NASA TM-82774

DOE/NASA/51040-37
NASA TM-82774

NASA-TM-82774
19830004089

Computer Program for a Four-Cylinder-Stirling-Engine Controls Simulation

Carl J. Daniele and Carl F. Lorenzo
National Aeronautics and Space Administration
Lewis Research Center

June 1982

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

DOE/NASA/51040-37
NASA TM-82774

Computer Program for a Four-Cylinder-Stirling-Engine Controls Simulation

Carl J. Daniele and Carl F. Lorenzo
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

June 1982

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77CS51040

NOTICE

Contents

Summary

A four-cylinder-Stirling-engine, transient-engine-simulation computer program is presented. The program is intended for controls analysis. The associated engine model has been simplified to shorten computer calculation time. The model includes engine mechanical drive dynamics and vehicle load effects. The computer program also includes subroutines that allow (1) acceleration of the engine by addition of hydrogen to the system and (2) braking of the engine by short circuiting of the working spaces. Subroutines to calculate degraded engine performance (e.g., due to piston ring and piston rod leakage) are provided. Input data required to run the program are described and flow charts are provided. The program is modular to allow easy modification of individual routines. Examples of steady-state and transient results are presented.

Introduction

A Stirling engine is a mechanical device that operates on a closed regenerative cycle. Cycle expansion and compression of working fluid is done at different temperature levels. Flow is controlled by volume changes. Heat is supplied continuously and externally and extracted with a net conversion of heat to work. In its simplest form a Stirling process consists of two pistons, one operating in a hot space and one in a cold space. A working fluid between the pistons moves continuously back and forth within a working space between the hot and cold spaces, where it is continuously heated and cooled. The fluid passes through a regenerator, which is a heat storage device. The regenerator stores or gives off heat depending on the temperature of the fluid passing through it. The result of the process is the Stirling cycle. Stirling engines are used for stationary power generation, heat pumps, refrigeration systems, and artificial hearts. Another application is the automotive Stirling engine. In this application there are four pistons, all interconnected by four working spaces (fig. 1). This report presents a computer simulation of an automotive Stirling engine that can be used for controls research.

Stirling engine modeling is usually done for the purpose of predicting engine performance. The models are, of necessity, complex since Stirling engine performance (e.g., efficiency and fuel consumption) is quite sensitive to factors such as pressure drop within the engine. In general a Stirling engine performance model includes two pistons and the working space between them. The pistons are positioned as a function of time and are 90° out of phase. Control volumes are used to segment the working space into its components – expansion space, heater, regenerator, cooler, and compression space. More than one control volume can be used to describe a component. Various heat transfer paths are usually included. Although many Stirling engines have more than one working space, the models used to predict performance generally do so for a single working space, and the resultant power generated is multiplied by the number of working spaces. One such model has been developed by Tew, Jeffries, and Miao and is described in reference 1. It contains 13 control volumes in the working space. The model calculates flow resistances and heat transfer coefficients as well as performance over a single engine cycle. Daniele and Lorenzo (ref. 2) have reduced the number of control volumes in the working space to seven, one each for the expansion space, heater, cooler, and compression space and three for the regenerator. Also, a metal volume has been associated with each regenerator gas volume. Average flow resistances and heat transfer coefficients are derived from the Tew model. Within each gas volume the continuity and energy equations are integrated and a simplified, first-order momentum term (flow resistance) is calculated. Upwind differencing (ref. 3) is used to calculate the interface volume temperatures for use in the energy equation. The resultant model has 17 state variables and uses a backward-difference integration scheme for problem solution. Results generated by that model compare well with experimental power and torque data over the entire speed and pressure ranges of the engine.

The aforementioned modeling approach produces acceptable steady-state (power and torque) predictions when working spaces in the engine are isolated. However, proposed control schemes for four-cylinder Stirling engines require that the working spaces not remain isolated. One such scheme is engine braking by short circuiting. In this case, all four working spaces are connected to high- and low-pressure manifolds. Flow enters or leaves a working space depending on the pressure differential and the orientation of the check valves between the pressure manifolds and the working spaces. A complete four-cylinder model is needed to analyze this controls problem.

One such four-cylinder controls model is described in reference 2. In that model, each working space model is further simplified to reduce computer run time. This simplification involves reducing the number of control volumes in a working space from seven to three – one for the expansion space and the heater, one for the regenerator, and one for the cooler and the compression space. It is also assumed (1) that the temperature within a control volume remains constant and (2) that the gas and regenerator mesh temperatures are equal. This reduces the number of state variables in a working space to three (or 12 for the whole engine). Results from this simplified model are presented in references 2 and 4 and agree well with steady-state experimental data. The model has been used to predict the steady-state performance of the engine with short circuiting and with piston ring leakage. Reference 4 describes the use of the simulation to study supply transients with and without piston rod leakage.

This report documents the simplified four-cylinder model and its implementation. A users manual is given on how to run the simulation. Both steady-state and transient results are presented and a printout is provided for a test case. Finally flow charts are given for the subroutines and the overall simulation.

Model Description

A schematic of the four-cylinder-Stirling-engine controls model is shown in figure 1. The four cylinders are shown interconnected by the four working spaces. Each working space contains three volumes – one for the expansion space and the heater, one for the regenerator, and one for the cooler and the compression space. Each volume is assumed to be at constant temperature. Variations in volume temperature can be scheduled as a function of engine speed. Variable names shown in figure 1 correspond to the computer coding. A complete symbols list is given in appendix A.

Besides the engine thermodynamic elements, three other system models are shown in figure 1 – a drive geometry model, a working-fluid supply model, and a short-circuiting model. Torque is calculated as a function of differential forces on the pistons and summed in the drive geometry model. Losses due to auxiliaries, load effects, etc., are included. The net torque is then integrated once to give engine speed and again to give crank angle. The remaining models shown in figure 1 are associated with control schemes for accelerating and decelerating the engine. The acceleration system is indicated by alternate long- and short-dashed lines and is described in appendix B. Engine deceleration is accomplished by short circuiting the working spaces. This deceleration system is indicated by short-dashed lines. This system is also described in appendix B.

A schematic of the drive dynamics is shown in figure 2. Differential forces on the pistons are translated into torque through the vehicle drive geometry and summed to form total torque (TORQT). Torque due to engine friction is subtracted to form brake torque. This is available to drive the auxiliaries and the vehicle load. The vehicle inertia and the gear ratio are used to compute the effective load. The summation of torques is integrated to give engine speed (PSIDT) and again to give crank angle (PSI). The crank angle is used to generate piston position (by using the crank geometry). The model can be run in this manner, or piston position can be input as a function of time with torque and cycle performance calculated at constant speed.

Relative to the performance models, the controls model is simple, yet it contains the essential elements for controls analysis. It has been shown in reference 2 that simulation predictions compare well with experimental data. However, it should be noted that heat flow dynamics are not included in the model. These effects may, in some instances, be significant and thus necessitate expansion of the model.

Users Manual

Simulation Flow Diagram

The overall simulation structure is shown in figure 3. Run conditions are set in the main program (MAINSE). Subroutine ICSTUP is then called to calculate initial conditions. SHORT2 and PISTN3 are called from ICSTUP to calculate the initial conditions for short circuiting and initial piston positions, respectively. ICSTUP then calls FOURW2, which is the integration subroutine. FOURW2 handles the incrementing of time, data output, and run termination. FOURW2 calls the Stirling engine simulation subroutine FWS3V2 to generate the information it needs for the Jacobian matrix associated with the backward difference integration. FWS3V2 calls LOSSES to calculate engine friction and auxiliary losses and vehicle load effects; PISTN3, to calculate piston positions from crank angle and crank geometry; PLEAK2, to calculate leakage flow if piston ring leakage effects are considered; SHORT2, to calculate short-circuiting flows if engine braking is desired; and SUPPL2, to calculate the flow into the engine and the phasing of the injected flows. SUPPL2 calls SUPLRK if rod leakage is considered. FWS3V2 then returns to FOURW2.

In figure 3, the body of FOURW2 is shown within the dashed line. The subroutines enclosed are actually subroutines to FOURW2. Although they are all called by and return to FOURW2, they are shown as calling one another to illustrate the looping that takes place within the subroutine. Once a Jacobian matrix is calculated, FOURW2 calls DMINV for a matrix inversion or BROYF1 for updates to a previously generated matrix. Subroutine BROYF1 contains the Broyden update algorithm. This algorithm is used to try to eliminate the need to calculate new Jacobian matrices as the simulation moves away from an operating point. The algorithm tries to accomplish this by continually updating the inverted Jacobian matrix. The reason for using the algorithm is to try to shorten computer calculation time since generating Jacobian matrices and taking inverses is very time consuming. The use of this algorithm is discussed in more detail in appendix C. Convergence is then checked. If the

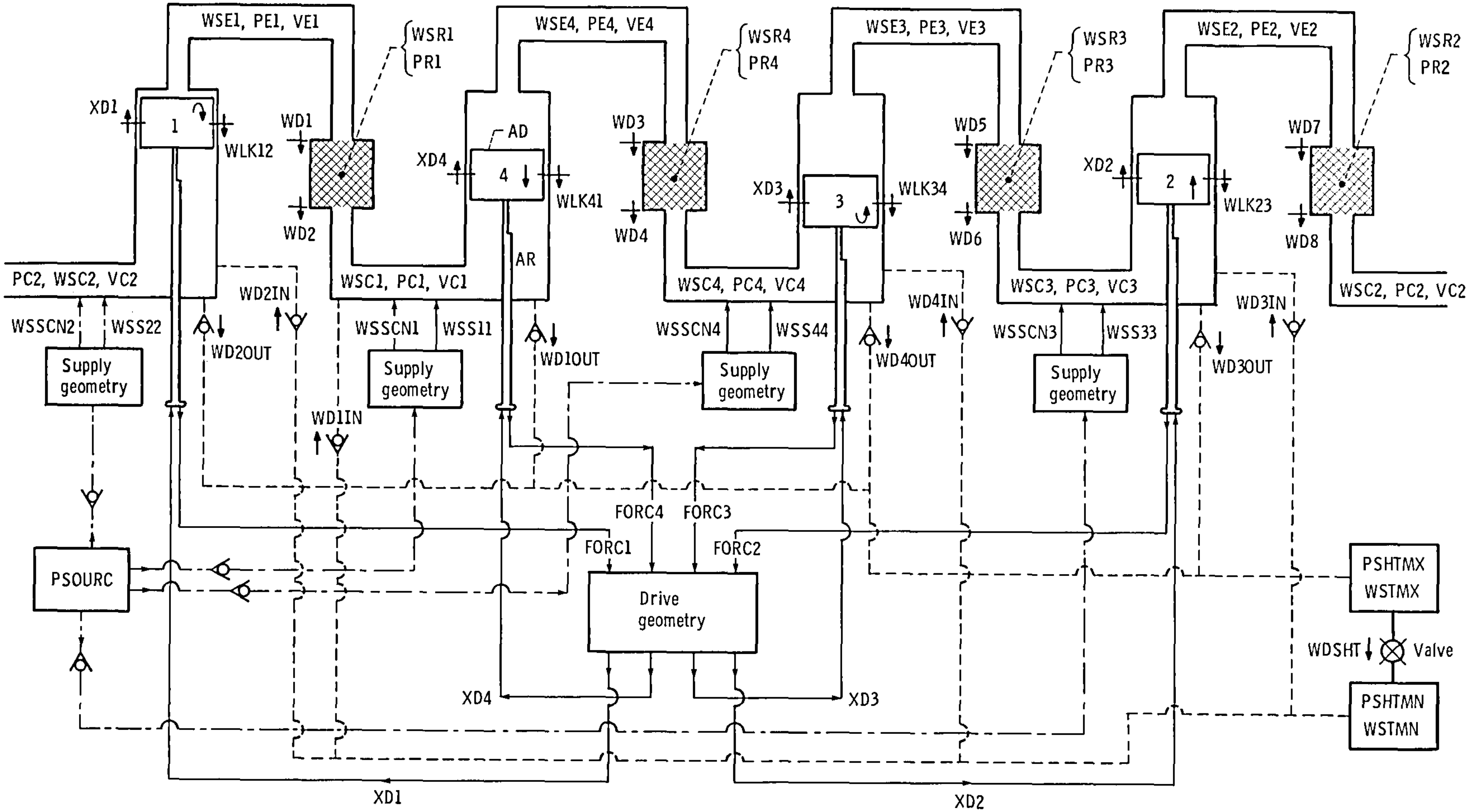


Figure 1. - Schematic of four-working-space (FWS) model.

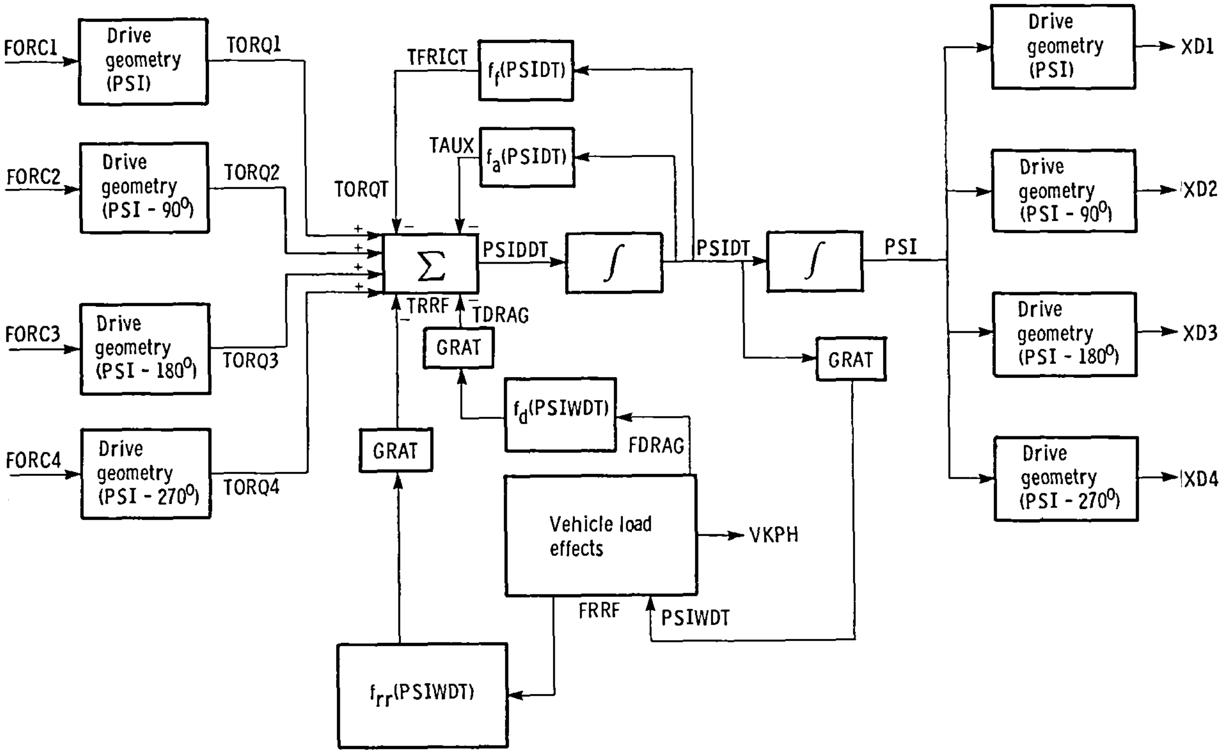


Figure 2. - Stirling engine drive dynamics.

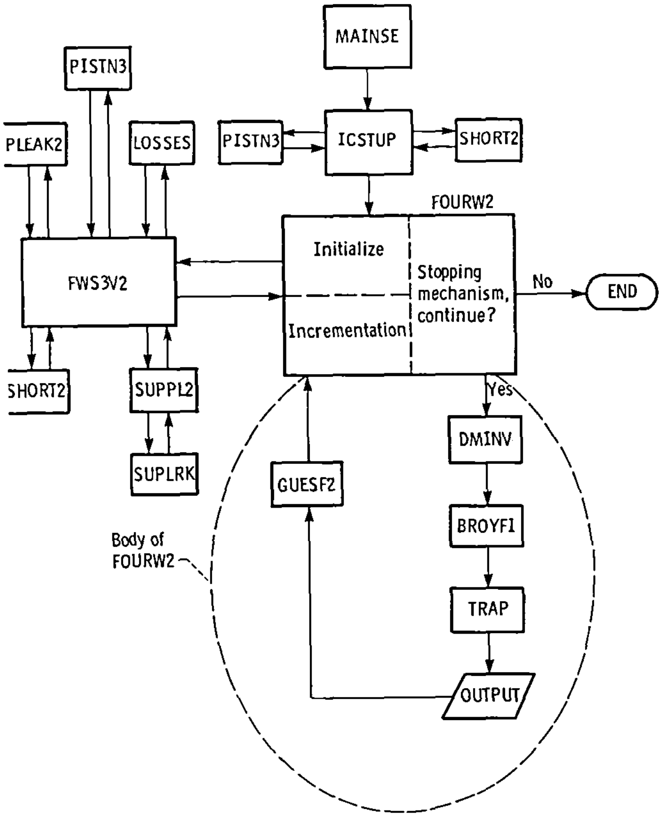


Figure 3. - Overall simulation structure.

simulation is not converged, more passes are made through FOURW2 to generate better iteration guesses or a new Jacobian matrix. If converged, FOURW2 calls TRAP to do a trapezoidal integration on the product of pressure and volume in the expansion and compression spaces. TRAP returns to FOURW2, which then calls OUTPUT if a printout is desired at the current time. OUTPUT returns to FOURW2; then GUESF2 is called to predict the next set of state variables for the next time step. This is done until the desired maximum number of time steps has been run, at which time FOURW2 terminates the run. Flow charts for all subroutines are given in appendix C.

Program Setup

The program setup is done in the main program MAINSE: Switches are set to indicate the type of transient desired, and engine geometry and flow data are input. Tables I to X indicate the required input as well as the options available. In table I engine geometric data are specified. The expansion-space dead volume (VOE) includes the heater volume; the compression-space dead volume (VOC) includes the cooler volume. The total regenerator volume excluding the volume of the mesh is denoted by VR. Table II lists the required heater and cooler wall temperatures. Table III lists the flow resistances between the volumes. All the constants are listed in table IV. Data for the implicit integration method are listed in table V. Most of the integration settings should be kept the same. However, increasing MPAS and/or TOLPCG sometimes is helpful for difficult convergence problems (not observed in this application). The simulation will continue to run if MPAS is exceeded but will output an error message indicating it has been exceeded.

The different options available can be selected by a set of switches defined in table VI. ISS must be set equal to zero and MATRIX, equal to 1. The rest of the switches are user definable. Table VII lists all the run conditions that must be specified. Table VIII defines the load characteristics. Table IX describes the cycle data – the number of cycles to be run and the number of integrations per cycle. Table X lists the required transient data. If no supply or short-circuiting transients are desired, the cycle start-and-stop conditions for these options should be set higher than the number of cycles desired. Table XI lists all the common blocks and the subroutines that contain them. This table is provided so that the user may more easily define data transfer between subroutines.

Output Options

The user may select from a number of output and debug options. If ICALC = 1, a short printout is specified. The output, where all symbols are defined in appendix A, is given in table XII. Outputs include heater temperature (TWH), cooler temperature (TWC), cycle mean pressure (CYCLPR), engine drive mode (NONENG), number of cycles to be run (NUMBCY), piston ring leakage area scalar (ALEAK), piston rod leakage area (ARLEAK), supply pressure (PSOURC), the time step to start the supply (ISUPST), and the time step to start short circuiting (ISHTST). No output values are given in this example since this output option was used for all the test cases.

Next, results from the output data are printed out at the desired time steps. Power and torque calculations along with crank angle, mean pressure, and engine speed are output. ITRAN indicates the number of time steps taken up to the printout; and KWORK indicates the number of time steps in the calculation of the pressure-volume area. (Note that if KWORK = 101, 100 time steps were taken, since the first time step printed out is the initial condition.)

If ICALC = 0, a long printout is specified. An example of a long printout is shown in table XIII. At each time point a complete listing of all engine variables is given. Note that the output is arranged in rows of four (except for the overall parameters). The first row is for the first working space; the second, for the second working space; etc. The output includes pressure, temperature and volume data, flow data, convergence data (guess variables (VS) and errors (E)), the short-circuiting system, and finally, power and torque data. Data are given for this printout as an example; subsequent examples will make use of the short printout (ICALC = 1).

There is also a debug option to aid in solving problems that may occur in the simulation, This option is specified in MAINSE by NOBUG. If NOBUG = 1, the option is not used unless (1) there is a problem with convergence (the maximum number of allowable iteration passes (MPAS) is exceeded without convergence) or (2) there is a problem in generating a partial derivative for the Jacobian matrix. In both cases the debug option comes from FWS3V2. No printout of variable names is given. However, an indicator shows where and what subroutine the debug output comes from. For example, if "DEBUG PRINTOUT FROM FWS3V2 NUMBER 1" is printed, the user can go to FWS3V2 and look for the comment that indicates debug printout number 1. Using the data printed and the FORTRAN listing of the variable names, the user should be able to debug his program.

If the debug option is called (NOBUG = 0), a dump of all variables as they are calculated comes from FOURW2 and FWS3V2. This option should be used judiciously because of the amount of data printed. Again, an indicator points to the source of the debug output to help the user find the source of a problem. A sample debug is shown in table XIV. The first part of the output comes from ICSTUP and gives all the initial conditions calculated. Next comes the heading "DEBUG OUTPUT FROM FOURW2 NUMBER 1." Here the variable TIME is listed. Next "DEBUG PRINTOUT FROM FWS3V2 NUMBER 1" is printed. Here the variables are not labeled, so the user must trace through the FORTRAN for FWS3V2 to the proper area of code to begin debugging the problem. In the sample the second debug output from FWS3V2 is also given. The output "CONVERGENCE IN ERR VECTOR" is printed if NOBUG = 0 and convergence occurs.

Output – Test Cases

Two output test cases – a supply transient and a short-circuiting transient are given. Input and output data are provided for both cases.

Supply Transient (100 Points per Cycle)

A supply transient is used as the first test case. The assumed initial conditions for the engine are a mean pressure of 5 MPa and a speed of 2000 rpm. After five cycles, hydrogen is injected to accelerate the engine for 1000 engine cycles. The supply pressure is 10 MPa and is constant. Leakage through piston rings and piston rods is not considered.

The FORTRAN input in MAINSE for this case is shown in table XV. The transient is defined by CYCLPR = 5.0, SPDRPM = 2000.0, NCYSUP = 5, NUMBCY = 1000, PSOURC = 10.0, ALEAK = 0.0, and ARLEAK = 0.0. For this case the Broyden update algorithm is not used (IBRYTH = 0); the step size is set by the desired 100 integration points per cycle (NPTPCY = 100); the desired printout is at every 100 points (IPRTOP = 100); the short printout option is desired (ICALC = 1); and no short circuiting is used. (NCYSHT is set above NUMBCY, or at 50 000).)

A sample output for the test case is shown in table XVI. Note that TIME is incremented in such a way that the specified number of integration points per cycle is obtained. Therefore the time step is variable as a function of engine speed. For the example presented, only parts of the printout are shown because of the large number of engine cycles simulated. Before a specified limit on CPU time was exceeded, 803 engine cycles (20.77 sec of engine time) were simulated. The simulation was run on an IBM 370/3033 computer and used 20 minutes of CPU time. Thus the simulation takes about 1.5 seconds of CPU time per engine cycle. Figure 4 shows a plot of the results. Note that the engine mean pressure (PAVEMP) and output power (POWERT) rise quickly. Engine speed rises more slowly because of the effective inertia of the load.

Supply Transient (25 Points per Cycle)

The second test case is the same as the first case but has NPTPCY = 25 instead of 100. Sample output is presented in table XVII. Note that KWORK = 26 since there are 25 points per cycle. POSDEG is somewhat off after each cycle (270.2°) since the integration is coarser than for the 100-points-per-cycle case. Also, at some time points the simulation does not converge. Since MPAS is set equal to 20 in MAINSE, the simulation prints a debug output after 21 iteration passes. The message "ITERATION FAILURE 13 21" "DEBUG OUTPUT FROM FWS3V2, FLOW CONTINUES" contains the number of converged errors, 13 (this will vary), and MPAS plus 1, 21. Note in the first debug printout that there are 13 converged errors but 14 states. Error 7 is −.115E-3, which is greater than the specified error tolerance (TOLSS in MAINSE), −0.1E-3. This convergence failure occurs because this is a rather coarse integration (large step size). The simulation continues, however, and eventually recovers.

Since the simulation fails to converge, there may be some question about the validity of the output. Figure 5 shows a comparison of the 25- and 100-points-per-cycle cases. There is excellent agreement between the cases because the errors that do not converge are very close to the tolerance band. For the 25-points-per-cycle case, all 1000 cycles were simulated in 14 minutes of CPU time on the IBM 370/3033 computer, or about 0.81 second of CPU time per cycle. This amounts to 25.33 seconds of engine run time.

As a matter of interest, the 25-points-per-cycle case was rerun by using the Broyden update algorithm

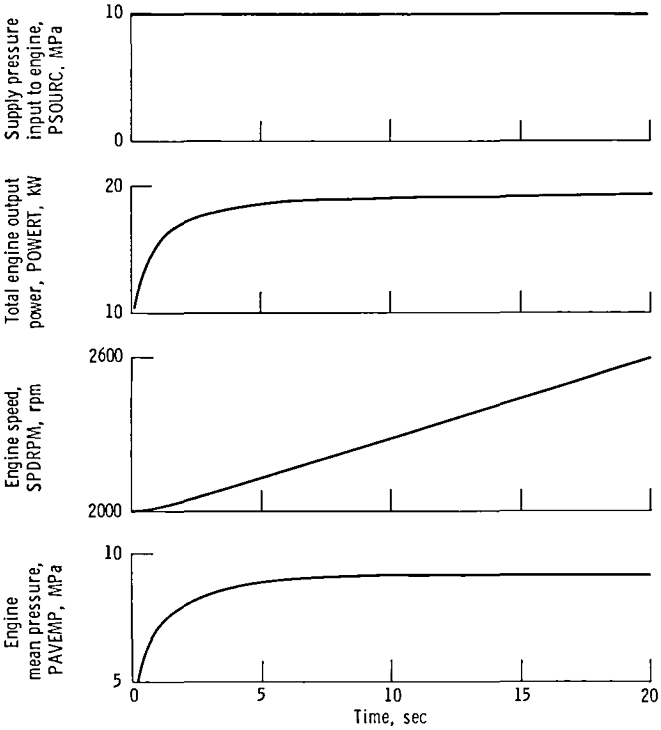


Figure 4. - Supply transient (100 integration points per cycle).

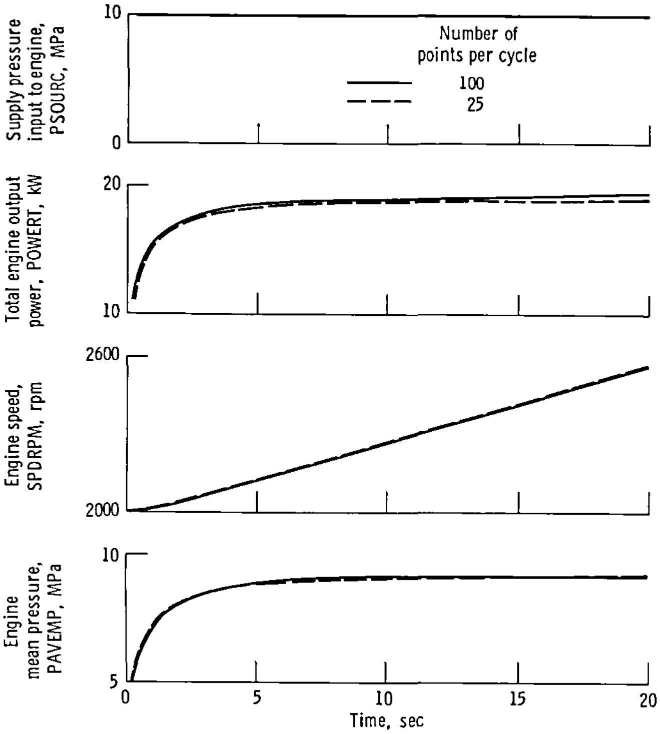


Figure 5. - Comparison of supply transients for different integration step sizes.

(IBRYTH = 1). The case took about the same amount of CPU time for 1000 cycles as it did without the algorithm, the only difference being that two more iteration failures occurred. It may be that the number of calculations required for the algorithm to update the inverted matrix approaches that required for generating a new matrix and its inverse for low-order systems. The algorithm is supplied in this simulation package to allow for expansion of the simulation to include more volumes, the energy equation dynamics, and a control system.

The increase in the time step (decrease in the number of integration points per cycle) is desirable to decrease the computer run time. However, as the integration becomes coarser, some iteration failures can occur. Good agreement may still result, depending on how close the unconverged error was to the tolerance band at the convergence failure. This is problem dependent. The same supply case was run with 50 integration points per cycle. No iteration failures occurred, and 1000 engine cycles took 18 minutes of 370/3033 CPU time, or 1.1 seconds of CPU time per cycle. Again good agreement was obtained with the 100-points-per-cycle case.

Short-Circuit Transient

The final test case is a short-circuit transient. This is set up in MAINSE by setting the short-circuit valve area (ASHTT), the cycle at which to start the short circuiting (NCYSHT), and the cycle at which to stop the short circuiting (NCYSHS) and by setting the supply start (NCYSUP) and the supply stop (NCYSTP) cycles greater than the maximum number of cycles (NUMBCY). The plenum pressures PSHTMX and PSHTMN are set internally in the program to 1 MPa above and 1 MPa below the mean pressure, respectively. The MAINSE statements for this case are given in table XVIII. The output for this case is shown in figure 6. Maximum and minimum plenum pressures are shown at the top of the figure. Their initial values are 16 and 14 MPa, respectively. At five cycles (126 time steps) a short-circuiting sequence is begun. The valve area (ASHTT) is set equal to zero initially so that the plenums come to maximum and minimum pressures of 18.9 and 11.7 MPa, respectively. Then, 500 time steps later (internally set in the program), the short-circuiting valve is opened. The plenum pressures respond immediately, as indicated. Total engine power drops from 56 to 36 MPa when the valve opens. Speed drops off more slowly because of inertia effects. The torque, after 18 seconds of engine run time, is still slightly negative. Hence, speed continues to decrease. Mean pressure in the engine stays fairly constant.

The test cases show that the simulation is capable of producing transients that are representative of Stirling engine controls analysis. The input routine (MAINSE) allows for user selection of the desired transient and for detailed study of all or part of the transient. Results can be obtained over many engine cycles (as in the test cases) or on an individual cycle basis (as was done in ref. 4).

Concluding Remarks

A four-cylinder-Stirling-engine computer program is presented. The program is intended for controls analysis. The associated engine model has been derived from a more complex four-cylinder engine model. The simpler controls model results in a decrease in computer calculation times. The model includes drive dynamics and vehicle load effects. The computer program also includes subroutines that allow simulation of control strategies such as acceleration of the engine by adding to the inventory of hydrogen in the system and braking of the engine by short circuiting between the working spaces. Subroutines are provided to calculate degraded engine performance due to piston ring leakage.

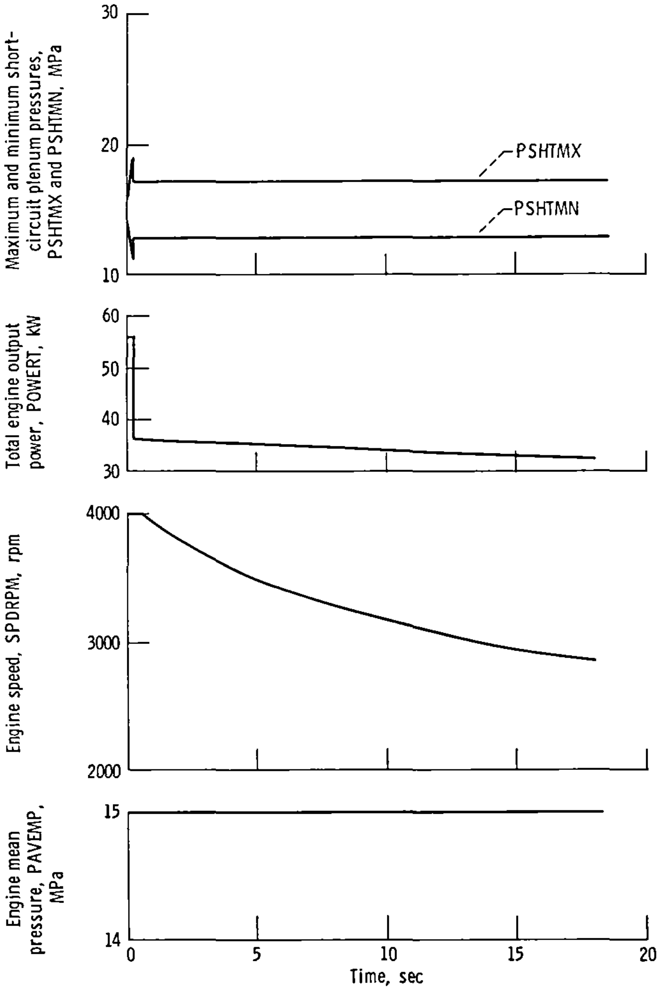


Figure 6. - Short-circuit transient. Valve area, ASHTT, 0.2 cm^2.

All input data required to run the program are described, and complete FORTRAN listings of the main program and all the subroutines are provided. Flow charts of the overall simulation and the subroutines are also given. The simulation is modular to allow for easy modification of the model.

An input routine is provided in which the user specifies the transient to be run by setting switches and supplying the proper geometric and engine data. The output is also selected by the user by setting a switch in the input routine. A very detailed printout at the desired printout increment or a less detailed printout can be selected. The integration step size and the printout interval do not have to be the same.

The simulation has been run to generate both steady-state and transient results. Power and torque predictions from the simulation compare well with experimental data over a wide range of engine speeds and pressures. The simulation is capable of predicting steady-state performance with piston ring leakage and short circuiting between the working spaces. Engine acceleration and deceleration data are presented, along with associated printouts that can be used as test cases.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 26, 1982

Appendix A

Symbols

A	piston ring leakage area, cm^2
AAN	problem order
AD	piston area, cm^2
ADJCMP	adjustment to compression-space temperature due to speed, K
ADJEXP	adjustment to expansion space temperature due to speed, K
ADM	piston area, m^2
ADR	piston rod area, cm^2
ADRM	piston rod area, m^2
ADS1 ADS2 ADS3 ADS4	slot area in piston rods 1 to 4 for working-fluid supply, cm^2
AGDN1 AGDN2 AGDN3	adjustments to cycle pressures 2, 3, and 4, kg/(m^2 N)
AIE	engine moment of inertia, N-m/sec^2
AINERT	total effective moment of inertia, N-m/sec^2
AIVEH	equivalent load moment of inertia, N-m/sec^2
AIWHEL	wheel moment of inertia, N-m/sec^2
AKG1 AKG2 AKG3	adjustment to cycle pressure, N-m/kg
ALEAK	piston ring leakage area scalar
ALPHA	crank angle lag, deg
AMPLIT	half of piston stroke, cm
AO	piston ring leakage area, cm^2
APSI	number of crank rotations
APTS	number of integrations per cycle
AR	piston rod area, cm^2
AREA	trapezoidal integration area, N-m
AREAO	summed trapezoidal integration area, N-m
ARLEAK	piston rod leakage area, cm^2
AS	square of half stroke, cm^2
ASHTT	short-circuit valve area, cm^2
BIGA	pivot element in matrix invert routine
BIGDEL	scalar for matrix predictor (biggest change)
BIGNUM	scalar for matrix predictor (biggest number)
CCCHK	change of piston 3 position from initial value, cm
CCCHKP	previous change in piston 3 position, cm
CCCKKK	scalar change to time increment to predict when piston 3 will again reach its initial value
CMAT	storage matrix in BROYF1
COS1 COS2 COS3 COS4	cosine of crank angle and 90° offsets
CYCLPM	maximum cycle pressure, MPa
CYCLPR	current cycle pressure, MPa
DEGR	conversion factor, rad/deg
DELE	vector of changes in error vector
DELPSI	change in crank angle, rad
DELT	change in time, sec
DELTAV	vector change in guess variables
DELX	vector change in guess variables (Broyden algorithm)
DELY	vector change in error variables (Broyden algorithm)
DENOM	scalar change to cycle pressure, cm^3/K
DETERM	matrix determinant
DIAM	orifice diameter, cm
DIR1 DIR2 DIR3 DIR4	piston ring leakage flow direction
DIV	stored mass scalar
DRIVO	initial condition for drive torque, N-m
E	error vector
EMAT	Jacobian matrix for 14th-order system
ERRBSE	past error vector
FDRAG	force due to vehicle air drag, N
FFFF1 FFFF2 FFFF3 FFFF4	torque scalar for each piston
FORC1 FORC2 FORC3 FORC4	force on each piston, N
FRAC	external control for matrix convergence
FREQ	engine rotational speed, rps
FREQQ	engine rotational speed, rpm
FREQRP	engine rotational speed, rpm
FRRF	force due to rolling resistance, N

G	gravitational constant, kg/(MPa sec^2)
GR	gear ratio
GRAT	overall gear ratio
GTRAN	transmission gear ratio
HOLD	variable for row and column interchange in matrix invert routine
I	integer
IBRYTH	switch for using Broyden algorithm
ICALC	switch for output options
ICON	counter for converged errors
IDB	switch for internal DEBUG output
IHPCNV	switch for causing a matrix to be generated at every time point
IICC	counter for partial derivative generation
IJ	index
IK	index
INDICA	switch for sign change on error variable
IPRTOP	switch for number of printouts per cycle
IROT	switch for indicating a complete crank rotation
ISHSP2	two time points after short circuiting starts
ISHSTP	time point for end of short circuiting
ISHSUP	one time point after short circuiting starts
ISHTST	time point for start of short circuiting
ISPSTP	time point for end of supply
ISS	switch for initial conditions
ISTEP	counter
ISUPST	time point for start of supply transient
ITRAN	counter for time steps
ITRMAX	maximum number of time steps
IZ J JI JN JP JQ JR	index
JWORK	index for setting time increment for crank rotation
K	index
KBROY	counter for calls to Broyden algorithm
KI KJ KK	index
KWORK	counter for pressure-volume integration
KWRIT	counter for printout
L	index
LW	scratch vector
M	index
MATRIX	switch for generating a new Jacobian matrix
MATTOT	counter for number of matrices generated during a transient run
MBUG	debug switch for iteration failure
MPAS	maximum allowable iteration passes
MW	scratch vector
N	system order
NCYSHS	cycle at which to stop short circuiting
NCYSHT	cycle at which to start short circuiting
NCYSTP	cycle at which to stop supply
NCYSUP	cycle at which to start supply
NITER	counter for number of iterations at a time point
NK	index
NMAT	counter for number of Jacobian matrices generated at a time point
NOBUG	switch for a debug printout
NONENG	switch for type of piston motion
NPSI	reset PSI to zero after 360° rotation
NPTPCC	number of integration points per cycle plus 1
NPTPCY	number of integration points per cycle
NSTP	switch for storing past converged scale factors for iteration guesses
NTMAX	maximum number of iteration variables
NUMBCY	number of engine cycles to be run
PAUX	power lost due to engine auxiliaries, kW
PAVEMP	cycle mean pressure for all four cylinders after iteration, MPa
PCCBAR	cycle mean pressure for all four cylinders during iteration, MPa
PCCMAX	cycle maximum pressure for all four cylinders during iteration, MPa
PCCMIN	cycle minimum pressure for all four cylinders during iteration, MPa
PCMAX	cycle maximum compression-space pressure for all four cylinders after iteration, MPa
PCMIN	cycle minimum compression-space pressure for all four cylinders after iteration, MPa
PCNCHG	iteration convergence rate
PCOLD1 PCOLD2 PCOLD3 PCOLD4	compression-space pressure from previous time step for pressure-volume integration, MPa

PCVCO1 PCVCO2 PCVCO3 PCVCO4	summation of pressure-volume integration in compression space to previous time step, kW
PCVCR1 PCVCR2 PCVCR3 PCVCR4	summation of pressure-volume integration in compression space to current time step, kW
PCY	cycle pressure, MPa
PCY1 PCY2 PCY3 PCY4	cycle pressure in each working space, MPa
PC1 PC2 PC3 PC4	compression-space pressure in each working space, MPa
PC1MAX PC2MAX PC3MAX PC4MAX	maximum compression-space pressure in each working space, MPa
PC1MIN PC2MIN PC3MIN PC4MIN	minimum compression-space pressure in each working space, MPa
PDRAG	power loss due to air drag, kW
PEMAX	cycle maximum expansion-space pressure for all four cylinders after iteration, MPa
PEMIN	cycle minimum expansion-space pressure for all four cylinders after iteration, MPa
PENG	engine power loss due to auxiliaries and mechanical friction, kW
PEOLD1 PEOLD2 PEOLD3 PEOLD4	expansion space pressure from previous time step for pressure-volume integration, M
PEVEO1 PEVEO2 PEVEO3 PEVEO4	summation of pressure-volume integration in expansion space to previous time step, kW
PEVER1 PEVER2 PEVER3 PEVER4	summation of pressure-volume integration in expansion space to current time step, kW
PE1 PE2 PE3 PE4	expansion-space pressure in each working space, MPa
PFRICT	power loss due to mechanical engine friction, kW
PIE	constant (3.14159)
PLOAD	power loss due to load, kW
PNET	net power, kW
POSDEG	crank angle, deg
POSDEO	initial-condition crank angle, deg
POSDT	speed, rad/sec
POSEOO	initial-condition speed, rad/sec
POWERT	total engine power, kW
POWER1 POWER2 POWER3 POWRE4	power from each working space, kW
PP1 PP2 PP3 PP4	average pressure at piston ring, MPa
PRRF	power loss due to rolling resistance, kW
PR1 PR2 PR3 PR4	regenerator pressure in each working space, MPa
PSHTMN	minimum-pressure manifold pressure, MPa
PSHTMX	maximum-pressure manifold pressure, MPa
PSI	crank angle, rad
PSIDDT	crank angle acceleration, rad/sec^2
PSIDEG	crank angle, deg
PSIDT	crank angle velocity, rad/sec
PSIM	crank angle adjusted to remain between 0 and 2π radians, rad
PSIMD	adjusted crank angle, deg
PSIWDT	wheel velocity, rad/sec
PSI1 PSI2 PSI3 PSI4	piston crank position, rad
PSOURC	working-fluid storage pressure, MPa
R	gas constant, (MPa cm^3)/(K kg)
RAT	scalar change on step size for iteration
RATIO	largest step-size change
RATOO	ratio of slot valve opening length to piston rod length
RATT	length of slot valve opening, cm
RATTT	scalar adjustment to expansion- and compression-space temperatures due to speed
REF	desired value of summation of error changes

RER	flow resistance between expansion space and regenerator, (MPa sec)/kg
RMAT	Jacobian matrix for 16th-order system
RODL	crank rod length, cm
RODLS	SQRT(RODL**2+AMPLIT**2), cm
RR	maximum error value
RRC	flow resistance betwen regenerator and compression space, (MPa sec)/kg
RS	square of crank length, cm^2
RSHT	flow resistance between manifolds and compression spaces, (MPa sec)/kg
RSHTCT	flow resistance between high- and low-pressure manifolds, (cm^2 MPa sec)/kg
RSHTT	short-circuit flow scalar, kg/(sec MPa)
RSUP	supply flow resistance, (cm^2 MPa sec)/kg
RWHEEL	radius of car wheel, cm
SES	summation of squares of present errors
SESP	summation of squares of past errors
SGN	sign of perturbation step
SIN1 SIN2 SIN3 SIN4	square of sines of crank angle and offsets
SIN11 SIN22 SIN33 SIN44	sine of crank angle and offsets
SPEEDR	engine speed, rad
SPDMAX	maximum engine speed, rpm
SPDRPM	engine speed, rpm
STROKE	piston stroke length, cm
TAUX	torque loss due to auxiliaries, N-m
TCO1 TCO2 TCO3 TCO4	initial value of compression-space temperatures for each working space, K
TC1 TC2 TC3 TC4	compression-space temperature for each working space, K
TDRAG	torque loss due to air drag, N-m
TEMP	Broyden update scalar
TEMP1	Broyden update scalar
TEMP2	Broyden update vector
TEMP3	Broyden update vector
TENG	total torque loss due to engine auxiliaries and mechanical friction, N-m
TEST1 TEST2 TEST3 TEST4	pressure drop across piston rings for each piston, MPa
TEO1 TEO2 TEO3 TEO4	initial value of expansion-space temperatures for each working space, K
TE1 TE2 TE3 TE4	expansion-space temperature for each working space, K
TFRICT	torque loss due to mechanical friction, N-m
TIME	time, sec
TIMPRV	time at previous time step, sec
TLOAD	torque loss due to load, N-m
TNET	net torque, N-m
TOLPCG	convergence rate at which a decision is made to generate a new Jacobian matrix
TOLSS	error tolerance
TOL1	lower limit for good partial derivatives
TOL2	upper limit for good partial derivatives
TORMAX	maximum torque, N-m
TORMIN	minimum torque, N-m
TORQT	total torque, N-m
TORQ1 TORQ2 TORQ3 TORQ4	torque generated by each piston, N-m
TRRF	torque loss due to rolling friction, N-m
TRO1 TRO2 TRO3 TRO4	initial-condition regenerator gas temperature for all four working spaces, K
TR1 TR2 TR3 TR4	regenerator gas temperature for all four working spaces, K
TSH	short-circuit manifold temperature, K
TST31H TST32H TST33H TST34H	pressure drop from compression spaces to high-pressure plenum, MPa
TST31L TET32L TST33L TST34L	pressure drop from low-pressure plenum to compression spaces, MPa

TT1 TT2 TT3 TT4	average temperature at piston ring for each piston, K
TWC	adjusted compression-space temperature, °C
TWCIN	cooler wall temperature, °C
TWH	adjusted expansion-space temperature, °C
TWHIN	heater wall temperature, °C
VCC1 VCC2 VCC3 VCC4	initial-condition compression-space volume for each working space, cm^3
VCOLD1 VCOLD2 VCOLD3 VCOLD4	compression-space volume from previous time step for pressure-volume integration, cm^3
VCONV	vector of converged state variables from previous time step
VC1 VC2 VC3 VC4	compression-space volume, cm^3
VDELTA	initial perturbation on state variables for matrix generation
VDENOM	vector of past converged state variables used in error vector calculation
VDOT	vector of state variable derivatives at current time
VDOTSV	vector of state variable derivatives at previous time
VDOTT	vector of average values of state variable derivatives from present and past time steps
VEE1 VEE2 VEE3 VEE4	initial-condition expansion-space volume for each working space, cm^3
VEOLD1 VEOLD2 VEOLD3 VEOLD4	expansion-space volume from previous time step for pressure-volume integration, cm^3
VE1 VE2 VE3 VE4	expansion-space volume, cm^3
VGUESS	state variable guess vector
VKPH	car velocity, km/hr
VMAT	vector of changes in state variables during iteration
VOC	compression-space dead volume, cm^3
VOE	expansion-space dead volume, cm^3
VR	regenerator volume, cm^3
VR1 VR2 VR3 VR4	regenerator volumes for the four working spaces, cm^3
VS	state variable guess vector
VSAVE	vector of saved, converged state variables used for generating a Jacobian matrix
VSH	short-circuit low- and high-pressure plenum volumes, cm
WDSHT	short-circuit flow from high-pressure plenum to low-pressure plenum, kg/sec
WD1 WD2	mass flow rates in working space 1, kg/sec
WD3 WD4	mass flow rates in working space 4, kg/sec
WD5 WD6	mass flow rates in working space 3, kg/sec
WD7 WD8	mass flow rates in working space 2, kg/sec
WD1IN WD2IN WD3IN WD4IN	short-circuit mass flows from low-pressure plenum to compression spaces, kg/sec
WD1OUT WD2OUT WD3OUT WD4OUT	short-circuit mass flows from compression spaces to high-pressure plenum, kg/sec
WLK12 WLK23 WLK34 WLK41	piston ring leakage flow from working space i to j, kg/sec
WSC1DT WSC2DT WSC3DT WSC4DT	stored mass derivative in compression volume for each working space, kg/sec
WSE1DT WSE2DT WSE3DT WSE4DT	stored mass derivative in expansion volume for each working space, kg/sec
WSMN1	initial stored mass in low-pressure plenum, kg
WSMX1	initial stored mass in high-pressure plenum, kg

WSR1DT WSR2DT WSR3DT WSR4DT	stored mass derivative in regenerator volume for each working space, kg/sec
WSSCN1 WSSCN2 WSSCN3 WSSCN4	piston rod leakage flow for each working space, kg/sec
WSS11 WSS22 WSS33 WSS44	stored mass supply flow into each working space, kg/sec
WSTMN	stored mass in low-pressure plenum, kg
WSTMND	stored mass derivative in low-pressure plenum, kg/sec
WSTMX	stored mass in high-pressure plenum, kg
WSTMXD	stored mass derivative in high-pressure plenum, kg/sec
WSTOTL	total stored mass in engine, kg
WSWANT	initial stored mass in each working space, kg
WTCAR	mass of car, kg
WTENG	mass of engine, kg
WTOT	total stored mass in engine during integration, kg
WTWHEL	mass of wheels, kg
WT1 WT2 WT3 WT4	stored mass in each working space during integration, kg
XDST	slide valve opening position, cm
XD1 XD2 XD3 XD4	piston position with zero reference at midstroke, cm
XD1P XD2P XD3P XD4P	piston position with zero reference at top of crank, cm
XD30	initial position of piston 3, cm
XD3PRV	position of piston 3 at previous time step, cm
XXX	summation of squares of changes in errors to maximum error
Y	present abscissa value for trapezoidal integration
YOLD	past abscissa value for trapezoidal integration
YSCALE	stored mass scalar
YYY	scalar vector for changes in state
YYYX	summation of squares of changes in errors to maximum error for debug output
Z	present ordinate value for trapezoidal integration
ZEROBS	position bias to change zero reference of piston position from top crank to center stroke, cm
ZMAT	Jacobian matrix for 12th-order system
ZOLD	past ordinate value for trapezoidal integration

Appendix B

Analytical Model

The dynamic equations used to model the four-cylinder controls model were simplified from those used to represent the single-working-space model. Both sets of equations are given in reference 2. For completeness, the equations of the four-cylinder model are presented here. All equations are in FORTRAN.

Dynamic Equations

A schematic of the four-cylinder controls model is given in figure 1. The pistons are numbered in the order in which they reach top stroke as indicated by the arrows in the piston heads. The dynamic equations are

WSE1DT = −WD1 − WLK12

WSR1DT = WD1 − WD2

WSC1DT = WD2 + WLK41 + WSS11 + WSSCN1 + WD1IN − WD1OUT

WSE2DT = −WD7 − WLK23

WSR2DT = WD7 − WD8

WSC2DT = WD8 + WLK12 + WSS22 + WSSCN2 + WD2IN − WD2OUT

WSE3DT = −WD5 − WLK34

WSR3DT = WD5 − WD6

WSC3DT = WD6 + WLK23 + WSS33 + WSSCN3 + WD3IN − WD3OUT

WSE4DT = −WD3 − WLK41

WSR4DT = WD3 − WD4

WSC4DT = WD4 + WLK34 + WSS44 + WSSCN4 + WD4IN − WD4OUT

The first-order approximations to the momentum equations are

WD1 = (PE1 − PR1)/RER

WD2 = (PR1 − PC1)/RRC

WD3 = (PE4 − PR4)/RER

WD4 = (PR4 − PC4)/RRC

WD5 = (PE3 - PR3)/RER

WD6 = (PR3 - PC3)/RRC

WD7 = (PE2 - PR2)/RER

WD8 = (PR2 - PC2)/RRC

Pressure

Pressures are given by the ideal-gas law:

PE1 = (TE1*R*WSE1)/VE1

PR1 = (TR1*R*WSR1)/VR1

PC1 = (TC1*R*WSC1)/VC1

PE2 = (TE2*R*WSE2)/VE2

PR2 = (TR2*R*WSR2)/VR2

PC2 = (TC2*R*WSC2)/VC2

PE3 = (TE3*R*WSE3)/VE3

PR3 = (TR3*R*WSR3)/VR3

PC3 = (TC3*R*WSC3)/VC3

PE4 = (TE4*R*WSE4)/VE4

PR4 = (TR4*R*WSR4)/VR4

PC4 = (TC4*R*WSC4)/VC4

Temperatures

Temperatures are set as a weak function of speed. The temperature functions in the expansion and compression spaces are derived from steady-state data from the single-working-space model results (ref. 2). The speed ratio is

RATTT = (SPDMAX - FREQRP)/1000.0

and the temperatures in the volumes are given by

TE1 = TWH + RATTT*5.555 - 55.55

TE2 = TWH + RATTT*5.555 − 55.55

TE3 = TWH + RATTT*5.555 − 55.55

TE4 = TWH + RATTT*5.555 − 55.55

TC1 = TWC − RATTT*3.888 + 55.55

TC2 = TWC − RATTT*3.888 + 55.55

TC3 = TWC − RATTT*3.888 + 55.55

TC4 = TWC − RATTT*3.888 + 55.55

TR1 = (TE1 + TC1)/2.0

TR2 = (TE2 + TC2)/2.0

TR3 = (TE3 + TC3)/2.0

TR4 = (TE4 + TC4)/2.0

Volumes

Variable volumes are a function of piston position:

VE1 = VOE + (STROKE/2.0 − XD1)*AD

VC1 = VOC + (STROKE/2.0 + XD4)*(AD − AR)

VE2 = VOE + (STROKE/2.0 − XD2)*AD

VC2 = VOC + (STROKE/2.0 + XD1)*(AD − AR)

VE3 = VOE + (STROKE/2.0 − XD3)*AD

VC3 = VOC + (STROKE/2.0 + XD2)*(AD − AR)

VE4 = VOE + (STROKE/2.0 − XD4)*AD

VC4 = VOC + (STROKE/2.0 + XD3)*(AD − AR)

The regenerator volumes are fixed:

VR1 = VR

```
VR2=VR

VR3=VR

VR4=VR
```

Piston Positions

Piston positions are calculated from the drive geometry and the crank angle:

```
XD1 =(STROKE/2.0)*COS(PSI)

     +SQRT(RODL**2-(STROKE/2.0)**2*(SIN(PSI))**2)

     -SQRT(RODL**2-(STROKE/2.0)**2)-ZEROBS

XD2 =(STROKE/2.0)*COS(PSI-PIE/2.0)

     +SQRT(RODL**2-(STROKE/2.0)**2*(SIN(PSI-PIE/2.0))**2)

     -SQRT(RODL**2-(STROKE/2.0)**2)-ZEROBS

XD3 =(STROKE/2.0)*COS(PSI-PIE)

     +SQRT(RODL**2-(STROKE/2.0)**2*(SIN(PSI-PIE))**2)

     -SQRT(RODL**2-(STROKE/2.0)**2)-ZEROBS

XD4 =(STROKE/2.0)*COS(PSI-3.*PIE/2.)

     +SQRT(RODL**2-(STROKE/2.0)**2*(SIN(PSI-3.*PIE/2.))**2)

     -SQRT(RODL**2-(STROKE/2.0)**2)-ZEROBS
```

where ZEROBS is a small bias to center the piston stroke around zero reference rather than at the top of the crank.

Torque

Torque is calculated from piston areas, cycle pressures, and drive geometry. The forces on the pistons are

```
FORC1=PE1*AD-PC2*(AD-AR)

FORC2=PE2*AD-PC3*(AD-AR)

FORC3=PE3*AD-PC4*(AD-AR)

FORC4=PE4*AD-PC1*(AD-AR)
```

The torques generated by each piston are

TORQ1 = (STROKE/2.0)*FORC1*SIN(PSI)*(1.0 + COS(PSI)

/SQRT(RODL**2 – (STROKE/2.0)**2*(SIN(PSI))**2))

TORQ2 = (STROKE/2.0)*FORC2*SIN(PSI – PIE/2.0)*(1.0 + COS(PSI – PIE/2.0)

/SQRT(RODL**2 – (STROKE/2.0)**2*(SIN(PSI – PIE/2.0))**2))

TORQ3 = (STROKE/2.0)*FORC3*SIN(PSI – PIE)*(1.0 + COS(PSI – PIE)

/SQRT(RODL**2 – (STROKE/2.0)**2*(SIN(PSI – PIE))**2))

TORQ4 = (STROKE/2.0)*FORC4*SIN(PSI – 3.*PIE/2.)*(1. + COS(PSI – 3.*PIE/2.)

/SQRT(RODL**2 – (STROKE/2.0)**2*(SIN(PSI – 3.*PIE/2.))**2))

where total torque is

TORQT = TORQ1 + TORQ2 + TORQ3 + TORQ4

Losses

Vehicle load effects, engine auxiliary power loss, and mechanical friction are calculated from

PAUX = 1.57667E – 10*FREQRP**3 – 4.3E – 7*FREQRP**2 + 8.9331E

– 4*FREQRP – + .78002

PFRICT = 12.8/20.0*(FREQRP/SPDMAX)*(PCCBAR + 5.0)

where

PCCBAR = .462*PCCMAX + .538*PCCMIN

and PCCMAX and PCCMIN are the average maximum and minimum compression-space pressures for each of the four working spaces.

Rolling resistance and air drag are considered as part of the vehicle load. For rolling resistance it is assumed that there is a 4.51-hp loss at 50 mph; thus

PRRF = (4.51*.7457/(73.333*30.48)*GRAT*RWHEEL*PSIDT

where

GRAT = GTRAN*(1.0/GR)

The force due to air drag is

FDRAG = .010353*4.448*(RWHEEL*GRAT*PSIDT)**2/(30.48)**2

The power loss is

PDRAG = FDRAG*RWHEEL*GRAT*PSIDT/100000.0

The associated torque losses are

TFRICT = 33000.0*1.356*PFRICT/(2.0*PIE*.7457*FREQRP)

TAUX = 33000.0*1.356*PAUX/(2.0*PIE*.7457*FREQRP)

TRRF = 4.51*550.0*1.356*RWHEEL/(73.333*30.48)*GRAT

TDRAG = FDRAG*RWHEEL*GRAT/100.0

The vehicle speed is

VKPH = (3600.0*RWHEEL*GRAT*PSIDT)/100000.0

The net torque is

TNET = TORQT − TRRF − TDRAG − TFRICT − TAUX

From the net torque when the drive dynamics are integrated, the equation of motion is

AINERT*PSIDDT = TNET

Supply Flow

Supply flow into each working space is calculated as a function of differential pressure between the compression spaces and the supply. Flow is let in by a timing slot in the piston rod. When the rod is near bottom stroke, the slot allows flow into the compression space. A schematic of the system is shown in figure 7. The supply check valves function such that

$$\text{WSS11} = \begin{cases} (\text{PSOURC} - \text{PC1})*\text{ADS1}/\text{RSUP} & \text{for PC1} \le \text{PSOURC} \\ 0.0 \quad \text{for PC1} > \text{PSOURC} & \end{cases}$$

$$\text{WSS22} = \begin{cases} (\text{PSOURC} - \text{PC2})*\text{ADS2}/\text{RSUP} & \text{for PC2} \le \text{PSOURC} \\ 0.0 \quad \text{for PC2} > \text{PSOURC} & \end{cases}$$

$$\text{WSS33} = \begin{cases} (\text{PSOURC} - \text{PC3})*\text{ADS3}/\text{RSUP} & \text{for PC3} \le \text{PSOURC} \\ 0.0 \quad \text{for PC3} > \text{PSOURC} & \end{cases}$$

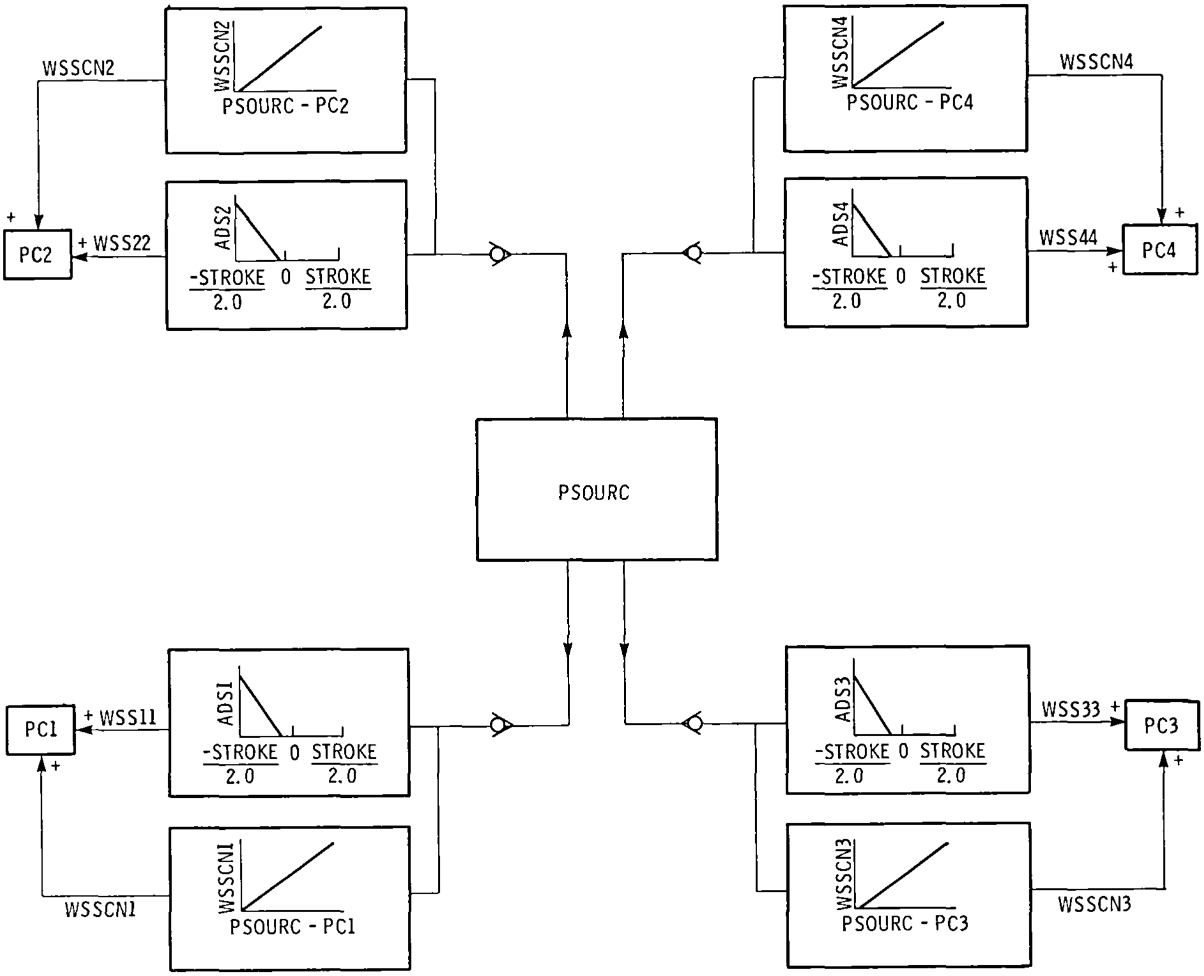


Figure 7. - Supply system.

$$\text{WSS44} = \begin{cases} (\text{PSOURC} - \text{PC4})*\text{ADS4}/\text{RSUP} & \text{for } \text{PC4} \le \text{PSOURC} \\ 0.0 & \text{for } \text{PC4} > \text{PSOURC} \end{cases}$$

where

$$\text{ADS1} = \begin{cases} 1.0 - (\text{XD4} + (\text{STROKE}/2.0))/(\text{RATOO}*\text{STROKE}) \\ \qquad \text{for } \text{XD4} \le -\text{STROKE}*(.5 - \text{RATOO}) \\ 0.0 \qquad \text{for } \text{XD4} > -\text{STROKE}*(.5 - \text{RATOO}) \end{cases}$$

$$\text{ADS2} = \begin{cases} 1.0 - (\text{XD1} + (\text{STROKE}/2.0))/(\text{RATOO}*\text{STROKE}) \\ \qquad \text{for } \text{XD1} \le -\text{STROKE}*(.5 - \text{RATOO}) \\ 0.0 \qquad \text{for } \text{XD1} > -\text{STROKE}*(.5 - \text{RATOO}) \end{cases}$$

$$\text{ADS3} = \begin{cases} 1.0-(\text{XD2}+(\text{STROKE}/2.0))/(\text{RATOO}*\text{STROKE}) & \\ \qquad \text{for } \text{XD2} \leq -\text{STROKE}*(.5-\text{RATOO}) & \\ 0.0 \qquad \text{for } \text{XD2} > -\text{STROKE}*(.5-\text{RATOO}) & \end{cases}$$

$$\text{ADS4} = \begin{cases} 1.0-(\text{XD3}+(\text{STROKE}/2.0))/(\text{RATOO}*\text{STROKE}) & \\ \qquad \text{for } \text{XD3} \leq -\text{STROKE}*(.5-\text{RATOO}) & \\ 0.0 \qquad \text{for } \text{XD3} > -\text{STROKE}*(.5-\text{RATOO}) & \end{cases}$$

Rod leakage flow is also modeled. A schematic of the flow is shown in figure 8.

$$\text{WSSCN1} = \begin{cases} \text{ARLEAK}*(\text{PSOURC}-\text{PC1})/\text{RSUP} & \text{for } \text{PC1} \leq \text{PSOURC} \\ 0.0 \qquad \text{for } \text{PC1} >= \text{PSOURC} & \end{cases}$$

$$\text{WSSCN2} = \begin{cases} \text{ARLEAK}*(\text{PSOURC}-\text{PC2})/\text{RSUP} & \text{for } \text{PC2} \leq \text{PSOURC} \\ 0.0 \qquad \text{for } \text{PC2} >= \text{PSOURC} & \end{cases}$$

$$\text{WSSCN3} = \begin{cases} \text{ARLEAK}*(\text{PSOURC}-\text{PC3})/\text{RSUP} & \text{for } \text{PC3} \leq \text{PSOURC} \\ 0.0 \qquad \text{for } \text{PC3} >= \text{PSOURC} & \end{cases}$$

$$\text{WSSCN4} = \begin{cases} \text{ARLEAK}*(\text{PSOURC}-\text{PC4})/\text{RSUP} & \text{for } \text{PC4} \leq \text{PSOURC} \\ 0.0 \qquad \text{for } \text{PC4} >= \text{PSOURC} & \end{cases}$$

Piston Rod Leakage

An orifice equation is used to model piston ring leakage:

$$\text{WLK12} = .9*\text{AO}*\text{ALEAK}*\text{SQRT}(2.0*\text{G}*\text{PP1}/(\text{R}*\text{TT1}))*\text{SQRT}(\text{ABS}(\text{TEST1}))*\text{DIR1}$$

$$\text{WLK23} = .9*\text{AO}*\text{ALEAK}*\text{SQRT}(2.0*\text{G}*\text{PP2}/(\text{R}*\text{TT2}))*\text{SQRT}(\text{ABS}(\text{TEST4}))*\text{DIR4}$$

$$\text{WLK34} = .9*\text{AO}*\text{ALEAK}*\text{SQRT}(2.0*\text{G}*\text{PP3}/(\text{R}*\text{TT3}))*\text{SQRT}(\text{ABS}(\text{TEST3}))*\text{DIR3}$$

$$\text{WLK41} = .9*\text{AO}*\text{ALEAK}*\text{SQRT}(2.0*\text{G}*\text{PP4}/(\text{R}*\text{TT4}))*\text{SQRT}(\text{ABS}(\text{TEST2}))*\text{DIR2}$$

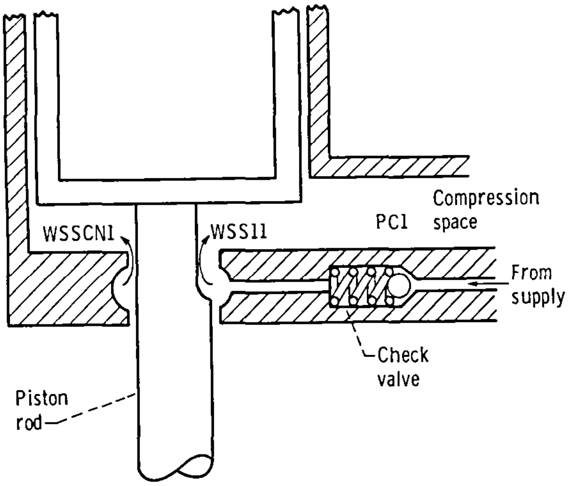


Figure 8. - Piston rod slot valve.

where

AO = PIE/4.0*(DIAM**2 - (DIAM - .0001)**2)

and

DIAM = SQRT(4.0*AD/PIE)

Also

TEST1 = PE1 - PC2

TEST2 = PE4 - PC1

TEST3 = PE3 - PC4

TEST4 = PE2 - PC3

PP1 = (PE1 + PC2)/2.0

PP2 = (PE4 + PC1)/2.0

PP3 = (PE3 + PC4)/2.0

PP4 = (PE2 + PC3)/2.0

TT1 = (TE1 + TC2)/2.0

TT2 = (TE4 + TC1)/2.0

TT3 = (TE3 + TC4)/2.0

$$TT4=(TE2+TC3)/2.0$$

DIR determines the flow direction:

$$DIR1=\begin{cases} 1.0 & \text{for } TEST1\geq 0.0 \\ -1.0 & \text{for } TEST1<0.0 \end{cases}$$

$$DIR2=\begin{cases} 1.0 & \text{for } TEST2\geq 0.0 \\ -1.0 & \text{for } TEST2<0.0 \end{cases}$$

$$DIR3=\begin{cases} 1.0 & \text{for } TEST3\geq 0.0 \\ -1.0 & \text{for } TEST3<0.0 \end{cases}$$

$$DIR4=\begin{cases} 1.0 & \text{for } TEST4\geq 0.0 \\ -1.0 & \text{for } TEST4<0.0 \end{cases}$$

Short Circuiting

A schematic of a short-circuit system is shown in figure 9. The high- and low-pressure plenums are modeled by constant-temperature volumes. The gas temperature is assumed to be that of the compression space. For the check valves

$$TST31H=PC1-PSHTMX$$

$$TST32H=PC2-PSHTMX$$

$$TST33H=PC3-PSHTMX$$

$$TST34H=PC4-PSHTMX$$

$$TST31L=PSHTMN-PC1$$

$$TST32L=PSHTMN-PC2$$

$$TST33L=PSHTMN-PC3$$

$$TST34L=PSHTMN-PC4$$

The flows are

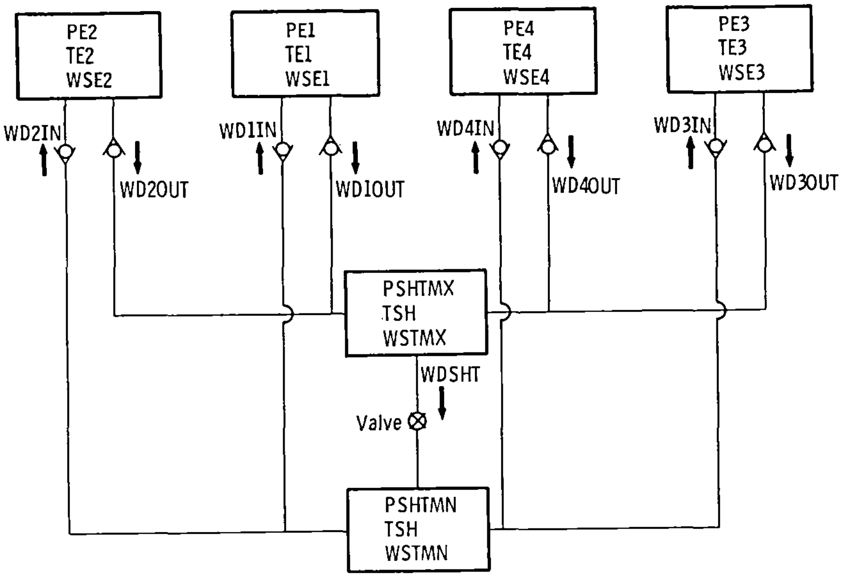


Figure 9. - Short-circuit system.

$$\mathrm{WD1IN} = \begin{cases} \mathrm{TST31L/RSHT} & \text{for } \mathrm{TST31L} \geq 0.0 \\ 0.0 & \text{for } \mathrm{TST31L} < 0.0 \end{cases}$$

$$\mathrm{WD2IN} = \begin{cases} \mathrm{TST32L/RSHT} & \text{for } \mathrm{TST32L} \geq 0.0 \\ 0.0 & \text{for } \mathrm{TST32L} < 0.0 \end{cases}$$

$$\mathrm{WD3IN} = \begin{cases} \mathrm{TST33L/RSHT} & \text{for } \mathrm{TST33L} \geq 0.0 \\ 0.0 & \text{for } \mathrm{TST33L} < 0.0 \end{cases}$$

$$\mathrm{WD4IN} = \begin{cases} \mathrm{TST34L/RSHT} & \text{for } \mathrm{TST34L} \geq 0.0 \\ 0.0 & \text{for } \mathrm{TST34L} \leq 0.0 \end{cases}$$

$$\mathrm{WD1OUT} = \begin{cases} \mathrm{TST31H/RSHT} & \text{for } \mathrm{TST31H} > 0.0 \\ 0.0 & \text{for } \mathrm{TST31H} < 0.0 \end{cases}$$

$$\mathrm{WD2OUT} = \begin{cases} \mathrm{TST32H/RSHT} & \text{for } \mathrm{TST32H} \geq 0.0 \\ 0.0 & \text{for } \mathrm{TST32H} \geq 0.0 \end{cases}$$

$$\text{WD3OUT} = \begin{cases} \text{TST33H/RSHT} & \text{for TST33H} \geq 0.0 \\ 0.0 & \text{for TST33H} < 0.0 \end{cases}$$

$$\text{WD4OUT} = \begin{cases} \text{TST34H/RSHT} & \text{for TST34H} \geq 0.0 \\ 0.0 & \text{for TST34H} < 0.0 \end{cases}$$

The short-circuit valve flow is

$$\text{WDSHT} = (\text{PSHTMX} - \text{PSHTMN})^*\text{ASHTT/RSHTCT}$$

where

$$\text{PSHTMX} = \text{WSTMX}^*\text{R}^*\text{TSH/VSH}$$

$$\text{PSHTMN} = \text{WSTMN}^*\text{R}^*\text{TSH/VSH}$$

The dynamic equations are

$$\text{WSTMXD} = \text{WD1OUT} + \text{WD2OUT} + \text{WD3OUT} + \text{WD4OUT} - \text{WDSHT}$$

$$\text{WSTMND} = -\text{WD1IN} - \text{WD2IN} - \text{WD3IN} - \text{WD4IN} + \text{WDSHT}$$

Appendix C

Flow Charts

This appendix contains flow charts for the main program and all the subroutines in the simulation. Most flow charts should be easy to follow, with the possible exception of that for subroutine FOURW2. FOURW2 performs both the incrementing of time and the integration of the state equations. The integration scheme is implicit. It is a backward-difference integration that uses a multivariable Newton-Raphson iteration for convergence at a time point. The reason for using this type of integration is that it is stable for both large and small step sizes. This is important when there is a large spread in eigenvalues for the system being simulated. Although only pressure-flow dynamics are being simulated, the addition of temperature dynamics may be desirable (ref. 2). This would add slow dynamics to the simulation. In that event, the implicit integration scheme will be available to handle the widespread dynamics while insuring stability.

To help in understanding how subroutine FOURW2 works, the following description is provided. Statement numbers corresponding to the FORTRAN listing are given in the flow chart.

Integration Scheme

The integration scheme is a backward-difference method that uses a multivariable Newton-Raphson iteration scheme for convergence. State variables are updated by using the old state vector $\mathbf{VS}_{\text{old}}$, the current error vector **E**, and the inverse of a Jacobian matrix **EMAT** (ref. 5).

$$\mathbf{VS}_{\text{new}} = -\mathbf{EMAT}^{-1} \times \mathbf{E} + \mathbf{VS}_{\text{old}} \qquad \text{(C1)}$$

EMAT is a Jacobian matrix of partial derivatives (i.e., changes in error variables with respect to changes in state variables):

$$\mathbf{EMAT(I,J)} = \mathbf{(E(J) - ERRBSE(J))/DELTAV(I)} \qquad \text{(C2)}$$

Updating takes place when the errors are converged within tolerance. With this technique, both steady-state and transient solutions can be obtained by changing the error variables. In steady state, all states are at rest; thus

$$\mathbf{VDOT} = \mathbf{0.0} = \mathbf{E} \qquad \text{(C3)}$$

For a transient case

$$\mathbf{VDOT} \times \text{DELT} - (\mathbf{VS}_{\text{new}} - \mathbf{VS}_{\text{old}}) = \mathbf{E} \qquad \text{(C4)}$$

Equations (C3) and (C4) are converged when all the elements of **E** are within a specified tolerance.

To use this method, a Jacobian matrix must be calculated (usually by finite differences) and then inverted. This is usually very time consuming. Therefore the logic in FOURW2 allows for calculation of a new matrix only under adverse conditions such as when the rate of convergence of the simulation is getting too slow (PCNCHG less than TOLPCG), or when the number of allowable passes (MPAS) has been exceeded.

Perturbation Calculation

There are several features in FOURW2 that help the implicit integration scheme converge. Of primary importance is the generation of a "good" Jacobian matrix. All the partial derivatives must be representative of the linear behavior of the system at a given operating point. Since finite differences are used, the sizes of the perturbations of the states are important. If they are too large, errors will be introduced by the system nonlinearities. If they are too small, the partials will be in error because of numerical problems (without double-precision arithmetic). Thus a tuning mechanism has been included in FOURW2 to optimize the sizes of the perturbations. First, the sum of squares of all the changes in the errors is calculated for each perturbation. Once this is done, the "goodness" of the partial is checked by calculating for each state variable

$$\text{XXX} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} [(\mathbf{E(I) - ERRBSE(I)}]^2} \qquad \text{(C5)}$$

and then checking if

$$\text{TOL1} \le \text{XXX} \le \text{TOL2} \qquad \text{(C6)}$$

If all XXX's fall within the tolerance band, the matrix is considered "good". For this simulation, TOL1 = 0.001 and TOL2 = 0.01. Since all the errors are scaled, this tolerance band lies between 0.1 and 1 percent. For a more linear system the band could be larger; for a more nonlinear system, smaller.

Scaling of Perturbations

In general, for the initial perturbations at a point, the XXX's will not fall within the tolerance band described above. Thus, FOURW2 scales the perturbations to try to force the XXX's within the band. This is done by calculating

$$YYY = REF/XXX \tag{C7}$$

for each state variable. REF is defined as being in the center of the tolerance band:

$$REF = (TOL1 + TOL2)/2.0 \tag{C8}$$

Once a set of YYY's has been calculated such that the XXX's fall within the band, the set of YYY's is stored. After this has been done for all N states, the scaling vector **YYY** is generated. When a new matrix is needed, the scaling vector **YYY** is applied to the current states to determine first guesses for the perturbations needed to obtain new partial derivatives. If for any state variable the new XXX falls outside the tolerance band, YYY is updated and the new result stored. This method generally reduces the number of passes required for subsequent matrix generation.

Error Messages

In generating a partial derivative a situation may arise where XXX never gets within tolerance. When this happens, the program prints out an error message "CHECK INPUT - BAD PARTIAL DERIVATIVE," prints out a debug output to help the user diagnose the problem, and then *stops* the simulation. This is the only time when the simulation is stopped except for the normal exit when ITRAN has been incremented to its maximum value (ITRMAX). In general, this problem will occur when coding is added to the simulation that is not consistent throughout the simulation. One example would be calculating a piston ring leakage flow from one working space but neglecting to add it to the adjacent working space.

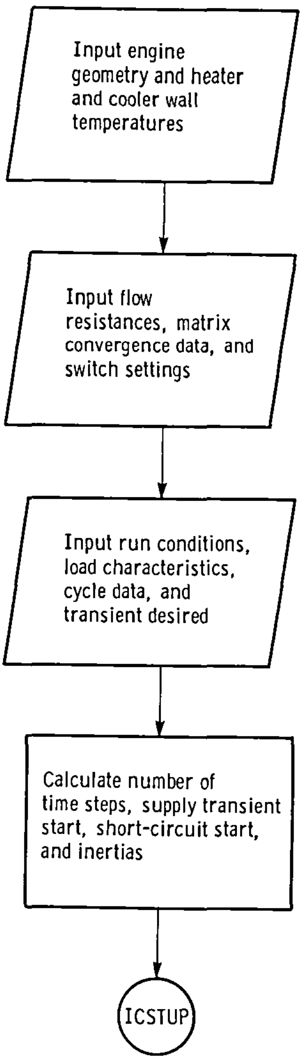
Broyden Update Algorithm

As stated earlier, it is time consuming to calculate a Jacobian matrix and even more time consuming to invert the matrix for a large system. Usually double precision is required (as in DMINV). Lack of speed in the inverse algorithm can be prohibitive, especially in a controls model, where long transients are usually needed to evaluate controls schemes. One possible means of avoiding this problem is to generate the inverse and then to update it continually with information gained as the inverse is used. This method is the Broyden update algorithm (ref. 6) and is found in subroutine BROYF1.

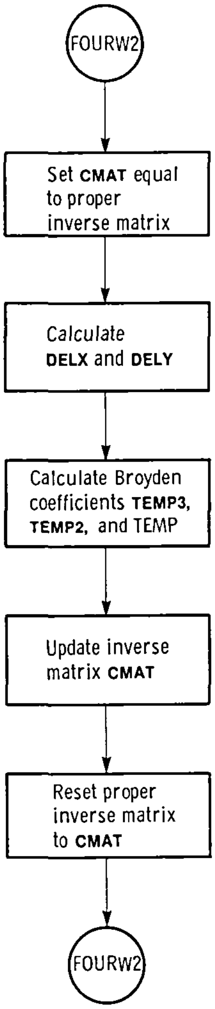
However, it should be noted that using the method is also time consuming and, for low-order systems, may not help much in reducing the computation time for the simulation even when using large time steps. Table XIX contains the matrix update strategy for the simulation. If the Broyden algorithm is not used, a new Jacobian is generated only when the convergence rate (PCNCHG) falls below 0.5. At values of PCNCHG above 0.5 the original inverse is used. When using the Broyden algorithm a new Jacobian matrix is calculated only when TOLPCG falls below 0.0 or when the algorithm has been called more than twice the order of the system plus one (2*N+1) times. Since it is time consuming to use the algorithm, the inverse is updated only when PCNCHG falls below 0.7. Above PCNCHG equal to 0.7 the inverse is not updated.

Even though the algorithm does not shorten computer time in the current simulation, it has been included in the program. If the energy equation is added to the volume dynamics or if a control system is added such that the number of states in the simulation increases significantly, the algorithm will prove much more useful.

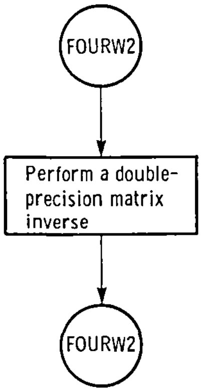
Main program MAINSE



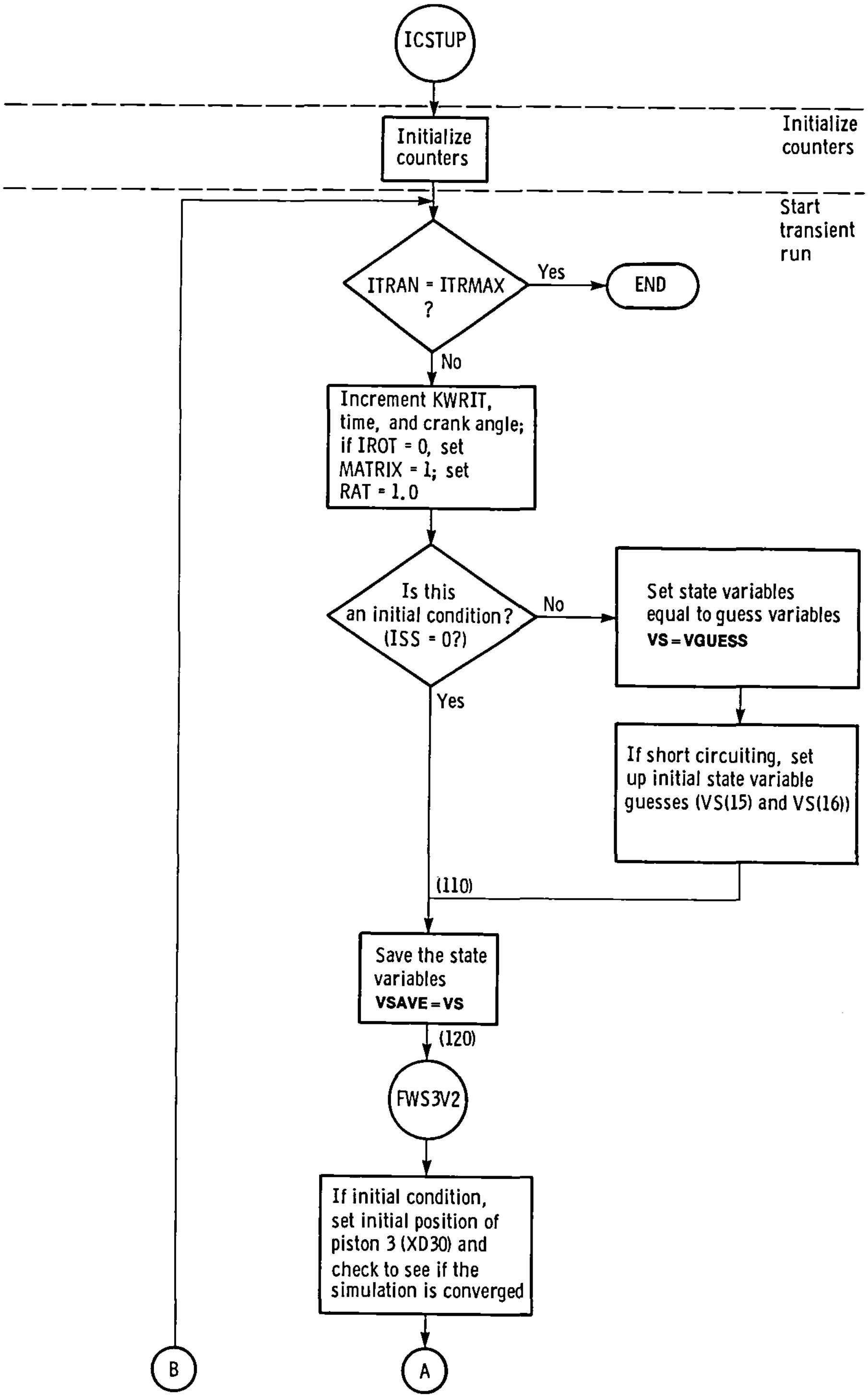
Subroutine BROYF1

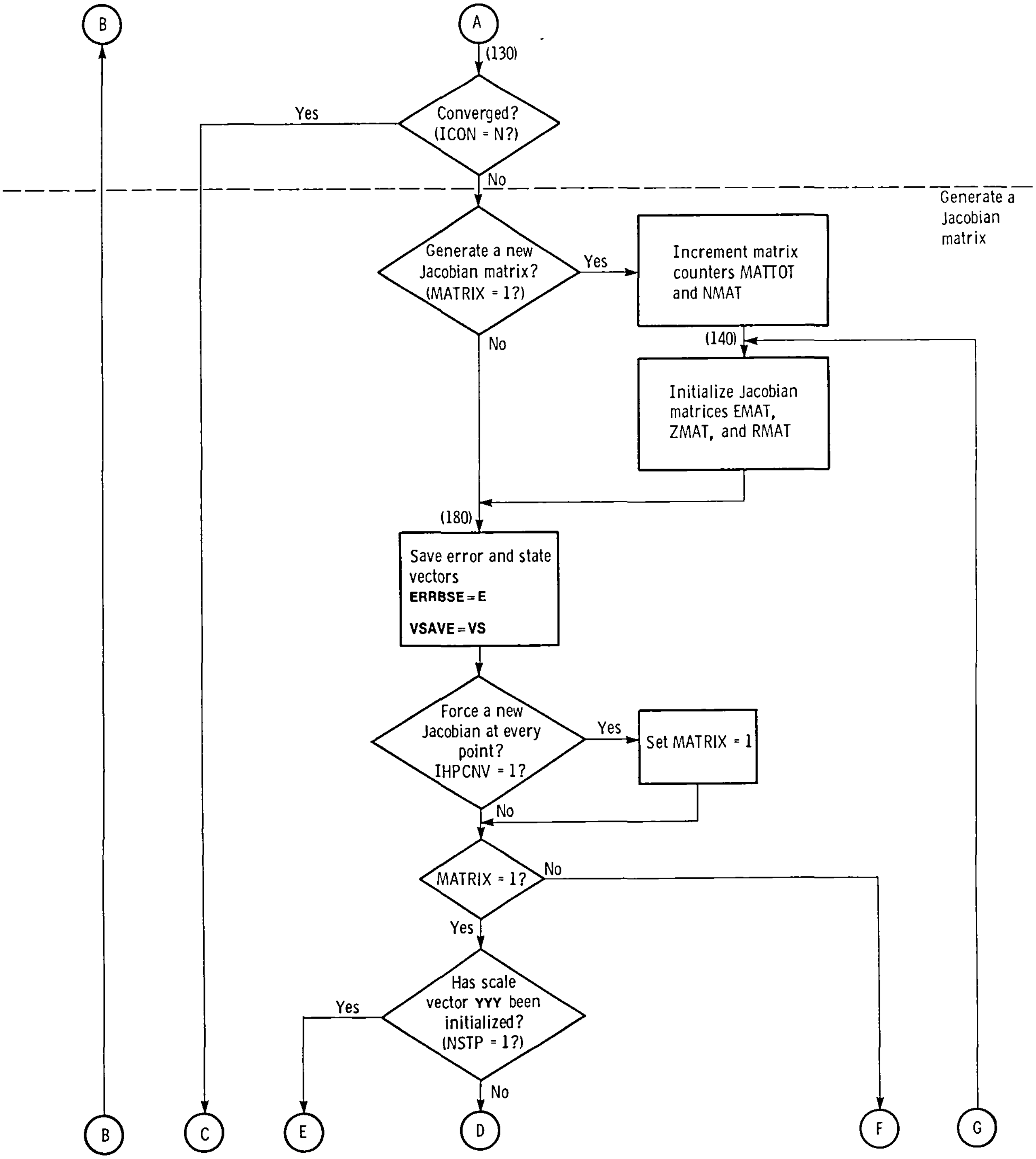


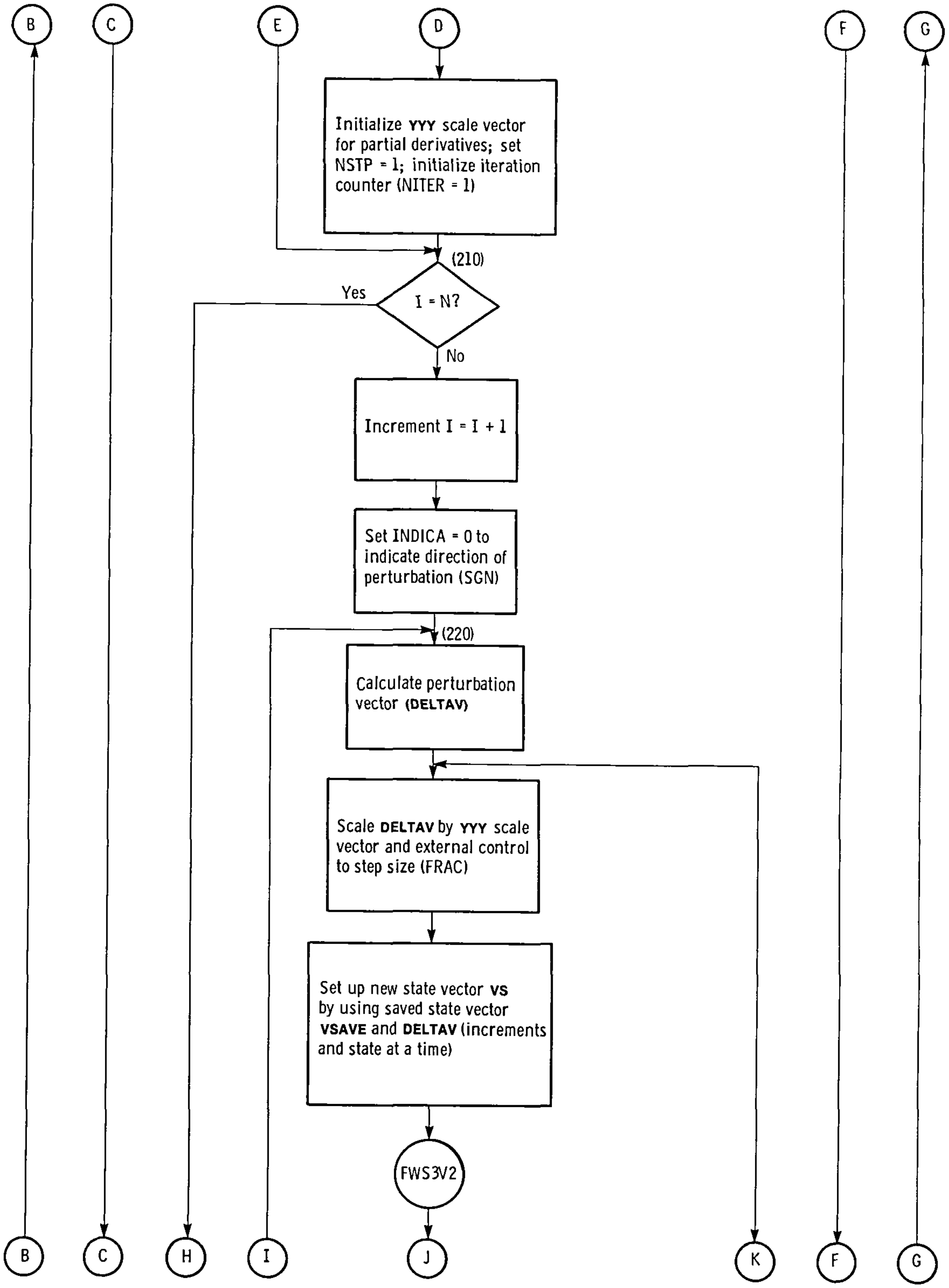
Subroutine DMINV

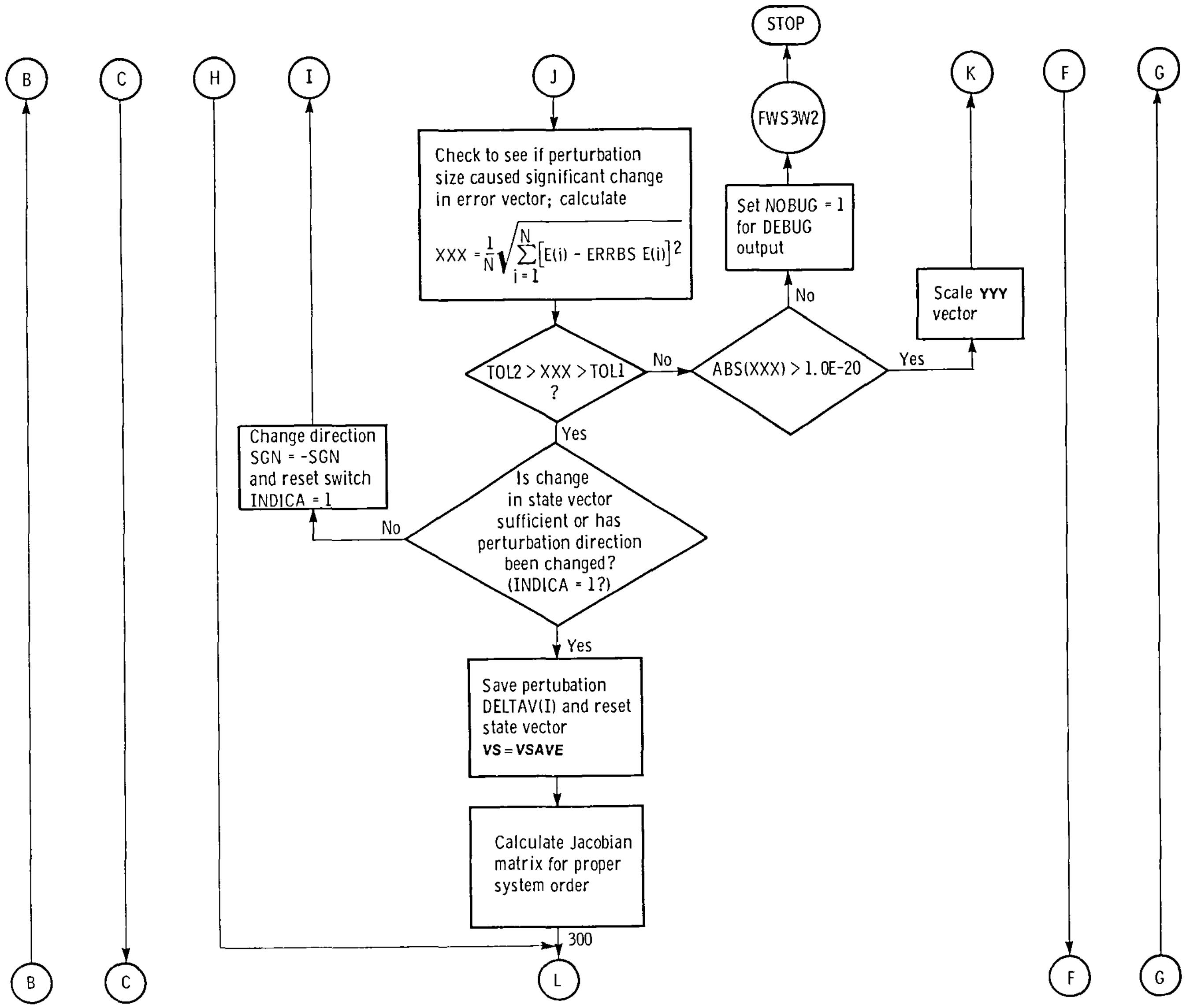


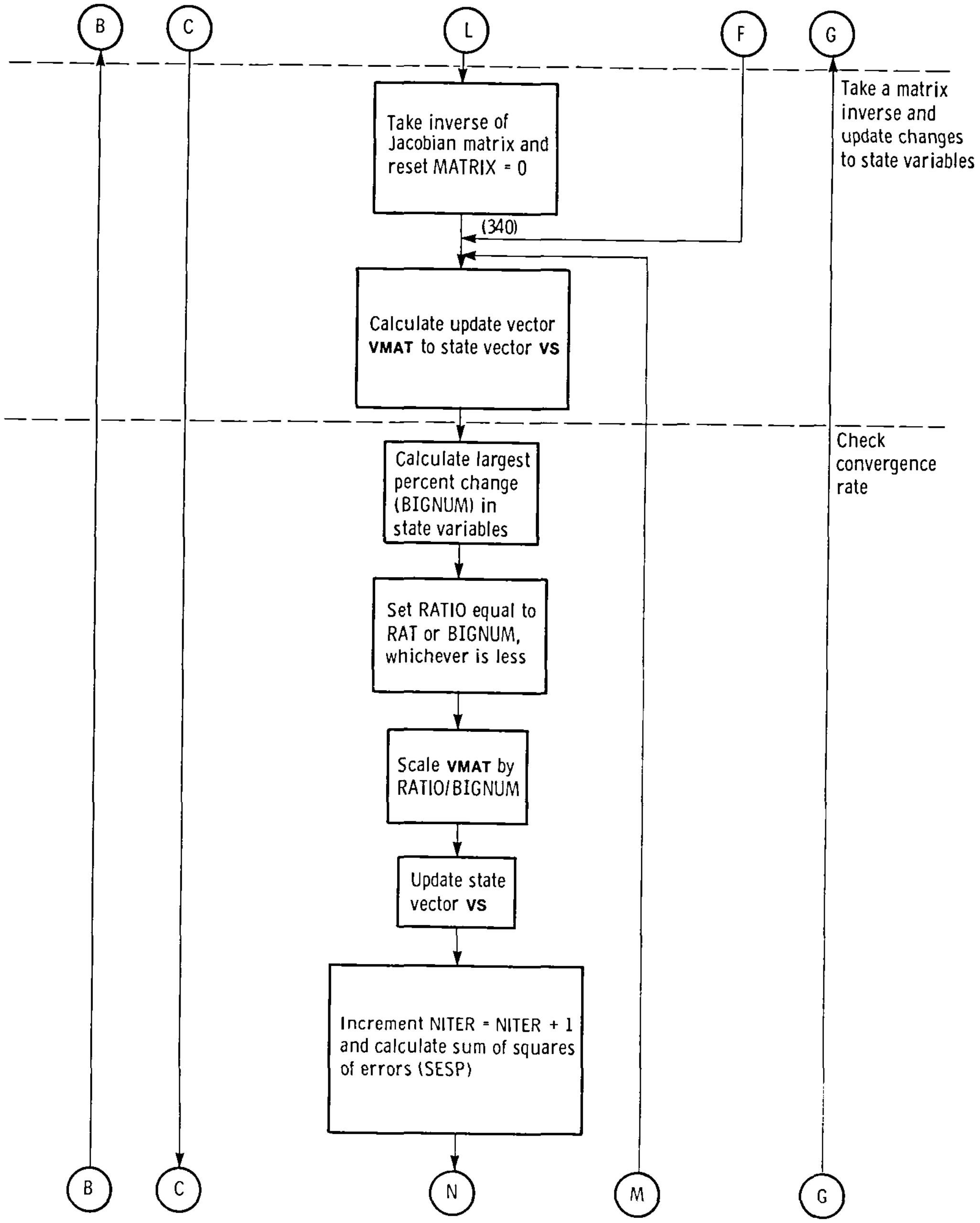
Subroutine FOURW2

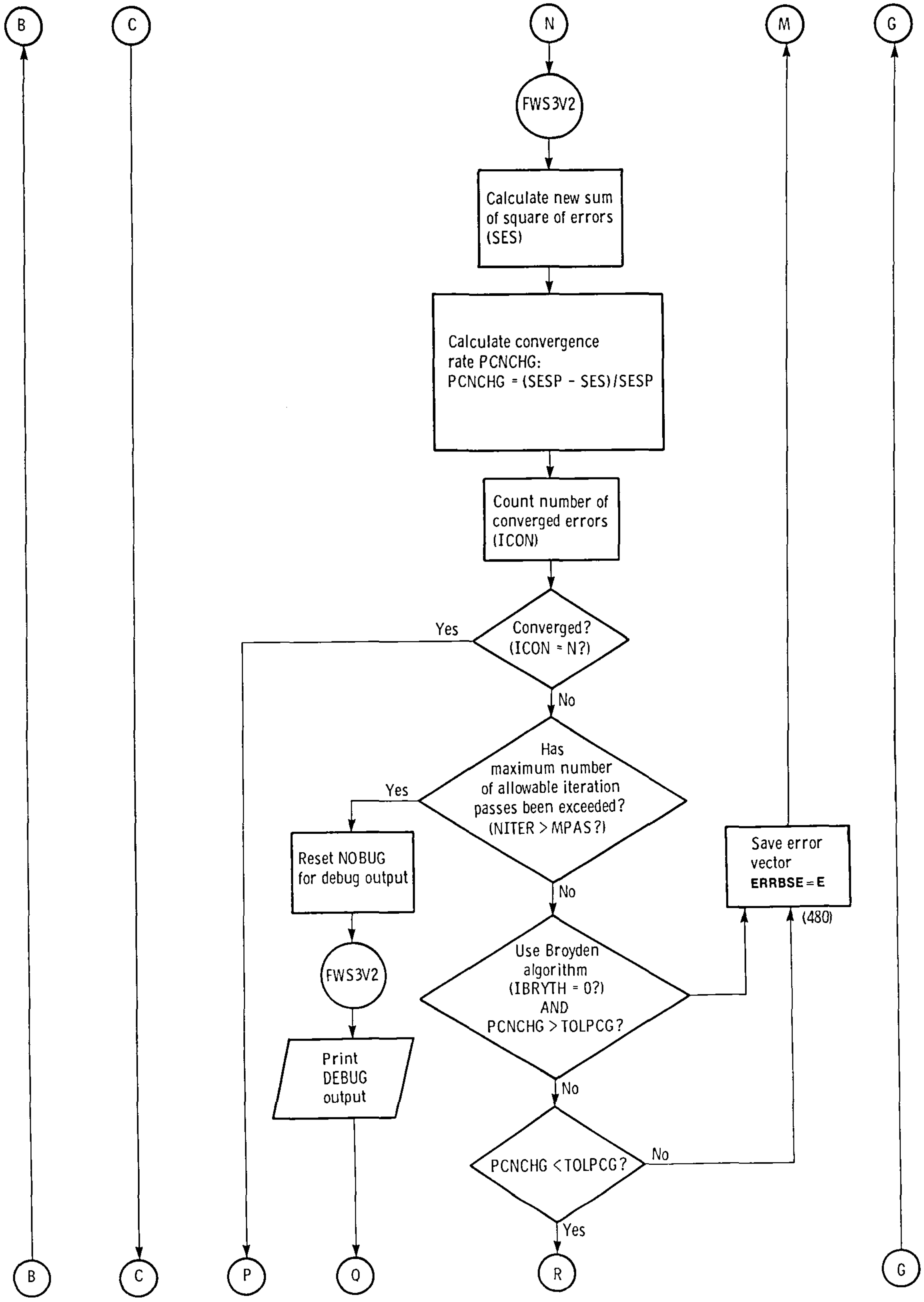


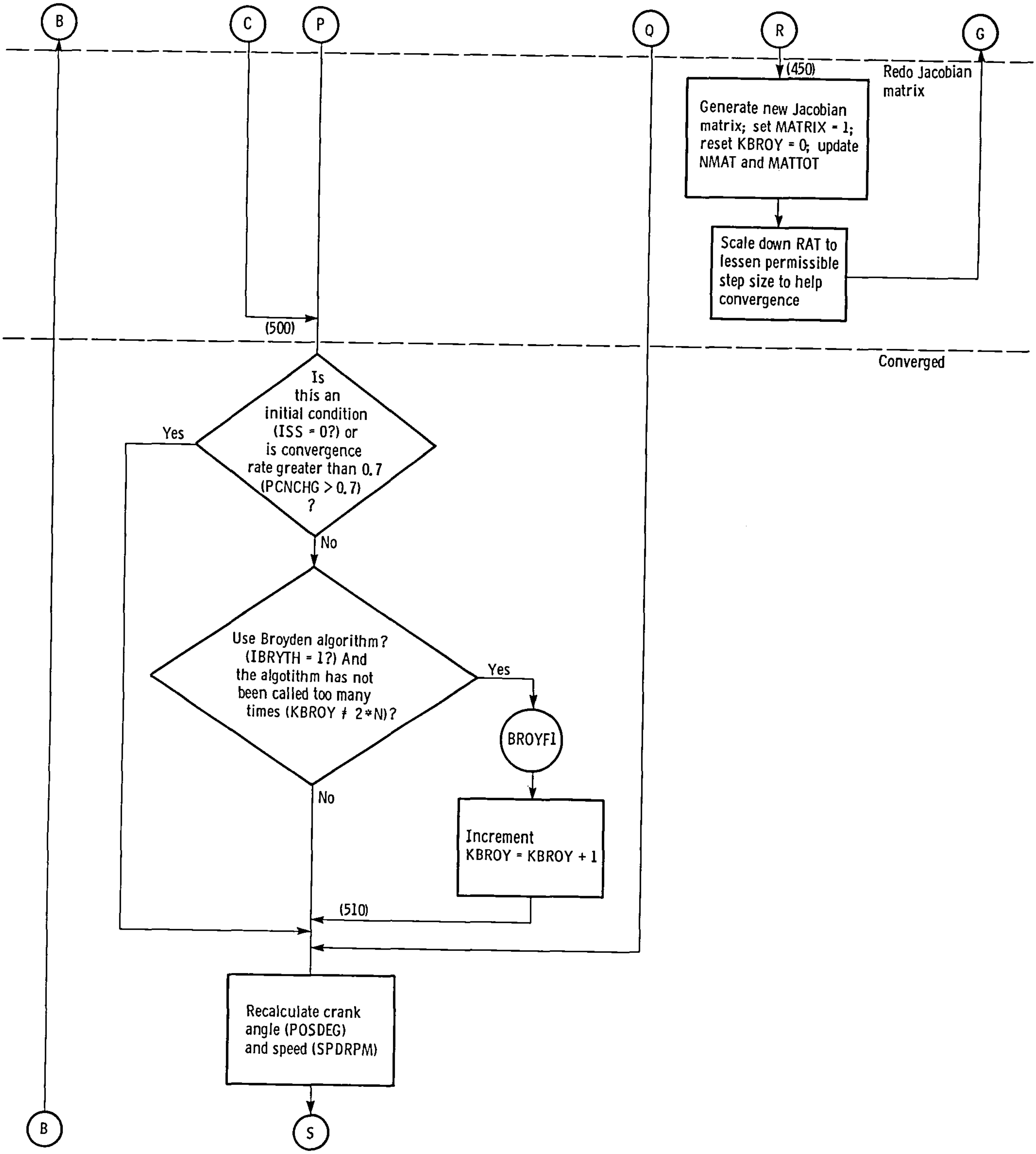

A
(130)
Converged? (ICON = N?)
Yes
No
Generate a Jacobian matrix
Generate a new Jacobian matrix? (MATRIX = 1?)
Yes
Increment matrix counters MATTOT and NMAT
No
(140)
Initialize Jacobian matrices EMAT, ZMAT, and RMAT
(180)
Save error and state vectors
ERRBSE = E
VSAVE = VS
Force a new Jacobian at every point? IHPCNV = 1?
Yes
Set MATRIX = 1
No
MATRIX = 1?
No
Yes
Has scale vector YYY been initialized? (NSTP = 1?)
Yes
No
B
B
C
E
D
F
G


B
C
E
D
F
G
Initialize YYY scale vector for partial derivatives; set NSTP = 1; initialize iteration counter (NITER = 1)
(210)
Yes
I = N?
No
Increment I = I + 1
Set INDICA = 0 to indicate direction of perturbation (SGN)
(220)
Calculate perturbation vector (DELTAV)
Scale DELTAV by YYY scale vector and external control to step size (FRAC)
Set up new state vector VS by using saved state vector VSAVE and DELTAV (increments and state at a time)
FWS3V2
B
C
H
I
J
K
F
G

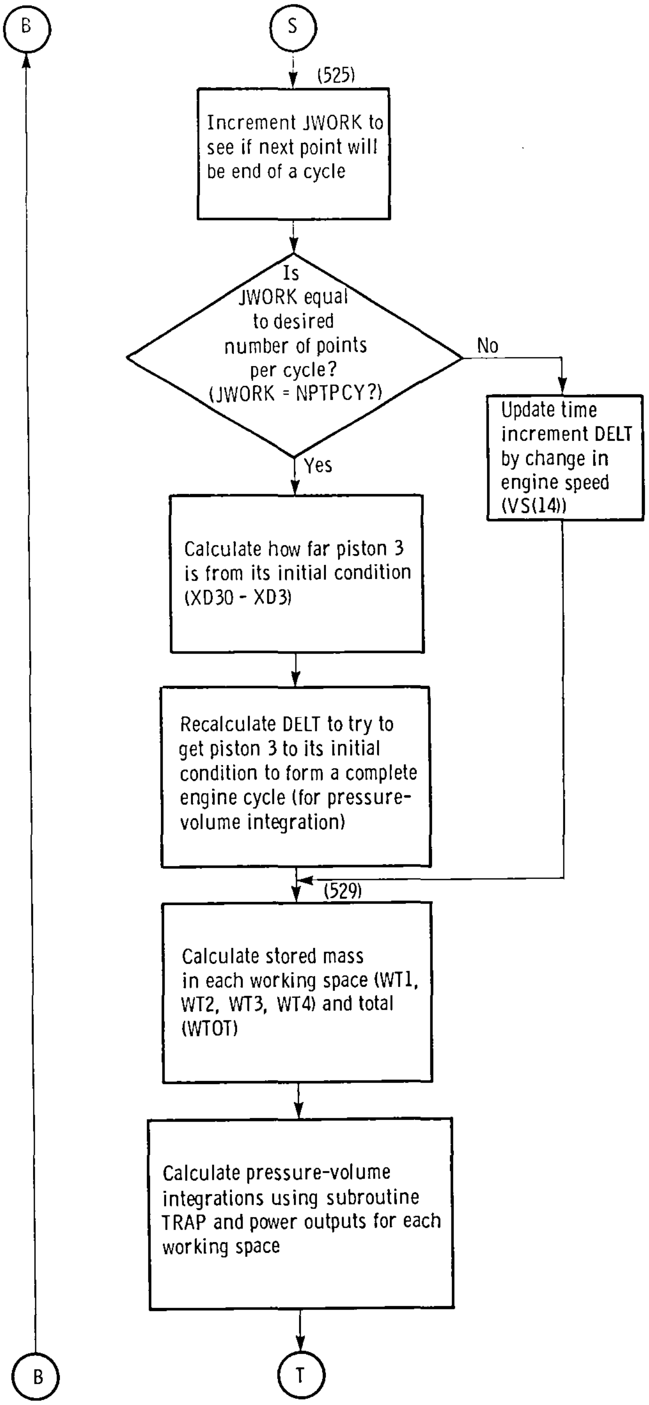

STOP
B
C
H
I
J
FWS3W2
K
F
G
Check to see if perturbation size caused significant change in error vector; calculate
$XXX = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left[E(i) - ERRBS\ E(i)\right]^2}$
Set NOBUG = 1 for DEBUG output
No
Scale YYY vector
TOL2 > XXX > TOL1 ?
No
ABS(XXX) > 1.0E-20
Yes
Yes
Change direction SGN = -SGN and reset switch INDICA = 1
No
Is change in state vector sufficient or has perturbation direction been changed? (INDICA = 1?)
Yes
Save pertubation DELTAV(I) and reset state vector VS = VSAVE
Calculate Jacobian matrix for proper system order
300
B
C
L
F
G

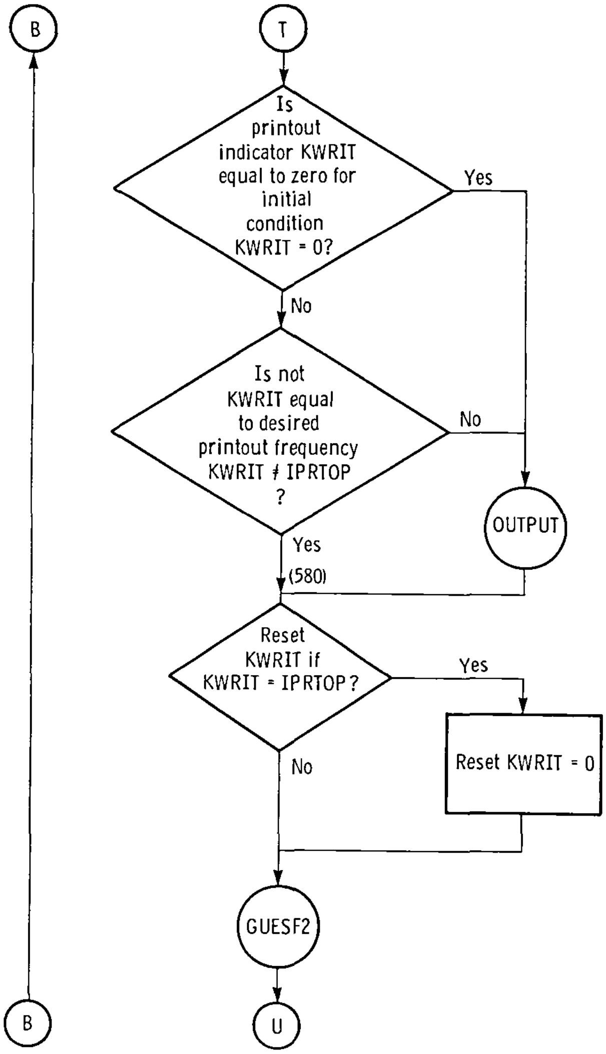

B
C
L
F
G
Take a matrix inverse and update changes to state variables
Take inverse of Jacobian matrix and reset MATRIX = 0
(340)
Calculate update vector **VMAT** to state vector **VS**
Check convergence rate
Calculate largest percent change (BIGNUM) in state variables
Set RATIO equal to RAT or BIGNUM, whichever is less
Scale **VMAT** by RATIO/BIGNUM
Update state vector **VS**
Increment NITER = NITER + 1 and calculate sum of squares of errors (SESP)
B
C
N
M
G

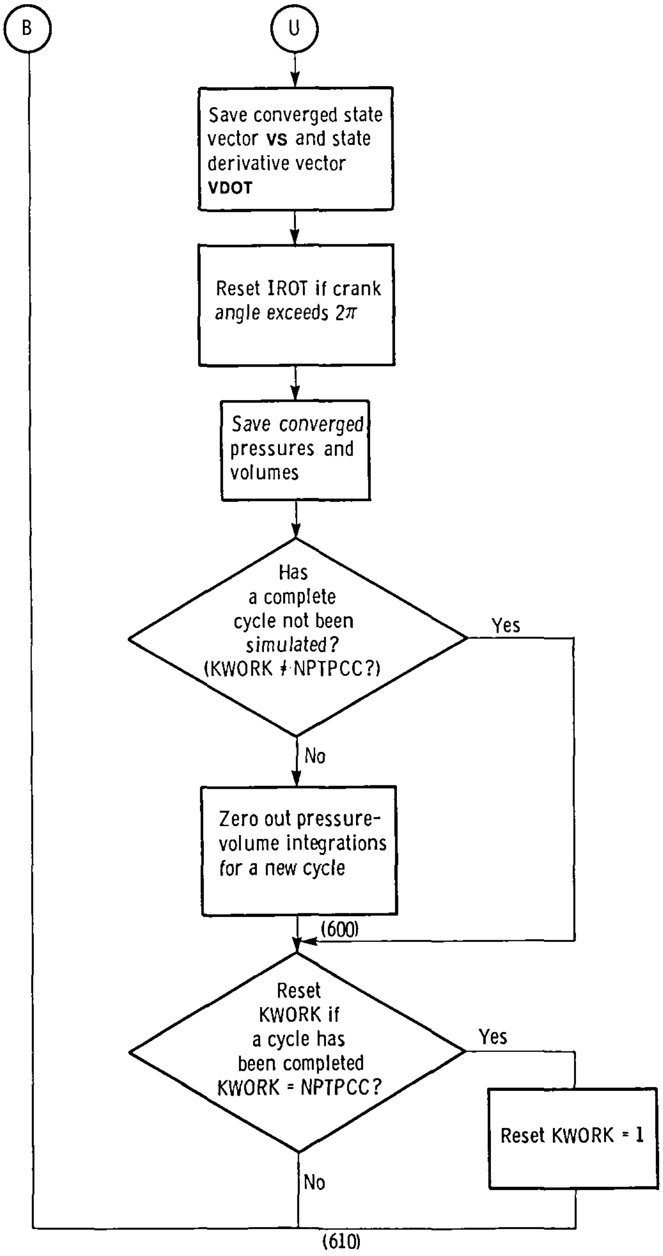

B
C
N
M
G
FWS3V2
Calculate new sum of square of errors (SES)
Calculate convergence rate PCNCHG:
PCNCHG = (SESP - SES)/SESP
Count number of converged errors (ICON)
Converged? (ICON = N?)
Yes
No
Has maximum number of allowable iteration passes been exceeded? (NITER > MPAS?)
Yes
Reset NOBUG for debug output
FWS3V2
Print DEBUG output
No
Use Broyden algorithm (IBRYTH = 0?) AND PCNCHG > TOLPCG?
Save error vector ERRBSE = E
(480)
No
PCNCHG < TOLPCG?
No
Yes
B
C
P
Q
R
G



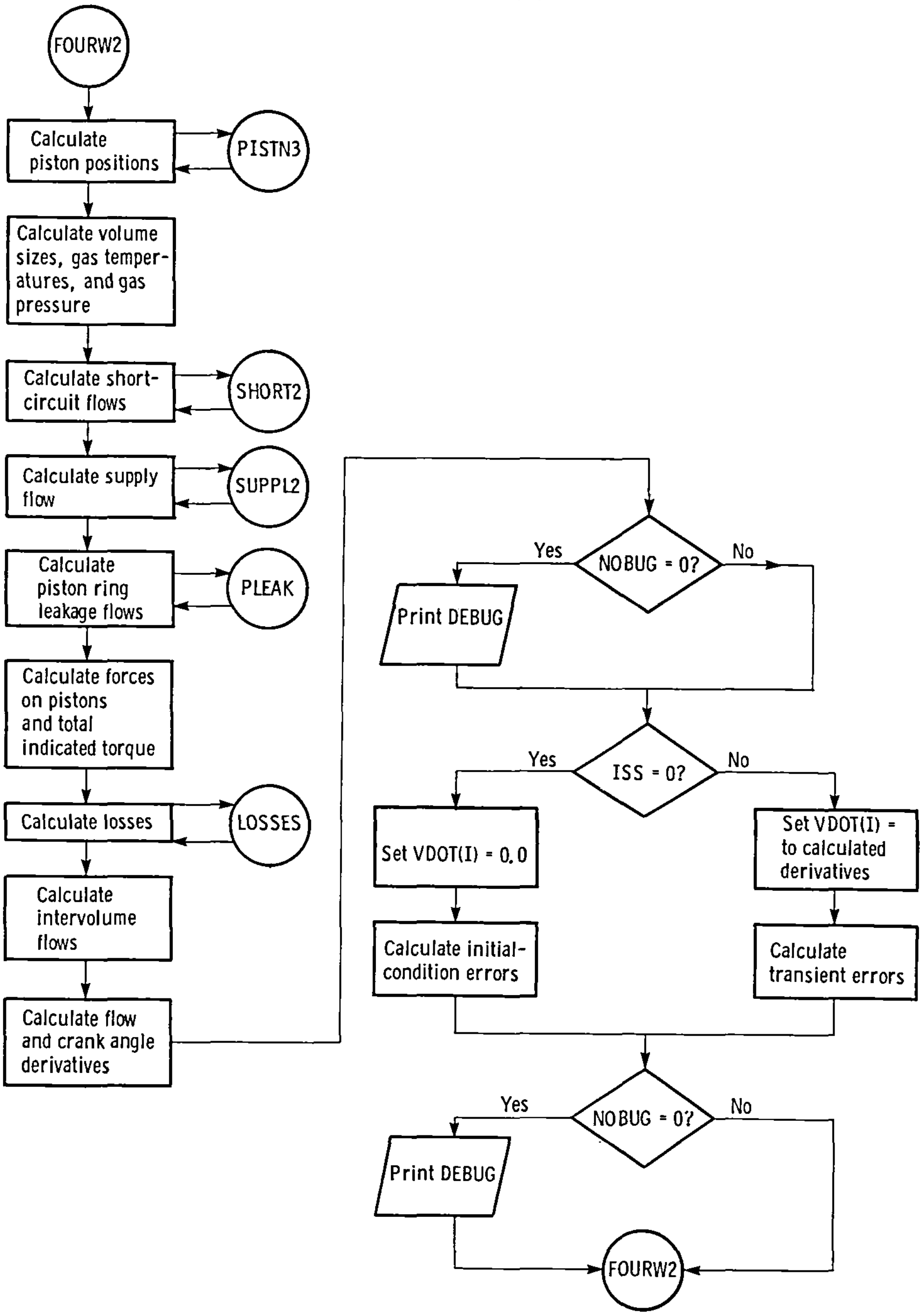
B
C
P
Q
R
G
(450)
Redo Jacobian matrix
Generate new Jacobian matrix; set MATRIX = 1; reset KBROY = 0; update NMAT and MATTOT
Scale down RAT to lessen permissible step size to help convergence
(500)
Converged
Is this an initial condition (ISS = 0?) or is convergence rate greater than 0.7 (PCNCHG > 0.7) ?
Yes
No
Use Broyden algorithm? (IBRYTH = 1?) And the algotithm has not been called too many times (KBROY ≠ 2*N)?
Yes
BROYF1
No
Increment KBROY = KBROY + 1
(510)
Recalculate crank angle (POSDEG) and speed (SPDRPM)
B
S


B
S
(525)
Increment JWORK to see if next point will be end of a cycle
Is JWORK equal to desired number of points per cycle? (JWORK = NPTPCY?)
No
Update time increment DELT by change in engine speed (VS(14))
Yes
Calculate how far piston 3 is from its initial condition (XD30 - XD3)
Recalculate DELT to try to get piston 3 to its initial condition to form a complete engine cycle (for pressure-volume integration)
(529)
Calculate stored mass in each working space (WT1, WT2, WT3, WT4) and total (WTOT)
Calculate pressure-volume integrations using subroutine TRAP and power outputs for each working space
B
T

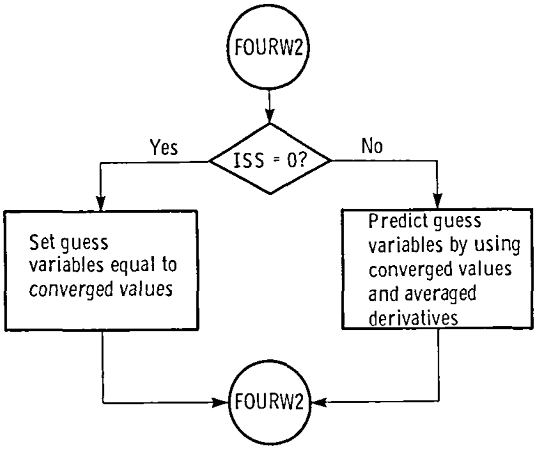

B
T
Is printout indicator KWRIT equal to zero for initial condition KWRIT = 0?
Yes
No
Is not KWRIT equal to desired printout frequency KWRIT ≠ IPRTOP ?
No
OUTPUT
Yes
(580)
Reset KWRIT if KWRIT = IPRTOP?
Yes
Reset KWRIT = 0
No
GUESF2
B
U


B
U
Save converged state vector **VS** and state derivative vector **VDOT**
Reset IROT if crank angle exceeds 2π
Save converged pressures and volumes
Has a complete cycle not been simulated? (KWORK ≠ NPTPCC?)
Yes
No
Zero out pressure-volume integrations for a new cycle
(600)
Reset KWORK if a cycle has been completed KWORK = NPTPCC?
Yes
Reset KWORK = 1
No
(610)

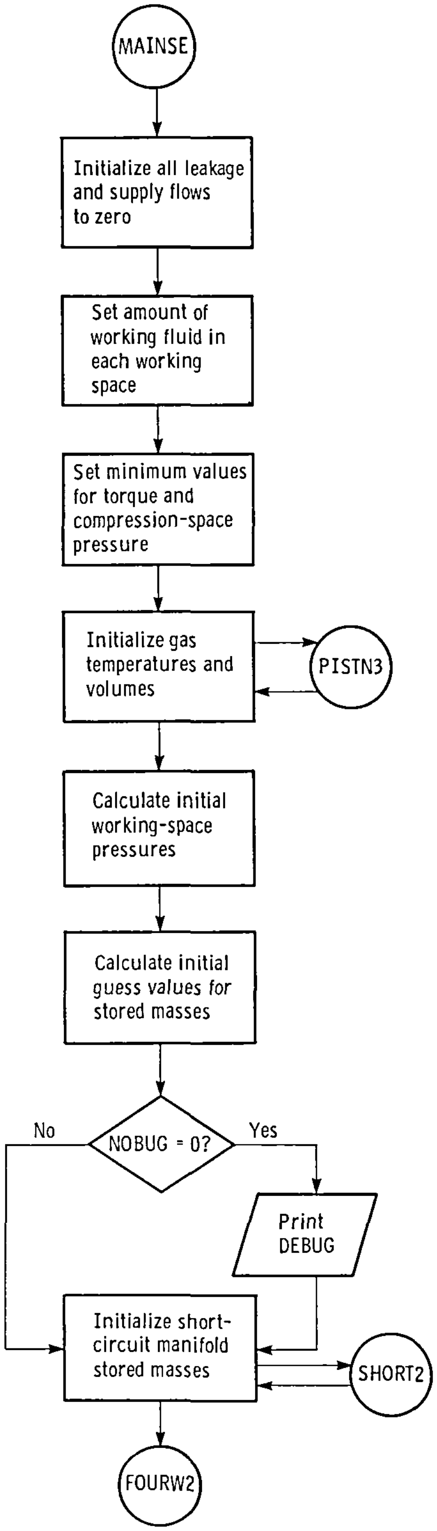
Subroutine FWS3V2



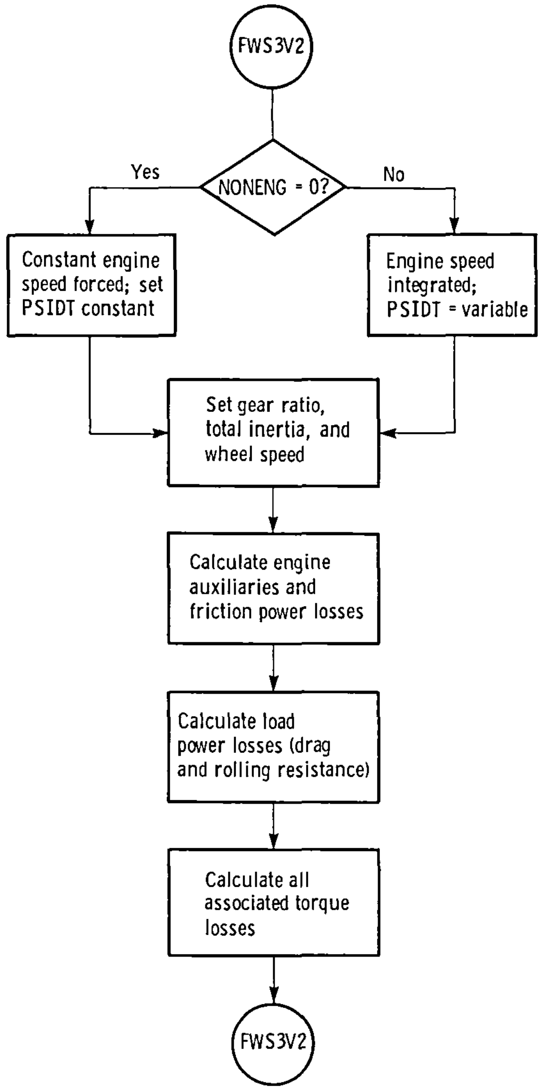
Subroutine GUESF2



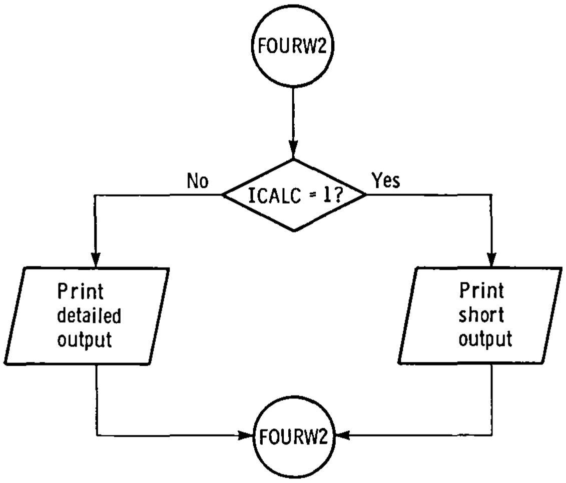
Subroutine ICSTUP



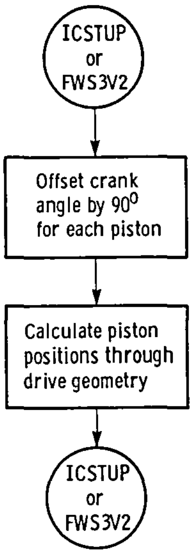
Subroutine LOSSES



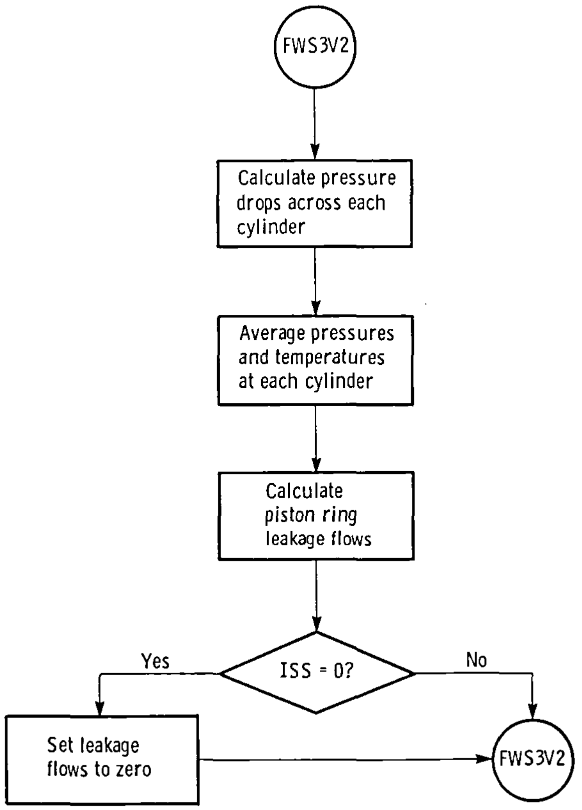
Subroutine OUTPUT

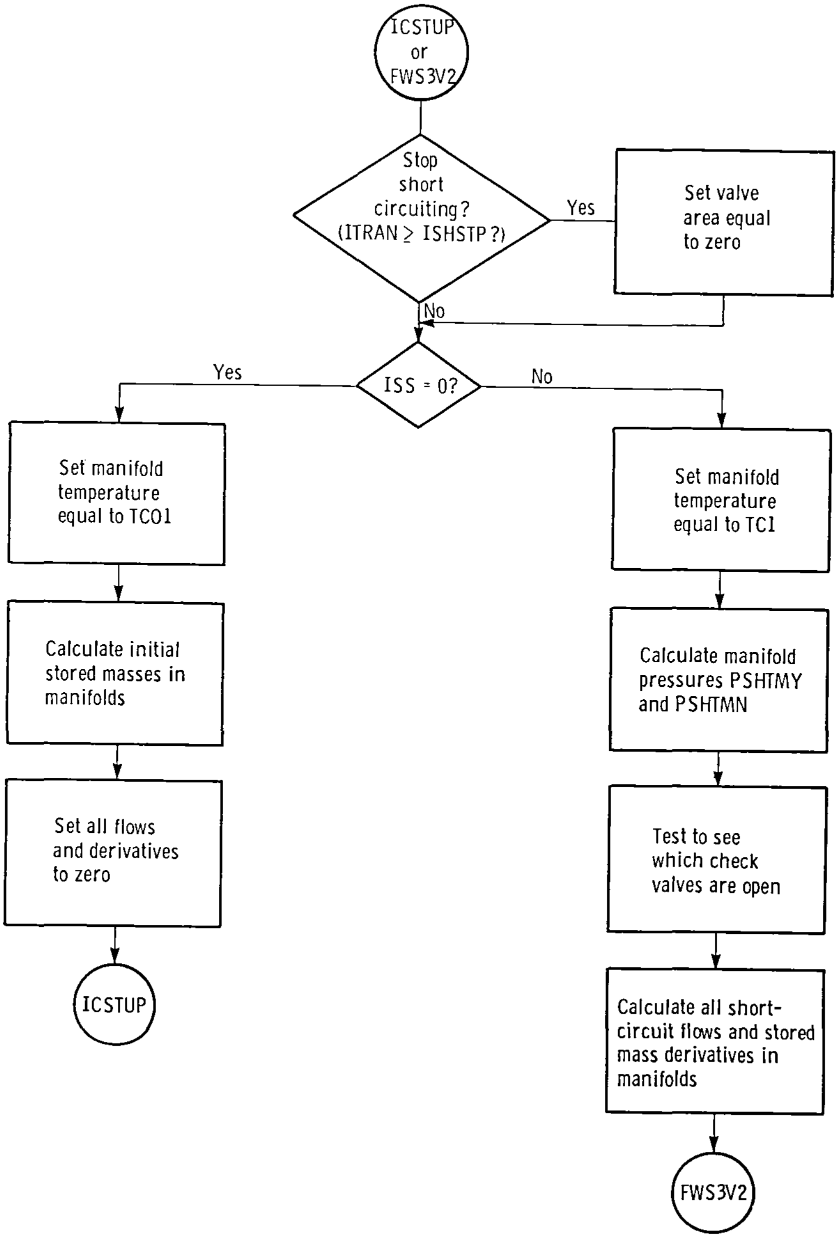


Subroutine PISTN3

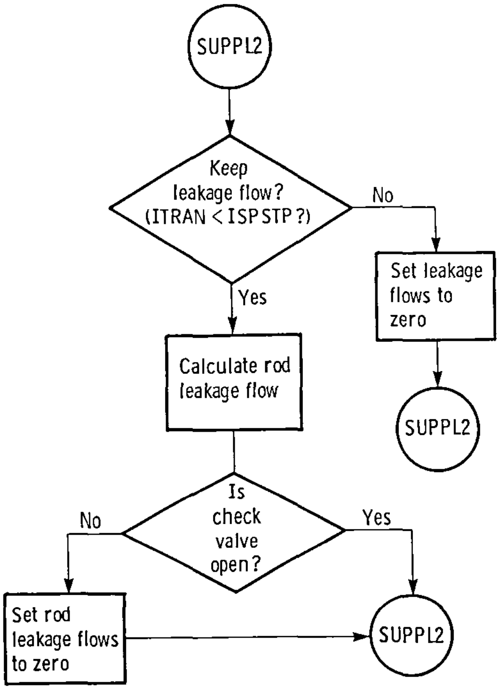


Subroutine PLEAK2

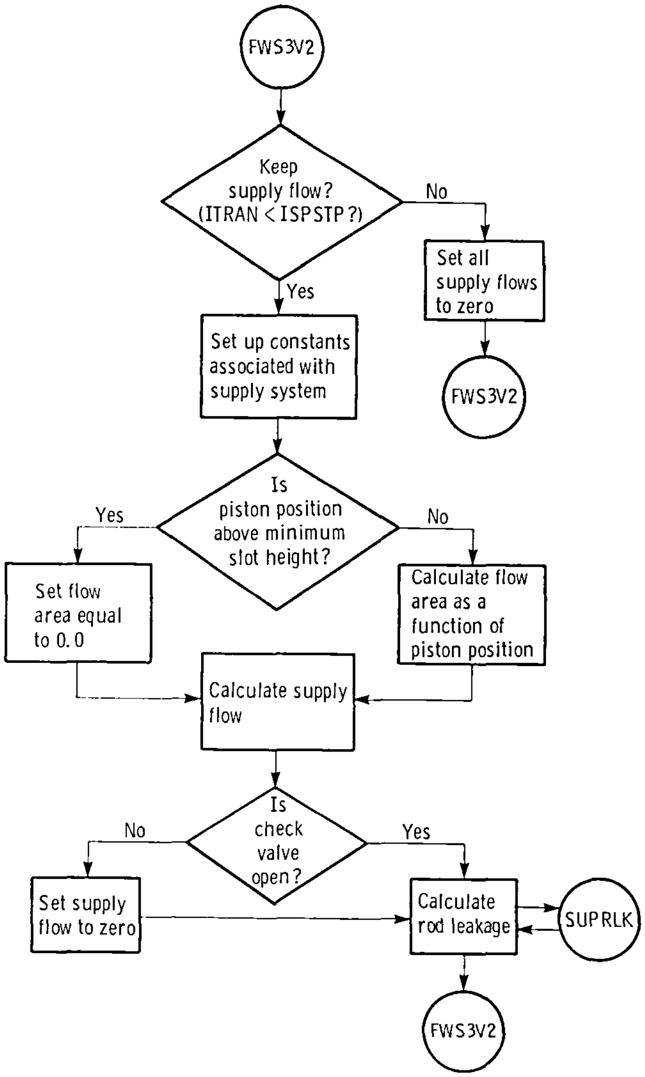



Subroutine SHORT2

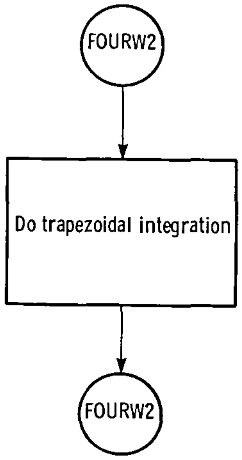
Subroutine SUPLRK



Subroutine SUPPL2



Subroutine TRAP



Appendix D
Steady-State Results

Steady-state results using the simulation are presented in figures 10 to 13. These results are presented here to help the user understand the mode of program operation.

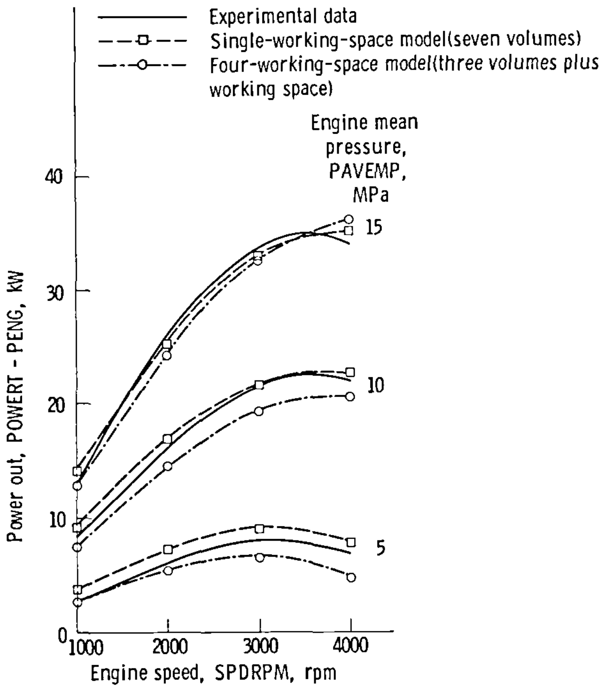


Figure 10. - Net power as a function of speed for single- and four-working-space models and engine data.

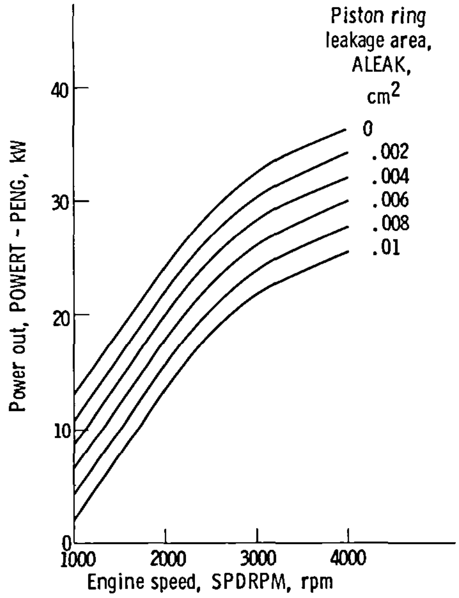


Figure 11. - Net power as a function of speed for various piston ring leakage areas. Engine mean pressure, PAVEMP, 15 MPa.

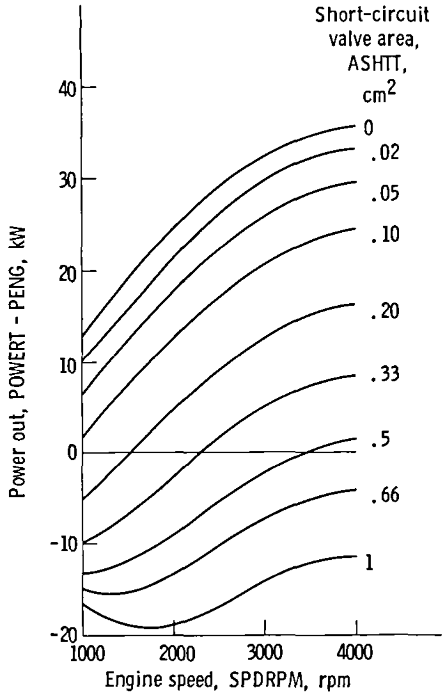


Figure 12. - Net power as a function of engine speed for various short-circuit valve areas. Engine mean pressure, PAVEMP, 15 MPa.

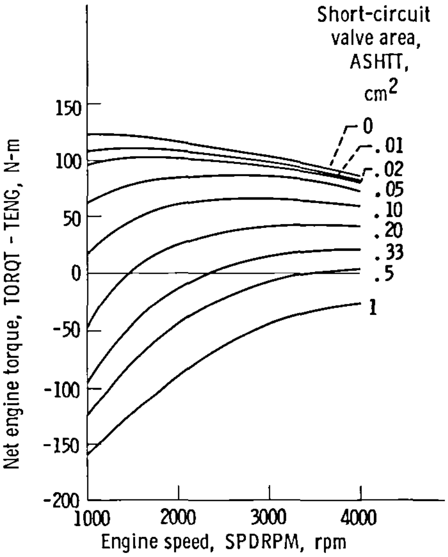


Figure 13. - Net torque as a function of engine speed for various short-circuit valve areas. Engine mean pressure, PAVEMP, 15 MPa.

The term "steady state" for a Stirling engine actually refers to a transient run in which the engine is simulated over many cycles at constant input conditions (constant heater and cooler wall temperatures and constant speed; i.e., no supply fluid). Figures 10 to 13 were also presented in reference 2. All steady-state cases were run by forcing piston position as a function of time (NONENG = 0).

Figure 10 shows a comparison of results from the simplified four-cylinder Stirling engine controls model with results from the seven-volume, single-working-space model (which includes the energy equation). Also shown are experimental data run at Lewis. The simulation data were obtained by setting constant engine mean pressure (CYCLPR = 5., 10., or 15. MPa) and constant engine speed (SPDRPM = 1000., 2000., 3000., or 4000. rpm). After steady state was reached, cycle data were recorded. Figure 10 shows that the simplified model agrees well with the experimental data over the ranges of engine speed and mean pressure.

Steady-state power versus engine speed at different piston ring leakage areas is given in figure 11. To obtain these data, mean pressure was held constant at 15 MPa (CYCLPR = 15.0), while speed and leakage area were varied (SPDRPM = 1000., 2000., 3000., and 4000. and ALEAK = 0.0, 0.002, 0.004, 0.006, 0.008, and 0.010, respectively). As expected, performance degrades as leakage area increases. However, power loss due to leakage seems to be independent of speed.

Net power versus speed for different short-circuit valve areas is shown in figure 12. These curves were generated by setting engine mean pressure constant (CYCLPR = 15.0) and varying engine speed (SPDRPM) and short-circuit valve area (ASHTT). Note the large drop in engine power with short circuiting. The corresponding torque curve is given in figure 13. Torque reversal occurs for leakage areas above 0.1.

Appendix E
Transient Results

For controls analysis, transient data over a number of engine cycles are of interest. To obtain these data, the simulation calculates each cycle individually. Thus the simulation can also be used to obtain information regarding engine parameters during a single cycle. Data on an individual cycle basis were presented in reference 4. Data are presented herein to help the user understand how to obtain transient information.

A working-fluid supply transient for six cycles is shown in figure 14. Because for this case speed must change, the simulation must be run with the drive dynamics (NONENG = 1). The initial engine pressure is 5 MPa (CYCLPR = 5.0); the source pressure for the working fluid is 13.8 MPa (PSOURC = 13.8); the supply is started at the second engine cycle (NCYSUP = 2); there is no rod leakage (ARLEAK = 0.0). To get the desired printout, set IPRTOP equal to 1; this gives a printout at every point during the cycle (NPTPCY = 100).

The same transient with piston rod leakage is shown in figure 15. In this case, all the input data are the same except ARLEAK = 0.5. Note that the transient results for the two cases are markedly different.

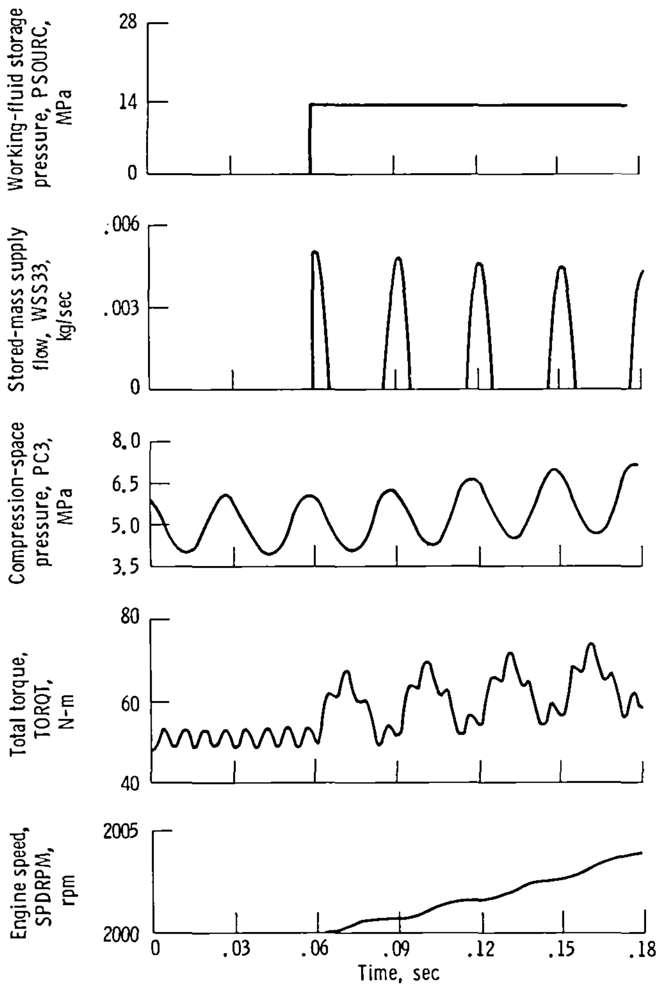


Figure 14. - Working-fluid supply transient with no piston rod leakage. Working-fluid storage pressure, PSOURC, 13.8 MPa at 0.06 sec.

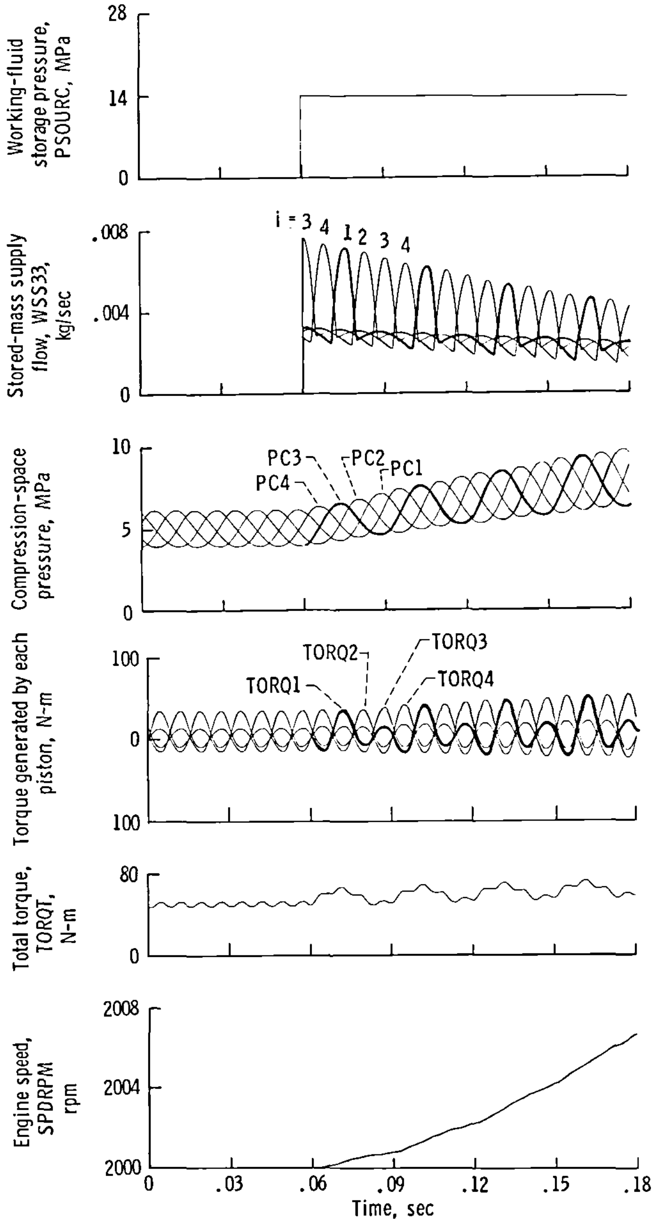


Figure 15. - Working-fluid supply transient with uniform piston rod leakage. Piston rod leakage area, ARLEAK, 0.5 cm^2; working-fluid storage pressure, PSOURC, 13.8 MPa at 0.06 sec.

References

1. Tew, R. C.; Jefferies, K.; and Miao, D.: A Stirling Engine Computer Model for Performance Calculations. DOE/NASA/1011-78/24, NASA TM-78884, 1978.
2. Daniele, Carl J.; and Lorenzo, Carl F. : Preliminary Results from a Four Working Space, Double-Acting Piston, Stirling Engine Controls Model. DOE/NASA/1040-17, NASA TM-81569, 1980.
3. Roache, Patrick J. : Computational Fluid Dynamics. Hermosa Publishers, 1972, pp. 64-67.
4. Lorenzo, Carl F.; and Daniele, Carl J.: A Four Cylinder Stirling Engine Controls Model. DOE/NASA/51040-21, NASA TM-81648, 1980.
5. Carnahan, B.; Luther, H. A.; and Wilkes, J: Applied Numerical Methods. John Wiley & Sons, Inc., 1969, pp. 319-320.
6. Broyden, C. G.: Quasi-Newton Methods and Their Applications to Function Minimization. Mathematics of Computation, vol. 21, July 1967, pp. 368-381.

TABLE I. - SIMULATION INPUT: ENGINE GEOMETRY

Name	Setting	Function
AD	23.7613	Piston area
AR	1.1290	Piston rod area
RODL	10.0	Crank rod length
VR	115.339	Regenerator volume
VOE	63.87	Expansion-space dead volume
VOC	61.70	Compression-space dead volume
STROKE	4.0	Piston stroke
ALPHA	90.0	Crank angle lag

TABLE II. - SIMULATION INPUT: HEATER AND COOLER WALL TEMPERATURES

Name	Setting	Function
TWHIN	705.0	Heater wall temperature
TWCIN	86.0	Cooler wall temperature

TABLE III. - SIMULATION INPUT: FLOW RESISTANCES

Name	Setting	Function
RER	1.9	Resistance between expansion space and regenerator
RRC	1.9	Resistance between regenerator and compression space

TABLE IV. - SIMULATION INPUT: CONSTANTS

Name	Setting	Function
DEGR	57.296	Degrees to radians
PIE	3.1416	----------------------
R	4125.6	Gas constant
G	10017.0	Gravitational constant

TABLE V. - SIMULATION INPUT: MATRIX CONVERGENCE

Name	Setting	Function
VDELTA	0.01	Initial perturbation of guesses, 1 percent
FRAC	1.0	External control of iteration step magnitude
TOL1	0.001	Bottom limit on error tolerance for matrix linearity
TOL2	0.01	Top limit on error tolerance for matrix linearity
TOLSS	0.0001	Solution tolerance
N	12	System order when NONENG = 0
	14	System order when NONENG = 1
NTMAX	16	Largest system order (when short circuiting)
MPAS	20	Maximum allowable convergence passes
TOLPCG	0.5	Switch for calculating new matrix

TABLE VI. - SIMULATION INPUT: SWITCHES

Name	Setting	Function
ISS	0	Set up initial conditions
	1	Transient (set internally)
ICALC	0	Detailed printout
	1	Short printout
MATRIX	1	Generate a new Jacobian matrix
NONENG	0	Force crank angle as a function of time
	1	Runs with drive dynamics in
IPRTOP	NN	Print out data every NN points
IBRYTH	0	Do not use Broyden algorithm
	1	Use Broyden algorithm
IHPCNV	0	Use logic to generate a new matrix
	1	Generate a new matrix at every point
NOBUG	0	No debug output[a]
	1	Desire debug output

[a] If iteration convergence fails or matrix generation problems occur, a debug output is given.

TABLE VII. - SIMULATION INPUT: RUN CONDITIONS

Name	Setting	Function
ALEAK	0.0	Piston ring leakage area scalar
ARLEAK	0.0	Piston rod leakage area
PSOURC	10.0	Hydrogen bottle pressure
CYCLPM	15.0	Maximum engine pressure
SPDMAX	4000.0	Maximum engine speed
CYCLPR	5.0	Initial engine pressure
POSDEO	270.0	Initial crank angle
WSTOTL	0.007786	Total stored mass at 15 MPa
VSH	32.78	Short-circuit volume
RSHT	38.0	Flow resistance between plenums and compression spaces
ASHTT	0.2	Short-circuit valve area

TABLE VIII. - SIMULATION INPUT: LOAD CHARACTERISTICS

[Vehicle information values given in this report are representative and do not correspond to any actual vehicle.]

Name	Setting	Function
GTRAN	1.0/2.53	Transmission gear ratio
GR	1.5	Gear ratio
WTENG	0.0	Engine mass
WTWHEL	20.48	Mass of a wheel
WTCAR	1420.0	Car mass
RWHEEL	30.48	Wheel radius

TABLE IX. - SIMULATION INPUT: CYCLE DATA

Name	Setting	Function
NUMBCY	100	Desired number of cycles
NPTPCY	100	Integration points per cycle

TABLE X. - SIMULATION INPUT: TRANSIENT DESIRED

Name	Setting	Function
NCYSHT	5	Start of short circuit at fifth cycle
NCYSUP	[a]15000	Start of supply at 15 000th cycle
NCYSTP	[a]40000	End of supply at 40 000th cycle
NCYSHS	500	End of short circuiting at 500th cycle

[a] Note that if no supply (or short-circuiting) is desired, set the corresponding start and end parameters very large (greater than the number of cycles desired).

TABLE XI. - COMMON BLOCK LOCATIONS

Common block	Subroutine														
	MAINSE	BROYF1	DMINV	FOURW2	FWS3V2	GUESF2	ICSTUP	LOSSES	OUTPUT	PISTN3	PLEAK2	SHORT2	SUPLRK	SUPPL2	TRAP
ANGLS				X	X		X		X	X			X	X	
CARLOD	X				X			X							
CONST	X			X	X		X	X			X	X			
CYDATA	X			X			X		X						
DERIVT					X				X						
ITCONV		X		X	X	X	X	X	X	X		X			
MATRX		X		X											
MATXIN	X	X		X	X	X	X								
OUTPT	X			X	X		X	X				X	X	X	
PCBARR				X	X		X								
PLEKS					X		X				X				
PST	X			X	X		X		X	X	X			X	
RUNCON	X			X	X		X	X	X		X		X	X	
SAVIT				X	X	X			X						
SHRTCT	X			X	X		X		X			X			
STEPIT				X	X		X	X				X			
STRIC				X	X		X		X		X	X	X	X	
SUPLY					X		X		X				X	X	
SWITCH	X	X		X	X	X	X	X	X			X			
TEMPS					X				X		X	X			
TORSUM				X	X		X	X	X						
TRANDS	X			X	X		X					X	X	X	
VOLS				X					X						

TABLE XII. - SAMPLE OUTPUT FOR SHORT PRINTOUT OPTION (ICALC = 1)

```
   RUN CONDITIONS FOR THIS TRANSIENT
TWH =    978.0           TWC =    359.0          CYCLPR =   5.000          NONENG =           1     NUMBCY =       1000
ALEAK =   0.0000         ARLEAK =   0.0000       PSOURC =   10.00          ISUPST =         251     ISHTST =    2500001

TIME        POWERT      PFRICT      PAUX        PRRF        PDRAG       PLOAD       PENG        PNET        ITRAN       PAVEMP
POSDEG      TORQT       TFRICT      TAUX        TRRF        TDRAG       TLOAD       TENG        TNET        KWORK       SPDRPM   VKPH
```

TABLE XIII. - SAMPLE OUTPUT FOR DETAILED PRINTOUT OPTION (ICALC = 0)

```
STIRLING ENGINE FOUR CYLINDER, THREE VOLUMES PER CYLINDER, CONTROLS MODEL

   RUN CONDITIONS FOR THIS TRANSIENT
TWH =   978.0         TWC =   359.0         CYCLPR =   5.000         NONENG =           1     NUMBCY =           1
ALEAK =  0.0000       ARLEAK =  0.0000      PSOURC =   10.00         ISUPST =         501     ISHTST =     5000001

TIME       XD1        XD2        XD3        XD4        POSDEG     SPDRPM     PAVEMP     WTOT       DELT       ITRAN
           PE1        PR1        PC1        TE1        TR1        TC1        VE1        VR1        VC1        WT1
           PE2        PR2        PC2        TE2        TR2        TC2        VE2        VR2        VC2        WT2
           PE3        PR3        PC3        TE3        TR3        TC3        VE3        VR3        VC3        WT3
           PE4        PR4        PC4        TE4        TR4        TC4        VE4        VR4        VC4        WT4

           WD1        WD2        WSS11      WSSCN1     WD1IN      WD1OUT     WLK12      WSE1DT     WSR1DT     WSC1DT
           WD7        WD8        WSS22      WSSCN2     WD2IN      WD2OUT     WLK23      WSE2DT     WSR2DT     WSC2DT
           WD5        WD6        WSS33      WSSCN3     WD3IN      WD3OUT     WLK34      WSE3DT     WSR3DT     WSC3DT
           WD3        WD4        WSS44      WSSCN4     WD4IN      WD4OUT     WLK41      WSE4DT     WSR4DT     WSC4DT

           VS(1)      VS(2)      VS(3)      VS(13)     E(1)       E(2)       E(3)       E(13)      TORQ1      POWER1
           VS(4)      VS(5)      VS(6)      VS(14)     E(4)       E(5)       E(6)       E(14)      TORQ2      POWER2
           VS(7)      VS(8)      VS(9)      VS(15)     E(7)       E(8)       E(9)       E(15)      TORQ3      POWER3
           VS(10)     VS(11)     VS(12)     VS(16)     E(10)      E(11)      E(12)      E(16)      TORQ4      POWER4

           WSTMXD     WSTMND     WDSHT      PSHTMX     PSHTMN     TSH        WSMX1      WSMN1

           POWERT     PFRICT     PAUX       PRRF       PDRAG      PLOAD      PENG       PNET
POSDEG     TORQT      TFRICT     TAUX       TRRF       TDRAG      TLOAD      TENG       TNET       KWORK      SPDRPM  VKPH

0.3000E-01-0.2031     -2.000    -0.2008      2.000      270.0      2000.      5.003     0.2609E-02 0.3000E-03   101
            4.031      4.015      4.004      933.6      670.2      406.8      116.2      115.3      152.2     0.6523E-03
            4.552      4.539      4.511      933.6      670.2      406.8      158.9      115.3      102.4     0.6523E-03
            5.985      6.007      6.017      933.6      670.2      406.8      116.2      115.3      61.70     0.6523E-03
            5.445      5.453      5.481      933.6      670.2      406.8      63.87      115.3      102.4     0.6523E-03

           0.8571E-02 0.5987E-02 0.0000     0.0000     0.0000     0.0000     0.0000    -0.8571E-02 0.2584E-02 0.5987E-02
           0.7222E-02 0.1462E-01 0.0000     0.0000     0.0000     0.0000     0.0000    -0.7222E-02-0.7403E-02 0.1462E-01
          -0.1133E-01-0.5490E-02 0.0000     0.0000     0.0000     0.0000     0.0000     0.1133E-01-0.5836E-02-0.5490E-02
          -0.4178E-02-0.1491E-01 0.0000     0.0000     0.0000     0.0000     0.0000     0.4178E-02 0.1073E-01-0.1491E-01

           0.1216E-03 0.1675E-03 0.3632E-03  4.712     0.9936E-05-0.1462E-05-0.1090E-05 0.9294E-07  12.60      2.671
           0.1878E-03 0.1893E-03 0.2752E-03  209.4     0.1049E-05-0.6665E-05 0.2206E-05 0.4292E-07-0.2490E-01  2.664
           0.1805E-03 0.2506E-03 0.2212E-03 0.1172E-03-0.8438E-04 0.2859E-04-0.1996E-04 0.0000      36.32      2.662
           0.9029E-04 0.2275E-03 0.3345E-03 0.7813E-04 0.1733E-05-0.1554E-04 0.6429E-05 0.0000    -0.5058E-01  2.671

           0.0000     0.0000     0.0000      6.000      4.000     0.0000     0.1172E-03 0.7813E-04

            10.67      3.221      2.108      2.531      2.360      4.891      5.329     0.3469
 270.0      48.84      15.38      10.07      12.09      11.27      23.35      25.45     0.4489E-01  101     2000.06  60.56
```

TABLE XIV. - SAMPLE DEBUG PRINTOUT (NOBUG = 0)

```
-0.20196623     -1.9998884    -0.20191854      2.0001106
  12.062994      12.062994      12.062994     0.00000000     0.00000000      116.19153      152.23161
  13.569489      13.569489      13.569489     0.00000000     0.00000000      158.91251      102.39359
  17.951859      17.951859      17.951859     0.00000000     0.00000000      116.19040      61.702515
  16.429947      16.429947      16.429947     0.00000000     0.00000000      63.867355      102.39467
  922.44482      668.49976      414.55493      922.44482      668.49976      414.55493
  922.44482      668.49976      414.55493      922.44482      668.49976      414.55493
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  16.000000      14.000000     0.00000000     0.00000000     0.00000000
DEBUG OUTPUT FROM FOURW2 NUMBER      1
         TIME =  0.00000000
DEBUG PRINTOUT FROM FWS3V2 NUMBER      1
-0.20196623     -1.9998884    -0.20191854      2.0001106
  12.062987      12.062986      12.062989 0.50193393E-06-0.15058013E-05      116.19153      152.23161
  13.569483      13.569486      13.569482     0.00000000     0.00000000      158.91251      102.39359
  17.951843      17.951843      17.951843     0.00000000     0.00000000      116.19040      61.702515
  16.429932      16.429932      16.429932-0.15058013E-05 0.20077350E-05      63.867355      102.39467
  922.44482      668.49976      414.55493      922.44482      668.49976      414.55493
  922.44482      668.49976      414.55493      922.44482      668.49976      414.55493
  418.87988      7.9077196      80.492523      150.37494      21.255264      2.6879129
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  16.000000      14.000000     0.00000000     0.00000000     0.00000000
DEBUG PRINTOUT FROM FWS3V2 NUMBER      2
              1 0.36830036E-03-0.81770270E-06 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              2 0.50447881E-03 0.23878920E-05 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              3 0.10737202E-02-0.84144904E-06 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              4 0.56662294E-03 0.15945006E-05 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              5 0.56748115E-03-0.37148757E-05 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              6 0.81239524E-03 0.14828265E-05 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              7 0.54809055E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              8 0.75075356E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
              9 0.64765452E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
             10 0.27573225E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
             11 0.68710651E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
             12 0.98365918E-03 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
             13  4.7123709     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
             14  418.87988     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  CONVERGENCE IN ERR VECTOR
```

TABLE XV. - INPUT ROUTINE (MAINSE) FOR SUPPLY TRANSIENT (100 POINTS/CYCLE)

```
C      INPUT DATA FOR THE FOUR WORKING SPACE THREE VOLUME
C      STIRLING ENGINE MODEL.
C
      COMMON/PST/AD,AR,RODL,VOE,VOC,VR,RER,RRC,STROKE,ALPHA,PSIMD
      COMMON/CARLOD/GTRAN,GR,AIE,AIWHEL,AIVEH,RWHEEL,AINERT
      COMMON/CONST/R,G,PIE,DEGR
      COMMON/MATXIN/VDELTA,FRAC,TOL1,TOL2,TOLSS,N,NTMAX,MPAS,
     1               TOLPCG,REF
      COMMON/SWITCH/ISS,ICALC,MATRIX,NONENG,IPRTOP,IBRYTH,
     1               IHPCNV,NOBUG
      COMMON /SHRTCT/ WD1IN,WD2IN,WD3IN,WD4IN,WD1OUT,WD2OUT,WD3OUT,WD4OU
     1T,WDSHT,WSTMXD,WSTMND,PSHTMX,PSHTMN,WSMX1,WSMN1,VSH,RSHT,RSHTT
      COMMON/RUNCON/ALEAK,ARLEAK,PSOURC,CYCLPR,SPDRPM,POSDEO,
     1              WSTOTL,TWHIN,TWCIN,CYCLPM,SPDMAX
      COMMON/CYDATA/NPTPCY,ITRMAX,NUMBCY
      COMMON/TRANDS/ISUPST,ISHTST,TIME,KWORK,ISPSTP,ISHSTP
      COMMON/OUTPT/POSDEG,WTOT,ITRAN,WT1,WT2,WT3,WT4,WD1,WD2,WD3,WD4,
     1WD5,WD6,WD7,WD8,TORQ1,TORQ2,TORQ3,TORQ4,POWER1,POWER2,POWER3,
     2POWER4,POWERT,TORQT,TLOAD,TENG,PLOAD,PENG,PNET,PAVEMP,CCCHK
C
C
C      ENGINE GEOMETRY
      AD=23.7613
      AR=1.1290
      RODL=10.0
      VR=115.339
      VOE=63.87
      VOC=61.70
      STROKE=4.00
      ALPHA=90.0
C
C      HEATER AND COOLER WALL TEMPERATURES
      TWHIN=705.0
      TWCIN=86.0
C
C      FLOW RESISTANCES BETWEEN VOLUMES
      RER=1.9
      RRC=1.9
C
C      CONSTANTS
      DEGR=57.296
      PIE=3.1416
      R=4125.6
      G=10017.0
C
C      MATRIX CONVERGENCE INPUT
      VDELTA=.01
      FRAC=1.0
      TOL1=.001
      TOL2=.01
      TOLSS=.0001
      N=14
      NTMAX=16

      MPAS=20
      TOLPCG=.5
C
C      SWITCHES
      ISS=0
      ICALC=1
      MATRIX=1
      NONENG=1
      IPRTOP=100
      IBRYTH=0
      IHPCNV=0
      NOBUG=1
C
C      RUN CONDITIONS
```

```
      ALEAK=0.0
      ARLEAK=0.0
      PSOURC=10.0
      CYCLPM=15.0
      SPDMAX=4000.0
      CYCLPR=5.0
      SPDRPM=2000.0
      POSDEO=270.0
      WSTOTL=.007786
      VSH=32.78
      RSHT=38.0
      ASHTT=.20
C
C      LOAD CHARACTERISTICS
      GTRAN=1.0/2.53
      GR=1.5
      WTENG=0.0
      WTWHEL=29.48
      WTCAR=1420.0
      RWHEEL=30.48
C
C      CYCLE DATA
      NPTPCY=100
      NUMBCY=1000
C
C      TRANSIENT DESIRED
      NCYSHT=50000
      NCYSUP=5
      NCYSTP=50000
      NCYSHS=50000
C
C      CALCULATED INPUT
      PSHTMX=CYCLPR+1.0
      PSHTMN=CYCLPR-1.0
      IF (NONENG .EQ. 0) N=12
      REF=(TOL1+TOL2)/2.0
      RWHELM=RWHEEL/100.0
      ITRMAX=NPTPCY*NUMBCY+1
      ISUPST=NCYSUP*NPTPCY+1

      ISHTST=NCYSHT*NPTPCY+1
      ISPSTP=NCYSTP*NPTPCY+1
      ISHSTP=NCYSHS*NPTPCY+1
      RSHTCT=RSHT
      RSHTT=ASHTT/RSHTCT
      AIE=0.0
      WTWHEL=WTWHEL*4.0
      AIWHEL=(WTWHEL/2.0)*(RWHELM**2+(RWHELM/2.0)**2)
      AIVEH=WTCAR*RWHELM**2
      CALL ICSTUP
      STOP
      END
```

page 59 missing From original

TABLE XVI. - SAMPLE OUTPUT FOR SUPPLY TRANSIENT (100 POINTS/CYCLE)

```
STIRLING ENGINE FOUR CYLINDER, THREE VOLUMES PER CYLINDER, CONTROLS MODEL

   RUN CONDITIONS FOR THIS TRANSIENT
TWH =    978.0         TWC =    359.0         CYCLPR =   5.000         NONENG =           1   NUMBCY =        1000
ALEAK =  0.0000        ARLEAK =  0.0000       PSOURC =   10.00         ISUPST =         501   ISHTST =     5000001

TIME        POWERT      PFRICT      PAUX        PRRF        PDRAG       PLOAD       PENG        PNET          ITRAN       PAVEMP
POSDEG      TORQT       TFRICT      TAUX        TRRF        TDRAG       TLOAD       TENG        TNET          KWORK       SPDRPM  VKPH
0.0000      0.0000       3.201       2.108       2.531       2.359       4.890       5.309      -10.20           1          4.93
 270.0       52.25       15.29       10.07       12.09       11.26       23.35       25.35       3.543           1       2000.00   60.56

0.3000E-01   10.67       3.221       2.108       2.531       2.360       4.891       5.329      0.3469         101          5.00
 270.0       48.84       15.38       10.07       12.09       11.27       23.35       25.45      0.4489E-01     101       2000.06   60.56

0.6000E-01   10.67       3.234       2.108       2.531       2.360       4.891       5.342      0.3330         201          5.00
 270.0       48.85       15.44       10.07       12.09       11.27       23.35       25.51     -0.9811E-02     101       2000.12   60.56

0.8999E-01   10.67       3.298       2.108       2.531       2.360       4.891       5.407      0.2684         301          5.00
 270.0       48.86       15.75       10.07       12.09       11.27       23.35       25.82     -0.3075         101       2000.17   60.56

0.1200       10.67       3.264       2.108       2.531       2.360       4.891       5.372      0.3022         401          5.00
 270.0       48.85       15.59       10.07       12.09       11.27       23.35       25.65     -0.1534         101       2000.23   60.56

0.1500       10.67       3.215       2.108       2.531       2.360       4.892       5.323      0.3522         501          5.00
 270.0       48.99       15.35       10.07       12.09       11.27       23.35       25.41      0.2215         101       2000.29   60.57

0.1800       11.38       3.245       2.108       2.532       2.361       4.892       5.354       1.028         601          5.05
 270.0       50.14       15.49       10.07       12.09       11.27       23.36       25.56       1.221         101       2000.45   60.57

0.2100       11.61       3.328       2.109       2.532       2.362       4.893       5.436       1.177         701          5.17
 270.0       51.30       15.89       10.07       12.09       11.27       23.36       25.95       1.994         101       2000.64   60.58

0.2399       11.84       3.344       2.109       2.532       2.362       4.894       5.453       1.384         801          5.29
 270.0       52.41       15.96       10.07       12.09       11.27       23.36       26.03       3.023         101       2000.85   60.58

0.2699       12.06       3.343       2.109       2.532       2.363       4.896       5.452       1.599         901          5.40
 270.0       53.45       15.96       10.07       12.09       11.28       23.36       26.02       4.066         101       2001.09   60.59

0.2999       12.27       3.395       2.109       2.533       2.364       4.897       5.505       1.753        1001          5.51
 270.0       54.48       16.20       10.07       12.09       11.28       23.37       26.27       4.850         101       2001.35   60.60

0.3299       12.47       3.478       2.110       2.533       2.365       4.898       5.588       1.870        1101          5.62
 270.0       55.50       16.59       10.07       12.09       11.28       23.37       26.66       5.468         101       2001.64   60.61

0.3598       12.67       3.498       2.110       2.533       2.366       4.900       5.608       2.041        1201          5.72
 270.0       56.43       16.69       10.07       12.09       11.29       23.37       26.76       6.305         101       2001.94   60.62

0.3898       12.86       3.478       2.110       2.534       2.367       4.901       5.588       2.246        1301          5.81
 270.0       57.36       16.59       10.07       12.09       11.29       23.38       26.65       7.325         101       2002.28   60.63

0.4198       13.04       3.524       2.111       2.534       2.369       4.903       5.635       2.378        1401          5.91
 270.0       58.24       16.80       10.07       12.09       11.29       23.38       26.87       7.992         101       2002.63   60.64
```

0.4497 270.0	13.21 59.09	3.609 17.21	2.111 10.07	2.535 12.09	2.370 11.30	4.905 23.38	5.720 27.28	2.464 8.432	1501 101	6.00 2003.01	60.65
0.4797 270.0	13.38 59.91	3.631 17.31	2.112 10.07	2.535 12.09	2.371 11.30	4.907 23.39	5.742 27.37	2.608 9.151	1601 101	6.09 2003.40	60.66
0.5096 270.0	13.54 60.72	3.595 17.13	2.112 10.07	2.536 12.09	2.373 11.31	4.909 23.39	5.707 27.20	2.802 10.12	1701 101	6.17 2003.81	60.67
0.5396 270.0	13.70 61.51	3.647 17.38	2.113 10.07	2.536 12.09	2.374 11.31	4.911 23.40	5.759 27.44	2.903 10.67	1801 101	6.25 2004.24	60.69
0.5695 270.0	13.85 62.25	3.724 17.74	2.113 10.07	2.537 12.09	2.376 11.32	4.913 23.40	5.837 27.81	2.973 11.03	1901 101	6.33 2004.69	60.70
0.5994 270.0	14.00 62.94	3.738 17.81	2.113 10.07	2.538 12.09	2.378 11.32	4.915 23.41	5.852 27.87	3.100 11.66	2001 101	6.40 2005.15	60.71
0.6293 270.0	14.14 63.66	3.700 17.62	2.114 10.07	2.538 12.09	2.379 11.33	4.917 23.41	5.814 27.69	3.275 12.56	2101 101	6.48 2005.64	60.73
0.6592 270.0	14.28 64.32	3.748 17.84	2.115 10.07	2.539 12.09	2.381 11.33	4.920 23.42	5.862 27.91	3.359 12.99	2201 101	6.55 2006.13	60.74
0.6891 270.0	14.41 64.96	3.822 18.19	2.115 10.07	2.539 12.09	2.383 11.34	4.922 23.43	5.938 28.26	3.411 13.27	2301 101	6.61 2006.65	60.76
0.7190 270.0	14.53 65.57	3.816 18.16	2.116 10.07	2.540 12.09	2.385 11.35	4.925 23.43	5.931 28.22	3.539 13.92	2401 101	6.68 2007.17	60.77
0.7489 270.0	14.65 66.17	3.790 18.03	2.116 10.07	2.541 12.09	2.387 11.35	4.927 23.44	5.906 28.10	3.682 14.64	2501 101	6.74 2007.71	60.79
0.7788 270.0	14.77 66.74	3.833 18.23	2.117 10.07	2.541 12.09	2.389 11.36	4.930 23.44	5.950 28.30	3.751 15.00	2601 101	6.80 2008.27	60.81
0.8087 270.0	14.88 67.29	3.907 18.57	2.117 10.07	2.542 12.09	2.391 11.36	4.933 23.45	6.024 28.64	3.786 15.20	2701 101	6.86 2008.84	60.82
0.8385 270.0	14.99 67.83	3.894 18.51	2.118 10.07	2.543 12.09	2.393 11.37	4.936 23.46	6.013 28.58	3.902 15.79	2801 101	6.92 2009.41	60.84
0.8684 270.0	15.10 68.32	3.865 18.37	2.119 10.07	2.544 12.09	2.395 11.38	4.939 23.46	5.984 28.43	4.031 16.42	2901 101	6.97 2010.01	60.86
0.8982 270.0	15.20 68.85	3.909 18.57	2.119 10.07	2.544 12.09	2.397 11.38	4.942 23.47	6.029 28.64	4.084 16.74	3001 101	7.03 2010.61	60.88
0.9281 270.0	15.30 69.32	3.981 18.90	2.120 10.07	2.545 12.09	2.399 11.39	4.944 23.48	6.101 28.97	4.105 16.87	3101 101	7.08 2011.23	60.90
0.9579 270.0	15.39 69.78	3.972 18.85	2.121 10.07	2.546 12.09	2.402 11.40	4.947 23.48	6.092 28.92	4.204 17.37	3201 101	7.12 2011.85	60.92
0.9877 270.0	15.48 70.22	3.937 18.69	2.121 10.07	2.547 12.09	2.404 11.41	4.951 23.49	6.059 28.75	4.324 17.97	3301 101	7.17 2012.49	60.94

TABLE XVI. - Continued.

1.017 270.0	15.57 70.64	3.977 18.87	2.122 10.07	2.548 12.09	2.406 11.41	4.954 23.50	6.099 28.93	4.367 18.21	3401 101	7.22 2013.14	60.95
1.047 270.0	15.65 71.05	4.049 19.20	2.123 10.07	2.548 12.09	2.408 11.42	4.957 23.51	6.172 29.27	4.374 18.28	3501 101	7.26 2013.79	60.97
1.077 270.0	15.73 71.45	4.036 19.14	2.123 10.07	2.549 12.09	2.411 11.43	4.960 23.51	6.160 29.20	4.463 18.73	3601 101	7.30 2014.45	60.99
1.107 270.0	15.81 71.81	3.995 18.93	2.124 10.07	2.550 12.09	2.413 11.44	4.963 23.52	6.119 29.00	4.578 19.28	3701 101	7.34 2015.13	61.02
1.136 270.0	15.89 72.21	4.035 19.12	2.125 10.07	2.551 12.09	2.416 11.44	4.967 23.53	6.160 29.18	4.608 19.50	3801 101	7.38 2015.81	61.04
1.166 270.0	15.96 72.56	4.105 19.44	2.126 10.07	2.552 12.09	2.418 11.45	4.970 23.54	6.231 29.51	4.606 19.51	3901 101	7.42 2016.50	61.06
1.196 270.0	16.03 72.91	4.115 19.48	2.126 10.07	2.553 12.09	2.421 11.46	4.973 23.55	6.242 29.55	4.660 19.81	4001 101	7.46 2017.19	61.08
1.226 270.0	16.10 73.23	4.053 19.18	2.127 10.07	2.554 12.09	2.423 11.47	4.977 23.55	6.180 29.25	4.786 20.43	4101 101	7.49 2017.90	61.10
1.255 270.0	16.16 73.55	4.089 19.35	2.128 10.07	2.555 12.09	2.426 11.48	4.980 23.56	6.217 29.41	4.810 20.57	4201 101	7.53 2018.61	61.12
1.285 270.0	16.22 73.85	4.162 19.68	2.129 10.07	2.555 12.09	2.428 11.48	4.984 23.57	6.291 29.75	4.794 20.53	4301 101	7.56 2019.32	61.14
1.315 270.0	16.28 74.12	4.165 19.69	2.130 10.07	2.556 12.09	2.431 11.49	4.987 23.58	6.294 29.76	4.846 20.79	4401 101	7.59 2020.04	61.16
1.344 270.0	16.34 74.43	4.100 19.38	2.130 10.07	2.557 12.09	2.434 11.50	4.991 23.59	6.230 29.45	4.965 21.40	4501 101	7.62 2020.78	61.19
1.374 270.0	16.40 74.70	4.133 19.53	2.131 10.07	2.558 12.09	2.436 11.51	4.995 23.59	6.264 29.59	4.983 21.51	4601 101	7.65 2021.52	61.21
1.404 270.0	16.45 74.95	4.212 19.89	2.132 10.07	2.559 12.09	2.439 11.52	4.998 23.60	6.344 29.96	4.953 21.39	4701 101	7.68 2022.26	61.23
1.433 270.0	16.50 75.21	4.213 19.89	2.133 10.07	2.560 12.09	2.442 11.53	5.002 23.61	6.346 29.96	4.999 21.64	4801 101	7.70 2023.00	61.25
1.463 270.0	16.55 75.45	4.142 19.55	2.134 10.07	2.561 12.09	2.444 11.53	5.005 23.62	6.276 29.62	5.115 22.21	4901 101	7.73 2023.76	61.28
1.492 270.0	16.60 75.66	4.161 19.63	2.134 10.07	2.562 12.09	2.447 11.54	5.009 23.63	6.295 29.70	5.139 22.34	5001 101	7.76 2024.52	61.30
1.522 270.0	16.65 75.92	4.244 20.01	2.135 10.07	2.563 12.09	2.450 11.55	5.013 23.64	6.379 30.08	5.098 22.20	5101 101	7.78 2025.28	61.32

1.551 270.0	16.69 76.13	4.226 19.92	2.136 10.07	2.564 12.09	2.453 11.56	5.017 23.65	6.362 29.99	5.155 22.49	5201 101	7.80 2026.04	61.35
1.581 270.0	16.74 76.34	4.179 19.69	2.137 10.07	2.565 12.09	2.456 11.57	5.020 23.66	6.316 29.76	5.241 22.92	5301 101	7.83 2026.82	61.37
1.611 270.0	16.78 76.54	4.212 19.84	2.138 10.07	2.566 12.09	2.458 11.58	5.024 23.66	6.349 29.91	5.245 22.97	5401 101	7.85 2027.60	61.39
1.640 270.0	16.82 76.73	4.283 20.17	2.139 10.07	2.567 12.09	2.461 11.59	5.028 23.67	6.421 30.24	5.209 22.82	5501 101	7.87 2028.38	61.42
1.670 270.0	16.86 76.92	4.287 20.18	2.139 10.07	2.568 12.09	2.464 11.60	5.032 23.68	6.427 30.25	5.238 22.99	5601 101	7.89 2029.16	61.44
1.699 270.0	16.90 77.10	4.214 19.82	2.140 10.07	2.569 12.09	2.467 11.60	5.036 23.69	6.354 29.89	5.344 23.51	5701 101	7.91 2029.95	61.46
1.729 270.0	16.93 77.27	4.241 19.95	2.141 10.07	2.570 12.09	2.470 11.61	5.040 23.70	6.382 30.02	5.347 23.55	5801 101	7.93 2030.74	61.49
1.758 270.0	16.97 77.44	4.322 20.32	2.142 10.07	2.571 12.09	2.473 11.62	5.044 23.71	6.464 30.39	5.296 23.34	5901 101	7.95 2031.54	61.51
1.788 270.0	17.00 77.60	4.296 20.19	2.143 10.07	2.572 12.09	2.476 11.63	5.048 23.72	6.439 30.26	5.351 23.62	6001 101	7.96 2032.33	61.54
1.817 270.0	17.03 77.76	4.243 19.93	2.144 10.07	2.573 12.09	2.479 11.64	5.051 23.73	6.387 30.00	5.430 24.03	6101 101	7.98 2033.14	61.56
1.847 270.0	17.06 77.89	4.260 20.00	2.145 10.07	2.574 12.09	2.482 11.65	5.055 23.74	6.404 30.07	5.438 24.08	6201 101	8.00 2033.95	61.58
1.876 270.0	17.09 78.07	4.343 20.39	2.146 10.07	2.575 12.09	2.484 11.66	5.059 23.75	6.489 30.46	5.380 23.87	6301 101	8.01 2034.75	61.61
1.905 270.0	17.12 78.21	4.347 20.39	2.147 10.07	2.576 12.09	2.487 11.67	5.063 23.76	6.493 30.46	5.401 23.99	6401 101	8.03 2035.56	61.63
1.935 270.0	17.15 78.34	4.270 20.03	2.147 10.07	2.577 12.09	2.490 11.68	5.067 23.76	6.418 30.10	5.500 24.48	6501 101	8.04 2036.37	61.66
1.964 270.0	17.18 78.47	4.286 20.09	2.148 10.07	2.578 12.09	2.493 11.69	5.071 23.77	6.434 30.16	5.506 24.53	6601 101	8.06 2037.19	61.68
1.994 270.0	17.20 78.63	4.369 20.47	2.149 10.07	2.579 12.09	2.496 11.70	5.075 23.78	6.518 30.54	5.444 24.30	6701 101	8.07 2038.01	61.71
2.023 270.0	17.23 78.76	4.348 20.37	2.150 10.07	2.580 12.09	2.499 11.71	5.080 23.79	6.498 30.44	5.486 24.52	6801 101	8.08 2038.83	61.73
2.052 270.0	17.26 78.88	4.295 20.11	2.151 10.07	2.581 12.09	2.502 11.72	5.084 23.80	6.446 30.18	5.560 24.90	6901 101	8.10 2039.65	61.76
2.082 270.0	17.28 79.00	4.324 20.24	2.152 10.07	2.582 12.09	2.506 11.73	5.088 23.81	6.476 30.31	5.551 24.88	7001 101	8.11 2040.48	61.78

TABLE XVI. - Continued.

4.703	18.39	4.888	2.243	2.683	2.810	5.493	7.131	5.590	16101	8.68	
270.0	84.70	22.02	10.11	12.09	12.66	24.74	32.13	27.83	101	2119.95	64.19
4.731	18.40	4.779	2.245	2.684	2.813	5.497	7.023	5.698	16201	8.69	
270.0	84.74	21.52	10.11	12.09	12.67	24.75	31.63	28.36	101	2120.83	64.22
4.760	18.40	4.670	2.246	2.685	2.817	5.502	6.915	5.807	16301	8.69	
270.0	84.77	21.02	10.11	12.09	12.68	24.76	31.13	28.88	101	2121.72	64.24
4.788	18.41	4.700	2.247	2.686	2.820	5.507	6.947	5.779	16401	8.69	
270.0	84.82	21.15	10.11	12.09	12.69	24.77	31.26	28.79	101	2122.62	64.27
4.816	18.42	4.787	2.248	2.687	2.824	5.511	7.035	5.691	16501	8.70	
270.0	84.86	21.53	10.11	12.09	12.70	24.79	31.64	28.44	101	2123.51	64.30
4.844	18.42	4.781	2.249	2.688	2.828	5.516	7.030	5.697	16601	8.70	
270.0	84.90	21.49	10.11	12.09	12.71	24.80	31.60	28.50	101	2124.39	64.32
4.872	18.43	4.683	2.250	2.690	2.831	5.521	6.933	5.794	16701	8.70	
270.0	84.94	21.05	10.11	12.09	12.72	24.81	31.16	28.98	101	2125.29	64.35
4.901	18.43	4.710	2.251	2.691	2.835	5.525	6.961	5.767	16801	8.71	
270.0	84.99	21.16	10.11	12.09	12.73	24.82	31.27	28.90	101	2126.18	64.38
4.929	18.44	4.800	2.252	2.692	2.838	5.530	7.052	5.677	16901	8.71	
270.0	85.03	21.55	10.11	12.09	12.74	24.83	31.67	28.53	101	2127.07	64.40
4.957	18.44	4.795	2.253	2.693	2.842	5.535	7.048	5.683	17001	8.71	
270.0	85.07	21.52	10.11	12.09	12.75	24.84	31.63	28.60	101	2127.95	64.43
4.985	18.45	4.695	2.254	2.694	2.845	5.539	6.949	5.784	17101	8.72	
270.0	85.11	21.06	10.11	12.09	12.76	24.85	31.18	29.08	101	2128.85	64.46
5.013	18.46	4.722	2.255	2.695	2.849	5.544	6.978	5.756	17201	8.72	
270.0	85.15	21.18	10.11	12.09	12.77	24.86	31.29	29.00	101	2129.74	64.49
5.041	18.46	4.810	2.256	2.696	2.852	5.549	7.066	5.667	17301	8.72	
270.0	85.19	21.56	10.11	12.09	12.78	24.87	31.67	28.65	101	2130.63	64.51
5.069	18.47	4.806	2.257	2.697	2.856	5.553	7.063	5.671	17401	8.73	
270.0	85.23	21.53	10.11	12.09	12.80	24.88	31.65	28.70	101	2131.51	64.54
5.098	18.47	4.707	2.258	2.699	2.860	5.558	6.966	5.769	17501	8.73	
270.0	85.27	21.08	10.12	12.09	12.81	24.89	31.20	29.18	101	2132.41	64.57
10.00	18.98	5.188	2.462	2.896	3.535	6.432	7.650	4.703	35601	9.06	
270.0	91.08	21.65	10.28	12.09	14.75	26.84	31.92	32.32	101	2288.65	69.30
10.03	18.98	5.162	2.463	2.897	3.539	6.437	7.625	4.724	35701	9.06	
270.0	91.09	21.53	10.28	12.09	14.76	26.85	31.81	32.44	101	2289.48	69.32
10.05	18.98	5.173	2.465	2.898	3.543	6.441	7.637	4.710	35801	9.06	
270.0	91.12	21.57	10.28	12.09	14.77	26.86	31.85	32.41	101	2290.30	69.35

10.08 270.0	18.98 91.11	5.248 21.88	2.466 10.28	2.899 12.09	3.547 14.78	6.446 26.87	7.714 32.16	4.629 32.08	35901 101	9.06 2291.12	69.37
10.11 270.0	18.98 91.08	5.261 21.92	2.467 10.28	2.900 12.09	3.551 14.79	6.451 26.88	7.728 32.20	4.612 32.00	36001 101	9.06 2291.94	69.40
10.13 270.0	18.98 91.11	5.183 21.59	2.468 10.28	2.901 12.09	3.554 14.80	6.456 26.89	7.651 31.87	4.685 32.35	36101 101	9.06 2292.77	69.42
10.16 270.0	18.99 91.09	5.198 21.64	2.469 10.28	2.903 12.09	3.558 14.81	6.461 26.90	7.667 31.93	4.665 32.27	36201 101	9.07 2293.59	69.45
10.18 270.0	18.99 91.08	5.199 21.64	2.470 10.28	2.904 12.09	3.562 14.83	6.466 26.91	7.669 31.92	4.660 32.25	36301 101	9.07 2294.41	69.47
10.21 270.0	18.99 91.10	5.210 21.68	2.472 10.28	2.905 12.09	3.566 14.84	6.471 26.92	7.681 31.96	4.644 32.21	36401 101	9.07 2295.24	69.50
10.24 270.0	18.99 91.08	5.252 21.85	2.473 10.29	2.906 12.09	3.570 14.85	6.475 26.93	7.725 32.13	4.597 32.01	36501 101	9.07 2296.05	69.52
10.26 270.0	18.99 91.11	5.193 21.59	2.474 10.29	2.907 12.09	3.574 14.86	6.480 26.94	7.667 31.88	4.651 32.28	36601 101	9.07 2296.87	69.55
10.29 270.0	18.99 91.09	5.207 21.64	2.475 10.29	2.908 12.09	3.577 14.87	6.485 26.95	7.682 31.93	4.633 32.21	36701 101	9.07 2297.69	69.57
10.31 270.0	18.99 91.09	5.194 21.58	2.476 10.29	2.909 12.09	3.581 14.88	6.490 26.96	7.670 31.87	4.641 32.25	36801 101	9.07 2298.52	69.60
10.34 270.0	18.99 91.11	5.202 21.61	2.477 10.29	2.910 12.09	3.585 14.89	6.495 26.98	7.679 31.90	4.628 32.24	36901 101	9.07 2299.34	69.62
10.37 270.0	19.00 91.09	5.255 21.82	2.478 10.29	2.911 12.09	3.589 14.90	6.500 26.99	7.734 32.11	4.570 31.99	37001 101	9.07 2300.15	69.65
14.94 270.0	19.12 87.97	5.637 22.06	2.690 10.53	3.088 12.09	4.285 16.77	7.373 28.85	8.327 32.59	3.237 26.52	55101 101	9.20 2440.15	73.88
14.96 270.0	19.12 87.94	5.650 22.11	2.691 10.53	3.089 12.09	4.289 16.78	7.378 28.86	8.342 32.64	3.218 26.44	55201 101	9.20 2440.87	73.91
14.99 270.0	19.12 87.91	5.583 21.84	2.693 10.53	3.090 12.09	4.293 16.79	7.382 28.87	8.276 32.37	3.279 26.66	55301 101	9.20 2441.60	73.93
15.01 270.0	19.12 87.88	5.597 21.89	2.694 10.53	3.091 12.09	4.296 16.80	7.387 28.88	8.291 32.42	3.259 26.57	55401 101	9.20 2442.33	73.95
15.04 270.0	19.12 87.85	5.577 21.80	2.695 10.54	3.092 12.09	4.300 16.81	7.392 28.89	8.272 32.34	3.274 26.62	55501 101	9.20 2443.06	73.97
15.06 270.0	19.12 87.82	5.591 21.85	2.696 10.54	3.093 12.09	4.304 16.82	7.397 28.90	8.287 32.39	3.254 26.53	55601 101	9.20 2443.79	73.99
15.09 270.0	19.12 87.79	5.636 22.02	2.697 10.54	3.094 12.09	4.308 16.83	7.401 28.91	8.333 32.56	3.203 26.31	55701 101	9.20 2444.51	74.02

TABLE XVI. - Continued.

15.11 270.0	19.12 87.76	5.595 21.86	2.698 10.54	3.094 12.09	4.311 16.84	7.406 28.92	8.294 32.39	3.239 26.44	55801 101	9.20 2445.14	74.04
15.14 270.0	19.12 87.73	5.617 21.93	2.699 10.54	3.095 12.09	4.315 16.85	7.410 28.93	8.316 32.47	3.213 26.32	55901 101	9.20 2445.75	74.05
15.16 270.0	19.12 87.70	5.589 21.82	2.700 10.54	3.096 12.09	4.318 16.85	7.414 28.94	8.289 32.36	3.236 26.40	56001 101	9.20 2446.36	74.07
15.18 270.0	19.12 87.67	5.653 22.06	2.701 10.54	3.097 12.09	4.321 16.86	7.418 28.95	8.354 32.61	3.167 26.11	56101 101	9.20 2446.96	74.09
15.21 270.0	19.12 87.64	5.666 22.11	2.702 10.54	3.097 12.09	4.324 16.87	7.422 28.96	8.369 32.66	3.149 26.03	56201 101	9.20 2447.57	74.11
15.23 270.0	19.12 87.62	5.600 21.85	2.703 10.55	3.098 12.09	4.327 16.88	7.426 28.97	8.303 32.39	3.210 26.26	56301 101	9.20 2448.18	74.13
15.26 270.0	19.12 87.58	5.614 21.89	2.704 10.55	3.099 12.09	4.331 16.89	7.430 28.97	8.318 32.44	3.192 26.16	56401 101	9.20 2448.80	74.15
15.28 270.0	19.12 87.55	5.593 21.81	2.705 10.55	3.100 12.09	4.334 16.90	7.434 28.98	8.299 32.36	3.208 26.21	56501 101	9.20 2449.41	74.16
19.81 269.9	19.13 82.50	5.890 21.95	2.900 10.80	3.244 12.09	4.966 18.50	8.210 30.59	8.790 32.75	1.958 19.16	76101 101	9.27 2563.11	77.61
19.83 269.9	19.13 82.49	5.937 22.12	2.901 10.81	3.244 12.09	4.969 18.51	8.213 30.60	8.837 32.92	1.907 18.97	76201 101	9.27 2563.64	77.62
19.86 269.9	19.13 82.47	5.895 21.96	2.902 10.81	3.245 12.09	4.972 18.52	8.217 30.60	8.797 32.77	1.943 19.10	76301 101	9.27 2564.17	77.64
19.88 269.9	19.13 82.45	5.915 22.03	2.902 10.81	3.246 12.09	4.975 18.52	8.221 30.61	8.817 32.83	1.919 19.01	76401 101	9.27 2564.69	77.66
19.90 269.9	19.13 82.43	5.887 21.92	2.903 10.81	3.246 12.09	4.978 18.53	8.224 30.62	8.790 32.73	1.942 19.09	76501 101	9.27 2565.22	77.67
19.93 269.9	19.13 82.42	5.942 22.12	2.904 10.81	3.247 12.09	4.981 18.54	8.228 30.63	8.846 32.93	1.883 18.86	76601 101	9.27 2565.74	77.69
19.95 269.9	19.13 82.40	5.961 22.19	2.905 10.81	3.248 12.09	4.984 18.55	8.232 30.63	8.867 33.00	1.859 18.77	76701 101	9.27 2566.26	77.70
19.97 269.9	19.13 82.39	5.900 21.95	2.906 10.81	3.248 12.09	4.987 18.55	8.236 30.64	8.806 32.77	1.916 18.98	76801 101	9.27 2566.78	77.72
19.99 269.9	19.13 82.37	5.914 22.00	2.907 10.81	3.249 12.09	4.990 18.56	8.239 30.65	8.821 32.82	1.897 18.91	76901 101	9.27 2567.31	77.73
20.02 269.9	19.13 82.35	5.891 21.91	2.908 10.82	3.250 12.09	4.993 18.57	8.243 30.66	8.799 32.73	1.915 18.97	77001 101	9.27 2567.83	77.75

20.04 269.9	19.13 82.33	5.903 21.95	2.909 10.82	3.250 12.09	4.996 18.58	8.247 30.66	8.812 32.77	1.898 18.90	77101 101	9.27 2568.36	77.77
20.06 269.9	19.13 82.32	5.949 22.12	2.910 10.82	3.251 12.09	5.000 18.58	8.250 30.67	8.859 32.94	1.847 18.71	77201 101	9.27 2568.88	77.78
20.09 269.9	19.13 82.30	5.908 21.96	2.911 10.82	3.252 12.09	5.003 18.59	8.254 30.68	8.819 32.78	1.884 18.84	77301 101	9.27 2569.40	77.80
20.11 269.9	19.13 82.29	5.927 22.03	2.912 10.82	3.252 12.09	5.006 18.60	8.258 30.69	8.839 32.85	1.860 18.75	77401 101	9.27 2569.92	77.81
20.13 269.9	19.13 82.27	5.900 21.92	2.913 10.82	3.253 12.09	5.009 18.61	8.262 30.69	8.813 32.74	1.883 18.83	77501 101	9.27 2570.44	77.83
20.15 269.9	19.13 82.25	5.954 22.12	2.914 10.82	3.254 12.09	5.012 18.61	8.265 30.70	8.867 32.94	1.825 18.61	77601 101	9.27 2570.96	77.84
20.18 269.9	19.13 82.23	5.974 22.19	2.915 10.83	3.254 12.09	5.015 18.62	8.269 30.71	8.888 33.01	1.800 18.51	77701 101	9.27 2571.46	77.86
20.20 269.9	19.13 82.21	5.913 21.96	2.916 10.83	3.255 12.09	5.018 18.63	8.273 30.72	8.828 32.78	1.857 18.71	77801 101	9.27 2571.98	77.88
20.22 269.9	19.13 82.19	5.927 22.00	2.917 10.83	3.255 12.09	5.021 18.64	8.276 30.72	8.844 32.83	1.838 18.64	77901 101	9.27 2572.50	77.89
20.25 269.9	19.13 82.18	5.904 21.92	2.918 10.83	3.256 12.09	5.024 18.64	8.280 30.73	8.822 32.74	1.856 18.70	78001 101	9.27 2573.01	77.91
20.27 269.9	19.13 82.15	5.916 21.95	2.918 10.83	3.257 12.09	5.027 18.65	8.283 30.74	8.834 32.79	1.840 18.63	78101 101	9.27 2573.53	77.92
20.29 269.9	19.13 82.13	5.962 22.12	2.919 10.83	3.257 12.09	5.030 18.66	8.287 30.75	8.881 32.95	1.789 18.43	78201 101	9.27 2574.03	77.94
20.32 269.9	19.13 82.11	5.921 21.97	2.920 10.83	3.258 12.09	5.033 18.67	8.291 30.75	8.842 32.80	1.825 18.56	78301 101	9.27 2574.55	77.95
20.34 269.9	19.13 82.09	5.940 22.03	2.921 10.83	3.259 12.09	5.036 18.67	8.294 30.76	8.861 32.87	1.802 18.46	78401 101	9.27 2575.05	77.97
20.36 269.9	19.13 82.07	5.913 21.92	2.922 10.84	3.259 12.09	5.039 18.68	8.298 30.77	8.835 32.76	1.825 18.54	78501 101	9.27 2575.56	77.98
20.38 269.9	19.13 82.05	5.965 22.12	2.923 10.84	3.260 12.09	5.042 18.69	8.302 30.78	8.888 32.95	1.768 18.33	78601 101	9.27 2576.07	78.00
20.41 269.9	19.13 82.03	5.986 22.19	2.924 10.84	3.261 12.09	5.045 18.70	8.305 30.78	8.910 33.02	1.743 18.23	78701 101	9.27 2576.57	78.01
20.43 269.9	19.13 82.02	5.926 21.96	2.925 10.84	3.261 12.09	5.048 18.70	8.309 30.79	8.851 32.80	1.799 18.43	78801 101	9.28 2577.08	78.03
20.45 269.9	19.13 82.00	5.940 22.01	2.926 10.84	3.262 12.09	5.051 18.71	8.312 30.80	8.866 32.85	1.780 18.36	78901 101	9.28 2577.58	78.05

TABLE XVI. - Concluded.

```
 20.48    19.13    5.917    2.927    3.263    5.053    8.316    8.844    1.799   79001       9.28
 269.9    81.98    21.92    10.84    12.09    18.72    30.80    32.76    18.41     101    2578.08   78.06

 20.50    19.13    5.928    2.928    3.263    5.056    8.320    8.856    1.783   79101       9.28
 269.9    81.96    21.96    10.84    12.09    18.73    30.81    32.80    18.34     101    2578.59   78.08

 20.52    19.13    5.975    2.929    3.264    5.059    8.323    8.903    1.732   79201       9.28
 269.9    81.94    22.12    10.84    12.09    18.73    30.82    32.97    18.15     101    2579.09   78.09

 20.54    19.13    5.934    2.929    3.264    5.062    8.327    8.863    1.768   79301       9.28
 269.9    81.92    21.97    10.85    12.09    18.74    30.83    32.82    18.28     101    2579.59   78.11

 20.57    19.13    5.953    2.930    3.265    5.065    8.330    8.883    1.745   79401       9.28
 269.9    81.91    22.03    10.85    12.09    18.75    30.83    32.88    18.19     101    2580.09   78.12

 20.59    19.13    5.925    2.931    3.266    5.068    8.334    8.857    1.768   79501       9.28
 269.9    81.90    21.93    10.85    12.09    18.75    30.84    32.78    18.28     101    2580.59   78.14

 20.61    19.13    5.977    2.932    3.266    5.071    8.338    8.909    1.712   79601       9.28
 269.9    81.89    22.11    10.85    12.09    18.76    30.85    32.96    18.08     101    2581.09   78.15

 20.64    19.13    5.998    2.933    3.267    5.074    8.341    8.931    1.687   79701       9.28
 269.9    81.87    22.19    10.85    12.09    18.77    30.86    33.04    17.98     101    2581.60   78.17

 20.66    19.13    5.938    2.934    3.268    5.077    8.345    8.872    1.742   79801       9.28
 269.9    81.86    21.96    10.85    12.09    18.78    30.86    32.82    18.18     101    2582.10   78.18

 20.68    19.13    5.952    2.935    3.268    5.080    8.348    8.887    1.723   79901       9.28
 269.9    81.84    22.01    10.85    12.09    18.78    30.87    32.87    18.11     101    2582.60   78.20

 20.70    19.13    5.930    2.936    3.269    5.083    8.352    8.865    1.742   80001       9.28
 269.9    81.83    21.92    10.85    12.09    18.79    30.88    32.78    18.17     101    2583.10   78.21

 20.73    19.13    5.941    2.937    3.270    5.086    8.356    8.878    1.726   80101       9.28
 269.9    81.81    21.96    10.86    12.09    18.80    30.88    32.82    18.11     101    2583.60   78.23

 20.75    19.13    5.987    2.938    3.270    5.089    8.359    8.924    1.676   80201       9.28
 269.9    81.80    22.13    10.86    12.09    18.81    30.89    32.98    17.92     101    2584.10   78.24

 20.77    19.13    5.947    2.939    3.271    5.092    8.363    8.885    1.711   80301       9.28
 269.9    81.78    21.97    10.86    12.09    18.81    30.90    32.83    18.05     101    2584.61   78.26
OVER TIME LIMIT


                         CPU TIME=    20.00 MINUTES.
```

TABLE XVII. - SAMPLE OUTPUT FOR SUPPLY TRANSIENT (25 POINTS/CYCLE)

```
STIRLING ENGINE FOUR CYLINDER, THREE VOLUMES PER CYLINDER  CONTROLS MODEL

   RUN CONDITIONS FOR THIS TRANSIENT
TWH =    978.0          TWC =    359.0          CYCLPR =   5.000        NONENG =             1    NUMBCY =        1000
ALEAK =   0.0000        ARLEAK =   0.0000       PSOURC =   10.00        ISUPST =           126    ISHTST =     1250001

TIME         POWERT       PFRICT       PAUX         PRRF         PDRAG        PLOAD        PENG         PNET          ITRAN        PAVEMP
POSDEG       TORQT        TFRICT       TAUX         TRRF         TDRAG        TLOAD        TENG         TNET          KWORK        SPDRPM   VKPH
0.0000       0.0000        3.201        2.108        2.531        2.359        4.890        5.309       -10.20            1          4.93
 270.0        52.25        15.29        10.07        12.09        11.26        23.35        25.35        3.543            1       2000.00   60.56

0.1200        10.55        3.214        2.108        2.531        2.360        4.892        5.322     -0.8021E-01  101          5.00
 270.2        48.78        15.35        10.07        12.09        11.27        23.35        25.41      0.1758E-01   26       2000.25   60.56

0.2400        11.71        3.310        2.109        2.532        2.362        4.895        5.419       0.9541          201          5.29
 270.2        52.68        15.80        10.07        12.09        11.27        23.36        25.87        3.450           26       2000.89   60.58

0.3599        12.52        3.464        2.110        2.534        2.366        4.900        5.574        1.576          301          5.72
 270.2        56.56        16.52        10.07        12.09        11.29        23.37        26.59        6.593           26       2002.01   60.62

0.4797        13.23        3.573        2.112        2.535        2.372        4.907        5.685        2.133          401          6.09
 270.2        59.92        17.03        10.07        12.09        11.30        23.39        27.10        9.436           26       2003.49   60.66

0.5995        13.84        3.676        2.114        2.538        2.378        4.916        5.790        2.601          501          6.40
 270.2        62.85        17.51        10.07        12.09        11.32        23.41        27.58        11.86           26       2005.26   60.72

0.7191        14.36        3.783        2.116        2.540        2.385        4.925        5.898        2.986          601          6.68
 270.2        65.40        18.00        10.07        12.09        11.35        23.43        28.06        13.90           26       2007.30   60.78

0.8386        14.82        3.849        2.118        2.543        2.393        4.936        5.968        3.340          701          6.91
 270.2        67.62        18.29        10.07        12.09        11.37        23.46        28.36        15.80           26       2009.56   60.85

0.9579        15.21        3.923        2.121        2.546        2.402        4.948        6.044        3.627          801          7.12
 270.2        69.55        18.62        10.07        12.09        11.40        23.49        28.69        17.37           26       2012.01   60.92

 1.077        15.54        3.983        2.124        2.549        2.411        4.961        6.106        3.874          901          7.30
 270.2        71.22        18.88        10.07        12.09        11.43        23.52        28.95        18.75           26       2014.63   61.00

 1.196        15.84        4.038        2.127        2.553        2.421        4.974        6.165        4.082         1001          7.45
 270.2        72.68        19.12        10.07        12.09        11.46        23.55        29.18        19.95           26       2017.38   61.08

 1.315        16.09        4.087        2.130        2.557        2.432        4.988        6.216        4.256         1101          7.58
 270.2        73.93        19.32        10.07        12.09        11.49        23.58        29.39        20.96           26       2020.26   61.17

 1.434        16.30        4.130        2.133        2.560        2.442        5.003        6.263        4.403         1201          7.70
 270.2        75.04        19.49        10.07        12.09        11.53        23.61        29.56        21.87           26       2023.23   61.26

 1.552        16.49        4.168        2.136        2.564        2.454        5.018        6.305        4.525         1301          7.80
 270.2        75.97        19.65        10.07        12.09        11.56        23.65        29.72        22.61           26       2026.29   61.35

 1.670        16.65        4.206        2.140        2.568        2.465        5.033        6.345        4.623         1401          7.88
 270.2        76.82        19.79        10.07        12.09        11.60        23.68        29.86        23.27           26       2029.42   61.45
```

TABLE XVII. - Continued.

```
 1.789    16.79    4.257    2.143    2.572    2.477    5.049    6.400    4.685    1501       7.96
 270.2    77.52    20.00    10.07    12.09    11.64    23.72    30.07    23.73      26    2032.61   61.54

 1.906    16.91    4.261    2.147    2.576    2.488    5.065    6.408    4.775    1601       8.02
 270.2    78.10    19.99    10.07    12.09    11.67    23.76    30.06    24.28      26    2035.85   61.64

 2.024    17.02    4.286    2.150    2.580    2.501    5.081    6.437    4.832    1701       8.08
 270.2    78.67    20.08    10.07    12.09    11.71    23.80    30.15    24.73      26    2039.13   61.74

 2.142    17.11    4.310    2.154    2.585    2.513    5.097    6.464    4.881    1801       8.13
 270.2    79.20    20.15    10.07    12.09    11.75    23.83    30.23    25.14      26    2042.45   61.84

 2.259    17.20    4.374    2.158    2.589    2.525    5.114    6.532    4.879    1901       8.17
 270.2    79.66    20.42    10.07    12.09    11.79    23.87    30.49    25.30      26    2045.80   61.94

 2.376    17.28    4.352    2.162    2.593    2.538    5.131    6.514    4.957    2001       8.21
 270.2    80.14    20.28    10.07    12.09    11.83    23.91    30.36    25.87      26    2049.18   62.05

 2.493    17.36    4.376    2.165    2.598    2.550    5.148    6.541    4.983    2101       8.25
 270.2    80.54    20.36    10.08    12.09    11.87    23.95    30.43    26.16      26    2052.59   62.15

 2.610    17.42    4.392    2.169    2.602    2.563    5.165    6.561    5.011    2201       8.29
 270.2    80.94    20.40    10.08    12.09    11.90    23.99    30.48    26.47      26    2056.01   62.25

 2.727    17.49    4.409    2.173    2.606    2.576    5.182    6.582    5.032    2301       8.32
 270.2    81.29    20.45    10.08    12.09    11.94    24.03    30.52    26.74      26    2059.47   62.36

 2.843    17.54    4.430    2.177    2.611    2.589    5.200    6.607    5.046    2401       8.35
 270.2    81.63    20.51    10.08    12.09    11.98    24.07    30.59    26.97      26    2062.93   62.46

 2.959    17.60    4.443    2.181    2.615    2.602    5.217    6.624    5.063    2501       8.37
 270.2    81.92    20.53    10.08    12.09    12.03    24.11    30.62    27.19      26    2066.41   62.57

 3.075    17.65    4.459    2.185    2.619    2.615    5.235    6.644    5.075    2601       8.40
 270.2    82.21    20.58    10.08    12.09    12.07    24.15    30.66    27.40      26    2069.90   62.67

 3.191    17.70    4.476    2.189    2.624    2.629    5.253    6.665    5.082    2701       8.43
 270.2    82.51    20.62    10.08    12.09    12.11    24.19    30.70    27.62      26    2073.41   62.78

 3.307    17.74    4.516    2.193    2.628    2.642    5.271    6.709    5.063    2801       8.45
 270.2    82.83    20.77    10.08    12.09    12.15    24.23    30.85    27.74      26    2076.93   62.89

 3.422    17.79    4.527    2.197    2.633    2.656    5.288    6.724    5.072    2901       8.47
 270.2    83.11    20.78    10.09    12.09    12.19    24.28    30.87    27.96      26    2080.45   62.99

 3.537    17.83    4.521    2.201    2.637    2.669    5.306    6.722    5.093    3001       8.49
 270.2    83.37    20.72    10.09    12.09    12.23    24.32    30.81    28.24      26    2083.99   63.10

 3.652    17.87    4.558    2.205    2.642    2.683    5.325    6.764    5.069    3101       8.51
 270.2    83.67    20.85    10.09    12.09    12.27    24.36    30.94    28.37      26    2087.53   63.21

ITERATION FAILURE       13     21
DEBUG OUTPUT FROM FWS3V2, FLOW CONTINUES
```

```
DEBUG PRINTOUT FROM FWS3V2 NUMBER      1
 -1.8488522     0.67807871      1.7777653     -1.0093956
  8.4473810      8.4344292      8.3919554     0.68167634E-02 0.22354629E-01  155.32368      84.119629
  10.520517      10.571616      10.618118     0.16364049E-01 0.17652512E-01  95.280518      65.120804
  8.3913279      8.3846169      8.4137440     0.35321091E-02-0.15330065E-01  69.150574      122.31100
  6.7948027      6.7637110      6.7301712    -0.26894122E-01-0.24474800E-01  135.37712      147.19943
  933.05029      670.09106      407.13184      933.05029      670.09106      407.13184
  933.05029      670.09106      407.13184      933.05029      670.09106      407.13184
  218.94711      3.6300240      24.396973      90.201843      34.976685      9.6353846
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  6.0000000      4.0000000     0.00000000     0.00000000     0.00000000
DEBUG PRINTOUT FROM FWS3V2 NUMBER      2
              1 0.34085358E-03-0.15308842E-05 0.18807023E-05-0.68167634E-02 0.34576468E-03-0.17407069E-02-0.42787343E-02
              2 0.35189348E-03 0.19668678E-05 0.15282376E-05-0.15537865E-01 0.36992598E-03-0.15878677E-01-0.15708271E-01
              3 0.42028003E-03-0.36629757E-07 0.38049284E-05 0.22354629E-01 0.39727031E-03 0.17734930E-01 0.20044778E-01
              4 0.26040501E-03 0.90656331E-05 0.10422764E-05 0.26894122E-01 0.22953982E-03 0.26885588E-01 0.26889853E-01
              5 0.44105924E-03-0.21163014E-05 0.17917191E-05-0.24193227E-02 0.44039311E-03 0.35782866E-02 0.57948194E-03
              6 0.41166646E-03-0.36774009E-05 0.47990270E-05-0.24474800E-01 0.44319732E-03-0.30463874E-01-0.27469337E-01
              7 0.15074215E-03-0.11467416E-03 0.81206042E-06-0.35321091E-02 0.15737723E-03-0.80595501E-02-0.57958290E-02
              8 0.34981524E-03 0.52733361E-04 0.11413758E-05 0.18862173E-01 0.32948749E-03 0.16584896E-01 0.17723534E-01
              9 0.61267894E-03-0.80659611E-05 0.63257085E-05-0.15330065E-01 0.62636589E-03-0.85253455E-02-0.11927705E-01
             10 0.23896278E-03-0.59822432E-05 0.99459339E-06-0.16364049E-01 0.25784690E-03-0.16540229E-01-0.16452137E-01
             11 0.28218934E-03 0.13787368E-04 0.88281422E-06-0.12884624E-02 0.28549996E-03-0.44727325E-02-0.28805975E-02
             12 0.58980775E-03-0.39224651E-05 0.54192342E-05 0.17652512E-01 0.56761317E-03 0.21012962E-01 0.19332737E-01
             13  2.7060757     0.36422080E-06 0.82929730E-02  218.94711      2.4547462      218.94292      218.94495
             14  218.94711     0.56013025E-07  15.669580      3.6300240      218.94292      3.7022800      3.6661520
  3.767     17.90       4.549    2.209       2.646       2.697      5.343        6.758      5.091   3201        8.53
  270.2     83.94       20.78    10.09       12.09       12.31      24.40      30.87      28.67       26     2091.08  63.31


ITERATION FAILURE        13     21
DEBUG OUTPUT FROM FWS3V2, FLOW CONTINUES
DEBUG PRINTOUT FROM FWS3V2 NUMBER      1
 -1.8488550     0.67807108      1.7777700     -1.0093880
  8.4564724      8.4434786      8.4009447     0.68388470E-02 0.22386253E-01  155.32376      84.119797
  10.532256      10.583419      10.630010     0.16398180E-01 0.17685641E-01  95.280701      65.120743
  8.4006414      8.3939114      8.4231005     0.35421478E-02-0.15362691E-01  69.150452      122.31084
  6.8018503      6.7706938      6.7370911    -0.26927751E-01-0.24521481E-01  135.37694      147.19954
  933.04053      670.08960      407.13867      933.04053      670.08960      407.13867
  933.04053      670.08960      407.13867      933.04053      670.08960      407.13867
  219.13310      3.6251764      24.417908      90.293518      34.929977      9.6353846
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  6.0000000      4.0000000     0.00000000     0.00000000     0.00000000
DEBUG PRINTOUT FROM FWS3V2 NUMBER      2
              1 0.34122425E-03-0.30216620E-06 0.18827641E-05-0.68388470E-02 0.34614024E-03-0.17336798E-02-0.42862631E-02
              2 0.35227183E-03 0.13753242E-05 0.15298938E-05-0.15547406E-01 0.37032505E-03-0.15932381E-01-0.15739892E-01
              3 0.42072404E-03-0.25613804E-06 0.38089847E-05 0.22386253E-01 0.39768941E-03 0.17780669E-01 0.20083461E-01
              4 0.26069884E-03 0.10765216E-05 0.10434396E-05 0.26927751E-01 0.22979786E-03 0.26956864E-01 0.26942305E-01
              5 0.44155261E-03-0.22081795E-05 0.17937127E-05-0.24062693E-02 0.44088671E-03 0.35657398E-02 0.57973526E-03
              6 0.41212025E-03 0.75434764E-06 0.48043148E-05-0.24521481E-01 0.44368673E-03-0.30522604E-01-0.27522042E-01
              7 0.15091080E-03-0.10253876E-03 0.81312339E-06-0.35421478E-02 0.15755363E-03-0.80695897E-02-0.58058687E-02
              8 0.35020383E-03 0.44601446E-04 0.11427246E-05 0.18904839E-01 0.32985443E-03 0.16605478E-01 0.17755158E-01
              9 0.61334926E-03-0.59714303E-05 0.63330199E-05-0.15362691E-01 0.62705064E-03-0.85358880E-02-0.11949290E-01
             10 0.23921287E-03-0.90203696E-06 0.99563658E-06-0.16398180E-01 0.25811652E-03-0.16565826E-01-0.16482003E-01
             11 0.28248131E-03 0.13715817E-05 0.88372758E-06-0.12874603E-02 0.28579566E-03-0.44913068E-02-0.28893836E-02
             12 0.59040473E-03-0.51222283E-07 0.54247266E-05 0.17685641E-01 0.56818686E-03 0.21057133E-01 0.19371387E-01
             13  2.7060795     0.33993888E-06 0.79968683E-02  219.13310      2.4547501      219.12891      219.13098
             14  219.13310     0.75821980E-08  15.682890      3.6251764      219.12891      3.6948719      3.6600237
ITERATION FAILURE        13     21
DEBUG OUTPUT FROM FWS3V2, FLOW CONTINUES
DEBUG PRINTOUT FROM FWS3V2 NUMBER      1
 -1.8487787     0.67828947      1.7776604     -1.0095730
  8.4610968      8.4481249      8.4055243     0.68273023E-02 0.22421386E-01  155.32195      84.115616
  10.537929      10.589179      10.635817     0.16410727E-01 0.17707225E-01  95.275513      65.122467
  8.4049740      8.3982439      8.4274426     0.35421478E-02-0.15367709E-01  69.153061      122.31578
  6.8053713      6.7741909      6.7405472    -0.26973929E-01-0.24546076E-01  135.38133      147.19705
  933.03564      670.08887      407.14209      933.03564      670.08887      407.14209
  933.03564      670.08887      407.14209      933.03564      670.08887      407.14209
  219.22597      3.6283350      24.428360      90.333954      34.960403      9.6353846
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
 0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000     0.00000000
  6.0000000      4.0000000     0.00000000     0.00000000     0.00000000
```

TABLE XVII. - Continued.

```
DEBUG PRINTOUT FROM FWS3V2 NUMBER       2
                    1 0.34140865E-03 0.22348377E-05 0.18837527E-05-0.68273023E-02 0.34632487E-03-0.17477339E-02-0.42875148E-02
                    2 0.35246601E-03-0.15709418E-06 0.15307351E-05-0.15594084E-01 0.37052715E-03-0.15913814E-01-0.15753947E-01
                    3 0.42092893E-03-0.15726409E-05 0.38108865E-05 0.22421386E-01 0.39788615E-03 0.17775830E-01 0.20098608E-01
                    4 0.26082643E-03-0.50635174E-06 0.10439426E-05 0.26973929E-01 0.22990997E-03 0.26959874E-01 0.26966900E-01
                    5 0.44179335E-03 0.33051456E-05 0.17946668E-05-0.24278536E-02 0.44112327E-03 0.35993680E-02 0.58575720E-03
                    6 0.41235285E-03-0.31140107E-05 0.48070524E-05-0.24546076E-01 0.44393935E-03-0.30559242E-01-0.27552657E-01
                    7 0.15099508E-03-0.10750498E-03 0.81359502E-06-0.35421478E-02 0.15764408E-03-0.80866553E-02-0.58143996E-02
                    8 0.35038497E-03 0.43564258E-04 0.11433212E-05 0.18909857E-01 0.33002486E-03 0.16633585E-01 0.17771721E-01
                    9 0.61368523E-03-0.54550219E-05 0.63364050E-05-0.15367709E-01 0.62739034E-03-0.85469298E-02-0.11957318E-01
                   10 0.23934574E-03-0.30426918E-05 0.99618319E-06-0.16410727E-01 0.25825924E-03-0.16585402E-01-0.16498063E-01
                   11 0.28262753E-03 0.90044668E-05 0.88419540E-06-0.12964979E-02 0.28594467E-03-0.44857822E-02-0.28911401E-02
                   12 0.59069274E-03-0.27902615E-05 0.54273296E-05 0.17707225E-01 0.56846230E-03 0.21071184E-01 0.19389205E-01
                   13  2.7059689     0.33995417E-06 0.60149133E-02  219.22597       2.4546394       219.22177       219.22375
                   14  219.22597     0.18097808E-07  15.689538       3.6283350      219.22177       3.6988306       3.6635828
   3.882       17.94       4.568       2.214       2.651       2.710       5.361       6.781       5.082     3301        8.55
   270.2       84.18       20.83       10.09       12.09       12.36       24.44       30.92       28.82       26     2094.63   63.42

ITERATION FAILURE          13       21

   5.130       18.23       4.702       2.260       2.700       2.865       5.566       6.962       4.974     4401        8.71
   270.2       85.50       21.04       10.12       12.09       12.82       24.91       31.16       29.43       26     2133.85   64.61

   5.242       18.25       4.719       2.265       2.705       2.880       5.585       6.983       4.953     4501        8.72
   270.2       85.59       21.08       10.12       12.09       12.87       24.95       31.20       29.44       26     2137.42   64.72

   5.354       18.27       4.725       2.269       2.709       2.894       5.604       6.994       4.942     4601        8.73
   270.2       85.70       21.08       10.12       12.09       12.91       25.00       31.20       29.51       26     2140.97   64.83

   5.466       18.28       4.736       2.273       2.714       2.909       5.623       7.010       4.925     4701        8.74
   270.2       85.82       21.09       10.12       12.09       12.95       25.04       31.22       29.57       26     2144.54   64.93

   5.578       18.30       4.753       2.278       2.718       2.923       5.642       7.031       4.901     4801        8.75
   270.2       85.95       21.13       10.13       12.09       12.99       25.08       31.26       29.61       26     2148.09   65.04

   5.690       18.32       4.765       2.282       2.723       2.938       5.661       7.047       4.883     4901        8.77
   270.2       86.07       21.15       10.13       12.09       13.04       25.12       31.28       29.67       26     2151.64   65.15

   5.801       18.34       4.815       2.286       2.727       2.952       5.680       7.102       4.825     5001        8.78
   270.2       86.18       21.34       10.13       12.09       13.08       25.17       31.47       29.55       26     2155.19   65.26

   5.912       18.35       4.825       2.291       2.732       2.967       5.699       7.116       4.807     5101        8.79
   270.2       86.29       21.35       10.13       12.09       13.12       25.21       31.48       29.60       26     2158.73   65.36

   6.023       18.37       4.798       2.295       2.736       2.981       5.718       7.093       4.825     5201        8.80
   270.2       86.43       21.19       10.14       12.09       13.17       25.25       31.33       29.84       26     2162.27   65.47

   6.134       18.38       4.812       2.300       2.741       2.996       5.737       7.111       4.802     5301        8.80
   270.2       86.56       21.22       10.14       12.09       13.21       25.30       31.36       29.91       26     2165.81   65.58

   6.245       18.40       4.820       2.304       2.745       3.011       5.756       7.124       4.783     5401        8.81
   270.2       86.68       21.22       10.14       12.09       13.25       25.34       31.36       29.98       26     2169.33   65.68

   6.355       18.41       4.868       2.308       2.750       3.025       5.775       7.176       4.724     5501        8.82
   270.2       86.82       21.40       10.15       12.09       13.30       25.38       31.54       29.90       26     2172.86   65.79
```

6.466 270.2	18.43 86.95	4.835 21.22	2.313 10.15	2.754 12.09	3.040 13.34	5.794 25.43	7.148 31.37	4.746 30.16	5601 26	8.83 2176.38	65.90
6.576 270.2	18.44 87.06	4.847 21.24	2.317 10.15	2.759 12.09	3.055 13.38	5.814 25.47	7.164 31.39	4.724 30.21	5701 26	8.84 2179.90	66.00
6.686 270.2	18.45 87.17	4.857 21.25	2.322 10.16	2.763 12.09	3.070 13.43	5.833 25.51	7.179 31.40	4.700 30.26	5801 26	8.85 2183.41	66.11
10.01 270.2	18.69 88.76	5.202 21.70	2.463 10.28	2.897 12.09	3.537 14.76	6.434 26.84	7.665 31.98	3.840 29.94	8901 26	9.01 2288.98	69.31
10.12 270.2	18.70 88.77	5.213 21.72	2.467 10.28	2.901 12.09	3.552 14.80	6.453 26.88	7.680 32.00	3.809 29.89	9001 26	9.01 2292.27	69.41
10.22 270.2	18.70 88.81	5.171 21.51	2.472 10.28	2.905 12.09	3.567 14.84	6.472 26.93	7.643 31.80	3.831 30.08	9101 26	9.01 2295.54	69.51
10.32 270.2	18.70 88.83	5.205 21.63	2.477 10.29	2.909 12.09	3.583 14.88	6.492 26.97	7.682 31.91	3.776 29.94	9201 26	9.02 2298.81	69.60
10.43 270.2	18.71 88.85	5.214 21.63	2.481 10.29	2.913 12.09	3.598 14.92	6.511 27.01	7.695 31.92	3.747 29.92	9301 26	9.02 2302.08	69.70
10.53 270.2	18.71 88.87	5.222 21.63	2.486 10.30	2.917 12.09	3.613 14.97	6.531 27.05	7.708 31.93	3.718 29.88	9401 26	9.02 2305.33	69.80
10.64 270.2	18.72 88.90	5.231 21.64	2.490 10.30	2.921 12.09	3.629 15.01	6.550 27.10	7.721 31.94	3.689 29.86	9501 26	9.03 2308.58	69.90
10.74 270.2	18.72 88.95	5.214 21.54	2.495 10.31	2.926 12.09	3.644 15.05	6.569 27.14	7.709 31.85	3.685 29.96	9601 26	9.03 2311.81	70.00
10.84 270.2	18.72 88.97	5.248 21.65	2.500 10.31	2.930 12.09	3.659 15.09	6.589 27.18	7.747 31.96	3.630 29.83	9701 26	9.03 2315.04	70.10
10.95 270.2	18.73 89.00	5.278 21.74	2.504 10.32	2.934 12.09	3.674 15.14	6.608 27.22	7.782 32.06	3.579 29.72	9801 26	9.04 2318.26	70.19
11.05 270.2	18.73 89.04	5.244 21.57	2.509 10.32	2.938 12.09	3.690 15.18	6.627 27.26	7.753 31.90	3.592 29.88	9901 26	9.04 2321.47	70.29
11.16 270.2	18.73 89.10	5.248 21.56	2.514 10.33	2.942 12.09	3.705 15.22	6.647 27.31	7.762 31.89	3.566 29.91	10001 26	9.04 2324.68	70.39
11.26 270.2	18.74 89.13	5.259 21.58	2.518 10.33	2.946 12.09	3.720 15.26	6.666 27.35	7.777 31.91	3.534 29.88	10101 26	9.05 2327.88	70.48
11.36 270.2	18.74 89.19	5.267 21.58	2.523 10.34	2.950 12.09	3.736 15.30	6.686 27.39	7.790 31.92	3.504 29.88	10201 26	9.05 2331.06	70.58
11.46 270.2	18.74 89.24	5.275 21.58	2.528 10.34	2.954 12.09	3.751 15.34	6.705 27.43	7.803 31.92	3.474 29.88	10301 26	9.05 2334.24	70.68
14.59 270.2	18.79 89.74	5.568 21.90	2.672 10.51	3.074 12.09	4.225 16.61	7.299 28.70	8.240 32.40	2.485 28.64	13401 26	9.12 2428.74	73.54

TABLE XVII. - Continued.

14.68 270.2	18.79 89.72	5.576 21.90	2.677 10.51	3.077 12.09	4.240 16.65	7.318 28.74	8.252 32.41	2.455 28.57	13501 26	9.13 2431.66	73.63
14.78 270.2	18.79 89.70	5.583 21.90	2.681 10.52	3.081 12.09	4.256 16.69	7.337 28.78	8.264 32.42	2.424 28.50	13601 26	9.13 2434.57	73.72
14.88 270.2	18.79 89.71	5.538 21.70	2.686 10.52	3.085 12.09	4.271 16.73	7.356 28.82	8.224 32.22	2.446 28.67	13701 26	9.13 2437.48	73.80
14.98 270.2	18.79 89.69	5.546 21.70	2.691 10.53	3.088 12.09	4.286 16.77	7.374 28.86	8.237 32.23	2.416 28.60	13801 26	9.13 2440.37	73.89
15.08 270.2	18.79 89.69	5.563 21.74	2.695 10.54	3.092 12.09	4.301 16.81	7.393 28.90	8.258 32.28	2.377 28.51	13901 26	9.13 2443.26	73.98
15.18 270.2	18.79 89.69	5.560 21.71	2.700 10.54	3.095 12.09	4.316 16.85	7.412 28.94	8.260 32.25	2.356 28.50	14001 26	9.14 2446.08	74.06
15.27 270.2	18.79 89.67	5.567 21.71	2.704 10.55	3.099 12.09	4.331 16.89	7.430 28.97	8.272 32.26	2.327 28.43	14101 26	9.14 2448.83	74.15
15.37 270.2	18.79 89.65	5.574 21.71	2.709 10.55	3.102 12.09	4.345 16.93	7.448 29.01	8.283 32.27	2.299 28.37	14201 26	9.14 2451.56	74.23
15.47 270.2	18.79 89.63	5.581 21.72	2.713 10.56	3.106 12.09	4.360 16.96	7.466 29.05	8.294 32.28	2.270 28.30	14301 26	9.14 2454.30	74.31
15.57 270.2	18.79 89.60	5.588 21.72	2.718 10.56	3.109 12.09	4.375 17.00	7.484 29.09	8.305 32.28	2.241 28.23	14401 26	9.14 2457.03	74.40
15.67 270.2	18.79 89.57	5.595 21.72	2.722 10.57	3.113 12.09	4.389 17.04	7.502 29.13	8.317 32.29	2.213 28.15	14501 26	9.14 2459.76	74.48
15.76 270.2	18.79 89.55	5.601 21.72	2.727 10.58	3.116 12.09	4.404 17.08	7.520 29.16	8.328 32.30	2.184 28.08	14601 26	9.15 2462.49	74.56
15.86 270.2	18.79 89.51	5.608 21.73	2.731 10.58	3.120 12.09	4.418 17.12	7.538 29.20	8.339 32.31	2.155 28.00	14701 26	9.15 2465.22	74.64
15.96 270.2	18.79 89.47	5.615 21.73	2.736 10.59	3.123 12.09	4.433 17.15	7.556 29.24	8.351 32.32	2.127 27.92	14801 26	9.15 2467.95	74.73
18.90 270.1	18.80 88.60	5.813 21.78	2.874 10.77	3.225 12.09	4.882 18.29	8.108 30.38	8.686 32.55	1.251 25.67	17901 26	9.20 2548.65	77.17
18.99 270.1	18.80 88.58	5.819 21.78	2.878 10.78	3.228 12.09	4.897 18.33	8.125 30.42	8.697 32.56	1.223 25.61	18001 26	9.20 2551.16	77.25
19.09 270.1	18.80 88.55	5.832 21.81	2.883 10.78	3.232 12.09	4.911 18.37	8.143 30.45	8.715 32.59	1.188 25.51	18101 26	9.20 2553.67	77.32
19.18 270.1	18.80 88.53	5.838 21.81	2.887 10.79	3.235 12.09	4.926 18.40	8.161 30.49	8.725 32.60	1.160 25.44	18201 26	9.20 2556.18	77.40

19.27	18.80	5.837	2.892	3.238	4.940	8.178	8.729	1.138	18301	9.20	
270.1	88.50	21.79	10.79	12.09	18.44	30.52	32.58	25.40	26	2558.67	77.47
19.37	18.80	5.844	2.896	3.241	4.955	8.196	8.740	1.109	18401	9.20	
270.2	88.48	21.79	10.80	12.09	18.47	30.56	32.59	25.34	26	2561.15	77.55
19.46	18.80	5.850	2.901	3.244	4.969	8.213	8.750	1.081	18501	9.21	
270.2	88.47	21.79	10.81	12.09	18.51	30.59	32.60	25.28	26	2563.62	77.62
19.55	18.80	5.856	2.905	3.247	4.983	8.231	8.761	1.053	18601	9.21	
270.2	88.44	21.79	10.81	12.09	18.54	30.63	32.61	25.21	26	2566.09	77.70
19.64	18.80	5.862	2.909	3.250	4.998	8.248	8.771	1.025	18701	9.21	
270.2	88.42	21.80	10.82	12.09	18.58	30.67	32.61	25.14	26	2568.54	77.77
19.74	18.80	5.868	2.914	3.254	5.012	8.265	8.782	0.9974	18801	9.21	
270.2	88.39	21.80	10.82	12.09	18.62	30.70	32.62	25.07	26	2570.97	77.85
19.83	18.80	5.874	2.918	3.257	5.026	8.283	8.792	0.9692	18901	9.21	
270.2	88.37	21.80	10.83	12.09	18.65	30.74	32.63	25.01	26	2573.41	77.92
19.92	18.80	5.880	2.923	3.260	5.040	8.300	8.803	0.9412	19001	9.21	
270.2	88.36	21.80	10.84	12.09	18.69	30.77	32.64	24.95	26	2575.83	77.99
20.02	18.80	5.886	2.927	3.263	5.054	8.317	8.813	0.9135	19101	9.21	
270.2	88.34	21.80	10.84	12.09	18.72	30.81	32.65	24.88	26	2578.26	78.07
20.11	18.80	5.899	2.931	3.266	5.069	8.335	8.831	0.8780	19201	9.21	
270.0	88.36	21.83	10.85	12.09	18.76	30.84	32.68	24.83	26	2580.67	78.14
20.20	18.80	5.913	2.936	3.269	5.083	8.352	8.849	0.8431	19301	9.22	
270.0	88.35	21.86	10.85	12.09	18.79	30.88	32.72	24.75	26	2583.06	78.21
24.35	18.80	6.172	3.135	3.401	5.723	9.124	9.307	-0.3788	23901	9.28	
270.1	87.42	21.93	11.14	12.09	20.34	32.42	33.08	21.92	26	2687.30	81.37
24.44	18.80	6.180	3.139	3.403	5.737	9.140	9.319	-0.4072	24001	9.28	
270.1	87.43	21.95	11.15	12.09	20.37	32.46	33.09	21.88	26	2689.43	81.43
24.53	18.80	6.185	3.144	3.406	5.751	9.157	9.329	-0.4332	24101	9.28	
270.1	87.45	21.95	11.15	12.09	20.40	32.49	33.10	21.86	26	2691.57	81.50
24.62	18.80	6.184	3.148	3.409	5.764	9.173	9.332	-0.4534	24201	9.28	
270.2	87.46	21.93	11.16	12.09	20.43	32.52	33.09	21.85	26	2693.70	81.56
24.71	18.80	6.193	3.152	3.412	5.778	9.189	9.346	-0.4822	24301	9.28	
270.2	87.48	21.94	11.17	12.09	20.47	32.55	33.11	21.82	26	2695.83	81.63
24.79	18.80	6.194	3.156	3.414	5.792	9.206	9.351	-0.5041	24401	9.28	
270.2	87.49	21.93	11.17	12.09	20.50	32.59	33.10	21.81	26	2697.95	81.69
24.88	18.80	6.217	3.161	3.417	5.805	9.222	9.378	-0.5472	24501	9.28	
270.2	87.51	21.99	11.18	12.09	20.53	32.62	33.17	21.72	26	2700.06	81.75
24.97	18.80	6.249	3.165	3.420	5.819	9.238	9.414	-0.5995	24601	9.29	
270.2	87.51	22.09	11.19	12.09	20.56	32.65	33.27	21.59	26	2702.17	81.82

TABLE XVII. - Concluded.

```
25.06      18.80      6.211      3.169      3.422      5.832      9.255      9.380     -0.5825     24701          9.29
270.2      87.53      21.93      11.19      12.09      20.60      32.68      33.13       21.73        26       2704.28  81.88

25.15      18.80      6.218      3.174      3.425      5.846      9.271      9.392     -0.6115     24801          9.29
270.2      87.58      21.94      11.20      12.09      20.63      32.71      33.14       21.72        26       2706.38  81.95

25.24      18.80      6.228      3.178      3.428      5.860      9.287      9.406     -0.6420     24901          9.29
270.2      87.59      21.96      11.21      12.09      20.66      32.75      33.17       21.68        26       2708.49  82.01

25.33      18.80      6.252      3.182      3.430      5.873      9.304      9.434     -0.6865     25001          9.29
270.2      87.62      22.03      11.21      12.09      20.69      32.78      33.24       21.61        26       2710.58  82.07

           TERMINATED: STOP

                                 CPU TIME=    13.48 MINUTES.
```

TABLE XVIII. - INPUT ROUTINE (MAINSE) FOR SHORT-CIRCUIT TRANSIENT

```
C       INPUT DATA FOR THE FOUR WORKING SPACE THREE VOLUME
C       STIRLING ENGINE MODEL.
C
      COMMON/PST/AD,AR,RODL,VOE,VOC,VR,RER,RRC,STROKE,ALPHA,PSIMD
      COMMON/CARLOD/GTRAN,GR,AIE,AIWHEL,AIVEH,RWHEEL,AINERT
      COMMON/CONST/R,G,PIE,DEGR
      COMMON/MATXIN/VDELTA,FRAC,TOL1,TOL2,TOLSS,N,NTMAX,MPAS,
     1              TOLPCG,REF
      COMMON/SWITCH/ISS,ICALC,MATRIX,NONENG,IPRTOP,IBRYTH,
     1              IHPCNV,NOBUG
      COMMON /SHRTCT/ WD1IN,WD2IN,WD3IN,WD4IN,WD1OUT,WD2OUT,WD3OUT,WD40U
     1T,WDSHT,WSTMXD,WSTMND,PSHTMX,PSHTMN,WSMX1,WSMN1,VSH,RSHT,RSHTT
      COMMON/RUNCON/ALEAK,ARLEAK,PSOURC,CYCLPR,SPDRPM,POSDEO,
     1             WSTOTL,TWHIN,TWCIN,CYCLPM,SPDMAX
      COMMON/CYDATA/NPTPCY,ITRMAX,NUMBCY
      COMMON/TRANDS/ISUPST,ISHTST,TIME,KWORK,ISPSTP,ISHSTP
      COMMON/OUTPT/POSDEG,WTOT,ITRAN,WT1,WT2,WT3,WT4,WD1,WD2,WD3,WD4,
     1WD5,WD6,WD7,WD8,TORQ1,TORQ2,TORQ3,TORQ4,POWER1,POWER2,POWER3,
     2POWER4,POWERT,TORQT,TLOAD,TENG,PLOAD,PENG,PNET,PAVEMP,CCCHK
C
C
C       ENGINE GEOMETRY
      AD=23.7613
      AR=1.1290
      RODL=10.0
      VR=115.339
      VOE=63.87
      VOC=61.70
      STROKE=4.00
      ALPHA=90.0
C
C       HEATER AND COOLER WALL TEMPERATURES
      TWHIN=705.0
      TWCIN=86.0
C
C       FLOW RESISTANCES BETWEEN VOLUMES
      RER=1.9
      RRC=1.9
C
C       CONSTANTS
      DEGR=57.296
      PIE=3.1416
      R=4125.6
      G=10017.0
C
```

```
C      MATRIX CONVERGENCE INPUT
      VDELTA=.01
      FRAC=1.0
      TOL1=.001
      TOL2=.01
      TOLSS=.0001
      N=14
      NTMAX=16

      MPAS=20
      TOLPCG=.5
C
C      SWITCHES
      ISS=0
      ICALC=1
      MATRIX=1
      NONENG=1
      IPRTOP=100
      IBRYTH=0
      IHPCNV=0
      NOBUG=1
C
C      RUN CONDITIONS
      ALEAK=0.0
      ARLEAK=0.0
      PSOURC=10.0
      CYCLPM=15.0
      SPDMAX=4000.0
      CYCLPR=15.0
      SPDRPM=4000.0
      POSDEO=270.0
      WSTOTL=.007786
      VSH=32.78
      RSHT=38.0
      ASHTT=.20
C
C      LOAD CHARACTERISTICS
      GTRAN=1.0/2.53
      GR=2.84
      WTENG=0.0
      WTWHEL=29.48
      WTCAR=1420.0
      RWHEEL=30.48
C
C      CYCLE DATA
      NPTPCY=25
      NUMBCY=1000
C
C      TRANSIENT DESIRED
      NCYSHT=5
      NCYSUP=50000
      NCYSTP=50000
      NCYSHS=60000
C
C      CALCULATED INPUT
      PSHTMX=CYCLPR+1.0
      PSHTMN=CYCLPR-1.0
      IF (NONENG .EQ. 0) N=12
      REF=(TOL1+TOL2)/2.0
      RWHELM=RWHEEL/100.0
      ITRMAX=NPTPCY*NUMBCY+1
      ISUPST=NCYSUP*NPTPCY+1

      ISHTST=NCYSHT*NPTPCY+1
      ISPSTP=NCYSTP*NPTPCY+1
      ISHSTP=NCYSHS*NPTPCY+1
      RSHTT=ASHTT/RSHT
      AIE=0.0
      WTWHEL=WTWHEL*4.0
      AIWHEL=(WTWHEL/2.0)*(RWHELM**2+(RWHELM/2.0)**2)
      AIVEH=WTCAR*RWHELM**2
      CALL ICSTUP
      STOP
      END
```

TABLE XIX. - UPDATE STRATEGIES FOR JACOBIAN MATRIX

Broyden algorithm used	TOLPCG	Strategy
No	1.0 - 0.5	Use current matrix
	<0.5	Generate new matrix
Yes	1.0 - 0.7	Use current inverse
	0.7 - 0.0	Update inverse with algorithm
	<0.0	Generate new matrix

1. Report No. NASA TM-82774	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle COMPUTER PROGRAM FOR A FOUR-CYLINDER-STIRLING-ENGINE CONTROLS SIMULATION	5. Report Date June 1982 6. Performing Organization Code 778-35-03
7. Author(s) Carl J. Daniele and Carl F. Lorenzo	8. Performing Organization Report No. E-1103
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Vehicle and Engine R&D Washington, D.C. 20545	13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/51040-37

15. Supplementary Notes

Final report. Prepared under Interagency Agreement DE-AI01-77CS51040.

16. Abstract

A four-cylinder-Stirling-engine, transient-engine-simulation computer program is presented. The program is intended for controls analysis. The associated engine model has been simplified to shorten computer calculation time. The model includes engine mechanical drive dynamics and vehicle load effects. The computer program also includes subroutines that allow (1) acceleration of the engine by addition of hydrogen to the system and (2) braking of the engine by short circuiting of the working spaces. Subroutines to calculate degraded engine performance (e.g., due to piston ring and piston rod leakage) are provided. Input data required to run the program are described and flow charts are provided. The program is modular to allow easy modification of individual routines. Examples of steady-state and transient results are presented.

17. Key Words (Suggested by Author(s)) Stirling engine; Controls; Modeling; Automotive; Computer program	18. Distribution Statement Unclassified - unlimited STAR Category 34 DOE Category UC-96

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 80	22. Price* A05

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1982

National Aeronautics and
Space Administration

Washington, D.C.
20546