# Methods for Calculation of Thrust Coefficients

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### *ABSTRACT*

*When one wishes to predict or analyze rocket motor/engine performance accurately, a method for determining the nozzle thrust coefficient at each point in time is essential. If the vacuum thrust coefficient for the nozzle is known, the thrust coefficient for other conditions can easily be determined. This paper outlines several methods for determining the vacuum thrust coefficient in the hope that it will encourage this type of calculation and lead to new and better methods for simulation and analysis in the future.*

**Key Words:** vacuum thrust coefficient, thrust coefficient, expansion ratio, specific heat ratio, chamber pressure, thrust, rocket propulsion theory

## Introduction

This paper will neither present nor attempt to explain any of the theory involved, as references[1,2,3] exist that do this more than adequately and far better than this writer could. It will attempt to outline and present methods that may be used to simplify basic design and analysis calculations. While graphs[1] and tables[4] exist for thrust coefficients etc., determining more accurate values than can be obtained from a graph or table is often desirable. Also, incorporating their real time calculation in a simulation or analysis program or procedure is often beneficial, and graphs and tables are not always available or convenient to use. One equation[5] used to calculate values for the thrust coefficient ($C_F$) is:

$$C_F = \Gamma \sqrt{\frac{2\gamma}{\gamma - 1}} \sqrt{1 - \left[\frac{P_e}{P_c}\right]^{\left(\frac{\gamma-1}{\gamma}\right)}} + \frac{A_e}{A_t}\left(\frac{P_e - P_a}{P_c}\right) \tag{1}$$

where capital gamma ($\Gamma$), also known as the Vandenkerckhove function,[6] is defined by:

$$\Gamma = \sqrt{\gamma}\left[\frac{2}{\gamma + 1}\right]^{\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \tag{2}$$

in addition, gamma ($\gamma$) is the ratio of specific heats (or specific heat ratio) for the exhaust gases. The pressure at the nozzle exit plane ($P_e$), the chamber pressure ($P_c$), and the ambient pressure ($P_a$) need to be in absolute pressure units. Nozzle exit area ($A_e$) and nozzle throat area ($A_t$) should be given using the same units for each. Nozzle expansion ratio[5] ($\varepsilon$) can be defined as:

$$\varepsilon = \frac{A_e}{A_t} \tag{3}$$

or by:

$$\varepsilon = \Gamma \sqrt{\frac{\gamma - 1}{2\gamma}} \left[ \frac{\left[\frac{P_c}{P_e}\right]^{\left(\frac{1}{\gamma}\right)}}{\sqrt{1 - \left[\frac{P_e}{P_c}\right]^{\left(\frac{\gamma-1}{\gamma}\right)}}} \right] \tag{4}$$

Equation 4 can be shortened by defining alpha ($\alpha$) as:

$$\alpha = \sqrt{\frac{\gamma - 1}{2\gamma}} \tag{5}$$

beta ($\beta$) as:

$$\beta = \frac{\gamma - 1}{\gamma} \tag{6}$$

and delta ($\Delta$) as:

$$\Delta = \frac{1}{\gamma} \tag{7}$$

This allows equation 4 to be rewritten as:

$$\varepsilon = \Gamma\alpha \frac{\left[\frac{P_c}{P_e}\right]^{\Delta}}{\sqrt{1-\left[\frac{P_e}{P_c}\right]^{\beta}}} \tag{8}$$

Except for pressure terms, all variables in equation 8 are defined in terms of the specific heat ratio ($\gamma$). The specific heat ratio is usually known or can be calculated using one of the many PEP programs (PROPEP, CETPC, ISP, SP-273 etc.). However, if it is not known, a value of 1.25 can be used (not a bad assumption for most solid propellants used in high power rocketry).

If atmospheric pressure is reduced to zero in equation 1, then the thrust coefficient becomes the vacuum thrust coefficient ($C_{F_{Vac}}$):

$$C_{F_{Vac}} = \Gamma\sqrt{\frac{2\gamma}{\gamma-1}}\sqrt{1-\left(\frac{P_e}{P_c}\right)^{\beta}} + \varepsilon\left(\frac{P_e}{P_c}\right) \tag{9}$$

This allows equation 1 to be rewritten in a simpler form:

$$C_F = C_{F_{Vac}} - \varepsilon\left(\frac{P_a}{P_c}\right) \tag{10}$$

Tools are now in place for further calculations.

Short BASIC program listings are included in the appendices to illustrate each calculation method described. The simplest, a method for calculating the optimum expansion ratio and thrust coefficient for a fixed pressure ratio is outlined first. A method for calculating thrust coefficients using a fixed expansion ratio is then presented. Following this is an approximate method for calculation of thrust coefficients (again using a fixed expansion ratio). The final method is for converting thrust levels to chamber pressures. This method can be reversed to predict thrust versus time in simulation programs (after using *Kn* values to determine pressures). For all methods, it is assumed that a specific heat ratio has been provided for use.

## A Method for Calculation of Optimum Thrust Coefficient Using a Fixed Pressure Ratio[Appendix A]

The easiest thrust coefficient calculation is determination of the optimum expansion ratio and thrust coefficients for a fixed pressure ratio. Ambient pressure at the operation or simulation location of the motor must be known or selected. Motor operating pressure is then selected. A nozzle's optimum thrust coefficient is obtained when its exit pressure is equal to ambient pressure. The pressure ratio is calculated using:

$$PR = \frac{P_c}{P_e} = \frac{P_c}{P_a} \tag{11}$$

Values for equations 5, 6, and 7 are determined and the results, to this point, are inserted into equations 2 and 8 to produce values for capital gamma and the expansion ratio. Final steps are the calculation of the vacuum thrust coefficient and thrust coefficient using equations 9 and 10.

## A Method for Calculation of Thrust Coefficient Using a Specific Expansion Ratio [Appendix B]

In the real world, the expansion ratio is usually a fixed value for initial design and testing, with possible optimization occurring during final development. One very accurate method of calculating vacuum thrust coefficients is to select an expansion ratio and then calculate a temporary expansion ratio using an arbitrarily chosen pressure ratio. This result is then compared with the selected expansion ratio. If they do not match, a new temporary expansion ratio is calculated using a new pressure ratio (selected to ensure convergence of expansion ratio values). This process is repeated until the temporary expansion ratio matches the selected expansion ratio. This pressure ratio is then used to calculate the vacuum thrust coefficient using equation 9. The thrust coefficient for any chamber operating pressure can now be calculated using equation 10, if ambient pressure is known for motor operation location. This method gives results for vacuum thrust coefficients and pressure ratios that have very good agreement with tables.[4]

## A Brute Force Method for Calculation of Thrust Coefficients Using Specified Expansion Ratios[Appendix C]

The writer believes that calculating the pressure ratio directly from the specific heat ratio and expansion ratio may be advantageous. While this may not be true, he has been unable to accomplish this to date. An attempt to "force" a solution to the problem has been made. Using the method outlined in Appendix B, vacuum thrust coefficients and pressure ratios were calculated for expansion ratios ranging from one to eight (by increments of 0.5) for specific heat ratios ranging from 1.1 to 1.4 (by increments of 0.5). A shareware program, *CurveFit*[7] was then used for each ratio of specific heat to relate pressure ratio and expansion ratio. An equation having the form:

$$PR = a + b\varepsilon + c\varepsilon^2 \tag{12}$$

seemed to fit each group of data. A new problem was that $a$, $b$, and $c$ had differing values for each specific heat ratio. In an attempt to make the results more universal, another round of curve fitting was attempted to relate each coefficient to specific heat ratios. This resulted in the following results:

$$a = \frac{38.7019}{\gamma} - \frac{15.5227}{\gamma^2} - 25.6441 \tag{13}$$

$$b = \frac{1}{0.3283(\gamma - 1.5242)^2 + 0.1423} \tag{14}$$

$$c = (52.4092)\gamma^{15.0965}(0.0013)^{\gamma} \tag{15}$$

The equations for coefficients $a$ and $b$ were the first listed by the program while the equation for $c$ was the third listed (but appeared to fit the data almost as well and was much easier to calculate).

Next, a short program was written using these equations to see if results were comparable to table values or those produced using the method in Appendix B. The program produced very good agreement for vacuum thrust coefficients, but only good agreement for pressure ratios. Since these pressure ratios are only being used for calculating vacuum thrust coefficients, this method may be an acceptable substitute for other calculation methods. Table 1 compares results from programs in Appendix B and Appendix C using a specific heat ratio of 1.25.

**Table 1. Comparison of Results Using Appendix B and Appendix C Methods.**

| $\varepsilon$ | Appendix B ($C_{F_{Vac}}$) | Appendix B ($PR$) | Appendix C ($C_{F_{Vac}}$) | Appendix C ($PR$) |
|---|---|---|---|---|
| 1.0 | 1.248592 | 1.845 | 1.248586 | 1.747 |
| 1.5 | 1.391232 | 5.405 | 1.391338 | 5.211 |
| 2.0 | 1.463144 | 8.827 | 1.463145 | 8.863 |
| 2.5 | 1.510494 | 12.557 | 1.510502 | 12.703 |
| 3.0 | 1.545099 | 16.569 | 1.545105 | 16.73 |
| 3.5 | 1.571987 | 20.829 | 1.571989 | 20.945 |
| 4.0 | 1.593750 | 25.305 | 1.593750 | 25.349 |
| 4.5 | 1.611888 | 29.989 | 1.611888 | 29.94 |
| 5.0 | 1.627345 | 34.861 | 1.627346 | 34.718 |
| 5.5 | 1.640747 | 39.901 | 1.640749 | 39.685 |
| 6.0 | 1.652532 | 45.101 | 1.652533 | 44.84 |
| 6.5 | 1.663012 | 50.445 | 1.663013 | 50.182 |
| 7.0 | 1.672423 | 55.935 | 1.672424 | 55.712 |
| 7.5 | 1.680943 | 61.553 | 1.680943 | 61.431 |
| 8.0 | 1.688710 | 67.297 | 1.688710 | 67.337 |

## Determining Operating Pressures from Thrust Levels Using Vacuum Thrust Coefficients [8, Appendix D]

Thrust levels used to calculate chamber pressures may come from thrust curve data, manufacturer supplied information or any other reasonable source. Nozzle throat and exit areas are needed (easily calculated if we measure or are given throat and exit diameters). A simple equation[5] for thrust ($F$) is:

$$F = C_F P_c A_t \tag{16}$$

Rearranging to solve for chamber pressure gives:

$$P_c = \frac{F}{C_F A_t} \tag{17}$$

Multiplying both sides of equation 10 by $P_c$ gives:

$$C_F P_c = C_{F_{Vac}} P_c - \varepsilon P_a \tag{18}$$

Rearranging this to solve for chamber pressure ($P_c$):

$$P_c = \frac{C_F P_c + \varepsilon P_a}{C_{F_{Vac}}} \tag{19}$$

Reexamining equation 17 and multiplying both sides by $C_F$ produces:

$$C_F P_c = \frac{F}{A_t} \tag{20}$$

which can easily be solved using throat areas and thrust levels. Inserting this and earlier results into equation 19 produces a value for chamber pressure. While many other factors can (and perhaps should) be considered,[1,2,3] chamber pressure values calculated using this method give surprisingly good agreement with measured pressures. In this writer's opinion, thrust levels are much easier to obtain than pressure measurements.

## Summary

Several methods of calculating vacuum thrust coefficients and a method for calculating chamber pressure have been presented. Once the vacuum thrust coefficient has been calculated, it is an easy matter to calculate the thrust coefficient for any chamber pressure using equation 10. A value for the thrust coefficient is essential for simulating or analyzing motor performance. A word of warning, if the nozzle is severely overexpanded, separation of flow will occur in the nozzle with an effective reduction in expansion ratio. Although most of the discussion has implied usage with solid motors, these methods apply to hybrid motors or liquid rocket engines as well. The programs in the appendices include a calculation for approximate characteristic exhaust velocity ($c^*$) if the chamber temperature and molecular weight of the exhaust gases are known. If not, enter any positive number when prompted for them. They do not affect the calculation of the other values. The programs are written anticipating the use of English units. It is hoped that encouragement of development of more and better methods for simulating and analyzing motor performance has been accomplished.

## References


1) M. Summerfield, "Performance Analysis of the Ideal Rocket Motor", *High Power Rocketry*, January 1997. [A partial reprint with a foreword by C. Rogers.]

2) G. Sutton, *Rocket Propulsion Elements*, 6th ed., John Wiley and Sons (1992).

3) R. Humble, G. Henry, and W. Larson, *Space Propulsion Analysis and Design*, McGraw-Hill (1995).

4) H. Siefert and J. Crum, *Thrust Coefficient and Expansion Ratio Tables*, Ramo-Wooldridge Corp. (1956).

5) G. Mandell, "The Wayward Wind", *Model Rocketry*, January and February (1970).

6) J. Louwers, TNO Prins Maurits Laboratory, personal communication 1997.

7) T. Cox, *CurveFit 2.11B*, July 1988. [A shareware program.]

8) E. Brown, "Model Rocket Engine Performance / A Method for Calculating Chamber Pressures for Estes Model Rocket Engines", Estes Industries, 1971/1978.

## Appendix A

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10   CLS        ' PROGRAM NAME IS APPENDXA.BAS
20   PRINT "PLEASE ENTER RATIO OF SPECIFIC HEATS."
30   INPUT "ENTER NUMBER BETWEEN 1.05 AND 1.71"; GAMMA
40   IF GAMMA >= 1.05 AND GAMMA <= 1.71 THEN GOTO 50 ELSE BEEP: GOTO 20
50   '     ***            CALCULATE VALUE FOR CAPITAL GAMMA           ***
60   CAPITAL.GAMMA = SQR(GAMMA) * (2 / (GAMMA + 1)) ^ ((GAMMA + 1) / (2 *
     (GAMMA - 1)))
70   ALPHA = SQR((GAMMA - 1) / (2 * GAMMA)): BETA = (GAMMA - 1) / GAMMA:
     DELTA = 1 / GAMMA
80   INPUT "ENTER ATMOSPHERIC PRESSURE (PSIA)"; ATMOS.PRESS
90   INPUT "ENTER CHAMBER PRESSURE (PSIA)"; CHAMBER.PRESS
100  PRESS.RATIO = CHAMBER.PRESS / ATMOS.PRESS
110  PRESS.RATIO = INT(PRESS.RATIO * 1000 + .5) / 1000
120  NUMERATOR = CAPITAL.GAMMA * ALPHA * (PRESS.RATIO) ^ DELTA
130  DENOMINATOR = SQR(1 - (1 / PRESS.RATIO) ^ BETA)
140  '      ***             CALCULATE EXPANSION RATIO                   ***
150  EXPANSION.RATIO = NUMERATOR / DENOMINATOR
160  EXPANSION.RATIO = INT(EXPANSION.RATIO * 1000 + .5) / 1000
170  PRINT "OPTIMUM EXPANSION RATIO IS"; EXPANSION.RATIO
180  INPUT "ENTER ADIABATIC FLAME TEMPERATURE IN DEGREES RANKINE";
     FLAME.TEMP
190  INPUT "ENTER MOLECULAR WEIGHT OF COMBUSTION PRODUCTS"; MOL.WEIGHT:
     PRINT
200  '     ***            CALCULATE VACUUM THRUST COEFFICIENT          ***
210  DENOMINATOR = SQR(1 - (1 / PRESS.RATIO) ^ ((GAMMA - 1) / GAMMA))
220  VACTHRUST.COEFF = CAPITAL.GAMMA * SQR(2 * GAMMA / (GAMMA - 1)) * DE-
     NOMINATOR + EXPANSION.RATIO *
     (1 / PRESS.RATIO)
230  PRINT "VACUUM THRUST COEFFICIENT IS"; VACTHRUST.COEFF
240  '     ***         CALCULATE CHARACTERISTIC EXHAUST VELOCITY       ***
250  C.STAR = SQR(49800! * FLAME.TEMP / MOL.WEIGHT) / CAPITAL.GAMMA
260  PRINT "CHARACTERISTIC EXHAUST VELOCITY IS"; C.STAR; "FEET PER SECOND."
270  PRINT "PRESSURE RATIO IS"; PRESS.RATIO: PRINT
280  THRUST.COEFF = VACTHRUST.COEFF - EXPANSION.RATIO * (1 / PRESS.RATIO)
290  PRINT "THRUST COEFFICIENT AT"; CHAMBER.PRESS; "PSIA IS"; THRUST.COEFF
300  INPUT "DO YOU WISH TO CONTINUE (Y/N)"; ANSWER$
310  IF ANSWER$ = "y" OR ANSWER$ = "Y" THEN GOTO 10 ELSE END
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## Appendix B

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10   CLS          ' PROGRAM NAME IS APPENDXB.BAS
20   PRINT "PLEASE ENTER RATIO OF SPECIFIC HEATS."
30   INPUT "ENTER NUMBER BETWEEN 1.05 AND 1.71"; GAMMA
40   IF GAMMA >= 1.05 AND GAMMA <= 1.71 THEN GOTO 50 ELSE BEEP: GOTO 20
50   '     ***            CALCULATE VALUE FOR CAPITAL GAMMA            ***
60   CAPITAL.GAMMA = SQR(GAMMA) * (2 / (GAMMA + 1)) ^ ((GAMMA + 1) / (2 *
     (GAMMA - 1))) '
70   ALPHA = SQR((GAMMA - 1) / (2 * GAMMA)): BETA = (GAMMA - 1) / GAMMA:
     DELTA = 1 / GAMMA
80   '     ***        INITIALIZE CHAMBER PRESSURE/EXIT PRESSURE        ***
90   LET PRESS.RATIO = 1.72
100  PRINT "ENTER SELECTED EXPANSION RATIO."
110  INPUT "VALUE MUST BE BETWEEN 1.00 AND 50.00"; EXPANSION.RATIO:  PRINT
     :          PRINT
120  EXPANSION.RATIO = INT(EXPANSION.RATIO * 1000 + .5) / 1000
130  IF EXPANSION.RATIO >= 1 AND EXPANSION.RATIO <= 50 THEN GOTO 140 ELSE
     BEEP: GOTO 100
140  LET TEMP.EXP.RATIO = 0: COUNT = 0
150  '     ***         LOOP TO MATCH SELECTED EXPANSION RATIO          ***
160  WHILE TEMP.EXP.RATIO <> EXPANSION.RATIO
170      IF TEMP.EXP.RATIO < EXPANSION.RATIO THEN PRESS.RATIO = PRESS.RATIO
     + (EXPANSION.RATIO - TEMP.EXP.RATIO) * 4! + .001 ELSE GOTO 180
180      PRESS.RATIO = PRESS.RATIO - (TEMP.EXP.RATIO - EXPANSION.RATIO) *
     4! - .002
190      PRESS.RATIO = INT(PRESS.RATIO * 1000 + .5) / 1000
200      NUMERATOR = CAPITAL.GAMMA * (PRESS.RATIO) ^ DELTA * ALPHA
220      DENOMINATOR = SQR(1 - (1 / PRESS.RATIO) ^ BETA)
230      TEMP.EXP.RATIO = NUMERATOR / DENOMINATOR
240      TEMP.EXP.RATIO = INT(TEMP.EXP.RATIO * 1000 + .5) / 1000
250      COUNT = COUNT + 1
260  WEND
270  '     ***           CONTINUE WITH FURTHER CALCULATIONS           ***
280  INPUT "ENTER LOCAL ATMOSPHERIC PRESSURE (14.7 IF UNSURE)"; ATMOS.PRESS
290  INPUT "ENTER ADIABATIC FLAME TEMPERATURE IN DEGREES RANKINE";
     FLAME.TEMP
300  INPUT "ENTER MOLECULAR WEIGHT OF COMBUSTION PRODUCTS"; MOL.WEIGHT:
     PRINT
310  '     ***           CALCULATE VACUUM THRUST COEFFICIENT          ***
320  VACTHRUST.COEFF = CAPITAL.GAMMA * SQR(2 / BETA) * DENOMINATOR + EXPAN-
     SION.RATIO * (1 / PRESS.RATIO)
330  PRINT "VACUUM THRUST COEFFICIENT IS"; VACTHRUST.COEFF
340  '     ***        CALCULATE CHARACTERISTIC EXHAUST VELOCITY        ***
350  C.STAR = SQR(49800! * FLAME.TEMP / MOL.WEIGHT) / CAPITAL.GAMMA
360  PRINT "CHARACTERISTIC EXHAUST VELOCITY IS"; C.STAR; "FEET PER SECOND."
370  PRINT "PRESSURE RATIO IS"; PRESS.RATIO: PRINT
380  INPUT "WHAT IS THE DESIRED CHAMBER PRESSURE"; CHAMBER.PRESS
390  THRUST.COEFF = VACTHRUST.COEFF - EXPANSION.RATIO * (1 / PRESS.RATIO)
400  PRINT "THE THRUST COEFFICIENT AT"; CHAMBER.PRESS; "PSIA IS";
     THRUST.COEFF
410  INPUT "DO YOU WISH TO CONTINUE (Y/N)"; ANSWER$
420  IF ANSWER$ = "Y" OR ANSWER$ = "y" THEN GOTO 10 ELSE END
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## Appendix C

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10   CLS          ' PROGRAM NAME IS APPENDXC.BAS
20   PRINT "PLEASE ENTER RATIO OF SPECIFIC HEATS."
30   INPUT "ENTER NUMBER BETWEEN 1.05 AND 1.71"; GAMMA
40   IF GAMMA >= 1.05 AND GAMMA <= 1.71 THEN GOTO 50 ELSE BEEP: GOTO 20
50   '     ***            CALCULATE VALUE FOR CAPITAL GAMMA            ***
60   CAPITAL.GAMMA = SQR(GAMMA) * (2 / (GAMMA + 1)) ^ ((GAMMA + 1) / (2 *
     (GAMMA - 1))) '
70   BETA = (GAMMA - 1) / GAMMA
80   '     ***        INITIALIZE CHAMBER PRESSURE/EXIT PRESSURE        ***
90   PRINT "ENTER SELECTED EXPANSION RATIO."
100  INPUT "VALUE MUST BE BETWEEN 1.00 AND 50.00"; EXPANSION.RATIO:  PRINT
     :         PRINT
110  IF EXPANSION.RATIO >= 1 AND EXPANSION.RATIO <= 50 THEN GOTO 120 ELSE
     BEEP: GOTO 90
120  '    ***          CALCULATE COEFFICIENTS A, B, AND C            ***
130  A = 38.7019 / GAMMA - 15.5227 / GAMMA ^ 2 - 25.6441
140  B = 1 / (.3283 * (GAMMA - 1.5242) ^ 2 + .1423)
150  C = 52.4092 * GAMMA ^ 15.0965 * .0013 ^ GAMMA
160  '     ***            CALCULATE PRESSURE RATIO                    ***
170  PRESS.RATIO = A + B * EXPANSION.RATIO + C * EXPANSION.RATIO ^ 2:
     PRESS.RATIO = INT(PRESS.RATIO * 1000 + .5) / 1000
180  DENOMINATOR = SQR(1 - (1 / PRESS.RATIO) ^ BETA)
190  '    ***            CONTINUE WITH FURTHER CALCULATIONS           ***
200  INPUT "ENTER LOCAL ATMOSPHERIC PRESSURE (14.7 IF UNSURE)"; ATMOS.PRESS
210  INPUT "ENTER ADIABATIC FLAME TEMPERATURE IN DEGREES RANKINE";
     FLAME.TEMP
220  INPUT "ENTER MOLECULAR WEIGHT OF COMBUSTION PRODUCTS"; MOL.WEIGHT:
     PRINT
230  '     ***           CALCULATE VACUUM THRUST COEFFICIENT           ***
240  VACTHRUST.COEFF = CAPITAL.GAMMA * SQR(2 / BETA) * DENOMINATOR + EXPAN-
     SION.RATIO * (1 / PRESS.RATIO)
250  PRINT "VACUUM THRUST COEFFICIENT IS"; VACTHRUST.COEFF
260  '     ***        CALCULATE CHARACTERISTIC EXHAUST VELOCITY        ***
270  C.STAR = SQR(49800! * FLAME.TEMP / MOL.WEIGHT) / CAPITAL.GAMMA
280  PRINT "CHARACTERISTIC EXHAUST VELOCITY IS"; C.STAR; "FEET PER SECOND."
290  PRINT "PRESSURE RATIO IS"; PRESS.RATIO: PRINT
300  INPUT "ENTER DESIRED CHAMBER PRESSURE"; CHAMBER.PRESS
310  THRUST.COEFF = VACTHRUST.COEFF - EXPANSION.RATIO * (AT-
     MOS.PRESS/CHAMBER.PRESS)
320  PRINT "THE THRUST COEFFICIENT AT"; CHAMBER.PRESS; "PSIA IS";
     THRUST.COEFF
340  INPUT "DO YOU WISH TO CONTINUE? (Y/N)"; ANSWER$
350  IF ANSWER$ = "y" OR ANSWER$ = "Y" GOTO 10 ELSE END
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## Appendix D

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10   CLS          ' PROGRAM NAME IS APPENDXD.BAS
20   PRINT "PLEASE ENTER RATIO OF SPECIFIC HEATS."
30   INPUT "ENTER NUMBER BETWEEN 1.05 AND 1.71"; GAMMA
40   IF GAMMA >= 1.05 AND GAMMA <= 1.71 THEN GOTO 50 ELSE BEEP: GOTO 20
50   '     ***           CALCULATE VALUE FOR CAPITAL GAMMA          ***
60   CAPITAL.GAMMA = SQR(GAMMA) * (2 / (GAMMA + 1)) ^ ((GAMMA + 1) / (2 *
(GAMMA - 1))) '
70   ALPHA = SQR((GAMMA - 1) / (2 * GAMMA)): BETA = (GAMMA - 1) / GAMMA:
DELTA = 1 / GAMMA
80   '     ***        INITIALIZE CHAMBER PRESSURE/EXIT PRESSURE        ***
90   LET PRESS.RATIO = 1.72
100  PRINT "ENTER SELECTED EXPANSION RATIO."
110  INPUT "VALUE MUST BE BETWEEN 1.00 AND 50.00"; EXPANSION.RATIO:  PRINT
:         PRINT
120  EXPANSION.RATIO = INT(EXPANSION.RATIO * 1000 + .5) / 1000
130  IF EXPANSION.RATIO >= 1 AND EXPANSION.RATIO <= 50 THEN GOTO 140 ELSE
BEEP: GOTO 100
140  LET TEMP.EXP.RATIO = 0: COUNT = 0
150  '     ***         LOOP TO MATCH SELECTED EXPANSION RATIO         ***
160  WHILE TEMP.EXP.RATIO <> EXPANSION.RATIO
170      IF TEMP.EXP.RATIO < EXPANSION.RATIO THEN PRESS.RATIO = PRESS.RATIO
         + (EXPANSION.RATIO - TEMP.EXP.RATIO) * 4! + .001 ELSE GOTO 180
180      PRESS.RATIO = PRESS.RATIO - (TEMP.EXP.RATIO - EXPANSION.RATIO) *
4! - .002
190      PRESS.RATIO = INT(PRESS.RATIO * 1000 + .5) / 1000
200      NUMERATOR = CAPITAL.GAMMA * (PRESS.RATIO) ^ DELTA * ALPHA
220      DENOMINATOR = SQR(1 - (1 / PRESS.RATIO) ^ BETA)
230      TEMP.EXP.RATIO = NUMERATOR / DENOMINATOR
240      TEMP.EXP.RATIO = INT(TEMP.EXP.RATIO * 1000 + .5) / 1000
250      COUNT = COUNT + 1
260  WEND
270  '     ***          CONTINUE WITH FURTHER CALCULATIONS            ***
280  INPUT "ENTER LOCAL ATMOSPHERIC PRESSURE (14.7 IF UNSURE)"; ATMOS.PRESS
290  INPUT "ENTER ADIABATIC FLAME TEMPERATURE IN DEGREES RANKINE";
FLAME.TEMP
300  INPUT "ENTER MOLECULAR WEIGHT OF COMBUSTION PRODUCTS"; MOL.WEIGHT:
PRINT
310  '     ***          CALCULATE VACUUM THRUST COEFFICIENT           ***
320  VACTHRUST.COEFF = CAPITAL.GAMMA * SQR(2 / BETA) * DENOMINATOR + EXPAN-
SION.RATIO * (1 / PRESS.RATIO)
330  PRINT "VACUUM THRUST COEFFICIENT IS"; VACTHRUST.COEFF
340  '     ***        CALCULATE CHARACTERISTIC EXHAUST VELOCITY        ***
350  C.STAR = SQR(49800! * FLAME.TEMP / MOL.WEIGHT) / CAPITAL.GAMMA
360  PRINT "CHARACTERISTIC EXHAUST VELOCITY IS"; C.STAR; "FEET PER SECOND."
370  PRINT "PRESSURE RATIO IS"; PRESS.RATIO: PRINT
380  INPUT "ENTER NOZZLE THROAT DIAMETER (IN INCHES)"; THROAT.DIA
390  THROAT.AREA = 3.14159 * (THROAT.DIA / 2) ^ 2
400  INPUT "ENTER THRUST LEVEL (POUNDS)"; THRUST
410  CFPC = THRUST / THROAT.AREA
420  CHAMBER.PRESS = (CFPC + EXPANSION.RATIO * ATMOS.PRESS) / VAC-
THRUST.COEFF
430  PRINT "CHAMBER PRESSURE WHEN THRUST IS"; THRUST; "POUNDS IS"; CHAM-
BER.PRESS; "PSIA."
1000 INPUT "DO YOU WISH TO CONTINUE (Y/N)"; ANSWER$
1010 IF ANSWER$ = "Y" OR ANSWER$ = "y" THEN GOTO 10 ELSE END
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