

GOX / Paraffin Hybrid Motor - Nozzle Design

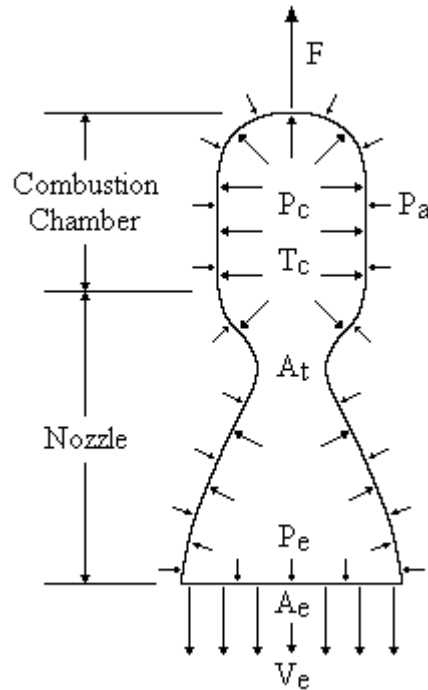
The following is an analysis for the design of a graphite nozzle to be use in the gox/paraffin hybrid motor. The analysis borrows heavily from the overview on nozzle theory done by Richard Nakka [1] and Benito Loyala [2]. The formula derivations were done with the help of Cengels Thermodynamics text [3] and Munsons Fluid Mechanics text [4]. Also used was PROPEP software package [5] to determine gox/paraffin propellant properties.

Theory:

The force produced by a rocket motor can be described as being equivalent to the pressure acting over the motor's chamber and nozzle:

$$\text{Force} := \int \text{Pressure } d\text{Area}$$

This is illustrated in the following figure:



The force can be expressed as the sum of the force produced by expelling the mass of the exhaust products out at a specified rate and velocity plus the 'pressure thrust' created by the difference in the exit pressure and the ambient pressure applied to the end of the rocket motor.

$$\text{Thrust} := \int \text{Pressure } d\text{Area}$$

$$\text{Thrust} := \text{ForceMassExpelled} + \text{ForcePressureThrust}$$

$$\text{Thrust} := \dot{m} \cdot V_e + (P_e - P_a) \cdot A_e$$

Where :

\dot{m} = Mass flow rate of exhaust products.

V_e = Exhaust velocity.

P_e = Nozzle exit pressure

P_a = Ambient pressure

A_e = Nozzle exit area

If we assume that the nozzle throat is choked and that conservation of mass holds true then the amount of mass passing through the nozzle throat area at a speed of Mach 1 (choked flow) is going to equal the amount of fuel and oxidizer being consumed:

$$\dot{m} = \rho^* A^* V^*$$

Where :

ρ^* = ρ_{star} = Critical exhaust products density

A^* = A_{star} = Critical throat area

V^* = V_{star} = Critical throat velocity (Ma=1)

Therefore we can reexpress the thrust of our motor as:

$$\text{Thrust} = \rho^* A^* V^* V_e + (P_e - P_a) A_e$$

Using the magical equations for:

1. Energy

2. Continuity

3. Momentum

4. Equation of state

This section to be expanded upon

We achieve the following equation:

$$\text{Thrust} := A_{\text{star}} \cdot P_c \cdot \sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{k-1}{k}} \right]} + (P_e - P_a) \cdot A_e$$

Where :

k = Ratio of specific heats

P_c = Combustion chamber pressure

Dividing both sides by $P_c \cdot A_{\text{star}}$ yields:

$$\frac{\text{Thrust}}{P_c \cdot A_{\text{star}}} := \sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{k-1}{k}} \right]} + \frac{(P_e - P_a) \cdot A_e}{P_c \cdot A_{\text{star}}}$$

The expression on the right hand side of the equal sign is known as the **Thrust Coefficient** (Cf).

$$Cf := \sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]} + \frac{(Pe - Pa) \cdot Ae}{Pc \cdot Astar}$$

Therefore :

$$\frac{\text{Thrust}}{Pc \cdot Astar} := Cf$$

Since force is Pressure * Area, the thrust coefficient can be thought of as a measure of amount of thrust amplification the nozzle produces.

$$\text{Thrust} := (Pc \cdot Astar) \cdot Cf$$

In this particular case we would like to solve for Astar (A*) to find the throat area we need for our nozzle design.

$$Astar := \frac{\text{Thrust}}{Pc \cdot Cf}$$

Therefore :

$$Astar := \frac{\text{Thrust}}{Pc \cdot \left[\sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]} + \frac{(Pe - Pa) \cdot Ae}{Pc \cdot Astar} \right]}$$

We see that Astar now appears on both side so the equal sign. We have a relationship that will remove it from the right side of the equation.

Once again using the magical equations for:

1. Energy
2. Continuity
3. Momentum
4. Equation of state

We achieve the following equation:

This section to be expanded upon

$$\frac{Astar}{Ae} := \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(\frac{Pe}{Pc}\right)^{\frac{1}{k}} \cdot \sqrt{\frac{k+1}{k-1} \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]}$$

or inverting it yields:

$$\frac{Ae}{Astar} := \frac{1}{\left[\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(\frac{Pe}{Pc}\right)^{\frac{1}{k}} \cdot \sqrt{\frac{k+1}{k-1} \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]} \right]}$$

This is known as the **optimal expansion ratio** for the nozzle. This is our target design condition to achieve maximum thrust.

We can substitute this equation into the previous equation to get rid of the Astar term on the right hand side of the expression. Doing this yields:

$$Astar := \frac{Thrust}{Pc \cdot Cf}$$

$$Astar := \frac{Thrust}{Pc \cdot \left[\sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \cdot \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]} + \frac{(Pe - Pa)}{Pc} \cdot \frac{1}{\left[\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(\frac{Pe}{Pc}\right)^{\frac{1}{k}} \cdot \sqrt{\frac{k+1}{k-1}} \cdot \left[1 - \left(\frac{Pe}{Pc}\right)^{\frac{k-1}{k}}\right]\right]}} \right]}$$

This monster of an equation now is able to solve for Astar (the design target nozzle throat area) in terms of the following variables:

Thrust = Motor output force
 k = Ratio of specific heats
 Pe = Exit pressure of nozzle
 Pc = Combustion chamber pressure
 Pa = Ambient pressure

Calculations:

For our static test firing of the gaseous oxygen/ paraffin hybrid motor we know the following:

- 1) Our design requirements specify the motor has and output thrust of 50 lbf.

$$Thrust := 50 \text{ lbf}$$

- 2) The ratio of specific heats for an oxygen and paraffin propellant mixture is approx. 1.2. This number was generated by PEP and is the average of the k value of the gases in combustion chamber and the k value for the gases in the exhaust stream. See **appendix A** for details:

$$k := 1.2$$

- 3) We will assume that the pressure at the nozzle exit (Pe) is equal to the ambient pressure (Pa) which is equal to 14.6 psi.

$$Pa := 14.7 \text{ psi}$$

$$Pe := Pa$$

- 4) Our design requirements specify motor chamber pressure to be 500 psi.

$$Pc := 500 \text{ psi}$$

We now have enough information to solve for our required throat area. Substituting ; Thrust, k, Pa, Pe, and Pc into the equation for Astar yields:

$$A_{star} := \frac{\text{Thrust}}{P_c \cdot \left[\sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \cdot \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}} \right]} + \frac{(P_e - P_a)}{P_c} \cdot \frac{1}{\left[\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(\frac{P_e}{P_c}\right)^{\frac{1}{k}} \cdot \sqrt{\frac{k+1}{k-1} \cdot \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}} \right]} \right]} \right]}$$

$$A_{star} = 0.067 \text{ in}^2$$

In our particular situation of static firing the motor we will target our exit pressure to equal that of the ambient pressure $P_e = P_a$ the term in the denominator simplifies to :

$$A_{star} := \frac{\text{Thrust}}{P_c \cdot \left[\sqrt{\frac{2 \cdot k^2}{k-1} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \cdot \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}} \right]} \right]}$$

$$A_{star} = 0.067 \text{ in}^2$$

We can calculate the required nozzle throat diameter from:

$$A_{star} := \frac{\pi \cdot D_{throat}^2}{4}$$

or

$$D_{throat} := \sqrt{\frac{4 \cdot A_{star}}{\pi}}$$

$$D_{throat} = 0.292 \text{ in}$$

We can now simply solve for our nozzle exit area by using our formula for optimal expansion ratio combined with the nozzle throat area we have just determined.

$$A_e := A_{star} \cdot \frac{A_e}{A_{star}}$$

$$A_e := A_{star} \cdot \frac{1}{\left[\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(\frac{P_e}{P_c}\right)^{\frac{1}{k}} \cdot \sqrt{\frac{k+1}{k-1} \cdot \left[1 - \left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}} \right]} \right]}$$

Therefore

$$A_e = 0.354 \text{ in}^2$$

We can calculate the required nozzle throat diameter from:

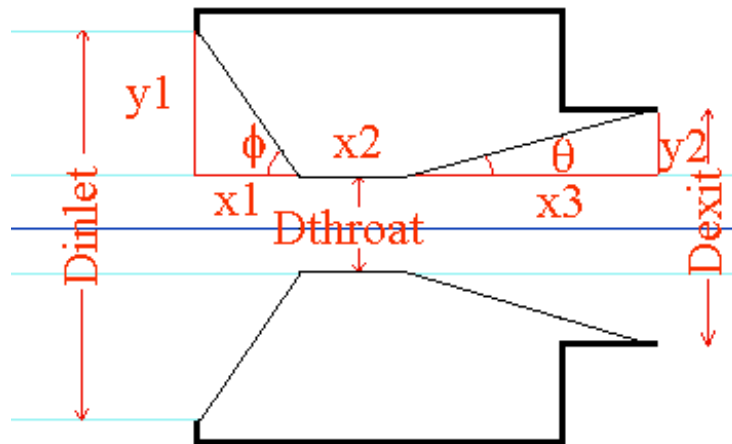
$$A_e := \frac{\pi \cdot \text{Dexit}^2}{4}$$

or

$$\text{Dexit} := \sqrt{\frac{4 \cdot A_e}{\pi}}$$

$$\text{Dexit} = 0.672 \text{ in}$$

We are now ready to determine the other dimensions for that nozzle that will fully define the geometry so that we may fabricate a test article:



We will set the following parameters based on what has worked well for other amateur motor builders in the past.

$$\theta := 17\text{deg}$$

$$\phi := 60\text{deg}$$

We arbitrarily will set the nozzle throat thickness (x2) to 0.25inches. This will hopefully minimize any effects of erosion to the graphite during static firing.

$$x2 := 0.5\text{in}$$

We would now like to find the required depth of the converging section of the nozzle (x1):

From our prototype design specifications we know Dinlet to be 1.75 inches.

$$D_{\text{inlet}} := 1.75\text{in}$$

Therefore we know that:

$$y1 := \frac{D_{\text{inlet}} - D_{\text{throat}}}{2}$$

$$y1 = 0.729\text{ in}$$

and we know from the trigonometric relation:

$$\tan(\phi) := \frac{y1}{x1}$$

or

$$x1 := \frac{y1}{\tan(\phi)}$$

$$x1 = 0.421\text{ in}$$

We would now like to find the required depth of the diverging section of the nozzle (x3)

Therefore we know that:

$$y3 := \frac{D_{\text{exit}} - D_{\text{throat}}}{2}$$

$$y3 = 0.191\text{ in}$$

and we know from the trigonometric relation:

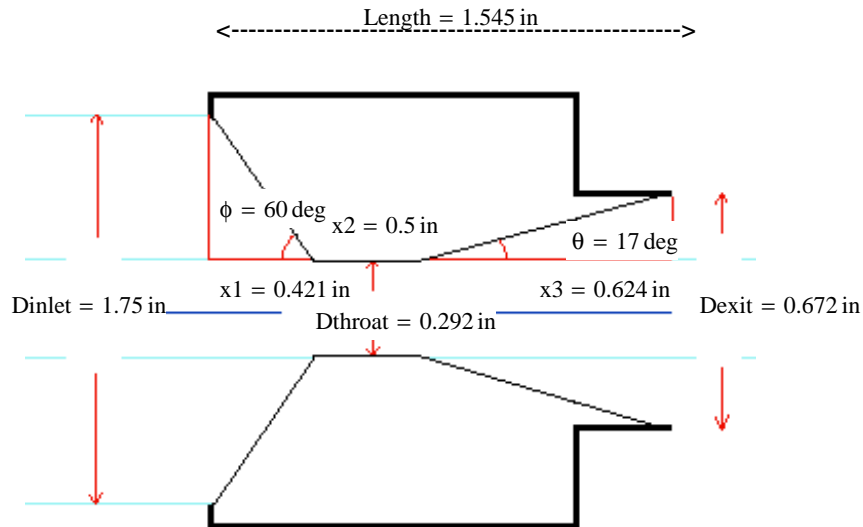
$$\tan(\phi) := \frac{y3}{x3}$$

or

$$x3 := \frac{y3}{\tan(\theta)}$$

$$x3 = 0.624\text{ in}$$

The design of the hybrid nozzle is now fully defined.



Since our ratio of specific heats was calculated using a software package that assumes ideal conditions we would like to do a check for sensitivity of throat diameter and optimal expansion ratio to small changes in k . The following spread sheet shows the results.

Sensitivity of Ae/A^* and D_{throat} to k				
Given: $P_c = 500$ psi				
$P_e = P_a = 14.7$ psi				
Ratio of specific heats (k)	Expansion ratio (Ae/A^*)	Throat areat (A^*) in ²	Throat diameter (D_{throat}) inches	
1.01	7.60	0.062	0.282	
1.10	6.31	0.065	0.287	
1.20	5.31	0.067	0.292	
1.30	4.58	0.068	0.295	
1.40	4.03	0.069	0.297	
1.50	3.61	0.070	0.299	

For a 0.50 change in k which is fairly significant the nozzle throat diameter changes only 0.017 inches. Leading us to the conclusion that the a nozzle throat diameter of 0.29 inches will be a good first choice even if we are not precisely sure what our k value for the GOX/Paraffin mixture is.

Footnotes :

- [1] <http://members.aol.com/ricnakk/>
- [2] "The Design, Construction and Testing of a Liquid Propellant Rocket", Benito Loyola Midshipman 1/c 1988. GDM & Co., Santa Paula, CA. Distributed by Pacific Rocket Society
- [3] "Thermodynamics, An Engineering Approach" 4th Ed., Yunus A Cengel, Michael A Boles. 2002, McGraw-Hill
- [4] "Fundamentals of Fluid Mechanics" 4th Ed., Bruce R. Munson, Donald F. Young, Theodore K Okiishi. 2002 John Wiley & Sons, Inc.
- [5] NWC Propellant Evaluation Program
<http://lekstutis.com/Artie/PEP/>

Appendix A

GOXHybrid Run using June 1988 Version of PEP,
Case 1 of 1 14 Nov 2003 at 8: 4:56.72 pm

CODE	WEIGHT	D-H	DENS	COMPOSITION
736 OXYGEN (GAS)	648.000	0	0.00001	2O
1098 EICOSANE (PARAFFIN)	240.000	-469	0.00001	20C 42H

THE PROPELLANT DENSITY IS 0.00001 LB/CU-IN OR 0.0003 GM/CC
THE TOTAL PROPELLANT WEIGHT IS 888.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

35.674343 H 16.987783 C 40.500000 O

*****CHAMBER RESULTS FOLLOW *****

T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
3610.	6039.	34.01	500.00	-112.56	2474.92	1.2166	38.729	0.878

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL= 11.156 11.160
NUMBER MOLS GAS AND CONDENSED= 38.7285 0.0000

12.45997 H2O	11.58498 CO	5.40181 CO2	3.25228 H2
2.79286 HO	1.45048 H	1.06695 O2	0.71277 O
5.55E-03 HO2	6.69E-04 CHO	1.84E-05 CH2O	

THE MOLECULAR WEIGHT OF THE MIXTURE IS 22.929

*****EXHAUST RESULTS FOLLOW*****

T(K) T(F) P(ATM) P(Psi) ENTHALPY ENTROPY CP/CV GAS RT/V
2655. 4319. 1.00 14.70 -922.01 2474.92 1.2027 35.611 0.028

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL= 11.789 11.790
NUMBER MOLS GAS AND CONDENSED= 35.6109 0.0000

14.65390 H2O 9.16824 CO 7.81922 CO2 2.63041 H2
0.64330 HO 0.46202 H 0.16220 O2 0.07132 O
1.38E-04 HO2 1.34E-05 CHO

THE MOLECULAR WEIGHT OF THE MIXTURE IS 24.936

*****PERFORMANCE: FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE*****

IMPULSE IS EX T* P* C* ISP* OPT-EX D-ISP A*M EX-T
266.2 1.2271 3242. 19.02 5729.6 5.09 0.1 0.35624 1880.
281.7 1.1274 3444. 19.69 5923.8 226.7 6.04 0.1 0.36832 2655.

OOST VELOCITIES FOR PROPELLANT DENSITY OF 0.00001 (S.G. OF 0.000)

5./ 31. 10./ 16. 15./ 10. 25./ 6. 30./ 5. 55./ 3.
60./ 3. 69./ 2. 71./ 2. 88./ 2. 100./ 2. 150./ 1.
175./ 1. 200./ 1. 300./ 1. 1000./ 0. 3000./ 0. 5000./ 0.

EXP. EXIT EXIT EXIT OPTIMUM OPTIMUM VACUUM VACUUM SEA LV SEA LV
RATIO PRESS PRESS TEMP IMPULSE IMPULSE IMPULS IMPULS IMPULS IMPULS
ATM SI K SEC SI SEC SI SEC SI

1. 19.689 1994.5 3444. 120.1 1178. 226.7 2223. 221.3 2192.
2. 6.563 664.8 3132. 202.1 1982. 273.2 2679. 262.3 2599.
3. 2.534 256.7 2880. 247.6 2428. 288.8 2832. 272.5 2700.
4. 1.716 173.8 2783. 262.9 2578. 300.0 2942. 278.4 2757.
5. 1.278 129.4 2712. 273.4 2681. 308.0 3020. 280.9 2783.
6. 1.008 102.1 2656. 281.4 2760. 314.1 3081. 281.7 2790.
7. 0.827 83.8 2611. 287.8 2822. 319.1 3129. 281.2 2786.
8. 0.697 70.6 2572. 293.0 2873. 323.2 3169. 279.9 2773.
9. 0.601 60.9 2538. 297.4 2917. 326.7 3204. 278.0 2754.
10. 0.526 53.3 2509. 301.3 2954. 329.8 3234. 275.6 2730.
11. 0.467 47.3 2483. 304.6 2987. 332.4 3260. 272.9 2703.
12. 0.419 42.4 2459. 307.6 3017. 334.8 3283. 269.9 2673.
13. 0.379 38.4 2438. 310.3 3043. 337.0 3305. 266.6 2641.
14. 0.346 35.0 2418. 312.7 3067. 339.0 3324. 263.2 2607.
15. 0.318 32.2 2400. 315.0 3089. 340.7 3341. 259.6 2571.
16. 0.293 29.7 2383. 317.0 3109. 342.4 3358. 255.8 2534.
17. 0.272 27.6 2368. 318.9 3127. 343.9 3373. 251.9 2495.
18. 0.254 25.7 2353. 320.6 3144. 345.4 3387. 247.9 2456.
19. 0.237 24.0 2340. 322.3 3160. 346.7 3400. 243.8 2415.
20. 0.223 22.6 2327. 323.8 3175. 347.9 3412. 239.7 2374.
21. 0.210 21.3 2314. 325.2 3189. 349.1 3423. 235.4 2332.

21.	0.210	21.0	2303.	326.6	3203.	350.2	3434.	231.1	2289.
22.	0.198	20.1	2303.	326.6	3203.	350.2	3434.	231.1	2289.
23.	0.188	19.0	2292.	327.9	3215.	351.3	3444.	226.7	2246.
24.	0.178	18.1	2282.	329.1	3227.	352.2	3454.	222.3	2202.
25.	0.170	17.2	2272.	330.2	3238.	353.2	3463.	217.9	2158.

EXP. EXIT EXIT EXIT OPTIMUM OPTIMUM VACUUM VACUUM SEA LV SEA LV
RATIO PRESS PRESS TEMP IMPULSE IMPULSE IMPULS IMPULS IMPULS IMPULS

	ATM	SI	K	SEC	SI	SEC	SI	SEC	SI
26.	0.162	16.4	2262.	331.3	3249.	354.1	3472.	213.3	2113.
27.	0.155	15.7	2253.	332.4	3259.	354.9	3481.	208.8	2068.
28.	0.148	15.0	2244.	333.4	3269.	355.8	3489.	204.2	2023.
29.	0.142	14.4	2236.	334.3	3278.	356.5	3496.	199.6	1977.
30.	0.136	13.8	2228.	335.2	3287.	357.3	3504.	194.9	1931.
31.	0.131	13.2	2220.	336.1	3296.	358.0	3511.	190.2	1884.
32.	0.126	12.7	2213.	336.9	3304.	358.7	3518.	185.5	1837.
33.	0.121	12.3	2205.	337.7	3312.	359.4	3524.	180.7	1790.
34.	0.117	11.8	2198.	338.5	3320.	360.0	3531.	176.0	1743.
35.	0.113	11.4	2192.	339.3	3327.	360.7	3537.	171.2	1696.
36.	0.109	11.0	2185.	340.0	3334.	361.3	3543.	166.4	1648.
37.	0.105	10.7	2179.	340.7	3341.	361.8	3548.	161.5	1600.
38.	0.102	10.3	2173.	341.4	3348.	362.4	3554.	156.7	1552.
39.	0.099	10.0	2167.	342.0	3354.	362.9	3559.	151.8	1504.
40.	0.096	9.7	2161.	342.7	3360.	363.5	3564.	146.9	1456.
41.	0.093	9.4	2155.	343.3	3366.	364.0	3569.	142.0	1407.
42.	0.091	9.2	2150.	343.9	3372.	364.5	3574.	137.1	1358.
43.	0.088	8.9	2144.	344.5	3378.	365.0	3579.	132.2	1310.
44.	0.086	8.7	2139.	345.0	3384.	365.4	3584.	127.2	1261.
45.	0.083	8.4	2134.	345.6	3389.	365.9	3588.	122.3	1211.
46.	0.081	8.2	2129.	346.1	3394.	366.3	3592.	117.3	1162.
47.	0.079	8.0	2124.	346.6	3399.	366.8	3597.	112.3	1113.
48.	0.077	7.8	2120.	347.2	3404.	367.2	3601.	107.4	1063.
49.	0.075	7.6	2115.	347.6	3409.	367.6	3605.	102.4	1014.
50.	0.073	7.4	2111.	348.1	3414.	368.0	3609.	97.3	964.
51.	0.072	7.3	2106.	348.6	3418.	368.4	3613.	92.3	915.
52.	0.070	7.1	2102.	349.1	3423.	368.8	3616.	87.3	865.
53.	0.068	6.9	2098.	349.5	3427.	369.2	3620.	82.3	815.
54.	0.067	6.8	2093.	350.0	3432.	369.5	3624.	77.2	765.
55.	0.066	6.6	2089.	350.4	3436.	369.9	3627.	72.2	715.
56.	0.064	6.5	2085.	350.8	3440.	370.2	3631.	67.1	665.
57.	0.063	6.4	2082.	351.2	3444.	370.6	3634.	62.0	614.
58.	0.061	6.2	2078.	351.6	3448.	370.9	3637.	56.9	564.
59.	0.060	6.1	2074.	352.0	3452.	371.2	3641.	51.9	514.
60.	0.059	6.0	2070.	352.4	3456.	371.6	3644.	46.8	463.
61.	0.058	5.9	2067.	352.8	3459.	371.9	3647.	41.7	413.
62.	0.057	5.7	2063.	353.1	3463.	372.2	3650.	36.6	362.
63.	0.056	5.6	2060.	353.5	3467.	372.5	3653.	31.5	312.
64.	0.055	5.5	2056.	353.9	3470.	372.8	3656.	26.4	261.
65.	0.054	5.4	2053.	354.2	3474.	373.1	3659.	21.2	210.

	EXP. RATIO	EXIT PRESS ATM	EXIT PRESS SI	EXIT PRESS K	EXIT TEMP SEC	OPTIMUM IMPULSE SI	OPTIMUM IMPULSE SEC	VACUUM IMPULS SI	VACUUM IMPULS SEC	SEA LV IMPULS	SEA LV IMPULS
66.	0.053	5.3	2050.	354.6	3477.	373.4	3661.	16.1	160.		
67.	0.052	5.2	2047.	354.9	3480.	373.7	3664.	11.0	109.		
68.	0.051	5.1	2043.	355.2	3483.	373.9	3667.	5.8	58.		
69.	0.050	5.1	2040.	355.6	3487.	374.2	3670.	0.7	7.		
70.	0.049	5.0	2037.	355.9	3490.	374.5	3672.	-4.4	-44.		
71.	0.048	4.9	2034.	356.2	3493.	374.8	3675.	-9.6	-95.		
72.	0.047	4.8	2031.	356.5	3496.	375.0	3677.	-14.7	-146.		
73.	0.047	4.7	2028.	356.8	3499.	375.3	3680.	-19.9	-197.		
74.	0.046	4.7	2025.	357.1	3502.	375.5	3682.	-25.1	-248.		
75.	0.045	4.6	2023.	357.4	3505.	375.8	3685.	-30.2	-300.		
76.	0.045	4.5	2020.	357.7	3508.	376.0	3687.	-35.4	-351.		
77.	0.044	4.4	2017.	358.0	3510.	376.2	3690.	-40.6	-402.		
78.	0.043	4.4	2014.	358.3	3513.	376.5	3692.	-45.8	-453.		
79.	0.043	4.3	2012.	358.5	3516.	376.7	3694.	-50.9	-505.		
80.	0.042	4.2	2009.	358.8	3519.	376.9	3696.	-56.1	-556.		
81.	0.041	4.2	2006.	359.1	3521.	377.2	3699.	-61.3	-607.		
82.	0.041	4.1	2004.	359.3	3524.	377.4	3701.	-66.5	-659.		
83.	0.040	4.1	2001.	359.6	3526.	377.6	3703.	-71.7	-710.		
84.	0.040	4.0	1999.	359.9	3529.	377.8	3705.	-76.9	-762.		
85.	0.039	3.9	1996.	360.1	3531.	378.0	3707.	-82.1	-813.		
86.	0.038	3.9	1994.	360.4	3534.	378.2	3709.	-87.3	-865.		
87.	0.038	3.8	1991.	360.6	3536.	378.5	3711.	-92.5	-916.		
88.	0.037	3.8	1989.	360.8	3539.	378.7	3713.	-97.7	-968.		
89.	0.037	3.7	1987.	361.1	3541.	378.9	3715.	-102.9	-1020.		
90.	0.036	3.7	1984.	361.3	3543.	379.1	3717.	-108.1	-1071.		
91.	0.036	3.6	1982.	361.6	3545.	379.3	3719.	-113.4	-1123.		
92.	0.035	3.6	1980.	361.8	3548.	379.4	3721.	-118.6	-1175.		
93.	0.035	3.5	1978.	362.0	3550.	379.6	3723.	-123.8	-1226.		
94.	0.035	3.5	1975.	362.2	3552.	379.8	3725.	-129.0	-1278.		
95.	0.034	3.5	1973.	362.5	3554.	380.0	3726.	-134.3	-1330.		
96.	0.034	3.4	1971.	362.7	3556.	380.2	3728.	-139.5	-1382.		
97.	0.033	3.4	1969.	362.9	3559.	380.4	3730.	-144.7	-1434.		
98.	0.033	3.3	1967.	363.1	3561.	380.6	3732.	-149.9	-1485.		
99.	0.033	3.3	1965.	363.3	3563.	380.7	3734.	-155.2	-1537.		
100.	0.032	3.3	1963.	363.5	3565.	380.9	3735.	-160.4	-1589.		