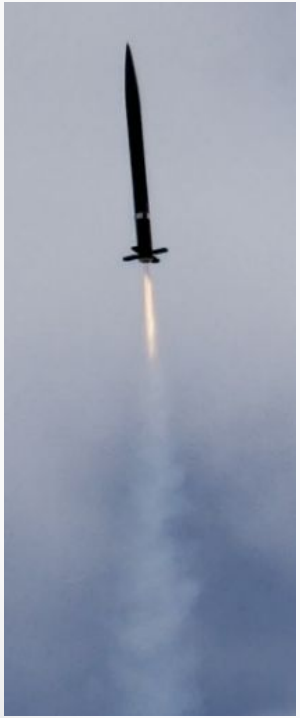
Colorado State University - Aries IV Liquid Motor



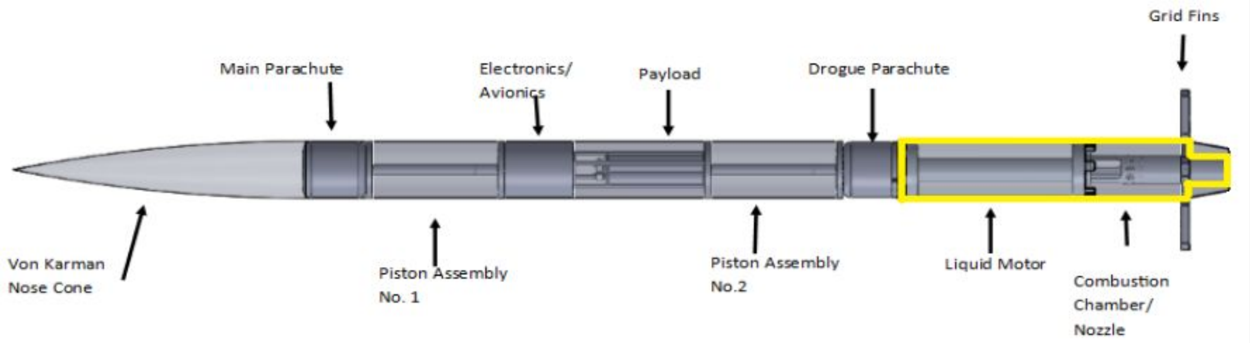
Colum Ashlin, Eric Lufkin, Trent Sieg

Introduction

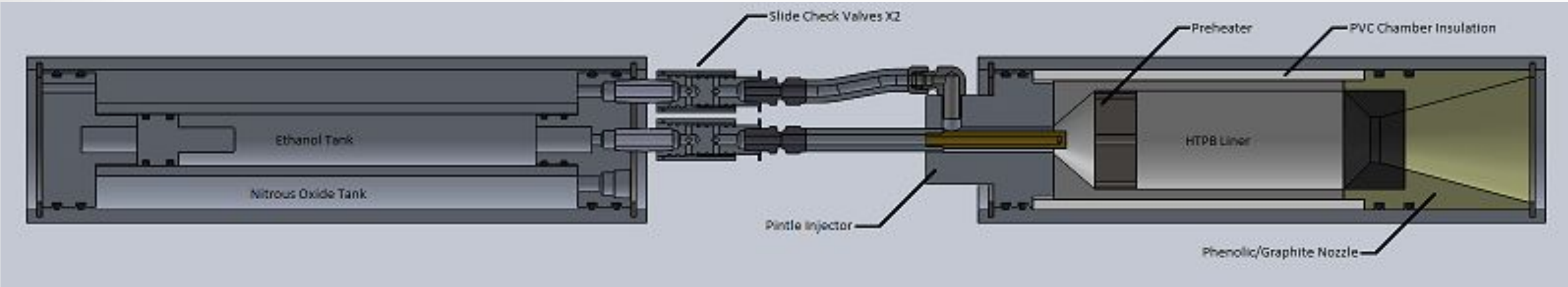
Project Overview

Mission: Optimize and improve the Aries III tribrid liquid propellant rocket motor design to reach 10,000 ft

- Develop an efficient, robust, and re-launchable design
- Optimize motor to increase efficiency
- Design reliable plumbing system
- Increase accessibility of motor



Design Summary Overview

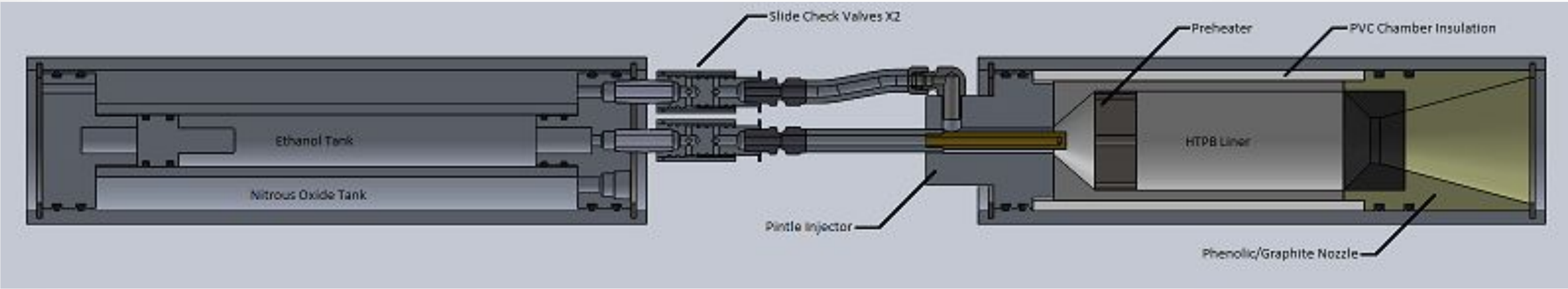


Major Design Innovations:

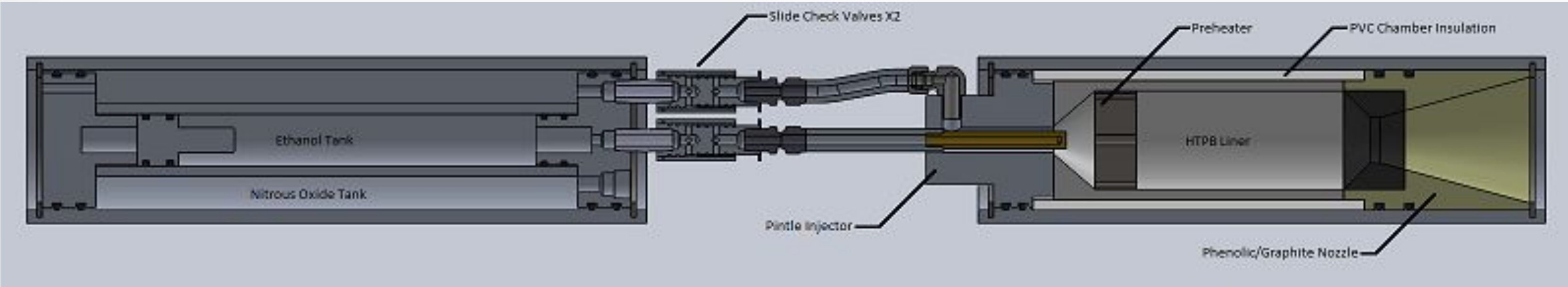
- Separation of propellant tanks and combustion chamber
- Custom slide check valves
- Pintle Injector

Design Summary

Tribrid Liquid Propellant Engine

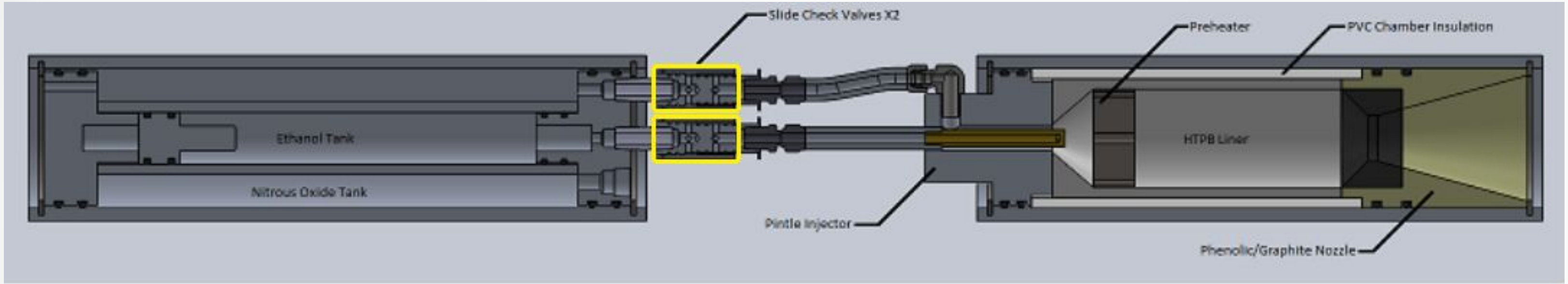


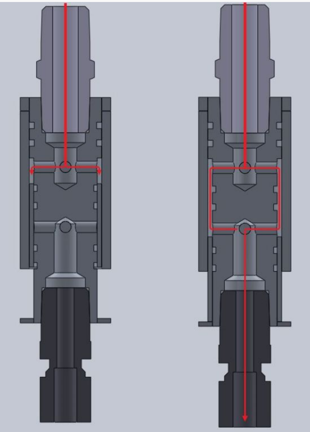
Design Summary
Tank/Chamber Separation

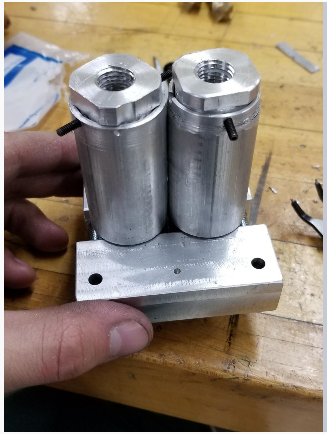


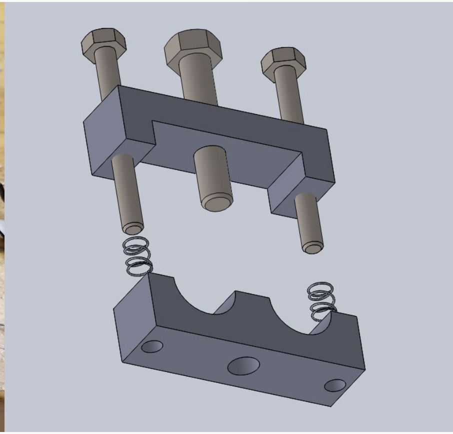
Design Summary

Slide Check Valves



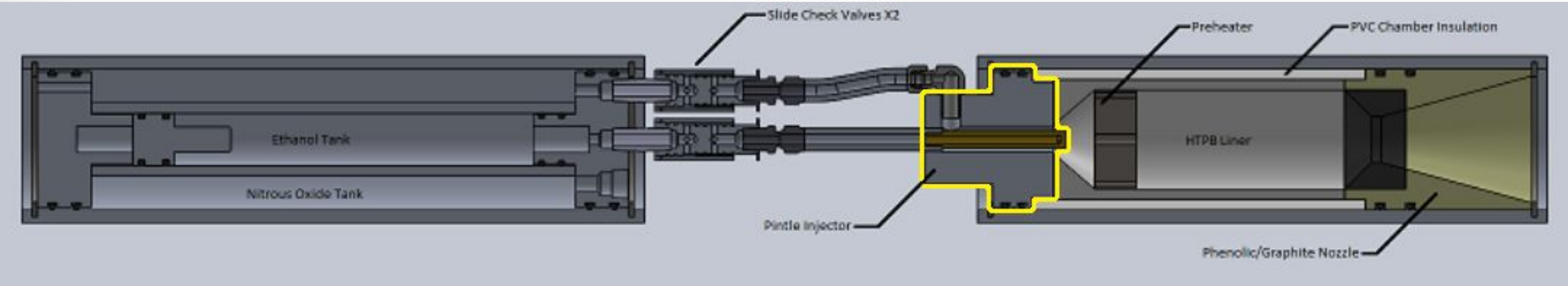


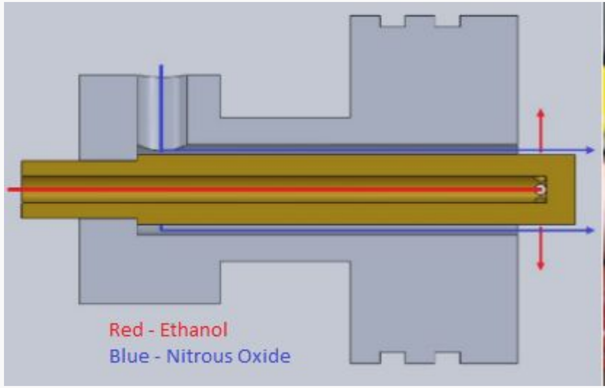




Design Summary

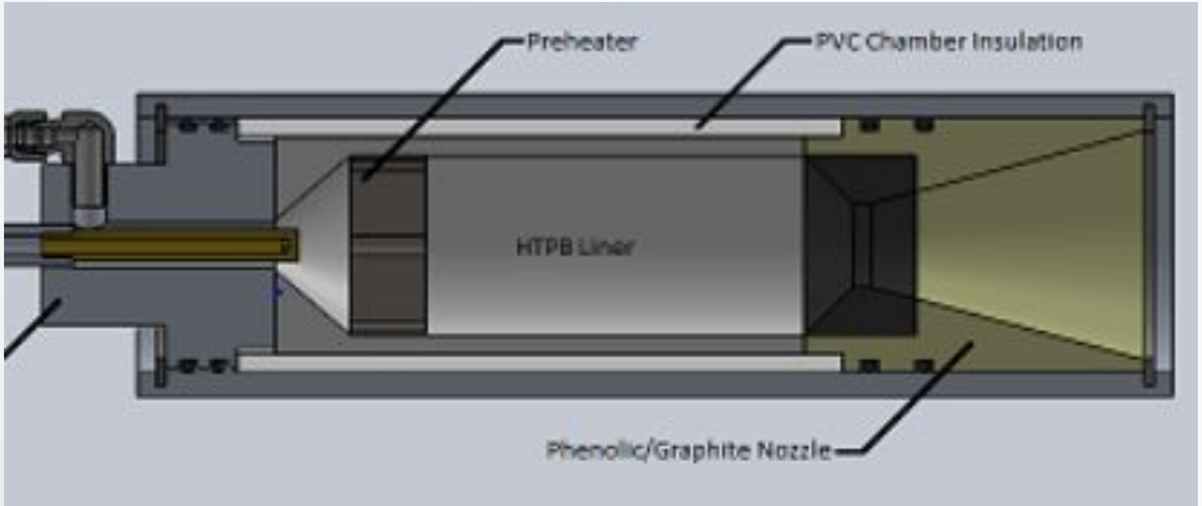
Pintle Injector



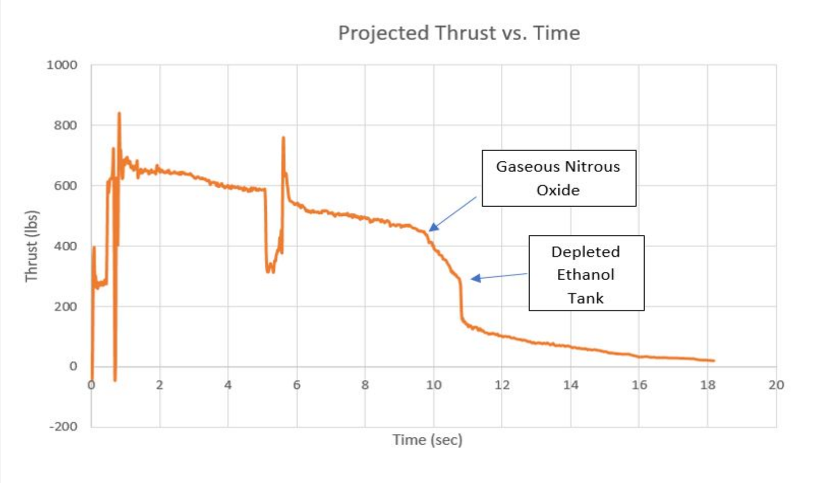


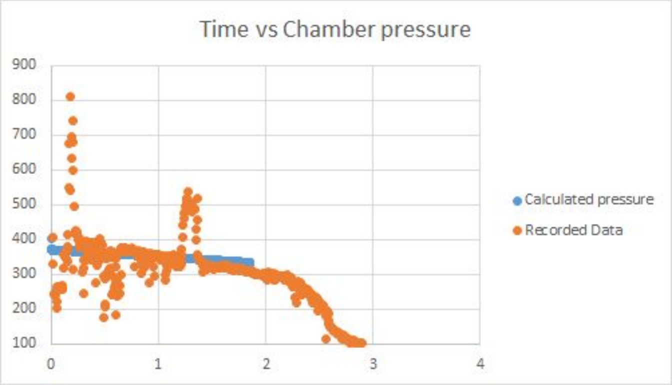
Design Summary

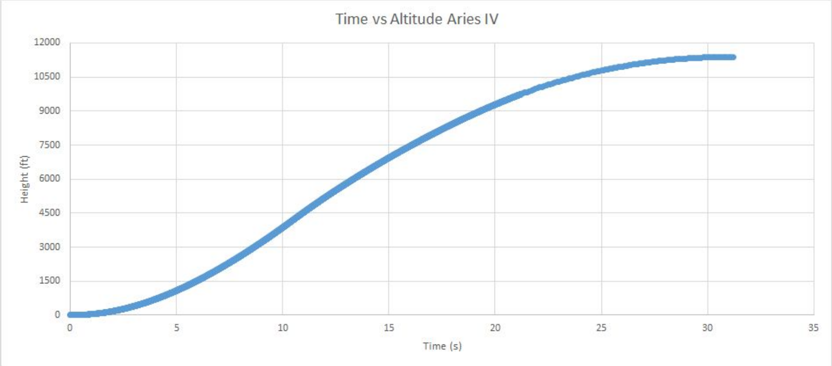
Ignition Process

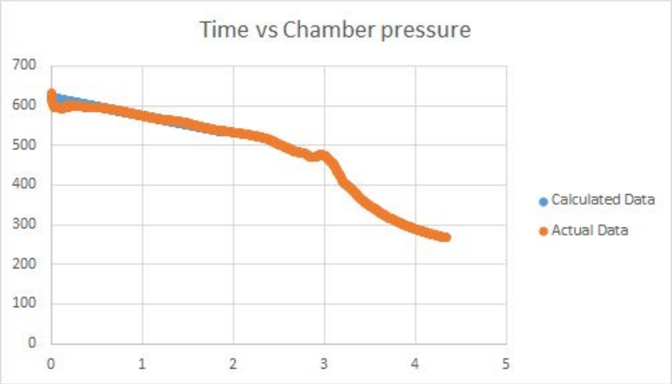


Details of Design and Supporting Analysis







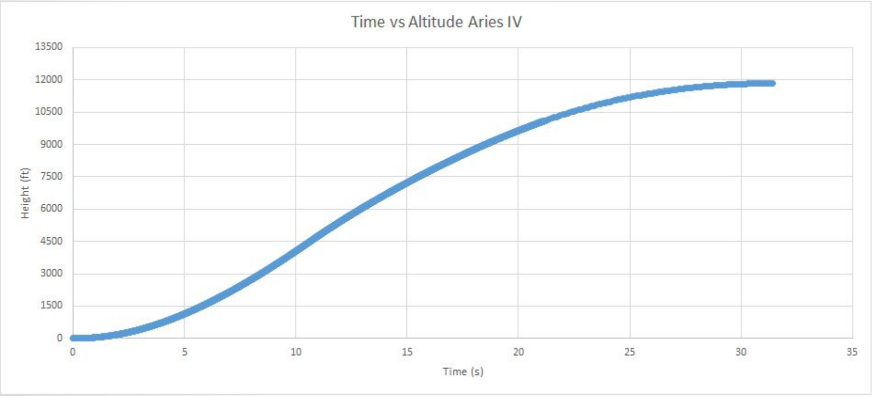


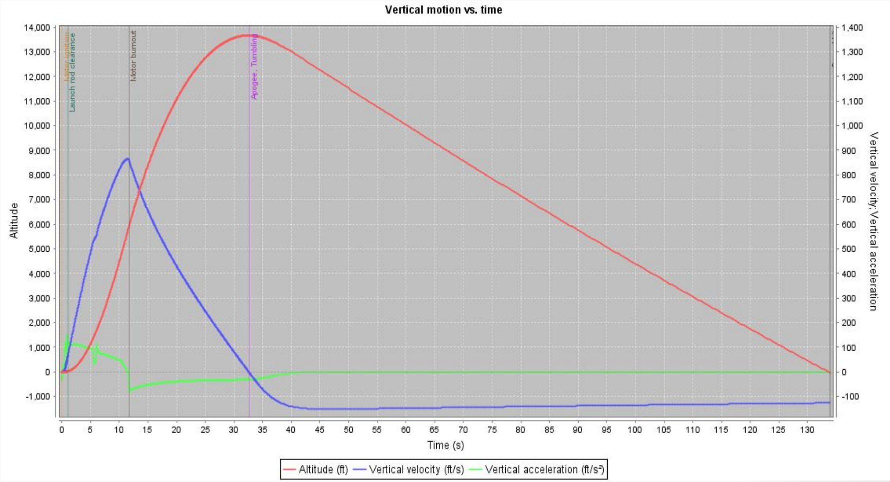
Details of Design and Supporting Analysis

Full scale volume: $V = c_{tf} \cdot c_{time} \cdot V_0$

Throat to Oxidizer ratio: $\dfrac{A_{throat}}{A_{nos}} \geq 16$

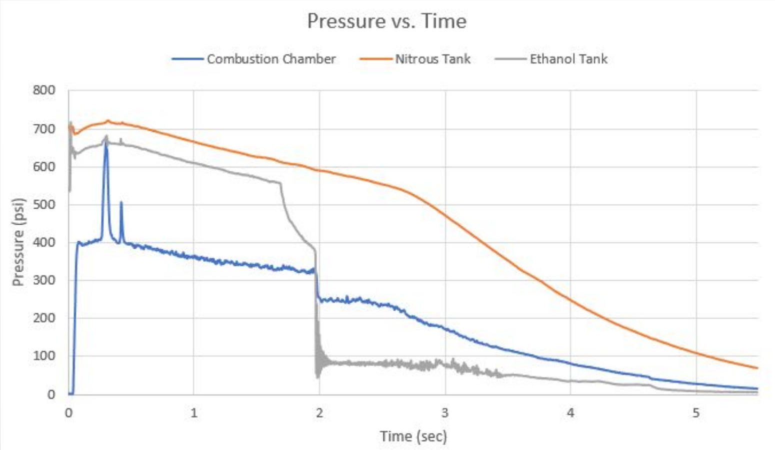
Normalized combustion chamber length: $L_{star} = \dfrac{L_c \cdot A_c}{A_{throat}}$

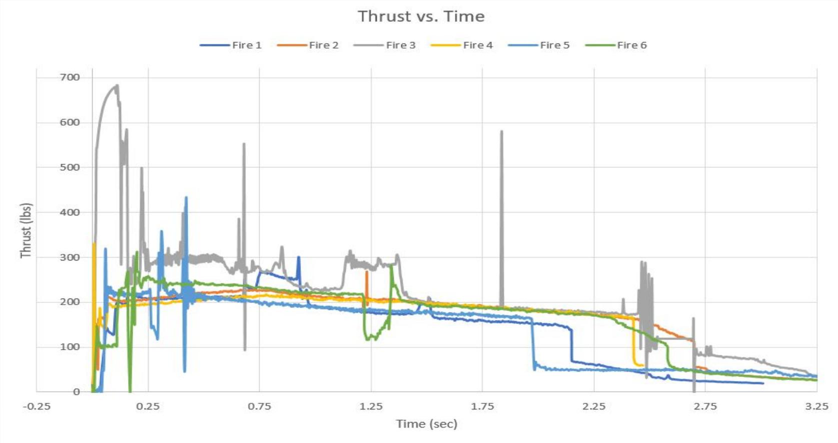




Testing and Evaluation

- Impulse is the area under the thrust curve
- Around 85% of the total impulse during ethanol phase





Testing and Evaluation

Full ethanol combustion

Hybrid mode (depleted ethanol)

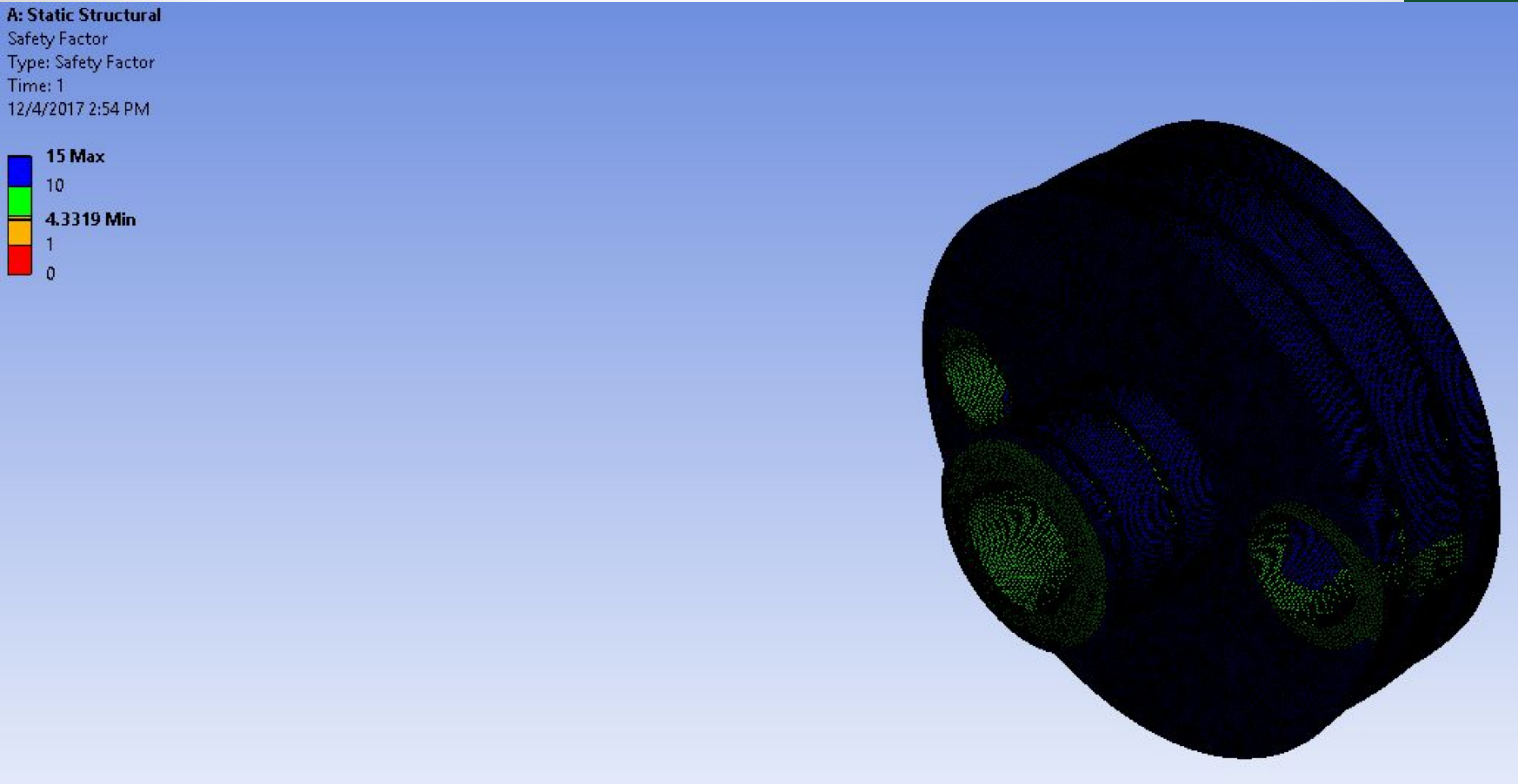
Testing and Evaluation

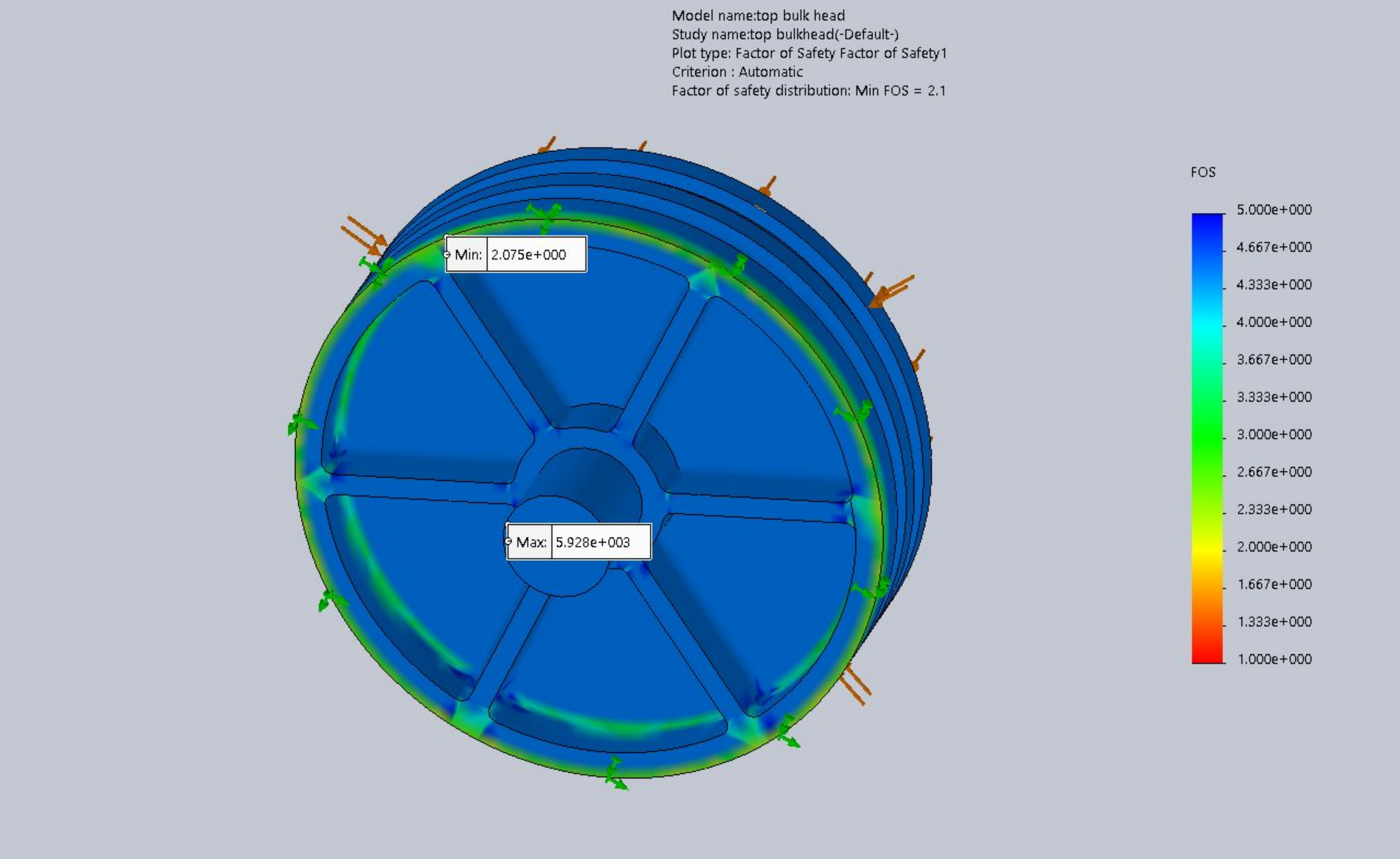
Measure of Tendency	Impulse (lb*s)	Thrust (lbs)
Average	524*	187
Median	503*	191
Range	490-560*	182-196

*Hybrid mode included

- Total impulse needs to be met to reach apogee

Appendix


A: Static Structural
Safety Factor
Type: Safety Factor
Time: 1
12/4/2017 2:54 PM
15 Max
10
4.3319 Min
1
0



Model name:top bulk head
Study name:top bulkhead(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 2.1
Min: 2.075e+000
Max: 5.928e+003
FOS
5.000e+000
4.667e+000
4.333e+000
4.000e+000
3.667e+000
3.333e+000
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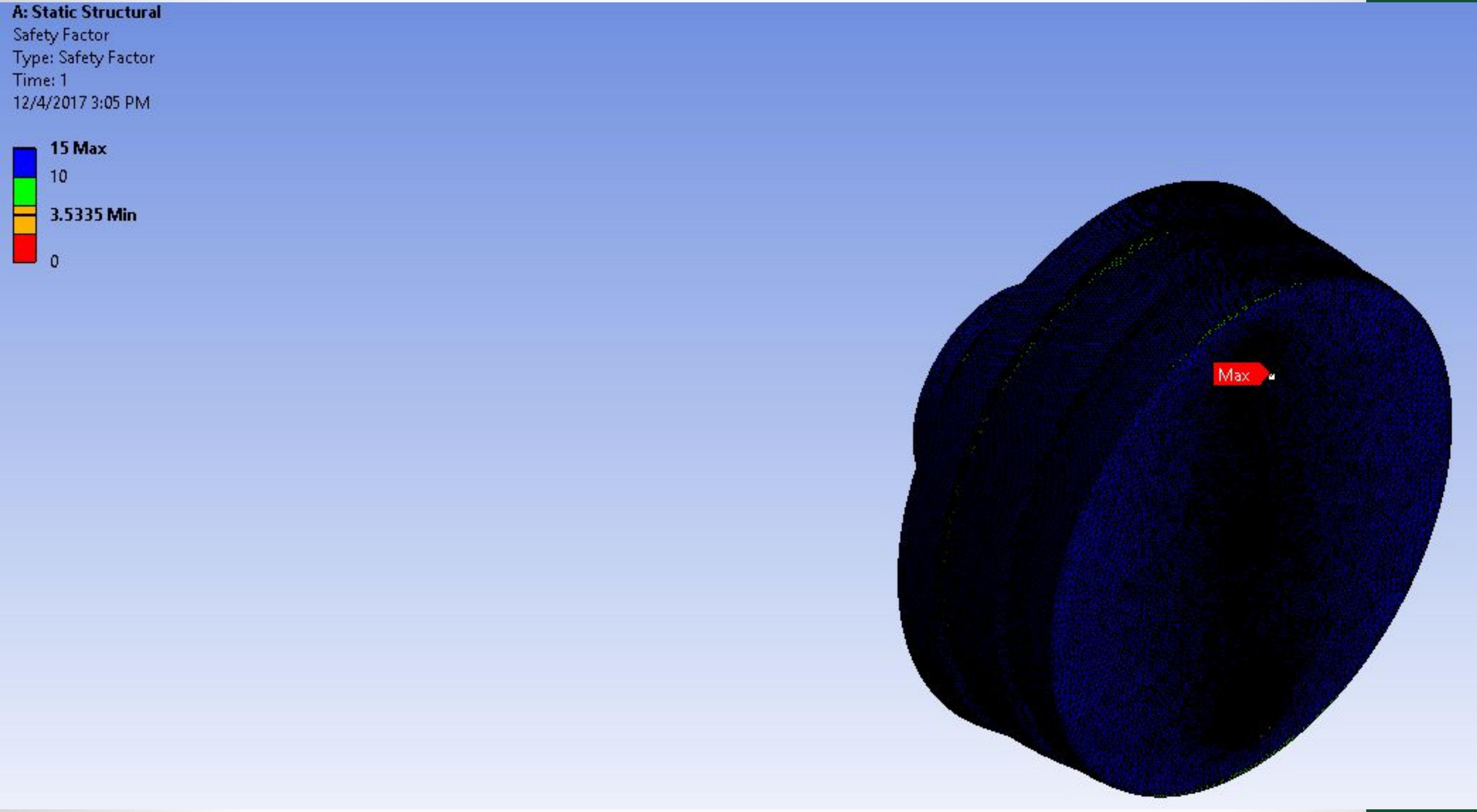
A: Static Structural
Safety Factor
Type: Safety Factor
Time: 1
12/4/2017 3:05 PM
15 Max
10
3.5335 Min
0
Max

Appendix Combustion Tank Thick Walled Pressure Vessel Analysis

Material :Al6061-T6	ID(in)	OD(in)	P(bar)	T (Deg K)	T (DegF)	Hoop Stress (Mpa)	LongitudinalStress	SF1
	5.499999824	6.000000074	76.675255	313		-47.967944	-47.967944	4.068516731
	5.625000033	6.125000283	76.675255	313		-48.922892	-48.922892	3.989106655
	5.750000242	6.249999906	76.675255	313		-49.877928	-49.877928	3.91272974
	5.874999865	6.375000115	76.675255	313		-50.832888	-50.832888	3.839228153
	6.000000074	6.499999738	76.675255	313		-51.787984	-51.787984	3.768426895
	6.125000283	6.624999947	76.675255	313		-52.743048	-52.743048	3.700191736
	6.249999906	6.750000157	76.675255	313		-53.698072	-53.698072	3.634386539
	6.375000115	6.874999779	76.675255	313		-54.653228	-54.653228	3.570872068
	6.499999738	6.999999989	76.675255	313		-55.60828	-55.60828	3.509545803
	6.624999947	7.125000198	76.675255	313		-56.5634	-56.5634	3.45028615
	6.750000157	7.249999821	76.675255	313		-57.518592	-57.518592	3.392990351
	6.874999779	7.37500003	76.675255	313		-58.47366	-58.47366	3.33757329
	6.999999989	7.500000239	76.675255	313		-59.428796	-59.428796	3.283933401
	7.125000198	7.624999862	76.675255	313		-60.384	-60.384	3.231986761
	7.249999821	7.750000071	76.675255	313		-61.339068	-61.339068	3.181664944
	7.37500003	7.875000281	76.675255	313		-62.2942	-62.2942	3.132882833
	7.500000239	7.999999903	76.675255	313		-63.249396	-63.249396	3.085570812
	7.624999862	8.125000113	76.675255	313		-64.204448	-64.204448	3.039673328
	7.750000071	8.249999735	76.675255	313		-65.159632	-65.159632	2.99511528
	7.875000281	8.374999945	76.675255	313		-66.114736	-66.114736	2.95184803
	7.999999903	8.500000154	76.675255	313		-67.069756	-67.069756	2.909816742
	8.125000113	8.624999777	76.675255	313		-68.024912	-68.024912	2.868959904
	8.249999735	8.749999986	76.675255	313		-68.979904	-68.979904	2.829241276
	8.374999945	8.875000195	76.675255	313		-69.93496	-69.93496	2.790604591
	8.500000154	8.999999818	76.675255	313		-70.890072	-70.890072	2.753006935

Appendix Combustion Tank Thick Walled Pressure Vessel Analysis

Material :Al6061-T6	ID(in)	OD(in)	P(bar)	T (Deg K)	T (DegF)	Hoop Stress (Mpa)	LongitudinalStress	SF1
	2.875000121	3.499999994	76.675255	313		-23.563664	-23.563664	8.281176567
	3.000000037	3.62499991	76.675255	313		-24.322416	-24.322416	8.022983551
	3.124999953	3.75000012	76.675255	313		-25.081638	-25.081638	7.78024435
	3.249999869	3.875000036	76.675255	313		-25.84129	-25.84129	7.551625729
	3.375000078	3.999999952	76.675255	313		-26.601328	-26.601328	7.335944653
	3.499999994	4.124999868	76.675255	313		-27.361692	-27.361692	7.13214922
	3.62499991	4.250000077	76.675255	313		-28.122344	-28.122344	6.939294338
	3.75000012	4.374999993	76.675255	313		-28.883288	-28.883288	6.756521702
	3.875000036	4.499999909	76.675255	313		-29.64446	-29.64446	6.583076
	3.999999952	4.625000118	76.675255	313		-30.405836	-30.405836	6.41826582
	4.124999868	4.750000034	76.675255	313		-31.16742	-31.16742	6.261462212
	4.250000077	4.87499995	76.675255	313		-31.929192	-31.929192	6.112099171
	4.374999993	5.00000016	76.675255	313		-32.691098	-32.691098	5.969670296
	4.499999909	5.124999782	76.675255	313		-33.45317	-33.45317	5.833697796
	4.625000118	5.249999992	76.675255	313		-34.215364	-34.215364	5.70375967
	4.750000034	5.375000201	76.675255	313		-34.977656	-34.977656	5.579467297
	4.87499995	5.499999824	76.675255	313		-35.740084	-35.740084	5.460454464
	5.00000016	5.625000033	76.675255	313		-36.502592	-36.502592	5.346400738
	5.124999782	5.750000242	76.675255	313		-37.265156	-37.265156	5.237005234
	5.249999992	5.874999865	76.675255	313		-38.02786	-38.02786	5.131977558
	5.375000201	6.000000074	76.675255	313		-38.790604	-38.790604	5.03107357
	5.499999824	6.125000283	76.675255	313		-39.55338	-39.55338	4.934056759
	5.625000033	6.249999906	76.675255	313		-40.316276	-40.316276	4.840696335
	5.750000242	6.375000115	76.675255	313		-41.079192	-41.079192	4.75080061
	5.874999865	6.499999738	76.675255	313		-41.842148	-41.842148	4.664177895

Appendix NASA CEA Output

Pin =	450.0 PSIA						
O/F=	6.00000 %FUE	L= 14.2	85714 R,E	Q.RAT	IO= 0.961	508	PHI,EQ.RATIO= 0.955379
CHAMB		ER TH	ROAT E	XIT	EXIT	EX	IT
Pinf/P	1.0	000 1	.7354 45	0	50	55	0
P, BAR	31.	026 1	7.878 0.6	8947	0.62053	0.56	411
T, K	3168	.06 29	91.18 201	9.44	1985.85	1955	0.28
RHO, KG/CU M	3.145	1 0 1.9	406 0 1.15	65-1	1.0590-1	9.781	42737
H, KJ/KG	742	.67 2	17.08 -223	7.8	-2300.07	-2355	0.48
U, KJ/KG	-243	.83 -7	04.21 -283	3.95	-2886.04	-2932	0.22
G, KJ/KG	-3052	4.4 -29	304.3 -221	68.6	-21899.4	-2165	3.1
S, KJ/(KG)(K)	9.8	695 9	.8695 9.	8695	9.8695	9.8	695
M, (1/n)	26.	701 2	6.995 28	0.165	28.178	28	188
GAMMAs	1.1	425 1	.1410 1.	1932	1.1977	1.2	18
SON VEL,M/SEC	106	1.6 1	025.3 8	43.4	837.7	83	2.5
MACH NUMBER	0.	0	1.000 2	0.895	2.945	2	990
Ae/At		1	.0000 7.	462	7.6162	8.1	719
CSTAR, M/SEC		1	559.4 15	59.4	1559.4	155	9.4
CF		0	.6575 1.	5657	1.5819	1.5	963
Ivac, M/SEC		1	923.8 26	85.7	2704.4	272	0.9
Isp, M/SEC		1	025.3 24	41.5	2466.9	248	9.2
Pin =	500.0 PSIA						
O/F=	6.00000 %FUE	L= 14.2	85714 R,E	Q.RAT	IO= 0.961	508	PHI,EQ.RATIO= 0.955379
CHAMB		ER TH	ROAT E	XIT	EXIT	EX	IT
Pinf/P	1.0	000 1	.7358 45	0	50	55	0
P, BAR	34.	474 1	9.860 0.7	6608	0.68947	0.62	679
T, K	3177	.39 29	98.90 201	8.82	1985.02	1954	0.28
RHO, KG/CU M	3.487	1 0 2.1	517 0 1.28	56-1	1.1773-1	1.087	1-Apr
H, KJ/KG	742	.67 2	15.81 -224	1.22	-2303.46	-2358	0.84
U, KJ/KG	-245	.95 -7	07.20 -283	7.11	-2889.12	-2935	0.23
G, KJ/KG	-3051	2.3 -29	283.4 -220	99.7	-21829.5	-2158	2.5
S, KJ/(KG)(K)	9.8	367 9	.8367 9.	8367	9.8367	9.8	367
M, (1/n)	26.	723 2	7.014 28	0.169	28.181	28	191
GAMMAs	1.1	431 1	.1416 1.	1945	1.1989	1.2	29
SON VEL,M/SEC	106	3.1 1	026.5 8	43.7	838	83	2.7
MACH NUMBER	0.	0	1.000 2	0.896	2.946	2	991
Ae/At		1	.0000 7.	329	7.6013	8.1	553
CSTAR, M/SEC		1	560.8 15	60.8	1560.8	156	0.8
CF		0	.6577 1.	5652	1.5814	1.5	957
Ivac, M/SEC		1	925.7 26	86.8	2705.5	272	2

Appendix Combustion Chamber Sizing

	Chamber	Throat	Exit	Constants/inputs		dm (kg/s)	At (m^2)	Ae(m^2)	Dt (in)	De(in)	Chamber Length (in)	Expansion Ratio	Thrust (N)	Thrust (lbf)
Pressure(Pa)	3447400	1986000	62679	Gas constant	8314.46	0.25	0.000107318	0.00087521	0.460212	1.314249	0.92648654	8.1553	622.29375	139.8972356
Temp (K)	3177	2998.9	1954.28	kb	1.38065E-23	0.300000012	0.000128782	0.00105025	0.504137	1.439688	1.111783892	8.1553	746.7525297	167.8766894
Density (kg/m^3)	3.487	2.1517	0.1087	L* (m)	1	0.349999994	0.000150245	0.00122529	0.54453	1.55504	1.297081133	8.1553	871.2112352	195.8561266
H (KJ/K)	742.67	217.08	-2355.5	Chamber Area (m^2)	0.004560367	0.400000006	0.000171709	0.00140034	0.582127	1.662408	1.482378485	8.1553	995.6700148	223.8355804
M(1/n)	26.723	27.014	28.191			0.449999988	0.000193172	0.00157538	0.617439	1.76325	1.667675727	8.1553	1120.12872	251.8150175
gamma	1.1431	1.1416	1.229			0.5	0.000214636	0.00175042	0.650838	1.858629	1.852973079	8.1553	1244.5875	279.7944713
SonicV (m/sec)	1063.1	1026.5	832.7			0.550000012	0.0002361	0.00192546	0.682604	1.949346	2.038270431	8.1553	1369.04628	307.7739251
Ae/At		1	8.1553			0.600000024	0.000257563	0.00210051	0.712957	2.036026	2.223567783	8.1553	1493.505059	335.7533789
ISP(s)			253.8838			0.649999976	0.000279027	0.00227555	0.742069	2.119163	2.408864915	8.1553	1617.963691	363.7327993
Mach Number		1	2.991			0.699999988	0.00030049	0.00245059	0.770081	2.199159	2.594162267	8.1553	1742.42247	391.7122531
Velocity (m/s)		832.7	2489.175			0.75	0.000321954	0.00262563	0.79711	2.276346	2.779459619	8.1553	1866.88125	419.6917069
						0.800000012	0.000343418	0.00280067	0.823252	2.351	2.964756971	8.1553	1991.34003	447.6711607
						0.850000024	0.000364881	0.00297572	0.848588	2.423355	3.150054323	8.1553	2115.798809	475.6506145
						0.899999976	0.000386345	0.00315076	0.87319	2.493612	3.335351454	8.1553	2240.257441	503.630035
						0.949999988	0.000407808	0.0033258	0.897118	2.561943	3.520648806	8.1553	2364.71622	531.6094888
						1	0.000429272	0.00350084	0.920423	2.628498	3.705946158	8.1553	2489.175	559.5889426
						1.049999952	0.000450736	0.00367588	0.943153	2.693409	3.89124329	8.1553	2613.633631	587.568363
						1.100000024	0.000472199	0.00385093	0.965348	2.756792	4.076540863	8.1553	2738.092559	615.5478502
						1.149999976	0.000493663	0.00402597	0.987044	2.81875	4.261837994	8.1553	2862.551191	643.5272706
						1.200000048	0.000515127	0.00420101	1.008273	2.879375	4.447135567	8.1553	2987.010119	671.5067578
						1.25	0.00053659	0.00437605	1.029065	2.93875	4.632432698	8.1553	3111.46875	699.4861782
						1.299999952	0.000558054	0.0045511	1.049444	2.996949	4.817729829	8.1553	3235.927381	727.4655987
						1.350000024	0.000579517	0.00472614	1.069435	3.054039	5.003027402	8.1553	3360.386309	755.4450858
						1.399999976	0.000600981	0.00490118	1.08906	3.110081	5.188324533	8.1553	3484.844941	783.4245063
						1.450000048	0.000622445	0.00507622	1.108337	3.165131	5.373622106	8.1553	3609.303869	811.4039934
						1.5	0.000643908	0.00525126	1.127284	3.219239	5.558919238	8.1553	3733.7625	839.3834139

Appendix Special Trajectory Code Ascent

```
gh = 54
told = 0
ttold = 0
tnew = ActiveSheet.Cells(hg, gh)
ttnew = ActiveSheet.Cells(hg, gh + 1)
For hg = 101 To 131 'Import the thrust curve
    Do While t <= tnew      'Loop for while the rocket is burning
        rho = (3.775 * 10 ^ -8 * ((h + 1594) ^ 2) - 0.00116425 * (h + 1594) + 12.24675) / 10   'kg/m^3 2nd degre
        mu = (-1.313417396 * 10 ^ -25) * (h + 1594) ^ 2 - (3.2 * 10 ^ -10) * (h + 1594) + 0.0000179     'N*s/m^2
        Tout = Touto - 0.0058 * h
        x = 2 * 0.3048      'Starting after nosecone which should have low skin friction drag
        Rex = rho * (Height * 0.0254) * vv / mu + 0.01
        Lturb = (Height * 0.0254) - 2 * 0.3048
        cfxturb = 0.055 * (Rex) ^ -0.182
        sfa = -((3.141592654 * (OD * 0.0254) * 0.5 * (vv ^ 2) * rho * (cfxturb * Lturb))) / m
        fda = -0.5 * cdf * rho * FA * (vv ^ 2) / m
        cda = -0.5 * cdc * rho * CSA * (vv ^ 2) / m
        b = 0.5 * cd * rho * a          'Specific Drag coefficient in N*s^2/m^2
        da = -(b * vv ^ 2) / m + sfa + fda + cda          'm^s^2 Drag Force divided by mass of rocket
        ga = -G * mearth / (re ^ 2)     'm^s^2 Gravitational acceleration
        coa = 2 * vv * we * slat        'm^s^2 Coriolis Acceleration
        ca = clat * re * we ^ 2         'm^s^2 Centrifugal Acceleration
        thrust = ttold + (t - told) * (ttnew - ttold) / (tnew - told)
        ta = thrust / m                 'm^s^2 ThrustAcceleration
        va = ga + ca + ta + da          'm^s^2 Vertical Acceleration
        vv = vv + va * dt               'm^s Vertical Velocity
        h = h + vv * dt + 0.5 * va * dt ^ 2
        If vv < 0 Then
            vv = 0
            h = 0
        End If
        ha = (0.5 * hcd * AH * rho * (hv0 - hv) ^ 2) / m      'Horizontal Acceleration due to wind speed
        hv = hv + ha * dt                                   'Horizontal velocity
        d = d + hv * dt + ha * dt ^ 2           'Horizontal distance travelled
        re = reo + h            'Radius of Earth
        m = m - dm * dt         'New mass of rocket after propellant loss
        t = t + dt              'Total time passed since ignition
        count = count + 1
        ActiveSheet.Cells(count, 2).Value = vv    'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 3).Value = va / 9.81  'Print max vertical velocity in gs
        ActiveSheet.Cells(count, 1).Value = h / 0.3048      'Print vertical displacement in ft
        ActiveSheet.Cells(count, 4).Value = t    'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 11).Value = da / 9.81  'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 12).Value = sfa / 9.81  'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 13).Value = fda / 9.81  'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 14).Value = cda / 9.81  'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 15).Value = thrust  'Print max vertical velocity in ft/s
        ActiveSheet.Cells(count, 16).Value = ha          'Print max vertical velocity in m/s^2
        ActiveSheet.Cells(count, 17).Value = hv          'Print horizontal velocity in m/s
        ActiveSheet.Cells(count, 18).Value = d / 0.3048  'Print distance in ft/s
    Loop
told = tnew
ttold = ttnew
tnew = ActiveSheet.Cells(hg, gh)
ttnew = ActiveSheet.Cells(hg, gh + 1)
```

```
ActiveSheet.Cells(count, 1).Activate
Selection.EntireRow.Interior.ColorIndex = 3
ta = 0
thrust = 0
dm = 0
Do While vv > 0     'Continue calculating trajectory until rocket begins decent
    rho = (3.775 * 10 ^ -8 * ((h + 1594) ^ 2) - 0.00116425 * (h + 1594) + 12.24675) / 10   'kg/m^3 2
    mu = ((-1.313417396 * 10 ^ -25) * (h + 1594) ^ 2 - (3.2 * 10 ^ -10) * (h + 1594) + 0.0000179) /
    Lturb = 0
    Rex = rho * (Height * 0.0254) * vv / mu
    Lturb = (Height * 0.0254) - 2 * 0.3048
    cfxturb = 0.055 * (Rex ^ -0.182)
    sfa = -((3.141592654 * (OD * 0.0254) * 0.5 * (vv ^ 2) * rho * (cfxturb * Lturb))) / m
    fda = -0.5 * cdf * rho * FA * (vv ^ 2) / m
    cda = -0.5 * cdc * rho * CSA * (vv ^ 2) / m
    b = 0.5 * cd * rho * a
    da = -(b * vv ^ 2) / m + sfa + fda + cda
    ga = -G * mearth / (re ^ 2)
    coa = 2 * vv * we * slat
    ca = clat * re * we ^ 2
    va = ga + ca + da
    vv = vv + va * dt
    h = h + vv * dt + 0.5 * va * dt ^ 2
    ha = (0.5 * hcd * AH * rho * (hv0 - hv) ^ 2) / m      'Horizontal Acceleration due to wind speed
    hv = hv + ha * dt                                   'Horizontal velocity
    d = d + hv * dt + ha * dt ^ 2           'Horizontal distance travelled
    re = reo + h
    m = m - dm * dt
    t = t + dt
    count = count + 1
    ActiveSheet.Cells(count, 2).Value = vv    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 3).Value = va / 9.81  'Print max vertical velocity in gs
    ActiveSheet.Cells(count, 1).Value = h / 0.3048      'Print vertical displacement in ft
    ActiveSheet.Cells(count, 4).Value = t    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 11).Value = da / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 12).Value = sfa / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 13).Value = fda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 14).Value = cda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 16).Value = ha          'Print max vertical velocity in m/s^2
    ActiveSheet.Cells(count, 17).Value = hv          'Print horizontal velocity in m/s
    ActiveSheet.Cells(count, 18).Value = d / 0.3048  'Print distance in ft/s
Loop
```

Appendix Special Trajectory Code Descent

```
td = t
Do While h > hd - 200
rho = (3.775 * 10 ^ -8 * ((h + 1594) ^ 2) - 0.00116425 * (h + 1594) + 12.24675) / 10   'kg/m^3 2nd degre
    mu = ((-1.313417396 * 10 ^ -25) * (h + 1594) ^ 2 - (3.2 * 10 ^ -10) * (h + 1594) + 0.0000179) / 10
    Lturb = 0
    Rex = (-1) * rho * (Height * 0.0254) * vv / mu
    Lturb = (Height * 0.0254) - 2 * 0.3048
    cfxturb = 0.055 * (Rex ^ -0.182)
    sfa = ((3.141592654 * (OD * 0.0254) * 0.5 * (vv ^ 2) * rho * (cfxturb * Lturb))) / m
    fda = 0.5 * cdf * rho * FA * (vv ^ 2) / m
    cda = 0.5 * cdc * rho * CSA * (vv ^ 2) / m
    pda = 0.5 * cdp * rho * PAR * (vv ^ 2) / m
    b = 0.5 * cd * rho * a
    da = (b * vv ^ 2) / m + sfa + fda + cda + pda
    ga = -G * mearth / (re ^ 2)
    coa = 2 * vv * we * slat
    ca = clat * re * we ^ 2
    va = ga + ca + da
    vv = vv + va * dt
    h = h + vv * dt + 0.5 * va * dt ^ 2
    ha = (0.5 * hcd * AH * rho * (hv0 - hv) ^ 2) / m      'Horizontal Acceleration due to wind speed
    hv = hv + ha * dt                                   'Horizontal velocity
    d = d + hv * dt + ha * dt ^ 2            'Horizontal distance travelled
    re = reo + h
    m = m - dm * dt
    t = t + dt
    PAR = PAR + tota * (hl - h) / 200
    hl = h
    count = count + 1
    ActiveSheet.Cells(count, 2).Value = vv    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 3).Value = va / 9.81  'Print max vertical velocity in gs
    ActiveSheet.Cells(count, 1).Value = h / 0.3048      'Print vertical displacement in ft
    ActiveSheet.Cells(count, 4).Value = t    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 11).Value = da / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 12).Value = sfa / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 13).Value = fda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 14).Value = cda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 16).Value = ha          'Print max vertical velocity in m/s^2
    ActiveSheet.Cells(count, 17).Value = hv          'Print horizontal velocity in m/s
    ActiveSheet.Cells(count, 18).Value = d / 0.3048  'Print distance in ft/s
Loop
ActiveSheet.Cells(count, 1).Activate
Selection.EntireRow.Interior.ColorIndex = 5
ActiveWorkbook.Save
PAR = 9.3
```

```
dt = 1
Do While h > 0     'Continue calculating trajectory after rocket begins decent
    rho = (3.775 * 10 ^ -8 * ((h + 1594) ^ 2) - 0.00116425 * (h + 1594) + 12.24675) / 10   'kg/m^3 2nd de
    mu = ((-1.313417396 * 10 ^ -25) * (h + 1594) ^ 2 - (3.2 * 10 ^ -10) * (h + 1594) + 0.0000179) / 10
    Lturb = 0
    Rex = (-1) * rho * (Height * 0.0254) * vv / mu
    Lturb = (Height * 0.0254) - 2 * 0.3048
    cfxturb = 0.055 * (Rex ^ -0.182)
    sfa = ((3.141592654 * (OD * 0.0254) * 0.5 * (vv ^ 2) * rho * (cfxturb * Lturb))) / m
    fda = 0.5 * cdf * rho * FA * (vv ^ 2) / m
    pda = 0.5 * cdp * rho * PAR * (vv ^ 2) / m
    cda = 0.5 * cdc * rho * CSA * (vv ^ 2) / m
    b = 0.5 * cd * rho * a
    da = (b * vv ^ 2) / m + sfa + fda + cda + pda
    ga = -G * mearth / (re ^ 2)
    coa = 2 * vv * we * slat
    ca = clat * re * we ^ 2
    va = ga + ca + da
    vv = vv + va * dt
    h = h + vv * dt + 0.5 * va * dt ^ 2
    ha = (0.5 * hcd * AH * rho * (hv0 - hv) ^ 2) / m      'Horizontal Acceleration due to wind speed
    hv = hv + ha * dt                                   'Horizontal velocity
    d = d + hv * dt + ha * dt ^ 2            'Horizontal distance travelled
    re = reo + h
    m = m - dm * dt
    t = t + dt
    count = count + 1
    ActiveSheet.Cells(count, 2).Value = vv    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 3).Value = va / 9.81  'Print max vertical velocity in gs
    ActiveSheet.Cells(count, 1).Value = h / 0.3048      'Print vertical displacement in ft
    ActiveSheet.Cells(count, 4).Value = t    'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 11).Value = da / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 12).Value = sfa / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 13).Value = fda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 14).Value = cda / 9.81  'Print max vertical velocity in ft/s
    ActiveSheet.Cells(count, 16).Value = ha          'Print max vertical velocity in m/s^2
    ActiveSheet.Cells(count, 17).Value = hv          'Print horizontal velocity in m/s
    ActiveSheet.Cells(count, 18).Value = d / 0.3048  'Print distance in ft/s
Loop
ActiveSheet.Cells(count, 1).Activate
Selection.EntireRow.Interior.ColorIndex = 4
```

Appendix Semiempirical Fluid Analysis

```
athroat = 0.00064516 * 0.25 * pi * 0.8 ^ 2
ae = athroat * 8
odn = 3.365
ode = 1.878
lhs = 1.33
lpis = 2.25
ide = 1.6
leth = 11.875
vnhs = (lhs * 0.25 * pi * (odn ^ 2 - ode ^ 2)) * 0.0000163871
vnot = leth * 0.25 * pi * (odn ^ 2 - ode ^ 2) * 0.0000163871
vehs = 0
pp = 700 * 6894.76
pc = 400 * 6894.76
Pco = pc - 100000
deltap = pp - pc
pn = 0.029 * 27679.9                'lb/in^3
pe = 0.0285 * 27679.9                'lb/in^3
cstar = 1500
cf = 1.1
mo = (vnot - vnhs) * pn + 0.3 * pn * vhs
mf = (leth - lpis) * 0.25 * 0.0000163871 * pi * ide ^ 2 * pe
cdo = 0.3
cfo = 0.8
anos = 0.039475 * 0.00064516
aeth = 6 * 0.25 * pi * (0.0008 ^ 2)
gamma = 1.15
Tc = 3000
mw = 26.6
count = 2
vnhso = vnhs
cvap = 500
dt = 0.001
t = 0
count2 = 2

Do While mf > 0
    ep = 2
    Do While ep > 1
        deltap = pp - Pco
        dmn = cdo * (anos * ((2 * deltap * pn) ^ 0.5))
        If mf > 0 Then
            dme = cfo * (aeth * ((2 * deltap * pe) ^ 0.5))
            otf = dmn / dme
        Else
            dme = 0
            otf = 0
        End If
        gamma = -0.00126 * otf ^ 4 + 0.0234 * otf ^ 3 - 0.146 * otf ^ 2 + 0.31936 * otf + 1.05515
        cstar = ((8.9105 * (otf ^ 4)) - 115.25 * otf ^ 3 + 390.87 * otf ^ 2 + 159.69 * otf + 3473) * 0.3048
        pc = (dmn + dme) * cstar / athroat
        ep = pc - Pco
        ep = (ep ^ 2) ^ 0.5
        Pco = (pc + Pco) / 2
        count2 = count2 + 1
```

```
    Loop
    count2 = 2
    Pco = pc
    mf = mf - dme * dt
    mo = mo - dmn * dt
    vnhs = vnhs + dmn * dt / pn
    If vnhs > 0.00119126 Then
        vnhs = leth * 0.25 * pi * (odn ^ 2 - ode ^ 2) * 0.0000163871
        pn = 0.3 * 0.029 * 27679.9
    End If
    pp = (-45.633 * t + 620.57) * 6894.76
    ActiveSheet.Cells(count, 12).Value = vnhso
    vnhso = vnhs
    t = t + dt
    deltap = pp - pc
    ActiveSheet.Cells(count, 1).Value = t
    ActiveSheet.Cells(count, 2).Value = pc
    ActiveSheet.Cells(count, 3).Value = pp
    ActiveSheet.Cells(count, 4).Value = vn
    ActiveSheet.Cells(count, 5).Value = ve
    ActiveSheet.Cells(count, 6).Value = dmn
    ActiveSheet.Cells(count, 7).Value = dme
    ActiveSheet.Cells(count, 8).Value = cstar
    ActiveSheet.Cells(count, 9).Value = mf
    ActiveSheet.Cells(count, 10).Value = mo
    ActiveSheet.Cells(count, 11).Value = vnhs
    ActiveSheet.Cells(count, 13).Value = pp * cvap * vnhs * dt
    count = count + 1
Loop
End Sub
```

Appendix Propellant Expansion Equations

Throat Calculation

A*=(mdot/P0)*((T0*R/k)^.5)*((2/(k+1))^(2*(k-1)))^-1

Lc=(L*)*At/Ac

Appendix Safety Factor

The 1.5 & 1.4 Ultimate Factors of Safety
for Aircraft & Spacecraft –
History, Definition and Applications

C. T. Modlin
J. J. Zipay
February, 2014

Establishment of the Factor of Safety of 1.5 as an Aircraft Design Criterion

- In March 1934, Revision G of The Handbook of Instructions for Airplane Design (HIAD) established the 1.5 Ultimate Factor of Safety as a formal Air Corps design requirement.
- Aircraft could continue operation if within limit load conditions.
  - Criteria for no detrimental, permanent deformation was first established.
- If loads beyond limit are experienced and detrimental deformation is suspected to have occurred:
  - Inspect and repair, if necessary, before continued flight.
- In service, loads above limit may be part of the statistical distribution (e.g. Turbulence), may exceed a selected criteria (e.g. a 3-sigma distribution and prescribed confidence interval), or may be a unique, stand-alone event.
- **Federal Airworthiness Regulation Part 25.303 Factor of Safety**
  - **Unless otherwise specified, a factor of safety of 1.5 must be applied to the prescribed limit loads which are considered external loads on the structure.**

Sources