Identification of the OF value for maximising the specific impulse of the BT-4 Cygnus engine

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ABSTRACT In this paper a CEA analysis of the BT-4 Cygnus engine is presented. IHI Aerospace of Japan designed and built the BT-4, a pressure-fed liquid rocket engine. The engine uses Monomethylhydrazine fuel and a Nitrogen Tetroxide Oxidizer to produce 450 N of thrust. The propellants are kept in spherical tanks that are helium-pressured. The aim of this project is to evaluate the best mixing ratio to optimise the specific impulse developed by the BT-4 Cygnus. Attention is also drawn to the comparison between the case of efflux from the nozzle in equilibrium and frozen or frozen efflux in the divergent section of the nozzle.

KEYWORDS *BT-4 (Cygnus), CEA, Thermal Analysis, Rocket Problem*

I. INTRODUCTION

In the field of satellite dynamics, small thrusters with liquid propellants are often used to control the attitude of a satellite or to *rendezvous* another object flying in space. Nitrogen tetroxide (N_2O_4) is a highly concentrated storable oxidant.It was developed for the LUNAR-A project, however it has since been employed as a liquid apogee engine in various geostationary communications satellites based on Lockheed Martin's A2100 and GEOStar-2 satellite buses.

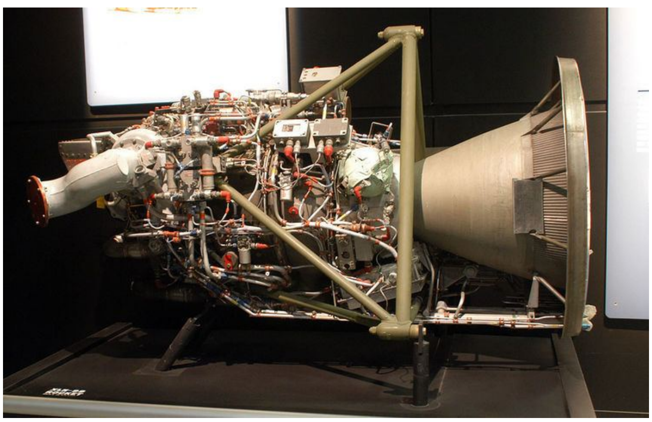

Figure 1: BT-4 (Cygnus)

It was also used on the autonomous cargo spacecraft HTV and Cygnus. For many space applications, hydrazine monomethyl (MMH) and N_2O_4 are a frequently used pair. Despite their known toxicity, due to their ability to provide a high specific impulse and extreme storage stability, this combination is widely used in orbital manoeuvres and launch vehicle propulsion. For re-orientation and minor rendezvous burns, Cygnus' ACS is used.

II. CASE STUDY AND SOFTWARE IMPLEMENTATION

The hypotheses and data used in this work are shown in tabular form Tab.1.

The analyses were carried out under two conditions: in the case of evolutionary equilibrium or frozen. The most real hypothesis is that of frozen reactions (*frozen*) in the divergent part of the nozzle: there will be many atoms leaving the system, representing lost energy. At this point it is possible to run the CEA software using the data in Tab. 1 and plot the obtained results. The results of the CEA software are reported in the Appendix.

III. RESULTS

It can be seen from the plot Fig. 5 that, as designed, the maximum impulse is obtained around a mixing ratio of about 1.6. It should be noted that this result has also been obtained in the literature [1]. At this point it is possible to analyse the trend of the concentrations both in the combustion chamber and in the nozzle.

BT-4	
Pressure	1 atm
OF	[1,2,6]
Fuel	CH_6N_2(L),MMH
Oxidizer	N_2O_4

Table 1: Input Data

Figure 2: The Canadarm2 moves toward the Orbital Sciences Corp. Cygnus commercial cargo craft as it approaches the International Space Station on Jan. 12, 2014. [2]

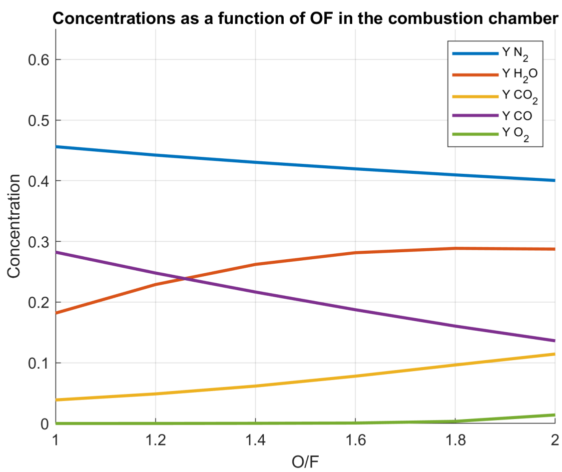

Figure 3: Concentrations as a function of mixing ratio in the combustion chamber

However, it is of fundamental importance to understand the parameters that characterise this trend. This is possible by analysing the trends of the functions that constitute it. The specific impulse is given by the

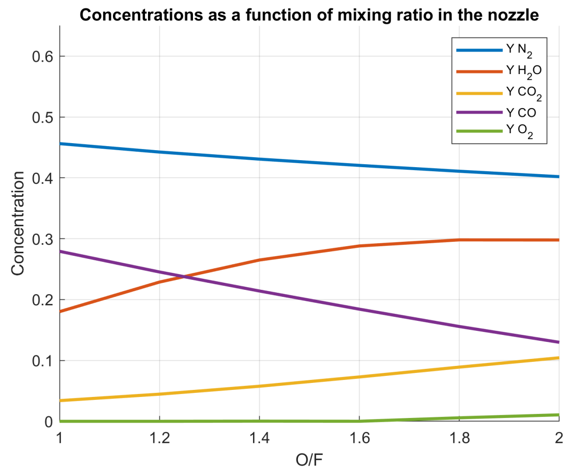

Figure 4: Concentrations as a function of mixing ratio in the nozzle

product of the characteristic speed c^* and the thrust coefficient c_f:

$$I_{sp} = c_f \cdot c^* \quad (1)$$

Note that the characteristic velocity, exclusively related to what happens in the combustion chamber, is given by:

$$c^* = f(T_{ch}, \text{Molecular Weight}) \quad (2)$$

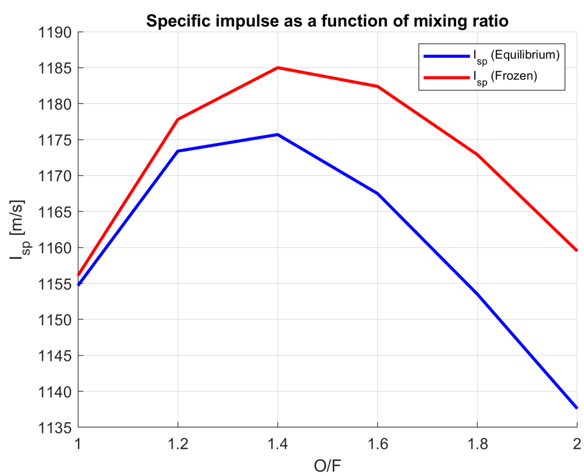

Figure 5: Specific impulse plot

It is also desired to emphasise the difference between the case of efflux in equilibrium and frozen efflux in the divergent part of the convergent-divergent nozzle. It can be seen immediately that the specific impulse in the second case mentioned is actually lower. This is because, when the efflux is frozen, the characteristic time of the chemical reactions t_{eq} is much greater than the characteristic convective time, i.e. the crossing time t_c. Under these conditions, the exothermic reactions that would lead to the re-association of the dissociated species generated in the combustion chamber do not occur. Re-association would lead to an increase in the enthalpy of association and thus a consequent increase in temperature. When the efflux is frozen, and therefore this does not occur, the chemical energy to be converted into kinetic energy through the nozzle, and therefore into thrust, is less than in the case of efflux at equilibrium, where instead the exothermic reactions would have the necessary time to start. In conclusion, therefore, the difference in specific impulses in the case of frozen efflux and in the case of efflux at equilibrium will be hardly noticeable for low OF ratios since they will correspond to low temperatures. In this case the dissociated species from combustion would be present in small quantities. If they were to be re-associated, there would be no major energy emissions. A much sharper distinction between the two cases can be seen at high temperatures and thus as the mixing ratio increases.

APPENDIX. CEA LISTING

Listing 1: CEA Listing

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         NASA-GLENN CHEMICAL EQUILIBRIUM PROGRAM CEA2, FEBRUARY 5, 2004
                   BY  BONNIE MCBRIDE AND SANFORD GORDON
      REFS: NASA RP-1311, PART I, 1994 AND NASA RP-1311, PART II, 1996

 *******************************************************************************


### CEA analysis performed on Wed 05-May-2021 16:53:51

# Problem Type: "Rocket" (Infinite Area Combustor)

prob case=dmt____________1812 ro equilibrium frozen

# Pressure (1 value):
p,atm= 10

# Oxidizer/Fuel Wt. ratio (6 values):
o/f= 1, 1.2, 1.4, 1.6, 1.8, 2

# You selected the following fuels and oxidizers:
reac
fuel CH6N2(L),MMH      wt%=100.0000
oxid N2O4              wt%=100.0000

# You selected these options for output:
# short version of output
output short
# Proportions of any products will be expressed as Mass Fractions.
output massf
# Heat will be expressed as siunits
output siunits

# Input prepared by this script:/var/www/sites/cearun.grc.nasa.gov/cgi-bin/CEARU
N/prepareInputFile.cgi

### IMPORTANT:  The following line is the end of your CEA input file!
end

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)      KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.00000  %FUEL= 50.000000  R,EQ.RATIO= 2.496406  PHI,EQ.RATIO= 2.496406

                CHAMBER   THROAT
Pinf/P            1.0000   1.8109
P, BAR            10.133   5.5954
T, K             2396.24  2125.90
RHO, KG/CU M    8.5052-1 5.3001-1
H, KJ/KG          588.21  -78.453
U, KJ/KG         -603.12 -1134.17
G, KJ/KG        -32567.9 -29493.9
S, KJ/(KG)(K)    13.8367  13.8367
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M, (1/n)          16.724   16.743
(dLV/dLP)t      -1.00084 -1.00027
(dLV/dLT)p        1.0193   1.0066
Cp, KJ/(KG)(K)    2.5931   2.4137
GAMMAs            1.2475   1.2630
SON VEL,M/SEC     1219.1   1154.7
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1655.6
CF                         0.6974
Ivac, M/SEC                2069.0
Isp, M/SEC                 1154.7

MASS FRACTIONS

*CO              0.28236  0.27932
*CO2             0.03397  0.03875
*H               0.00018  0.00006
*H2              0.04508  0.04541
H2O              0.18186  0.18015
NH3              0.00001  0.00001
*NO              0.00002  0.00000
*N2              0.45622  0.45624
*OH              0.00028  0.00006

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.00000  %FUEL= 50.000000  R,EQ.RATIO= 2.496406  PHI,EQ.RATIO= 2.496406

                CHAMBER   THROAT
Pinf/P            1.0000   1.8170
P, BAR            10.133   5.5764
T, K             2396.24  2110.20
RHO, KG/CU M    8.5052-1 5.3153-1
H, KJ/KG          588.21  -80.032
U, KJ/KG         -603.12 -1129.15
G, KJ/KG        -32567.9 -29278.3
S, KJ/(KG)(K)    13.8367  13.8367

M, (1/n)          16.724   16.724
Cp, KJ/(KG)(K)    2.3588   2.3119
GAMMAs            1.2671   1.2740
SON VEL,M/SEC     1228.6   1156.1
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1648.9
CF                         0.7011
Ivac, M/SEC                2063.6
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Isp, M/SEC                 1156.1

MASS FRACTIONS

*CO             0.28236   *CO2            0.03397   *H              0.00018
*H2             0.04508   H2O             0.18186   NH3             0.00001
*NO             0.00002   *N2             0.45622   *OH             0.00028

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.20000  %FUEL= 45.454545  R,EQ.RATIO= 2.080338  PHI,EQ.RATIO= 2.080338

                CHAMBER   THROAT
Pinf/P            1.0000   1.7911
P, BAR            10.133   5.6570
T, K             2691.24  2429.96
RHO, KG/CU M    8.1468-1 5.0545-1
H, KJ/KG          534.74  -153.66
U, KJ/KG         -709.00 -1272.87
G, KJ/KG        -35700.3 -32870.8
S, KJ/(KG)(K)    13.4641  13.4641

M, (1/n)          17.991   18.052
(dLV/dLP)t      -1.00295 -1.00125
(dLV/dLT)p        1.0632   1.0292
Cp, KJ/(KG)(K)    2.9373   2.5904
GAMMAs            1.2120   1.2302
SON VEL,M/SEC     1227.8   1173.4
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1708.5
CF                         0.6868
Ivac, M/SEC                2127.2
Isp, M/SEC                 1173.4

MASS FRACTIONS

*CO              0.24795  0.24534
*CO2             0.04460  0.04872
*H               0.00053  0.00024
*H2              0.03340  0.03379
H2O              0.22898  0.22878
NH3              0.00001  0.00001
*NO              0.00023  0.00006
*N2              0.44233  0.44242
*O               0.00003  0.00001
*OH              0.00190  0.00064
*O2              0.00002  0.00000

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K
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NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                  1.0000000     54200.000    298.150
OXIDANT     N2O4                          1.0000000         0.000      0.000

O/F=    1.20000  %FUEL= 45.454545  R,EQ.RATIO= 2.080338  PHI,EQ.RATIO= 2.080338

                CHAMBER   THROAT
Pinf/P            1.0000   1.8071
P, BAR            10.133   5.6072
T, K             2691.24  2386.58
RHO, KG/CU M    8.1468-1 5.0838-1
H, KJ/KG          534.74  -158.82
U, KJ/KG         -709.00 -1261.76
G, KJ/KG        -35700.3 -32291.9
S, KJ/(KG)(K)    13.4641  13.4641

M, (1/n)          17.991   17.991
Cp, KJ/(KG)(K)    2.2958   2.2558
GAMMAs            1.2520   1.2576
SON VEL,M/SEC     1247.9   1177.8
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1692.3
CF                         0.6960
Ivac, M/SEC                2114.2
Isp, M/SEC                 1177.8

MASS FRACTIONS

*CO             0.24795   *CO2            0.04460   *H              0.00053
*H2             0.03340   H2O             0.22898   NH3             0.00001
*NO             0.00023   *N2             0.44233   *O              0.00003
*OH             0.00190   *O2             0.00002

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                  1.0000000     54200.000    298.150
OXIDANT     N2O4                          1.0000000         0.000      0.000

O/F=    1.40000  %FUEL= 41.666667  R,EQ.RATIO= 1.783147  PHI,EQ.RATIO= 1.783147

                CHAMBER   THROAT
Pinf/P            1.0000   1.7708
P, BAR            10.133   5.7219
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T, K              2910.05  2674.25
RHO, KG/CU M    8.0132-1 4.9552-1
H, KJ/KG           490.18  -200.92
U, KJ/KG          -774.29 -1355.65
G, KJ/KG         -37671.0 -35270.0
S, KJ/(KG)(K)     13.1136  13.1136

M, (1/n)           19.135   19.256
(dLV/dLP)t       -1.00692 -1.00366
(dLV/dLT)p         1.1423   1.0808
Cp, KJ/(KG)(K)     3.5314   2.9980
GAMMAs             1.1815   1.1970
SON VEL,M/SEC      1222.3   1175.7
MACH NUMBER         0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                       1.0000
CSTAR, M/SEC                1739.3
CF                          0.6760
Ivac, M/SEC                 2157.9
Isp, M/SEC                  1175.7

MASS FRACTIONS

*CO               0.21664  0.21409
*CO2              0.05763  0.06163
*H                0.00094  0.00054
*H2               0.02403  0.02431
H2O               0.26217  0.26503
*NO               0.00112  0.00043
*N2               0.43042  0.43075
*O                0.00027  0.00007
*OH               0.00650  0.00306
*O2               0.00026  0.00007

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL       K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.40000  %FUEL= 41.666667  R,EQ.RATIO= 1.783147  PHI,EQ.RATIO= 1.783147

                CHAMBER   THROAT
Pinf/P             1.0000   1.8001
P, BAR             10.133   5.6290
T, K              2910.05  2593.36
RHO, KG/CU M    8.0132-1 4.9953-1
H, KJ/KG           490.18  -211.99
U, KJ/KG          -774.29 -1338.85
G, KJ/KG         -37671.0 -34220.3
S, KJ/(KG)(K)     13.1136  13.1136

M, (1/n)           19.135   19.135
Cp, KJ/(KG)(K)     2.2340   2.1992
GAMMAs             1.2415   1.2462
SON VEL,M/SEC      1252.9   1185.0
MACH NUMBER         0.000    1.000
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PERFORMANCE PARAMETERS

Ae/At                       1.0000
CSTAR, M/SEC                1711.7
CF                          0.6923
Ivac, M/SEC                 2135.9
Isp, M/SEC                  1185.0

MASS FRACTIONS

*CO             0.21664   *CO2            0.05763   *H              0.00094
*H2             0.02403   H2O             0.26217   *NO             0.00112
*N2             0.43042   *O              0.00027   *OH             0.00650
*O2             0.00026

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.60000  %FUEL= 38.461538  R,EQ.RATIO= 1.560254  PHI,EQ.RATIO= 1.560254

                CHAMBER   THROAT
Pinf/P            1.0000   1.7526
P, BAR            10.133   5.7813
T, K             3059.15  2854.26
RHO, KG/CU M    8.0264-1 4.9533-1
H, KJ/KG          452.47  -229.04
U, KJ/KG         -809.93 -1396.20
G, KJ/KG        -38677.4 -36738.2
S, KJ/(KG)(K)    12.7911  12.7911

M, (1/n)          20.148   20.333
(dLV/dLP)t      -1.01302 -1.00809
(dLV/dLT)p        1.2624   1.1735
Cp, KJ/(KG)(K)    4.3967   3.7096
GAMMAs            1.1581   1.1678
SON VEL,M/SEC     1209.2   1167.5
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                       1.0000
CSTAR, M/SEC                1752.1
CF                          0.6663
Ivac, M/SEC                 2167.2
Isp, M/SEC                  1167.5

MASS FRACTIONS

*CO              0.18744  0.18422
*CO2             0.07289  0.07795
*H               0.00122  0.00084
*H2              0.01692  0.01689
H2O              0.28144  0.28811
```

```
*NO               0.00328  0.00168
*N2               0.41968  0.42043
*O                0.00110  0.00046
*OH               0.01441  0.00869
*O2               0.00161  0.00071

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.60000  %FUEL= 38.461538  R,EQ.RATIO= 1.560254  PHI,EQ.RATIO= 1.560254

                CHAMBER   THROAT
Pinf/P            1.0000   1.7952
P, BAR            10.133   5.6441
T, K             3059.15  2735.53
RHO, KG/CU M    8.0264-1 4.9998-1
H, KJ/KG          452.47  -246.51
U, KJ/KG         -809.93 -1375.36
G, KJ/KG        -38677.4 -35237.0
S, KJ/(KG)(K)    12.7911  12.7911

M, (1/n)          20.148   20.148
Cp, KJ/(KG)(K)    2.1749   2.1438
GAMMAs            1.2342   1.2384
SON VEL,M/SEC     1248.2   1182.4
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1714.0
CF                         0.6898
Ivac, M/SEC                2137.1
Isp, M/SEC                 1182.4

MASS FRACTIONS

*CO             0.18744   *CO2            0.07289   *H              0.00122
*H2             0.01692   H2O             0.28144   *NO             0.00328
*N2             0.41968   *O              0.00110   *OH             0.01441
*O2             0.00161

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
```

```
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.80000  %FUEL= 35.714286  R,EQ.RATIO= 1.386892  PHI,EQ.RATIO= 1.386892

                CHAMBER   THROAT
Pinf/P            1.0000   1.7389
P, BAR            10.133   5.8269
T, K             3148.38  2969.93
RHO, KG/CU M    8.1407-1 5.0194-1
H, KJ/KG          420.15  -245.11
U, KJ/KG         -824.52 -1405.99
G, KJ/KG        -38925.6 -37360.6
S, KJ/(KG)(K)    12.4971  12.4971

M, (1/n)          21.032   21.271
(dLV/dLP)t      -1.02066 -1.01484
(dLV/dLT)p        1.4113   1.3132
Cp, KJ/(KG)(K)    5.4098   4.7357
GAMMAs            1.1427   1.1461
SON VEL,M/SEC     1192.6   1153.5
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1750.1
CF                         0.6591
Ivac, M/SEC                2159.9
Isp, M/SEC                 1153.5

MASS FRACTIONS

*CO              0.16044  0.15575
*CO2             0.08906  0.09644
*H               0.00129  0.00099
HO2              0.00001  0.00001
*H2              0.01188  0.01153
H2O              0.28862  0.29810
*NO              0.00678  0.00431
*N2              0.40970  0.41086
*O               0.00270  0.00154
*OH              0.02372  0.01693
*O2              0.00575  0.00352

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    1.80000  %FUEL= 35.714286  R,EQ.RATIO= 1.386892  PHI,EQ.RATIO= 1.386892

                CHAMBER   THROAT
Pinf/P            1.0000   1.7921
P, BAR            10.133   5.6541
T, K             3148.38  2821.69
RHO, KG/CU M    8.1407-1 5.0686-1
H, KJ/KG          420.15  -267.67
U, KJ/KG         -824.52 -1383.19
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G, KJ/KG        -38925.6 -35530.7
S, KJ/(KG)(K)    12.4971  12.4971

M, (1/n)          21.032   21.032
Cp, KJ/(KG)(K)    2.1192   2.0907
GAMMAs            1.2293   1.2332
SON VEL,M/SEC     1237.0   1172.9
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1704.4
CF                         0.6881
Ivac, M/SEC                2124.0
Isp, M/SEC                 1172.9

MASS FRACTIONS

*CO             0.16044   *CO2            0.08906   *H              0.00129
HO2             0.00001   *H2             0.01188   H2O             0.28862
*NO             0.00678   *N2             0.40970   *O              0.00270
*OH             0.02372   *O2             0.00575

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

             THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM

          COMPOSITION DURING EXPANSION FROM INFINITE AREA COMBUSTOR

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    2.00000  %FUEL= 33.333333  R,EQ.RATIO= 1.248203  PHI,EQ.RATIO= 1.248203

                CHAMBER   THROAT
Pinf/P            1.0000   1.7309
P, BAR            10.133   5.8538
T, K             3192.43  3030.36
RHO, KG/CU M    8.3199-1 5.1280-1
H, KJ/KG          392.14  -254.88
U, KJ/KG         -825.73 -1396.40
G, KJ/KG        -38652.2 -37317.1
S, KJ/(KG)(K)    12.2303  12.2303

M, (1/n)          21.795   22.072
(dLV/dLP)t      -1.02750 -1.02216
(dLV/dLT)p        1.5434   1.4629
Cp, KJ/(KG)(K)    6.2301   5.7575
GAMMAs            1.1342   1.1336
SON VEL,M/SEC     1175.3   1137.6
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1737.0
CF                         0.6549
Ivac, M/SEC                2141.0
Isp, M/SEC                 1137.6
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MASS FRACTIONS

*CO              0.13624  0.12983
*CO2             0.10434  0.11442
*H               0.00121  0.00097
HNO              0.00001  0.00000
HO2              0.00003  0.00002
*H2              0.00849  0.00796
H2O              0.28741  0.29791
*N               0.00001  0.00000
*NO              0.01100  0.00798
NO2              0.00001  0.00000
*N2              0.40050  0.40192
*O               0.00475  0.00322
*OH              0.03192  0.02512
*O2              0.01408  0.01064

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K

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

          THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION

Pin =   147.0 PSIA
CASE = dmt____________

            REACTANT                    WT FRACTION      ENERGY      TEMP
                                         (SEE NOTE)     KJ/KG-MOL      K
FUEL        CH6N2(L),MMH                 1.0000000     54200.000    298.150
OXIDANT     N2O4                         1.0000000         0.000      0.000

O/F=    2.00000  %FUEL= 33.333333  R,EQ.RATIO= 1.248203  PHI,EQ.RATIO= 1.248203

                CHAMBER   THROAT
Pinf/P            1.0000   1.7900
P, BAR            10.133   5.6605
T, K             3192.43  2865.29
RHO, KG/CU M    8.3199-1 5.1785-1
H, KJ/KG          392.14  -280.04
U, KJ/KG         -825.73 -1373.11
G, KJ/KG        -38652.2 -35323.4
S, KJ/(KG)(K)    12.2303  12.2303

M, (1/n)          21.795   21.795
Cp, KJ/(KG)(K)    2.0677   2.0408
GAMMAs            1.2262   1.2299
SON VEL,M/SEC     1222.0   1159.5
MACH NUMBER        0.000    1.000

PERFORMANCE PARAMETERS

Ae/At                      1.0000
CSTAR, M/SEC               1687.5
CF                         0.6871
Ivac, M/SEC                2102.2
Isp, M/SEC                 1159.5

MASS FRACTIONS

*CO             0.13624   *CO2            0.10434   *H              0.00121
HNO             0.00001   HO2             0.00003   *H2             0.00849
H2O             0.28741   *N              0.00001   *NO             0.01100
NO2             0.00001   *N2             0.40050   *O              0.00475
*OH             0.03192   *O2             0.01408

 * THERMODYNAMIC PROPERTIES FITTED TO 20000.K
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NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
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References

[1] Muhalim, Noor Muhammad Feizal B., and Subramaniam Krishnan, *"Design Of Nitrogen-Tetroxide/Monomethyl-Hydrazine Thruster For Upper Stage Application"*, Department of Aeronautical Engineering, Faculty of Mechanical Engineering Universiti Teknologi Malaysia, 81310 Skudai, Malaysia
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