

DIRECTORY:

.41762/CSC SUPPT/CSC BVS+C

2 MOURD

1 2 TRAN, FIXED

16 114

7, 8, 2 TRAN
FIXED

5, 6 TRAN FIXED

CSC SL-3 4-point support
time = 0.10000E+01

QUASI-KINEMATIC SUPPORT
PROPOSED BY S.G. & H.

1mm FORCED CORNER DISPLACEMENT
ALL OTHER CORNERS HELD DOWN IN Z

disp. scale factor = 0.100E+03

CSC SL-3 4-point support
time = 0.10000E+01

disp. scale factor = 0.100E+03

Long-Edge Displacement Deviation from Linear
vs. Normalized Long-Edge Location
for SL-3 (Outer) Chamber
with 1mm Imposed Corner Displacement

file: cornerdispc
jah 7/21/93

15. Copper-On-Mylar Cathodes

Contents:

Summary viewgraph for SL-3 CSC with Cu-on-mylar cathodes (1 page)

Deflection as a function of mylar thickness for 5 μ and 7 μ copper cathodes (1 page)

Spreadsheet bending analyses showing mass distribution (2 pages)

Summary:

Copper-on-mylar cathodes have very little effect on chamber gravity sag.

The thickness of the mylar and adhesive must be accounted for in determining cathode-to-cathode gap size.

Only the precision cathodes need to be copper-on-mylar since the coarse cathodes do not have precise etched patterns.

Structural Effects of Mylar/Cu Cathodes *

1 of 1

Minor structural effects of mylar/Cu cathodes

SL-3

- 5.4% increase in bending deflection (for outer superlayer CSC)
- 4.3% increase in chamber mass (for outer superlayer CSC)

component	mass added		% carried
	(kg)	(%)	
500μ G10 panel skins	62.8	38.9	80.5
glass/epoxy gap frame	27.7	17.2	6.8
epoxy edge filler	19.4	12.1	9.0
5μ copper cathode	2.1	1.3	2.2
100μ mylar film	7.0	4.3	1.5
honeycomb core	17.2	10.7	0.0
hardware & utilities	25.0	15.5	0.0

- Mylar-to-G10 adhesive also adds small amount of mass
- Consider using mylar/copper material on precise cathodes only

* HARRY VAN DER GRAAF MATERIAL, REF. GEM TN-93-268

Chamber Design Workshop August 27, 1993

J.A. Horvath

1 of 1

jah 8/28/93
file: mylar.delta

15-2

SL-3 bending sag using 17-micron Cu cathodes (TDR Baseline)

shaded denotes input value

	metric	English (in, lb)
chamber w (mm)	1330	52.362
chamber length (mm)	3500	137.795
sandwich h (mm)	20	0.787
sandwich face (mm)	0.5	0.020
gap h (mm)	10	0.394
gap frame w (mm)	25	0.984
core frame w (mm)	25	0.984
extension w (mm)	0	0.000
extension h (mm)	0	0.000
Cu plating w (mm)	1200	47.244
precise cath. cvr. (%)	85.6	
coarse cath. cvr. (%)	100	
Cu plating l (mm)	0.017	0.001
prec.cath.substr. l (mm)	0.000	0.000
crs.cath.substr. l (mm)	0.000	0.000
hardware+utilities (g)	25000	55.0

(rel=0.017
0.005 w/mylar)

allowable material choices	E (psi)	E (MPa)	density (lb/in3)	density (g/cm3)
MAT1 G10 laminate	3,300,000	22,759	0.069	1.0264
MAT2 glass-fiber/epoxy	1,600,000	11,034	0.067	1.85
MAT3 C-fiber/epoxy (FR-337)	5,000,000	34,483	0.060	1.66
MAT4 aluminum	10,000,000	68,966	0.098	2.718
MAT5 copper	18,000,000	124,138	0.322	8.9317
MAT6 epoxy (F 954-3) 350F	400,000	2,759	0.043	1.19
MAT7 ultra-low density	100,000	690	0.015	0.42
MAT8 syntactic (CG 1617-A)	350,000	2,414	0.025	0.7
MAT9 mylar	550,000	3,793	0.050	1.3889
MAT10 nomex @ 1.8lb/ft3	0	0	0.001041673	0.028894

composition	component	% of total wt.	% of tot. carried	%carried-%wt.	mass (kg)
MAT2 glass-fiber/epoxy	gap frame	12.2	8.6	-3.6	19.43
MAT6 epoxy (F 954-3) 350F	core edge filler	17.4	6.6	-10.8	27.70
MAT4 aluminum	extensions	0.0	0.0	0.0	0.00
MAT1 G10 laminate	sandwich skins	39.4	77.5	38.1	62.77
MAT10 nomex @ 1.8lb/ft3	sandwich core	10.8	0.0	-10.8	17.22
MAT5 copper	cathode planes	4.5	7.3	2.8	7.10
MAT9 mylar	cath. substrate	0.0	0.0	0.0	0.00
	hddr + util	15.7	0.0	-15.7	25.00
totals =		100.0	100.0	0.0	159.21
					weight (lb) = 350.3

chamber h (mm)	200.0
sandwich w (mm)	1330.0
core w (mm)	1280.0
core h (mm)	19.0
mode-1 freq. = 18.5 hertz	

	sandwich skins	gap frame	core edge filler	extensions	sandwich core	cathode	cathode substrate	Totals	
sum Eln.a. =	7.829E+11	8.717E+10	6.659E+10	0.000E+00	0.000E+00	7.375E+10	0.000E+00	1.010E+12	(Mpa mm^4)
ln.a. =	3.440E+07	7.900E+06	2.414E+07	0.000E+00	0.000E+00	5.941E+05	0.000E+00	6.704E+07	(mm^4)
weight/l =	0.1755	0.0543	0.0774	0.0000	0.0481	0.0199	0.0000	0.3752	(N/mm)
mass/l =	17.9348	5.5500	7.9135	0.0000	4.9189	2.0291	0.0000	38.35	(g/mm)
length =	3,500	3,500	3,500	3,500	3,500	3,500	3,500	---	(mm)
E =	22,759	11,034	2,759	68,966	0	124,138	3,793	233,448	(MPa)
mass density =	0.001926	0.001850	0.001190	0.002718	0.000029	0.008932	0.001387	0.018032	(g/mm^3)
wt. density =	1.885E-05	1.810E-05	1.164E-05	2.660E-05	2.827E-07	8.740E-05	1.357E-05	1.765E-04	(N/mm^3)
displacement =	0.726	0.726	0.726	0.000	(dead load)	0.726	0.000	---	(mm)
sum Eln.a. =	2.727E+08	3.037E+07	2.320E+07	0.000E+00	0.000E+00	2.569E+07	0.000E+00	3.520E+08	(lb in^2)
ln.a. =	82.65	18.98	58.00	0.00	0.00	1.43	0.00	161.05	(in^4)
weight/l =	1.00	0.31	0.44	0.00	0.27	0.11	0.00	2.14	(lb/in)
mass/l =	2.594E-03	8.026E-04	1.144E-03	0.000E+00	7.114E-04	2.934E-04	0.000E+00	5.546E-03	(lb sec^2/in)
length =	137.80	137.80	137.80	137.80	137.80	137.80	137.80	---	(in)
E =	3,300,000	1,600,000	400,000	10,000,000	0	18,000,000	550,000	---	(lb/in^2)
mass density =	1.797E-04	1.726E-04	1.110E-04	2.536E-04	2.696E-06	8.333E-04	1.294E-04	1.682E-03	(lb sec^2/in^4)
wt. density =	0.069	0.067	0.043	0.098	0.001	0.322	0.050	0.650	(lb/in^3)
displacement =	28.58	28.58	28.58	0.00	(dead load)	28.58	0.00	---	(mils)
sum A =	9.3100E+03	3.0000E+03	6.6500E+03	0.0000E+00	1.7024E+05	2.2717E+02	0.0000E+00	1.894E+05	(mm^2)
sum Ay =	9.3100E+05	3.0000E+05	6.6500E+05	0.0000E+00	1.7024E+07	2.2717E+04	0.0000E+00	---	(mm^3)
Yna=sum AY/sum A =	1.0000E+02	1.0000E+02	1.0000E+02	0.0000E+00	1.0000E+02	1.0000E+02	0.0000E+00	---	(mm)
sum AY^2 =	1.2750E+08	3.7875E+07	9.0440E+07	0.0000E+00	2.3153E+09	2.8658E+06	0.0000E+00	2.574E+09	(mm^4)
Yna.*AY =	9.3100E+07	3.0000E+07	6.6500E+07	0.0000E+00	1.7024E+09	2.2717E+06	0.0000E+00	---	(mm^4)
sum Ioo =	1.9396E+02	2.5000E+04	2.0005E+05	0.0000E+00	5.1214E+06	5.4711E-03	0.0000E+00	5.347E+06	(mm^4)
AY^2-Yna.*AY =	3.4401E+07	7.8750E+06	2.3940E+07	0.0000E+00	6.1286E+08	5.9407E+05	0.0000E+00	---	(mm^4)
section Ioo =	3.4401E+07	7.9000E+06	2.4140E+07	0.0000E+00	6.1799E+08	5.9407E+05	0.0000E+00	6.850E+08	(mm^4)

1 OF 2

TDR
BASELINE
17A Cu

15-3

SL-3 bending sag using 5-micron Cu cathodes on 100-micron mylar substrates

shaded denotes input value

	metric	English (in, lb)
chamber w (mm)	1330	52.362
chamber length (mm)	3500	137.795
sandwich h (mm)	20	0.787
sandwich face (mm)	0.5	0.020
gap h (mm)	10	0.394
gap frame w (mm)	25	0.984
core frame w (mm)	25	0.984
extension w (mm)	0	0.000
extension h (mm)	0	0.000
Cu plating w (mm)	1200	47.244
precise cath. cvr. (%)	85.8	
coarse cath. cvr. (%)	100	
Cu plating t (mm)	0.005	0.000
prec.cath.substr. t (mm)	0.100	0.004
crs.cath.substr. t (mm)	0.100	0.004
hardware+utilities (g)	25000	55.0

(ref=0.017
0.005 w/mylar)

allowable material choices	E (psi)	E (MPa)	density (lb/in ³)	density (g/cm ³)
MAT1 G10 laminate	3,300,000	22,759	0.069	1.9264
MAT2 glass-fiber/epoxy	1,600,000	11,034	0.067	1.85
MAT3 C-fiber/epoxy (FR-337)	5,000,000	34,483	0.060	1.66
MAT4 aluminum	10,000,000	68,966	0.098	2.718
MAT5 copper	18,000,000	124,138	0.322	8.9317
MAT6 epoxy (F 954-3) 350F	400,000	2,759	0.043	1.19
MAT7 ultra-low density	100,000	690	0.015	0.42
MAT8 syntactic (CG 1617-A)	350,000	2,414	0.025	0.7
MAT9 mylar	550,000	3,793	0.050	1.3889
MAT10 nomex @ 1.8lb/ft ³	0	0	0.001041673	0.028894

composition	component	% of total wt.	% of tot. carried	%carried-%wt.	mass (kg)
MAT2 glass-fiber/epoxy	gap frame	12.1	9.0	-3.1	19.43
MAT6 epoxy (F 954-3) 350F	core edge filler	17.2	6.8	-10.3	27.70
MAT4 aluminum	extensions	0.0	0.0	0.0	0.00
MAT1 G10 laminate	sandwich skins	38.9	80.5	41.5	62.77
MAT10 nomex @ 1.8lb/ft ³	sandwich core	10.7	0.0	-10.7	17.22
MAT5 copper	cathode planes	1.3	2.2	0.9	2.09
MAT9 mylar	cath. substrate	4.3	1.5	-2.8	6.99
	htrdr + util	15.5	0.0	-15.5	25.00
	totals =	100.0	100.0	0.0	161.19

weight (lb) = 354.6

chamber h (mm)	200.0
sandwich w (mm)	1330.0
core w (mm)	1280.0
core h (mm)	19.0
mode-1 freq. =	18.0 hertz

	sandwich skins	gap frame	core edge filler	extensions	sandwich core	cathode	cathode substrate	Totals	
sum Eln.a. =	7.829E+11	8.717E+10	6.659E+10	0.000E+00	0.000E+00	2.169E+10	1.447E+10	9.728E+11	(Mpa mm ⁴)
ln.a. =	3.440E+07	7.900E+06	2.414E+07	0.000E+00	0.000E+00	1.747E+05	3.815E+06	7.043E+07	(mm ⁴)
weight/l =	0.1755	0.0543	0.0774	0.0000	0.0481	0.0058	0.0195	0.3808	(N/mm)
mass/l =	17.9348	5.5500	7.9135	0.0000	4.9189	0.5968	1.9971	38.91	(g/mm)
length =	3,500	3,500	3,500	3,500	3,500	3,500	3,500	---	(mm)
E =	22,759	11,034	2,759	68,966	0	124,138	3,793	233,448	(MPa)
mass density =	0.001926	0.001850	0.001190	0.002718	0.000029	0.008932	0.001387	0.018032	(g/mm ³)
wt. density =	1.885E-05	1.810E-05	1.164E-05	2.660E-05	2.827E-07	8.740E-05	1.357E-05	1.765E-04	(N/mm ³)
displacement =	0.765	0.765	0.765	0.000	(dead load)	0.765	0.765	---	(mm)
sum Eln.a. =	2.727E+08	3.037E+07	2.320E+07	0.000E+00	0.000E+00	7.555E+06	5.041E+06	3.389E+08	(lb in ²)
ln.a. =	82.65	18.98	58.00	0.00	0.00	0.42	9.17	169.21	(in ⁴)
weight/l =	1.00	0.31	0.44	0.00	0.27	0.03	0.11	2.17	(lb/in)
mass/l =	2.594E-03	8.026E-04	1.144E-03	0.000E+00	7.114E-04	8.630E-05	2.888E-04	5.627E-03	(lb sec ² /in)
length =	137.80	137.80	137.80	137.80	137.80	137.80	137.80	---	(in)
E =	3,300,000	1,600,000	400,000	10,000,000	0	18,000,000	550,000	---	(lb/in ²)
mass density =	1.797E-04	1.726E-04	1.110E-04	2.536E-04	2.696E-06	8.333E-04	1.294E-04	1.682E-03	(lb sec ² /in ⁴)
wt. density =	0.069	0.067	0.043	0.098	0.001	0.322	0.050	0.650	(lb/in ³)
displacement =	30.12	30.12	30.12	0.00	(dead load)	30.12	30.12	---	(mils)
sum A =	9.3100E+03	3.0000E+03	6.6500E+03	0.0000E+00	1.7024E+05	6.6816E+01	1.4400E+03	1.907E+05	(mm ²)
sum Ay =	9.3100E+05	3.0000E+05	6.6500E+05	0.0000E+00	1.7024E+07	6.6816E+03	1.4400E+05	---	(mm ³)
Yna=sum AY/sum A =	1.0000E+02	1.0000E+02	1.0000E+02	0.0000E+00	1.0000E+02	1.0000E+02	1.0000E+02	---	(mm)
sum AY^2 =	1.2750E+08	3.7875E+07	9.0440E+07	0.0000E+00	2.3153E+09	8.4287E+05	1.8215E+07	2.590E+09	(mm ⁴)
Yna.*AY =	9.3100E+07	3.0000E+07	6.6500E+07	0.0000E+00	1.7024E+09	6.6816E+05	1.4400E+07	---	(mm ⁴)
sum Ioo =	1.9396E+02	2.5000E+04	2.0005E+05	0.0000E+00	5.1214E+06	1.3920E-04	1.2000E+00	5.347E+06	(mm ⁴)
AY^2-Yna.*AY =	3.4401E+07	7.8750E+06	2.3940E+07	0.0000E+00	6.1286E+08	1.7471E+05	3.8153E+06	---	(mm ⁴)
section Ioo =	3.4401E+07	7.9000E+06	2.4140E+07	0.0000E+00	6.1799E+08	1.7471E+05	3.8153E+06	6.884E+08	(mm ⁴)

"ideal chamber" v4.0

2 of 2
5 μ Cu
+ 100 μ Mylar

16. Miscellaneous 4-Gap CSC Finite Element Analyses

Contents:

No frame on long edges, frame on ends only (2 pages)

No sandwich core material, frames on all edges (2 pages)

Support along ends and along one long edge (2 pages)

Massless solid "post" added to center of chamber (3 pages)

12.5mm wide G-10 frame, skin thickness = 0.5mm (2 pages)

25.0mm wide G-10 frame, skin thickness = 0.5mm (2 pages)

25.0mm wide G-10 frame, skin thickness = 1.0mm (2 pages)

Baseline 4-gap CSC analysis using non-linear NIKE3D analysis code (2 pages)

Baseline 4-gap CSC analysis using linear GEMINI analysis code (2 pages)

Summary:

Various extreme conditions are explored in order to develop an understanding of the relative importance of components or support conditions.

Non-linear analysis using NIKE3D allows the prediction of membrane sag of 0.5mm G-10 skins without sandwich cores, providing an upper limit to the effect of skin-to-core bond failure. Supporting along one edge gives an upper limit to the effect of chamber "pairing" in phi. Varying parameters such as frame width and skin thickness provide insight into the sensitivity of gravity sag to these values.

CSC 3000x1289x140 J.H. no frame
time = 1.00000e+00

disp. scale factor = 1.000e+02

CSC 3000x1289x140 J.H. no frame
time = 1.00000e+00

disp. scale factor = 1.000e+02

CSC 3000x1289x140 J.H. no frame
time = 1.00000e+00

4-GAP CSC

NO FRAME ON LONG EDGES
FRAME ON ENDS ONLY

disp. scale factor = 1.000e+02

CSC 3000x1289x140 J.H. no frame
time = 1.00000e+00

disp. scale factor = 1.000e+02

NO SIDE FRAME
1/2

16-2

1 file:
 2 readme
 3
 4 directory:
 5 .411762:csc:noedge[all.]
 6
 7 objective:
 8 Test effect of quasi-kinematic mount on overall deflections.
 9 Remove side frames and observe change in deflection pattern.
 10 Compare with 25mm and 12.5mm wide frames to study shear coupling.
 11
 12 Quasi-kinematic mount (4 points in z)
 13 node 1: x y z displacement restrained (code 7)
 14 node 15: x z displacement restrained (code 6)
 15 node 113: z displacement restrained (code 3)
 16 node 120: z displacement restrained (code 3)
 17 skin thickness = 0.5mm
 18 3500mm x 1289mm x 140mm
 19 4 gaps @ 10mm, 5 panels @ 20mm
 20
 21 observations:
 22 max. deflection = 4.449mm
 23 deflection at edges = 4.449mm
 24 deflection at center = 4.263mm
 25 Curvature due to shear-free edges is apparent.
 26 Deflection is only four times greater than the 1.161mm value for 25mm frames.
 27 Panel separation varies severely along length. (Most apparent from side.)
 28 Top three gas gaps close at center of span (analysis shows overlap).
 .9 panel deflection = 0.053mm (4.6% of total)
 30
 31 (Solution time = 604sec. or \$25.17)
 32 (Total run time 60.5 sec.)

no $f_{max}(side)$
 2/2
 $t = 0.5$

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+01

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+01

NIKE3D

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

4-GAP CSC
NO CORE MATERIAL

DISP. X10.

QUASI-KINEMATIC
(4 SUPPORTS IN Z)

$t_{SKIN} = 0.5 \text{ mm}$

WITHOUT HONEYCOMB CORE

disp. scale factor = 1.000e+01

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+01

NO H.C. CORE
1/2

4-4

1 file:
 2 readme
 3
 4 directory:
 5 .4117672:csc:nocore[all.]
 6
 7 objective:
 8 Remove all honeycomb material to see effect of it's presence.
 9
 10 Quasi-kinematic mount (4 points in z)
 11 node 1: x y z displacement restrained (code 7)
 12 node 15: x z displacement restrained (code 6)
 13 node 113: z displacement restrained (code 3)
 14 node 120: z displacement restrained (code 3)
 15 skin thickness = 0.5mm
 16 3500mm x 1289mm x 140mm
 17 4 gaps @ 10mm, 5 panels (no cores) @ 20mm
 18
 19 observations:
 20 max. deflection = 14.43mm
 21 frame deflection = 0.4992mm (3.5% of total)
 22 skin deflection = 13.93mm (96.5% of total)
 23 Catenary sag of skin dominates.
 24 Skin weight not carried by side frames as with honeycomb core.
 25
 26 25 step load curve needed for solution.
 27 79 stiffness reformations needed for solution.
 28 (Total run time 1,183 sec. can be reduced by using 8:9 = 1)

$t = 0.5$
 no core
 in H.C.
 2/2

e0210a.1 CSC 3000x1289x140 JAH
time = 1.00000e+00

e0210a.1 CSC 3000x1289x140 JAH
time = 1.00000e+00

SUPPORT ALONG 3-EDGES

DISP. X 1,000.

disp. scale factor = 1.000e+03

disp. scale factor = 1.000e+03

e0210a.1 CSC 3000x1289x140 JAH
time = 1.00000e+00

e0210a.1 CSC 3000x1289x140 JAH
time = 1.00000e+00

disp. scale factor = 1.000e+03

disp. scale factor = 1.000e+03

EDGE SUPP

1/2

16-6

EDGE SUP1

$$t = 0.5^{3/2}$$

$$f_{max} = 25 \text{ mm}$$

1 file:
2 readme
3
4 directory:
5 .4117672:csc:edgesup[all.]
6
7 objective:
8 Observe effect of supporting one long edge in vertical direction.
9 This represents a bounding condition for linked panels (the improvement
10 achieved if the paired panel edges are infinitely stiff.)
11
12 Quasi-kinematic mount (4 points in z)
13 node 1: x y z displacement restrained (code 7)
14 node 15: x z displacement restrained (code 6)
15 node 113: z displacement restrained (code 3)
16 node 120: z displacement restrained (code 3)
17 Also nodes 17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37, & 39 (code 3)
18 skin thickness = 0.5mm
19 3500mm x 1289mm x 140mm
20 4 gaps @ 10mm, 5 panels (no cores) @ 20mm
21
22 observations:
23 max. deflection = 0.661mm
24 compared to max. deflection of 1.161mm w/o edge support.
25
26 (Total run time 60 sec. can be reduced by using 8:9 = 1)

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

RIGID MASSLESS "POST" THROUGH CENTER OF CSC

SOLID
POST
250 mm

SOLID
POST
500 mm

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

DISP. x 1000,

SOLID
POST

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Hervath 2/1/93
time = 1.00000e+00

(98.9%)

1.048 mm (FRAME DEF.)

0.012 mm
(1.1%)

BOUND
POST

NOTE:
250 mm WIDE POST

disp. scale factor = 1.000e+03

disp. scale factor = 1.000e+03

CENTER
POST
1/3

8-9T

b-9f

CSC 2000-1300-100 J. Novak 2/1/93
INCHES display

CSC 2000-1300-100 J. Novak 2/1/93
INCHES display

CSC 2000-1300-100 J. Novak 2/1/93
INCHES display

CENTER POST
2/3

MASSLESS GEO
POST SIMULATION (Solid for rotation)

1 file:
 2 readme
 3
 4 directory:
 5 .4117672:csc:ctrpost[all.]
 6
 7 objective:
 8 Identify effect of center post on deflections by adding a
 9 248mm x 575mm post through the center of the CSC.
 10 The post has the mechanical properties of G10 but is massless.
 11 This represents an extreme bounding condition on the beneficial
 12 effects (if any) of the gas gap spacers on overall deflections.
 13
 14 Quasi-kinematic mount (4 points in z)
 15 node 1: x y z displacement restrained (code 7)
 16 node 15: x z displacement restrained (code 6)
 17 node 113: z displacement restrained (code 3)
 18 node 120: z displacement restrained (code 3)
 19 skin thickness = 0.5mm
 20 3500mm x 1289mm x 140mm
 21 4 gaps @ 10mm, 5 panels (no cores) @ 20mm
 22 Solid massless G10 post (247.8mm x 575.0mm) at center of CSC.
 23
 24 observations:
 25 max. frame deflection = 1.048mm
 26 compared to frame def. of 1.108 without large post.
 27 Reduction in panel sag from 0.053mm to 0.012mm due to unrealistic
 28 250mm post width in model.
 29
 30 (Solution time 77 sec.)

WITH
 CENTER POST
 3/3
 $t = 0.5 \text{ mm}$
 $t_{\text{frame}} = 25 \text{ mm}$

16-41

CSC 3000x1200x140 (12.5mm frame)
time = 1.00000e+00

diag. scale factor = 1.000e+03

CSC 3000x1200x140 (12.5mm frame)
time = 1.00000e+00

CSC 3000x1200x140 (12.5mm frame)
time = 1.00000e+00

diag. scale factor = 1.000e+03

CSC 3000x1200x140 (12.5mm frame)
time = 1.00000e+00

diag. scale factor = 1.000e+03

GA10 frame = 12.5 mm
x = 0.5 mm
1/2

610

frame = 12.5mm

 $t = 0.5 \text{ mm}$ $2/2$

1 file:
 2 readme
 3
 4 directory:
 5 .4117672:csc:frm12.5[all.]
 6
 7 objective:
 8 Observe the effect of reducing the frame width from 25mm to 12.5mm.
 9 Do this by removing material from the outer edges (reduce total width).
 10
 11 Quasi-kinematic mount (4 points in z)
 12 node 1: x y z displacement restrained (code 7)
 13 node 15: x z displacement restrained (code 6)
 14 node 113: z displacement restrained (code 3)
 15 node 120: z displacement restrained (code 3)
 16 skin thickness = 0.5mm
 17 3500mm x (1289mm - 25mm) x 140mm
 18 4 gaps @ 10mm, 5 panels (no cores) @ 20mm
 19 frame width 12.5mm
 20
 21 observations:
 22 Max. deflection = 1.211mm
 23 frame deflection = 1.158mm (95.6%)
 24 panel sag = 0.053mm (4.4%)
 25 Reduction of frame width by 50% (from 25mm to 12.5mm) caused a
 26 4.3% increase in maximum deflection (from 1.161mm to 1.211mm).
 27
 28 Solution time 80.3 sec. (\$3.35)

single bending products 1.063

= R.M.E. WIDTH (mm)	SPIKED		(SPREADSHEET)	Δ def (of frame)
	TOTAL	BEAM BENDING ONLY	SIMPLE BENDING (1mm)	
12.5	1.211	1.158	1.063	→ 0.148 (12%)
25.	1.161	1.108	1.045	→ 0.063 (6%)

16-13

CSC 3000x1200x140 JAM (q-line.) 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAM (q-line.) 2/1/93
time = 1.00000e+00

CSC 3000x1200x140 JAM (q-line.) 2/1/93
time = 1.00000e+00

DIKE 50

QUALI - KINEMATIC
(4 SUPPORTS IN 2)

$\lambda_{SKW} = 0.5 \text{ mm}$

WITH HONEYCOMB CORE

DISP. X 1000.

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAM (q-line.) 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

G10 frame = 25 mm
 $\lambda = 0.5$
1/2

1 file:
 2 readme
 3
 4 directory:
 5 .411762:csc:ver0202:quasi[all.]
 6
 7 objective:
 8 Test effect of quasi-kinematic mount on overall deflections.
 9 Compare to case where all four corners are pinned in x,y,z.
 10
 11 Quasi-kinematic mount (4 points in z)
 12 node 1: x y z displacement restrained (code 7)
 13 node 15: x z displacement restrained (code 6)
 14 node 113: z displacement restrained (code 3)
 15 node 120: z displacement restrained (code 3)
 16 skin thickness = 0.5mm
 17 3500mm x 1289mm x 140mm
 18 4 gaps @ 10mm, 5 panels @ 20mm
 19
 20 observations:
 21 max. deflection = 1.161mm
 22 frame deflection = 1.108mm (95.4% of total)
 23 panel deflection = 0.053mm (4.6% of total)
 24 Deflection of frame in simple bending dominates.
 25 Panel weight carried by side frames.
 26
 27 (Total run time 60.5 sec.)

$t = 0.5$
 G/10 frame = 25 mm
 2/2

simple bending dominates
 1.045

46-15

CSC 3000x1200x140 JAH (q-line.) t=1mm
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAH (q-line.) t=1mm
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAH (q-line.) t=1mm
time = 1.00000e+00

[DISP. x 1,000.]

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAH (q-line.) t=1mm
time = 1.00000e+00

disp. scale factor = 1.000e+03

NIKE 3D

QUASI-VISUALLY
4-SUPPLY (2x2)
 $\lambda_{SEM} = 1.0 \mu m$

G10 frame = 25 mm
 $\lambda = 1.0$
1/2

1 file:
 2 readme
 3
 4 directory:
 5 .411762:csc:ver0202:tlmm[all.]
 6
 7 objective:
 8 Test the effect of increasing thickness of all skins to 1.0mm
 9 Compare with t = 0.5mm base case.
 10
 11 Quasi-kinematic mount (4 points in z)
 12 node 1: x y z displacement restrained (code 7)
 13 node 15: x z displacement restrained (code 6)
 14 node 113: z displacement restrained (code 3)
 15 node 120: z displacement restrained (code 3)
 16 skin thickness = 1.0mm
 17 3500mm x 1289mm x 140mm
 18 4 gaps @ 10mm, 5 panels @ 20mm
 19
 20 observations:
 21 max. deflection = 1.131mm
 22 frame deflection = 1.067mm (94.3% of total)
 23 panel deflection = 0.064mm (5.7% of total)
 24 Deflection of frame in simple bending dominates.
 25 Panel weight carried by side frames.
 26
 27 Increasing skin thickness 100% reduced maximum deflection
 28 from 1.161mm @ t = 0.5 to 1.131mm @ t=1.0 (2.6%)
 29
 30 Panel weight increased 4.1kg.
 31
 32 (Total run time 60.1 sec.)

G-10 EDGE FILLER

$t = 1.0$ 2/2
 frame 25 mm

CSC 3000x1289x140 J.Horvath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/93
time = 1.00000e+00

GEMINI
(NO ORTHOTROPIC PROPS.)

DISP. x 1,000.

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

GEMINI LINEAR

1/2

16-17

1 file:
 2 readme
 3
 4 directory:
 5 .411762:csc:ver0202:ver0202g[all.]
 6
 7 objective:
 8 Model CSC with GEMINI.
 9 Compare turn-around time of GEMINI run with NIKE3D runs.
 10 Compare these linear GEMINI results with non-linear results.
 11 List advantages/disadvantages of each.
 12
 13 Pinned corners (like NIKE3D directory .411762:csc:allpins[all.])
 14 skin thickness = 0.5mm
 15 3500mm x 1289mm x 140mm
 16 4 gaps @ 10mm, 5 panels @ 20mm
 17
 18 observations:
 19 max. deflection = 0.664mm
 20 frame deflection = 0.608mm (91.6% of total)
 21 panel deflection = 0.056mm (8.4% of total)
 22 Deflection of frame in simple bending dominates.
 23 Panel weight carried by side frames.
 24 Comparison with NIKE3D
 25

	GEMINI	NIKE3D
26 max. def.	0.664	0.686
27 frame def.	0.608	0.619
28 panel disp.	0.056	0.067
29 run time	41.8sec.	60.5sec.

 30
 31
 32 GEMINI advantages:
 33 Shorter cpu time.
 34
 35 GEMINI disadvantages:
 36 No orthotropic material model.
 37 No material input generation through INGRID (must use SLIC)
 38 Lengthy model setup time due to hand editing.
 39 Not a significant cpu time savings.

GEMINI LINEAR
 COMPARISON
 RUN 2/2
 (P. 2.15)

CSC 3000x1289x140 J.Horvath 2/1/83
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/83
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/83
time = 1.00000e+00

NIKE 3D

4 supports in x, y, z dir.

$\delta_{SKIN} = 0.5 \text{ mm}$

DISP. x 1,000.

disp. scale factor = 1.000e+03

CSC 3000x1289x140 J.Horvath 2/1/83
time = 1.00000e+00

disp. scale factor = 1.000e+03

NIKE 3D
NON-LINEAR
1/2

16-19

1 file:
 2 readme
 3
 4 directory:
 5 .411762:csc:allpins[all.]
 6
 7 objective:
 8 All four corners restrained in x,y,z-displacement.
 9 Compare with quasi-kinematic and kinematic support.
 10
 11 Pinned corners
 12 node 1: x y z displacement restrained (code 7)
 13 node 15: x y z displacement restrained (code 7)
 14 node 113: x y z displacement restrained (code 7)
 15 node 120: x y z displacement restrained (code 7)
 16 skin thickness = 0.5mm
 17 3500mm x 1289mm x 140mm
 18 4 gaps @ 10mm, 5 panels @ 20mm
 19
 20 observations:
 21 max. deflection = 0.686mm
 22 frame deflection = 0.619mm (90.2% of total)
 23 panel deflection = 0.067mm (9.8% of total)
 24 Deflection of frame in simple bending dominates.
 25 Panel weight carried by side frames.
 26 Compared to quasi-kinematic support, deflection is reduced
 27 from 1.161mm to 0.686mm (41% less)
 28
 29 (Total run time 60.5 sec.)

NICK 3D
 COMPARISON RUN
 (ALL PINS)
 NON-LINEAR

~2

17. Creep

Contents:

Adhesive bond Line summary viewgraph (1 page)

Sandwich panel material viewgraph (1 page)

Summary:

Bond-line shear between sandwich panel skins are prone to creep. Proper selection of adhesives and low stresses will reduce susceptibility to creep over life of the structure.

The abstract for GEM TN-93-508, *Estimating Creep Deformations of Large Precision Cathode Strip Chamber Panels*, by S.J. Wineman reads as follows:

"Existing work on the creep behavior of honeycomb panels and glass-reinforced epoxy panel skins was reviewed. Creep data for glass-reinforced epoxy is used to obtain a lower bound for creep deformation of the panels. An upper bound for creep deformation would depend on the properties of the adhesive and the fabrication process. Therefore, creep tests of prototype panels are needed for a better estimate of creep deformation."

Adhesive Bond Line Shear Stresses Are Low

- Thermoset adhesive bonds resist creep (oven cured)
- Room temperature adhesive bonds are stable if the bond line shear stress is less than 700 psi which is 10% of ultimate
- Stress in region of external supports is controlled by design of the connection

Sandwich Panel Materials Influence Long Term Stability

- In general, high temperature bonds are stable and room temperature bonds are not.
- Bond lines under shear are most likely to creep if stress is above 10% of ultimate or the operating temperature is high.
- The critical bond line between the honeycomb and the face sheets is only 0.005" thick. Precise control of adhesive viscosity that is needed to form adhesive fillets is difficult for room temperature bonding systems.
- Bonding is best performed at the same humidity the part will experience during operation. Water can take years to equilibrate by diffusion.
- Glass fibers are "dirt cheap", but Kevlar fibers are more water resistant.
- Standard edge seal materials with 50% fiber content can transmit loads and are well suited for honeycomb edge bolt regions.
- "Nomex" is a generic term covering a variety of performance specifications.
- Employing a plastics specialist to review vendor processes is essential.

17-3

18. Single Sandwich Panel Gravity Sag

Contents:

Two independent finite element analyses of single TDR panel gravity sag (2 pages)

Hand calculation of single panel gravity sag (2 pages)

Summary:

A single TDR SL-3 sandwich panel simply supported at the ends sags about 20mm under its own weight.

FINITE ELEMENT ANALYSIS
BY H.P. HALL

DIRECTORY:

.911762/CSCBASE3/SAG ONE 1

(NO RIDGE FILL / H.C. CORR 1.8 LB/FT³)

CSC outer (single sandwich panel)
time = 0.10000E+01

CSC outer (single sandwich panel)
time = 0.10000E+01

diag. scale factor = 0.500E+02

diag. scale factor = 0.500E+02

CSC outer (single sandwich panel)
time = 0.10000E+01

CSC outer (single sandwich panel)
time = 0.10000E+01

diag. scale factor = 0.500E+02

diag. scale factor = 0.500E+02

SINGLE
PAGE 1/4

18-2

Single Honeycomb Sandwich (No Gap Frame)

Overall width : 1250 mm

Overall length : 3402 mm

ends simply supported across width (bottom skin)

Super Collider, Detector Panels

time = 0.10000E+01

$$G_{ab} = 1.034e+05 \quad \frac{g}{mm \cdot sec^2}$$

$$G_{bc} = 2.620e+07 \quad "$$

$$G_{ca} = 1.034e+05 \quad "$$

(FINITE ELEMENT ANALYSIS BY McMICHELIS)

	Analytical	N3D-S ₀ -L	N3D-S _H L-L	N3D-S _H H-L
center deflection	18.2	19.00	20.06	18.32
edge deflection	—	19.72	20.82	19.02

disp. scale factor = 0.100E+02

Analytical : Hexcel based hand calcs, 0.5mm skins, 19mm core $\Rightarrow$ 20mm shN3D-S₀-L : Nike3d analysis, solid elements for skins $\Rightarrow$ 20mm stack height
Highest shear modulus oriented along lengthN3D-S_HL-L : Nike3d analysis, shell elements for skins, 19mm core $\Rightarrow$ 19mm stack
Highest shear modulus oriented along lengthN3D-S_HH-L : Nike3d analysis shell elements for skins, 20mm core $\Rightarrow$ 20mm stack
Highest shear modulus oriented along length

Analysis of Flat Rectangular Sandwich Beams

SINGLE
PANEL 3/4

Figure 6

$$h = \frac{t_1}{2} + \frac{t_2}{2} + t_c$$

Figure 7
Beam Chart

BEAM TYPE	MAXIMUM SHEAR FORCE V	MAXIMUM BENDING MOMENT M	BENDING DEFLECTION CONSTANT K_b	SHEAR DEFLECTION CONSTANT K_s
SIMPLE SUPPORT UNIFORM LOAD	0.5P	0.125PL	0.01302	0.125
BOTH ENDS FIXED UNIFORM LOAD	0.5P	.00333PL	.002604	0.125
SIMPLE SUPPORT CENTER LOAD	0.5P	0.25PL	0.02083	0.25
BOTH ENDS FIXED CENTER LOAD	0.5P	0.125PL	.00521	0.25
CANTILEVER UNIFORM LOAD	P	0.5PL	0.125	0.5
CANTILEVER END LOAD	P	PL	0.3333	1
CANTILEVER TRIANGULAR LOAD	P	0.3333PL	0.06666	0.3333
ONE END FIXED, ONE END FREE UNIFORM LOAD	0.625P	0.125PL	0.005405	.07042

*If deflections are critical, actual deflections should be verified by tests

Bending Stress in Facings

$$\sigma_i = \frac{M}{t_i h b} \quad \text{where } M \text{ is determined by Figure 7} \quad i = 1 \text{ or } 2$$

Core Shear Stress

$$\tau_c = \frac{V}{hb} \quad V \text{ is from Figure 7}$$

Deflection K_b and K_s from Figure 7

$$\Delta = \frac{2K_b PL^3 \lambda}{E_f t_i h^3 b} + \frac{K_s PL}{h G_c b} \quad (\text{for same skin materials})$$

or

$$\Delta = \frac{K_b PL^3}{D} + \frac{K_s PL}{h G_c b} \quad (\text{see D below})$$

(For most long beams, the second term is relatively small, but should be checked if deflection is critical.)

Face Dimpling

$$\sigma_{cr} = \frac{2E_f}{\lambda} \left[\frac{t_f}{s} \right]^2$$

Face Wrinkling

$$\sigma_{cr} = 0.82 E_f \left[\frac{E_c t_f}{E_f t_c} \right]^{1/2}$$

$$D = \frac{E_{t1} E_{t2} t_2^2 b}{E_{t1} \lambda_2 + E_{t2} \lambda_1} \quad \text{or} \quad \frac{E_{t1} t_2^2 b}{(t_1 + t_2) \lambda} \quad \text{or} \quad \frac{E t h^2 b}{2 \lambda}$$

List of Terms

P = Total Load
L = Span
 σ_i = Facing Stress
 t_i = Skin Thickness
h = Centroid Distance
 τ_c = Core Shear Stress

Δ = Deflection
 E_f = Facing Modulus
 G_c = Core Shear Modulus
b = Width
 σ_{cr} = Critical Facing Stress
D = Panel Stiffness

$\lambda = 1 - \mu^2$
 μ = Facing Poisson's Ratio
S = Cell Size
 E_c = Core Compression Modulus
 t_c = Core Thickness
I = Moment of Inertia

honeycomb

$$\Delta = \underbrace{\frac{2K_b PL^3}{E_f t_f h^2 b}}_{\text{BENDING}} + \underbrace{\frac{K_s PL}{h G_c b}}_{\text{SHEAR}}$$

5-8T

parameters	simple sup't metric	simple sup't english		
Kb =		0.01302		
Ks =		0.125		
P =		44.39	(1/7 of the total wt/l times L)	
P* =		24.48	(1/7 of the sandwich wt/l times L)	
L =	3402	133.94		
b =	1250	49.21		
Ef =		3,300,000		
tf =	0.5	0.01969		
mu =	0.27	0.27		
lambda =	0.9271	0.92710		
h =	19	0.74803		
Gc =		2,000		
			with gap frm.	
	bending	shear	total	%shear
disp. (in)	1.439	0.010	1.450	0.7
disp. (mm)	36.562	0.256	36.818	0.7
			w/o gap frame	
disp. (in)	0.794	0.006	0.799	0.7
disp. (mm)	20.160	0.141	20.302	0.7

BENDING

SHEAR

SHEAR < 1% OF TOTAL Δ

∴ G_c SHOULD HAVE LESS THAN 1% EFFECT ON Δ

SINGLE SANDWICH PANEL SAG
REF. HEXCEL TSB-124 (p. 14)

SINGLE
PANEL
4/4

19. Superpanels

Contents:

Superpanel layout, SL-2 panels at 5.0m x 1.9m (3 pages)

Superpanel gravity sag calculation (1 page)

Summary:

Maximum gravity sag of 4mm is now dominated by center w/t edge panel sag. This could be reduced without adding much mass by using stiffer sandwich panels (i.e. sandwiches with thicker core to separate skins more).

LOP 3

SL-2 SUPERPANELS
(~5.0 m x 1.9 m)

19-2

SL-2 2 OF 3 SUPERPANELS
(~5.0 m x 1.9 m)

2 MIDDLE SUPERPANELS
UPPER ARRANGEMENT
DIMENSIONS ARE IN MILLIMETERS
LENGTHS ARE OVERALL
ANGLES INCLUDE HEADER ZONES

19-3

SL-2 SUPERPANELS
(~5.0m x 1.9m)

MIDDLE SUPERPANELS
DIMENSIONS ARE IN MILLIMETERS

19-4

0

5.0 m x 1.9 m SUPERPANEL

SAG CALCULATIONS (FIRST ORDER)

$$\begin{aligned} \text{TOTAL MAX. SAG} &= 3.622 + 0.283 \\ &= 3.905 \text{ mm} \end{aligned}$$

FOR A BASELINE II MIDDLE SUPERLAYER CSC WHICH IS 188 mm TOTAL (7 @ 20 mm + 6 @ 8 mm)

OPTIMUM LONG-EDGE SUPPORT WOULD REDUCE THIS TO THE FOLLOWING:

$$\begin{aligned} \text{TOTAL MAX. SAG} &= \frac{3.622}{48} + 0.283 \\ &= 0.076 + 0.283 \\ &= \underline{0.359 \text{ mm}} \end{aligned}$$

(THE CENTER w/ EDGE COMPONENT NOW DOMINATES)

20. Finite Element Model Error Analyses

Contents:

Element mesh density error analysis (7 pages)

Sandwich skin shell element error analysis (5 pages)

Summary:

The required mesh density of Hughes-Liu shell elements for adequate representation of sandwich panel skins is determined by performing a series of analyses with different mesh densities. The maximum deflection is plotted against the number of degrees-of-freedom and an asymptotic limit is established. Excessive mesh density slows down convergence while inadequate mesh density underestimates deflection and overestimates stress.

The use of shell elements rather than solid elements for sandwich skins introduces a slight error due to the geometric definition of the element. For a sandwich skin thickness of 0.5mm the shell approximation error is about 4 percent.

2-02

Finite Element Model Error Analysis

ERROR
ANALYSIS
1/7
jah 2/20/93

ERROR ANALYSIS

CSC 3000x1289x140 job double check 2/1/93
INCRID nodes

OF EQNS. = 12,533

$\delta_{MAX} = 1.178 \text{ mm}$

ERROR
ANALYSIS
2/7

27

24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
13	55	63	71	79	87	95	103	111	119	127	135	143	151	159	167															
14	56	64	72	80	88	96	104	112	120	128	136	144	152	160	168															
15	57	65	73	81	89	97	105	113	121	129	137	145	153	161	169															
16	58	66	74	82	90	98	106	114	122	130	138	146	154	162	170															
17	59	67	75	83	91	99	107	115	123	131	139	147	155	163	171															
18	60	68	76	84	92	100	108	116	124	132	140	148	156	164	172															
19	61	69	77	85	93	101	109	117	125	133	141	149	157	165	173															
20	62	70	78	86	94	102	110	118	126	134	142	150	158	166	174															

29

CSC 3000x1200x140 job double check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job double check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job double check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job double check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

20-4

ERR
ANALYSIS
3/7

CSC 3000x1289x140 J.Horvath 2/1/93

INGRID nodes

bottom SKIN

ERROR A: 115
OF EQNS = 7193

$\delta_{MAX} = 1.161 \text{ mil}$

20-5

ERROR
ANALYSIS
4/7

20-6

CSC 3000x1200x140 JAN (q-kino.) 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAN (q-kino.) 2/1/93
time = 1.00000e+00

DIKE 50

CSC 3000x1200x140 JAN (q-kino.) 2/1/93
time = 1.00000e+00

DISP. x 1,000.

disp. scale factor = 1.000e+03

CSC 3000x1200x140 JAN (q-kino.) 2/1/93
time = 1.00000e+00

QUALI - KINEMATIC
(4 SUPPORTS IN 2)

$\lambda_{SKW} = 0.5$

WITH HONEYCOMB CORE

disp. scale factor = 1.000e+03

ERROR
ANALYSIS
5/7

CSC 3000x1289x140 |ah error check 2/1/93
 INGRID nodes

ERROR ANALYSIS

OF EQNS = 2693

$\delta_{MAX} = 1.062 \text{ mm}$

ERROR
 ANALYSIS
 6/7

CSC 3000x1200x140 job error check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job error check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job error check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

CSC 3000x1200x140 job error check 2/1/93
time = 1.00000e+00

disp. scale factor = 1.000e+03

ERROR ANALYSIS

N DOF_P 2693 δ_{max} 1.062
" 7193 " 1.161

ERROR
ANALYSIS
7/7

20-8

Chart3

When shell elements
are used for skins
AND H.C. edge filler is G10

Percent Error in Frame Stiffness vs. Skin Thickness

↑
BASELINE SKIN THICKNESS = 0.5mm

SHELL
ASSUMPTION
1/5

DOUBLE THE SKIN THK.

SHELLS AT 20. mm ϵ TO ϵ
JUST AS IN FRM

SHELL
ASSUMPTION $\frac{3}{5}$

(ACTUAL CASE IS 24 mm FACE TO FACE)

$$I_{NA_{0.5}} = 2I_0 + \sum A_{\gamma_{NA}}^2$$

$$= \left[W \frac{(0.5)^3}{12} \right] (2) + \left[W (0.5) (10)^2 \right] (2)$$

$$I_{NA_{0.5}} = 100.02 \text{ mm}^4 / W \text{ mm}$$

$$I_{NA_{1.0}} = \sum I_0 + \sum A_{\gamma_{NA}}^2$$

$$= \left[W \frac{(1.0)^3}{12} \right] (2) + \left[W (1.0) (10)^2 \right] (2)$$

$$I_{NA_{1.0}} = 200.17 \text{ mm}^4 / W \text{ mm}$$

STIFFNESS ~ DOUBLED & WT. DOUBLES $\therefore$ NO GAIN

WHAT ABOUT END CONDITIONS (SIDE RAIL ROTATION)?

NODE 27 1.108 $\alpha = \tan^{-1} \left(\frac{1.108 - 1.107}{25} \right)$

NODE 28 1.107 $\alpha = 0.00229$

NODE 27 1.067 $\alpha = \tan^{-1} \left(\frac{1.067 - 1.066}{25} \right)$

NODE 28 1.066 $\alpha = 0.00229$

SAME ROTATION $\therefore$ NO GAIN

WHAT ABOUT SPAN SHORTENING (REDUCTION IN PANEL WIDTH DUE TO FRAME SIDE BEND)?

γ_{DISP}

NODE 27 8.801×10^{-4} (TOWARD CENTER)

γ_{DISP}

NODE 27 7.597×10^{-4} (TOWARD CENTER)

42.182 100 SHEETS
Made in U. S. A.
NATIONAL

$$\bar{I}_{WA} = \frac{w (140)^3}{12}$$

$$\begin{aligned} I_{WA} &= \sum I_o + \sum x_{WA}^2 A \\ &= 10 \frac{w(t^3)}{12} + 2 \bar{w} t \left[10^2 + 20^2 \right. \\ &\quad \left. + 40^2 + 50^2 \right. \\ &\quad \left. + 70^2 \right] \end{aligned}$$

SHELLS

SHELLS

20-12

20-13

CSC 3000x1289x140 J.Hervath 2/1/93
time = 0.

disp. scale factor = 1.000e+00 (default)

CSC 3000x1289x140 J.Hervath 2/1/93
time = 0.

disp. scale factor = 1.000e+00 (default)

CSC 3000x1289x140 J.Hervath 2/1/93
time = 0.

disp. scale factor = 1.000e+00 (default)

CSC 3000x1289x140 J.Hervath 2/1/93
time = 0.

disp. scale factor = 1.000e+00 (default)

SHELL
ASSUMPTION
5/5

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DATE

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5/16/94

END