Finite Area Combustor Theoretical Rocket Performance

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ABSTRACT

Previous to this report, the computer program of NASA SP-273 and NASA TM-86885 was capable of calculating theoretical rocket performance based only on the assumption of an infinite area combustion chamber (IAC). An option has been added to this program which now also permits the calculation of rocket performance based on the assumption of a finite area combustion chamber (FAC). In the FAC model, the combustion process in the cylindrical chamber is assumed to be adiabatic, but nonisentropic. This results in a stagnation pressure drop from the injector face to the end of the chamber and a lower calculated performance for the FAC model than the IAC model.

INTRODUCTION

The calculation of theoretical rocket performance involves a number of assumptions. For the same propellant and operating conditions, theoretical performance can vary depending on which assumptions are used. Rocket performance calculated by the computer program of references 1 and 2 assumes adiabatic combustion in an infinite area combustion chamber (IAC) followed by isentropic expansion in the nozzle. In order to have a more realistic model, this supplement to references 1 and 2 presents an additional option for calculating rocket performance based on the
assumption of adiabatic combustion in a finite area combustor (FAC) followed by isentropic expansion. Two input options are available for the FAC problem. Input option 1 is an assigned contraction ratio, while input option 2 is for an assigned mass flow per unit combustor area.

The addition of this new FAC option required changes in only two of the subroutines of the reference 1 program; namely, ROCKET and RKOUT. A short description is given herein of the equations and iteration procedures. Three sample cases are given to facilitate the discussion of input options, output, and analysis of the effect on performance for the assumptions of FAC and IAC.

FINITE AREA COMBUSTION

Combustion in a rocket chamber is a nonisentropic, irreversible process. During the burning process, part of the energy released is used to raise the entropy, an undesirable form of energy inasmuch as it is unavailable to do work. This energy utilization loss is reflected in a total pressure drop as the gases are being accelerated from the beginning of the combustion process (at or near the injector face) to the end of the chamber. The combustion process may still be considered to be adiabatic; however, due to heat not being added at constant pressure during combustion, "the energy available for producing nozzle exit velocities is less than exists under ideal conditions of negligible chamber velocity." (ref. 3). Calculated rocket performance will therefore be less for the model of FAC than for the more commonly used ideal model of IAC.

A sketch of a rocket is given in figure 1. The positions in figure 1 are numbered in the same order as they appear in the performance output tables. The entrance to the finite chamber will be referred to as the injector face and will be indicated by 'inj' or '1' as subscript. The end of the finite chamber (nozzle entrance) will be indicated with the subscript '4' or 'c'. The infinite area position is indicated by subscript 'inf' or '2' while the throat is indicated by subscript 't' or '3'.

Equations

Unless otherwise stated, the International System of Units (SI Units) is used. The relationship of forces between points 1 and 4 for the nonisentropic process of combustion in a finite area is given by the following equation (ref. 3, p. 81)

\[
\left( P + \frac{m u}{A} \right)_1 = \left( P + \frac{m u}{A} \right)_4
\]  

(1)
where $P$ is pressure, $A$ is the combustor area, $\dot{m}$ is the mass flow rate, and $u$ is velocity. Equation (1) may be written as

$$ (P + \rho u^2)_1 = (P + \rho u^2)_4 $$

(2)

by using the continuity relationship

$$ \dot{m} = \rho Au \quad (3) $$

where $\rho$ is density.

When velocity at the injector face is negligible, equations (1) and (2) reduce to

$$ P_1 = P_{inj} = \left( P + \frac{\dot{m} u}{A} \right)_4 = (P + \rho u^2)_4 \quad (4) $$

### Iteration Procedure

An iteration procedure is required to satisfy Eq. 4. Two input options are available for FAC. In option 1, the contraction ratio $\frac{A_c}{A_t}$ is assigned. In option 2, the mass flow rate per unit combustor area $\frac{\dot{m}}{A}$ is assigned. The iteration procedure for option 1 is simpler and therefore will be described first. All of the first four points shown in figure 1 are involved in the iteration procedure. Thermodynamic parameters at point 1 are obtained by a combustion calculation (HP problem in reference 1). Starting with an estimated value for $P_2$, calculations are then made for points 2, 3, and 4 (the assigned contraction ratio) as would usually be done for infinite area combustion, throat, and an assigned area ratio as described in reference 1. A check is made to see if equation 4 is satisfied to within the following tolerance

$$ \frac{|P_{inj} - (P + \rho u^2)_4|}{P_{inj}} \leq 2 \times 10^{-5} \quad (5) $$

If Eq. 5 is satisfied, then the calculations for the finite area combustor are complete for points 1, 2, 3 and 4. Calculations are then continued if other values of pressure ratio and/or area ratio have been specified in the input dataset. If Eq. 5 is not satisfied, then an improved estimate for $P_2$ is obtained as described in a later section and the procedure for points 2, 3 and 4 is repeated until Eq. 5 is satisfied.

A similar procedure is used for option 2 as was described for option 1. However, the contraction ratio is not known for option 2. Therefore, the iteration procedure involves starting with an estimated value for $\frac{A_c}{A_t}$ as well as for $P_2$ and then obtaining improved estimates for both $P_2$ and $\frac{A_c}{A_t}$. Not surprisingly, more iterations are required for option 2 than for option 1 which requires improved estimates for $P_2$ only. As in the case of option 1, iteration is complete when Eq. 5 is satisfied.
Initial Estimates

A curve is given in figure 3-18 of reference 3 which relates \( \frac{P_2}{P_{inj}} \) with \( \frac{A_c}{A_t} \) for an assumed value of \( \gamma = 1.2 \). The following empirical equation was derived by fitting three selected points read from the curve:

\[
P_2 = P_{inj} \left[ \frac{1.0257 - 1.2318 \frac{A_c}{A_t}}{1 - 1.26505 \frac{A_c}{A_t}} \right]
\] (6)

Eq. 6 is used only to obtain an initial estimate for \( P_2 \).

For option 1, the assigned value of \( \frac{A_c}{A_t} \) is used in Eq. 6. For option 2, an initial estimate of \( \frac{A_c}{A_t} \) is required (see Input Option Parameters section). This initial estimate is used in Eq. 6 to obtain a value for \( P_2 \), which is then used in the following equation to obtain an improved initial estimate for \( \frac{A_c}{A_t} \):

\[
\frac{A_c}{A_t} = \frac{P_2}{2350 \frac{m}{A_c}}
\] (7)

Eq. 7 was derived by starting with the relationship for characteristic velocity \( c^* = P_2 \frac{A_t}{m} \), multiplying both sides by \( A_c \) and using an arbitrary value of \( c^* = 2350 \text{ m/s} \).

Somewhat better initial estimates for both \( P_2 \) and \( \frac{A_c}{A_t} \) are obtained by repeating several times the sequence of substituting values of \( \frac{A_c}{A_t} \) from Eq. 7 into Eq. 6 and values of \( P_2 \) from Eq. 6 into Eq. 7. If the input value of \( \frac{m}{A_c} \) is so large that Eq. 7 calculates a value less than 1, the program will stop the calculations and print out the error message "INPUT VALUE OF MDOT/A = (value) IS TOO LARGE. GIVES CR ESTIMATE LESS THAN 1".

Improved Estimates

For option 1, an improved estimate for \( P_2 \) is obtained by assuming that the ratio of the assigned value of \( P_{inj} \) to the current value of \( P_{inj} \) (obtained by means of Eq. 4) is equal to the ratio of the final value of \( P_2 \) to the current value of \( P_2 \). This assumption leads to the following equation:

\[
P_{2,\text{new}} = P_2 \frac{P_{inj,a}}{P_{inj}}
\] (8)

The use of Eq. 8 often gives such an excellent improved estimate for \( P_2 \) that it need be used only once to obtain convergence (Eq. 5).
For option 2, an improved estimate for \( \frac{A_c}{A_t} \) is required in addition to the one for \( P_2 \) and is obtained from the following equation

\[
\frac{A_c}{A_t} = \frac{m}{m_c}
\]

(9)

Inasmuch as both \( P_2 \) and \( \frac{A_c}{A_t} \) are changing, the iteration procedure is longer for option 2 than for option 1. For option 2, as well as for option 1, convergence is complete when Eq. 5 is satisfied.

**Input Option Parameters**

Two options are available for obtaining finite combustor area performance. In addition to the usual required input parameters described in ref. 1 for namelist &RKTINP, several additional parameters are required. For option 1 these are: FAC = T and ACAT = some assigned value for \( \frac{A_c}{A_t} \). For option 2, the additional parameters are FAC = T and MA = some assigned value for \( \frac{m}{m_c} \). Option 2 also requires an initial estimate of \( \frac{A_c}{A_t} \). A default value of ACAT = 2 is provided in the program for this initial estimate. However, if desired, a different initial estimate for ACAT may be included in the &RKTINP data. Thus, for option 2, a value of MA is required in &RKTINP, whereas an estimated value for ACAT is optional.

In FAC, the PCP values \( \frac{P_{inf}}{P_c} \) are relative to the injector face pressure, whereas in IAC, the PCP values \( \frac{P_{inf}}{P_c} \) are relative to the infinite area chamber pressure. Due to this definition of PCP, the assigned values of PCP must be larger than \( \frac{P_{inf}}{P_{inf}} \). Otherwise, this will give values of \( P_c \) larger than \( P_{inf} \), which is an impossible condition. For example, in table III, the value of \( \frac{P_{inf}}{P_{inf}} = 1.0848 \). If a value of PCP less than this had been assigned, 1.05 for example, this would have given a value of 

\[
P_c = \frac{P_{inf}}{P_{inf}} = \frac{5331700}{1.05} = 5077810 \text{ Pa}
\]

which is more than the value of \( P_{inf} = 4914900 \text{ Pa} \), an impossible condition. If impossible values of PCP are inadvertently included in the input data set, these values will automatically be omitted by the program and the following error message printed: PRESSURE RATIO OF (value) GIVES PE GREATER THAN PINF. OMIT THIS POINT.

**SAMPLE PROBLEMS**

Three sample problems were selected, one for IAC (case 1) and two for FAC (cases 2 and 3), to illustrate some input and output features and to provide performance data for a comparison of results. The input datasets for these problems
are given in table I and the output is given in tables II to IV. All sample problems are for the same propellant, o/f and chamber pressure. The propellant is $H_2(1)$ at 20.17K and $O_2(1)$ at 90.18K, o/f = 5.55157, and chamber pressure is 5331721 $N_\text{m}^2$ (52.62 atm). A number of assigned pressure ratios, PCP, and supersonic area ratios, SUPAR ($\frac{A_s}{A_i}$) are common to all problems. The PCP values selected are 10, 100, and 1000. The SUPAR values are 25, 50 and 75. In addition, the FAC case 2 has as assigned contraction ratio $\frac{A_c}{A_s} = 1.58$ while the FAC case 3 has an assigned $\frac{m}{A_c} = 1332.0$. The value of $\frac{m}{A_c}$ was calculated from the results of case 2 as follows: from table III, in the column for $\frac{A_c}{A_i} = 1.58$, $\rho = 2.0353$ and $u = I_{sp} = 654.5$. The product, $\rho u = 1332$, is equal to $\frac{m}{A_c}$ from the continuity relationship (Eq. 3). Case 3, therefore, should reproduce the case 2 contraction ratio of 1.58, which indeed it does. Cases 2 and 3 both have FAC = T. For comparison purposes, the IAC problem includes an assigned subsonic area ratio SUBAR = 1.58. In the FAC cases, the output column for the contraction ratio appears before the assigned pressure ratios, while in IAC, the SUBAR column appears after the assigned pressure ratio columns.

**Output Format**

The output format previously used for IAC has been somewhat revised to accommodate FAC. These revisions are as follows:

1. The first line of the output headings are the same for both cases and now read as follows: THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION. The second line for IAC reads FROM AN INFINITE AREA COMBUSTOR, while for FAC it reads FROM A FINITE AREA COMBUSTOR.

2. The line following the heading which gives chamber pressure in units of psia has been changed from PC to PINJ for FAC and PINF for IAC.

3. An additional line has been added for FAC which gives either $\frac{\text{MDOT}}{AC} =$ (value) if the input data set contains an assigned value for $\frac{m}{A_c}$ or $\frac{AC}{AT} =$ (value) if input contains an assigned value for contraction ratio $\frac{A_c}{A_i}$.

4. An additional row of output has been added for FAC; namely, PINJ/P (ratio of pressure at the injector face to exit pressure $\frac{P_{inj}}{P_e}$).

5. The next row gives the ratio of pressure at infinite chamber area to exit pressure. The label PC/P formerly used for IAC for this row has now been changed to PINF/P.
6. The first four columns for FAC are INJECTOR, INF CHAM, THROAT, and CN RATIO for conditions at the injector face, infinite area chamber, throat and contraction ratio. The columns for conditions at the injector face and contraction ratio are two additional columns which have been added for FAC and do not appear for IAC.

7. When more than 13 columns of data are required, the first two columns of data are repeated on the second sheet of output data for IAC as before, while the first three columns of data are repeated for FAC.

8. For IAC, the option remains, as before, of calculating rocket performance based on the assumption of either equilibrium composition, frozen composition or both during expansion. For FAC, only the equilibrium option is permitted.

9. An option is provided to print intermediate output pertaining to the convergence process for $\alpha$, $\alpha'_m$, $\frac{A_t}{A_c}$ or $\frac{m_t}{m_c}$. This output is obtained by setting IDBUGF = 1 in namelist &RKTINP.

**EFFECT ON PERFORMANCE**

Table II presents rocket performance data for the infinite area combustor (case 1) while tables III and IV present similar data for the finite area combustor cases 2 and 3. As expected, the results in tables III and IV are identical (see discussion in SAMPLE PROBLEMS). Table V summarizes and compares some of the data in tables II and III. It may be noted in table V that for the same pressure ratios, the area ratios and specific impulse for the case of finite area combustor are less than for case of infinite area combustor. This is due to a loss in total pressure during the non-isentropic combustion from the injector face to the end of the finite combustor.

The term $1 - \frac{P_{out}}{P_{in}}$ represents the energy utilization loss due to this non-isentropic combustion. The energy utilization loss for this particular example (contraction ratio equal 1.58) is about 3.12% at a pressure ratio of 10 and about 0.62% at a pressure ratio of 1000. There are two general trends in energy utilization losses. The first trend, which was just illustrated, is that for the same contraction ratio, energy utilization losses decrease with increasing pressure ratios $P_{out}/P_{in}$. The second trend, for which data are not given in this report, is that for the same pressure ratio $P_{out}/P_{in}$, energy losses decrease with increasing contraction ratios.

The previous numerical comparisons of table V data are for the same pressure ratios for IAC and FAC. However, the area ratios are not the same. When the comparison in energy utilization loss is for the assumption of the same area ratios,
the losses are negligible. For example, as may be seen in table V, for area ratios of 25, 50 and 75, the energy utilization loss is only 0.05% or less.

**CONCLUDING REMARKS**

Previous to this report, the computer program of ref. 1 permitted calculation of theoretical rocket performance based on combustion in an infinite area combustor. An option has now been added to this program that permits performance calculations based on the assumption of a finite area combustor. Calculations were made for a typical example ($H_2 - O_2$ propellant, contraction ratio of 1.58) based on the two assumptions of finite and infinite area combustion chambers in order to assess the size of energy utilization losses due to the nonisentropic combustion process in the finite area combustor. The comparison of an energy utilization loss term involving specific impulse was made at several assigned pressure ratios and several assigned area ratios. The comparison showed energy utilization losses of 0.6% to 3.0% for assigned pressure ratios of 1000 to 10 respectively, whereas for assigned area ratios of 25 to 75, the energy utilization losses were trivial (0.05% or less).

Further information on the code can be obtained from the authors. Contact COSMIC, The University of Georgia, Athens, Ga. 30602, concerning the availability of this program.

**ACKNOWLEDGEMENT**

Klaus W. Gross of the NASA George C. Marshall Space Flight Center initiated and supported this project.
### APPENDIX – SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>area, $m^2$</td>
</tr>
<tr>
<td>ACAT</td>
<td>symbol in program for contraction ratio</td>
</tr>
<tr>
<td>$A_e/A_t$</td>
<td>contraction ratio (ratio of finite chamber area to throat area)</td>
</tr>
<tr>
<td>$A_e/A_t$</td>
<td>ratio of nozzle exit area to throat area</td>
</tr>
<tr>
<td>$c^*$</td>
<td>characteristic velocity, $\frac{m}{sec}$</td>
</tr>
<tr>
<td>FAC</td>
<td>finite area combustor</td>
</tr>
<tr>
<td>HP</td>
<td>assigned enthalpy and pressure problem (combustion at constant pressure)</td>
</tr>
<tr>
<td>IAC</td>
<td>infinite area combustor</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>specific impulse with exit and ambient pressures equal, $\frac{N}{kg/sec}$ or $\frac{m}{sec}$</td>
</tr>
<tr>
<td>$\frac{m}{A_e}$</td>
<td>symbol in program for ratio of mass flow rate to chamber area, $\frac{kg}{sec}$</td>
</tr>
<tr>
<td>$m$</td>
<td>mass flow rate, $kg/sec$</td>
</tr>
<tr>
<td>P</td>
<td>pressure, $N/m^2$</td>
</tr>
<tr>
<td>PCP</td>
<td>symbol in program for ratio of chamber pressure to exit pressure (For FAC, PCP = $\frac{P_{ex}}{P_e}$). For IAC, PCP = $\frac{P_{ex}}{P_e}$</td>
</tr>
<tr>
<td>SUPAR</td>
<td>symbol in program for supersonic area ratio</td>
</tr>
<tr>
<td>$u$</td>
<td>velocity, $\frac{m}{sec}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heats</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density, $\frac{kg}{m^3}$</td>
</tr>
</tbody>
</table>

### Subscripts

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>assigned</td>
</tr>
<tr>
<td>c</td>
<td>combustor</td>
</tr>
<tr>
<td>e</td>
<td>exit</td>
</tr>
<tr>
<td>f</td>
<td>finite</td>
</tr>
<tr>
<td>i</td>
<td>infinite or ideal</td>
</tr>
<tr>
<td>inf</td>
<td>infinite</td>
</tr>
<tr>
<td>inj</td>
<td>injector</td>
</tr>
<tr>
<td>o/f</td>
<td>oxidant-to-fuel mass ratio</td>
</tr>
<tr>
<td>t</td>
<td>throat</td>
</tr>
</tbody>
</table>
REFERENCES


## Table I. - Input for Sample Cases

### Case 1 Input. - Infinite Area Combustor

**Reactants**

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Concentration</th>
<th>Temperature</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>100</td>
<td>-2154.</td>
<td>L 20.17 F</td>
</tr>
<tr>
<td>O₂</td>
<td>100</td>
<td>-3102.</td>
<td>L 90.18 O</td>
</tr>
</tbody>
</table>

**NameLists**

```plaintext
&INPT2 KASE=1, RKT=T, P=52.62, OF=T, MIX=5.55157,
   SIUNIT=T &END
&RTINP SUBAR=1.58,
   PCP=10,100,1000, SUPAR=25,50,75 &END
```

### Case 2 Input. - Finite Area Combustor, Option 1

**Reactants**

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Concentration</th>
<th>Temperature</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>100</td>
<td>-2154.</td>
<td>L 20.17 F</td>
</tr>
<tr>
<td>O₂</td>
<td>100</td>
<td>-3102.</td>
<td>L 90.18 O</td>
</tr>
</tbody>
</table>

**NameLists**

```plaintext
&INPT2 KASE=2, RKT=T, P=52.62, OF=T, MIX=5.55157,
   SIUNIT=T &END
&RTINP FAC=T, ACAT=1.58,
   PCP=10,100,1000, SUPAR=25,50,75 &END
```

### Case 3 Input. - Finite Area Combustor, Option 2

**Reactants**

<table>
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<tr>
<th>Reactant</th>
<th>Concentration</th>
<th>Temperature</th>
<th>Fuel</th>
</tr>
</thead>
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<tr>
<td>H₂</td>
<td>100</td>
<td>-2154.</td>
<td>L 20.17 F</td>
</tr>
<tr>
<td>O₂</td>
<td>100</td>
<td>-3102.</td>
<td>L 90.18 O</td>
</tr>
</tbody>
</table>

**NameLists**

```plaintext
&INPT2 KASE=3, RKT=T, P=52.62, OF=T, MIX=5.55157,
   SIUNIT=T &END
&RTINP FAC=T, MA=1332.0,
   PCP=10,100,1000, SUPAR=25,50,75 &END
```
### Table II. – Theoretical Rocket Performance Assuming Equilibrium Composition During Expansion From Infinite Area Combustor

<table>
<thead>
<tr>
<th>PINF = 773.3 psia</th>
<th>WT FRACTION (see note)</th>
<th>ENERGY STATE TEMP</th>
<th>DEG K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE NO. 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHEMICAL FORMULA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUEL H 2.00000</td>
<td>1.00000 -9012.332 L</td>
<td>20.17</td>
<td></td>
</tr>
<tr>
<td>OXIDANT O 2.00000</td>
<td>1.00000 -12978.762 L</td>
<td>90.18</td>
<td></td>
</tr>
</tbody>
</table>

**O/F = 5.5516 PERCENT FUEL = 15.2635 EQUIVALENCE RATIO = 1.4297 PHI = 1.4297**

<table>
<thead>
<tr>
<th>CHAMBER</th>
<th>THROAT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINF/P</td>
<td>1.0000</td>
<td>1.7397</td>
<td>10.000</td>
<td>100.00</td>
<td>100.00</td>
<td>1.0202</td>
<td>262.17</td>
</tr>
<tr>
<td>P, MPA</td>
<td>5.3317</td>
<td>3.0647</td>
<td>0.53317</td>
<td>0.05332</td>
<td>0.00533</td>
<td>4.8380</td>
<td>0.02034</td>
</tr>
<tr>
<td>T, DEG K</td>
<td>1395.7</td>
<td>3396.5</td>
<td>2572.9</td>
<td>1756.6</td>
<td>1112.1</td>
<td>3360.4</td>
<td>1461.6</td>
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<tr>
<td>EHO, KG/CU M</td>
<td>2.39950</td>
<td>31402.0</td>
<td>5.27071</td>
<td>4.82082</td>
<td>7.61503</td>
<td>2.20432</td>
<td>2.21012</td>
</tr>
<tr>
<td>H, KG/K</td>
<td>-1026.10</td>
<td>-2214.14</td>
<td>-5444.06</td>
<td>-8577.70</td>
<td>-10632.1</td>
<td>-1260.69</td>
<td>-9552.21</td>
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<tr>
<td>U, KG/K</td>
<td>-3298.13</td>
<td>-4284.56</td>
<td>-7074.23</td>
<td>-9683.68</td>
<td>-11332.3</td>
<td>-3435.67</td>
<td>-10472.4</td>
</tr>
<tr>
<td>G, KG/K</td>
<td>-6354.4</td>
<td>-61828.6</td>
<td>-53427.2</td>
<td>-41336.8</td>
<td>-31373.0</td>
<td>-63910.6</td>
<td>-36810.7</td>
</tr>
<tr>
<td>(DLV/DELP)</td>
<td>-1.02061</td>
<td>-1.01508</td>
<td>-1.00332</td>
<td>-1.0000</td>
<td>-1.0000</td>
<td>-1.01960</td>
<td>-1.0000</td>
</tr>
<tr>
<td>(DLV/DLT)</td>
<td>1.3760</td>
<td>1.2966</td>
<td>1.2761</td>
<td>1.2507</td>
<td>1.2000</td>
<td>1.3602</td>
<td>1.0001</td>
</tr>
<tr>
<td>GAMMA (S)</td>
<td>1.1453</td>
<td>1.1476</td>
<td>1.1745</td>
<td>1.2276</td>
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<td>1.2441</td>
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### Performance Parameters

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<th>25.000</th>
<th>50.000</th>
<th>75.000</th>
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<tr>
<td>GSTAR, M/SEC</td>
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<td>2337</td>
<td>2337</td>
<td>2337</td>
<td>2337</td>
<td>2337</td>
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<td>2337</td>
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<tr>
<td>CF</td>
<td>8.660</td>
<td>1.727</td>
<td>1.665</td>
<td>1.876</td>
<td>0.280</td>
<td>1.767</td>
<td>1.846</td>
<td>1.884</td>
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<td>3520.9</td>
<td>4170.9</td>
<td>4542.9</td>
<td>4005.3</td>
<td>4352.3</td>
<td>4490.3</td>
<td>4557.5</td>
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<td>ISP, M/SEC</td>
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<td>3886.3</td>
<td>4383.2</td>
<td>655.1</td>
<td>4129.4</td>
<td>4313.1</td>
<td>4402.6</td>
</tr>
</tbody>
</table>

### Mole Fractions

| H | 0.03442 | 0.02728 | 0.00811 | 0.00019 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| H2 | 0.00002 | 0.00001 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| H2 | 0.29457 | 0.29001 | 0.29697 | 0.30043 | 0.30555 | 0.29441 | 0.30547 | 0.3055 | 0.3055 |
| H2O | 0.63678 | 0.62546 | 0.60945 | 0.69335 | 0.69965 | 0.67296 | 0.69945 | 0.69965 | 0.69965 |
| H2O2 | 0.00001 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| O | 0.00225 | 0.00131 | 0.00088 | 0.00000 | 0.00000 | 0.00206 | 0.00000 | 0.00000 | 0.00000 |
| OH | 0.03396 | 0.02379 | 0.01433 | 0.00000 | 0.00000 | 0.00315 | 0.00000 | 0.00000 | 0.00000 |
| O2 | 0.00190 | 0.00115 | 0.00007 | 0.00000 | 0.00000 | 0.00176 | 0.00000 | 0.00000 | 0.00000 |

### Additional Products Which Were Considered But Whose Mole Fractions Were Less Than 0.5000E-05 for All Assigned Conditions

| O3 | H2O(S) | H2O(L) |

**Note.** Weight fraction of fuel in total fuels and of oxidant in total oxidants.


<table>
<thead>
<tr>
<th>TABLE III. - THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION FROM FINITE AREA COMBUSTOR</th>
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</thead>
<tbody>
<tr>
<td>PINJ = 773.3 PSIA</td>
</tr>
<tr>
<td>AC/AT = 1.5800</td>
</tr>
<tr>
<td>CASE NO. 2</td>
</tr>
<tr>
<td>CHEMICAL FORMULA</td>
</tr>
<tr>
<td>FUEL H 2.00000</td>
</tr>
<tr>
<td>OXIDANT O 2.00000</td>
</tr>
<tr>
<td>O/F = 5.5516 PERCENT FUEL = 15.2635 EQUIVALENCE RATIO = 1.4297</td>
</tr>
<tr>
<td>PH1 = 1.4297</td>
</tr>
<tr>
<td>W/FRACTION ENERGY STATE TEMP (SEE NOTE) KJ/KG-MOL DEG K</td>
</tr>
<tr>
<td>1.000000 -9012.332 L 20.17</td>
</tr>
<tr>
<td>1.000000 -12987.762 L 90.18</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>INJECTOR INF CHAM THROAT CN RATIO EXIT EXIT EXIT EXIT EXIT</td>
</tr>
<tr>
<td>PINJ/P 1.0000 1.0848 1.8868 1.1955 10.000 100.000 1000.00 283.87 714.18 1225.05</td>
</tr>
<tr>
<td>PINF/P 0.92182 1.0000 1.7393 1.1020 9.2182 92.182 921.82 261.68 658.35 1129.28</td>
</tr>
<tr>
<td>P, MPA 5.3317 4.9149 2.8258 4.6600 0.53317 0.05332 0.00533 0.01878 0.00747 0.00436</td>
</tr>
<tr>
<td>T, DEG K 3395.7 3387.6 3390.3 3352.6 2601.0 1784.2 1132.3 1463.7 1214.9 1084.4</td>
</tr>
<tr>
<td>RNO. KG/CU M 2.3995 0 2.2155 0 1.3666 0 2.0353 0 3.2325-1 4.7461-2 7.4796-3 2.0291-2 9.7609-3 6.3794-3</td>
</tr>
<tr>
<td>H, KJ/KG -1026.10 -1026.10 -2121.87 -1246.26 -5306.21 -848.37 -10572.3 -9547.52 -10323.7 -10713.9</td>
</tr>
<tr>
<td>U, KJ/KG -3248.13 -3244.56 -4279.62 -3431.63 -6955.64 -9606.76 -11283.1 -10468.6 -11088.5 -11396.6</td>
</tr>
<tr>
<td>G, KJ/KG -64356.4 -64383.5 -61800.17 -63963.6 -93952.3 -41852.2 -31748.9 -36911.2 -33045.2 -39995.8</td>
</tr>
<tr>
<td>(DLV/DLP)T -1.022061 -1.02105 -1.01543 -1.00203 -1.03372 -1.00000 -1.00000 -1.00000 -1.00000 -1.00000</td>
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<tr>
<td>(DLV/DLP)T 1.5750 1.3837 1.2982 1.3687 1.0860 1.0021 1.0001 1.0001 1.0001 1.0001</td>
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<tr>
<td>GAMA (S) 1.1453 1.1447 1.1449 1.1459 1.1717 1.2620 1.2680 1.2440 1.2611 1.2723</td>
</tr>
<tr>
<td>SGN VEL M/SEC 1590.3 1930.3 1540.0 1584.0 1390.2 1173.6 950.7 1070.4 982.1 932.0</td>
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<tr>
<td>MACH NUMBER 0.000 0.000 1.000 0.413 2.105 3.291 4.596 3.857 4.391 4.723</td>
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<td>PERFORMANCE PARAMETERS</td>
</tr>
<tr>
<td>AE/AT 1.0000 1.5800 2.2253 11.482 64.396 25.000 50.000 75.000</td>
</tr>
<tr>
<td>CSTAR, M/SEC 2335 2335 2335 2335 2335 2335 2335 2335 2335</td>
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<tr>
<td>CP 0.659 0.280 1.253 1.654 1.871 1.768 1.846 1.885</td>
</tr>
<tr>
<td>IVAC, M/SEC 2882.7 4002.8 3895.9 4152.8 4532.6 4531.4 4689.1 4556.9</td>
</tr>
<tr>
<td>ISP, M/SEC 1540.0 654.5 2925.8 3861.9 4369.3 4283.8 4312.2 4401.8</td>
</tr>
<tr>
<td>MOLE FRACTIONS</td>
</tr>
<tr>
<td>H 0.03442 0.03515 0.02793 0.03387 0.00910 0.00024 0.00000 0.00001 0.00000 0.00000</td>
</tr>
<tr>
<td>HO2 0.00002 0.00002 0.00001 0.00002 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000</td>
</tr>
<tr>
<td>H2 0.29457 0.29444 0.29387 0.29428 0.29661 0.30041 0.30055 0.30054 0.30055 0.30055</td>
</tr>
<tr>
<td>H2O 0.62758 0.62254 0.61940 0.63003 0.60961 0.69932 0.69945 0.69945 0.69945 0.69945</td>
</tr>
<tr>
<td>H2O2 0.00001 0.00001 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000</td>
</tr>
<tr>
<td>O 0.00225 0.00233 0.00136 0.00214 0.00010 0.00000 0.00000 0.00000 0.00000 0.00000</td>
</tr>
<tr>
<td>OH 0.0306 0.03356 0.02622 0.03163 0.00510 0.00004 0.00000 0.00000 0.00000 0.00000</td>
</tr>
<tr>
<td>O2 0.00195 0.00197 0.00120 0.00182 0.00009 0.00000 0.00000 0.00000 0.00000 0.00000</td>
</tr>
</tbody>
</table>

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

O3 H2O2(S) H2O2(L)

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

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### Table IV. - Theoretical Rocket Performance Assuming Equilibrium Composition During Expansion

From Finite Area Combustor

**PINJ = 773.3 FSTI**  
**MDOT/AC = 1332.000 (KG/S)/MM**²  
**CASE NO. 3**

<table>
<thead>
<tr>
<th>FUEL</th>
<th>OXIDANT</th>
<th>WT FRACTION</th>
<th>ENERGY STATE</th>
<th>TEMP</th>
<th>(SEE NOTE)</th>
<th>KG/KG-MOL</th>
<th>DEG K</th>
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<tbody>
<tr>
<td>H</td>
<td>O</td>
<td>1.000000</td>
<td>-901.332</td>
<td>L</td>
<td>20.17</td>
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<td></td>
</tr>
<tr>
<td>2.00000</td>
<td></td>
<td>1.000000</td>
<td>-1297.762</td>
<td>L</td>
<td>90.18</td>
<td></td>
<td></td>
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</table>

| O/F = 5.5516 | PERCENT FUEL = 15.2635 | EQUIVALENCE RATIO = 1.4297 | PHI = 1.4297 |

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<tr>
<th>INJECTOR</th>
<th>INF CHAM</th>
<th>THRAT CM RATIO</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
<th>EXIT</th>
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<tbody>
<tr>
<td>PINJ/P</td>
<td>1.0000</td>
<td>1.0848</td>
<td>1.8668</td>
<td>1.1955</td>
<td>10.0000</td>
<td>100.000</td>
<td>1000.00</td>
<td>283.87</td>
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<tr>
<td>PINF/P</td>
<td>0.92162</td>
<td>1.0000</td>
<td>1.7393</td>
<td>1.1020</td>
<td>9.2182</td>
<td>92.182</td>
<td>921.82</td>
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<tr>
<td>P, MPA</td>
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<td>4.9149</td>
<td>2.6238</td>
<td>4.4600</td>
<td>0.53317</td>
<td>0.05332</td>
<td>0.00533</td>
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<tr>
<td>T, DEG K</td>
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<td>319.05</td>
<td>352.66</td>
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<tr>
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<td>-843.37</td>
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**PERFORMANCE PARAMETERS**

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<tr>
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<td>1.253</td>
<td>4002.8</td>
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<td>929.8</td>
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<td>1.871</td>
<td>4152.8</td>
<td>2925.8</td>
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<tr>
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<td>1.768</td>
<td>4532.6</td>
<td>3661.9</td>
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<tr>
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<td>1.846</td>
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<td>4369.5</td>
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<td>4128.3</td>
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<td>1.846</td>
<td>4556.9</td>
<td>4312.2</td>
</tr>
</tbody>
</table>

**MOLE FRACTIONS**

| H    | 0.03442 | 0.03515 | 0.02793 | 0.03387 | 0.00910 | 0.00024 | 0.00000 | 0.00001 | 0.00000 | 0.00000 |
| H2   | 0.00002 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| O    | 0.29457 | 0.29444 | 0.29387 | 0.29428 | 0.29661 | 0.30041 | 0.30555 | 0.30554 | 0.30555 | 0.30555 |
| H2O  | 0.63378 | 0.63254 | 0.65140 | 0.63030 | 0.68910 | 0.69932 | 0.69945 | 0.69945 | 0.69945 | 0.69945 |
| H2O2 | 0.00001 | 0.00001 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| O    | 0.00225 | 0.00233 | 0.00316 | 0.00214 | 0.00100 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| H2O  | 0.03306 | 0.03354 | 0.02423 | 0.03183 | 0.00501 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| H2   | 0.00070 | 0.00092 | 0.00100 | 0.00010 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |

**ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS**

**O3**  
H2O(S)  
H2O(L)

**NOTE:** Weight fraction of fuel in total fuels and of oxidant in total oxidants
TABLE V. COMPARISON OF SPECIFIC IMPULSE OBTAINED UNDER ASSUMPTION OF EXPANSION FROM FINITE AND INFINITE COMBUSTION CHAMBERS

<table>
<thead>
<tr>
<th>Infinite chamber area</th>
<th>Finite chamber area</th>
<th>Energy Utilization loss due to finite chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{P_{\text{in}}}{P_e} )</td>
<td>( I_{sp} ) (m/sec)</td>
<td>( \frac{A_2}{A_1} )</td>
</tr>
<tr>
<td>10.00</td>
<td>2972.5</td>
<td>2.3469</td>
</tr>
<tr>
<td>100.00</td>
<td>3886.3</td>
<td>12.179</td>
</tr>
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<td>1000.00</td>
<td>4383.2</td>
<td>68.360</td>
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<tr>
<td>262.17</td>
<td>4129.4</td>
<td>25.</td>
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<td>659.57</td>
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<td>50.</td>
</tr>
<tr>
<td>1131.38</td>
<td>4402.6</td>
<td>75.</td>
</tr>
</tbody>
</table>
FIGURE 1. - THRUST CHAMBER SCHEMATIC WITH POSITIONS LABELED AS THEY APPEAR IN PROGRAM OUTPUT.
## Abstract

Previous to this report, the computer program of NASA SP-273 and NASA TM-86885 was capable of calculating theoretical rocket performance based only on the assumption of an infinite area combustion chamber (IAC). An option has been added to this program which now also permits the calculation of rocket performance based on the assumption of a finite area combustion chamber (FAC). In the FAC model, the combustion process in the cylindrical chamber is assumed to be adiabatic, but nonisentropic. This results in a stagnation pressure drop from the injector face to the end of the chamber and a lower calculated performance for the FAC model than the IAC model.