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Performance Estimates for the Space Station Power System Brayton Cycle Compressor and Turbine

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PERFORMANCE ESTIMATES FOR THE SPACE STATION POWER SYSTEM BRAYTON CYCLE COMPRESSOR AND TURBINE

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1.0 SUMMARY

The methods which have been used by the NASA Lewis Research Center for predicting Brayton Cycle compressor and turbine performance for different gases and flow rates are described. These methods were developed by NASA Lewis during the early days of Brayton cycle component development and they can now be applied to the task of predicting the performance of the CBC Space Station Freedom power system.

Computer programs are given for performing these calculations and data from previous NASA Lewis Brayton Compressor and Turbine tests is used to make accurate estimates of the compressor and turbine performance for the CBC power system. Results of these calculations are also given in following sections of this report.

This work has been sponsored by NASA in order to obtain an independent evaluation of the performance of the CBC power system. In general, these calculations confirm that the CBC Brayton Cycle contractor has made realistic compressor and turbine performance estimates.

2.0 INTRODUCTION

NASA has selected the closed Brayton cycle as the solar dynamic power system for the Space Station. This system uses helium-xenon mixture of 39.94 molecular weight and has an electrical output of the 30.7 kW at a reference design point. The accuracy of the performance predictions made by the contractor for the aerodynamic components of this system can be evaluated and established by reference to the extensive history of developmental and endurance testing previously performed on Brayton Cycle components at the Lewis Research Center.

The closed Brayton cycle system (known as the CBC) has been chosen for development for the Space Station electric power system since it has a high cycle efficiency and the working fluid is an inert, noble gas. This provides the advantage of single phase operation throughout the cycle, eliminating uncertainties associated with boiling and condensing while in orbit. The CBC has also achieved many thousands of hours of successful operation in development testing and is closely related to auxiliary power units and turbochargers which have accumulated millions of operating hours in aircraft and in vehicles.

This report provides a method for estimating aerodynamic performance of the CBC compressor and turbine by reference to the previous Brayton component test results. Taken into account will be the change in the working gas and also the change in size and flow rate. The performance will be correlated from one gas to another by establishing equivalent vector diagrams at the impeller inlets and exits and by equalizing Reynolds numbers. The CBC component performances will then be estimated by using data from several of the previous tests which were performed by NASA Lewis. The remainder of this report is devoted to these issues.

2.1 DESCRIPTION OF CBC SYSTEM

The CBC power system utilizes a radial outflow compressor and a radial inflow turbine. These are mounted on a single shaft, supported on gas lubricated foil-type bearings, with a straddle mounted four pole Rice alternator integral with the shaft. The CBC rotor layout, showing dimensions of the compressor and the turbine, is given in figure 1. The remainder of the CBC gas system consists of a solar heat receiver, with integral thermal energy storage, a waste heat recuperator, and a heat rejection cooler. A schematic drawing of this system is shown in figure 2. On the figure is also given the state point conditions for the typical CBC operating point.

2.2 NASA LEWIS BRAYTON COMPRESSOR AND TURBINE TEST DATA

During the extensive period beginning in the early 1960's NASA Lewis conducted performance evaluation and improvement tests on a number of different designs of the Brayton compressors and turbines. These were on different size units, operating over a range of weight flows and Reynolds numbers and the tests were directed both toward establishing the performance level which can be obtained from these relatively small machines and toward finding possible aerodynamic performance improvements.

This background of test data provides a valuable source from which the performance of the CBC system for the Space Station can be accurately predicted.

3.0 BRAYTON CYCLE COMPRESSOR ANALYSIS

A summary of the sizes of three of the compressors which were tested is given in table I. This data was taken using argon gas. Also given in this table is the design point weight flow, the inlet pressure and pressure ratio, the inlet temperature, the design point measured efficiency, and the Reynolds number.

The reference numbers of the NASA reports which served as the source of the data is also given. These numbers refer to the list of references, attached to this report. The final column, given in table I, is the equivalent data for the Brayton compressor for the CBC He/Xe power system.

3.1 EFFECT OF REYNOLDS NUMBER

Prior NASA test results have established that Reynolds number has a pronounced effect on Brayton systems compressor performance. These effects are described and discussed in reference 1. As the Reynolds number was decreased, a progressive degradation of efficiency was observed. A decreased Reynolds number was also found to reduce the maximum flow, the maximum pressure ratio, and the flow at the surge point. Effects on the compressor work factor, the slip factor, and the windage factor were also noted.

The Brayton system compressor for the Space Station will operate at a higher Reynolds number than the prior NASA and contractor tests. The above noted effects will therefore all be beneficial. The chief concern for the present review of the Space Station Brayton system performance evaluation is the effect of Reynolds number on compressor adiabatic efficiency.

As established in reference 1 and by a number of additional test programs, the relation between the compressor efficiency (ETAC), or more specifically the loss (1 - ETAC), and the Reynolds number is found to be:

$$(1 - ETACN)/(1 - ETACK) = (REK/REN)^{N}$$

where ETACK and REK are known values of adiabatic efficiency and Reynolds number which are used as a reference point to predict a new value of ETACN, the efficiency, at another value of REN, a new Reynolds number. The value of the exponent N, shown to be appropriate in reference 1 for the Reynolds number range of interest for the Solar Brayton cycle, is 0.20. The value for the loss exponent is, of course, based on the supposition that proper matching is maintained between the impeller and the diffuser.

3.2 IMPORTANCE OF BRAYTON PERFORMANCE CLAIMS

During the proposal evaluation phase of the space station dynamic power system selection process, it has been essential to accurately establish the efficiencies that would be obtainable from the competitive power systems. As the development program begins, it is also essential to confirm that realistic performance claims have been made for the Solar Brayton cycle turbocompressor since this will be a new design and new hardware that has not previously been built and tested. The solar collector, the radiator, the alternator and the heat transfer components, will also be new and will be designed and built to match the output of the turbocompressor. The procedures described in this report are also of interest and value for possible future performance estimates of different sized Brayton cycle systems.

3.3 METHOD OF CORRELATING COMPRESSOR PERFORMANCE

The procedures for predicting the performance of a centrifugal compressor for a new gas, when its performance is known on a different gas, is described in several of the reports named in the attached REFERENCES. In particular reference 1 has a good discussion.

Briefly, the basic principle of matching performance of a compressor of a given size and geometry between different gases is to establish geometric similarity between the vector diagrams for both gases at the compressor inlet and exit and also to adjust the inlet pressure so as to match Reynolds numbers. This is accomplished as follows:

(1) Assume a constant slip factor, inlet flow coefficient, efficiency, and static density ratio across the impeller, and, using, an iterative process, determine the overall pressure ratio and the wheel speed for the new gas.

(2) Also determine the weight flow and the inlet pressure for the new gas so as to match the Reynolds number.

If the compressor size is to be modified, with all geometric parameters maintained similar, the weight flow and the inlet pressure must be properly adjusted and the Reynolds number recomputed for the new set of conditions. The efficiency may then be estimated for the new size, as previously discussed.

3.4 DESCRIPTION OF COMPUTER PROGRAM

The procedure for matching compressors between different gases, while straightforward in concept, is complicated to perform, since the compressible flow and energy input equations cannot be solved in closed form and a series of iterations is required. A BASIC computer program has therefore been produced to perform these computations. This program, written for the IBM PC and compatible computers, has been named BRAYCOMP.BAS. A listing of this program is attached to this report.

This program has been written to output results to the CRT screen, to a printer, or to a data file for subsequent manipulation or plotting by a data base program. It also contains input statements with the geometric values and the design point performance results for three Brayton compressors which were tested by the NASA Lewis Research Center. Input statements for the geometric values and the proposed performance of the CBC system are also included. Thermodynamic properties and formulas for determining viscosity for air, argon, and the He/Xe mixture of 39.95 molecular weight are also contained. Properties for neon, krypton, and He/Xe mixtures of different molecular weights could also be easily added. For computation of the Brayton system for the space station the He/Xe mixture of molecular weight 39.95 (referred to as He/Xe(39.95)) is the one which should be selected.

3.5 PROCEDURE FOR COMPUTATION

A brief description of the procedure for using this program is as follows:

(1) Enter BASIC on the PC and open BRAYCOMP.BAS.

(2) Make the selection between SCREEN, PRINTER, or DATAFILE, for output. The DATAFILE option creates a new file which may be used for additional analysis, if desired.

(3) The final entry step is to make the selection for the compressor diameter and the known and new working gases.

The above selections are made in response to questions which appear on the CRT screen, so that the choices can be readily made.

3.6 CALCULATION OF EQUIVALENT CONDITIONS

NASA Lewis has previously conducted tests on Brayton cycle compressors using air and several monatomic gases and gas mixtures. In most instances, these tests were performed several times on compressors of different geometries. This multiple testing allowed verification that the methods of prediction of equivalent performances for different gases, as described in this report, are indeed correct and accurate.

3.7 CONVERSION OF ARGON TEST DATA

These prediction methods will therefore now be applied utilizing data that was initially obtained in the NASA Lewis compressor component performance evaluation tests so as to obtain an estimate of performance for the He/Xe, molecular weight 39.95, mixture which has been selected for use in the space station CBC. The three sizes of the compressors for which these predictions are to be made, as previously given in table I, are tip diameters of 4.25, 5.976, and 6.44 in. The known data for these predictions has been obtained from references 2, 1, and 3. The calculations for the 4.25, the 5.976, and the 6.44-in.-diam. compressors are summarized in tables II, III, and IV, respectively.

3.8 CALCULATION OF PARAMETERS FOR THE CBC

Estimates of the performances of the CBC compressor, using the He/Xe (molecular weight 39.95) working fluid, have been made by the Garrett Corporation and presented in the space station power system proposal. The geometric data and the performance estimates made by Garrett have been entered in the BRAYCOMP.BAS program and have been converted from He/Xe (39.95) to argon. This allows a direct comparison with the results of the previous tests in which argon was used. These results are given in table V.

3.9 PREDICTIONS OF THE CBC COMPRESSOR PERFORMANCE

An independent estimate of the adiabatic efficiency of the CBC compressor can now be made, using the CBC calculated Reynolds number, as listed in table V. This can be accomplished by converting the loss fractions from the measured argon data from NASA Lewis tests (as given in tables II to IV) by use of the 0.2 exponential power of the Reynolds ratio.

The computed mean efficiency value of 0.843 in table VI may be seen to compare very closely with the Garrett Corporation CBC compressor efficiency prediction. The higher computed value determined from the data from the 6.44-in.-diam. compressor test data would seem to provide further assurance that a CBC compressor efficiency will be obtained that will be at least as high as that predicted by the contractor.

4.0 BRAYTON CYCLE TURBINE ANALYSIS

A summary of the sizes of the three turbines which were tested by NASA Lewis and which have been used to estimate the CBC turbine efficiency is given in table VII. This data is for use of argon gas. Also given in this table is the design point weight flow, the inlet pressure and pressure ratio, the inlet temperature, the design point measured efficiency, and the Reynolds number. The reference numbers of the NASA reports which served as the source of this data is also given. These numbers refer to the list of references, attached to this report.

The final column, given in table VII is the design point data for the Brayton turbine proposed for the CBC He/Xe power system.

4.1 EFFECT OF REYNOLDS NUMBER

NASA turbine test results have been established that Reynolds number also has a significant effect on Brayton systems turbine performance, These effects are described and discussed in reference 4. During these tests it was found that, as the Reynolds number was decreased, a progressive degradation of efficiency was observed. Decreasing Reynolds number was also found to slightly reduce the turbine flow.

The Brayton system turbine for the space station will operate at a higher Reynolds number than the prior NASA and contractor tests. The above noted effects will therefore all be beneficial. The chief concern for the present review of the space station Brayton system performance evaluation is the effect of Reynolds number on the turbine adiabatic efficiency. As established by reference 4 and by a number of additional test programs, the relation between the turbine efficiency (ETAI), or more specifically the loss (1 - ETAT), and the Reynolds number is found to be:

$$(1 - ETATN)/(1 - ETATK) = A + B * (REK/REN)^N$$

where ETATK and REK are known values of adiabatic efficiency and Reynolds number which are used as a reference point to predict a new value of ETATN, the turbine efficiency at another value of the new Reynolds number (REN). The values of the constants A and B and the exponent N, shown to be appropriate in reference 4 for the Reynolds number range of interest for the Solar Brayton cycle, are A = 0.4, B = 0.6, and N = 0.20. The values for these loss constants are, of course, based on the supposition that good aerodynamic designs are maintained for the inlet nozzles, the impeller and the exit diffuser. These values for the loss constants will then subsequently be used to predict the CBC turbine performance from the measured efficiencies of the prior tests.

4.2 METHOD OF CORRELATING TURBINE PERFORMANCE

The procedures for predicting the performance of a radial inflow turbine for a new gas, when its performance is known for a different gas, is described in several of the reports named in the attached List of References. In particular, reference 6 has a good discussion, giving an example of the equivalence of air and argon performance for the 6.02-in.-diam. turbine. A general description of the method is as follows:

The basic principle of matching performance of a turbine of a given size and geometry between different gases is similar to that previously described for the compressor. Again it is needed to establish geometric similarity between the vector diagrams for both gases at the turbine inlet and exit and also to adjust the flow rate so as to match Reynolds numbers. This is accomplished as follows:

(1) Determine the weight flow for the new gas so as to match the Reynolds Number.

(2) Adjust the rotational speed, the inlet pressure, and the total to static pressure ratio so as to obtain the same equivalent flow, equivalent speed, and equivalent specific work.

If the turbine size is to be modified, with all geometric parameters maintained similar, the weight flow and the inlet pressure must then be properly adjusted and the Reynolds number recomputed for the new set of conditions. The efficiency may then be estimated for the new size, as previously discussed.

4.3 COMPUTER PROGRAM AND PROCEDURE FOR COMPUTATION

A listing of a BASIC computer program named BRAYTURB.BAS, which is used to perform turbine matching computations is attached to this report. This program already contains size and performance data for the 4.59, the 4.97, and the 6.02-in.-diam. turbines which were tested by NASA Lewis. The size and estimated performance data for the CBC turbine is also included. The further discussion and description of the procedure for computation previously given for the compressor also applies to use of this turbine program.

4.4 CONVERSION OF ARGON TURBINE TEST DATA

These prediction methods will now be applied utilizing the data that was initially obtained in the NASA Lewis turbine component performance evaluation tests so as to obtain an estimate of the turbine performance for the He/Xe, molecular weight 39.95, mixture which has been selected for use in the space station CBC. The three sizes of the turbines for which these calculations are to made were previously given in table VII with tip diameters of 4.59, 4.97, and 6.02 in. The known data for these predictions has been obtained from references 4, 5, and 6, and the calculations are summarized in tables VIII, IX, and X.

4.5 CALCULATION OF PERFORMANCE OF THE CBC TURBINE

Estimates of the performances of the CBC turbine, using the He/Xe (molecular weight 39.95) working fluid, have been made by the Garrett Corporation and presented in the space station power system proposal. The geometric data and the performance estimates made by Garrett have been entered in the BRAYTURB.BAS program and have been converted from He/Xe (39.95) to argon. This allows a direct comparison with the results of the previous tests in which argon was used. These results are given in table XI.

4.6 PREDICTION OF THE CBC TURBINE PERFORMANCE

An independent estimate of the adiabatic efficiency of the CBC turbine can now be made, using the CBC calculated Reynolds number as listed in table XI. This can be accomplished by converting the loss fractions from the measured argon data from NASA Lewis turbine tests (as given in tables VIII, IX, and X) by use of the equation using 0.2 exponential power of the Reynolds number ratio, previously given:

$$(1 - \mathrm{ETATN})/(1 - \mathrm{ETATK}) = 0.4 + 0.6 * (\mathrm{REK}/\mathrm{REN})^{0.2}$$

This computation is summarized in table XII. The computed mean efficiency value of 0.883 is found to be a significant amount lower than the Garrett Corporation CBC turbine efficiency prediction of 0.897. The higher computed values determined from the data from the 4.97- and the 6.02-in.-diam. turbine tests would seem to somewhat modify this result, but both of these tests predict an efficiency of about 0.007 below the CBC estimate.

A further direct experimental result, reported in reference 6 (TN D-2987), can also be used to check the above estimates. Here a measured total efficiency of 0.90 was reported for an air test of the 6.02-in.-diam. turbine at a Reynolds number of 225×10^3. Interpolation between this result and the value of efficiency of 0.88, measured for the 6.02-in.-diam turbine at the Reynolds number of 64×10^3, results in a CBC estimated adiabatic total efficiency of only 0.888.

In evaluating the above results, however, it should be considered that the CBC turbine, having a tip diamenter of 7.65 in., would also be expected to obtain some performance advantage from direct effect of scale and tip clearance ratio. This is further discussed in the following sections.

5.0 EFFECTS OF OTHER VARIABLES

In order to make a complete evaluation of the performance potential of the CBC compressor and turbine it would be necessary to consider the effects of such things as disk and vane clearances, inlet and exit Mach numbers, diffuser vane angle setting, and the design of the subsonic exit diffusers. These factors have all been found in prior NASA Lewis research programs to have significant effect on the efficiency of the Brayton cycle compressors and turbines. Both the CBC compressor and the turbine, however, will have a close family resemblance to previously tested units. The above enumerated design and construction variables may therefore be expected to have only a secondary effect on efficiency.

6.0 CONCLUDING REMARKS

This report has described the method whereby the measured performance of a Brayton cycle radial outflow centrifugal compressor and a radial inflow turbine, using a gas which has one set of thermodynamic properties, may be used to accurately predict the performance of an identical compressor and turbine, when operated with a gas having different properties.

The method for correcting the predicted performance of a geometrically similar compressor or turbine, when it is scaled upward or downward in size is also described.

Two BASIC computer programs are also included, in order that these types of performance computations can be made for any compressor or turbine performance matching application.

This program has then been used to predict the performance of the CBC compressor and the CBC turbine, using He/Xe, based upon measured argon tests results, obtained during prior NASA Lewis Brayton cycle development and research programs. These computations appear to confirm that an accurate compressor efficiency estimate has been made by the Brayton Cycle System Contractor. The turbine efficiency estimate compares reasonably well when consideration is given to possible direct effects of scale and turbine rotor inlet and exit diffuser differences. Further considerations may be warranted, however, in order to determine the reasons and the possible effects of the slightly lower predicted turbine efficiency.

APPENDIX A

COMPRESSOR MATCHING SYMBOLS

This is a list of symbols for the Brayton Cycle Compressor matching program (BRAYCOMP.BAS). This program provides matching for air and several different inert gases. A symbol ending with K refers to the known gas; one ending with N refers to the new gas. For example: CPK = Specific heat, known and CPN = Specific heat, new. However, in some cases the ending K is omitted.

AR3 = Exit flow area ($in.^2$)
AT3 = Exit stagnation sonic velocity (ft/sec)
AM2 = Inlet flow area ($in.^2$)
BH = Exit blade height (in.)
CPK = Specific heat, known gas (Btu/lb-°F)
CPN = Specific heat, new gas (Btu/lb-°F)
CN = 720/PI = 229.18
DEL = P1/14.7
DEL1 = Inlet velocity error increment
DEL2 = Exit velocity error increment
DI = Inlet tip diameter (in.)
DR = Static density ratio
DRN = Static density ratio, new
DH = Inlet hub diameter (in.)
DT = Tip diameter (in.)
DTA = Actual temperature rise (°R)
DTI = Ideal temperature rise (°R)
ETAC = Compressor adiabatic efficiency
ETACI = Impeller efficiency
FCW = Compressor work factor
FW = Windage factor
FS = FCW - FW
G = 32.17 ft/sec^2
GAMK = Specific heat ratio, known
GAMN = Specific heat ratio, new gas
H = Ideal head rise (ft)
HN = Ideal head, new (ft)
J = 778.16 ft - lb/Btu
K2&K3 = Known flow functions
K2N&K3N = New flow functions
KG$ = Name, known gas
MK = Molecular weight, known gas
MN = Molecular weight, new gas
MU2K = Viscosity, known (lb/ft-sec)
MU2N = Viscosity, new (lb/ft-sec)
NG$ = Name, new gas
NK = rpm, known
NKEQU = Corrected rpm, known
NN = rpm, new gas
NS = Specific speed
P2 = Inlet total pressure ($lb/in.^2$)
P2N = Inlet total pressure, new
PHI = Inlet flow coefficient, known
PHIN = Inlet flow coefficient, new
PI = 3.14159
PR = Pressure ratio, known
PRN = Pressure ratio, new
RHO2 = Inlet static density (lb/ft^3)
RHO2N = Inlet static density, new
RHO3 = Exit static density
RHO3N = Exit static density, new
REK = Reynolds number, known
REN = Reynolds number, new
RK = Gas constant, known gas
RN = Gas constant, new gas
T2 = Inlet total temperature (°R)
T2N = Inlet total temperature, new (°R)
T3 = Exit total temperature (°R)
T3N = Exit total temperature, new (°R)
THETA = T2/518.7
UTK = Tip speed, known (ft/sec)
UTN = Tip speed, new gas
VM2 = Inlet merid. velocity
VTT2&VT2 = Velocity ratio function
VTT3&VT3 = Exit velocity function
WK = Weight flow, known (lb/sec)
WN = Weight flow, new gas (lb/sec)
WEQU = Corrected weight flow
XK = (GAMK - 1)/GAMK, known
XN = (GAMN - 1)/GAMN, new
X2K = (GAMK - 1)/2, known
X2N = (GAMN - 1)/2, new
YK = 1/(GAMK - 1), known
YN = 1/(GAMN - 1), new

APPENDIX B

LIST OF TURBINE MATCHING SYMBOLS

This is a list of symbols for the Brayton Cycle Turbine matching program (BRAYTURB.BAS). This program provides matching for air and several different inert gases. A symbol ending with K refers to the known gas; one ending with N refers to the new gas. For example: CPK = Specfic heat, known & CPN = Specific heat new. However, in some cases the ending K is omitted

AR2 = Inlet flow area (in.^{2})
ALPH2 = Stator exit angle (deg)
AT3 = Exit stagnation sonic velocity (ft/sec)
AM3 = Exit flow area (in.^{2})
BW = Inlet blade width (in.)
CPK = Specific heat, known gas (Btu/lb-°F)
CPN = Specific heat, new gas (Btu/lb-°F)
CN = 720/PI=229.18
DEL = P1/14.7
DEL1 = Inlet velocity error increment
DEL2 = Exit velocity error increment
DELH = Specific work (Btu/lb)
DE = Exit tip diameter (in.)
DH = Exit hub diameter (in.)
DHEQU = Air standard specific work (Btu/lb)
DT = Tip diameter (in.)
DTA = Actual temperature rise (°R)
DTI = Ideal temperature rise (°R)
EPSI = Function of gamma
ETAT = Total to total efficiency
ETAS = Total to static efficiency
G = 32.1 ft/sec^2
GAMK = Specific heat ratio, known
GAMN = Specific heat ratio, new gas
H = Ideal head drop (ft)
HN = Ideal head, new
J = 778.16 ft-lb/Btu
K2&K3 = Known flow functions
K2N&K3N = New flow functions
KG$ = Name, known gas
MK = Molecular weight, known gas
MN = Molecular weight, new gas
MU2K = Viscosity, known(lb/ft-sec)
MU2N = Viscosity, new (lb/ft-sec)
NG$ = Name, new gas
NK = rpm, known
NKEQU = corrected rpm, known
NN = rpm, new gas
NS = specific speed
YN = 1/(GAMN - 1), new
NU = Blade to jet speed ratio
P2 = Inlet total pressure (lbs/in.^{2})
P2N = Inlet total pressure, new
PI = 3.14159
PR = Total pressure ratio
PRS = Total to static pressure
PRN = Pressure ratio, new
RHO2 = Inlet static density (lb/ft^3)
RHO2N = Inlet static density, new
RHO3 = Exit static density
RHO3N = Exit static density, new
REK = Reynolds number, known
REN = Reynolds number, new
RK = Gas constant known gas (ft/°R)
RN = Gas constant, new gas (ft/°R)
TAU = Torque (in.-lb)
T2 = Inlet total temperature (°R)
T2N = Inlet total temperature, new (°R)
T3 = Exit total temperature (°R)
T3N = Exit total temperature, new
THETA = T2/518.7
UTK = Tip speed, known (ft/sec)
UTN = Tip speed, new (ft/sec)
VACR2 = Inlet velocity ratio
VACR3 = Exit velocity ratio
VCR2K = Known credit sonic velocity
VJI = Ideal jet velocity
V2 = Inlet velocity
VM3 = Exit merid. velocity
WK = Weight flow known (lb/sec)
WN = Weight flow, new gas (lb/sec)
WEQU = Air standard corrected weight flow
XK = (GAMK - 1)/GAMK, known
XN = (GAMN - 1)/GAMN, new
X2K = (GAMK - 1)/2, known
X2N = (GAMN - 1)/2, new
X3 = (GAMN - 1)/(GAMN+1)
YK = 1/(GAMK - 1), known

APPENDIX C

BRAYCOMP.BAS PERFORMANCE PREDICTION PROGRAM

```
5 REM "THIS IS THE BRAYCOMP.BAS PROGRAM"
10 INPUT "SCREEN (S), PRINTER (P), OR FILE (F)? ";SD$
15 IF SD$="P" THEN 20
16 IF SD$="F" THEN 25
17 GOTO 30
20 OPEN "LPT1:" FOR OUTPUT AS #1:WIDTH "LPT1:",70:GOTO 35
25 OPEN "BCOMP001.REP" FOR OUTPUT AS #1:GOTO 35
30 OPEN "SCRN:"FOR OUTPUT AS #1:WIDTH "SCRN:",80
35 PRINT "This is the BRAYCOMP.BAS program.  This program matches
36 PRINT "Brayton cycle compressors for different gases.  Output
40 PRINT "is sent to file BCOMP001.REP.  Names of allowed gases
45 PRINT "are: AIR,NEON,ARGON,& KRYPTON. He/Xe mixtures may also
46 PRINT "be used:He/Xe(20.18,39.95 & 83.88) Test data is
50 PRINT "available for 4.25,5.976,& 6.44 inch diameter compressors
55 PRINT "Calculations can also be made for the 6.5-inch-diam.
56 PRINT "CBC Compressor."
60 PRINT "Input (KNOWN) compressor tip diameter (DT)":INPUT DT
65 PRINT  "Input name of gas for which data is known (KG$)":INPUT KG$
66 LET PI=3.14159:J=778.16:CN=229.18:G=32.17
70 IF KG$="AIR" THEN 1000
71 IF KG$="ARGON" THEN 1020
75 IF KG$="HE/XE(39.95)" THEN 1040
76 IF KG$="NEON" THEN 1060
80 IF KG$="HE/XE(20.18)" THEN 1080
85 IF KG$="KRYPTON" THEN 2000
90 IF KG$="HE/XE(83.88)" THEN 2020

100 LET AM2=PI*(DI^2-DH^2)/4:AR3=PI*DT*BH
110 LET K2=SQR(GAMK*G/(RK*T2))*AM2:VT2=WK/(K2*P2)
120 LET VTT2=VT2:LET VT2=(WK/(K2*P2))/((1-X2*VTT2^2)^(YK))
130 LET DEL1=ABS(VTT2-VT2):IF DEL1>.0001 GOTO 120
140 LET RHO2=(P2*144/(RK*T2))*((1-X2*VT2^2)^(YK)):UTK=DT*NK/CN
150 LET REK=RHO2*UTK*DT/(MU2K*12):DTI=T2*(PR^XK-1)
160 LET DTA=DTI/ETAC:T5=T2+DTA
170 LET VM2=144*WK/(RHO2*AM2):PHI=VM2/UTK
180 LET FCW=G*J*CPK*(T5-T2)/UTK^2:LET H=CPK*DTI*J
190 LET FS=FCW-FW
200 LET NS=NK*SQR(WK/RHO2)/(60*((G*H)^.75))
210 LET THETA=T2/518.7:LET DEL=P2/14.7:T3=T5
220 LET WEQU=WK*SQR(THETA)/DEL:NKEQU=NK/SQR(THETA)
230 LET K3=SQR(GAMK*G/(RK*T3))*AR3*P2*PRI
240 LET VT3=WK/K3:AT3=SQR(GAMK*G*RK*T3)
250 LET VTT3=VT3:VT3=SQR((((WK/K3)/((1-X2*VTT3^2)^YK))^2)
    +((FS*UTK/AT3)^2))
260 LET DEL2=ABS(VTT3-VT3):IF DEL2>.0001 GOTO 250
270 LET DR2=(PRI/(1+(PRI^XK-1)/ETACI))*((1-X2*VT3^2)
    /(1-X2*VT2^2))^YK
280 LET THETA=T2/518.7:DEL=P2/14.7:T3=T5
290 LET RHO3=(P2*PRI*144/(RK*T3))*((1-X2*VT3^2)^(YK)):DR=RHO3/RHO2
300 PRINT:PRINT "Input name of New gas (NG$)": INPUT NG$
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```
310 IF NG$="AIR" THEN 5000
320 IF NG$="ARGON" THEN 5020
330 IF NG$="HE/XE(39.95)" THEN 5040
340 IF NG$="ARGON" THEN 5020
350 IF NG$="HE/XE(83.88)" THEN 6020
360 LET WN=MU2N*WK/MU2K:K2N=AM2*SQR(GAMN*G/(RN*T2N)):VT2N=VT2
370 LET PRX=PRI:VT3N=VT3
380 LET P2NT=WN/(K2N*VT2N*(1-X2N*VT2N^2)^YN)
390 LET UTN=SQR(GAMN*RN/(GAMK*RK))*UTK*VT2N/VT2
400 LET NN=UTN*CN/DT
410 LET RHO2NT=(P2NT*144!/(RN*T2N))*((1-X2N*VT2^N2)^YN)
415 LET DTAN=FCW*UTN^2/(G*J*CPN):DTINT=DTAN*ETAC
420 LET HN=CPN*DTINT*J:RHO2N=WN/(NS*(60*((G*HN)^.75))/NN)^2
430 LET VT2N=(WN/(K2N*P2NT))/((1-X2N*VT2N^2)^YN)
440 LET P2N=RHO2N*RN*T2N/(((1-X2N*VT2N^2)^YN)*144)
450 LET DEL2N=ABS(P2N-P2NT)
460 LET VT2NT=(WN/(K2N*P2N))/((1-X2N*VT2N^2)^YN)
465 DEL6N=ABS(VT2NT-VT2N)
470 LET VT2N=VT2NT:IF ABS(DEL6N)>.001 THEN 460
480 IF DEL2N>.001 GOTO 380
490 LET VT2N=(WN/(K2N*P2N))/((1-X2N*VT2N^2)^YN)
500 LET PRIN=DR*(((PRX^XN-1)/ETACI)+1)*((1-X2N*VT2N^2)
    /(1-X2N*VT3N^2))^YN
505 LET DEL2=ABS(PRIN-PRX)
510 LET PRX=PRIN:IF DEL2>.0005 GOTO 500
520 LET PRN=(DTAN*ETAC/T2N+1)^(1/XN)
530 LET VM2N=VT2N*SQR(GAMN*G*RN*T2N):PHIN=VM2N/UTN
540 LET NNEQU=NN/SQR(THETA):DTIN=DTAN*ETAC
550 LET T5N=T2N+DTAN
560 LET K3N=SQR(GAMN*G/(RN*T5N))*AR3*P2N*PRIN:FCWN=G*J*CPN
    *(T5N-T2N)/UTN^2
570 LET AT3N=SQR(GAMN*G*RN*T5N):FSN=FCWN-FW:VTT3N=VT3N
580 LET VT3N=SQR((((WN/K3N)/((1-X2N*VTT3N^2)^YN))^2)
    +((FSN*UTN/AT3N)^2))
590 LET DEL3N=ABS(VTT3N-VT3N):IF DEL3N>.001 GOTO 500
600 LET DEL4N=ABS(DTINT-DTIN):IF DEL4N<1! GOTO 620
610 LET DTINT=DTIN:GOTO 420
620 LET RHO3N=(P2N*PRIN*144/(RN*T5N))*((1-X2N*VT3N^2)^YN)
630 LET NSN=NN*SQR(WN/RHO2N)/(60*((G*HN)^.75))
640 LET DRN=RHO3N/RHO2N:DEL5N=(DRN-DR)/DRN:IF ABS(DEL5N)<.001 THEN 660
650 LET VT2N=VT2N/(1-DEL5N):GOTO 380
660 LET REN=RHO2N*UTN*DT/(MU2N*12)
700 PRINT #1,"Compressor Data: Tip Diam.,DT"; FIX(1000*DT+.5)/1000;
710 PRINT #1,"Inlet Tip Diam.,DI";FIX(1000*DI+.5)/1000
715 PRINT #1,"Inlet Hub Diam.,DH";FIX(1000*DH+.5)/1000;
720 PRINT #1,",Exit Blade Height,BH";FIX(1000*BH+.5)/1000;
725 PRINT #1,"Windage Factor,FW";FIX(1000*FW+.5)/1000
730 PRINT #1,:PRINT #1,N1$:PRINT #1,D1$:PRINT #1,D2$
740 PRINT #1,:PRINT #1,"INPUT DATA"
750 PRINT #1,"Inlet Pressure,P2";;;FIX(100*P2+.5)/100
755 PRINT #1,"Inlet Temp.,T2"; FIX(T2+.5)
760 PRINT #1,"Weight Flow,WK";FIX(1000*WK+.5)/1000
765 PRINT #1,"Pressure Ratio,PR"; FIX(1000*PR+.5)/1000
770 PRINT #1,"Imp. Pressure Ratio,PRI"; FIX(1000*PRI+.5)/1000
775 PRINT #1,"Adiabatic Eff.,ETAC"; FIX(1000*ETAC+.5)/1000
```

```
780 PRINT #1,"Impeller Eff.,ETACI"; FIX(1000*ETACI+.5)/1000
785 PRINT #1,"Rotational Speed,NK";FIX(100000!*NK+.5)/100000!
790 PRINT #1,:PRINT #1,"KNOWN GAS(";KG$;") RESULTS"
800 PRINT #1,"Known Viscosity,MU2K";;;FIX(1000*(MU2K*10^5)+.5)/1000
    ;"E-05"
810 PRINT #1,"Total Temp. Ratio,T3/T2";FIX(1000*(T5/T2)+.5)/1000
815 PRINT #1,"Inlet Vel. Ratio,VT2"; FIX(1000*VT2+.5)/1000
820 PRINT #1,"Exit Vel. Ratio,VT3"; FIX(1000*VT3+.5)/1000
830 PRINT #1,"Density Ratio,DR";FIX(1000*DR+.5)/1000
840 PRINT #1,"Known Corr. RPM,NKEQU";FIX(NKEQU+.5)
845 PRINT #1,"Known Tip Speed,UTK"; FIX(10*UTK+.5)/10
850 PRINT #1,"Compr. Work Factor,FCW";FIX(1000*FCW+.5)/1000
855 PRINT #1,"Slip Factor,FS";FIX(1000*FS+.5)/1000
860 PRINT #1,"Inlet Flow Coeff.,PHI";FIX(1000*PHI+.5)/1000
870 PRINT #1,"Specific Speed,NS"; FIX(1000*NS+.5)/1000
880 PRINT #1,"Known Reynolds No.,REK"; FIX((REK/10^6)*100+.5)/100
    ;"E+06"
881 PRINT #1,:PRINT#1,N2$:PRINT #1,D3$:PRINT #1,D4$
882 PRINT #1,:PRINT#1,N3$
890 PRINT #1,"Inlet Pressure,P2N";;FIX(100*P2N+.5)/100
895 PRINT #1,"Inlet Temp.,T2N";FIX(T2N+.5)
900 PRINT #1,"Weight Flow,WN";FIX(1000*WN+.5)/1000
905 PRINT #1,"Pressure Ratio,PRN";FIX(100*PRN+.5)/100
910 PRINT #1,"Imp. Pressure Ratio,PRIN";FIX(100*PRIN+.5)/100
915 PRINT #1,"Adiabatic Eff.,ETAC"; FIX(1000*ETAC+.5)/1000
920 PRINT #1,"Impeller Eff.,ETACI"; FIX(1000*ETACI+.5)/1000
925 PRINT #1,"Rotational Speed,NN"; FIX(NN+.5):PRINT #1,:PRINT #1,:
930 PRINT #1,"New Viscosity,MU2N";FIX(1000*(MU2N*105)+.5)/1000;"E-05"
935 PRINT #1,"Total Temp. Ratio,T3/T2";FIX(1000*(T5N/T2N)+.5)/1000
940 PRINT #1,"Inlet Vel. Ratio,VT2N";FIX(1000*VT2N+.5)/1000
945 PRINT #1,"Exit Vel. Ratio,VT3N";FIX(1000*VT3N+.5)/1000
950 PRINT #1,"Density Ratio,DRN";FIX(1000*DRN+.5)/1000
955 PRINT #1,"New Corr. RPM,NNEQU";FIX(NNEQU +.5)
960 PRINT #1,"Tip Speed,UTN";FIX(10*UTN+.5)/10
965 PRINT #1,"New Work Factor,FCWN";FIX(1000*FCWN+.5)/1000
970 PRINT #1,"New Slip Factor,FSN";FIX(1000*FSN+.5)/1000
975 PRINT #1,"Inlet Flow Coeff.,PHIN";FIX(1000*PHIN+.5)/1000
980 PRINT #1,"New Specific Speed,NSN";FIX(1000*NSN+.5)/1000
985 PRINT #1,"New Reynolds No.,REN";FIX((REN/106)*100+.5)/100;"E+06"
990 PRINT "CALCULATION COMPLETE":STOP
1000 LET MK=29:RK=1545/MK:GAMK=1.4:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1001 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):N1$="THE KNOWN GAS IS AIR"
1002 LET D1$="Mol. Wt.=29.0,R=53.28":D2$="Sp. Heat=.24,Gam=1.4"
1003 IF ABS(DT-4.25) <=.0001 THEN 2000
1004 IF ABS(DT-5.976) <=.0001 THEN 2010
1005 IF ABS(DT-6.44) <=.0001 THEN 2020
1006 IF ABS(DT-6.5) <=.0001 THEN 2025
1007 LET MU2K=(.2361+.002173*T2-5.75E-07*(T2^2)+9.17E-11*(T2^3))*(10^-5)
1008 GOTO 100
1020 LET MK=39.948:RK=1545/MK:GAMK=1.667:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1021 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):N1$="THE KNOWN GAS IS ARGON."
1022 LET D1$="Mol. Wt.=39.948,R=38.68":D2$="Sp. Heat=.124,GAM=1.667."
1023 IF ABS(DT-4.25) <=.0001 THEN 2030
1024 IF ABS(DT-5.976) <=.0001 THEN 2040
```

```
1025 IF ABS(DT-6.44) <=.0001 THEN 2050
1026 IF ABS(DT-6.5) <=.0001 THEN 2055
1027 LET MU2K=(.323+.002454*T2-3.53E-07*(T2^2))*(10^-5)
1028 GOTO 100
1040 LET MK=39.948:RK=1545/MK:GAMK=1.667:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1041 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):N1$="THE KNOWN GAS IS HE/XE(39.95)"
1042 LET D1$=" Mol. Wt.=39.948,R=38.68":D2$="Sp. Heat=.124,GAM=1.667"
1043 IF ABS(DT-4.25) <=.0001 THEN 2060
1044 IF ABS(DT-5.976) <=.0001 THEN 2070
1045 IF ABS(DT-6.44) <=.0001 THEN 2080
1046 IF ABS(DT-6.5) <=.0001 THEN 2085
1047 LET MU2K=(.0764+.003819*T2-1.479E-06*(T2^2)+5.22E-10*T2^3
     -8.160001E-14*T2^4)*(10^-5)
1048 GOTO 100
1060 STOP
1080 STOP
2000 LET P2=21.64:T2=540:WK=.638:PR=1.71:ETAC=.8:NK=54600!:DI=2.6
2002 LET DH=1.44:BH=.205:PRI=1.81:ETACI=.895:FW=.039:GOTO 1007
2010 LET P2=6.41:T2=536:WK=.497:PR=2.09:ETAC=.798:NK=40300!:DI=3.528
2012 LET DH=1.858:BH =.217:PRI=2.27:ETACI=.896:FW=.039:GOTO 1007
2020 STOP
2022 GOTO 1007
2025 STOP
2027 GOTO 1007
2030 LET P2=20.25:T2=540:WK=.785:PR=1.9:ETAC=.8:NK=52200!:DI=2.6:DH=1.44
2032 LET BH=.205:PRI=2.03:ETACI=.895:FW=.039:GOTO 1027
2040 LET P2=6:T2=536:WK=.611:PR=2.38:ETAC=.798:NK=38500!:DI=3.528:DH=1.858
2042 LET BH=.217:PRI=2.62:ETACI=.896:FW=.039:GOTO 1027
2050 LET P2=6!:T2=536:WK=.611:PR=2.3:ETAC=.821:NK=38500!:DI=3.95:DH=2.19
2052 LET BH=.31:PRI=2.47:ETACI=.897:FW=.039:GOTO 1027
2055 STOP
2057 GOTO 1027
2060 STOP
2062 GOTO 1047
2070 LET P2=6.85:T2=536:WK=.704:PR=2.42:ETAC=.798:NK=38920!:DI=3.528
2072 LET DH=1.858:BH=.217:PRI=2.65:ETACI=.896:FW=.039:GOTO 1047
2080 LET P2=6.87:T2=536:WK=.704:PR=2.32:ETAC=.821:NK=38800!:DI=3.95:DH=2.19
2082 LET BH=.31:ETACI=.897:FW=.039:GOTO 1047
2085 LET P2=26.4:T2=520:WK=1.87:PR=1.9:ETAC=.842:NK=32000:DI=4!:DH=2.28
2087 LET BH=.351:PRI=2.04:ETACI=.91:FW=.039:GOTO 1047
5000 LET MN=29:RN=1545/MN:GAMN=1.4:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5001 LET X2N =(GAMN-1)/2:YN=1/(GAMN-1):T2N=T2
5002 LET N2$="THE NEW GAS IS AIR.": D3$="Mol. Wt.=29.0,R=53.28"
5003 LET D4$="Sp. Heat=.24,GAM=1.4.":N3$="PERF. USING AIR."
5004 LET MU2N=(.2361+.002173*T2^N-5.75E-07*(T2N^2)+9.17E -11*(T2N^3))*(10^-5)
5008 GOTO 360
5020 LET MN=39.948:RN=1545/MN:GAMN=1.667:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5021 LET X2N=(GAMN-1)/2:YN=1/(GAMN-1):T2N=T2
5022 LET N2$= "THE NEW GAS IS ARGON": D3$="Mol. Wt.=39.948,R=38.68"
5023 LET D4$="Sp. Heat=.124,GAM=1.667.":N3$="PERF. USING ARGON."
5024 LET MU2N=(.323+.002454*T2N-3.53E-07*(T2N^2))*(10^-5)
5028 GOTO 360
5040 LET MN=39.948:RN=1545/MN:GAMN=1.667:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5041 LET X2N=(GAMN-1)/2:YN=1/(GAMN-1):T2N=T2
```

```
5042 LET N2$="THE NEW GAS IS HE/XE(39.95)": D3$="Mol. Wt.=39.948,R=38.680"
5043 LET D4$="Sp. Heat=.124,GAM=1.667.":N3$="PERF. USING HE/XE(39.95)."
5044 LET MU2N=(.0764+.003819*T2-1.479E-06*(T2^2)+5.22E-10*T2^3-8.160001E
     -14*T2^4)*(10^-5)
5048 GOTO 360
6000 STOP
6020 STOP
```

APPENDIX D

LISTING NO. 2

BRAYTURB.BAS PERFORMANCE PREDICTION PROGAM

```
5  REM "THIS IS THE BRAYTURB.BAS PROGRAM"
10 INPUT "SCREEN (S), PRINTER (P), OR FILE (F)? ";SP$
15 IF SP$="P" THEN 30
20 IF SP$= "F" THEN 35
25 GOTO 40
30 OPEN "LPT1:" AS #1:GOTO 50
35 OPEN "BTURB001.REP" FOR OUTPUT AS #1:GOTO 50
40 OPEN "SCRN:"FOR OUTPUT AS #1
50 PRINT "This is the BRAYTURB.BAS program. This program matches Brayton
51 PRINT " Cycle  turbines for different gases."
60 LET PI=3.14159:J=778.16:CN=229.18:G=32.17
70 PRINT  "Names of allowed gases are: AIR,NEON,ARGON,& KRYPTON.
75 PRINT "He/Xe mixtures  may also be used:He/Xe(20.18,39.95, & 83.88)
80 PRINT "Test data is available for 4.59, 4.97, & 6.02 inch d. turbines."
85 PRINT "Calculations can also be made for the 7.65 in. d. CBC turbine."
90 PRINT "Input (Known) turbine tip diameter (DT)":INPUT DT
95 PRINT  "Input name of gas for which data is known (KG$)":INPUT KG$
100 IF KG$="AIR" THEN 1000
105 IF KG$="ARGON" THEN 1020
110 IF KG$="HE/XE(39.95)" THEN 1040
115 IF KG$="NEON" THEN 1050
120 IF KG$="HE/XE(20.18)" THEN 1060
125 IF KG$="KRYPTON" THEN 1070
130 IF KG$="HE/XE(83.88)" THEN 1080
140 LET AR2=PI*DT*BW
145 LET AM3=PI*(DE^2-DH^2)/4:ANOZ=AR2*COS(ALPH2/57.296)
150 LET K2=SQR(GAMK*G/(RK*T2))*ANOZ:VACR2=WK*SQR((GAMK+1)/2)/(K2*P2)
155 LET VCR2K=SQR(2*GAMK*G*RK*T2/(GAMK+1))
160 LET VACRT2=VACR2
165 LET VACR2=SQR((GAMK+1)/2)*(WK/(K2*P2))/((1-X3*VACRT2^2)^(YK))
170 LET DEL1=ABS(VACRT2-VACR2):IF DEL1>.0001 GOTO 160
175 LET RHO2=(P2*144/(RK*T2))*((1-X3*VACR2^2)^(YK)):LET UTK=DT*NK/CN
180 LET REK=WK*24/(MU2K*DT):DTI=T2*(1-1/(PRXK)):DELHI=CPK*DTI
185 LET DELH=DELHI*ETAT
190 LET DTA=DTI*ETAT:T3=T2-DTA
195 LET V2=144*WK/(RHO2*ANOZ)
200 LET H=DELHI*J:VJI=SQR(2*G*J*DELHI)
205 LET NU=UTK/VJI
210 LET DEL=P2/14.69:EPSI=(.7396*(((GAMK+1)/2)^(GAMK/(GAMK-1)))/GAMK)
215 LET WEQU=WK*VCR2K*EPSI/(DEL*1018.4):NKEQU=NK*1018.4/VCR2K
220 LET TAU=J*CN*WK*DELH/(NK*2):TAUEQU=TAU*EPSI/DEL
225 LET K3=SQR(GAMK*G/(RK*T3))*AM3*P2/PR
230 LET VACR3=WK*SQR((GAMK+1)/2)/K3
235 LET VCRT3=VACR3:VACR3=(WK/K3)*SQR((GAMK+1)/2)/((1-X3*VCRT3^2)^YK)
```

```
240 LET DEL2=ABS(VCRT3-VACR3):IF DEL2>.0001 GOTO 235
245 LET RHO3=(P2*PR*144/(RK*T3))*((1-X3*VACR3^2)^YK)
250 LET NS=NK*SQR(WK/RHO3)/(60*((G*H)^.75))
255 LET DHEQU=DELH*(1018.4/VCR2K)^2:TAUEQU=TAU*EPSI/DEL
260 LET PREQU=(1-DHEQU/(.24*518.7*ETAT))^(-3.5)
265 LET PRSEQU=(1-DHEQU/(.24*518.7*ETAS))^(-3.5)
270 LET DHIEQU=DHEQU/ETAS:VJEQU=SQR(2*G*J*DHIEQU):UTEQU=DT*NKEQU/CN
275 LET NUEQU=UTEQU/VJEQU
280 PRINT:PRINT "Input name of New gas (NG$)": INPUT NG$
285 IF NG$=" " THEN 7000?290 IF NG$="AIR" THEN 5000
295 IF NG$="ARGON" THEN 5020
300 IF NG$="HE/XE(39.95)" THEN 5040
305 IF NG$="ARGON" THEN 5020
310 IF NG$="HE/XE(83.88)" THEN 5060
315 LET WN=MU2N*WK/MU2K:K2N=ANOZ*SQR(GAMN*G/(RN*T2N)):VCRT2N=VACR2
320 LET VCR2N=SQR(2*GAMN*G*RN*T2N/(GAMN+1))
325 LET EPSIN=(.7396*(((GAMN+1)/2)^(GAMN/(GAMN-1)))/GAMN)
330 LET P2N=14.69*WN*VCR2N*EPSIN/(WEQU*1018.4)
335 LET DELHN=DHEQU*(VCR2N/1018.4)^2:DTAN=DELHN/CPN
337 LET NN=NKEQU*VCR2N/1018.4
339 LET UTN=DT*NN/CN
340 LET VACRT2N=VACR2
345 LET VACR2N=SQR((GAMN+1)/2)*(WN/(K2N*P2N))/((1-X3N*VCRT2N^2)^YN)
350 LET DEL1N=ABS(VCRT2N-VACR2N):VCRT2N=VACR2N
355 IF DEL1N>.0001 GOTO 350
370 LET PRN=(1-DTAN/(ETAT*T2N))^(-1/XN)
375 LET PRSN=(1-DTAN/(ETAS*T2N))^(-1/XN)
380 LET DTAN=DELHN/CPN
385 LET RHO2N=(P2N*144!/(RN*T2N))*((1-X3N*VACR2N^2)^YN)
390 LET DTIN=DTAN/ETAT:DELHIN=DTIN*CPN
395 LET T3N=T2N-DTAN:K3N=SQR(GAMN*G/(RN*T3N))*AM3*P2N/PRN:VCRT3N=VACR3
400 LET VCRT3N=VACR3N:VACR3N=SQR((GAMN+1)/2)*(WN/K3N)/((1-X3N*VCRT3N^2)^YN)
405 LET DEL3N=ABS(VCRT3N-VACR3N):IF DEL3N>.001 GOTO 400
410 LET RHO3N=(((P2N/PRN)*144)/(RN*T3N))*((1-X3N*VACR3N^2)^YN)
415 LET HN=CPN*DTIN*J
420 LET NSN=NN*SQR(WN/RHO3N)/(60*((G*HN)^.75))
425 LET P2NT=RHO2N*RN*T2N/(((1-X3N*VCRT2N^2)^YN)*144)
430 LET V2N=VCR2N*VACR2N:VJIN=SQR(2*G*J*DELHIN)
435 LET TAUN=J*CN*WN*DELHN/(NN*2)
440 LET UTN=DT*NN/CN:NUN=UTN/VJIN
445 LET REN=WN*24/(MU2N*DT)
500 PRINT #1,"TURBINE ";KG$;"-";NG$;" MATCHING"
501 PRINT #1,"Tip Diam.,DT";FIX (1000*DT+.5)/1000;
502 PRINT #1,";Inlet Blade Width,BW,";FIX (1000*BW+.5)/1000;
503 PRINT #1,";Stator Angle, ALPH2";ALPH2;";"
505 PRINT #1,"Exit Tip Diameter,DE";FIX (1000*DE+.5)/1000;
506 PRINT #1,";Exit Hub Diam.,DH";FIX(1000*DH+.5)/1000
510 PRINT #1,:PRINT #1,N1$:PRINT #1,D1$:PRINT #1,D2$
515 PRINT #1,:PRINT #1,"INPUT DATA"
520 PRINT #1, "Inlet Pressure,P2";FIX(100*P2+.5)/100
530 PRINT #1, "Inlet Temperature, T2";FIX(T2+.5)
535 PRINT #1,"Weight Flow,WK";FIX(1000*WK+.5)/1000
540 PRINT #1, "Total Pr. Ratio,PR";FIX(1000*PR+.5)/1000
545 PRINT #1,"Total/ Total Effic.,ETAT";FIX(1000*ETAT+.5)/1000
```

```
550 PRINT #1, "Total/Static Pr. Ratio,PRS";FIX(1000*PRS+.5)/1000
555 PRINT #1,"Total/Static Effic.,ETAS";FIX(1000*ETAS+.5)/1000
560 PRINT #1, "Rotor Speed, NK";FIX (100000!*NK+.5)/100000!
562 PRINT #1,:PRINT #1,"Known Gas ";KG$;" Results"
565 PRINT #1, "Inlet Vel. Ratio,VACR2";FIX(1000*VACR2+.5)/1000
570 PRINT #1, "Inlet Vel.,V2";FIX(10*V2+.5)/10
575 PRINT #1,"Ideal Jet Vel.,VJI";FIX(VJI+.5)
580 PRINT #1,"Function,EPSI";FIX(1000*EPSI+.5)/1000
585 PRINT #1, "Exit Cr. velocity,VACR3";FIX(1000*VACR3+.5)/1000
590 PRINT #1, "Inlet Viscosity,MU2K";FIX(1000*(MU2K*10^5)+.5)/1000;"E-5"
600 PRINT #1, "Total Temp. Ratio, T3/T2";FIX(1000*(T3/T2)+.5)/1000
610 PRINT #1,"Tip Speed,UTK";FIX(10*UTK+.5)/10
615 PRINT #1, "Specific Work,DELH";FIX(100*DELH+.5)/100
620 PRINT #1, "Blade/Jet Speed Ratio,NU";FIX(1000*NU+.5)/1000
625 PRINT #1, "Specific Speed=";FIX(1000*NS+.5)/1000
630 PRINT #1, "Reynolds No.=";FIX((REK/10^3)*100+.5)/100;"E+3"
635 PRINT #1, "Torque,TAU";FIX(100*TAU+.5)/100
640 PRINT #1,:PRINT #1,"Air equivalent (U.S. standard sea level) design";
645 PRINT #1, " values are as follows:"
650 PRINT #1,"Equiv. Weight Flow=";FIX(1000*WEQU+.5)/1000
655 PRINT #1, "Equiv. Speed=";FIX(NKEQU+.5)
660 PRINT #1,"Equiv. Tot/Tot.Pr. Ratio,PREQU";FIX(1000*PREQU+.5)/1000
665 PRINT #1,"Equ. Blade/Jet Speed Ratio,NUEQU";FIX(1000*NUEQU+.5)/1000
670 PRINT #1,"Equiv. Sp. Work=";FIX (100*DHEQU+.5)/100
672 PRINT #1, "Equiv. Torque,TAUEQU";FIX(100*TAUEQU+.5)/100
674 PRINT #1,"Equiv. Tot/Stat.Pr.Ratio,PRSEQU";FIX(1000*PRSEQU+.5)/1000
680 PRINT #1,:PRINT #1,N2$:PRINT #1, D3$:PRINT #1,D4$
682 PRINT #1,:PRINT #1,"PERF. USING ";NG$
685 PRINT #1,"Inlet Tot. Pr., P2N";FIX(100*P2N+.5)/100
686 PRINT #1,"Inlet Temp.,T2N";FIX(T2N+.5)
687 PRINT #1,"Weight flow,WN ";FIX(1000*WN+.5)/1000
690 PRINT #1,"New Pressure Ratio,PRN";FIX(100*PRN+.5)/100
691 PRINT #1,"Total/Total Effic.,ETAT";FIX(1000*ETAT+.5)/1000
700 PRINT #1,"New Static Pr. Ratio,PRSN";FIX(100*PRSN+.5)/100
705 PRINT #1,"Total to Static Effic.";FIX(1000*ETAS+.5)/1000
710 PRINT #1,"New Rotational Speed, NN";FIX(NN+.5)
714 PRINT#1,:
715 PRINT #1,:PRINT #1,"New Inlet Vel. Ratio,VACR2N";FIX(1000
    *VACR2N+.5)/1000
720 PRINT #1,"Inlet Velocity,V2N";FIX(V2N+.5)
730 PRINT #1,"New Ideal Jet Vel.,VJIN";FIX(VJIN+.5)
735 PRINT #1,"New Function,EPSIN";FIX(1000*EPSIN+.5)/1000
740 PRINT #1,"New Exit Cr. Vel.,VACR3N";FIX(1000*VACR3N+.5)/1000
750 PRINT #1,"New Inlet Viscosity,MU2N";FIX((1000*MU2N*10^5)+.5)/1000;"E-5"
760 PRINT #1, "Total Temp. Ratio,T3N/T2N";FIX(1000*(T3N/T2N)+.5)/1000
765 PRINT #1,"New Tip Speed,UTN";FIX(UTN+.5)
770 PRINT #1,"New Specific Work,DELHN";FIX(100*DELHN+.5)/100
775 PRINT #1,"Blade/Jet Speed Ratio,NUN";FIX(1000*NUN+.5)/1000
780 PRINT #1, "New Specific Speed,NSN";FIX(1000*NSN+.5)/1000
785 PRINT #1, "New Reynolds No.,REN";FIX((REN/10^3)*100+.5)/100;"E+3"
790 PRINT #1,"New Torque,TAUN";FIX(100*TAUN+.5)/100
795 PRINT "Calculation Complete":STOP
1000 LET MK=29:RK=1545/MK:GAMK=1.4:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1001 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):X3=(GAMK-1)/(GAMK+1)
     :N1$="THE KNOWN GAS IS AIR"
```

```
1002 LET D1$="Mol. Wt. = 29.0,R = 53.28,":D2$ = "Sp. Heat = .24,GAM = 1.4"
1003 IF ABS(DT-6.02)<=.0001 THEN 2000
1004 IF ABS(DT-7.65)<=.0001 THEN 2010
1005 IF ABS(DT-4.59)<=.0001 THEN 2060
1006 IF ABS(DT-4.97)<=.0001 THEN 3000
1007 LET MU2K=(.2361+.002173*T2-5.75E-07*(T2^2)+9.17E-11*(T2^3))*(10^-5)
1008 GOTO 140
1020 LET MK=39.948:RK=1545/MK:GAMK=1.667:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1021 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):X3=(GAMK-1)/(GAMK+1)
     :N1$="THE KNOWN GAS IS ARGON"
1022 LET D1$="Mol. Wt.=39.948,R=38.68":D2$="Sp. Heat=.124,GAM=1.667."
1023 IF ABS(DT-6.02)<=.0001 THEN 2020
1024 IF ABS(DT-7.65)<=.0001 THEN 2030
1025 IF ABS(DT-4.59)<=.0001 THEN 2070
1026 IF ABS(DT-4.97)<=.0001 THEN 2090
1027 LET MU2K=(.323+.002454*T2-3.53E-07*(T2^2))*(10^-5)
1028 GOTO 140
1040 LET MK=39.948:RK=1545/MK:GAMK=1.667:XK=(GAMK-1)/GAMK:CPK=RK/(XK*J)
1041 LET X2=(GAMK-1)/2:YK=1/(GAMK-1):X3=(GAMK-1)/(GAMK+1)
     :N1$="THE KNOWN GAS IS HE/XE(39.95)"
1042 LET D1$="Mol. Wt.=39.948,R=38.68":D2$="Sp. Heat=.124,GAM=1.667."
1043 IF ABS(DT-6.02)<=.0001 THEN 2040
1044 IF ABS(DT-7.65)<=.0001 THEN 2050
1045 IF ABS(DT-4.59)<=.0001 THEN 2080
1046 PRINT "No 4.97 in. d. data available":STOP
1047 LET MU2K=(.0764+.003819*T2-1.479E-06*(T2^2)+5.22E-10*T2^3
     -8.160001E-14*T2^4)*(10^-5)
1048 GOTO 140
1050 PRINT "No NEON data available":STOP
1060 PRINT "No HE/XE(20.18) data available":STOP
1070 PRINT "No KRYPTON data available":STOP
1080 PRINT "No HE/XE(83.88) data available":STOP
2000 REM "This is AIR/DT = 6.02 data"
2002 LET P2=13.24:T2 = 1950:WK = .481:PR = 1.5:ETAT = .88:NK = 43653!:DE = 4.294
2004 LET DH=1.5:DT=6.02:BW=.72:PRS=1.54:ETAS=.824:ALPH2=72
2008 GOTO 1007
2010 PRINT "NO DATA AVAILABLE":STOP
2020 REM "This is ARGON/DT=6.02 data"
2022 LET P2=13.5:T2=1950:WK=.611:PR=1.56:ETAT=.88:NK=38500!:DE=4.294
2024 LET DH=1.5:DT=6.02:BW=.72:PRS=1.613:ETAS=.824:ALPH2=72
2028 GOTO 1027
2030 REM "This is ARGON/DT=7.65 data"
2032 LET P2=39.61:T2=1810:WK=1.513:PR=1.77:ETAT=.897:NK=0000:DE=5.355
2034 LET DH=3.06:DT=7.65:BW=.64:PRS=1.85:ETAS=.84:ALPH2=72
2038 GOTO 1027
2040 REM "This is HE/XE(39.95)/DT=6.02 data"
2042 LET P2=16.45:T2=1950:WK=.745:PR=1.56:ETAT=.88:NK=38500!:DE=4.294
2044 LET DH=1.5:DT=6.02:BW=.72:PRS=1.61:ETAS=.824:ALPH2=72
2048 GOTO 1047
2050 REM "This is HE/XE(39.95)/DT=7.65 data"
2052 LET P2=47.9:T2=1810:WK=1.83:PR=1.768:ETAT=.897:NK=32000:DE=5.355
2054 LET DH=3.06:DT=7.65:BW=.64:PRS=1.828:ETAS=.84:ALPH2=72
```

```
2056 LET N2$="THE KNOWN GAS IS HE/XE(39.95)"
2057 LET D3$="Mol. Wt.=39.948,R=38.68":D4$="Sp. Heat=.124,GAM=1.667."
2058 GOTO 1047
2060 PRINT"NO DATA AVAILABLE:STOP
2070 REM "This is ARGON/DT=4.59 data"
2072 LET P2=22.7:T2=1950:WK=.611:PR=1.56:ETAT=.86:NK=50500!:DE=3.264
2074 LET DH=1.144:DT=4.59:BW=.55:PRS=1.613:ETAS=.81:ALPH2=72
2078 GOTO 1027
2080 REM"This is HE/XE(39.95)/DT=4.59 data"
2082 LET P2=27.67:T2=1950:WK=.745:PR=1.56:ETAT=.86:NK=50500!:DE=3.264
2084 LET DH=1.144:DT=4.59:BW=.55:PRS=1.61:ETAS=.81:ALPH2=72
2088 GOTO 1047
2090 REM "This is ARGON/DT=4.97 data.
2092 LET P2=7!:T2=610:WK=.266:PR=1.75:ETAT=.884:NK=28394:DE=3.46
2094 LET DH=1.822:DT=4.97:BW=.6:PRS=1.763:ETAS=.875:ALPH2=72.5
2098 GOTO 1027
3000 REM "This is Air/DT=4.97 data"
3002 P2=7.06:T2=610:WK=.216:PR=1.65:ETAT=.884:NK=32194:DE=3.46
3004 LET DH=1.822:DT=4.97:BW=.6:PRS=1.66:ETAS=.875:ALPH2=72.5
3008 GOTO 1027
5000 LET MN=29:RN=1545/MN:GAMN=1.4:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5001 LET X2N=(GAMN-1)/2:YN=1/(GAMN-1):X3N=(GAMN-1)/(GAMN+1)
5002 LET N2$= "THE NEW GAS IS AIR":D3$="Mol. Wt.=29.0,R=53.28"
5003 LET D4$="Sp. Heat=.24,GAM=1.4"
5004 LET T2N=T2
5006 LET MU2N=(.2361+.002173*T2N-5.75E-07*(T2N^2)+9.17E-11*(T2N^3))
     *(10^-5)
5008 GOTO 315
5020 LET MN=39.948:RN=1545/MN:GAMN=1.667:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5021 LET X2N=(GAMN-1)/2:YN=1/(GAMN-1):X3N=(GAMN-1)/(GAMN+1)
5022 LET N2$= "THE NEW GAS IS ARGON":D3$="Mol. Wt.=39.948,R=38.68"
5023 LET D4$="Sp. Heat=.124,GAM=1.667"
5024 LET T2N=T2
5026 LET MU2N=(.323+.002454*T2N-3.53E-07*(T2N^2))*(10^-5)
5028 GOTO 315
5040 LET MN=39.948:RN=1545/MN:GAMN=1.667:XN=(GAMN-1)/GAMN:CPN=RN/(XN*J)
5041 LET X2N=(GAMN-1)/2:YN=1/(GAMN-1):X3N=(GAMN-1)/(GAMN+1)
5042 LET N2$="THE NEW GAS IS HE/XE(39.95)":D3$="Mol. Wt.=39.948,R=38.68"
5043 LET D4$="Sp. Heat=.124,GAM=1.667"
5044 LET T2N=T2
5046 LET MU2N=(.0764+.003819*T2-1.479E-06*(T2^2)+5.22E-10*T2^3
     -8.160001E-14*T2^4)*(10^-5)
5048 GOTO 315
5060 STOP
7000 STOP
```

REFERENCES

1. Effect of Reynolds Number on Overall Performance of a 6-in. Radial Bladed Centrifugal Compressor. NASA TN D-5761.

2. Reynolds Number Effect On Overall Performance Of A 10.8 cm (4.25 in.) Sweptback-Bladed Centrifugal Compressor. NASA TN D-6640.

3. Overall Performance in Argon Of A 16.4 cm (6.44 in.) Sweptback-Bladed Centrifugal Compressor. NASA TM X-2269.

4. Experimental Performance Evaluation of a 4.59 in. Radial-Inflow Turbine Over a Range of Reynolds Number.

5. Cold Performance Evaluation of 4.97 in. Radial Inflow Turbine Designed For Single - Shaft Brayton Cycle Space - Power System. NASA TN D-5090.

6. Cold Performance Evaluation of a 6.02 in. Radial Inflow Turbine Designed for a 10 Kilowatt Shaft Output Brayton Cycle Space Power Generation System. NASA TN D-2987.

TABLE I. - NASA LEWIS COMPRESSOR TEST SUMMARY

Tip diameter, DT, in.	4.25	5.976	6.44	6.50 (CBC)
Rotational speed, rpm	52 200	38 500	38 500	32 000
Weight flow, lb/sec	0.785	0.611	0.611	1.87
Inlet pressure, $lb/in.^2$	20.25	6.00	6.00	26.40
Pressure ratio	1.90	2.38	2.30	1.90
Inlet temperature, °R	540	536	536	520
Efficiency	0.80	0.798	0.821	0.842
Reynolds number/10^5	3.03	1.30	1.53	5.30
Reference report	TN D-6640	TN D-5761	TM X-2269	RI/RD-86-186

TABLE II. - 4.25-in.-diam. COMPRESSOR - ARGON/He/Xe MATCHING

(Refer to Appendix A for units)

[Tip diameter, DT, 4.25 in.; inlet tip diam. DI, 2.60 in.; inlet hub diameter DH, 1.44 in.; exit blade height, BH, 0.205 in.; windage factor, FW, 0.039.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight	39.948	39.948
R	38.680	38.680
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure	P2 = 20.25	P2N = 23.36
Inlet temperature	T2 = 540.0	T2N = 540.0
Weight flow	WK = 0.785	WN = 0.906
Pressure ratio	PR = 1.900	PRN = 1.900
Impeller pressre ratio	PRI = 2.030	PRIN = 2.030
Adiabatic efficiency	ETAC = 0.800	ETAC = 0.800
Impeller efficiency	ETACI = 0.895	ETACI = 0.895
Rotational speed	NK = 52 200	NN = 52 200
	Known gas (argon) results	New results
Viscosity	MU2K = 1.545×10^5	MU2N = 1.78×10^{-5}
Total temperature ratio	T3/T2 = 1.366	T3/T2 = 1.366
Inlet velocity ratio	VT2 = 0.213	VT2N = 0.213
Exit velocity ratio	VT3 = 0.517	VT3N = 0.517
Density ratio	DR = 1.322	DRN = 1.322
Corrected rpm	NKEQU = 51 160	NNEQU = 51 160
Tip speed	UTK = 968.0	UTN = 968
Work factor	FCW = 0.656	FCWN = 0.656
Slip factor	FS = 0.617	FSN = 0.617
Inlet flow coefficient	PHI = 0.232	PHIN = 0.232
Specific speed	NS = 0.112	NSN = 0.112
Reynolds number	REK = 3.03×10^6	REN = 3.03×10^6

TABLE III. - 5.976-in.-diam. COMPRESSOR - ARGON/He/Xe MATCHING
(Refer to Appendix A for units)
[Tip diameter, DT, 5.976 in.; inlet tip diameter DI, 3.528 in.; hub diameter DH, 1.858 in.; exit blade height, BH, 0.217; windage factor, FW, 0.039.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight	39.948	39.948
R	38.68	38.680
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure	P2 = 6.000	P2N = 6.850
Inlet temperature	T2 = 536.0	T2N = 536.0
Weight flow	WK = 0.611	WN = 0.704
Pressure ratio	PR = 2.380	PRN = 2.420
Impeller pressure ratio	PRI = 2.620	PRIN = 2.650
Adiabatic efficiency	ETAC = 0.798	ETAC = 0.798
Impeller efficiency	ETACI = 0.896	ETACI = 0.896
Rotational speed	NK = 38 500	NN = 38 920
	Known gas (argon) results	New results
Viscosity	MU2K = 1.537×10^{-5}	MU2N = 1.77×10^{-5}
Total temperature ratio	T3/T2 = 1.520	T3/T2 = 1.531
Inlet velocity ratio	VT2 = 0.296	VT2N = 0.300
Exit velocity ratio	VT3 = 0.702	VT3N = 0.707
Density ratio	DR = 1.377	DRN = 1.377
Corrected rpm	NKEQU = 37 874	NNEQU = 38 287
Tip speed	UTK = 1003.9	UTN = 1014.9
Work factor	FCW = 0.859	FCWN = 0.859
Slip factor	FS = 0.820	FSN = 0.820
Inlet flow coefficient	PHI = 0.311	PHIN = 0.311
Specific speed	NS = 0.105	NSN = 0.105
Reynolds number	REK = 1.30×10^{6}	REN = 1.30×10^{6}

TABLE IV. - 6.44-in.-diam. COMPRESSOR - ARGON/He/Xe MATCHING

(Refer to Appendix A for units)

[Tip diameter, DT, 6.440 in.; inlet tip diameter DI, 3.950 in.; hub diameter DH, 2.190 in.; exit blade height, BH, 0.310; windage factor, FW, 0.039.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight R Specific heat GAM	39.948 38.68 0.124 1.667	39.948 38.680 0.124 1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure Inlet temperature Weight flow Pressure ratio Impeller pressure ratio Adiabatic efficiency Impeller efficiency Rotational Speed	P2 = 6.000 T2 = 536.0 WK = 0.611 PR = 2.300 PRI = 2.470 ETAC = 0.821 ETACI = 0.897 NK = 38 500	P2N = 6.87 T2N = 536.0 WN = 0.704 PRN = 2.320 PRIN = 2.490 ETAC = 0.821 ETACI = 0.897 NN = 38 787
	Known gas (argon) results	New results
Viscosity Total temperture ratio Inlet velocity ratio Exit velocity ratio Density ratio Corrected rpm Tip speed Work factor Slip factor Inlet flow coefficient Specific speed Reynolds number	MU2K = 1.537×10^{-5} T3/T2 = 1.482 VT2 = 0.243 VT3 = 0.577 DR = 1.440 NKEQU = 37 874 UTK = 1081.9 FCW = 0.686 FS = 0.647 PHI = 0.237 NS = 0.108 REK = 1.53×10^{6}	MU2N = 1.77×10^{-5} T3/T2 = 1.489 VT2N = 0.245 VT3N = 0.748 DRN = 1.440 NNEQU = 38 156 UTN = 1089.9 FCWN = 0.686 FSN = 0.647 PHIN = 0.237 NSN = 0.108 REN = 1.53×10^{6}

TABLE V. - CBC COMPRESSOR - He/Xe ARGON MATCHING
(Refer to Appendix A for units)
[Tip diameter, DT, 6.500 in.; inlet tip diameter DI, 4.00 in.; hub diameter DH, 2.280 in.; exit blade height, BH, 0.351; windage factor, FW, 0.039.]

	Known gas: argon (39.95)	New gas: He/Xe
Molecular weight	39.948	39.948
R	38.680	38.680
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using argon
Inlet pressure	P2 = 26.40	P2N = 21.97
Inlet temperature	T2 = 520.0	T2N = 520.0
Weight flow	WK = 1.870	WN = 1.626
Pressure ratio	PR = 1.900	PRN = 2.000
Impeller pressure ratio	PRI = 2.040	PRIN = 2.110
Adiabatic efficiency	ETAC = 0.842	ETACN = 0.842
Impeller efficiency	ETACI = 0.910	ETACIN = 0.910
Rotational Speed	NK = 32 000	NN = 38 463
	Known gas (CBC(He/Xe)) results	New results
Viscosity	MU2K = 1.73×10^{-5}	MU2N = 1.50×10^{-5}
Total temperture ratio	T3/T2 = 1.348	T3/T2 = 1.380
Inlet velocity ratio	VT2 = .164	VT2N = .171
Exit velocity ratio	VT3 = .500	VT3N = .517
Density ratio	DR = 1.346	DRN = 1.347
Corrected rpm	NKEQU = 31.960	NNEQU = 33 421
Tip speed	UTK = 907.6	UTN = 949.1
Work factor	FCW = .683	FCWN = .683
Slip factor	FS = .644	FSN = .644
Inlet flow coefficient	PHI = .188	PHIN = 188
Specific speed	NS = .094	NSN = .094
Reynolds number	REK = 5.30×10^{6}	REN = 5.30×10^{6}

TABLE VI. - CALCULATED EFFECT OF COMPRESSOR REYNOLDS NUMBER

Compressor diameter DT, in.	4.25	5.976	6.44
Adiabatic efficiency, ETAC	0.79	0.798	0.821
Loss factor 1 - ETAC	0.21	0.202	0.179
Reynolds number/10^6	3.03	1.30	1.53
REK/5.3^6	0.572	0.245	0.289
Reynolds ratio to 0.2	0.894	0.755	0.780
Corrected loss factor	0.179	0.153	0.140
Predicted CBC efficiency	0.821	0.847	0.860
Mean values of three		0.843	

TABLE VII. - NASA LEWIS TURBINE TEST SUMMARY

Tip diameter, DT, in.	4.59	4.97	6.02	7.65
Rotational speed, rpm	50 500	28 394	38 500	32 000
Weight flow, lb/sec	0.611	0.266	0.611	1.83
Inlet pressure, lb/in.^{2}	22.70	7.00	13.5	47.9
Pressure ratio	1.56	1.75	1.56	1.768
Inlet temperature, °R	1950	610	1950	1810
Efficiency	0.86	0.884	0.88	0.897
Reynolds number/10^3	84.83	76.07	64.68	131.59
Reference report	TN D-3835	TN D-5090	TN D-2987	RI/RD-86-186

TABLE VIII. - 4.59-in.-diam. TURBINE - ARGON-He/Xe (39.95) MATCHING
(Refer to Appendix B for units)
[Tip diamter, DT, 4.59 in.; inlet blade width, BW, 0.55 in.; stator angle, ALPH2, 72°; exit tip diameter, DE, 3.264 in.; exit hub diameter, DH, 1.144.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight	39.948	39.948
R	38.68	38.68
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure	P2 = 22.7	P2N = 27.67
Inlet temperature	T2 = 1950	T2N = 1950
Weight flow	WK = 0.611	WN = 0.745
Pressure ratio	PR = 1.56	PRN = 1.56
Total/total efficiency	ETAT = 0.86	ETAT = 0.86
Total/static pressure ratio	PRS = 1.613	PRSN = 1.61
Total/static efficiency	ETAS = 0.81	ETAS = 0.81
Rotational speed	NK = 50 500	NN = 50 500
	Known gas (argon) results	New results
Inlet velocity ratio	VACR2 = 0.531	VACR2N = 0.531
Inlet velocity	V2 = 924.1	V2N = 924
Ideal jet velocity	VJI = 1406	VJIN = 1406
Function	EPSI = 0.911	EPSIN = 0.911
Exit cr. velocity	VACR3 = 0.235	VACR3N = 0.235
Inlet viscosity	MU2K = 3.766×10^{-5}	MU2N = 4.59×10^{-5}
Total temperature ratio	T3/T2 = 0.86	T3N/T2N = 2.86
Tip speed	UTK = 1011.4	UTN = 1011
Specific work	DELH = 33.95	DELHN = 33.95
Blade/jet speed ratio	NU = 0.719	NUN = 0.719
Specific speed	NS = 0.076	NSN = 0.118
Reynolds number	RE = 84.83×10^{3}	REN = 84.83×10^{3}
Torque	TAU = 36.63	TAUN = 44.65

Air equivalent (U.S. Standard sea level) design values	
Equivalent weight flow	0.616
Equivalent speed	29 531
Equivalent total/total pressure ratio; PREQU	1.494
Equivalent blade/jet speed ratio, NUEQU	0.698
Equivalent specific work	11.61
Equivalent torque, TAUEQU	21.59
Equivalent total/static pressure ratio, PRSEQU	1.534

TABLE IX. - 4.97-in.-diameter TURBINE - ARGON-He/Xe (39.95) MATCHING
(Refer to Appendix B for units)
[Tip diameter DT 4.97 inlet blade width, BW, 0.6; stator angle, ALPH2 72.5; exit tip diameter, DE 3.46; exit hub diameter, DH 1.822.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight	39.948	39.948
R	38.68	38.68
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure	P2 = 7	P2N = 8.140001
Inlet temperature	T2 = 610	T2N = 610
Weight flow	WK = 0.266	WN = 0.309
Pressure ratio	PR = 1.75	PRN = 1.75
Total/total efficiency	ETAT = 0.884	ETAT = 0.884
Total/static pressure ratio	PRS = 1.763	PRSN = 1.76
Total/static efficiency	ETAS = 0.875	ETAS = 0.875
Rotational speed	NK = 28 394	NN = 28 394
	Known gas (argon) results	New results
Inlet velocity ratio	VACR2 = 0.342	VACR2N = 0.342
Inlet velocity	V2 = 332.7	V2N = 333
Ideal jet velocity	VJI = 872	VJIN = 872
Function	EPSI = 0.911	EPSIN = 0.911
Exit cr. velocity	VACR3 = 0.219	VACR3N = 0.219
Inlet viscosity	MU2K = 1.689×10^{-5}	MU2N = 1.963×10^{-5}
Total temperature ratio	T3/T2 = 0.823	T3N/T2N = 0.823
Tip speed	UTK = 615.8	UTN = 616
Specific work	DELH = 13.44	DELHN = 13.44
Blade/jet speed ratio	NU = 0.706	NUN = 0.706
Specific speed	NS = 0.053	NSN = 0.093
Reynolds number	RE = 76.07×10^3	REN = 76.06×10^3
Torque	TAU = 11.23	TAUN = 13.05

Air equivalent (U.S. Standard sea level) design values	
Equivalent weight flow	0.486
Equivalent speed	29 687
Equivalent total/total pressure ratio; PREQU	1.651
Equivalent blade/jet speed ratio, NUEQU	0.702
Equivalent specific work	14.69
Equivalent torque, TAUEQU	21.46
Equivalent total/static pressure ratio, PRSEQU	1.66

TABLE X. - 6.02-in.-diam. TURBINE - ARGON-He/Xe (39.95) MATCHING
(Refer to Appendix B for units)
[Tip diameter, DT, 6.02 in.; inlet tip diameter DT, 6.02 in.; inlet exit blade height, BW, 0.72 in.; stator angle, ALPH2 72; exit tip diameter, DE 4.294; exit hub diameter., DH 1.5.]

	Known gas: argon	New gas: He/Xe (39.95)
Molecular weight	39.948	39.948
R	38.680	38.680
Specific heat	0.124	0.124
GAM	1.667	1.667
	Input data	Performance using He/Xe (39.95)
Inlet pressure	P2 = 13.5	P2N = 16.45
Inlet temperature	T2 = 1950	T2N = 1950
Weight flow	WK = 0.611	WN = 0.745
Pressure ratio	PR = 1.56	PRN = 1.56
Total/total efficiency	ETAT = 0.88	ETAT = 0.88
Total/static pressure ratio	PRS = 1.613	PRSN = 1.61
Total/static efficiency	ETAS = 0.824	ETAS = 0.824
Rotational speed	NK = 38 500	NN = 38 500
	Known gas (argon) results	New results
Inlet velocity ratio	VACR2 = 0.5170001	VACRN = 0.517
Inlet velocity	V2 = 899.7	V2N = 900
Ideal jet velocity	VJI = 1406	VJIN = 1406
Function	EPSI = 0.911	EPSIN = 0.911
Exit cr. velocity	VACR3 = 0.227	VACR3N = 0.277
Inlet viscosity	MU2K = 3.766×10^{-5}	MU2N = 4.59×10^{-5}
Total temperature ratio	T3/T2 = 0.857	T3N/T2N = 0.857
Tip speed	UTK = 1011.3	UTN = 1011
Specific work	DELH = 34.74	DELHN = 34.74
Blade/jet speed ratio	NU = 0.719	NUN = 0.719
Specific speed	NS = 0.075	NSN = 0.116
Reynolds number	RE = 64.68×10^{3}	REN = 64.68×10^{3}
Torque	TAU = 49.17	TAUN = 59.93

Air equivalent (U.S. Standard sea level) design values	
Equivalent weight flow	0.616
Equivalent speed	29 531
Equivalent total/total pressure ratio; PREQU	1.494
Equivalent blade/jet speed ratio, NUEQU	0.698
Equivalent specific work	11.61
Equivalent torque, TAUEQU	21.59
Equivalent total/static pressure ratio, PRSEQU	1.534

TABLE XI. - CBC TURBINE - He/Xe (39.95) - ARGON MATCHING
(Refer to Appendix B for units)
[Tip diameter, DT 7.65; inlet blade width, BW, .64; stator angle, ALPH2 72; exit Tip diameter, DE 5.355; Exit Hub diameter, DH 3.06.]

	Known gas: He/Xe (39.95)	New gas: argon
Molecular weight R Specific heat GAM	39.948 38.680 0.124 1.667	39.948 38.680 0.124 1.667
	Input data	Performance using argon
Inlet pressure Inlet temperature Weight flow Pressure ratio Total/total efficiency Total/static pressure ratio Total/static efficiency Rotational speed	P2 = 47.9 T2 = 1810 WK = 1.83 PR = 1.768 ETAT = 0.897 PRS = 1.828 ETAS = 0.84 NK = 32 000	P2N = 39.61 T2N = 1810 WN = 1.513 PRN = 1.77 ETAT = 0.897 PRSN = 1.85 ETAS = 0.84 NN = 32 000
	Known gas He/Xe (39.95) results	New results New results
Inlet velocity ratio Inlet velocity Ideal jet velocity Function Exit cr. velocity Inlet viscosity Total temperature ratio Tip speed Specific work Blade/jet speed ratio Specific speed Reynolds number Torque	VACR2 = 0.352 V2 = 589.8 VJI = 1515 EPSI = 0.911 VACR3 = 0.17 MU2K = 4.363×10^{-5} T3/T2 = 0.817 UTK = 1.068.2 DELH = 41.12 NU = 0.705 NS = 0.045 RE = 131.59×10^{3} TAU = 209.67	VACR2N = 0.352 V2N = 590 VJIN = 1515 EPSIN = 0.911 VACR3N = 0.17 MU2N = 3.608×10^{-5} T3N/T2N = 0.817 UTN = 1068 DELHN = 41.12 NUN = 0.705 NSN = 0.79 REN = 131.59×10^{3} TAUN = 173.4

Air equivalent (U.S. Standard sea level) design values	
Equivalent weight flow	.842
Equivalent speed	19 423
Equivalent total/total pressure ratio; PREQU	1.666
Equivalent blade/jet speed ratio, NUEQU	0.682
Equivalent specific work	15.15
Equivalent torque, TAUEQU	58.57
Equivalent total/static pressure ratio, PRSEQU	1.729

TABLE XII. - CALCULATED EFFECT OF TURBINE REYNOLDS NUMBER

Tip diameter, DT, in.	4.59	4.97	6.02
Adiabatic efficiency, ETAK	0.86	0.884	0.88
Loss factor (1 - ETAK)	0.14	0.116	0.12
Reynolds number/10^3	84.83	76.07	64.68
REK/131.59×10^3	0.645	0.578	0.492
Reynolds ratio to 0.2 power	0.916	0.896	0.868
Corrected loss factor	0.133	0.109	0.110
Predicted CBC efficiency	0.867	0.891	0.890
Mean value of three		0.883	

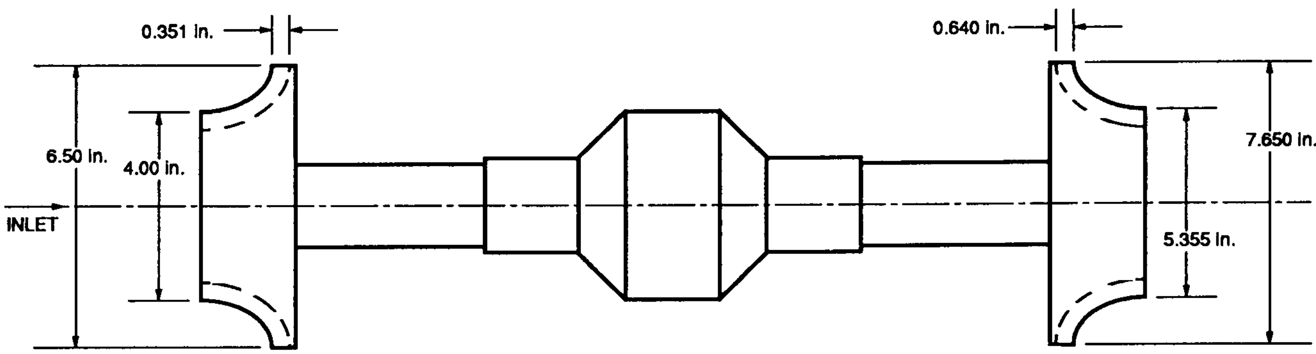

Figure 1. - CBC rotor layout.

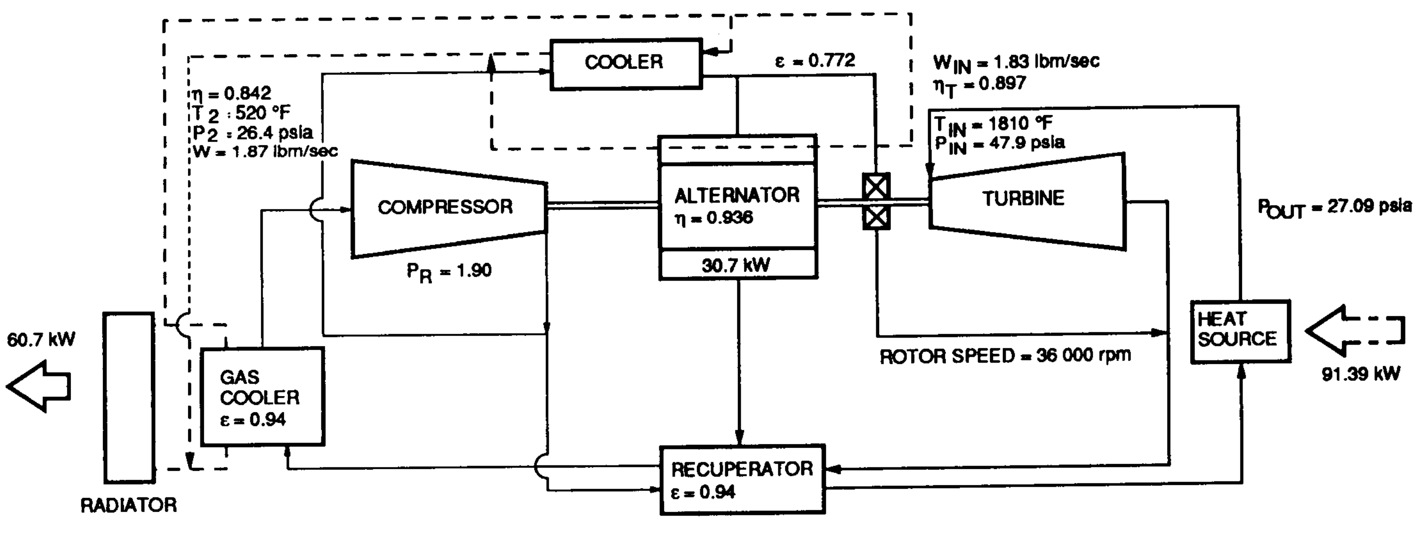

Figure 2. - CBC system schematic.

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16. Abstract

The methods which have been used by the NASA Lewis Research Center for predicting Brayton Cycle compressor and turbine performance for different gases and flow rates are described. These methods were developed by NASA Lewis during the early days of Brayton cycle component development and they can now be applied to the task of predicting the performance of the CBC Space Station Freedom power system. Computer programs are given for performing these calculations and data from previous NASA Lewis Brayton Compressor and Turbine tests is used to make accurate estimates of the compressor and turbine performance for the CBC power system. Results of these calculations are also given in following sections of this report. This work has been sponsored by NASA in order to obtain an independent evaluation of the performance of the CBC power system. In general, these calculations confirm that the CBC Brayton Cycle contractor has made realistic compressor and turbine performance estimates.

17. Key Words (Suggested by Author(s))

Solar Dynamic Power System
Brayton cycle
Space Station Freedom power system

18. Distribution Statement

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