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DEPARTMENT OF DEFENCE

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AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Propulsion Technical Memorandum 452

A COMPUTER PROGRAM FOR PREDICTION OF INTERNAL PERFORMANCE OF A RAMROCKET

by

Lincoln P. Erm

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SUMMARY

The operation of a computer program to predict idealised ramrocket performance is described. The program predicts performance for chosen aerodynamic and thermodynamic variables and contains provision for varying the gas generator propellant formulation.

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NOTATION

A	Flow area measured normal to flow direction
C_p	Specific heat at constant pressure
M	Mach number
m	Mass flow rate
P	Total pressure
p	Static pressure
R	Gas constant for a specific gas
SI	Specific impulse = $(m_4V_4-m_1V_1)/m_2'$
T	Total temperature
t	Static temperature
V	Gas velocity
γ	Ratio of specific heats
μ	Mass flow ratio = m_2''/m_2'

Subscripts

1-4	Refers to flow stations 1 to 4 in Figure 1

Superscripts

'	Refers to primary flow at station 2
"	Refers to secondary flow at station 2

1. INTRODUCTION

Program RR is an idealised ramrocket performance model written in standard FORTRAN 77 for use on the ARL Elxsi computer. This document outlines details of the program. A number of publications have reported use of earlier versions of the program, viz. References 1 to 4. The current document should be sufficient for a user to become familiar with the operation of the program and to be able to use it with confidence. It is not the purpose of this document to give a detailed description of the FORTRAN statements within program RR. The listing and the compiled version of the program, designated RR.F and RR respectively, are located on ARL magtape number M317.

2. FEATURES OF THEORETICAL MODEL

A diagrammatic representation of an idealised ramrocket, showing stations along the flow path, is given in Figure 1. A solid-propellant gas generator produces fuel-rich exhaust products which are expanded through a nozzle into a mixing tube/combustion chamber. This primary flow mixes with secondary air flow delivered from the atmosphere by an intake/diffuser system, and further combustion takes place. The mixture is then expanded through the exhaust nozzle to atmosphere.

The analysis is simplified to the extent that the flow variables are assumed to be constant across the entire cross section at all stations except of course at station 2 where both the primary and secondary flow variables are assumed to be constant across their respective cross sections. This implies that mixing is complete at station 3. Whilst for the purpose of calculation the flow is assumed to be one-dimensional, departures from loss-free flow are accommodated by the use of empirical coefficients for intake pressure recovery and combustion efficiency. The static pressure across both inlet and exit planes (1 and 4 respectively) is assumed to be equal to atmospheric pressure. In other words, there is no pre-entry diffusion of the inlet air and the final nozzle is always correctly expanded. The flow area between stations 2 and 3 is also assumed to be constant, i.e. $A_3 = A_2' + A_2''$.

A feature of the model is that all of the input variables are flow-related. Geometry is not directly specified so the intake duct, mixing tube/combustion chamber and exhaust nozzle are all allowed to vary in shape to suit the flow conditions assumed. Equations for conservation of mass, momentum and energy are used in the analysis which is detailed in Appendix 1.

In earlier versions of the program, it was not a simple matter to investigate ramrocket performance using a wide range of propellants, since the properties of each propellant had to be inserted into the program in tabular form and this was a time-consuming process. In program RR, the NASA thermochemical code given in Reference 5 is invoked during program execution, thus enabling ramrocket performance to be evaluated for a virtually unlimited range of propellant compositions.

The primary fuel jet issuing from the gas generator has sufficient kinetic energy to contribute significantly to the total pressure upstream of the final propelling nozzle, depending on the mode of its injection into the ramburner. The model can evaluate ramrocket performance for either axial or radial injection of the primary jet. However, there is no provision for a combination of these two modes of operation.

The model is intended primarily to reveal performance trends and to indicate sensitivity to certain variables. In making use of absolute values of output quantities in relation to flight performance of practical systems, it is important to appreciate the idealised nature of the model.

3. EVALUATION OF FLOW VARIABLES

For selected values of flight altitude, M_1, μ and M_2'', flow variables throughout the ramrocket are evaluated in a step-by-step manner. For the secondary flow through the diffuser, a standard intake loss law is used to determine P_2''. Considering the primary flow, for a chosen propellant and a chosen primary combustion chamber pressure, the program of Reference 5 is used to determine T_2', γ_2', Cp_2' and t_2' for a specified pressure ratio assuming frozen composition during expansion. This program is also used to determine T_3, γ_3 and Cp_3, for which purpose the inlet air is effectively included as a constituent of the propellant. When using the program to calculate these variables at station 3, the flow between stations 2 and 3 is assumed to be at constant pressure. Although this is only true for certain optimum operating conditions (see Reference 2), the approximation greatly simplifies the calculations by avoiding the need for multiple iterations, and is reasonably accurate provided the actual pressure change is not excessive. The actual calculated static pressure at station 3 is in general different from that at station 2.

Some details of use of the code given in Reference 5 are given in Reference 4 and an explanation of its use for the current study is outlined in Appendix 2.

4. SAMPLE CALCULATION OF RAMROCKET PERFORMANCE

To calculate ramrocket performance it is necessary to answer a series of questions asked during the execution of program RR. To explain the operation of the program, a typical sample case will be outlined. Listed below are the questions asked together with a set of answers. The questions are self-explanatory and the answers as well as user commands have been underlined. Additional information is contained within square brackets and this does not appear when using program RR. The following sample calculation should be read in conjunction with Appendices 1 and 2.

:RR
ENTER 0.0, 5000.0 OR 10000.0 TO SPECIFY ALTITUDE (M)
0.0
ENTER VALUE OF M1 [M_1]:E.G. 2.500
1.200
ENTER PRIMARY COMBUSTOR PRESSURE. (PSIA): E.G.. 900.0
1000.0
ENTER VALUE OF PRIMARY MASS FLOW RATE (KG/S): E.G. 1.000
1.000
ENTER VALUE OF MU [μ]: E.G. 6.00
15.00
ENTER VALUE OF M2S [M_2'']: E.G. 0.20
0.20
ENTER 1 FOR AXIAL INJECTION, 2 FOR RADIAL INJECTION
1
ENTER VALUE OF COMBUSTION EFFICIENCY: E.G. 0.90
1.00
PT2P [P_2'] = 1000.000 PSIA   PS2P [p_2'] = 34.357 PSIA
PRESS "BREAK" KEY, USE NASA PROG, TYPE "RESUME" AND THEN TYPE "1"
<BREAK>
[see Appendix 2 for use of NASA program]
:RESUME
1
ENTER VALUES OF TT2P [T_2'], GAM2P [γ_2'], CP2P [Cp_2'] AND TS2P [t_2']
2347.0,1.2986,0.3927,1141.0
ENTER VALUES OF GAM2P [γ_2'], CP2P [Cp_2'] AND TS2P [t_2']
FOR GAS GENERATOR EXPANDING TO ATMOSPHERE
1.3151,0.3769,935.0
MU [μ]=15.000   HEAT OF FORMATION=296 CAL/MOLE
TS2S [t_2'']=368.2 K   PS2P [p_2']=34.357 PSIA
PRESS "BREAK" KEY, USE NASA PROG, TYPE "RESUME" AND THEN TYPE "1"
<BREAK>
[see Appendix 2 for use of NASA program]

```
:RESUME
1
ENTER VALUES OF TT3 [T3], GAM3 [γ3] AND CP3 [Cp3]
913.0,1.3323,0.2748
```

The output file from program RR, listing values of flow variables, is shown in Table 1.

Table 1. Output File from Program RR.

```
CONSTANT AREA MIXING AND COMBUSTION
HEIGHT = .0 M
ATMOS TEMP = 288.1 K          ATMOS PRESS = 101325.0 N/M**2
        TT1         TT2P         TT2S         TT3         TT4
      371.1       2347.0        371.1       913.0       913.0
        TS1         TS2P         TS2S         TS3         TS4
      288.1       1141.0        368.2       896.2       724.2
        PT1         PT2P         PT2S         PT3         PT4
    245710.     6894733.      243583.     256474.     256474.
        PS1         PS2P         PS2S         PS3         PS4
    101325.      236884.      236884.     238055.      101325
         V1          V2P          V2S          V3          V4
      408.4       2095.7         76.9       196.7       659.0
         M1          M2P          M2S          M3          M4
      1.200        2.800         .200        .336       1.253
      MASS1       MASS2P       MASS2S       MASS3       MASS4
     15.000        1.000       15.000      16.000      16.000
         A1          A2P          A2S          A3          A4
      .0300        .0009        .0870       .0879       .0498
       RHO1        RHO2P        RHO2S        RHO3        RHO4
     1.2249        .5493       2.2411       .9259       .4877
       GAM1        GAM2P        GAM2S        GAM3        GAM4
     1.4000       1.2986       1.4000      1.3323      1.3323
         R1          R2P          R2S          R3          R4
    287.074      377.972      287.074     286.899     286.899
        CP1         CP2P         CP2S         CP3         CP4
   1004.759     1643.784     1004.759    1150.272    1150.272
COMBUSTION EFFICIENCY = 1.000
GROSS THRUST = 10544. N          NET THRUST = 4419. N
THRUST DENSITY (GROSS THRUST) = 120004. N/M**2
THRUST DENSITY (NET THRUST) = 50288. N/M**2
SPECIFIC IMPULSE (RAMROCKET) = 4419 N/(KG/S)
SPECIFIC IMPULSE (GAS GENERATOR) = 2271 N/(KG/S)
AUGMENTATION RATIO = 1.996
```

Explanation of terminology used in Table 1.

Numbers 1 to 4 refer to stations 1 to 4 - see Figure 1.

2P refers to primary flow at station 2

2S refers to secondary flow at station 2

TT refers to total temperature (K)

TS refers to static temperature (K)

PT refers to total pressure (N/m^2)

PS refers to static pressure (N/m^2)

V refers to velocity (m/s)

M refers to Mach number

MASS refers to mass flow rate (kg/s)

A refers to flow area (m^2)

RHO refers to density (kg/m^3)

GAM refers to ratio of specific heats

R refers to gas constant (J/kg.K)

CP refers to specific heat (J/kg.K)

Thrust density = Thrust (gross or net)/A_3

Specific impulse (ramrocket) - refers to total system

Specific impulse (gas generator) - refers to gas generator expanding to atmosphere

Augmentation ratio = Total net thrust/Thrust of gas generator in isolation

To assess the validity and accuracy of program RR, the results were compared with those of a code developed by the United States Air Force -see Reference 6. The US code was different from the current code in that ramjet geometry was specified rather than flow variables, as in the present case. Nevertheless, it was possible to manipulate the input conditions in the two cases so that meaningful comparisons could be made. When this was done, the two codes yielded virtually identical results.

5. CONCLUSION

A computer program has been developed which reveals the sensitivity of in-flight performance of an idealised ramrocket to a number of aerodynamic and thermodynamic variables, including gas generator fuel formulation.

6. ACKNOWLEDGEMENT

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APPENDIX 1

ANALYSIS OF FLOW THROUGH RAMROCKET

For selected values of altitude, M_1, μ and M_2'', flow conditions throughout the ramrocket can be evaluated. The equations used are presented below.

A1.1 Flow at Station 1

The known flow variables at station 1 are the independent variable M_1 and also t_1, p_1, γ_1 and R_1 corresponding to ambient conditions at the particular altitude being considered. For a chosen value of m_2', other flow variables can be determined as follows:

$$m_1 = \mu m_2' \tag{A1.1}$$

$$T_1 = t_1\left[1 + \frac{(\gamma_1 - 1)}{2} M_1^2\right] \tag{A1.2}$$

$$P_1 = p_1\left[1 + \frac{(\gamma_1 - 1)}{2} M_1^2\right]^{\gamma_1/(\gamma_1 - 1)} \tag{A1.3}$$

$$V_1 = M_1\sqrt{\gamma_1 R_1 t_1} \tag{A1.4}$$

$$\rho_1 = \frac{p_1}{R_1 t_1} \tag{A1.5}$$

$$A_1 = \frac{m_1}{\rho_1 V_1} \tag{A1.6}$$

A1.2 Flow at Station 2

A1.2.1 Secondary Flow

For the secondary flow, M_2'' is a known independent variable and P_2'' is calculated from an empirical intake loss law as follows:

$$P_2'' = P_1 \qquad (0.0 < M_1 \le 1.0) \tag{A1.7}$$

$$P_2'' = P_1(1.0 - 0.076(M_1 - 1.0)^{1.35}) \qquad (1.0 < M_1 < 5.0) \tag{A1.8}$$

Other flow variables can be determined as follows:

$$\gamma_2'' = \gamma_1 \tag{A1.9}$$

$$R_2'' = R_1 \tag{A1.10}$$

$$m_2'' = \mu m_2' \tag{A1.11}$$

$$T_2'' = T_1 \tag{A1.12}$$

$$t_2'' = \frac{T_2''}{\left[1 + \frac{(\gamma_2''-1)}{2} M_2''^2\right]} \tag{A1.13}$$

$$p_2'' = \frac{P_2''}{\left[1 + \frac{(\gamma_2''-1)}{2} M_2''^2\right]^{\gamma_2''/(\gamma_2''-1)}} \tag{A1.14}$$

$$\rho_2'' = \frac{p_2''}{R_2'' t_2''} \tag{A1.15}$$

$$V_2'' = M_2'' \sqrt{\gamma_2'' R_2'' t_2''} \tag{A1.16}$$

$$A_2'' = \frac{m_2''}{\rho_2'' V_2''} \tag{A1.17}$$

A1.2.2 Primary Flow

For a chosen propellant and a chosen value of P_2', values of T_2', γ_2', Cp_2' and t_2' are determined using the program of Reference 5, as shown in Appendix 2. Other flow variables can be determined as follows:

$$R_2' = Cp_2' \left[\frac{\gamma_2'-1}{\gamma_2'}\right] \tag{A1.18}$$

$$p_2' = p_2'' \tag{A1.19}$$

$$M_2' = \sqrt{\left[\frac{2}{(\gamma_2'-1)} \left[\left\{\frac{P_2'}{p_2'}\right\}^{(\gamma_2'-1)/\gamma_2'} - 1\right]\right]} \tag{A1.20}$$

$$\rho_2' = \frac{p_2'}{R_2' t_2'} \tag{A1.21}$$

$$V_2' = M_2' \sqrt{\gamma_2' R_2' t_2'} \tag{A1.22}$$

$$A_2' = \frac{m_2'}{\rho_2' V_2'} \tag{A1.23}$$

A1.3 Flow at Station 3

Values of T_3, γ_3 and C_{p3} are determined using the program of Reference 5, as shown in Appendix 2. If the secondary combustion efficiency is less than 1.00, then the value of T_3 is modified. The value of R_3 is determined as follows:

$$R_3 = C_{p3}\left[\frac{\gamma_3 - 1}{\gamma_3}\right] \tag{A1.24}$$

and for constant area mixing and combustion, A_3 is determined from

$$A_3 = A_2' + A_2'' \tag{A1.25}$$

In order to evaluate M_3, the equations of conservation of mass and momentum between stations 2 and 3 are used. These equations are

$$m_3 = m_2' + m_2'' \tag{A1.26}$$

and

$$m_2'V_2' + p_2'A_2' + m_2''V_2'' + p_2''A_2'' = m_3V_3 + p_3A_3 \tag{A1.27}$$

After manipulation, the following equation containing M_3 can be derived.

$$\frac{m_2'(V_2' + \mu V_2'') + p_2'A_2' + p_2''A_2''}{m_2'(1+\mu)} = \frac{M_3^2\gamma_3 + 1}{M_3\sqrt{\left[\frac{\gamma_3}{R_3T_3}\left[1 + \frac{(\gamma_3 - 1)}{2}M_3^2\right]\right]}} \tag{A1.28}$$

It is possible to rearrange this equation and obtain an explicit expression for M_3. However, because of the complexity of this expression, it is not given here. Equations used to determine other flow variables are as follows:

$$t_3 = \frac{T_3}{\left[1 + \frac{(\gamma_3 - 1)}{2}M_3^2\right]} \tag{A1.29}$$

$$p_3 = \frac{m_3}{A_3 M_3}\sqrt{\left[\frac{R_3 t_3}{\gamma_3}\right]} \qquad \text{(A1.30)}$$

$$P_3 = p_3\left[1 + \frac{(\gamma_3 - 1)}{2} M_3{}^2\right]^{\gamma_3/(\gamma_3 - 1)} \qquad \text{(A1.31)}$$

$$V_3 = M_3\sqrt{\gamma_3 R_3 t_3} \qquad \text{(A1.32)}$$

$$\rho_3 = \frac{p_3}{R_3 t_3} \qquad \text{(A1.33)}$$

A1.4 Flow at Station 4

The value of p_4 corresponds to ambient conditions. Equations used to determine other flow variables are given below

$$\gamma_4 = \gamma_3 \qquad \text{(A1.34)}$$

$$R_4 = R_3 \qquad \text{(A1.35)}$$

$$m_4 = m_3 \qquad \text{(A1.36)}$$

$$T_4 = T_3 \qquad \text{(A1.37)}$$

$$P_4 = P_3 \qquad \text{(A1.38)}$$

$$M_4 = \sqrt{\left[\frac{2}{(\gamma_4 - 1)}\left[\left\{\frac{P_4}{p_4}\right\}^{(\gamma_4 - 1)/\gamma_4} - 1\right]\right]} \qquad \text{(A1.39)}$$

$$t_4 = \frac{T_4}{\left[1 + \frac{(\gamma_4 - 1)}{2} M_4{}^2\right]} \qquad \text{(A1.40)}$$

$$V_4 = M_4\sqrt{\gamma_4 R_4 t_4} \qquad \text{(A1.41)}$$

$$\rho_4 = \frac{p_4}{R_4 t_4} \qquad \text{(A1.42)}$$

$$A_4 = \frac{m_4}{\rho_4 V_4} \qquad \text{(A1.43)}$$

APPENDIX 2

USE OF NASA COMPUTER PROGRAM

For a complete description of the NASA computer program given in Reference 5, the reader is referred to the original publication. In the following, the use of the program will only be outlined in very broad terms and will specifically apply to the current investigation. The compiled version of the NASA program, designated COMBN, is located on ARL magtape number M317.

Before running the program it is first necessary to create input files listing the chemical properties of the reactants of the propellant as well as other information including the pressures associated with the combustion process. The two input files associated with the typical sample calculation referred to in Section 4 are shown in Tables 2 and 3 and these two files, designated COMBN.IN1 and COMBN.IN2 respectively, are also located on ARL magtape number M317

Table 2. Input file for NASA program for combustion of propellant.

```
REACTANTS
N 1.00000H 4.00000CL1.000000 4.00000          0.8000  -70735.   S300.00  O
H 1.00000C 0.708700 0.00970                   0.2000  125.58    S300.00  F

NAMELISTS
 $INPT2 KASE=1, RKT=T,PSIA=T,P=1000.0                           $
 $RKTINP PCP=29.106,68.046            $
```

Table 3. Input file for NASA program for combustion of propellant and air.

```
REACTANTS
N 1.00000H 4.00000CL1.000000 4.00000          0.8000  -70735.   S300.00  O
H 1.00000C 0.708700 0.00970                   0.2000  125.58    S300.00  F
O 0.22400N 0.83500AR0.00500                   15.000     296.   G368.20  O

NAMELISTS
 $INPT2 KASE=1, RKT=T,PSIA=T,P=34.357,OF=T,MIX=79                        $
 $RKTINP PCP=2.338                              $
```

Table 2 applies to the propellant only and is used to determine the properties of the exhaust products at station 2 for the primary flow; these properties are required for entering into the conservation equations which are applied to the flow between stations 2 and 3. Table 3 applies to both the propellant and the inlet air and is used to determine the properties of the combustion products at station 3. The propellant considered for the sample calculation consists of ammonium perchlorate oxidant (NH_4ClO_4) mixed with a hydrocarbon fuel having the atomic fractions H:C:O 1.0:0.7087:0.0097 in the overall ratio 80:20 by mass.

As can be seen, each input file consists of two sections, headed by REACTANTS and NAMELISTS respectively. These sections will be described in turn.

The formatting for the section headed by REACTANTS is given in Table VI of the NASA publication. Columns 1 to 45 list the atomic symbols and formulae numbers of the constituents of the propellant. Columns 46 to 52 list the relative masses of the different constituents. Column 53 is blank for current purposes. Columns 54 to 62 list the heats of formation of the various constituents in cal/mole. The heat of formation of air at standard temperature is very close to zero. However, the inlet air has an increased total temperature as a consequence of the vehicle velocity and an effective heat of formation of air is used which takes into account its kinetic energy. Column 63 lists whether the constituent is a solid, liquid or gas, S, L or G, respectively. Columns 64 to 71 denote the temperature associated with the heat of formation given in columns 54 to 62. Column 72 indicates whether the constituent is a fuel or oxidant, F or O, respectively. Table VII of the NASA publication lists the above details for some oxidants and fuels.

Considering now the sections headed by NAMELISTS, details of entries are given in Tables V and VIII of the NASA publication

For all runs it is necessary to use the instruction $INPT2. This is followed by KASE = 1, where 1 (or 2 or 3 etc.) is an optional assigned number associated with each case. RKT = T (T for true) follows, which indicates that a rocket problem is being considered. This is followed by PSIA = T, which indicates that the assigned pressures are in PSIA units. The instruction P=n, where n is a number, indicates the chamber pressure in previously-defined units. Where applicable, the instruction OF = T indicates that the oxidant-to-fuel mass ratio is given in MIX, which follows. The statement MIX = 79 indicates the oxidant-to-fuel mass ratio, i.e. (0.8+15.0)/0.2 = 79.

For the rocket performance option, it is necessary to use the instruction $RKTINP at the commencement of the line following the $INPT2 line. The instruction PCP = n_1, n_2, etc., where n_1 and n_2 are numbers, indicates pressure ratios for which combustion products are to be computed; for the sample calculation, the program has been instructed to calculate gas properties for expansion to atmosphere as well as at the ramburner conditions.

To actually run the program, it is necessary to use an instruction of the form:
Input file name (COMBN.IN1 or COMBN.IN2) > COMBN > Output file name.

After running the NASA program twice, using the input files given in Tables 2 and 3, output files are obtained. The relevant parts of these output files corresponding to the two cases are shown in Tables 4 and 5 respectively. The data taken from these files and entered into program RR during the execution of program RR are shown underlined.

Table 4. Output file from NASA program for combustion of propellant.

	CHAMBER	THROAT	EXIT	EXIT
PC/P	1.0000	1.8070	29.106	68.0460
P, ATM	68.046	37.657	2.3379	1.0000
T, DEG K	2347	2082	1141	935
RHO, G/CC	7.7749-3	4.8514-3	5.4953-4	2.8691-4
H, CAL/G	-479.0	-597.2	-992.2	-1071.5
S, CAL/(G)(K)	2.4961	2.4961	2.4961	2.4961
M, MOL WT	22.008	22.008	22.008	22.008
CP, CAL/(G)(K)	.4492	.4409	.3927	.3769
GAMMA (S)	1.2515	1.2575	1.2986	1.3151
SON VEL,M/SEC	1053.5	994.5	748.2	681.5
MACH NUMBER	.000	1.000	2.770	3.267

Table 5. Output file from NASA program for combustion of propellant and air.

	CHAMBER	THROAT	EXIT
PC/P	1.0000	1.8606	2.3380
P, ATM	2.3378	1.2565	0.9999
T, DEG K	913	780	736
RHO, G/CC	9.0457-4	5.6886-4	4.8016-4
H, CAL/G	-12.0	-48.0	-59.9
S, CAL/(G)(K)	1.8838	1.8838	1.8838
M, MOL WT	28.994	28.994	28.994
CP, CAL/(G)(K)	.2748	.2672	.2644
GAMMA (S)	1.3323	1.3451	1.3499
SON VEL,M/SEC	590.7	548.7	533.7
MACH NUMBER	.000	1.000	1.186

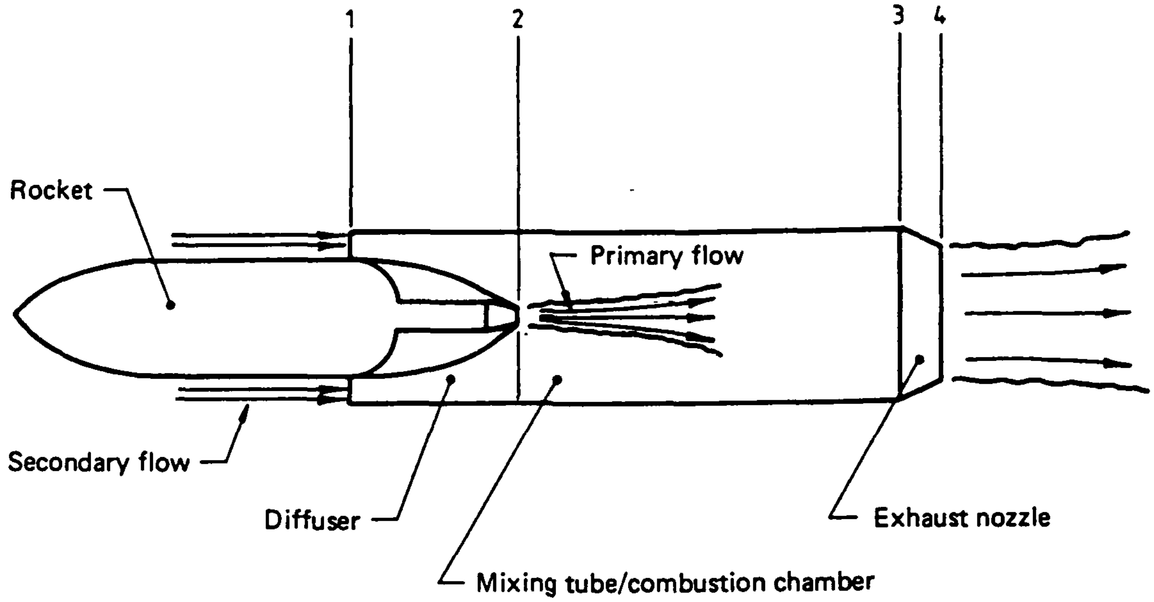

FIG. 1 DIAGRAMMATIC REPRESENTATION OF RAMROCKET SHOWING STATIONS ALONG FLOW PATH

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16. ABSTRACT

The operation of a computer program to predict idealised ramrocket performance is described. The program predicts performance for chosen aerodynamic and thermodynamic variables and contains provision for varying the gas generator propellant formulation.

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