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SUBJECT DIGITAL COMPUTER SIMULATION OF A FREE PISTON GASIFIER

PREPARED BY K. C. Cowan*

ISSUED TO Internal

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*Summer Student, 1965, University of Toronto.

1.0 INTRODUCTION

At present, considerable research is being carried out on the operating characteristics of the free piston gasifier. The chief application of such a gasifier is as a source of hot gases at high velocity to drive a gas turbine. The engine also has potential application as an air compressor and, with modifications, as a hydrostatic pump.

The dynamics of the free pistons are critically dependent on the controlled parameters of the engine, and hence engine control is an important branch of the research. The high operating speeds (in the region of 2000 rpm) do not allow a detailed study of transient responses on the engine itself. As a result, a computer simulation was constructed to study the control aspects.

This memo will provide a brief description of the actual engine and the model chosen to represent it. The simulation itself will be described in sufficient detail that the memo may be used as an operating manual. A complete list of the symbols used in the description and in the computer simulation is given in an Appendix.

2.0 DESCRIPTION OF THE FREE PISTON GASIFIER

The free piston gasifier consists of a cylinder in which two horizontally-opposed pistons are free to move under the influence of gas pressures in the bounce, compressor, and diesel cylinders. A typical configuration of these cylinders is shown in Figure 1.

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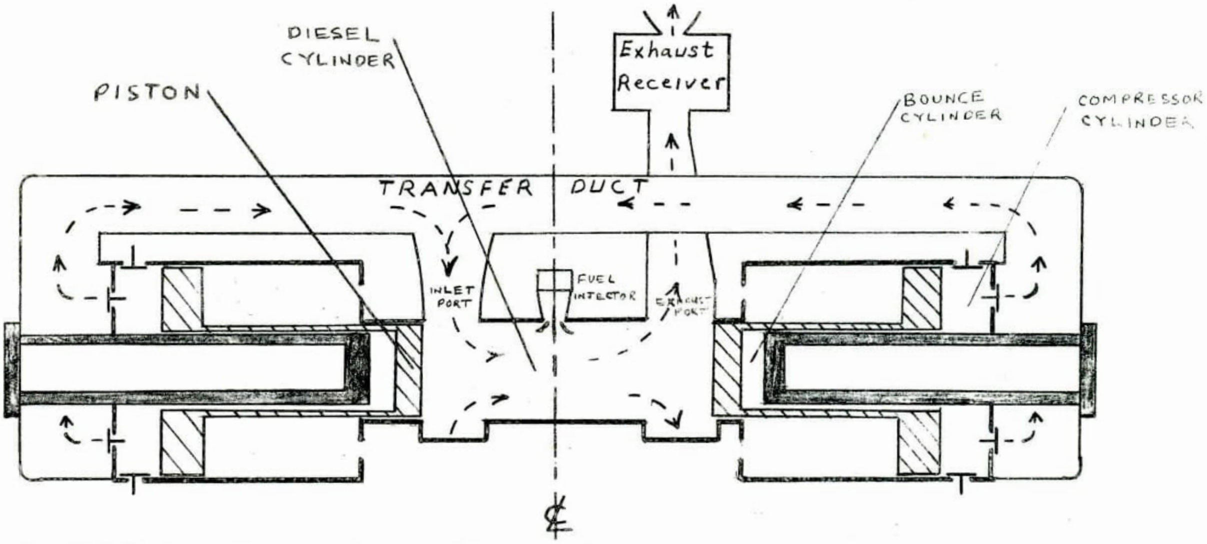


FIGURE 1: Typical Configuration in a Free Piston Gasifier

Combustion occurs in the diesel cylinder. The compressor cylinder is a source of compressed air; the bounce cylinder stops the pistons on their outward stroke after combustion and propels them on their inward stroke. The only mechanical constraint on the pistons is a rack and pinion arrangement which ensures that their motion is equal and opposite. As Figure 1 indicates, the engine is symmetrical about the centerline except for a slight difference in length of the transfer ducts, and hence only one half of the engine will be described.

2.1 Steady-State Operation

During steady-state operation, the following processes occur concurrently in the three cylinders:

(1) Diesel Cylinder - as the piston moves inward, it covers the exhaust ports and begins compressing the air in the diesel cylinder. When it reaches a specified displacement, diesel fuel is injected. The rising temperature in the cylinder causes combustion to begin and this in turn results in a rising pressure which rapidly brings the piston to rest at the 'inner dead point' (I.D.P.). As combustion

proceeds, the piston is forced outward by the hot expanding gas and, as the last of the fuel is burned, the pressure begins to drop. When the piston uncovers the exhaust ports, the diesel pressure 'blows down' very quickly to the delivery pressure in the exhaust receiver. The inlet ports are uncovered after blowdown, and pressurized gas from the compressor is forced into the diesel cylinder through the transfer duct. This, in turn, aids the flow of the hot exhaust gases into the exhaust receiver, and provides air for combustion on the next stroke. This process of removing the hot exhaust gases is known as 'scavenging'. The diesel pressure then remains at the delivery pressure while the piston reverses direction until the exhaust ports are again closed at the beginning of the next cycle.

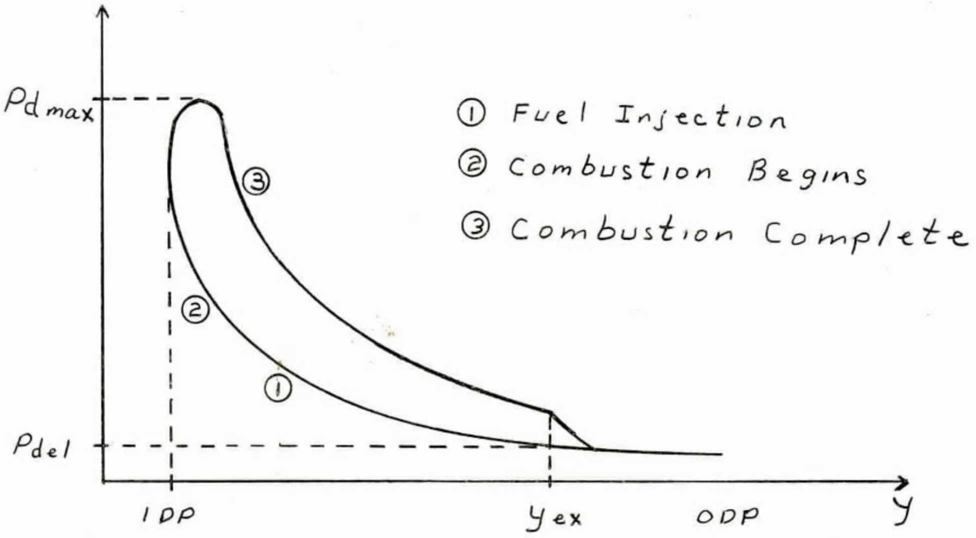


FIGURE 2: Variation of Diesel Pressure (P_d) with Piston Stroke (y).

(2) Bounce Cylinder - On the outward or power stroke, the air that is trapped in the bounce cylinder is compressed by the piston. The increasing force exerted by the trapped air ultimately brings the piston to a rest at 'outer dead point'(O.D.P.). At this point of the cycle, the bounce pressure predominates and propels the piston on its inward stroke. As the bounce pressure drops during expansion (diesel compression stroke), it is maintained above a specified 'bounce reference pressure' (P_{bref}) by an adjustable spring-loaded valve and an auxiliary supply of air.

Typical indicator diagrams are shown for all three cylinders. It should be noted that pressure is plotted against stroke (piston displacement) instead of volume in the respective cylinders; P-V diagrams for the bounce and compressor cylinders would show the highest pressures nearest the origin.

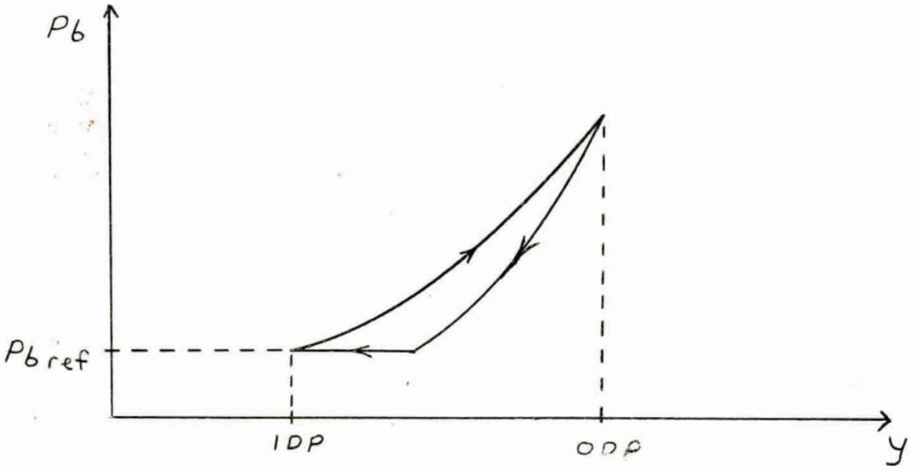


FIGURE 3: Bounce Pressure (P_b) Variation with Leakage

(3) Compressor Cylinder - As the piston approaches inner dead point, air is drawn into the compressor cylinder from the atmosphere. When the piston reverses, the inlet

valve closes, and the air is compressed until the pressure rises to the required inlet pressure for the diesel cylinder. At this point, the air is discharged through a valve into the transfer duct, and thus through the inlet ports into the diesel cylinder. Discharge continues until the piston reverses direction again. On the inward stroke, the clearance air in the compressor expands to atmospheric pressure after which more air is drawn into the cylinder from the atmosphere.

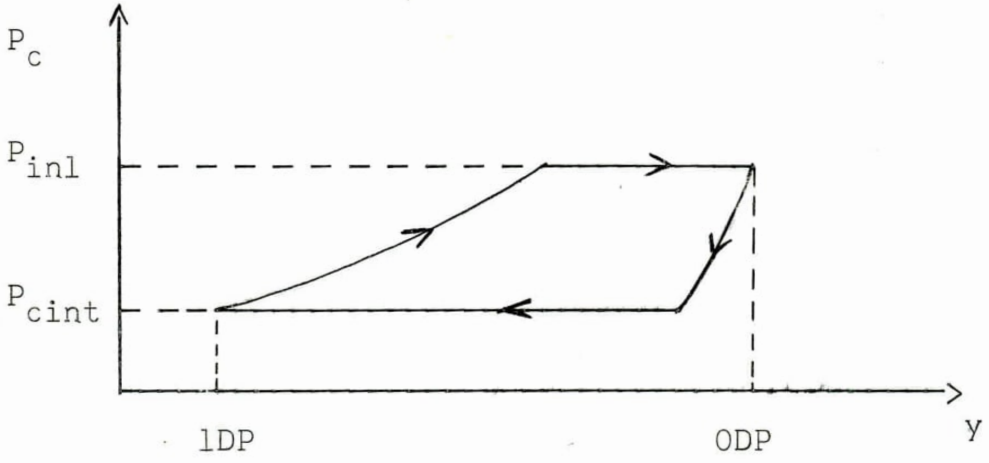


FIGURE 4: Compressor Pressure (P_c) Variation

In addition, the back of the piston in the compressor cylinder is open to the atmosphere. At present, throttling of the air through the openings causes a pressure variation about atmospheric. This back pressure opposes the effect of the bounce pressure. By suitable design, the pressure could be held below atmospheric pressure to supplement the bounce pressure. In such an application, this cylinder would be a negative bounce cylinder.

2.2 Transient Operation

Under transient conditions, it is necessary to consider the variations of physical quantities which are normally constant during steady-state running. The most severe transient condition occurs during engine starting. When the engine is cold, combustion is inefficient. For the first few cycles the inlet and delivery pressures are building up to their steady-state values. The inlet pressure build-up is determined by the size of the transfer duct and the delivery pressure build-up in the diesel cylinder.

The delivery pressure build-up is controlled by many factors such as the size and shape of the exhaust receiver, and the rate of gas discharged from the diesel cylinder. There is generally a pressure difference between the transfer duct and the exhaust receiver which may be attributed to throttling of the air by the inlet and exhaust ports.

3.0 METHOD OF SOLUTION

3.1 Type of Simulation

Since the model is intended for the investigation of transient responses associated with step changes in input and output, a dynamic simulation is necessary. The motion of the piston is determined by a summation of the forces acting on it, and a single and double integration of the resultant acceleration. Once the new displacement is known, corresponding pressures are calculated in the various cylinders and another summation of forces is carried out. Continuous calculation and integration provides the desired dynamic simulation.

Such operations can be performed most quickly on an analog computer, most accurately on a digital computer, and most satisfactorily on a hybrid system of both types.

3.2 The Model of the Engine

The dynamic simulation requires specific values of the cylinder pressures and hence a model of their pressure variations has to be chosen. Simulation of only one of the pistons is adequate on account of the symmetry of the engine. The assumptions made in the construction of the model are itemized below. In all cylinders, compression and expansion are assumed to be polytropic.

3.2.1 Diesel Cylinder

Since injection occurs on each cycle, the combustion process in the gasifier is similar to that of a reciprocating diesel engine. A good approximation to this process consists of a constant volume step followed by a constant pressure expansion. Figure 5 shows the idealized cycle that is simulated. The numbers in Figures 5, 6 and 7 refer to the descriptions following each.

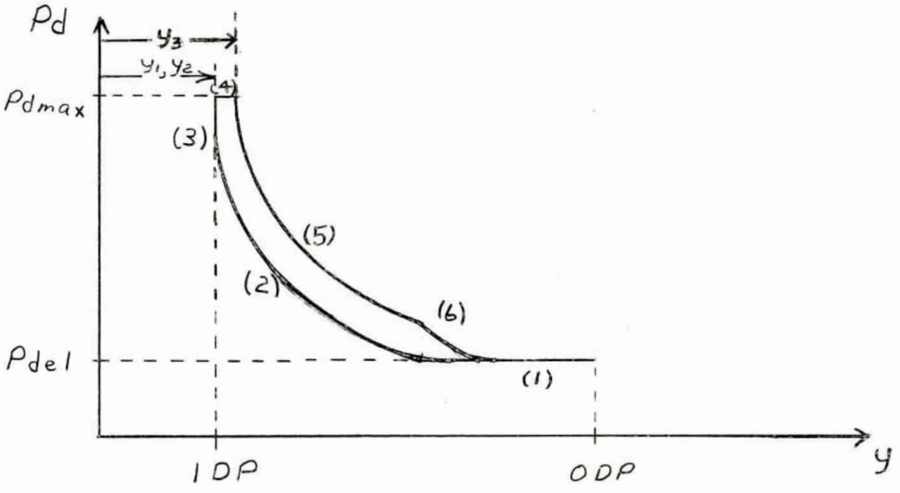


FIGURE 5: Diesel Pressure Variation

(1) Constant pressure (P_{del}) exhaust and intake.

(2) Compression obeying the equation

$$P_d y_d^{\gamma_2} = \text{CONSTANT}$$

(3) Constant volume combustion up to the maximum allowed diesel pressure (P_{dmax}) or some lower pressure, depending on the fuel setting.

(4) If the fuel setting is large enough, constant pressure combustion occurs, with the point y_3 being determined by an energy balance to be described later.

(5) Expansion obeying $P_d y_d^{\gamma 3}$ = CONSTANT

(6) Blow-down after exhaust ports open.

3.2.2 Bounce Cylinder

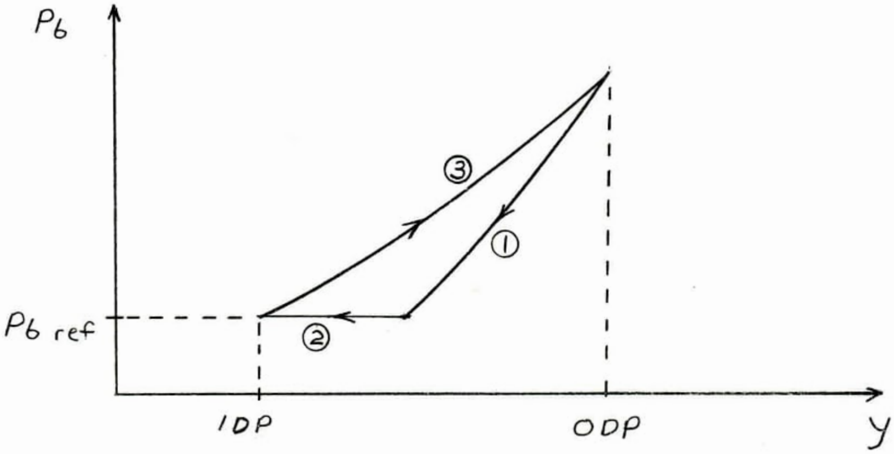


FIGURE 6: Bounce Pressure Variation

(1) Expansion according to $P_b y_b^{\gamma 4}$ = CONSTANT

(2) Constant pressure air intake if P_b drops to P_{bref}.

(3) Compression according to $P_b y^{\gamma 5}$ = CONSTANT.
Note: $\gamma 5 < \gamma 4$ provides a simulation of leakage.

3.2.3 Compressor Cylinder

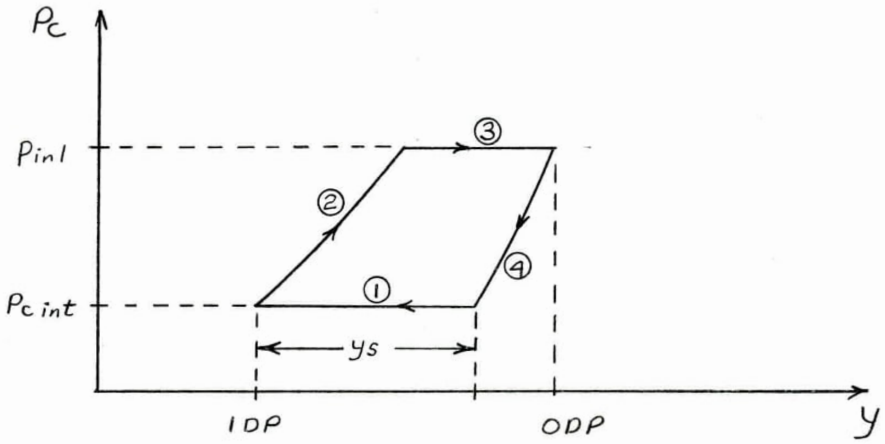


FIGURE 7: Compressor Pressure Variation

(1) Air intake from the atmosphere at P_{cint}

(2) Compression according to $P_c y_c^{\gamma 1}$? = CONSTANT ?

(3) Air discharge into transfer duct at P_{inl}, the pressure in the duct   Leakage ?

(4) Expansion according to $P_c y_c^{\gamma 1_x}$ = CONSTANT ? of the clearance air   ?

$\gamma_{1_x} < \gamma 1$

3.2.4 Negative Bounce Cylinder

This cylinder contributes a constant back pressure which is 1.0 psi below above atmospheric on outward stroke and 1.0 psi below atmospheric on the inward stroke. inward ?   reverse ? ?

3.2.5 Transfer Duct

To avoid excessive complexity in the simulation, the transfer duct is considered sufficiently large that the compressor can discharge air into it at constant pressure; otherwise, additional differential equations would be required to describe the gas dynamics within the duct. The pressure in the duct (P_{inl}) is estimated using the delivery pressure

(P_{del}) and the known pressure difference between inlet and exhaust through the diesel cylinder.

3.2.6 Exhaust Receiver

The exhaust receiver acts as a capacitor in that the slug of gas, which flows into it from the diesel cylinder during exhaust port opening, and the resulting pressure pulse are dissipated over a period of the complete cycle. An estimate of the actual pressure pattern over a series of cycles during starting is shown below superimposed on a diesel cylinder pressure record.

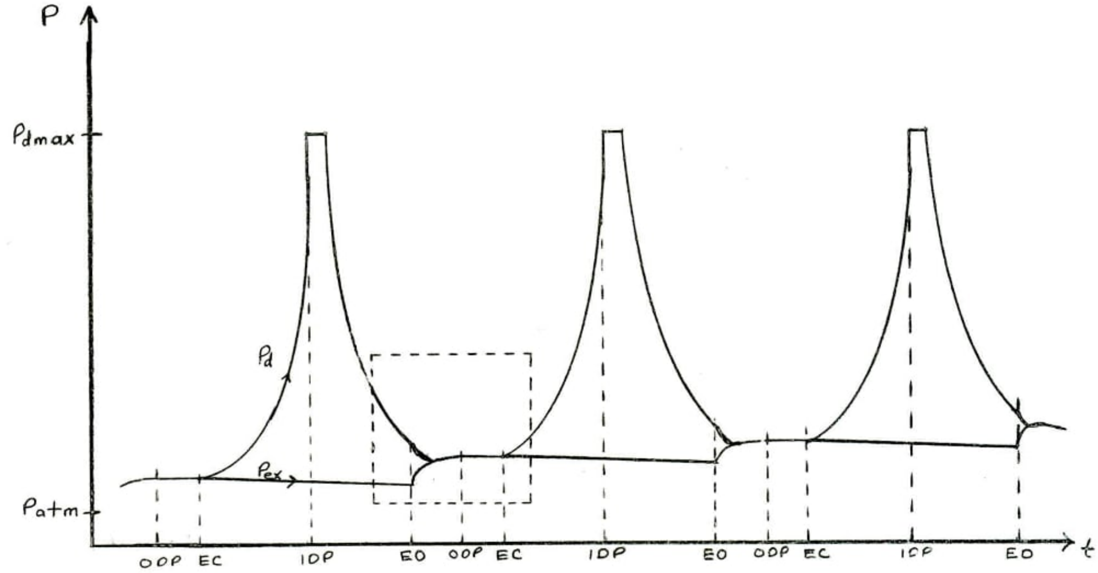


FIGURE 8: Diesel and Exhaust Pressure

where E.O. - exhaust port open
E.C. - exhaust port closed
I.O. - inlet port open
I.C. - inlet port closed

An enlarged view of the section enclosed by the dotted line is shown below.

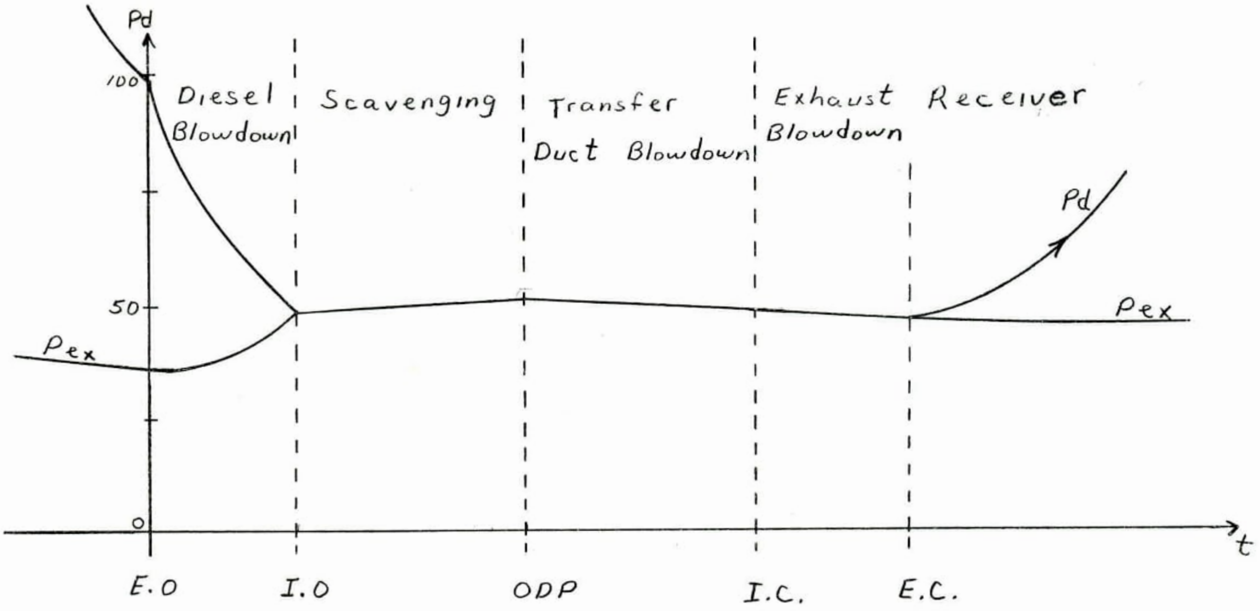


FIGURE 9: Exhaust Pressure Fluctuation

For steady operating conditions it can be shown by calculation that when the exhaust port is closed (E.C.), the pressure in the exhaust receiver has decayed to approximately 0.97 of its initial value at E.O. Since the pressure fluctuations during exhaust opening are small it is assumed that the exhaust receiver accepts the total slug of gas for the cycle at the ODP and the value of delivery pressure for that portion of the cycle is set at the pressure which exists in the exhaust receiver after it receives this slug of hot exhaust gas. Since fluctuations in mass and pressure are small it is assumed that the temperature remains constant during each cycle.

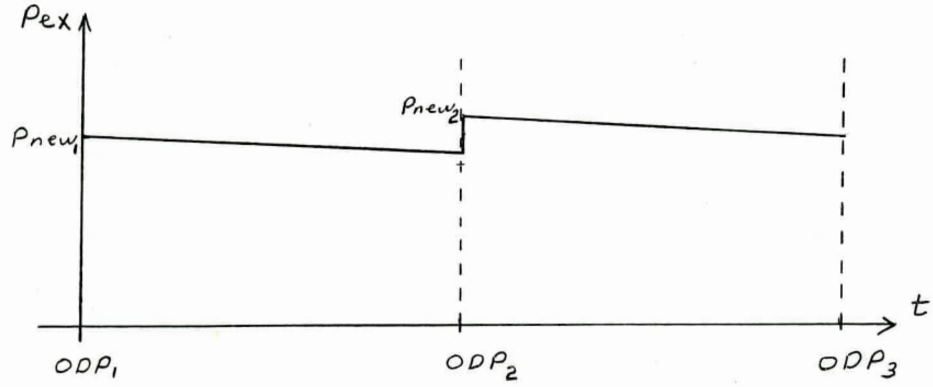


FIGURE 10: Idealized Exhaust Pressure Variation

3.3 Energy and Flow Equations

3.3.1 Mass Flow from Diesel Cylinder

Assuming constant suction pressure and temperature and therefore constant density of air, ρ_s, the mass of air (m_s) drawn into the compressor on each stroke is directly proportional to length (y_s) of that portion of the stroke during which the compressor intake valve is open, i.e.,

$$\begin{aligned} m_s &= \rho_s V_s \\ &= \rho_s \cdot A_c \cdot y_s \end{aligned}$$

The leakage ratio (R_L), defined as the mass output (m_{del}) per unit mass input, may be considered constant for a given engine under fixed operating conditions. Hence

$$R_L = \frac{m_{del}}{m_s}$$

or

$$m_{del} = R_L \cdot m_s = (R_L \cdot \rho_s \cdot A_c) y_s$$

Each half of the engine contributes this amount. Thus for the whole engine.

$$m_{del} = 2 \cdot k_1 \cdot y_s \qquad \ldots(3.1)$$

where $k_1 = R_L \cdot \rho_s \cdot A_c$

If the period of the engine cycle is known, the delivered or output mass flow rate is found from

$$\omega_{del} = \frac{m_{del}}{\text{period}} \qquad \ldots(3.2)$$

3.3.2 Temperature of Delivered Gas

If the gasifier is considered as an isolated system with imputs, outputs and losses, the delivery temperature may be calculated by means of an energy balance.

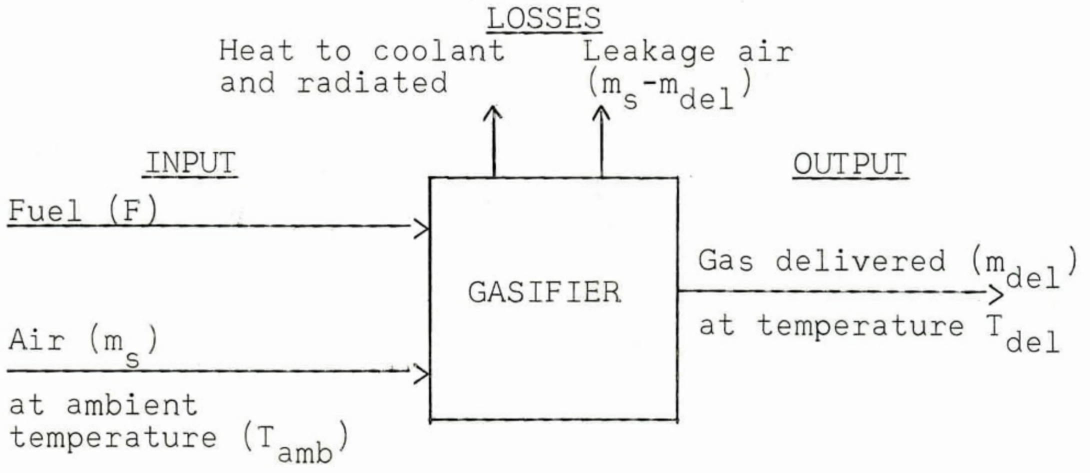


FIGURE 11: Isolated System

If the losses are included in an efficiency term η, and the calorific value of the fuel is C.V., then

$$m_{del} \cdot C_p \cdot (T_{del} - T_{amb}) = \eta \,.F.(C.V.)$$

where C_p = average specific heat (constant pressure) of delivered gas over the operating temperature range.

F_1 = fuel setting for whole engine.

Rearranging and solving for T_{del} gives

$$T_{del} = T_{amb} + \frac{k_2 F_1}{m_{del}} , \quad \text{where } k_2 = \frac{\eta .(C.V.)}{C_p}$$

$$\therefore \quad T_{del} = T_{amb} + \frac{k_2 F_1}{2 k_1 y_s} \qquad \ldots(3.3)$$

3.3.3 Combustion Process

The distance the piston moves during constant pressure combustion is evaluated by means of an energy balance between states 1 and 3 of Figure ~~13~~ 12.

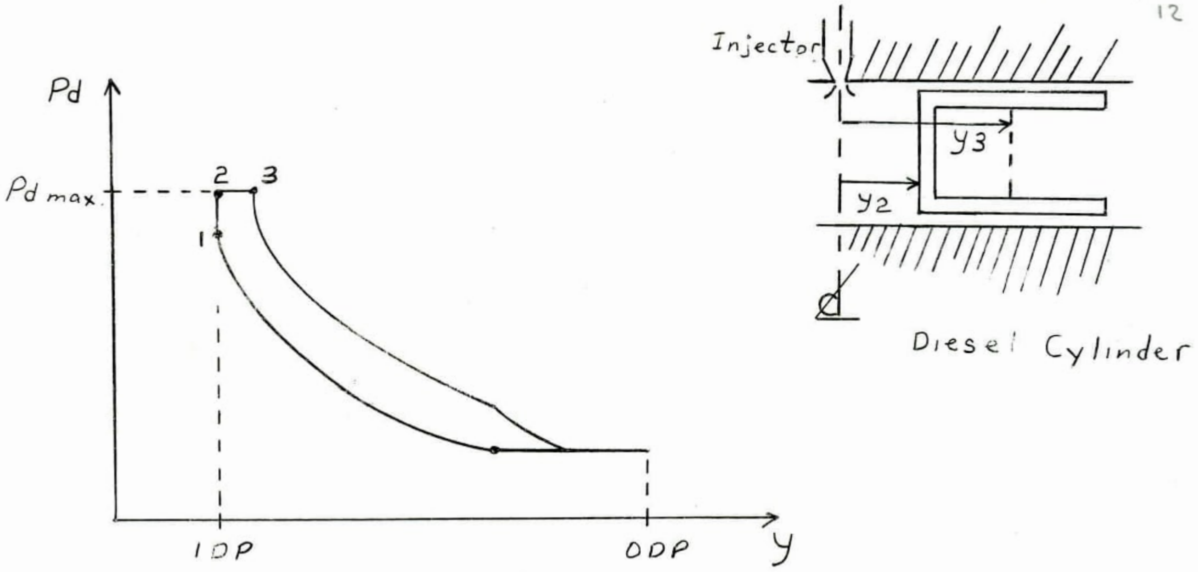


FIGURE 12: Combustion Process

The energy balance is performed for a control volume of gas in the diesel cylinder, under the assumption that the gas obeys the following perfect gas relationships:

(i) the specific heats, C_p and C_v, are constant, and $C_p-C_v = R/J$ where R is the gas constant for air and J is Joule's constant.

(ii) $PV = mRT$.

In addition, it is assumed that all losses due to combustion inefficiency, leakage, and heat transfer can be combined in a single efficiency factor, η_c.

Thus an energy equation can be written for the control volume

$$\underset{\substack{\uparrow \\ \text{net} \\ \text{energy added}}}{F.(C.V.)\eta_c} = \underbrace{\underset{\substack{\uparrow \\ \text{state 1 - 2}}}{mC_v(T_2-T_1)} + \underset{\substack{\uparrow \\ \text{state 2 - 3}}}{mC_p(T_3-T_2)}}_{\text{energy absorbed}}$$

Substituting

$$C_v = C_p - R/J \qquad 1/\gamma = 1 - R/C_pJ$$

$$T = PV/mR$$

$$F.(C.V.)\eta_c = m(C_p - \frac{R}{J})(T_2 - T_1) + mC_p(T_3 - T_2)$$

$$= \frac{C_p}{R}(P_3V_3 - P_1V_1) - \frac{1}{J}(P_2V_2 - P_1V_1)$$

but $P_3 = P_2$, $V_1 = V_2$, $\gamma = C_p/C_V$.

Then, multiplying by R/C_p and noting that $\frac{R}{C_pJ} = 1 - \frac{1}{\gamma}$

$$\frac{F.(C.V.)\eta_c R}{C_p} = (P_2V_3 - P_1V_2) - (1 - \frac{1}{\gamma})(P_2V_2 - P_1V_2)$$

$$= P_2[V_3 - V_2 + \frac{V_2}{\gamma}(\frac{P_2 - P_1}{P_2})]$$

Solving for V_3 yields

$$V_3 = V_2 + \frac{1}{P_2}[\frac{F.(C.V.)\eta_c R}{C_p} - \frac{V_2(P_2 - P_1)}{\gamma}]$$

Starting point or inner mechanical limit $y_0 = 0$

but since the effective diesel clearance distance is usually zero, then $V_d = A_d y_d$, and

$$y_3 = y_2 + \frac{1}{P_2}[F.k_5 - y_2 \frac{(P_2 - P_1)}{\gamma}] \qquad \ldots.(3.4)$$

where $k_5 = \dfrac{(C.V.)\eta_c R}{C_p A_d}$

This equation applies whenever the fuel setting F is sufficiently large for the diesel pressure to rise to its maximum allowed value (i.e. $P_2 = P_{dmax}$).

The critical fuel setting (F_2) when the diesel pressure just reaches its allowed maximum is found from the equation by putting $y_3 = y_2$, $P_2 = P_{dmax}$ and solving for $F = F_2$. If $F < F_2$, no constant pressure combustion will take place, and the maximum diesel pressure can be found by putting $y_3 = y_2$ and solving for P_2.

3.3.4 Mass Flow from Exhaust Receiver

The mean mass flow rate through the nozzle from the exhaust receiver is governed by the characteristics of the particular nozzle used. A typical nozzle characteristic is shown in Figure 13.

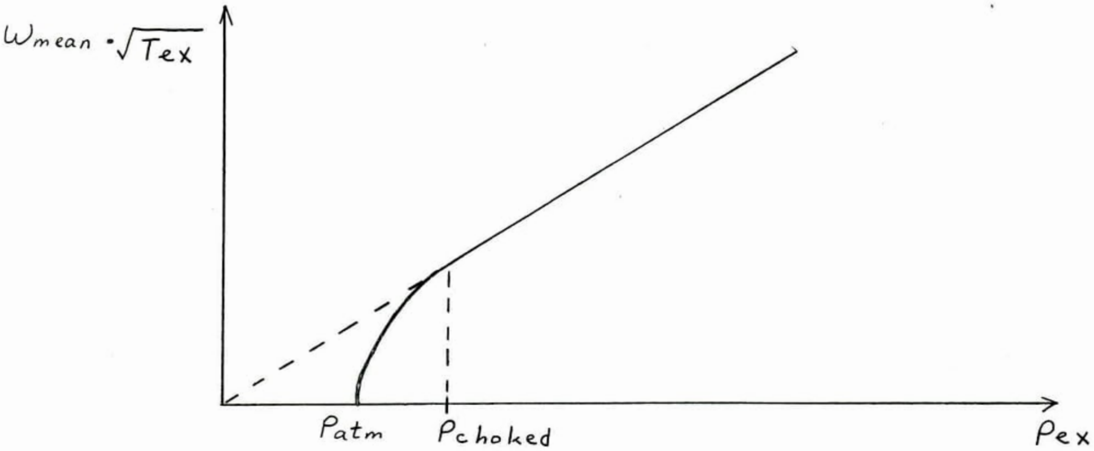


FIGURE 13: Typical Nozzle Characteristics

When the nozzle flow is choked, the simple linear portion of the curve yields

$$\omega_{mean} = k_3 \frac{P_{ex}}{\sqrt{T_{ex}}} \qquad \text{....(3.5)}$$

where k_3 is a constant for a given nozzle. For non-choked flow, the curve can be approximated by some polynomial with coefficients α_n such that

$$\omega_{mean} = \frac{\alpha_0 + \alpha_1 P_{ex} + \alpha_2 P_{ex}{}^2 + \ldots + \alpha_n P_{ex}{}^n}{\sqrt{T_{ex}}} \qquad \text{...(3.6)}$$

The air intake of a gas turbine can be approximated in a similar manner, using the characteristics of a representative nozzle.

3.3.5 Diesel Delivery Pressure Build-up

The calculation of the delivery pressure during engine starting is an essential part of the simulation since this pressure is the initial diesel pressure for the compression stroke, it also affects the point at which the compressor begins delivering air to the diesel cylinder.

The assumptions made in the calculation are that

(i) the mass delivered can be found from equation (3.1) even under transient conditions,
(ii) the exhaust gas is an ideal gas (i.e. C_p is constant).

During scavenging, the mass already in the exhaust receiver (m_{old}) is supplemented by a slug of gas (mass m_{del}) from the diesel so that the total mass (m_{new}) on each cycle is given by

$$m_{new} = m_{old} + m_{del}$$

The resulting temperature (T_{new}) is found by an energy balance

$$T_{new} = \frac{m_{old}\ T_{old} + m_{del}\ T_{del}}{m_{new}} \qquad \text{(constant } C_p\text{)}$$

and the new pressure is calculated

$$P_{new} = \frac{m_{new}\ R\ T_{new}}{V_{rec}}$$

During the remainder of the cycle, the gas in the exhaust receiver discharges through the nozzle and an estimate of the pressure at the end of the cycle is made. For example, if a two per cent pressure drop is assumed, the mean pressure is

$$P_{mean} = \frac{P_{new} + .98\ P_{new}}{2}$$

$$= .99\ P_{new}$$

and the mean flow rate can be found from the appropriate nozzle equation from section 3.3.4

$$\omega_{mean} = f(P_{mean})$$

The mass remaining in the exhaust receiver is found by

$$m = m_{new} - \omega_{mean} \text{ Period}$$

The estimated pressure remaining in the exhaust receiver is then

$$P = \frac{m\ R\ T_{new}}{V_{rec}}$$

If this pressure is close enough to the calculated mean pressure, the calculation is complete; otherwise, a new estimate of P_{mean} is made

$$P_{mean} = \frac{1}{2}(P_{mean} + \frac{P_{mean} + P}{2})$$

$$= .75\ P_{mean} + .25P$$

and the calculation is repeated until the pressure difference $\left|P_{mean} - P\right|$ is sufficiently small. Then this mean pressure is taken as the delivery pressure

$$P_{del} = P_{mean}$$

3.3.6 Gas Horsepower Developed

The gas power output can be estimated by an energy balance at the nozzle or through an ideal turbine (Fig. 14).

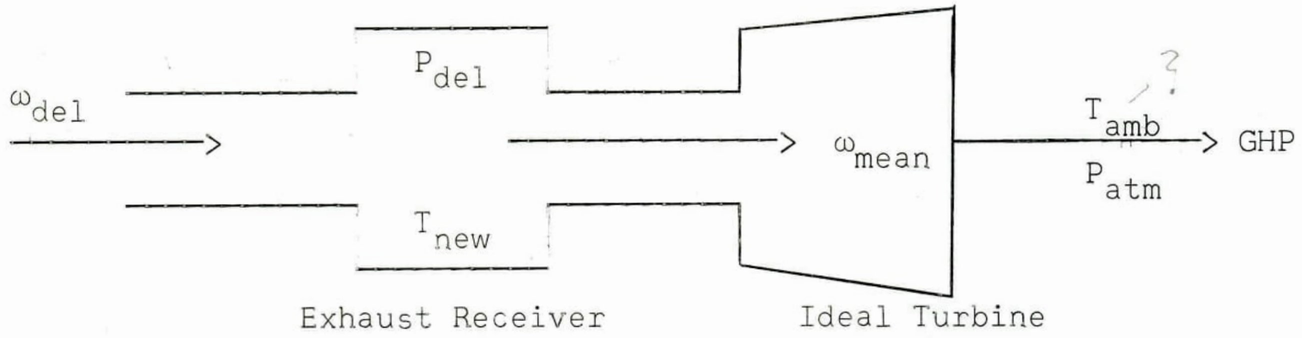


FIGURE 14: Ideal Power Output

If it is assumed that the discharge occurs adiabatically to ambient conditions (optimum condition), then the output power is simply the product of flow rate and enthalpy change.

$$G.H.P. = \omega_{mean} C_p J(T_{new} - T_{amb})$$

this is not
Tambient
only T after expansion
to Pambient (or
atmospheric)

but

$$\frac{T_{amb}}{T_{new}} = \frac{P_{atm}}{P_{del}}^{\frac{\gamma-1}{\gamma}}$$

thus

$$G.H.P. = k_4 \, \omega_{mean} \, T_{new}\left[1-\left(\frac{P_{atm}}{P_{del}}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad \ldots.(3.7)$$

where $k_4 = C_p J$.

3.3.7 Specific Fuel Consumption

The specific fuel consumption (S.F.C.), defined as the hourly fuel consumption per unit gas housepower output, can be calculated from

$$S.F.C. = \frac{3600 \cdot F_1}{\text{Period} \cdot (G.H.P.)} \qquad \ldots.(3.8)$$

4.0 DIGITAL COMPUTER SIMULATION

The dynamic simulation is composed of three major sections: the main program and two subprograms. The main program determines the pressures acting on the piston for any given piston displacement. A function subprogram calculates the acceleration using the correct pressures. Then an integration subroutine provides the main program with the new displacement that this acceleration will produce. A detailed description of each section follows. Although the present program is written in FORTRAN II for the SDS 920 computer, the method of simulation would require only minor alterations for use on any computer.

4.1 The Main Program

The large numbers of program variables and parameters involved in the calculations make communication with subprograms through their arguments impractical. Instead, a large array is placed in COMMON and the required quantities are made members of the array by an EQUIVALENCE statement.

Since the modes of input and output may vary widely among computer installations, the particular facilities used on the SDS 920 will be described separately.

To simplify the description of the program, reference will be made to the Flow Chart of Figure 16. The numbers in the blocks of the flow chart refer to statement numbers in the listing in Appendix D. Throughout the program, Sense Switch 1 SET causes a branch to a subsection which allows the alteration of program or control parameters; this subsection is not essential to the calculation. It will be described separately in the input-output section and S SW1 will be considered in the RESET position.

The program has been written with the compression stroke occurring first, to be compatible with an outer dea~~t~~d point starting position. A procedure which allows starting from inner dead point will be described in Section 5.2.

Within both compression and power strokes, a series of tests are performed on both the piston position and the cylinder pressures to determine the portions of the various cylinder pressure curves on which the engine is operating. Each portion is assigned a code number (as in Figure 15) which enables the acceleration subprogram to employ the correct pressure equation. An additional test is included to reduce the integration step size by 50% whenever any pressure increases above a specified level during adiabatic compression. A level of 600 p.s.i. was found to produce the optimum combination of integration accuracy and speed (see Appendix F and statements coded 'VS' in Appendix D).

Sense Switches two, three, and four are SET to obtain typeouts. Number two controls the important typeouts at the two dead points. Number three supplies information at the breakpoints in the pressure curves. The fourth can be used to determine the current state after each integration step.

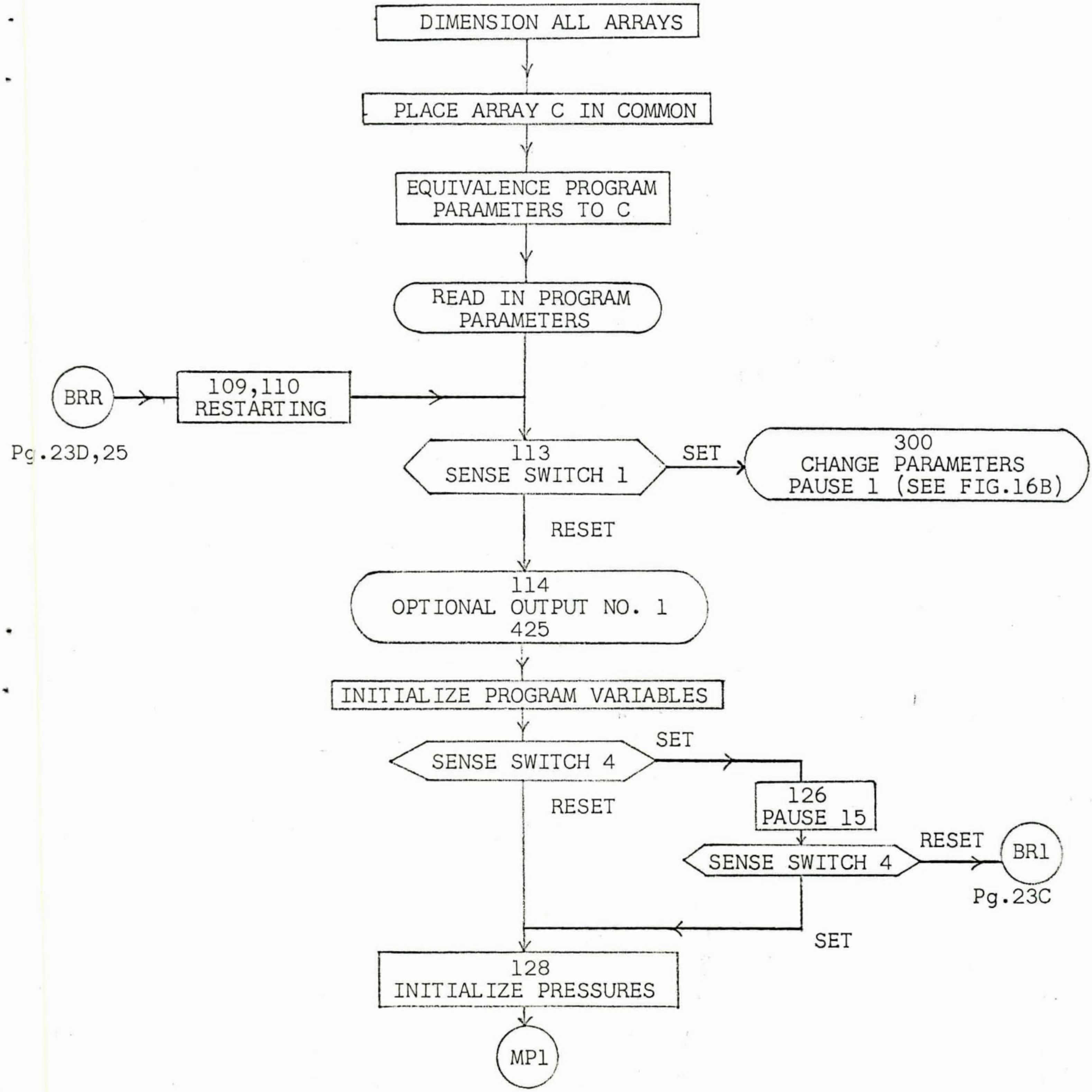
Both of the dead points are determined by testing for a change in sign of the piston velocity. At the I.D.P., the combustion calculations of Section 3.3.2 are performed only if the piston has reached a specified fuel injection point. The injection point specified is nearer the inner mechanical limit on the first stroke than on subsequent strokes to account for inefficiencies in the fuel injection apparatus. If the injection point is not reached, the piston comes to rest under the influence of the cylinder pressures and Coulomb friction. Other calculations made at the I.D.P. include:

(i) delivery temperature by equation (3.3),
(ii) delivery pressure by the method of Section 3.3.5,
(iii) G.H.P. by equation (3.7),
(iv) S.F.C. by equation (3.8).

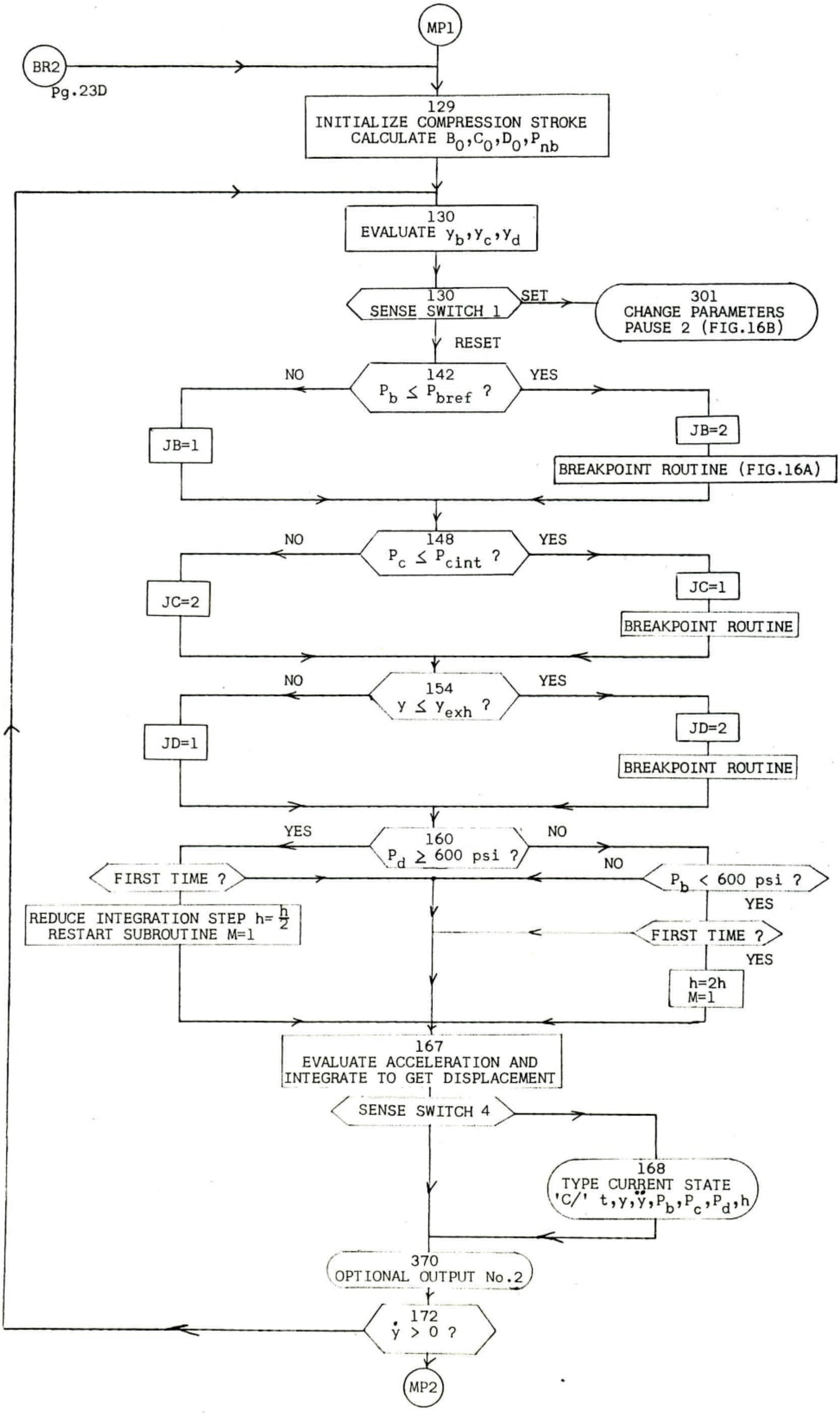
At the O.D.P., the engine speed is calculated in terms

FIGURE 16: FLOW CHART FOR MAIN PROGRAM

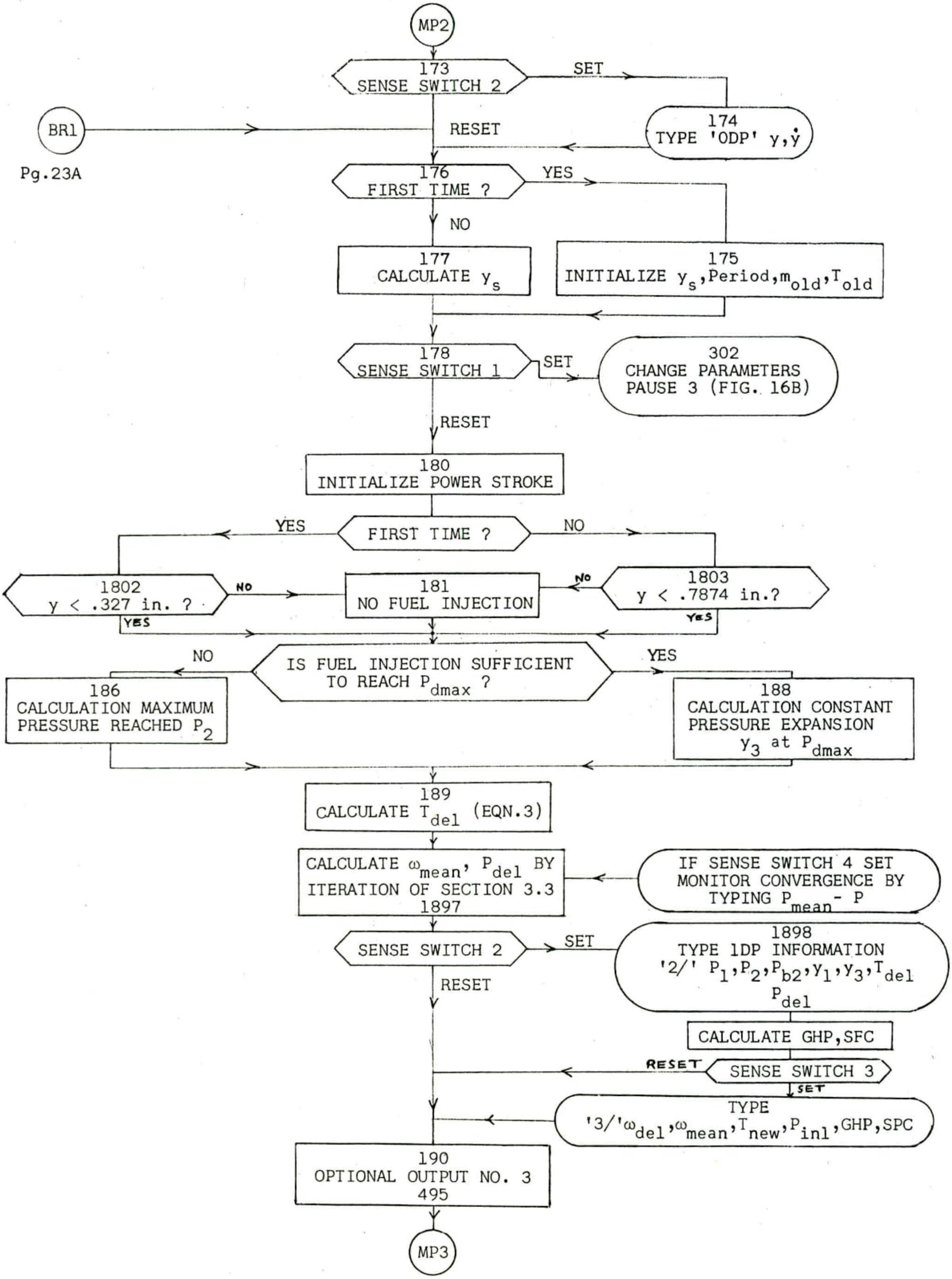
PROGRAM INITIALIZATION



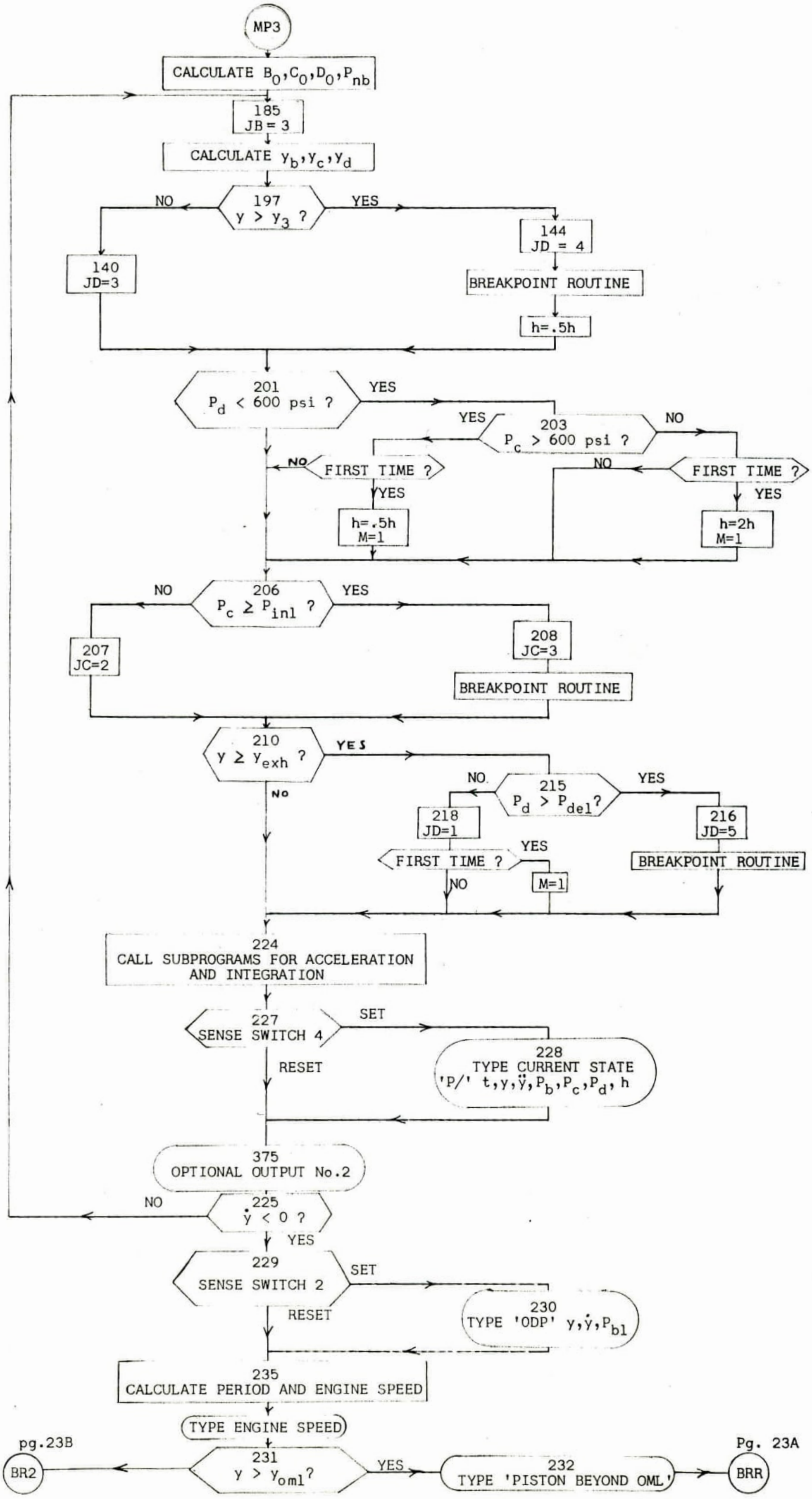
COMPRESSION STROKE

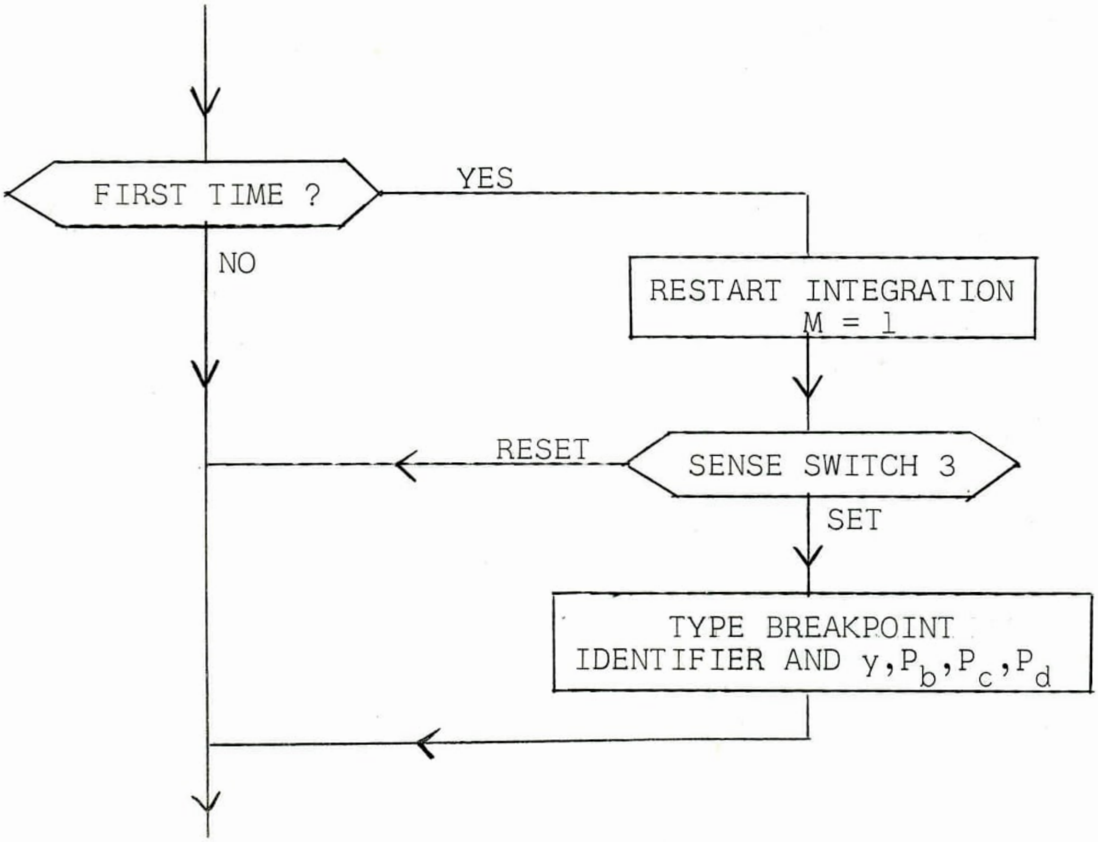


INNER DEAD POINT



POWER STROKE





IDENTIFIER	BREAKPOINT
EX CL EX OP	Exhaust Ports Closed Open
COMP INL COMP OUTL	Compressor Cylinder Air Inlet Outlet
PBREF	Bounce Reference Pressure Reached

FIGURE 16A: Breakpoint Routine

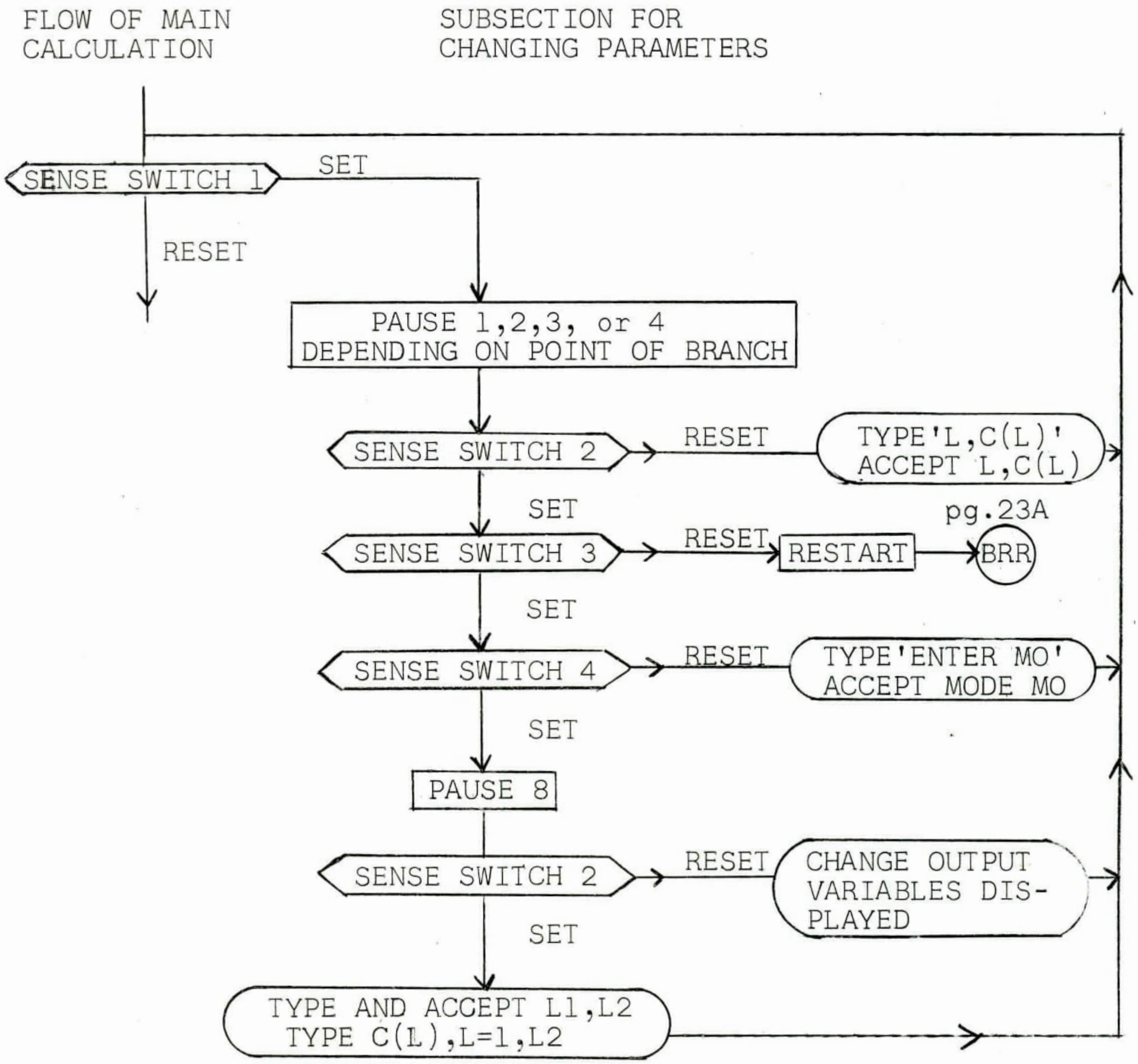


FIGURE 16B: Subsection of Main Program for Changing Program Control Parameters of cycles per minute to be comparable to reciprocating engine speeds. If the piston has gone beyond the outer mechanical limit, an indication is given and the calculation is stopped. Otherwise the compression stroke calculation is started again.

4.2 The Integration Subroutine

Any method of integration can be employed. A good compromise between accuracy and speed is the predictor-modifier-corrector (PMC) method with a Runge-Kutta-Gill (R-K) starter (Figure 27). In the first step the subroutine variables are initialized, and one R-K step is performed: - the interval is subdivided and the slope is estimated at each division, using the acceleration obtained from the function subprogram for that purpose. An average slope for the interval is calculated and the new displacement is estimated from this. The second and third integration steps are also performed by the Runge-Kutta method.

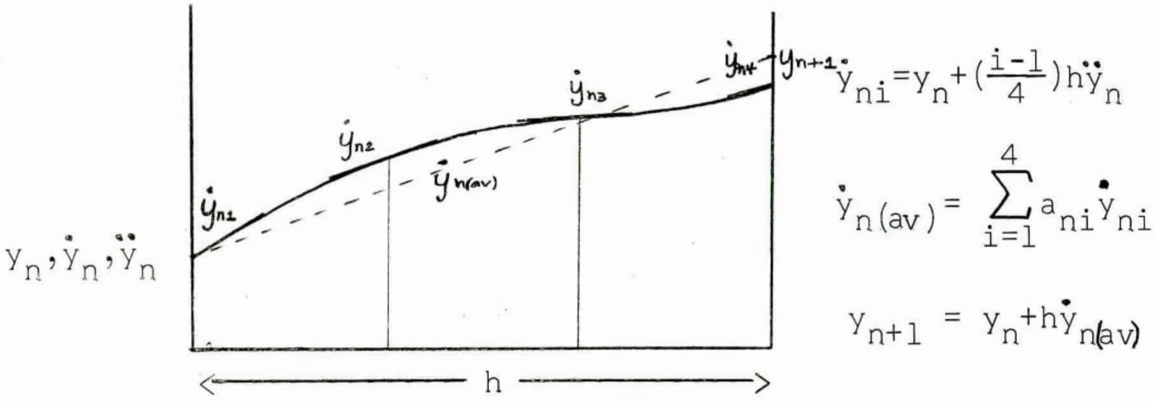


FIGURE 19: Simplified Runge-Kutta Step (Four Subdivisions)

The remainder of the integration steps are performed by a sixth-order (error) PMC method:

(i) Predictor - an estimate, p_{n+1}, of the new displacement, y_{n+1}, is made using a combination of past values (initially supplied by the three R-K steps):

$$p_{n+1} = y_n + y_{n-2} - y_{n-3} + \frac{5}{4} h^2(\ddot{y}_n + \frac{2}{5}\ddot{y}_{n-1} + \ddot{y}_{n-2}) \quad \ldots(4.1)$$

(ii) Modifier - the displacement estimate is modified using an error term (p_c) which is the difference between predictor and corrector estimates in the previous step

$$p_{n+1}' = p_{n+1} - 17/18\ p_c \quad \ldots(4.2)$$

(iii) Corrector - the final displacement is calculated using the latest (modified) acceleration estimate

$$\ddot{y}_{n+1} = f(p_{n+1}')$$

$$y_{n+1} = 2y_n - y_{n-1} + \frac{1}{12} h^2(\ddot{y}_{n+1} + 10\ddot{y}_n + \ddot{y}_{n-1}) \quad \ldots(4.3)$$

(iv) A new error term is calculated:

$$p_c = p_{n+1} - y_{n+1} \quad \ldots(4.4)$$

(v) In order to detect the dead points, velocity is calculated by a seventh order corrector formula

$$\dot{y}_{n+1} = \dot{y}_{n-3} + \frac{2}{45} h^2[7(\ddot{y}_{n+1} + \ddot{y}_{n-3}) + 32(\ddot{y}_n + \ddot{y}_{n-2}) + 12\ddot{y}_{n-1}] \quad \ldots(4.5)$$

During the first PMC step, the error term is supplied by using the predictor and unmodified corrector estimates. The coefficients in the estimates were found by Taylor series expansions about y_n.

Whenever an abrupt change in variables occurs such as a breakpoint in the pressure curves or a change in step size, the integration routine must be restarted by setting M = 1 (Figure 16A).

FIGURE 17: Flow Chart of Subroutine INTRKPMC for Double Integration of Acceleration

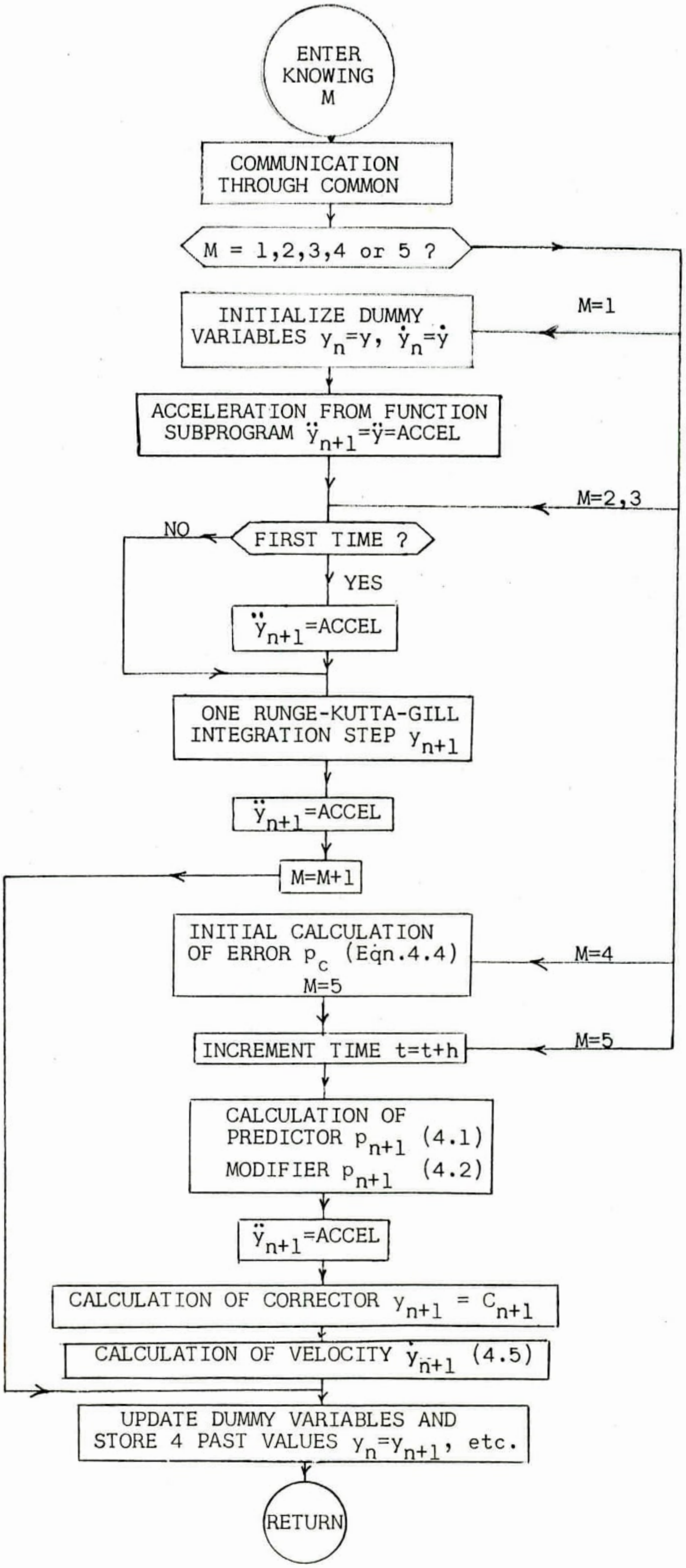
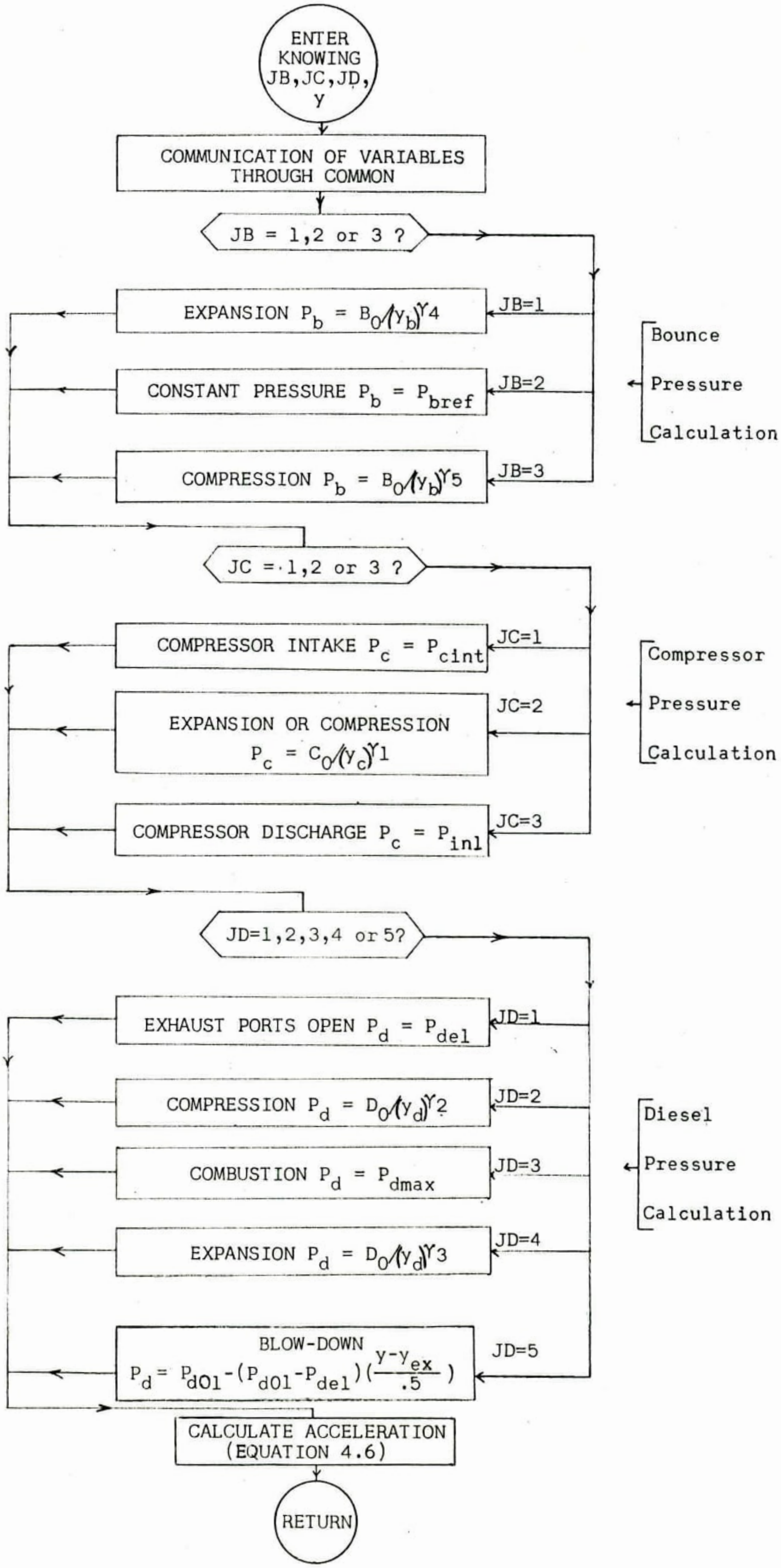


FIGURE 18: Flow Chart of FUNCTION ACCEL for Calculation of Cylinder Pressure and Acceleration



4.3 The Acceleration Subprogram

The main program has already determined the applicable portion of the pressure curve when the integration subroutine calls for the latest acceleration. This subprogram chooses the correct equations for the three cylinder pressures (using the indices JB, JC, JD, set by the main program) and calculates of the latest displacement using

$$\ddot{y} = \frac{g}{W}\left(P_dA_d - P_bA_b - P_cA_c + P_{nb}(A_c-A_d) - \text{Frict.sgn}\,\dot{y}\right)\text{..}(4.6)$$

A machine language subprogram may be used to speed up the calculation of this equation.

4.4 Input-Output

The only necessary input that must be supplied is the set of parameters that is required for the calculation. The typeouts available by setting Sense Switches 2 and 3 provide sufficient information to trace the operation of the gasifier. Optional output such as continuous visual display of variables (and the additional inputs that it may require) may be included in the unspecified blocks in the flow chart of Figure 16. For the actual blocks used, refer to the program listing in Appendix D (statements identified with an 'X').

4.4.1 Parameter Read-in

The set of parameters which must be supplied either on cards or tape consists of the appropriate members of the array in COMMON, (C(L), L = 15,35), as well as the cylinder areas, and effective clearance distances, piston weight, outer mechanical limit, exhaust receiver volume, and the constants (k_1,k_2,k_4,k_5) from Section 3.3.

4.4.2 Optional Output No. 1

This block contains a read-in statement for the scale factors used in the display of program variables (C(L), L = 1,11), as well as a specification of the variables to be displayed. Initialization of the display is done at this stage (drawing of axes).

4.4.3 Optional Output No. 2

This block permits the analog output of the program variables after each integration step. The fastest mode of display was found to be the direct conversion of the digital data into scaled voltages to drive a plotter. The integers K1 to K5 (statement 105 in Appendix D) specify the particular members of the array (C(L), L = 1,11) that are to be available on analog channels 1, 2, 4, 5, 6 respectively. The small integration steps and the time delay in the integration process, made the use of plotter subroutines unnecessary for good line quality. This block was made a common subsection of the main program to avoid duplication between the compression and power strokes.

4.4.4 Optional Output No. 3

The only application for this block was to provide a display of the constant volume combustion process in the diesel cylinder when a memory oscilloscope was being used to display the analog voltages.

4.4.5 Other Possibilities

The final version of the program is listed in a simplified form in Appendix B in order to show the statements required strictly for the simulation. The optional output is presented in Appendix D. In this final version there are four output modes available:

(1) Plotter using plotter subroutines, and three analog channels (4,5,6).

(2) Five analog channels, with 1 and 2 connected to plotter in the normal fashion.
(3) Punched paper tape and provision for an unmonitored run.
(4) Mode 2 with provision for unmonitored run.

The provisions for a unmonitored run are outlined below.

The parameters for operation may be presented either on cards or on paper tape (Sense Switch 4 SET or RESET respectively). Several counters must be read-in at this stage. First, the total number of cycles desired with this set of parameters (NUM) is specified and when this number has been completed, the program restarts and accepts a new set of parameters on tape. It may be desired to change some parameter during the run. This is done by giving the next counter (NC) a value less than NUM; after NC cycles the program will accept a tape with the number of parameters to be changed, the specific parameters and their new values, and a new value of NC. Often during an unmonitored run, a graph of starting characteristics may be desired as well as steady-state values. This is accomplished in output mode 4 (MO = 4) by supplying the number of cycles to be plotted at first (N1) and the number after which the steady-state plot is desired (N2). If the record of the data is desired on paper tape (MO = 3), every integration point need not be recorded, and a number (J1) specifies the number that would be omitted.

5.0 OPERATION OF THE SIMULATION

5.1 Starting at O.D.P.

This is the normal starting procedure for the simulation. After the program has been loaded, Sense Switch 4 must be SET to accept cards. Typical data and the method presentation on cards is shown in Appendix E. Scale factors for displayed variables must also be supplied at this point. If Sense Switch 3 (S.SW.3) is SET, the scale factors and parameters will be typed. If it is in the RESET position, the program will stop at a PAUSE 7. The parameters alone may then be typed by setting S.SW.3 and clearing the halt. The compression stroke calculations will be started and typeouts will occur as follows:

(1) S.SW.2 SET - IDP information - card code T1 (see App.D)
(2) S.SW.3 SET - Breakpoint information - card code T2
(3) S.SW.4 SET - Current state after each integration - card code T3

If S.SW.4 is SET at IDP, the convergence of the iteration to calculate P_{del} (Section 3.3.5) will be typed. If S.SW.3 is SET, information concerning the state of flow through the engine will be typed. Power stroke calculation will then be started with typeouts similar to those in the compression stroke.

If S.SW.1 is SET, the computer will branch to a subsection of the main program and pause, giving an indication to show the point of branching as follows:

PAUSE
1 - Before initialization of program variables
2 - At beginning of compression stroke
3 - Before IDP calculations
4 - At beginning of power stroke

During this pause, the remaining sense switches should be arranged according to the change to be performed:

(1) To alter C(L)	- 2R
(2) To restart	- 2S - 3R
(3) To change output mode	- 2S - 3S - 4R
(4) To change variables displayed (K1,K2,K3,K4,K5 on digital-analog channels 1,2,4,5,6 respectively)	- 2S - 3S - 4S, PAUSE 8, 2R
(5) To type C(L1) to C(L2)	- 2S - 3S - 4S, PAUSE 8, 2S

At present, with the optimum integration step (App. F), the calculation takes about 2.5 minutes per cycle with typeouts. A breakpoint typeout takes only 3 to 4 seconds.

5.2 Starting at I.D.P.

Parameter input is the same as before, but S.SW.4 must be SET at the end of the read-in process. The program will come to PAUSE 15. During this pause, S.SW.4 is RESET and S.SW.1 SET before clearing the halt. The calculation will branch to the inner dead point and initialize m_{old} and T_{old} for the delivery pressure calculation; hence, the desired values of P_{del_1} and T_{amb} must be supplied <u>before</u> the branch to I.D.P. A PAUSE 3 will be executed to show that the computer is in the program subsection to change parameters at I.D.P. Initialization is accomplished by entering the desired starting values of P_b, P_c, P_d, y, P_{dmax}, F_1. The calculation is started by resetting S.SW.1 and then returning from the subsection.

If, in the initialization, the length of constant pressure combustion (y_3-y_2) is to be specified instead of fuel setting on the first cycle, the procedure is more complicated. At the PAUSE 3 stage, the desired values of $P_d=P_{dmax}$ and $y = y_3$ are entered (with $F_1 = 0$), the power stroke initialization is performed, and the resulting diesel adiabatic constant B_0 is obtained through S.SW.1 in the power stroke (i.e. type C(L1)). A restart is performed (through S.SW.1) and the values of P_b, P_c, P_d, P_{dmax}, $y = y_2$, $F_1 > F_2$ are entered at the PAUSE 3 stage. Any fuel setting that is large enough that P_d reaches P_{dmax} is satisfactory. Upon entry to the power stroke, the desired values of y_3 and B_0 are entered through S.SW.1. Then the calculation proceeds in the usual manner.

APPENDIX A

LIST OF SYMBOLS

SYMBOLS	DESCRIPTION	COMPUTER SYMBOLS
$a_i, b_i, d_i, i=1,4$	Runge-Kutta-Gill integration coefficients	(A(I),B(I),D(I), I=1,4)
A_b, A_c, A_d	Cylinder areas--bounce, compressor, diesel	AB,AC,AD
B_0, C_0, D_0	Adiabatic constants--bounce, compressor, diesel	BO,CO,DO
cy_b, cy_c, cy_d	Effective clearance distances	CYB,CYC,CYD
F	Half-engine fuel setting	F
F_1	Input engine fuel setting	F1
F_2	Required fuel setting to reach maximum diesel pressure	F2
Frict	Coulomb friction force	FRICT
$\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5$	Ratios of specific heats for air and fuel-air mixtures	G1,G2,G3,G4,G5
g	Acceleration due to gravity	
G.H.P.	Gas horsepower available	GHP
h, h_1	Integration step size--effective, initial	H,H1
I.D.P.	Inner dead point	IDP
I.M.L.	Inner mechanical limit	IML
JB,JC,JD	Cylinder pressure code numbers	JB,JC,JD
k_1, k_2, k_3, k_4, k_5	Constants in flow equations	XK1,XK2,.....,XK5
M	Integration restart index	M
m_{old}	Mass of gas remaining in exhaust receiver	XMOLD
m_{new}	Latest total mass in exhaust receiver	XMNEW

SYMBOLS	DESCRIPTION	COMPUTER SYMBOLS
m_{del}	Mass delivered from diesel cylinder per cycle	XMDEL
m	Estimated mass remaining in exhaust receiver at end of cycle	XM
O.D.P.	Outer dead point	ODP
O.M.L.	Outer mechanical limit	OML
P_b,P_c,P_d	Cylinder pressures	PB,PC,PD
$P_{b_1},P_{c_1}\begin{Bmatrix}P_{d_1}\\P_1\end{Bmatrix}$	Pressures at ends of stroke	PB1,PC1,PD1
P_{atm}	Atmospheric pressure	PATM
P_{binit}	Initial bounce pressure	PBINIT
P_{bref}	Bounce reference pressure	PBREF
P_{cint}	Compressor intake pressure	PCINT
P_{del}	Diesel delivery pressure	PDEL
P_{del_1}	Initial delivery pressure	PDEL1
P_2,P_3	Maximum diesel pressure	PDM
P_{dmax}	Maximum allowed diesel pressure	PDMAX
P_{do_1}	Diesel pressure before blowdown	PDO1
P_{ex}	Instantaneous pressure in exhaust receiver	
P_{inl}	Inlet pressure to diesel cylinder	PINL
P_{nb}	Pressure in negative bounce cylinder	PNB
P_{new}	Exhaust receiver pressure after slug of hot gas from diesel	PNEW

SYMBOLS	DESCRIPTION	COMPUTER SYMBOLS
P_{mean}	Mean pressure in exhaust receiver during one cycle	PMEAN
P	Estimated exhaust pressure at end of cycle	P
Period	Time for one cycle in seconds	PERIOD
S.F.C.	Specific fuel consumption	SFC
T_{amb}	Ambient temperature	TAMB
T_{del}	Temperature of gas delivered from diesel cylinder	TDEL
T_{old}	Temperature of exhaust receiver gas on last cycle	TOLD
T_{new}	Temperature of exhaust receiver gas on present cycle	TNEW
t	Time from engine starting	X
V_b, V_c, V_d	Cylinder volumes	VB, VC, VD
V_{rec}	Exhaust receiver volume	VREC
W	Weight of piston	W
W_K	Acceleration constant = g/W	WK
ω_{del}	Gas flow rate from diesel cylinder	WDEL
ω_{mean}	Gas flow rate from exhaust receiver	WMEAN
y	Piston position from center-line (stroke)	Y(1)
$\dot{y}$	Piston velocity	Y(2), Z(1)
$\ddot{y}$	Piston acceleration	Z(2)
y_b, y_c, y_d	Distance of piston from end of cylinder	YB, YC, YD
y_1, y_2	Piston position at IDP	YO

SYMBOLS	DESCRIPTION	COMPUTER SYMBOLS
y_3	Piston position after combustion	YOO
	Piston position at ODP	YO
y_{cint}	Position at beginning of compressor intake	YCINT
y_{ex}	Inner edge of exhaust port	YEXH
y_{init}	Initial position of piston	YINIT
y_{oml}	Position of outer mechanical limit	YOML
y_s	Compressor suction distance	

APPENDIX B

SIMPLIFIED LISTING OF MAIN PROGRAM

```
      SIMPLIFIED LISTING OF MAIN PROGRAM WITH OUTPUT REMOVED      AN1001PA
      DIMENSION Y(2),Z(2),C(60),A(4),B(4),D(4)
      COMMON C,A,B,D
      EQUIVALENCE (PB,C(1)),(PC,C(2)),(PD,C(3)),(VB,C(4)),(VC,C(5)),
     1 (VD,C(6)),(X,C(7)),(Y(1),C(8)),(Z(1),C(10)),(PBREF,C(12)),
     2 (YEXH,C(15)),(YINIT,C(16)),(PBINIT,C(17)),(PDEL1,C(18)),
     3 (PCINT,C(19)),(PATM,C(20)),(G1,C(21)),(G2,C(22)),(G3,C(23)),
     4 (G4,C(24)),(G5,C(25)),(H,C(26)),(F1,C(27)),(TAMB,C(28)),(FRICT,
     5 C(29)),(PDMAX,C(30)),
     6 (PINL,C(36)),(PDEL,C(37)),(BO,C(38)),(CO,C(39)),(DO,C(40)),(YO,
     7 C(41)),(YOO,C(42)),(YB,C(43)),(YC,C(44)),(YD,C(45)),(PDO1,C(46)),
     8 (WK,C(47))
      A(1)=0.5
      A(2)=0.292893219
      A(3)=1.707106781
      A(4)=.166666666667
      B(1)=0.
      B(2)=1.
      B(3)=1.
      B(4)=2.
      D(1)=0.5
      D(2)=.292893219
      D(3)=1.707106781
      D(4)=0.5
      CALL DMATH1(PD,AD,PB,AB,PC,AC,PNB,FRICT,Y(2),WK)
      INITIALIZES SYMBOL SUBROUTINE TO CALCULATE ACCELERATION
      READ IN PARAMETERS
  105 READ 505,C(12),(C(I),I=15,35),AB,AC,AD,CYB,CYC,CYD,W,YOML,VREC,     X
     1  XK1,XK2,XK4,XK5                                                   X
  505 FORMAT(F12.6/6F12.6/5F12.6/6F12.6/4F12.6/6F12.6/3F12.6/4F12.6)      X
      H1=H                                                                VS
      GO TO 102
  110  TYPE 515                                                           X
  515 FORMAT(/$RESTARTING$//)                                             X
      PAUSE 7                                                             X
  102 IF(SENSE SWITCH 3) 103,113                                          T2
  103 TYPE 510,C(12),(C(I),I=15,35),AB,AC,AD,CYB,CYC,CYD,W,YOML,VREC      T2
  510 FORMAT(/$1/$F12.6/6F12.6/5F12.6/6F12.6/4F12.6/6F12.6/3F12.6)        T2
  113 IF(SENSE SWITCH 1) 300,114                                          X
      SENSE SWITCH 1 SET TO ALTER PROGRAM PARAMETERS AS FOLLOWS -
      TO ALTER C(L)         S SW  SEQUENCE              1S,2R
      TO RESTART                                        1S,2S-3R
      TO CHANGE OUTPUT MODE                             1S,2S-3S-4R
      TO CHANGE VARIABLES DISPLAYED                     1S,2S-3S-4S,2R
```

```
    TO SELECT AND TYPE MEMBERS OF C(L) ARRAY       1S,2S-3S-4S,2S
114 CONTINUE

    OPTIONAL OUTPUT NUMBER 1

    INITIALIZATION OF VARIABLES
    VB=AB*(CYB-YINIT)
    VC=AC*(CYC-YINIT)
    VD=AD*(CYD+YINIT)
    SENSE LIGHT 0
    Y(1)=YINIT
    Y(2)=0.
    Z(1)=0.
    Z(2)=0.
    X=0.
    T=0.
    WK=386.4/W
    F=.5*F1
    H=H1
    PDEL=PDEL1
    FOR IDP START  SET SENSE SWITCHES AS FOLLOWS -  4S,4R-1S
    IF(SENSE SWITCH 4) 126,128
126 PAUSE 15
    IF(SENSE SWITCH 4) 128,175
128 PB1=PBINIT
    PB=PB1
    PC=PCINT
    PD=PDEL

129 YO=Y(1)
    BO=PB1*(CYB-YO)**G4
    CO=PC1*(CYC-YO)**G1
    DO=PDEL*(CYD+YEXH)**G2
    PNB=PATM+1.
    M=1
    COMPRESSION STROKE BEGINS
130 CONTINUE
    YB=CYB-Y(1)
    YC=CYC-Y(1)
    YD=CYD+Y(1)
140 IF(SENSE SWITCH 1) 301,142                                    X
142 IF(PB-PBREF) 144,144,143
143 JB=1
    SENSE LIGHT 6
```

```
    GO TO 148
144 JB=2
    IF(SENSE LIGHT 6) 145,148
145 M=1
    S SW 3 SET FOR TYPEOUTS  T2
    IF(SENSE SWITCH 3) 146,148                                          T2
146 TYPE 525, PB,Y(1)                                                   T2
525 FORMAT(/$PB=PBREF,Y$2F10.4)                                         T2
148 IF(PC-PCINT) 150,150,149
149 SENSE LIGHT 1
    JC=2
    GO TO 154
150 JC=1
    IF(SENSE LIGHT 1) 151,154
151 YCINT=Y(1)
    M=1
    SENSE LIGHT 4
    IF(SENSE SWITCH 3) 152,154                                          T2
152 TYPE 526, Y(1),PB,PC,PD                                             T2
526 FORMAT(/$COMP INL $4F10.4)                                          T2
154 IF(Y(1)-YEXH) 156,156,155
155 SENSE LIGHT 2
    JD=1
    GO TO 160
156 JD=2
    IF(SENSE LIGHT 2) 157,160
157 M=1
    IF(SENSE SWITCH 3) 158,160                                          T2
158 TYPE 536, Y(1),PB,PC,PD                                             T2
536 FORMAT(/$EX CL     $4F10.4)                                         T2
160 IF(PD-600.) 161,165,165                                             VS
161 SENSE LIGHT 15                                                      VS
    IF(PB-600.) 163,162,162                                             VS
162 SENSE LIGHT 16                                                      VS
    GO TO 167                                                           VS
163 IF(SENSE LIGHT 16) 164,167                                          VS
164 M=1                                                                 VS
    H=H1                                                                VS
    GO TO 167                                                           VS
165 IF(SENSE LIGHT 15) 166,167                                          VS
166 M=1                                                                 VS
    H=H1*.5                                                             VS
167 CALL INTRKPMC(M,JB,JC,JD)
```

```
      S SW 4 SET FOR TYPEOUTS  T3
      IF(SENSE SWITCH 4) 168,170                                      T3
  168 TYPE 538,X,Y,Z(2),PB,PC,PD,H                                    T3
  538 FORMAT(/$C/ $F11.6,2F9.3,F10.1,3F9.3,F10.6)                     T3
  170 CONTINUE
  171 VB=AB*YB
      VC=AC*YC
      VD=AD*YD

      OPTIONAL OUTPUT NUMBER 2

  172 IF(Y(2)) 130,130,173
      COMPRESSION STROKE ENDS
  173 IF(SENSE SWITCH 2) 174,176                                      T1
      S SW 2 SET FOR TYPEOUTS  T1
  174 TYPE 540,Y                                                      T1
  540 FORMAT(/$IDP$2F10.4)                                            T1
  176 IF(SENSE LIGHT 4) 177,175
  175 YS=3.9
      SENSE LIGHT 10
      XMOLD=PDEL1*VREC/(TAMB*96.*12.)
      TOLD=TAMB
      PERIOD=1.8*X
      GO TO 178
  177 YS=YCINT-Y(1)
  178 IF(SENSE SWITCH 1) 302,180                                      X
      POWER STROKE INITIALIZATION
  180 YO=Y(1)
      XMDEL=2.*XK1*YS
      WDEL=XMDEL/PERIOD
      PB1=PB
      PC1=PC
      PD1=PD
      YOO=YO
      M=1
      F=.5*F1
      H=H1                                                            VS
      IF(SENSE LIGHT 10) 1802,1803
 1802 IF(Y(1)-.327)182,182,181
 1803 IF(Y(1)-.7874) 182,182,181
  181 F=0.
  182 IF(F) 110,1825,184
 1825 CONTINUE
  183 IF(PD-PDMAX) 1835,187,1865
```

```
1835 PDM=PD1
     F=.5*F1
     GO TO 189
 184 IF(PD-PDMAX) 1845,1875,1875
1845 F2=PDMAX*YO*(1.-PD1/PDMAX)/(G3*XK5)
     IF(F-F2) 186,187,188
 186 PDM=PD1+(F*G3*XK5/YO)
     GO TO 189
1865 CONTINUE
 187 PDM=PDMAX
     GO TO 189
1875 PDM=PDMAX
     YOO=YO+(F*XK5/PDM)
     GO TO 189
 188 PDM=PDMAX
     YOO=YO+((F*XK5-YO*(PDM-PD1)/G3)/PDM)
 189 TDEL=TAMB+(F1*XK2/XMDEL)
     XMNEW=XMOLD+XMDEL
     TNEW=(XMOLD*TOLD+XMDEL*TDEL)/XMNEW
     PMEAN=.99*XMNEW*TNEW*96.*12./VREC
1891 IF(PMEAN-30.) 1892,1893,1893
1892 DP=PMEAN-PATM
     WMEAN=(.000171938+DP*(.917949-DP*(.076107-.002597*DP)))/SQRT(TNEW)
     GO TO 1894
1893 WMEAN=.1575*PMEAN/SQRT(TNEW)
1894 XM=XMNEW-WMEAN*PERIOD
     P=XM*TNEW*96.*12./VREC
     IF(ABS(P-PMEAN)-.1) 1897,1897,1895
1895 PDIF=PMEAN-P
     PMEAN=.75*PMEAN+.25*P
     IF(SENSE SWITCH 4) 1896,1891                                       T2
1896 TYPE 550,PDIF                                                      T2
 550 FORMAT(F12.6)                                                      T2
     GO TO 1891
1897 PDEL=PMEAN
     PINL=1.13*PDEL
     XMOLD=XM
     TOLD=TNEW
     IF(SENSE SWITCH 2) 1898,190                                        T1
1898 TYPE 546,PD1,PDM,PB1,YO,YOO,TDEL,PDEL                              T1
 546 FORMAT(/$2/$7F10.4)                                                T1
     GHP=XK4*WMEAN*TNEW*(1.-(PATM/PDEL)**(1.-(1./G3)))
     SFC=F1*.0036/(PERIOD*GHP)
     IF(SENSE SWITCH 3) 1899,190                                        T2
```

```
1899 TYPE 551,WDEL,WMEAN,TNEW,PINL,GHP,SFC                          T2
 551 FORMAT(/$3/ $2F10.6,4F12.4)                                    T2
 190 CONTINUE

     OPTIONAL OUTPUT NUMBER 3

     BO=PB1*(CYB-YO)**G5
     CO=PC1*(CYC-YO)**G1
     DO=PDM*(CYD+YOO)**G3
     PNB=PATM-1.
     POWER STOKE BEGINS
 185 JB=3
     YB=CYB-Y(1)
     YC=CYC-Y(1)
     YD=CYD+Y(1)
 191 IF(SENSE SWITCH 1) 303,197                                     X
 197 IF(Y(1)-YOO) 198,199,199
 198 JD=3
     SENSE LIGHT 8
     GO TO 201
 199 JD=4
     IF(SENSE LIGHT 8) 200,201
 200 M=1
     H=H1*.5                                                        VS
 201 IF(PD-600.) 203,202,202
 202 SENSE LIGHT 13                                                 VS
     GO TO 206                                                      VS
 203 IF(PB-600.) 2035,2055,2055                                     VS
2035 IF(SENSE LIGHT 13) 204,205                                     VS
 204 M=1                                                            VS
     H=H1                                                           VS
 205 SENSE LIGHT 14                                                 VS
     GO TO 206                                                      VS
2055 IF(SENSE LIGHT 14) 2056,206                                    VS
2056 M=1                                                            VS
     H=H1*.5                                                        VS
 206 IF(PC-PINL) 207,208,208
 207 SENSE LIGHT 7
     JC=2
     GO TO 210
 208 JC=3
     IF(SENSE LIGHT 7) 209,210
 209 M=1
     IF(SENSE SWITCH 3) 212,210                                     T2
```

```
212 TYPE 561,Y(1),PB,PC,PD                                            T2
561 FORMAT(/$COMP OUTL$4F10.4)                                        T2
210 IF(Y(1)-YEXH) 211,215,215
211 SENSE LIGHT 3
    GO TO 224
215 IF(PD-PDEL) 218,218,216
216 JD=5
    SENSE LIGHT 11
    IF(SENSE LIGHT 3) 217,224
217 M=1
    PDO1=PD
    IF(SENSE SWITCH 3) 220,224                                        T2
220 TYPE 565, Y(1),PB,PC,PD                                           T2
565 FORMAT(/$EX OP    $4F10.4)                                        T2
    GO TO 224
218 JD=1
    IF(SENSE LIGHT 11) 219,224
219 M=1
224 CALL INTRKPMC(M,JB,JC,JD)

    OPTIONAL OUTPUT NUMBER 2

226 VB=AB*YB
    VC=AC*YC
    VD=AD*YD

227 IF(SENSE SWITCH 4) 228,225                                        T3
228 TYPE 560,X,Y,Z(2),PB,PC,PD,H                                      T3
560 FORMAT(/$P/ $F11.6,2F9.3,F10.1,3F9.3,F10.6)                       T3
225 IF(Y(2)) 229,229,185
229 IF(SENSE SWITCH 2) 230,235                                        T1
230 TYPE 575,Y,PB                                                     T1
575 FORMAT(/$ODP$3F10.4)                                              T1
235 PERIOD=X-T
    T=X
    MM=60./PERIOD
    TYPE 570,MM                                                       T1
570 FORMAT(/I5$ RPM$)                                                 T1
231 IF(Y(1)-YOML) 233,233,232
232 TYPE 578
578 FORMAT(/$PISTON BEYOND OML $)
    GO TO 129
233 CONTINUE
    PB1=PB
```

```
    PC1=PC
    GO TO 129
    SUBSECTION TO ALTER PROGRAM PARAMETERS -  BRANCH FROM SENSE SWITCH 1
300 ASSIGN 113 TO IJ                                                   X
    PAUSE 1                                                            X
    GO TO 304                                                          X
301 ASSIGN 140 TO IJ                                                   X
    PAUSE 2                                                            X
    GO TO 304                                                          X
302 ASSIGN 178 TO IJ                                                   X
    PAUSE 3                                                            X
    GO TO 304                                                          X
303 ASSIGN 191 TO IJ                                                   X
    PAUSE 4                                                            X
304 IF(SENSE SWITCH 2) 305,310                                         X
305 IF(SENSE SWITCH 3) 306,110
306 IF(SENSE SWITCH 4) 307,330                                         X
307 PAUSE 8                                                            X
    IF(SENSE SWITCH 2) 340,350                                         X
    ALTER C(L)
310 TYPE 600                                                           X
600 FORMAT(/$L,C(L)$/)                                                 X
    ACCEPT 605,L,C(L)                                                  X
605 FORMAT(I3,F12.6)                                                   X
    GO TO IJ                                                           X
    CHANGE OUTPUT MODE
330 TYPE 610                                                           X
610 FORMAT(/$ENTER MO$/)                                               X
    ACCEPT 615,MO                                                      X
615 FORMAT(I3)                                                         X
    GO TO IJ                                                           X
    CHANGE OUTPUT VARIABLES DISPLAYED
350 TYPE 635                                                           X
635 FORMAT(/$K1,K2,K3,K4,K5,$/)                                        X
    ACCEPT 640,K1,K2,K3,K4,K5                                          X
640 FORMAT(5I3)                                                        X
    GO TO IJ                                                           X
    TYPE C(L1) TO C(L2)
340 TYPE 620                                                           X
620 FORMAT(/$L1,L2$/)                                                  X
    ACCEPT 625,L1,L2                                                   X
625 FORMAT(2I3)                                                        X
    TYPE 630,(C(I),I=L1,L2)                                            X
630 FORMAT((6F11.5))                                                   X
```

```
GO TO IJ                                                               X

COMMON OUTPUT SECTION FROM OPTIONAL OUTPUT NUMBER 2

END
```

APPENDIX C

LISTING OF SUBPROGRAMS SUBROUTINE INTRKPMC FUNCTION ACCEL

```
      SUBROUTINE INTRKPMC(M,JB,JC,JD)
      DIMENSION C(60),U(5),V(5),W(5),Y(2),Z(2),A(4),B(4),D(4),Q(20)
      COMMON C,A,B,D
      EQUIVALENCE (Y(1),C(8)),(Z(1),C(10)),(H,C(26)),(X,C(7))
      GO TO (100,101,101,200,201),M
  100 U(4)=Y(1)
      V(4)=Y(2)
      Z(1)=Y(2)
      Z(2)=ACCEL(JB,JC,JD)
      W(4)=Z(2)
  101 L=1
      DO 105 J=1,4
      IF(J-1)102,102,103
  103 Z(1)=Y(2)
      Z(2)=ACCEL(JB,JC,JD)
  102 DO 104 I=1,2
      T=A(J)*(Z(I)-B(J)*Q(I))
      Y(I)=Y(I)+H*T
  104 Q(I)=B(J)*Q(I)+3.*T-D(J)*Z(I)
      X=X+L*H/2.
  105 L=IABS(L-1)
      Z(1)=Y(2)
      Z(2)=ACCEL(JB,JC,JD)
      U(5)=Y(1)
      V(5)=Y(2)
      W(5)=Z(2)
      M=M+1
      GO TO 250
  200 X=X+H
      PN=U(4)+U(2)-U(1)+H*H*1.25*(W(4)+0.4*W(3)+W(2))
      Y(1)=PN
      W(5)=ACCEL(JB,JC,JD)
      U(5)=2.*U(4)-U(3)+H*H*(W(5)+10.*W(4)+W(3))/12.
      PC=PN-U(5)
      M=5
      GO TO 270
  201 X=X+H
  270 PN=U(4)+U(2)-U(1)+H*H*1.25*(W(4)+0.4*W(3)+W(2))
      Y(1)=PN-PC*17./18.
      W(5)=ACCEL(JB,JC,JD)
      U(5)=2.*U(4)-U(3)+H*H*(W(5)+10.*W(4)+W(3))/12.
      PC=PN-U(5)
      U(5)=U(5)+PC/18.
```

```
      Y(1)=U(5)
      V(5)=V(1)+H*(7.*(W(5)+W(1))+32.*(W(4)+W(2))+12.*W(3))/22.5
      Y(2)=V(5)
      W(5)=ACCEL(JB,JC,JD)
      Z(2)=W(5)
  250 DO 251 I=1,4
      U(I)=U(I+1)
      V(I)=V(I+1)
  251 W(I)=W(I+1)
      RETURN
      END
```

```
      FUNCTION ACCEL(JB,JC,JD)
      DIMENSION Y(2),Z(2),C(60)
      COMMON C
      EQUIVALENCE (PB,C(1)),(PC,C(2)),(PD,C(3)),(VB,C(4)),(VC,C(5)),
     1 (VD,C(6)),(X,C(7)),(Y(1),C(8)),(Z(1),C(10)),(PBREF,C(12)),
     2 (YEXH,C(15)),(YINIT,C(16)),(PBINIT,C(17)),(PDEL1,C(18)),
     3 (PCINT,C(19)),(PATM,C(20)),(G1,C(21)),(G2,C(22)),(G3,C(23)),
     4 (G4,C(24)),(G5,C(25)),(H,C(26)),(F1,C(27)),(TAMB,C(28)),(FRICT,
     5 C(29)),(PDMAX,C(30)),
     6 (PINL,C(36)),(PDEL,C(37)),(BO,C(38)),(CO,C(39)),(DO,C(40)),(YO,
     7 C(41)),(YOO,C(42)),(YB,C(43)),(YC,C(44)),(YD,C(45)),(PDO1,C(46)),
     8 (WK,C(47))
      GO TO (11,12,13) JB
   11 PB=BO*YB**(-G4)
      GO TO (16,17,18) JC
   12 PB=PBREF
      GO TO (16,17,18) JC
   13 PB=BO*YB**(-G5)
      GO TO (16,17,18) JC
   16 PC=PCINT
      GO TO (21,22,23,24,25) JD
   17 PC=CO*YC**(-G1)
      GO TO (21,22,23,24,25) JD
   18 PC=PINL
      GO TO (21,22,23,24,25) JD
   21 PD=PDEL
      GO TO 26
   22 PD=DO*YD**(-G2)
      GO TO 26
   23 PD=PDMAX
      GO TO 26
   24 PD=DO*YD**(-G3)
      GO TO 26
   25 PD=PDO1-(PDO1-PDEL)*(Y(1)-YEXH)*2.
   26 ACCEL=FMATH1(PD)
      RETURN
      END
```

APPENDIX D

LISTING OF OPTIONAL BLOCKS IN MAIN PROGRAM

MAP AND ALLOCATION OF COMPLETE PROGRAM

```
      OUTPUT DISPLAY

      REQUIRES MODIFIED DIMENSION STATEMENT

      DIMENSION Y(2),Z(2),C(60),CS(15),CSM(15),SC(12),A(4),B(4),D(4)

      REQUIRES MODIFIED INPUT STATEMENTS

      READ IN PARAMETERS
      IF(SENSE SWITCH 4) 104,106                                           X
      S SW 4 SET FOR CARD INPUT, RESET FOR TAPE INPUT
  104 READ 500,CS                                                          X
  500 FORMAT(9F8.2/6F8.2)                                                  X
  105 READ 505,C(12),(C(I),I=15,35),AB,AC,AD,CYB,CYC,CYD,W,YOML,VREC,      X
     1  XK1,XK2,XK4,XK5,K1,K2,K3,K4,K5,MO,NUM,NC,N1,N2,J1                  X
  505 FORMAT(F12.6/6F12.6/5F12.6/6F12.6/4F12.6/6F12.6/3F12.6/4F12.6/11I5   X
     1  )                                                                  X
      H1=H                                                                 VS
      GO TO 107                                                            X
  106 ACCEPT TAPE 500,CS                                                   X
      ACCEPT TAPE 505,C(12),(C(I),I=15,35),AB,AC,AD,CYB,CYC,CYD,W,YOML,    X
     1  VREC,XK1,XK2,XK4,XK5,K1,K2,K3,K4,K5,MO,NUM,NC,N1,N2,J1             X
      H1=H
  107 IF(SENSE SWITCH 3) 101,112                                           T2
  101 TYPE 500,CS                                                          T2
      GO TO 102                                                            T2
  109 TYPE 514,J                                                           X
  514 FORMAT(/$NUMBER OF INTEGRATION STEPS -$I6)                           X
      J=0                                                                  X
      JJ=0                                                                 X
  110  TYPE 515                                                            X
  515 FORMAT(/$RESTARTING$//)                                              X
  112 IF(MO-2) 111,111,425                                                 X
  111 CALL PENUP                                                           X
      CALL DACON(1,2,4,5,6,0.,0.,0.,0.,0.)                                 X
      PAUSE 7                                                              X
  102 IF(SENSE SWITCH 3) 103,113                                           T2
  103 TYPE 510,C(12),(C(I),I=15,35),AB,AC,AD,CYB,CYC,CYD,W,YOML,VREC,MO    T2
  510 FORMAT(/$1/$F12.6/6F12.6/5F12.6/6F12.6/4F12.6/6F12.6/3F12.6/I3)      T2
```

```
    BLOCK NUMBER 1

114 IF(MO-2) 115,115,425                               X
    PLOTTER AXES
115 IF(K2-7) 116,117,116                               X
116 CALL XYAXES(0.,0.)                                 X
    MN=1                                               X
    GO  TO  120                                        X
117 MN=2                                               X
118 DO 119 I=1,MN                                      X
119 CALL XYAXES(0.,10.-10.*I/MN)                       X
120 CONTINUE                                           X
    OSCILLOSCOPE AXES  (D-A CHANNEL OUTPUT)
416 XA=0.                                              X
    DO 420, I=1,200                                    X
    CALL DACON(4,5,6,0.,0.,XA)                         X
    XA=XA+.05                                          X
420 CONTINUE                                           X
    YA=0.                                              X
    DO 425  I=1,100                                    X
    CALL DACON(4,5,6,YA,YA,0.)                         X
    YA=YA+.1                                           X
425 CONTINUE                                           X
    J=0                                                X
    N=0                                                X
```

```
    BLOCK NUMBER 2

    OUTPUT    1- PLOTTER AND OSCILLOSCOPE,  2- OSCILLOSCOPE,  3- TAPE
370 ASSIGN 172 TO IK                                                    X
    FROM COMPRESSION STROKE

    GO TO 380                                                           X
375 ASSIGN 227 TO IK                                                    X
    FROM POWER STROKE

380 DO 381,I=1,12                                                       X
381 SC(I)=C(I)*.5/CS(I)                                                 X
    IF(SENSE LIGHT 24) 382,383                                          X
382 CALL PENDOWN                                                        X
383 IF(MO-2) 390,385,395                                                X
385 CALL DACON(1,2,4,5,SC(K1),SC(K2),SC(K3),SC(K4))                     X
    GO TO IK                                                            X
390 CALL TIMEPLOT(C(K1),BX+C(K2),XSCALE,YSCALE,XFIRST,YFIRST,MN,NO,AX,  X
   1 BX)                                                                X
    CALL DACON(4,5,6,SC(K3),SC(K4),SC(K5))                              X
    GO TO IK                                                            X
395 IF(MO-3) 398,396,400                                                X
396 IF(J-JJ) 398,397,397                                                X
397 PUNCH TAPE 650,PB,PC,PD,X,Y,Z(2)                                    X
650 FORMAT(3F8.3,2F7.5,F8.3,F8.1)                                       X
    JJ=J+J1                                                             X
398 GO TO IK                                                            X
400 IF(N-N1) 385,385,401                                                X
401 IF(N-N2) 402,403,403                                                X
402 CALL PENUP                                                          X
    GO TO IK                                                            X
403  SENSE LIGHT 24                                                     X
    GO TO IK                                                            X
```

```
    BLOCK NUMBER 3

190 IF(MO-2) 495,468,495                                                  X
    OSCILLOSCOPE DISPLAY OF DIESEL CONSTANT VOLUME COMBUSTION (D-A OUTPUT)
468 IF(K5-8) 495,469,495                                                  X
    IF(K5-8) 495,469,495                                                  X
469 IF(K3-3) 480,470,480                                                  X
470 NN=(PDM-PD1)/25.                                                      X
    DO 475, I=1,NN                                                        X
    SC(K3)=SC(K3)+.125                                                    X
475 CALL DACON(4,6,SC(K3),SC(K5))                                         X
480 IF(K4-3) 495,485,495                                                  X
485 NN=(PDM-PD1)/25.                                                      X
    DO 490, I=1,NN                                                        X
    SC(K4)=SC(K4)+.125                                                    X
490 CALL DACON(5,6,SC(K4),SC(K5))                                         X
495 CONTINUE                                                              X
    SENSE LIGHT 24                                                        X
```

THE FOLLOWING ADDITION MUST BE MADE TO THE SUBSECTION FOR CHANGING PARAMETERS

```
    CHANGE OUTPUT VARIABLES DISPLAYED
350 TYPE 635                                                        X
635 FORMAT(/$K1,K2,K3,K4,K5,$/)                                     X
    ACCEPT 640,K1,K2,K3,K4,K5                                       X
640 FORMAT(5I3)                                                     X
    IF(MO-2) 353,353,351                                            X
351 GO TO IJ                                                        X
352 ASSIGN 129 TO IJ                                                X
    GO TO 353                                                       X

    FOR PROGRAM INITIALIZATION
354 ASSIGN 129 TO IJ                                                X
    MN=1                                                            X
353 CALL PENUP                                                      X
    CSM(K2)=CS(K2)*MN                                               X
    TYPE 606,MN,CSM(K2)                                             X
606 FORMAT(/$MN,CSM  $I2,F9.2)                                      X
    NO=0                                                            X
    AX=0.                                                           X
    IF(MO-2) 355,356,356                                            X
355 BX=(10.-10.*NO/MN)*CSM(K2)                                      X
    GO TO 357                                                       X
356 BX=0.                                                           X
357 XSCALE=CS(K1)                                                   X
    YSCALE=CSM(K2)                                                  X
    XFIRST=C(K1)                                                    X
    YFIRST=BX+C(K2)                                                 X
    CALL SETPEN(XFIRST,YFIRST,0.,0.,XSCALE,YSCALE)                  X
    CALL PENDOWN                                                    X
    GO TO IJ                                                        X
```

THE FOLLOWING STATEMENTS ARE ADDED AS A SUBSECTION FOR UNMONITORED RUN IN PLACE OF STATEMENTS 232 TO 300 EXCLUSIVE

```
    IF(MO-2) 129,129,236                                          X
236 N=N+1                                                         X
    IF(N-NC) 237,238,238                                          X
237 IF(N-NUM) 129,238,238                                         X
    AUTOMATIC TAPE READ-IN OF NEW PARAMETERS    (UNMONITORED RUN)
238 ACCEPT TAPE 518,NL,NUM,NC                                     X
518 FORMAT(3I3)                                                   X
    TYPE 520,N                                                    X
520 FORMAT(/$N =$I4)                                              X
    DO 239, I=1,NL                                                X
    ACCEPT TAPE 521,L,C(L)                                        X
521 FORMAT(I3,F12.6)                                              X
    TYPE 522,L,C(L)                                               X
522 FORMAT(/$L,C(L)    $I3,F12.6)                                 X
239 CONTINUE                                                      X
    IF(N-NUM) 129,109,109                                         X
240 TYPE 580,PD1,PDMAX                                            X
580 FORMAT(/$PD1 GREATER THAN PDMAX$2F10.4)                       X
250 IF(NC-NUM) 251,109,109                                        X
251 ACCEPT TAPE 518,NL,NUM,NC                                     X
    GO TO 250                                                     X
```

MAP OF MAIN PROGRAM

```
          OCTAL OCTAL DEC   DEC
  NAME    ENTRY BASE  SIZE  PROG
920 CORE  0000  17777 08192
USED MEM              06556
ERASABLE  14414       01636
COMMON    17560       00144

$$$$$$$$  02730 06640 02227 01992
INTRKPMC  07213 07764 00465 00361
ACCEL     10134 10334 00151 00128
                10354 00225
TIMEPLOT  10724 11056 00130 00090
CONPLOT1  11126 11417 00242 00185
XYAXES   11510 11764 00196 00172
SETPEN    12014 12114 00093 00064
PENUP     12151 12177 00035 00022
PENDOWN   12214 12242 00035 00022
                12250 00067
                12353 00109
                12530 00139
                12743 00145
                13164 00084
                13310 00014
                13326 00014
                13344 00005
                13351 00009
                13362 00010
                13374 00020
                13420 00022
                13446 00012
                13462 00022
                13510 00016
               13530 00010
                13542 00010
                13554 00037
                13621 00008
                13631 00020
                13655 00029
               13712 00091
                14045 00232
```

```
FREE PISTON ENGINE ALLOCATION

#    470          END


COMMON ALLOCATION

   77610 C          77600 A          77570 B          77560 D
   77610 PB         77612 PC         77614 PD         77616 VB
   77620 VC         77622 VD         77624 X          77626 Y
   77632 Z          77636 PBREF      77644 YEXH       77646 YINIT
   77650 PBINIT     77652 PDEL1      77654 PCINT      77656 PATM
   77660 G1         77662 G2         77664 G3         77666 G4
  77670 G5         77672 H          77674 F1         77676 TAMB
   77700 FRICT      77702 PDMAX      77716 PINL       77720 PDEL
   77722 BO         77724 CO         77726 DO         77730 YO
   77732 YOO        77734 YB         77736 YC         77740 YD
   77742 PD01       77744 WK

PROGRAM ALLOCATION

   00022 CS         00060 CSM        00116 SC         00146 I
   00147 K1         00150 K2         00151 K3         00152 K4
   00153 K5         00154 MO         00155 NUM        00156 NC
   00157 N1         00160 N2         00161 J1         00162 J
   00163 JJ         00164 MN         00165 N         00166 M
   00167 JB         00170 JC         00171 JD         00172 NN
   00173 MM         00174 NL         00175 L          00176 IJ
   00177 L1         00200 L2         00201 NO         00202 IK
   00203 AD         00205 AB         00207 AC         00211 PNB
   00213 CYB        00215 CYC        00217 CYD        00221 W
   00223 YOML       00225 VREC       00227 XK1        00231 XK2
   00233 XK4        00235 XK5        00237 H1         00241 XA
   00243 YA         00245 T          00247 F         00251 PB1
   00253 PC1        00255 YCINT      00257 YS         00261 XMOLD
   00263 TOLD       00265 PERIOD     00267 XMDEL      00271 WDEL
   00273 PD1        00275 PDM        00277 F2         00301 TDEL
   00303 XMNEW      00305 TNEW       00307 PMEAN      00311 DP
   00313 WMEAN      00315 XM         00317 P          00321 PDIF
   00323 GHP        00325 SFC        00327 AX         00331 BX
   00333 XSCALE     00335 YSCALE     00337 XFIRST     00341 YFIRST


SUBPROGRAMS REQUIRED

   DMATH1     PENUP      DACON      XYAXES     INTRKPMC   SQRT
   ABS        SETPEN     PENDOWN    TIMEPLOT

THE END
```

APPENDIX E

TYPICAL DATA

The program has been designed to accept parameters and calculate variables in particular units as follows:

(1) Pressures - p.s.i.
(2) Lengths - inches
(3) Areas - square inches
(4) Volumes - cubic inches
(5) Time - seconds
(6) Temperature - degrees Kelvin
(7) Mass - pounds
(8) Specific fuel consumption - lb./(hr. x H.P.)
(9) Constants - k_1 - lb./in.
k_2 - $^{o}K \times 10^6$
k_3 - $in.^2 \times {}^{o}K^{1/2}/sec.$
k_4 - H.P. x sec./(lb. x ^{o}K)
k_5 - $in.^{-1} \times 10^6$

The data can be presented on cards and the order of presentation must be C(12),(C(L),L=15,35),AB,AC,AP,CYB,CYC,W,YOML,VREC,XK1, XK2,XK4,XK5. The following is a set of typical data cards in the input format required:

```
60.
 3.27      4.48      300.0     19.7       14.12     14.7
 1.4       1.4         1.33    1.4         1.35
  .00005  70.0       293.0    200.0     1500.0        0.0
 0.0       0.0         0.0     0.0
 7.4315   63.455       9.621    6.257        5.921    0.0
23.7       5.25     6912.0
  .00433    .0216      0.65     4.43
```

The engine fuel setting, F_1, is entered in micropounds per stroke for convenience, and the constants k_2 and k_5 are altered by a factor of 10^{-6} to compensate. Actual values used for all of the constants in Section 3.3 were calculated from the equations using typical operating data for an actual engine.

When the delivery pressure is low during the first few cycles after starting, the fuel setting must be kept low to represent combustion inefficiencies in the cold engine. A set of starting characteristics obtained from the simulation using the given data is shown in Figures E1 to E5. The effect of changing fuel setting and bounce reference pressure is illustrated. A small exhaust receiver volume of four cubic feet was used so that steady-state could be reached more quickly. Figures E6 to E11 show the steady-state condition.

The results of an inner dead point start are shown in Figure E12. The two pages preceding this figure provide a preliminary step-by-step outline of the IDP start that was performed in an attempt to find the required diesel pressure for continued operation.

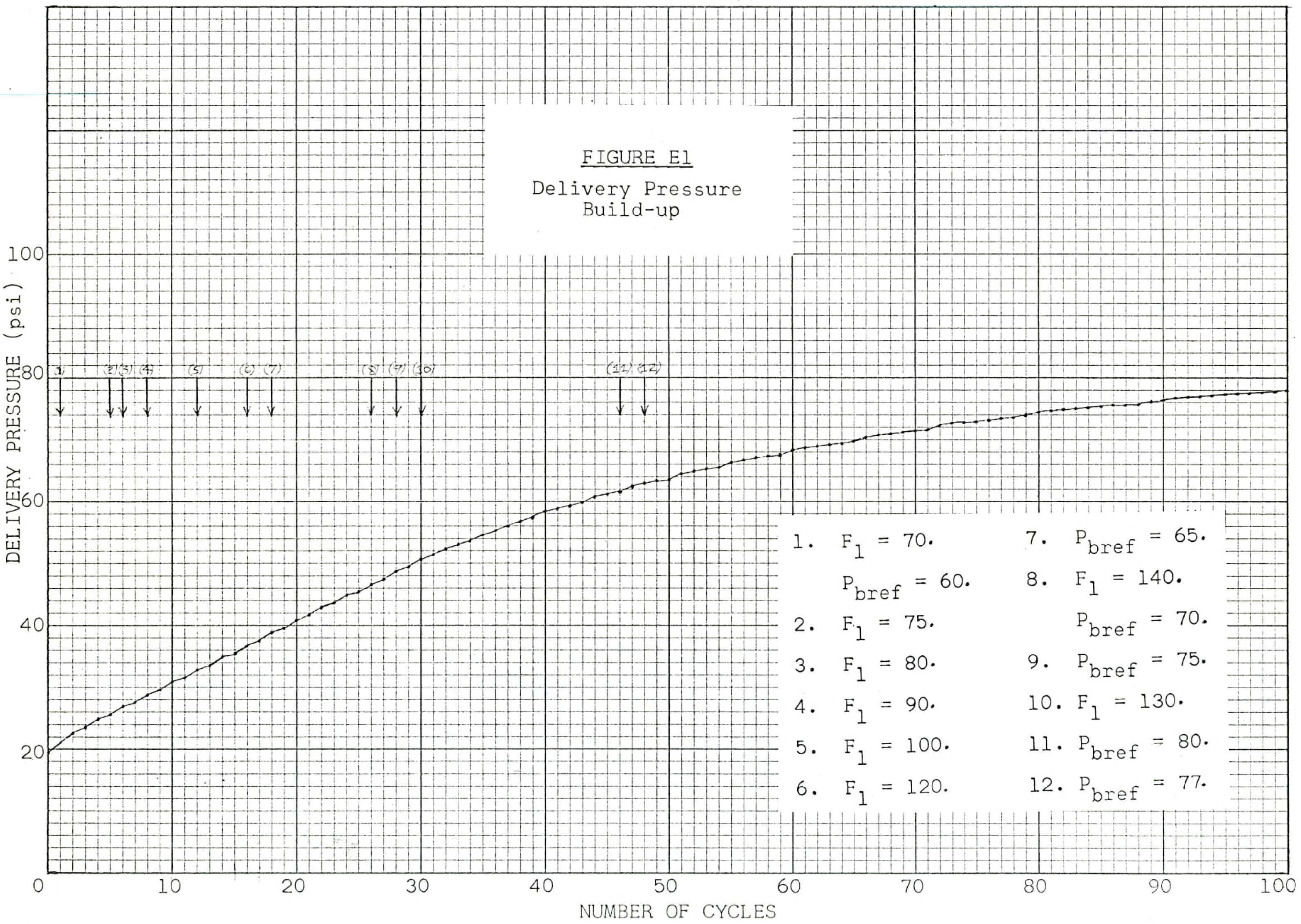


FIGURE E1

Delivery Pressure Build-up

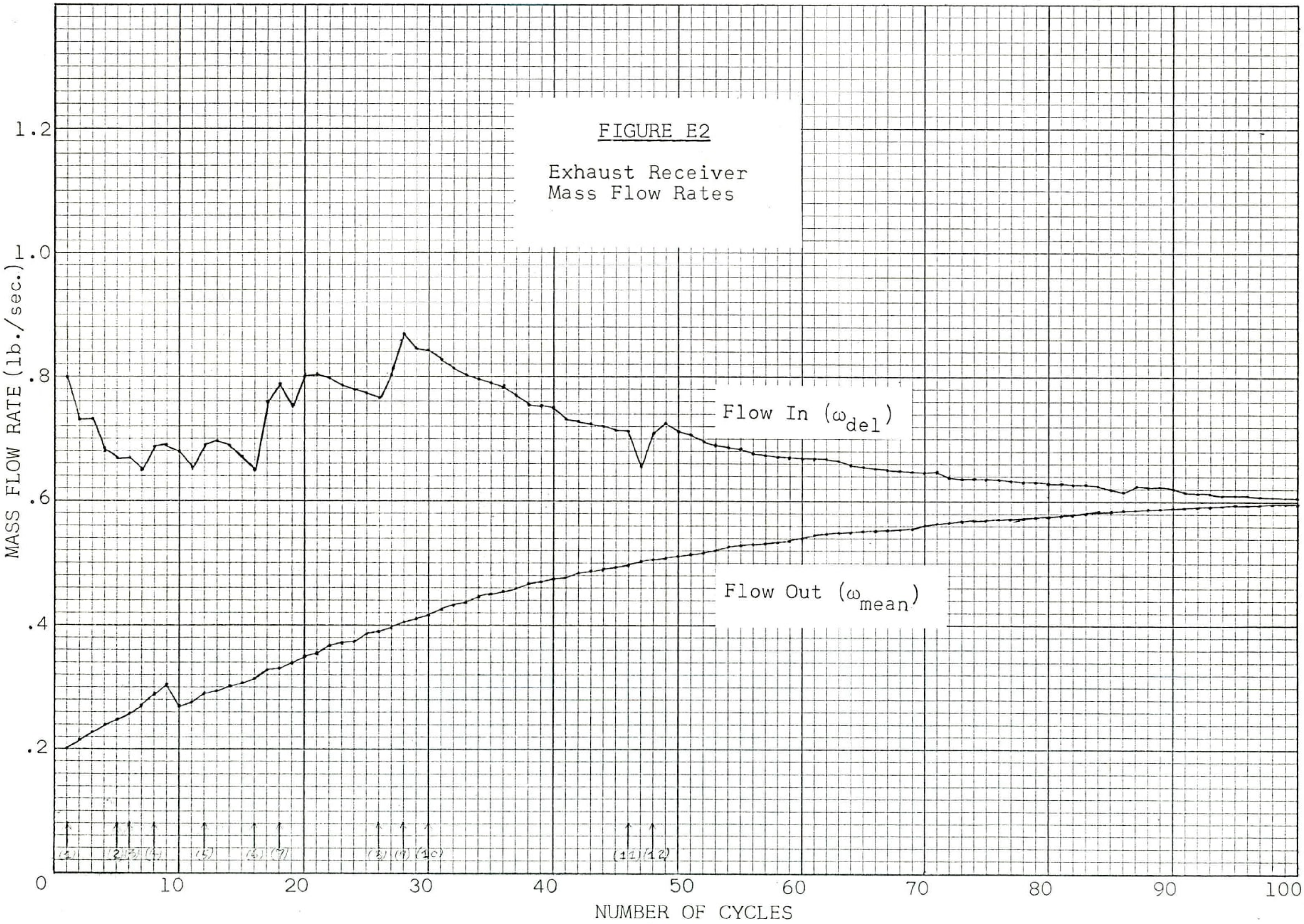


FIGURE E2

Exhaust Receiver Mass Flow Rates

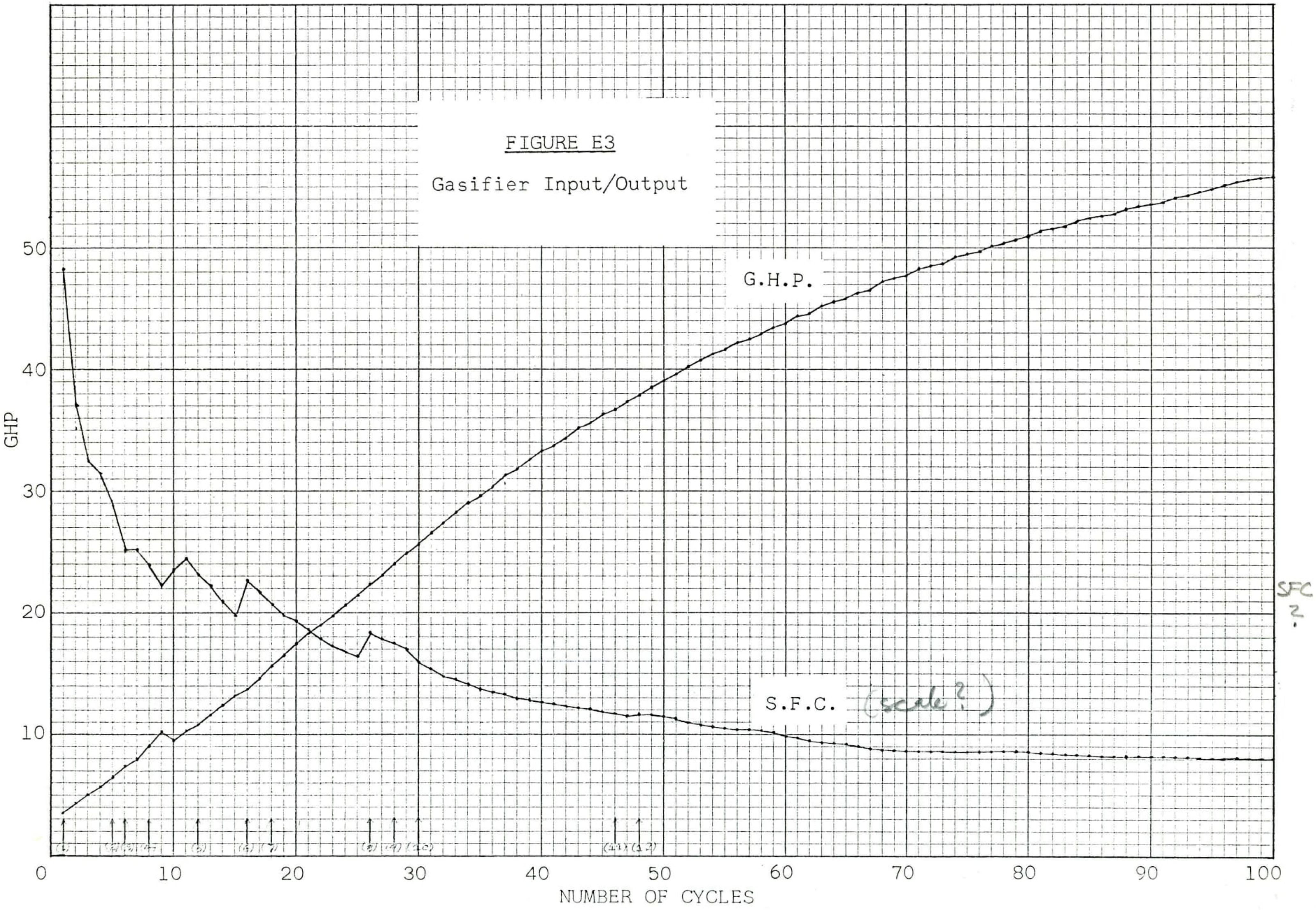


FIGURE E3

Gasifier Input/Output

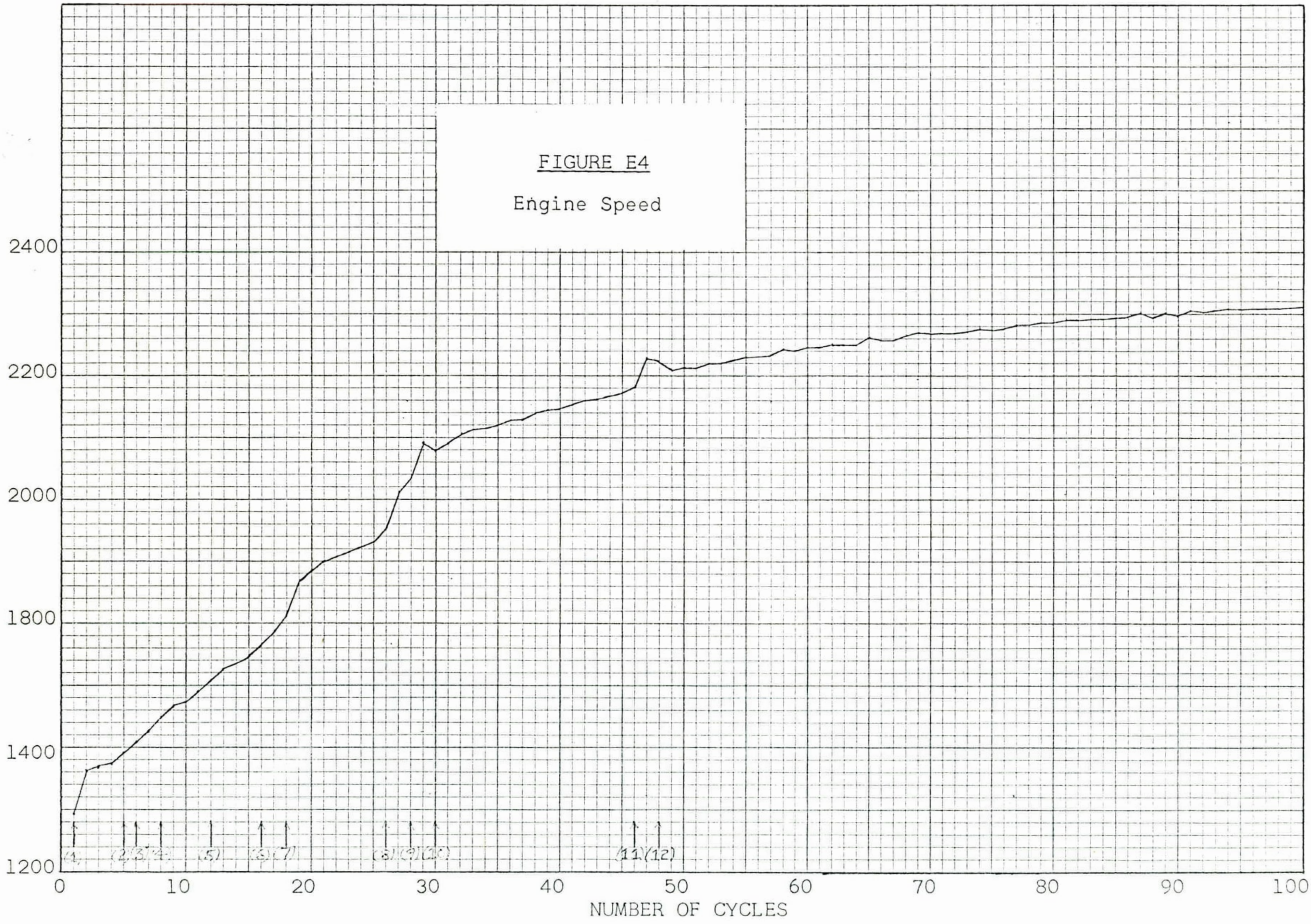


FIGURE E4

Engine Speed

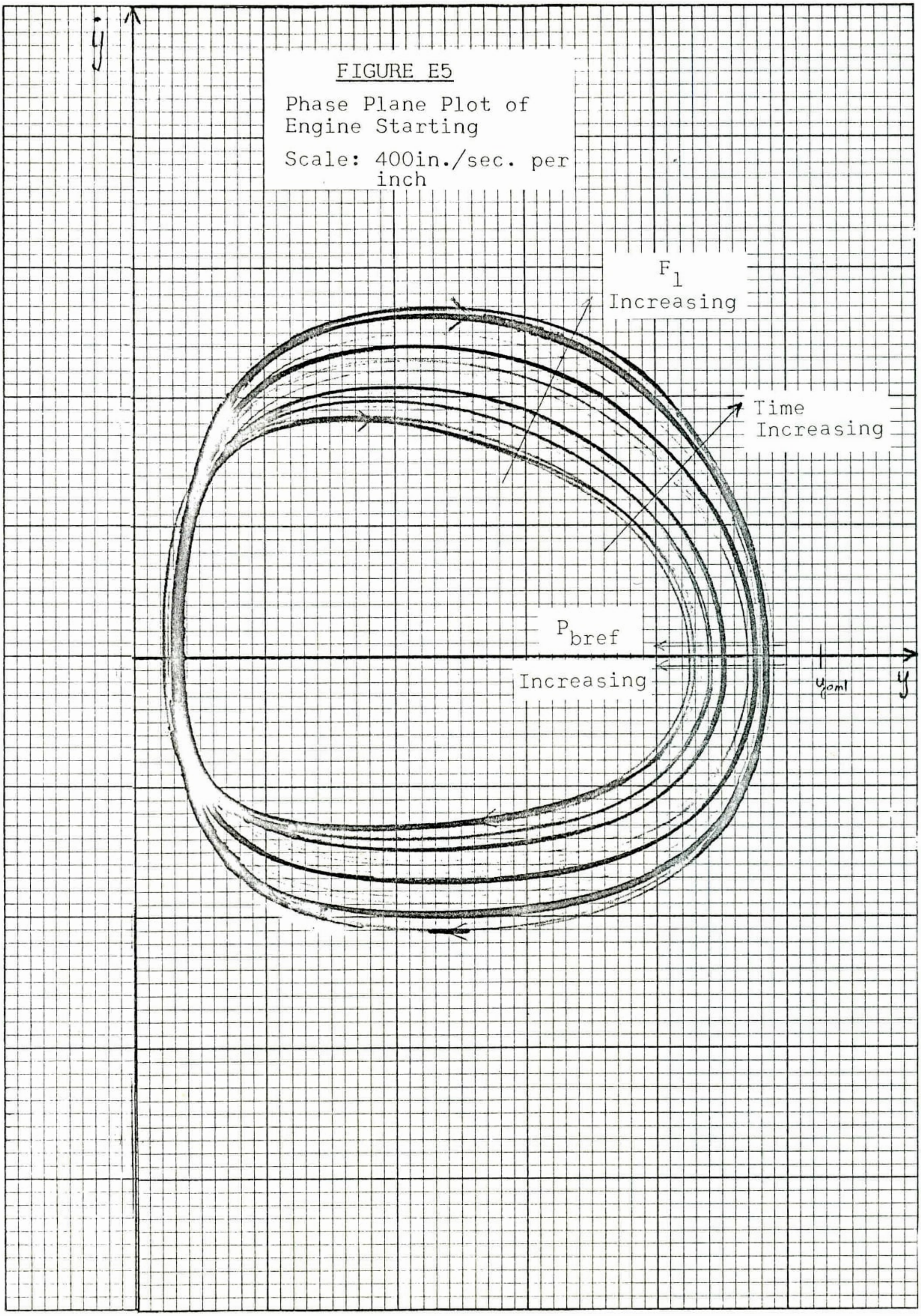


FIGURE E5

Phase Plane Plot of Engine Starting

Scale: 400in./sec. per inch

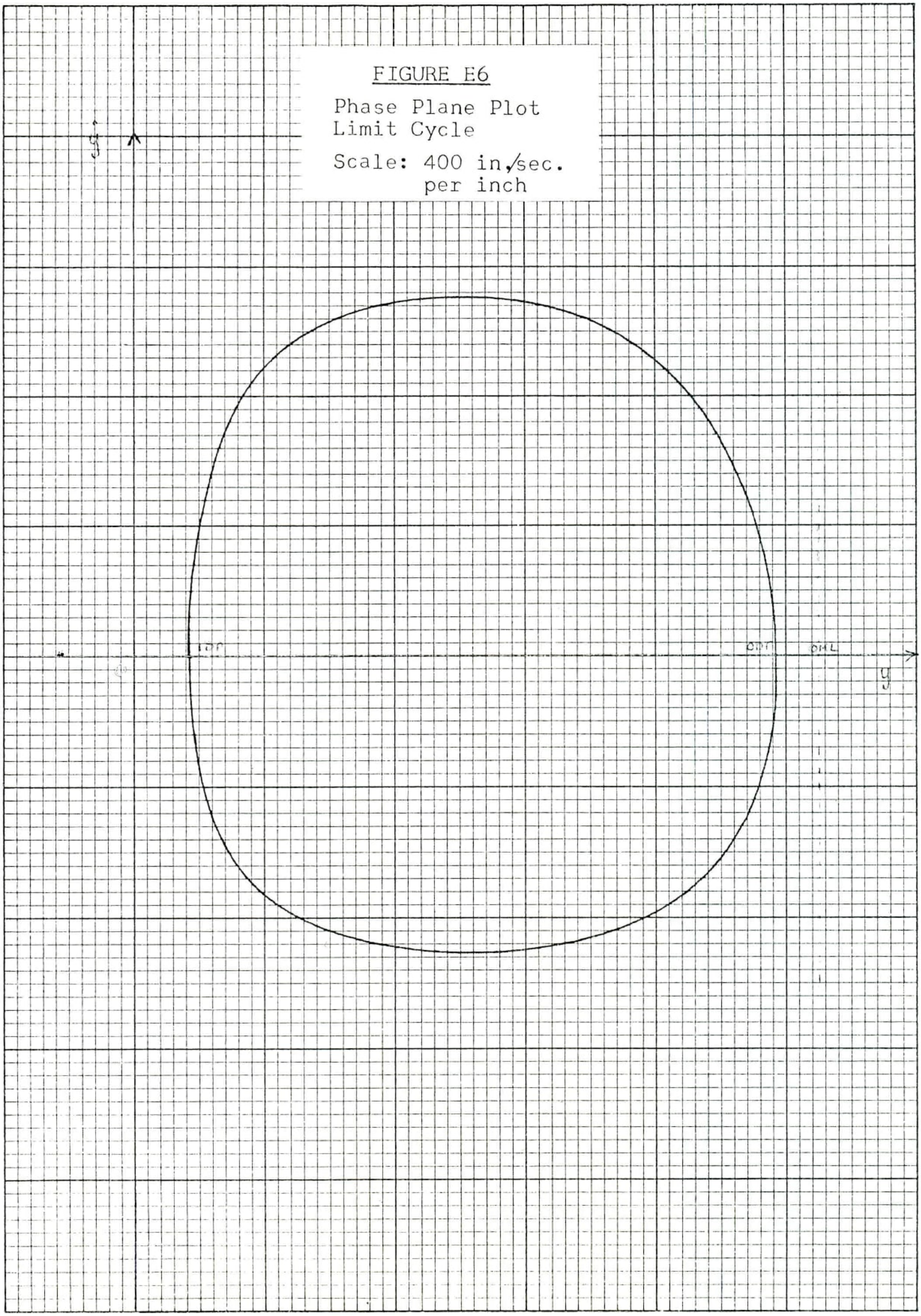


FIGURE E6

Phase Plane Plot
Limit Cycle

Scale: 400 in./sec.
per inch

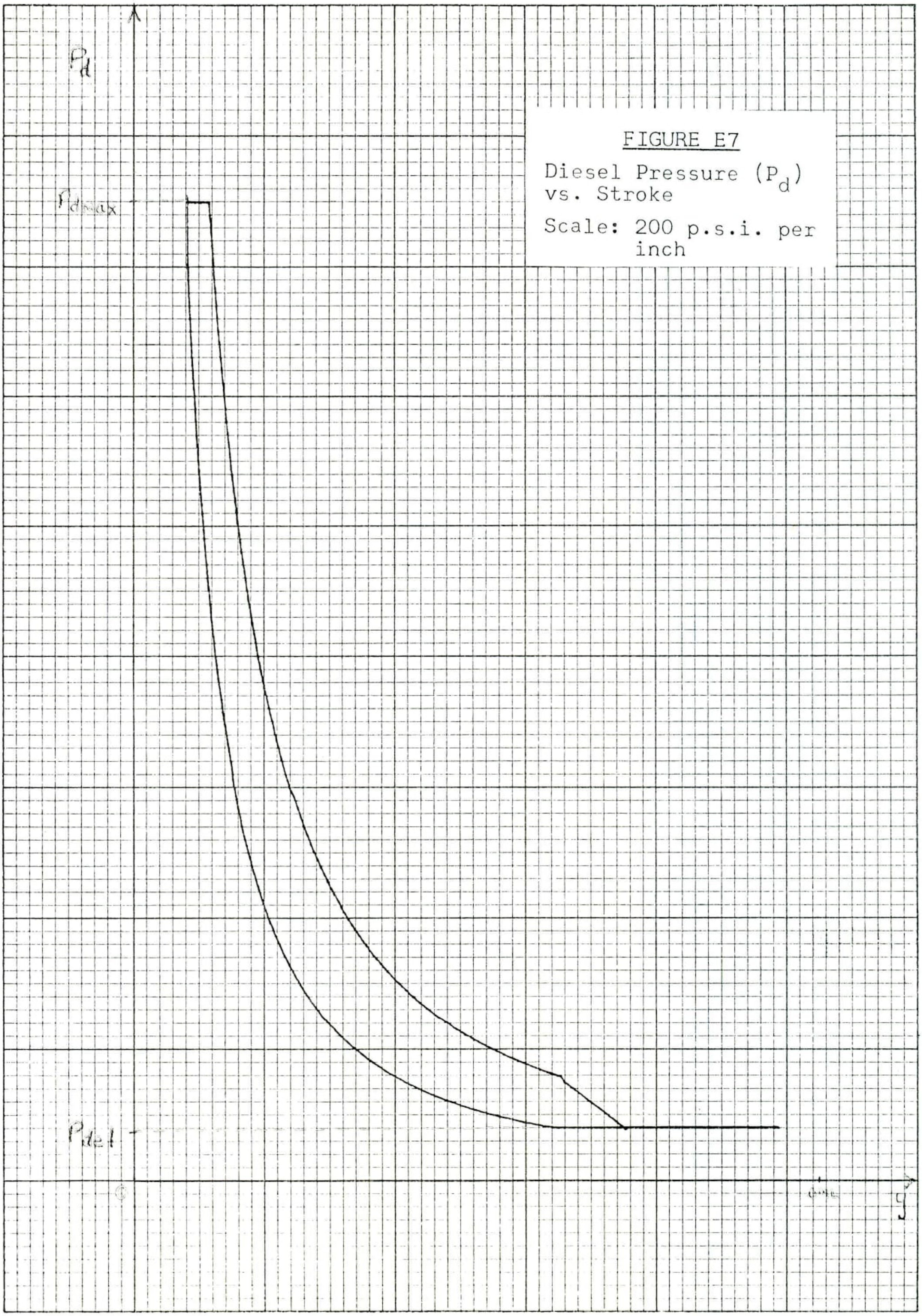


FIGURE E7

Diesel Pressure (P_d) vs. Stroke

Scale: 200 p.s.i. per inch

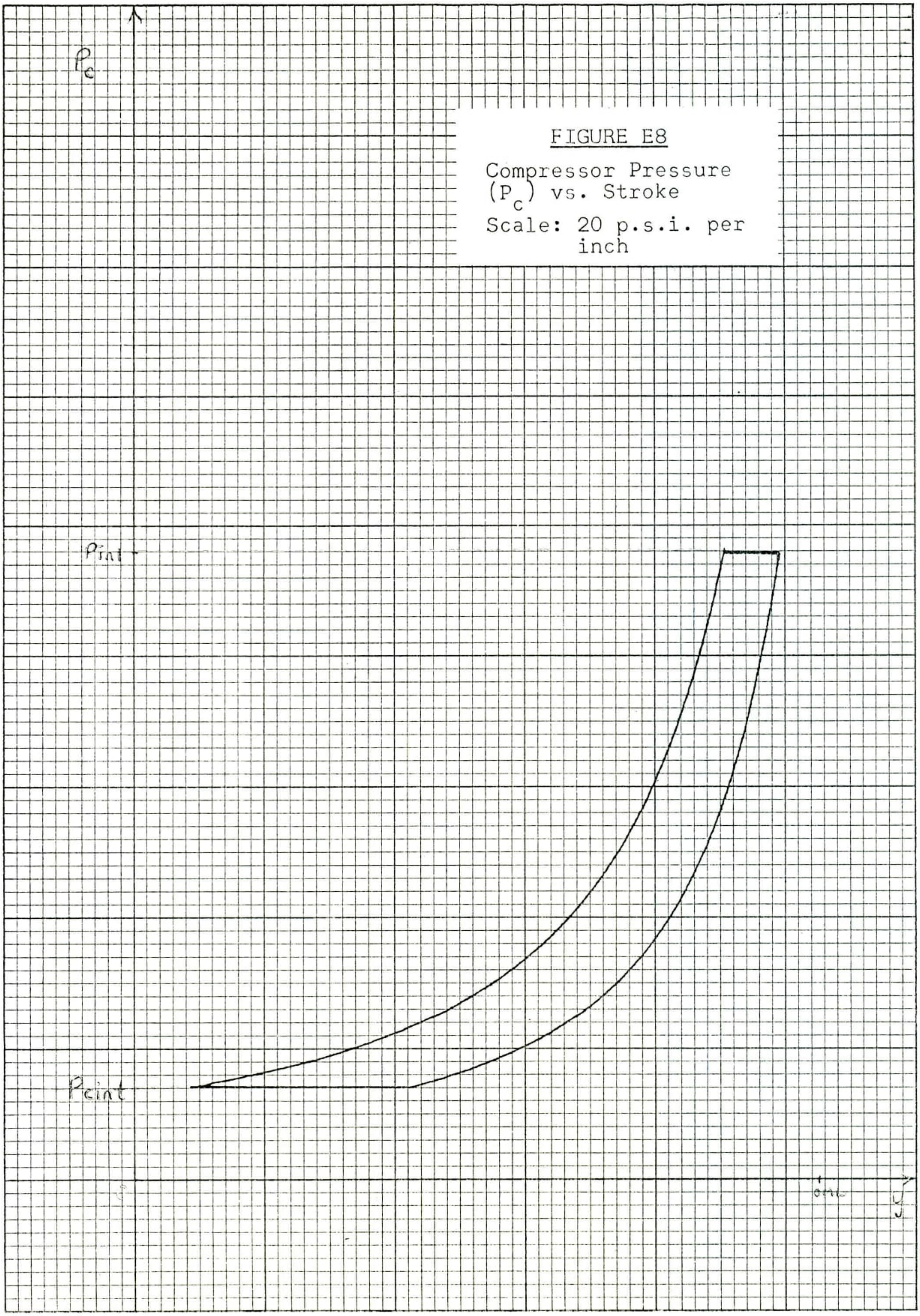


FIGURE E8

Compressor Pressure (P_c) vs. Stroke

Scale: 20 p.s.i. per inch

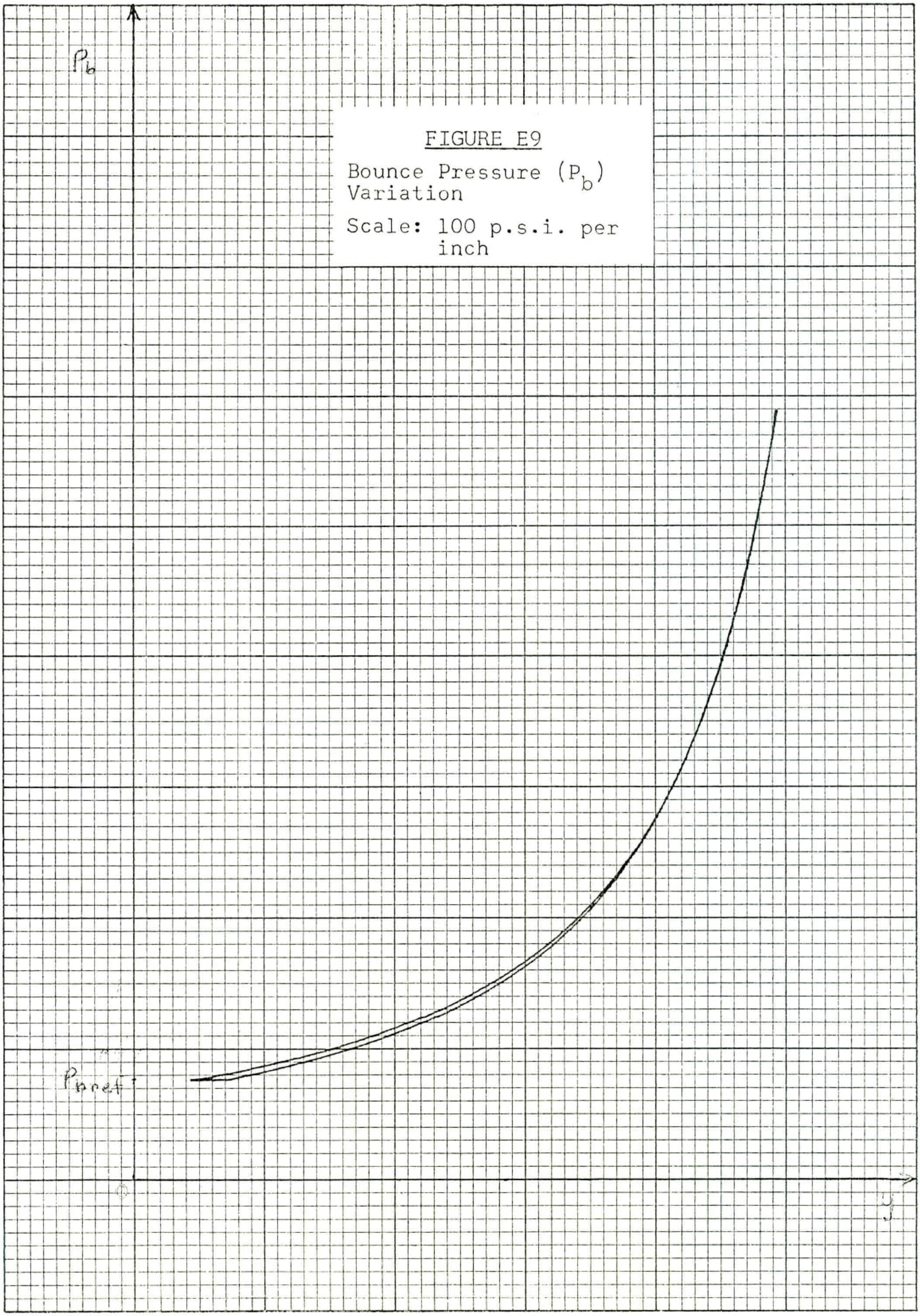


FIGURE E9

Bounce Pressure (P_b) Variation

Scale: 100 p.s.i. per inch

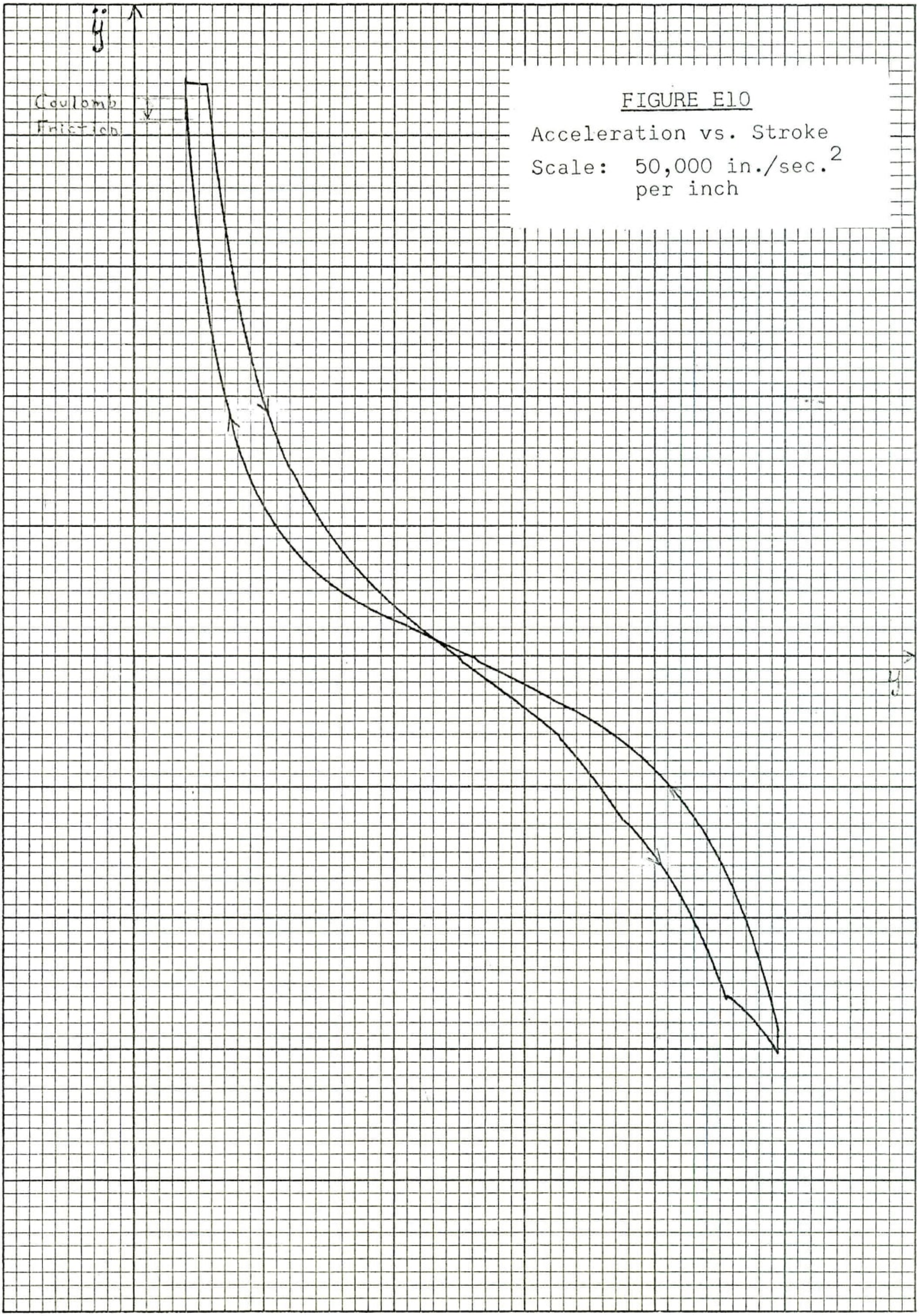


FIGURE E10

Acceleration vs. Stroke

Scale: 50,000 in./sec.^{2} per inch

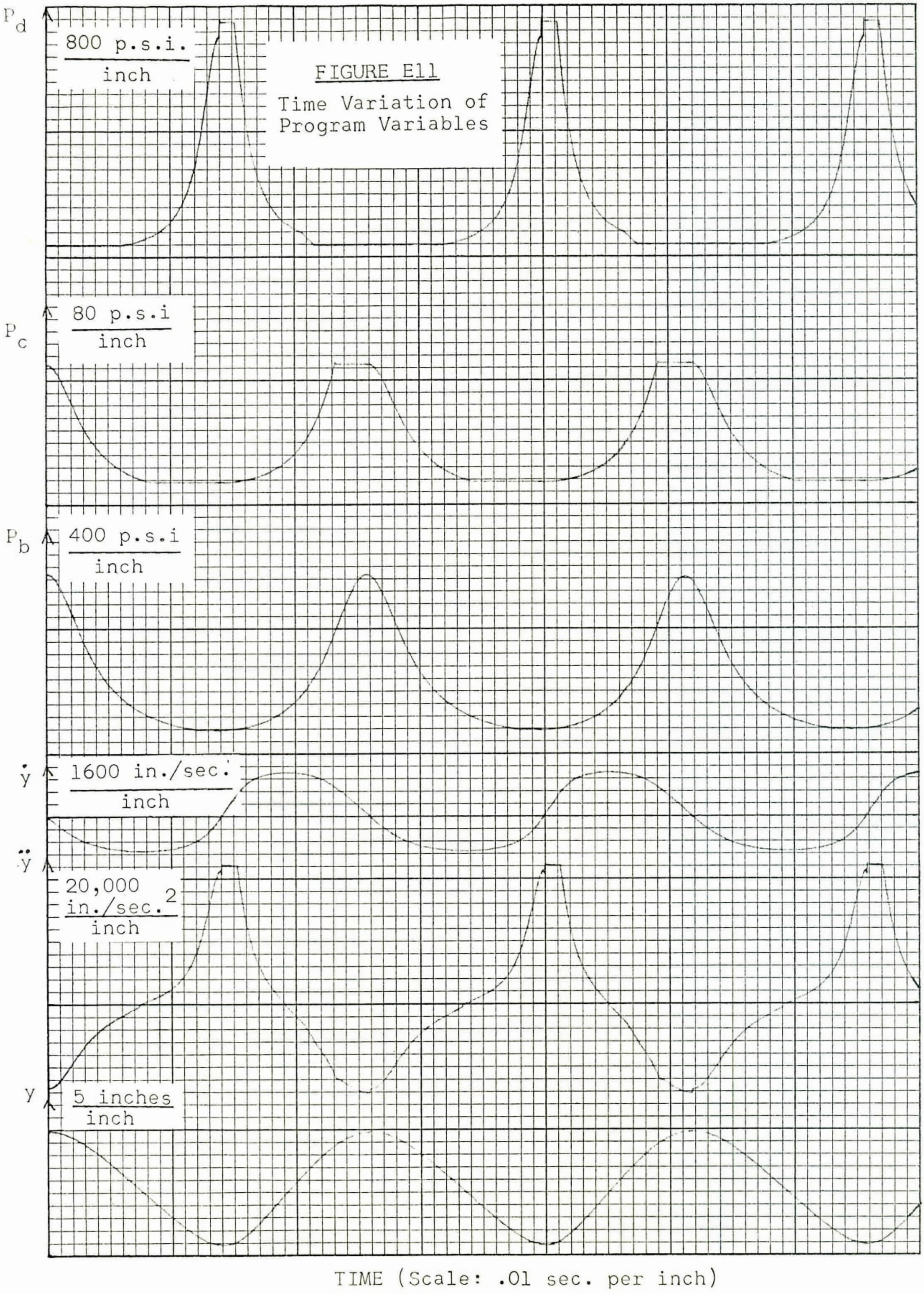


FIGURE E11

Time Variation of Program Variables

```
        FREE PISTON ENGINE INNER DEAD POINT STARTING PROCEDURE

1.  LOAD SIMULATION AND READ IN PARAMETERS

LOADING COMPLETE


        SET SENSE SWITCH 4

        SET SENSE SWITCH 3 TO OBTAIN TYPEOUT OF PARAMETERS


1/     60.000000
    3.270000    4.480000  300.000000   19.700000   14.120000   14.700000
    1.400000    1.400000    1.330000    1.400000    1.350000
    0.000050   70.000000  293.000000  200.000000 1500.000000    0.000000
    0.000000    0.000000    0.000000    0.000000
    7.431500   63.455000    9.621000    6.257000    5.921000    0.000000
   23.570000    5.250000 6912.000000


        SUPPOSE IT IS DESIRED TO MAINTAIN PD AT A CONSTANT VALUE FOR A
SPECIFIED PISTON TRAVEL YOO

        ENTER THE VALUE OF PD AND SET PDMAX TO THIS VALUE ALSO AS FOLLOWS

        RESET SENSE SWITCH 4, SET SENSE SWITCH 1, AND CLEAR THE HALT

        RESET SENSE SWITCH 2 AND CLEAR HALT

L,C[L]

3,150.,

CLEAR HALT AGAIN

L,C[L]

8,3.27,          NOW RESET SENSE SWITCH 1 BEFORE RETURNING

SET SENSE SWITCH 1 AGAIN AS SOON AS THE COMPUTER CYCLES
OBTAIN TYPEOUT OF DO


L1,L2

40,
  725.16990

NOW RESTART AND INITIALIZE THE POWER STROKE THROUGH SENSE SWITCH 1


RESTARTING
```

```
L,C[L]

1,60.,

L,C[L]

2,14.12,

L,C[L]

3,150.,

L,C[L]

30,150.,

L,C[L]

8,.30,


SET  S SW 2 FOR IDP TYPEOUT AND SET S SW 1 DURING TYPEOUT TO ENTER DO,YOO

2/  150.0000  150.0000   60.0000     0.3000     1.3337  337.7682   21.5102


L,C[L]

40,725.1699,

L,C[L]

42,3.27,

NOW SET S SW 4 TO ENSURE THAT THE CORRECT VALUES ARE BEING USED

P/     0.000050     0.300     0.524    10472.3    60.000    14.120   150.000   0.00005

P/     0.000100     0.300     1.047    10472.3    60.000    14.120   150.000   0.00005

SET S SW 2 FOR{DEAD POINT}TYPEOUTS
                
    S SW 3     {BREAKPOINT}

COMP OUTL     2.1188    97.9233    24.3533   150.0000

ODP     3.1312    -0.1079   143.2960

 1666 RPM

IN THIS CASE THE VALUE 150. IS TOO SMALL SO THE SAME PROCEDURE IS FOLLOWED
FOR THE NEXT ATTEMPT UNTIL A SUITABLE VALUE IS FOUND
```

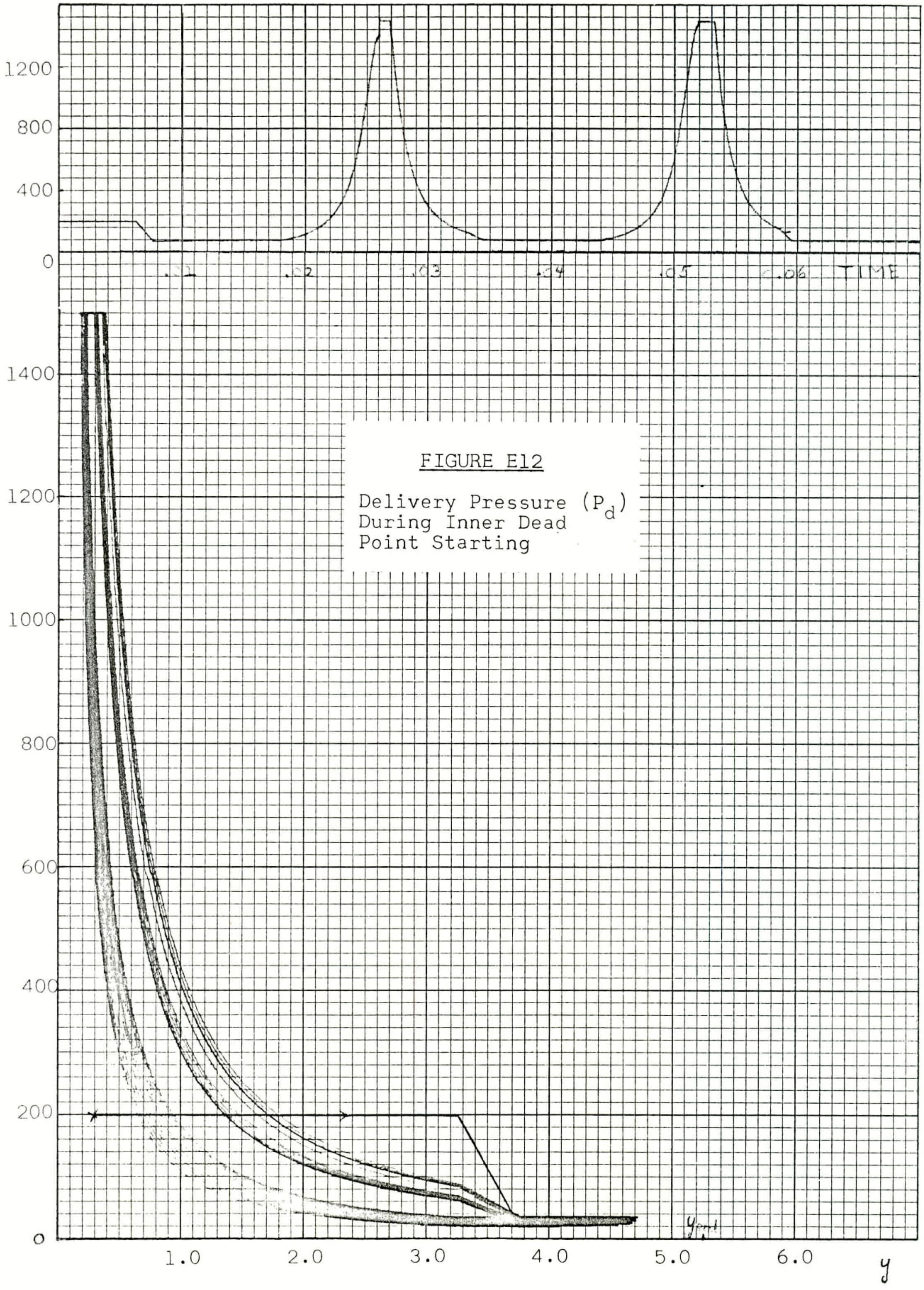


FIGURE E12

Delivery Pressure (P_d) During Inner Dead Point Starting

APPENDIX F

TEST CASE FOR INTEGRATION METHOD

The integration formulae used were checked on a test case. This consisted of a double-acting piston arrangement which had the same dynamic ranges in the main variables as the free piston problem but with an equation of motion that could be integrated directly.

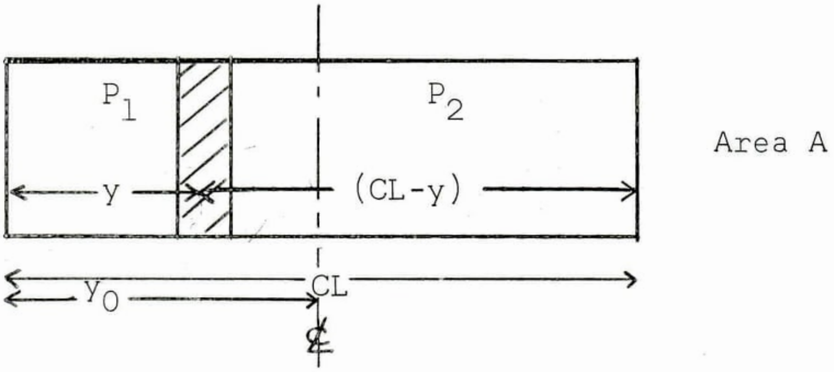


FIGURE F1: Double-Acting Piston

Equation of Motion:

$$y = \frac{g.A}{W}(P_2 - P_1)$$

$$P_1 = P_0\left(\frac{y_0}{y}\right)^{\gamma}, \quad P_2 = P_0\left(\frac{y_0}{CL-y}\right)^{\gamma}, \quad y_0 = CL/2$$

$$\therefore \ddot{y} = \frac{g.A\ P_0 y_0{}^{\gamma}}{W}\left[\frac{1}{(CL-y)^{\gamma}} - \frac{1}{y^{\gamma}}\right] \qquad \text{.....(F1)}$$

Now if the initial pressure P_0 and the maximum pressure $P_1 = P_{dmax}$ are specified, the inner dead point can be calculated by

$$y_{IDP} = y_0\left(\frac{P_0}{P_{dmax}}\right)^{\frac{1}{\gamma}} \qquad \text{.....(F2)}$$

The initial velocity that must be given to the piston in order to reach y_{IDP} can be found from equation (F1) by multiplying by $\dot{y}$ and integrating

$$\int_0^t \ddot{y}\,\dot{y}dt = c\int_0^t \left[\frac{\dot{y}}{(CL-y)^{\gamma}} - \frac{\dot{y}}{y^{\gamma}}\right]dt \qquad \text{where } c = \frac{g.A.P_0 y_0{}^{\gamma}}{W}$$

$$\int_{\dot{y}_0}^{\dot{y}_{IDP}} \dot{y}\,d\dot{y} = c\int_{y_0}^{y_{IDP}} \left[\frac{1}{(Cl-y)^{\gamma}} - \frac{1}{y^{\gamma}}\right]dy$$

$$\left[\frac{(\dot{y})^2}{2}\right]_{\dot{y}_0}^{0} = \frac{c}{(\gamma-1)}\left[(CL-y)^{(1-\gamma)} + y^{(1-\gamma)}\right]_{y_0}^{y_{IDP}}$$

$$0 - \frac{\dot{y}_0{}^2}{2} = \frac{c}{(\gamma-1)}\left[(CL-y_{IDP})^{(1-\gamma)}+y_{IDP}{}^{(1-\gamma)}-(CL-y_0)^{(1-\gamma)}-y_0{}^{(1-\gamma)}\right]$$

$$\therefore \dot{y}_0{}^2 = \frac{2.c}{(\gamma-1)}\left[(CL-y_0)^{(1-\gamma)}+y_0{}^{(1-\gamma)}-(CL-y_{IDP})^{(1-\gamma)}-y_{IDP}{}^{(1-\gamma)}\right] \quad \ldots(F3)$$

Now the initial velocity required is set as an initial condition at y_0 and the integration subroutine is used in the dynamic simulation of the motion of the piston. The resulting y_{IDP} and P_{dmax} should be the same as the specified values in equation (F2), and the initial values should be duplicated at the center point.

The agreement between successive IDP values was used as a measure of the stability of the integration process. In this manner, using a very small stepwidth, the stability of the integration formula was verified. Then a sequence of step changes was found experimentally that would produce the optimum combination of integration accuracy and speed.

FREE PISTON SIMULATION
COMPUTER CONTROL SHEET

1. TYPEOUTS

Sense Switch 2

IDP - Y(1),Y(2)
2/ - PD1,PDM,PB1,YO,YOO,TDEL,PDEL
ODP - Y(1),Y(2),PB1

Sense Switch 3

COMP INL - Y(1),PB,PC,PD
EX CL - Y(1),PB,PC,PD
PB = PBREF,Y - PBREF,Y(1)
3/ - WDEL,WMEAN,TNEW,PINL,GHP,SFC
COMP OUTL - Y(1),PB,PC,PD
EX OP - Y(1),PB,PC,PD

Sense Switch 4

C/ }
P/ } - X,Y(1),Y(2),Z(2),PB,PC,PD,H

2. CHANGE PARAMETERS

FUNCTION	SENSE SWITCH SETTING
ALTER C(L)	1S,2R
RESTART	1S,2S-3R
CHANGE OUTPUT MODE	1S,2S-3R-4R
CHANGE DISPLAYED VARIABLES	1S,2S-3S-4S,PAUSE8,2R
TYPE C(L1) TO C(L2)	1S,2S-3S-4S,PAUSE,2S

3. MEMBERS OF C(L) ARRAY

VARIABLES	
1	PB
2	PC
3	PD
4	VB
5	VC
6	VD
7	X
8	Y(1)
9	Y(2)
10	Z(L)
11	Z(2)
12	PBREF
13	
14	

PARAMETERS

INPUT	
15	YEXH
16	YINIT
17	PBINIT
18	PDEL1
19	PCINT
20	PATM
21	G1
22	G2
23	G3
24	G4
25	G5
26	H
27	F1
28	TAMB
29	FRICT
30	PDMAX
31	
.	
.	

CALCULATED	
36	PINL
37	PDEL
38	BO
39	CO
40	DO
41	YO
42	YOO
43	YB
44	YC
45	YD
46	PD01
47	WK
48	
.	
.	