Tim Patterson
3161 W. Cheryl Drive #N22
Poenix, AZ 85051

January 19, 1996

Dear Tim,

I have finally finished reviewing your rocket engine design , and have made a few constructive criticism. I ran a combustion chemistry code for your propellants and verified that 1.2 mixture ratio is optimum and that the equilibrium sea level Isp is 248 seconds. Because your engine is small, however, combustion kinetics will not have time to reach equilibrium in the nozzle, so the performance will probably be closer to frozen, which I have assumed. Also, in a real rocket engine some other losses need to be accounted for. First of all, there is combustion efficiency, also known as C* efficiency. I chose a value of 95% foe C* efficiency, which may be optimistic, but you have a generous L* (60 inch) and gas injection will promote good mixing. I also accounted for nozzle losses, including divergence and boundary layer friction and heat losses, for which I assumed a nozzle (Cf) efficiency of 97%. The bottom line is that I estimate a sea level Isp of 221 seconds, as summarized in the attached thermochemical printouts.

As far as the ox injector hole sizing, for an injection velocity of 200 ft/sec, I calculate a ΔP of only 20 psi. I think this is too low, and agree with your 100 psi ΔP requirement. For a ΔP of 100 psi I calculate an injection velocity of 509 ft/sec and 4 injection holes of 0.0465 diameter. The calculations I used are written in the margin of your design document.

Your engine design is clean and simple, but I believe it needs a few added details. I have sketched in o-ring groves for sealing the ox injector manifold and the chamber hot gas. I also suggest that you use o-rings to seal the injector inlet ports. As far as the injection pattern, I don't know what your fuel injector element looks like, but I know that a hollow cone swirl atomizer will yield good atomization and vaporization. The cone will spread to the wall to give a fuel rich wall zone, as desired. In line with the ox injection holes and upstream of the fuel cone, however, it is likely to be ox rich, and you may find high erosion rates in the graphite. I would move the ox injection holes as close to the center line as possible, or angle them inward, away from the wall. Also, gas injection tends to "pump" a lot of combustion gas, leading to strong recirculation cells near the injector. Watch for injector face burning because of this. You may want to back off the injection velocity of the ox to about 200 ft/sec by using the counter bore hole as I have shown in the sketches. This will also make it easier to drill, because the smaller "ΔP hole" is much shorter.

These of course are only suggestions, and by no means should they be considered absolute, accurate or even logical. Injector design is, to a large extent an art. By all means do what you feel is the correct, and let the test results lead you down the right path. Please keep me informed of your progress, and I would be interested in what the rest of your system looks like. Please keep in touch (If I haven't insulted you so far!). Good luck and welcome to the RRS!

Sincerely,

T.J. Mueller

Tom Mueller
VP, RRS

THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION

0PC = 300.0 PSIA

		WT FRACTION (SEE NOTE)	ENTHALPY CAL/MOL	STATE	TEMP DEG K	DENS G/C
	CHEMICAL FORMULA					
FUEL	C 1.00000 H 4.00000 O 1.00000	1.00000	-57040.000	L	298.15	.0
OXIDANT	O 2.00000	1.00000	.000	G	298.15	.0

0O/F=1.2000E+00 PERCENT FUEL=4.5455E+01 EQUIVALENCE RATIO=1.1753E+00 STOIC MIXTURE RATIO=1.4104E+00 DENSITY=0.0000E+

0	CHAMBER	THROAT	EXIT	EXIT
PC/P	1.0000	1.7701	20.408	1.0135
P, PSIA	300.0	169.5	14.70	296.0
T, DEG R	5668	5162	3404	5656
H, BTU/LB	-1456.5	-1730.3	-2647.0	-1463.2
S, BTU/(LB)(R)	2.8893	2.8893	2.8893	2.8893
DEN (LBM/FT3)	1.11E-01	6.86E-02	9.02E-03	1.09E-01
M, MOL WT	22.416	22.416	22.416	22.416
CP,BTU/(LB)(R)	.5440	.5375	.5006	.5438
GAMMA (S)	1.1945	1.1973	1.2151	1.1946
SON VEL,FT/SEC	3875.3	3702.5	3028.8	3871.2
MACH NUMBER	.0000	1.0000	2.5492	.1500
AE/AT		1.0000	3.6457	3.9998
CSTAR, FT/SEC		5474	5474	5474
CF VAC		1.241	1.589	
CF		.676	1.411	
IVAC,LBF-S/LBM		211.19	270.37	
I, LBF-SEC/LBM		115.08	239.97	

MOLE FRACTIONS

CO	.161678	CO2	.156305	H	.014559	HCO	.000003
HO2	.000053	H2	.073408	H2O	.535073	H2O2	.000006
O	.004763	OH	.040356	O2	.013797		

MASS FRACTIONS

CO	.202030	CO2	.306879	H	.000655	HCO	.000004
HO2	.000078	H2	.006602	H2O	.430030	H2O2	.000009
O	.003400	OH	.030619	O2	.019695		

0ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS

C CH CH4 C2 C2H2 C3 C4 C(GR) H2O(L)

Assume 95% ηC^* (C* efficiency), use Frozen C* Value (Small engine)

Actual $C^* = 0.95 \times 5474 = 5200$ ft/sec

Assume 97% Nozzle Efficiency (Divergence, friction, and boundary layer losses).

At sea level, $C_F = 0.97 \times 1.411 = 1.369$

SEA LEVEL $I_{sp} = \frac{C^* C_F}{G_c} = \frac{5200(1.369)}{32.174} =$ **221 seconds**

Total Flow: $W_t = \frac{F}{I_{sp}} = \frac{20}{221} = 0.0904$ lb/sec

$W_o = 0.0493$ lb/sec

$W_f = 0.0411$ lb/sec

$C^* = \frac{P_c A_t G_c}{W_t}$, $A_t = \frac{C^* W_t}{P_c G_c} = \frac{(5200)\,0.0904}{300\,(32.174)} = 0.0487\ \text{in}^2$

Throat $\varnothing = \sqrt{\frac{4A_t}{\pi}} =$ **0.249** inch, $\epsilon = 3.65$

Exit $\varnothing = .249\sqrt{3.65} =$ **0.475**

ZONE = 1 (shifting)

THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

0PC = 300.0 PSIA

CHEMICAL FORMULA	WT FRACTION (SEE NOTE)	ENTHALPY CAL/MOL	STATE	TEMP DEG K	DENS G/C
FUEL C 1.00000 H 4.00000 O 1.00000	1.00000	-57040.000	L	298.15	.0
OXIDANT O 2.00000	1.00000	.000	G	298.15	.0

0O/F=1.2000E+00 PERCENT FUEL=4.5455E+01 EQUIVALENCE RATIO=1.1753E+00 STOIC MIXTURE RATIO=1.4104E+00 DENSITY=0.0000E+

0	CHAMBER	THROAT	EXIT	EXIT
PC/P	1.0000	1.7263	20.408	1.0129
P, PSIA	300.0	173.8	14.70	296.2
T, DEG R	5668	5392	4119	5662
H, BTU/LB	-1456.5	-1722.4	-2736.0	-1462.9
S, BTU/(LB)(R)	2.8893	2.8893	2.8893	2.8893
DEN (LBM/FT3)	1.11E-01	6.81E-02	7.79E-03	1.09E-01
M, MOL WT	22.416	22.668	23.423	22.422
(DLV/DLP)T	-1.02521	-1.02014	-1.00176	-1.02509
(DLV/DLT)P	1.5128	1.4316	1.0491	1.5110
CP,BTU/(LB)(R)	1.4773	1.3599	.6431	1.4749
CP GAS(SF)	.5440	.5410	.5208	.5439
GAMMA GAS(SF)	1.1945	1.1932	1.1945	1.1945
GAMMA (S)	1.1262	1.1260	1.1673	1.1262
SON VEL,FT/SEC	3762.8	3649.3	3194.6	3760.0
MU,LBF-S/FT2	1.87E-06	1.81E-06	1.50E-06	1.87E-06
K,LBF/S-DEGR	4.05E-02	3.87E-02	3.06E-02	4.05E-02
PRANDTL NO	.62840	.63143	.63757	.62847
MACH NUMBER	.0000	1.0000	2.5056	.1511
AE/AT		1.0000	3.9841	4.0000
CSTAR, FT/SEC		5595	5595	5595
CF VAC		1.232	1.626	
CF		.652	1.431	
IVAC,LBF-S/LBM		214.16	282.73	
I, LBF-SEC/LBM		113.42	248.78	
MOL WT(MIX)	22.416	22.668	23.423	22.422

MOLE FRACTIONS

CO	.161678	.154922	.130165	.161519
CO2	.156305	.166645	.202105	.156551
H	.014559	.011965	.002379	.014496
HCO	.000003	.000002	.000000	.000003
HO2	.000053	.000029	.000000	.000052
H2	.073408	.070506	.069195	.073334
H2O	.535073	.550768	.592504	.535457
H2O2	.000006	.000003	.000000	.000006
O	.004763	.003256	.000076	.004725
OH	.040356	.031724	.003303	.040147
O2	.013797	.010180	.000274	.013710

MASS FRACTIONS

CO	.202030	.191431	.155660	.201776
CO2	.306879	.323535	.379741	.307279
H	.000655	.000532	.000102	.000652
HCO	.000004	.000002	.000000	.000004
HO2	.000078	.000042	.000000	.000077
H2	.006602	.006270	.005955	.006593
H2O	.430030	.437713	.455716	.430221
H2O2	.000009	.000005	.000000	.000009
O	.003400	.002298	.000052	.003371
OH	.030619	.023802	.002398	.030452
O2	.019695	.014370	.000374	.019566

0ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS

C CH CH4 C2 C2H2 C3 C4 C(GR) H2O(L)

NOTE

WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

(SF) STANDS FOR (SHIFTING FROZEN)

1

0 FROZEN TRANSPORT PROPERTIES CALCULATED FROM EQUILIBRIUM CONCENTRATIONS

STATION	MU (LBF-SEC/FT**2)	K (LBF/SEC-DEG R)	PR
CHAMBER	1.87077800E-06	4.05150300E-02	6.28398100E-01
THROAT	1.80718600E-06	3.87387200E-02	6.31429000E-01
EXIT	1.86926300E-06	4.04723900E-02	6.28473600E-01

0 VISCOSITY EXPONENT (OMEGA) FOR THE FORM MU=MUREF*(T/TREF)**OMEGA IS .69355

MUREF FOR INPUT TO BLM= 6.01903600E-05 LBM/(FT-SEC)

0 SPECIES CONSIDERED IN TRANSPORT PROPERTIES CALCULATIONS

C	CH	CH4	CO
CO2	C2	C2H2	H