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DEVELOPMENT OF STEADY-STATE AND DYNAMIC PERFORMANCE PREDICTION METHODS FOR TURBOPUMP SELF-COMPENSATING THRUST BALANCE SYSTEMS

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AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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TECHNOLOGY REPORT

DEVELOPMENT OF STEADY-STATE AND DYNAMIC PERFORMANCE PREDICTION METHODS FOR TURBOPUMP SELF-COMPENSATING THRUST BALANCE SYSTEMS

Interim Report for Tasks I, II, and III

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

This report describes the work completed in a program to develop performance prediction methods for turbopump self-compensating thrust balance systems.

The three tasks described encompass Phase I. They are the hydrodynamic design and mechanical layout of the test assembly (Task I), the formulation of analytical models to predict performance (Task II), and parametric studies (Task III).

The tester was designed to accommodate either a series flow (single acting) or a parallel flow (double acting) balance piston with provisions to permit the varying of sill lengths, pocket depths, orifices, mechanical spring rate, and friction damping. The drive consists of a 100 hp single-stage impulse turbine capable of testing the unit up to the design speed of 10,000 rpm. Digital and analog computer programs were formulated to predict the steady-state and dynamic performance. Then, these computer programs were used to determine the effect of selected changes in the test assembly.

Phase II, which consists of Tasks IV, V, and VI, includes the detailed design of the test assembly, fabrication, and thrust balance system tests of both the series and parallel flow balance pistons in water and gaseous nitrogen. The results from these tests will be used to refine and verify the analytical models.

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I. SUMMARY

The objective of the "Thrust Balance Stability" Program is to formulate and experimentally verify a computerized mathematical logic to predict steady-state and dynamic characteristics of selected turbomachinery axial thrust balance systems. This program is divided into two phases with each phase made up of three tasks. Phase I has been completed and the accomplishments of Tasks I, II, and III are summarized in this report. The complete program is being accomplished under Contract NAS 3-7978 for the Lewis Research Center of the National Aeronautics and Space Administration.

A. TASK I - HYDRODYNAMIC DESIGN AND MECHANICAL LAYOUT

A test assembly was designed to accommodate either a series flow (single acting) or a parallel flow (double acting) thrust balance piston with a hydrostatic load piston. This design includes a turbine drive, a variable axial mechanical spring rate system, a variable axial friction damping device, and instrumentation to measure flow, the pressure profiles of all of the major components, and the critical axial clearances.

B. TASK II - FORMULATION AND DEMONSTRATION OF COMPUTER SIMULATION

A steady-state digital computer program was formulated to determine the flow and pressure profiles throughout the assembly. The program which was developed will accept any fluid by substituting the fluid properties of the desired fluid into the fluid property input tables.

Analog computer simulations were developed to permit study of the test assembly dynamic behavior. These dynamic simulations were developed for both series and parallel flow configurations using either water or gaseous nitrogen as the test fluids.

C. TASK III - PARAMETRIC STUDIES

Parametric analyses were accomplished for both the steady-state and the dynamic behavior of the test assembly. It was found that the designs are quite stable using water as the test fluid. The designs also are stable with gaseous nitrogen at the design pressure of 1000 psi. However, both the series and parallel designs indicate instability with gaseous nitrogen at pressures below 400 psi when using large orifices and low clearances.

D. MAJOR CONCLUSIONS AND RECOMMENDATIONS

1. The parametric studies indicate that the test assembly design is quite stable with either water or gaseous nitrogen when operating at or near the design pressure of 1000 psi.

2. Both the series and parallel configurations were extremely stable for a wide range of parameter variations using water as the fluid. Some highly damped oscillations were noted in the series configuration analog study at approximately 700 cps.

3. Both the series and parallel configurations showed instability at low operating pressures and with large compensating orifices using gaseous nitrogen as the fluid. For the parallel flow configuration, oscillations at 720 cps to 740 cps were evident with operating pressures below 400 psi and an orifice diameter of 0.2-in. This occurred when the piston was displaced 0.004-in. from its mid-position. The series flow configuration also became unstable at operating pressures below 400 psi with an inlet orifice of 0.15-in. This occurred at a piston displacement of 0.003-in. from its mid-position.

4. Fabrication and testing will be accomplished during Phase II. Testing will encompass a range of speeds and pressures utilizing varying sill lengths, pocket depths, and orifices. A statistical approach is recommended for these parameter variations to minimize the number of tests needed to verify both the computer programs as well as the parametric studies.

II. INTRODUCTION

This report delineates the work performed by the Liquid Rocket Operations, Aerojet-General Corporation, Sacramento, California, to complete Tasks I, II, and III (Phase I) of Contract NAS 3-7978 (Thrust Balance Stability), which is under the cognizance of the NASA Lewis Research Center, Cleveland, Ohio.

Contractual effort was initiated during April 1967 and is scheduled for completion during January 1969. The three contractual tasks described herein are as follows:

- Task I - Hydrodynamic Design and Mechanical Layout
- Task II - Formulation and Demonstration of Computer Simulation
- Task III - Parametric Studies

The remaining three contractual tasks are as follows:

- Task IV - Detailed Design
- Task V - Fabrication
- Task VI - Thrust Balance System Tests

A major problem area in rocket engine turbopump design and development has been associated with the unbalanced axial thrust resulting from the hydraulic forces within the turbopump. Either completely self-compensating or partially self-compensating thrust balance systems with a pressure differential applied to a thrust piston are used to reduce the unbalanced thrust to a level that is within the thrust bearing capability. The self-compensating thrust balance system is an automatic feedback control device which counteracts axial forces and regulates shaft axial position. As with any feedback controller, the feedback can become regenerative and the system can become unstable under certain conditions. Therefore, it is desirable to ascertain whether or not the system is stable and what adjustments or changes can be made without causing instability.

In this program, the basic technology associated with both series and parallel flow thrust balance systems is being studied. The principal objective is to develop analytical models for predicting the steady-state and dynamic characteristics of the selected thrust balance systems as well as to experimentally verify the models using water and gaseous nitrogen as the test fluids. The models developed also are applicable to rocket engine technology using fluids such as liquid hydrogen by substituting the pertinent tabularized fluid properties into the computer programs.

III. TECHNICAL DISCUSSION

A. HYDROMECHANICAL DESIGN

The design criteria for the test assembly are shown on Table I.

The test configuration, which is shown on Figure No. 1, incorporates a hydrostatic load piston, a turbine drive, roller bearing shaft supports (with one set of roller bearings to apply radial load), a balance piston (which can be either a series or parallel flow configuration), supply orifices, and a spring-mounted duplex ball thrust bearing set with a variable friction damping device.

A single-stage turbine using gaseous nitrogen as the power source was selected to drive the test assembly. A Titan 87-5 first-stage turbine wheel is available and only requires modification of the nozzles for this application. Reamed nozzles for partial-admission were designed. The turbine with these nozzles will be capable of producing 100 hp at 10,000 rpm with gaseous nitrogen supplied at 217 psia and exhausted to atmosphere. Design data for this turbine are presented on Table II.

Oil-lubricated roller bearings were selected for the shaft support. Gaseous nitrogen is supplied to a loader piston attached to the bearing carrier on one set of roller bearings. This applies a radial load to build up stiffness in one direction which prevents the shaft whirl that is inherent in a well-balanced symmetrical design of this type.

The tester was designed to accommodate either a series or a parallel flow thrust balance piston with annular pockets. These pockets were designed into the thrust piston to provide more flexibility in varying the sill lengths, sill positions, and pocket depths. A relatively thick balance piston was designed to minimize the axial deflection associated with high-pressure differential across the piston. Deflection of the balance piston causes a different gap at the inner and outer sill. This difference is a function of the load on the piston. While provision is made in the mathematical model to correct the flow equations for eccentricity or deflection, it is desirable that this effect be minimized to simplify the verification of test results. Compensating orifices are provided in six inlet passages in the stationary housings on each side of the balance piston to feed the pockets on each side of the piston in a parallel flow configuration. In a series flow configuration, the feed holes are blocked on one side of the piston.

TABLE I

TEST ASSEMBLY THRUST BALANCE SYSTEM DESIGN CRITERIA

Operation in either water or gaseous nitrogen.

Basic hardware common to both series and parallel flow.

A hydrostatic type of load system.

Design inlet pressure - 1000 psi

Disk diameter - 8-in.

Shaft speed - 10,000 rpm

Capability to permit change in the following parameters:

- Axial mechanical spring rate.
- Thrust balance system areas and volumes.
- Fixed and variable orifice sizes and locations.
- Inlet and exit pressure levels.
- Damping.

A capability for inducing pressure perturbations in the thrust balance and load systems.

Shaft critical speed - 33,000 rpm

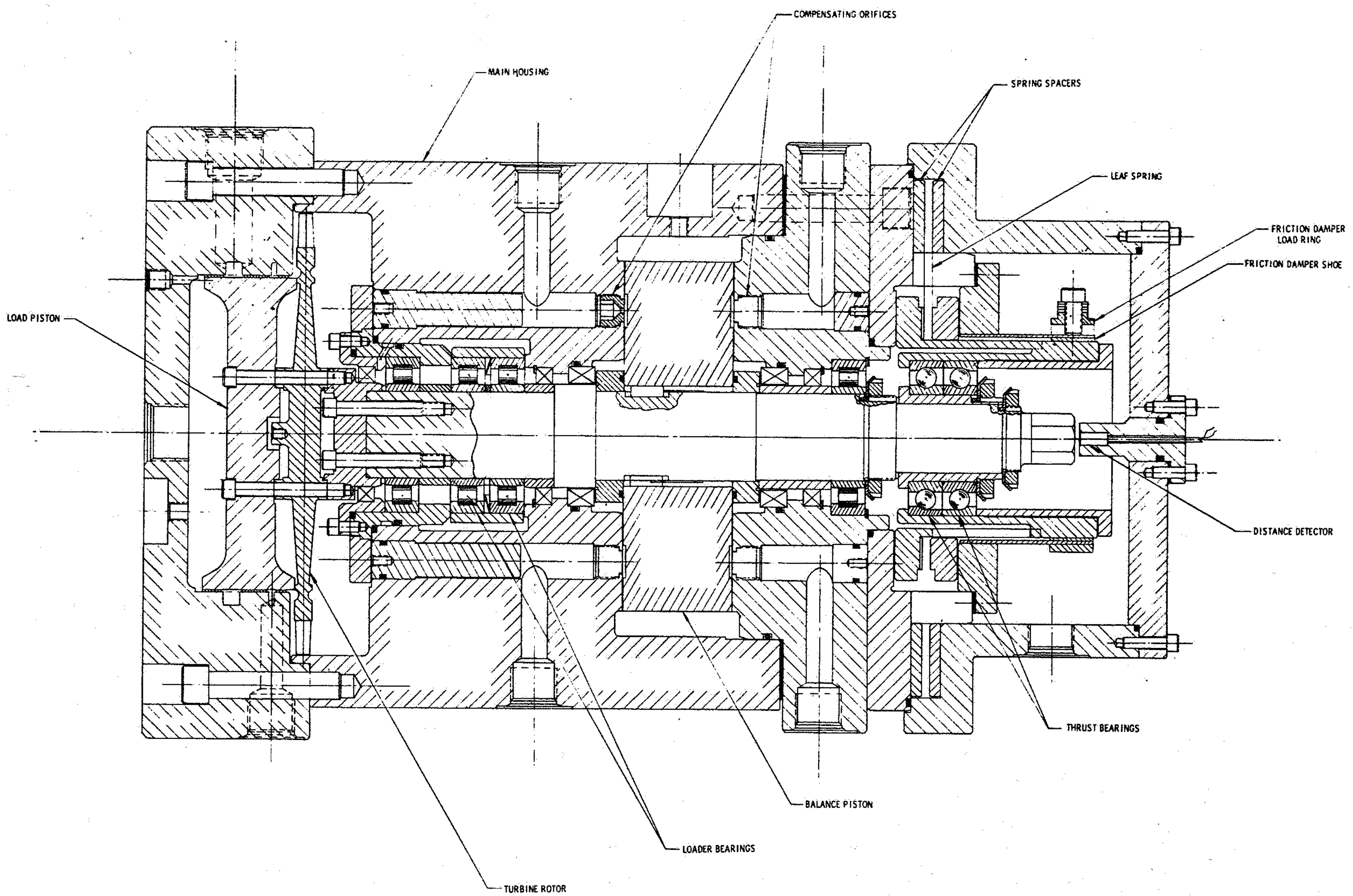

Figure 1: Thrust Balancer Test Assembly, Parallel Flow Configuration

TABLE II

TURBINE DESIGN DATA

Type	Impulse
Number of stages	1
Horsepower	100
Speed, rpm	10,000
Number of nozzles (1 additional provided)	3*
Nozzle throat diameter, in.	0.473
Nozzle throat area, $in.^2$ (3 nozzles)	0.5268
Nozzle exit area, $in.^2$ (3 nozzles)	1.289
Nozzle angle, degrees	17.5
Inlet pressure, psia	217
Inlet temperature, °F	200
Exhaust pressure, psia	20
Exhaust temperature, °F	-62
Exhaust manifold exit area, $in.^2$	4.561

*One additional nozzle will be provided but not used in this test series.

The thrust bearings are held in a carrier which is flexible both radially and axially. Axial slots are machined in the bearing carrier to minimize radial load with shaft deflection and/or misalignment. The bearing carrier is attached to the main housings by four flat leaf springs held between two spacers. Slots are machined in the spacers in the area where the leaf springs are attached. The depth of these slots can be altered to change the effective length of the leaf springs to vary the axial mechanical spring rate. The spacers are designed to vary the spring length which results in loading the thrust bearings to 750 lb, 1500 lb, or 3000 lb for a 0.004-in. axial movement of the balance piston. Stops are provided to limit the travel. This will protect the balance piston should a pressure supply system malfunction occur during testing.

Friction damping in the axial direction is provided by two spring-supported shoes. A ring circumvents these two shoes so that a bolt on one side of the ring exerts force upon one shoe while the opposite side of the ring exerts an equal force upon the remaining shoe. The amount of force exerted and therefore, the axial friction damping, can be varied by adding or removing shims under the bolt head.

Table III lists the materials selected for the test assembly. Stainless steel will be used for the major portion of the tester to resist corrosion and rust during water tests. Aluminum 7075 was selected for the balance piston and load piston to minimize weight as well as to facilitate fabrication. High-strength alloy bolts are used to fasten the major housings and provide a high factor of safety for the major load path.

Blade and disk vibration data for the turbine was available from tests conducted in the Titan program. Table IV is a summary of the natural frequency of the turbine blades and disk as well as the exciting frequencies with three turbine nozzles being used. The umbrella mode and the two nodal diameter mode of the disk could be excited by the third fundamental excitation frequency. An interference axial fit was designed between the load piston and the turbine disk to raise the frequency of the disk and to provide friction damping.

A critical speed analysis was performed using Aerojet-General Computer Program No. 913. The results of this analysis are shown on Figure No. 2. The calculated critical speed of the shaft assembly is 33,000 rpm for a bearing stiffness of 1×10^6 lb/in. This places the critical speed well above the maximum operating speed of 10,000 rpm.

A stress analysis of the critical stress areas was performed. In general, it was desirable to minimize deflection which caused stress to be low in all of the major components. The critical areas were in the bolts and fasteners. A summary of the factor of safety of the structural bolts under maximum load is shown on Table V. Deflection data for the critical areas are shown on Table VI. A minimum allowable yield strength factor of safety of 1.2 and an ultimate strength factor of safety of 1.6 were established for

TABLE III

THRUST BALANCE ASSEMBLY MATERIAL SELECTION

Housings	CAST 347 or 347 Plate
Shaft	AM 350 Bar
Load Piston	AL 7075 Plate
Balance Piston	AL 7075 Plate
Bearings	SAE 52100
Turbine Disk	Waspalloy
Turbine Buckets	713 C
Thrust Bearing Housing Springs	5160 H.R. Spring Steel
Thrust Bearing Housing Spacers	4130 Plate
Miscellaneous Parts	347

TABLE IV

TURBINE VIBRATION ANALYSIS

EXCITING FREQUENCIES (3 NOZZLES)

1st Fundamental	500 cps
2nd Fundamental	1000 cps
3rd Fundamental	1500 cps

BLADE FREQUENCIES (BASED UPON TESTS)*

1st Fundamental	9100 cps
2nd Fundamental	16,300 cps

DISK FREQUENCIES (BASED UPON TESTS)**

Two Nodal Diameter Mode	1345 cps
Three Nodal Diameter Mode	1927 cps
Umbrella Mode	1640 cps

NOTE: Force piston is designed with axial interference fit of 0.001-in. minimum to raise disk frequencies.

*Aerojet-General Memorandum 9635:71-306, dated 26 May 1967, I. K. Hall to L. K. Severud

**Aerojet-General Memorandum 9635:76-73, dated 26 April 1966, E. L. Kessler to N. M. Hachigian

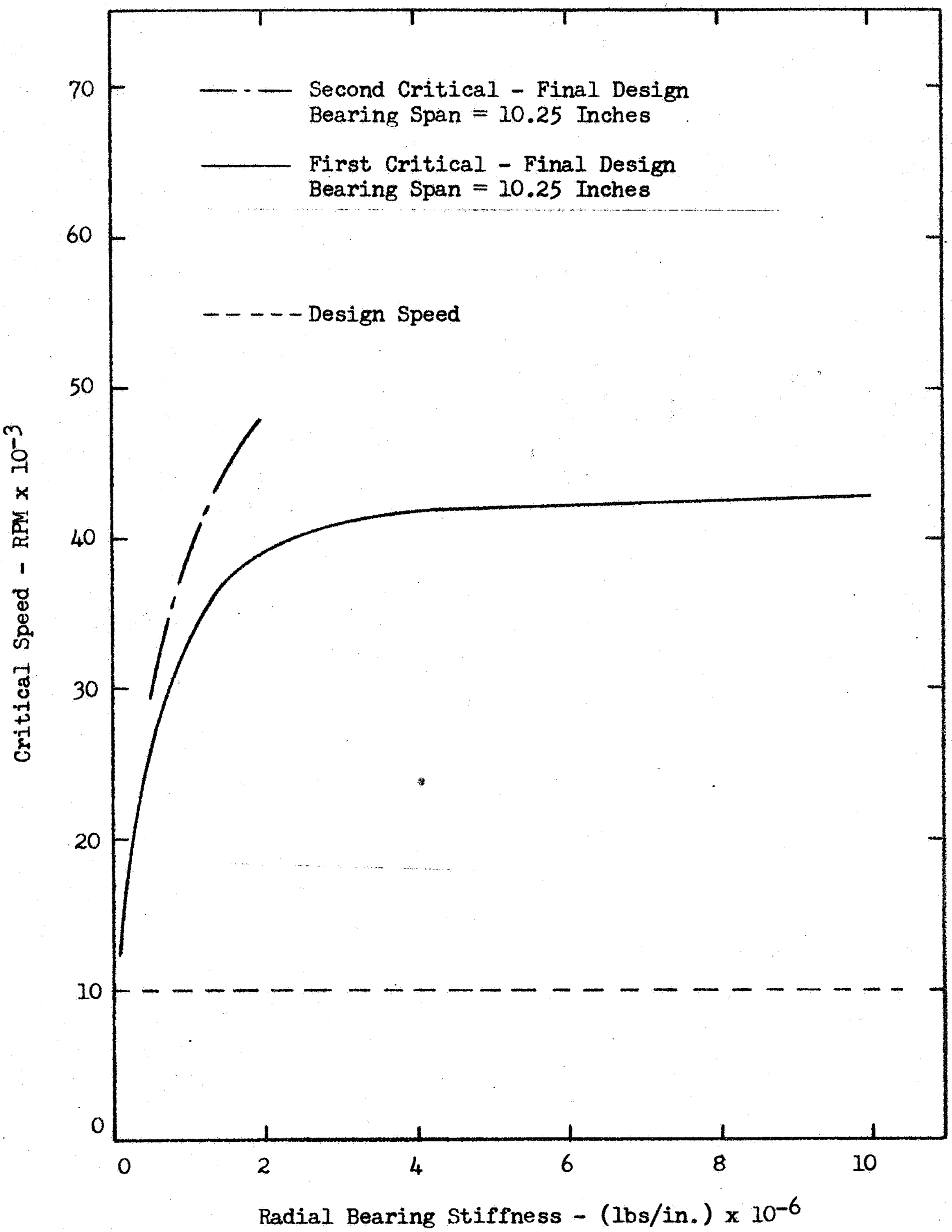

Figure 2

SHAFT CRITICAL SPEED AS A FUNCTION OF BEARING STIFFNESS

TABLE V

BOLT LOADS AND FACTOR OF SAFETY

Location	Bolt Size	Number of Bolts	Load	Margin of Safety Ultimate	Margin of Safety Yield
Main Housing - Turbine End	5/8	8	40,000	8.0	4.75
Main Housing - Thrust Bearing End	5/8	8	43,000 60,000	7.5 5.4	4.45 3.21
Thrust Bearing Housing	1/2	4	6,600	7.0	2.62
Cover Plate	1/4	8	3,300	6.85	2.56
Turbine Bolts	5/16	6	3,760 7,520 (1)	7.25 3.62	4.30 2.15
Shaft Coupling	Same as Turbine Bolts				
Movable Thrust Bearing Stop	5/16	12	9,500	11.5	6.85
Fixed Thrust Bearing Stop	1/4	8	3,000	15.0	8.9
Thrust Bearing Retainer	1/4	8	3,000	7.5	8.9

NOTE: (1) Shock load calculated for axial vibration of 0.012-in. amplitude at 650 cycles per second.

TABLE VI

DEFLECTION DATA FOR CRITICAL AREAS

Part	Load, lb	Deflection, in.
Thrust Bearing Cage	3,000	0.000267
Thrust Bearing Cage	5,000	0.000455
Ball Bearing	3,000	0.001
Balance Piston	36,635	0.00078
Housing (High-Pressure Side)	58,700	0.000885

pressure-loaded components based upon the maximum operating pressure. A minimum allowable ultimate strength factor of safety of 1.84 was established for bolts constituting the only load path or the failure of which would interfere with the proper functioning or integrity of the test assembly.

B. STEADY-STATE MODEL AND COMPUTER PROGRAM

Steady-state mathematical models were required to analyze the flow in series and parallel flow thrust balancer circuits for both compressible and incompressible fluids. A model which is usable for both subsonic compressible and incompressible fluids was developed and is applicable for any propellant in future studies by substituting appropriate tabularized fluid properties as input. Equations were derived that are applicable for either compressible or incompressible flow. Fluid property table iteration techniques are used to obtain the fluid properties for any stage of the circuit.

The ensuing discussion describes the schematic flow of typical parallel and series flow test configurations as well as defines the basic equations required for the various flow stages. The density, viscosity, specific heat, and bulk modulus used in all of the flow equations are obtained using an averaging coefficient (input) which permits the fluid property to be selected at any point between inlet and outlet conditions.

Figure No. 3 shows a parallel flow, self-compensating thrust balancer test assembly and its associated circuitry. Water is supplied to the test loop from a separate pump flow circuit and at a regulated pressure to the load piston as well as to the compensating supply orifices on each side of the balance piston. Return flow from both pistons travels to the suction side of the supply pump. The gaseous nitrogen circuitry is identical except that a cascade system replaces the feed pump and the gas is exhausted to atmosphere through back-pressure controllers.

Figure No. 4 illustrates the series flow system. The fluid supply and return is identical to the described parallel flow system except that fluid is supplied to one side of the balance piston only. The supply passages to the other side are blocked.

Only that portion of the circuits included between PFS and PFPRI, PLS and PBPRI, as well as PHS and PBPRI, are included in the mathematical model because these points are the controlled pressure locations.

The following equations define the various segments of the mathematical model.

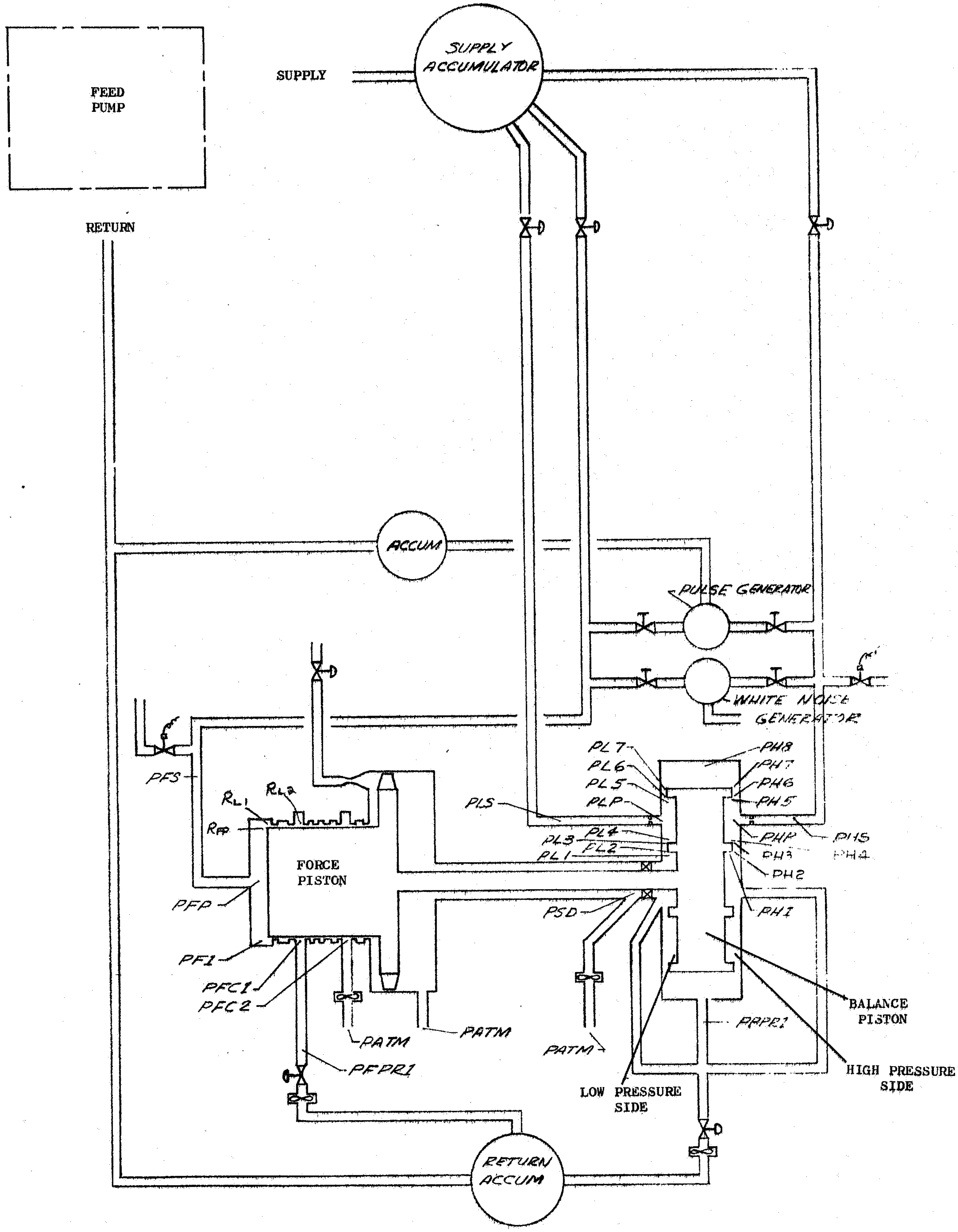

Figure 3 System Schematic - Parallel Flow

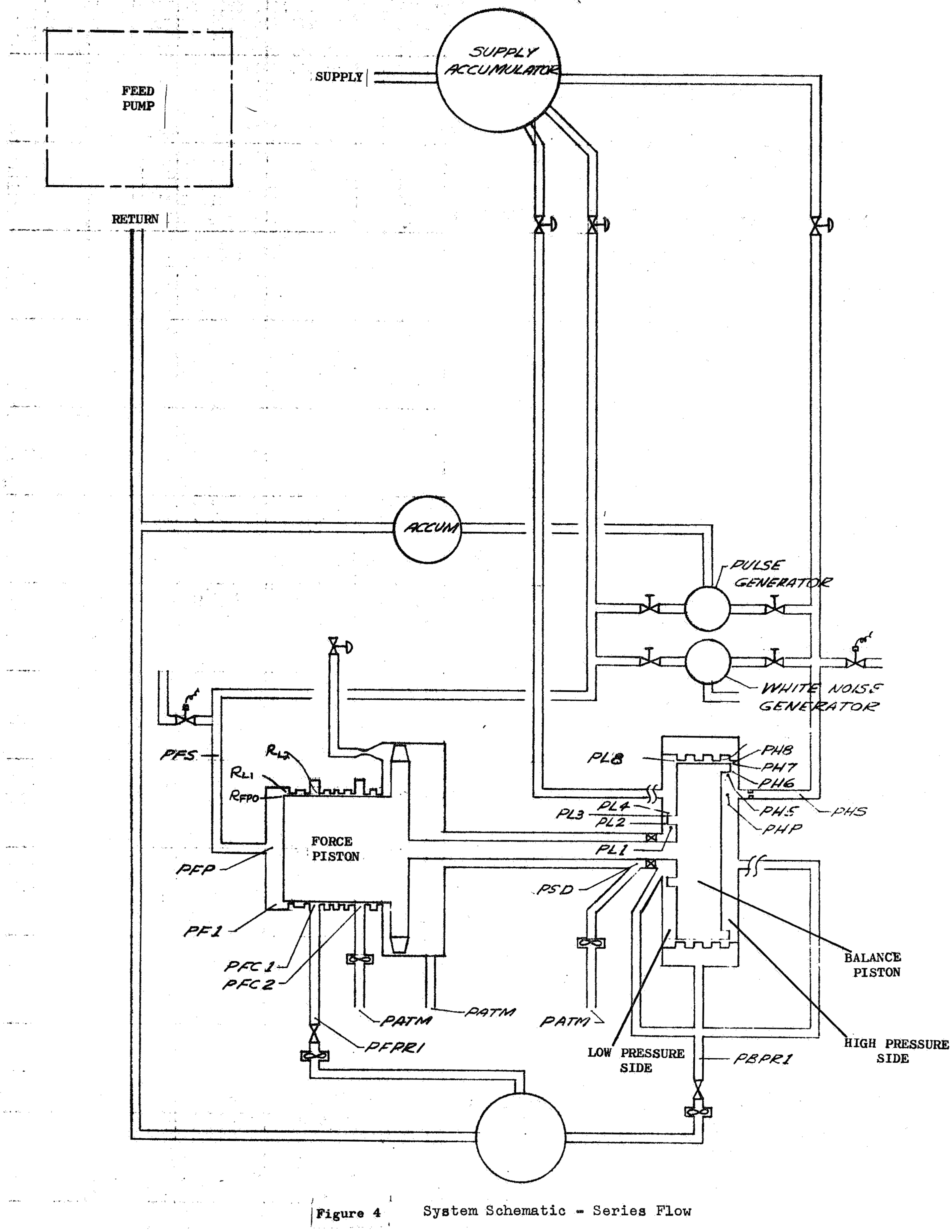

Figure 4 System Schematic - Series Flow

1. Flow Through an Orifice

Orifice weight flow can be described by the equation:

$$W = \frac{\pi}{4} C D^2 (2g \gamma_{12})^{1/2} (P_1 - P_2)^{1/2} \qquad \text{Eq. (1)}$$

derived from the conventional orifice equation(1)

$$Q = CA (2g H)^{1/2}$$

by substituting

$$W = Q \gamma$$

$$A = \frac{\pi}{4} D^2$$

$$H = \frac{P_1 - P_2}{\gamma_{12}}$$

$$\gamma_{12} = \gamma_1 - C_R (\gamma_1 - \gamma_2)$$

where C_R is the fluid property averaging coefficient.

2. Laminar Flow Through a Radial Slot (Sill)

Hydrostatic bearing theory is applied to describe the pressure drop with laminar flow through a radial slot. The final form of the equation for pressure drop is

$$P_1 - P_2 = \frac{6W \mu_{12} \ln \frac{R_2}{R_1}}{\pi h^3 \gamma_{12}} - \frac{\gamma_{12}}{2g} K^2 \omega^2 (R_2^2 - R_1^2) \qquad \text{Eq. (2)}$$

The first term is obtained by integrating the equation(2)

$$\frac{dp}{dx} = - \frac{f \gamma V_{avg}^2}{g h}$$

where:

$$f = \frac{24}{Re}$$

$$V_{avg} = \frac{W}{2\pi R \gamma_{12} h}$$

$$Re = \frac{W}{\pi R g \mu_{12}}$$

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(1) Vennard, J. K., Elementary Fluid Mechanics, John Wiley & Sons, Inc., 1961
(2) Pinkus, O., and Sternlicht, B., Theory of Hydrodynamic Lubrication, McGraw-Hill Book Co., 1961

The last term of the final equation is the pressure rise which occurs with increasing radius caused by the pumping effect(3). The coefficient, K, is defined in the discussion pertaining to rotational constants.

3. Turbulent Flow Through a Radial Slot (Sill)

Hydrostatic bearing theory also was used to describe the flow characteristics of turbulent flow through a radial slot. The final form of the equation is:

$$P_1 - P_2 = \frac{0.079\ \mu_{12}^{n}\ W^{2-n}\ (R_2^{1-n} - R_1^{1-n})\ \mathrm{Sec}^{1-n}}{2^n\ (2\pi)^{2-n}\ \gamma_{12}\ h^3\ g^{1-n}\ (1-n)\ R_2^{1-n}\ R_1^{1-n}\ \mathrm{Ecc}}$$

$$- \frac{\gamma_{12}}{2g} K^2\ \omega^2\ (R_2{}^2 - R_1{}^2) \qquad \text{Eq. (3)}$$

derived in the same manner as the equation for laminar flow except the friction factor is defined by

$$f = \frac{0.079}{Re^n}$$

and contains a secant term defined as(4)

$$\mathrm{Sec} = \frac{\text{Resultant Velocity}}{\text{Thru Flow Velocity}}$$

which corrects the Reynolds number, Re, for the rotational effect. Also included is a term, Ecc(5), to correct for misalignment between the face of the piston and the stationary wall. Table VII shows values of Ecc versus eccentricity ratio (e/h) where e is defined as 1/2 x Total Indicated Runout. The values for Ecc were obtained from published data(6).

4. Fluid Rotation Effect

Existing technology was applied to predict the pressure distribution caused by the pumping effect of fluid rotation between a rotating surface and a stationary surface. An investigation was conducted(7) to derive empirical equations for the rotational constant (k) in the equation for pressure rise with increasing radius:

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(3) Young, W. E., and Due, H. F., Investigation of Pressure Prediction Methods for Radial Flow Impellers, Phase II, Final Report PWA FR-1276, Contract NAS 8-5442, 8 March 1965

(4) Tao, L. N., and Donovan, W. F., "Through-Flow in Concentric and Eccentric Annuli of Five Clearance with and without Relative Motion of the Boundaries," Trans. ASME, November 1955

(5) Ibid.

(6) Ibid.

(7) Young, W. E., and Due, H. F., op. cit.

TABLE VII

Ecc VERSUS ECCENTRICITY RATIO

Type Flow	Eccentricity Ratio	Ecc
Laminar	0.0	1.000
	0.2	1.061
	0.4	1.243
	0.6	1.529
	0.8	1.929
	1.0	2.496
Turbulent	0.0	1.000
	0.2	1.007
	0.4	1.043
	0.6	1.100
	0.8	1.186
	1.0	1.286

NOTE: Data on this table were extracted from Reference No. 4.

$$P_2 - P_1 = \frac{\gamma_{12}}{2g} K^2 \omega^2 (R_2^2 - R_1^2)^{(8)} \qquad \text{Eq. (4)}$$

The rotational constant (K) for outward flow with water as a test fluid is defined by the empirical equation

$$K = 0.578 - 4.11\,\phi - 1.67\,h$$

and for inward flow by the equation

$$K = 0.3865 + 95.3\,\phi^2 - 12.6\,\phi\,(\frac{R_2}{R_1})$$

$$- 9.17 \times 10^5\,\phi\,(\frac{h}{R_1})^3 + 27.8\,(\frac{R_2}{R_1})^2\,(\frac{h}{R_1})$$

$$- 2.75 \times 10^3\,(\frac{R_2}{R_1})^4\,(\frac{h}{R_1})^2$$

$$+ 6.51 \times 10^4\,(\frac{R_2}{R_1})^6\,(\frac{h}{R_1})^3 + 2.13\,\phi^{0.5} - 6.59\,(\frac{h}{R_1})$$

where ϕ is the flow coefficient defined as the ratio of radial velocity to tangential velocity at the point of inlet for inward flow or at the point of outlet (outer periphery of the disk) for outward flow.

5. Sill Entrance and Exit Losses

Existing technology is applicable to develop equations for entrance and exit losses. Pressure drop can be represented by:

$$P_1 - P_2 = \frac{C\,w^2}{8\,g\,\pi^2\,R_2^2\,\gamma_{12}} \left(\frac{1}{h_1} - \frac{1}{h_2}\right)^2 \qquad \text{Eq. (5)}$$

derived from the relationship(9)

$$H_L = C\,\frac{(V_1 - V_2)^2}{2g}$$

where

$$H_L = \frac{P_1 - P_2}{\gamma}$$

$$V = \frac{w}{2\pi\,\gamma\,R\,h}$$

(8) Ibid.
(9) Vennard, J. K., op. cit.

6. Annulus Flow

Pressure drop for flow of a fluid through an axial annulus can be represented by

$$P_1 - P_2 = \frac{C_F \, L_{12} \, V_{12}^2 \, \gamma_{12}}{4 \, (Re)^n \, h \, g} \qquad \text{Eq. (6)}$$

derived from the relationship (10)

$$H_L = \frac{\Delta P}{\gamma} = \frac{f \, L \, V^2}{4 \, R_H \, 2g}$$

where the hydraulic radius (R_H) is equivalent to one-half of the clearance (h) and the friction factor becomes

$$f = \frac{C_F}{Re^n}$$

7. Pressure Drop in Lines - Laminar Flow

The pressure loss for laminar fluid flow in the lines can be represented by the equation

$$P_1 - P_2 = \frac{8 \, \mu_{12} \, W_{12} \, L}{\pi \, R^4 \, \gamma_{12}} \qquad \text{Eq. (7)}$$

derived from the expression(11)

$$H_L = \frac{\Delta P}{\gamma_{12}} = \frac{fL}{D} \frac{V^2}{2g}$$

where(12)

$$f = \frac{64}{Re}$$

$$V = \frac{W}{\gamma_{12} \, \pi \, R^2}$$

$$Re = \frac{2 \, W}{g \, \pi \, \mu_{12} \, R}$$

---

(10) Ibid.
(11) Ibid.
(12) Ibid.

8. Pressure Drop in Lines - Turbulent Flow

The pressure loss for turbulent flow in lines is expressed by the equation:

$$P_1 - P_2 = \frac{C_F W^{2-n} L \mu_{12}^n}{2^{2+n} \pi^{2-n} g^{1-n} R^{5-n} \gamma_{12}} \qquad \text{Eq. (8)}$$

derived from the expression

$$H_L = \frac{\Delta P}{\gamma} = \frac{fL}{D} \frac{V^2}{2g}$$

where(13)

$$f = \frac{C_F}{Re^n}$$

$$V = \frac{W}{\gamma_{12} \pi R^2}$$

$$Re = \frac{2W}{g \pi \mu_{12} R}$$

9. Pressure Loss in a Labyrinth

Pressure loss in a labyrinth is defined by the equation

$$P_1 - P_2 = \frac{W^2 N (1-\alpha)}{8 K g \pi^2 R^2 h^2 \gamma_{12}} \qquad \text{Eq. (9)}$$

where $K = C^2$

derived from the equation for flow through a narrow restriction

$$Q = CA \left(\frac{2g (P_1 - P_2)}{\gamma_{12}} \right)^{1/2}$$

The term $(1-\alpha)$ represents a correction for residual energy presented by Geza Vermes(14) where

$$\alpha = \frac{8.52}{\frac{P-L}{h} + 7.23}$$

where
P = Pitch
L = Width of sealing point
h = Clearance of sealing point

(13) Ibid.
(14) Vermes, G., "A Fluid Mechanics Approach to the Labyrinth Seal Leakage Problem," ASME Journal of Engineering for Power, April 1961, pp. 161-169

10. Static Stiffness

Static stiffness of the balance piston is defined as the change in load capacity per incremental change in axial piston movement. The method used in this model to determine the static stiffness for any clearance is to take the difference between the forces of a point on each side of the desired clearance divided by the difference in clearance between these two points. This is represented by:

$$\text{Static Stiffness} = \frac{F_{m+1} - F_{m-1}}{h_{m+1} - h_{m-1}} \qquad \text{Eq. (10)}$$

11. Horsepower

Equations for horsepower were derived from the common expressions for shear stress(15) and torque.

$$\text{Shear Stress} = \gamma = f\,\rho\,\frac{V_{avg}^{2}}{2} \qquad \text{Eq. (11)}$$

where $f = \dfrac{C_m}{Re^n}$

$\rho = \dfrac{\gamma}{g}$

V_{avg} = Average fluid velocity

$$\text{Moment} = M = \gamma\,A\,R \qquad \text{Eq. (12)}$$

where γ = Shear stress
A = Area
R = Moment arm

By substitution and rearranging terms, the equations for torque become

$$M_{radial\ slot} = \frac{C_m\,\gamma(U_{D\ avg})^2\,\pi\,(R_2^{\,2} - R_1^{\,2})(R_2 + R_1)}{4\,Re_{avg}^{n}\,g}$$

$$M_{annulus} = \frac{\pi\,C_m\,\gamma(U_{D\ avg})^2\,R^2\,L}{Re^n\,g}$$

(15) Pinkus, O., and Sternlicht, B., op. cit.

Horsepower is defined by the common equation:

$$HP = \frac{MN}{63{,}000} \qquad \text{Eq. (13)}$$

12. Temperature Rise Caused by Friction

The temperature rise of the fluid caused by the frictional resistance is expressed by

$$\Delta T \text{ (Radial Slot)} = \frac{\pi \, C_m \, \gamma \, U_{D12}^{3} \, (R_2^{2} - R_1^{2})}{24 \, Re^{n} \, g \, J \, W \, C_p} \qquad \text{Eq. (14)}$$

$$\Delta T \text{ (Axial Annulus)} = \frac{\pi \, C_m \, \gamma \, U_{D12}^{3} \, R \, L}{12 \, Re^{n} \, g \, J \, W \, C_p} \qquad \text{Eq. (15)}$$

where C_m = Moment frictional coefficient - 0.316

γ = Weight density - lb/in.^{3}

U_{D12} = Average disk tangential velocity - in./sec

R = Radius - in.

Re = Average Reynolds number

g = Gravitational constant - 386 in./sec^2

n = Reynolds number coefficient (0.43)

J = Mechanical equivalent of heat - ft-lb/Btu

W = Weight flow - lb/sec

C_p = Specific heat - Btu/lb-°F

L = Length - in.

The equations for heat generation were derived from the equations for frictional horsepower discussed previously in this report.

13. Force

Force upon the piston is obtained by integrating the pressure profile obtained from the flow equations over the applicable areas. The sills are subdivided into a number of rings to minimize the error present in the simplifying assumption of a linear pressure rise or loss with radius.

Force upon a pocket is obtained from the expression

$$F = P_1 \pi (R_2^2 - R_1^2) + \frac{\pi}{4} \frac{\gamma_{12}}{g} K_{12}^2 \omega^2 (R_2^4 - 2 R_2^2 R_1^2 + R_1^4) \quad \text{Eq. (16)}$$

by integrating the equation for pressure distribution in a pocket over the limits of the radius.

Force for each incremental ring of the sills is obtained from the expression

$$F = P_1 \pi (R_2^2 - R_1^2) + 2\pi \frac{(P_2 - P_1)}{R_2 - R_1} \times \left[\frac{R_2^3}{3} - \frac{R_1 R_2^2}{2} + \frac{R_1^3}{6}\right] \quad \text{Eq. (17)}$$

which is obtained by integrating the equation for pressure drop in the sill between the limits of radii, assuming a linear pressure drop with radius. By subdividing the sill into a number of rings, the error of assuming a linear pressure drop becomes negligible.

14. Steady-State Digital Computer Program

The steady-state digital computer program was designed with a subroutine to calculate each type of flow equation. Subroutines also were programmed to determine the fluid properties at any stage using table iteration techniques and fluid property input tables. This technique permits the user to write a short main program for any configuration by calling out the established subroutines in the proper sequence. Appropriate nomenclature is delineated in Appendix A. Complete details of the computer program, including the program listing and flow diagram, is included in Appendix B.

C. DYNAMIC MODEL FORMULATION

The dynamic model was developed to describe the dynamic behavior of both the series and parallel flow thrust balancer systems. The models represent the dynamics of the supply and return lines, the lumped fluid parameters of the balance and load piston circuits, the rotor mass, and the mechanical stiffness as well as damping of the rotor supports. The dynamic equations were derived based upon the steady-state flow equations described in this report. The significance of the various parameters were evaluated to determine valid approximations and modifications necessary for simulation on an analog computer. Complete details of the dynamic model formulation, including derivation of the equations and schematic diagrams of the various networks, are included in Appendix C.

D. PARAMETRIC STUDIES

1. Steady-State

The steady-state digital computer program was used to conduct parametric studies of series and parallel flow thrust balance systems with both water and gaseous nitrogen as the test fluids. Tables VIII and IX show the values assigned to each variable parameter for the test cases with water in a parallel flow and series flow system. Tables X and XI show similar data using gaseous nitrogen as the fluid. The studies include effects of variations in pocket depth, shaft speed, sill length, orifice diameter, and pressure. The effects of these variations are presented as a function of gap ratio, which is defined as the axial clearance on the low-pressure side of the balance piston (left side as viewed on Figures No. 3 and No. 4) divided by the total balance piston axial clearance.

Figures No. 5 through No. 19 are parametric plots of flow, force, and static stiffness for a parallel flow configuration with water as the fluid. Pocket depth has a negligible effect upon net flow, load capacity and stiffness. The sill length has a small effect upon flow when the flow is decreased and the sill length is increased. The 0.500-in. sill length appears to be optimum because it shows higher load capacity than either the 0.250-in. sill or the 0.750-in. sill. In addition, it has higher static stiffness than the 0.250-in. sill and approximately the same stiffness as the 0.750-in. sill at mid-position. At low clearances, static stiffness is higher with shorter sills.

Larger orifices have higher static stiffness and greater load carrying capability. However, these advantages are offset by a higher flow requirement.

Speed has a small effect; however, higher speeds generally require lower flow and they give higher load capacity as well as greater static stiffness. At high speeds and large clearances, it is possible to have reverse flow through the inner land even though there is little change in net flow as related to speed. The problem develops because a large pressure drop is taken across the compensating orifice and the pumping effect of the inner sill is greater than the remaining available pressure drop. The current mathematical model and computer program is not programmed to handle cases with this reverse flow.

Higher supply pressures give higher load capacity and greater static stiffness. However, these advantages are offset by higher flow requirements at the increased pressure.

Plots of the series flow parametric studies with water are shown on Figures No. 20 through No. 34. The results are similar to those obtained with the parallel piston except speed has more effect than was evident with the parallel piston. Higher speeds have lower flow requirements, lower load capacity, and lower static stiffness.

TABLE VIII

PARALLEL PISTON PARAMETRIC STUDY FOR WATER

Case	Pocket Depth (in.)	Shaft Speed (rpm)	Sill Length (in.)	Orifice Dia. (in.)	Supply Press. (psia)	Return Press. (psia)
1	0.050	0	0.500	0.120	1000	100
2	0.050	6K	0.500	0.120	1000	100
3	0.050	6K	0.250	0.120	1000	100
4	0.050	6K	0.750	0.120	1000	100
5	0.050	6K	0.500	0.130	1000	100
6	0.050	6K	0.500	0.140	1000	100
7	0.100	6K	0.500	0.120	1000	100
8	0.025	6K	0.500	0.120	1000	100
9	0.050	2K	0.500	0.120	1000	100
10	0.050	8K	0.500	0.120	1000	100
11	0.050	6K	0.500	0.120	800	100
12	0.050	6K	0.500	0.120	400	100
13	0.050	10K	0.500	0.120	1000	100

TABLE IX

SERIES PISTON PARAMETRIC STUDY
FOR WATER

Case	Pocket Depth (in.)	Shaft Speed (rpm)	Sill Length (in.)	Orifice Dia. (in.)	Supply Press. (psia)	Return Press. (psia)
1	0.050	0	0.500	0.080	1000	100
2	0.050	6K	0.500	0.080	1000	100
3	0.050	6K	0.250	0.080	1000	100
4	0.050	6K	0.750	0.080	1000	100
5	0.050	6K	0.500	0.100	1000	100
6	0.050	6K	0.500	0.120	1000	100
7	0.100	6K	0.500	0.080	1000	100
8	0.025	6K	0.500	0.080	1000	100
9	0.050	2K	0.500	0.080	1000	100
10	0.050	10K	0.500	0.080	1000	100
11	0.050	6K	0.500	0.080	800	100
12	0.050	6K	0.500	0.080	400	100

TABLE X

PARALLEL PISTON PARAMETRIC STUDY
FOR GASEOUS NITROGEN

Case	Pocket Depth (in.)	Shaft Speed (rpm)	Sill Length (in.)	Orifice Dia. (in.)	Supply Press. (psia)	Return Press. (psia)
1	0.005	0	0.500	0.080	1000	500
2	0.005	10K	0.500	0.080	1000	500
3	0.005	10K	0.250	0.080	1000	500
4	0.005	10K	0.750	0.080	1000	500
5	0.005	10K	0.500	0.060	1000	500
6	0.005	10K	0.500	0.100	1000	500
7	0.010	10K	0.500	0.080	1000	500
8	0.025	10K	0.500	0.080	1000	500
9	0.005	6K	0.500	0.080	1000	500
10	0.005	2K	0.500	0.080	1000	500
11	0.005	10K	0.500	0.080	400	200
12	0.005	10K	0.500	0.080	400	100
13	0.005	10K	0.500	0.080	200	100

TABLE XI

SERIES PISTON PARAMETRIC STUDY FOR GASEOUS NITROGEN

Case	Pocket Depth (in.)	Shaft Speed (rpm)	Sill Length (in.)	Orifice Dia. (in.)	Supply Press. (psia)	Return Press. (psia)
1	0.005	0	0.500	0.060	1000	500
2	0.005	10K	0.500	0.060	1000	500
3	0.005	10K	0.250	0.060	1000	500
4	0.005	10K	0.750	0.060	1000	500
5	0.005	10K	0.500	0.040	1000	500
6	0.005	10K	0.500	0.080	1000	500
7	0.010	10K	0.500	0.060	1000	500
8	0.025	10K	0.500	0.060	1000	500
9	0.005	6K	0.500	0.060	1000	500
10	0.005	2K	0.500	0.060	1000	500
11	0.005	10K	0.500	0.060	400	200
12	0.005	10K	0.500	0.060	400	100
13	0.005	10K	0.500	0.060	200	100

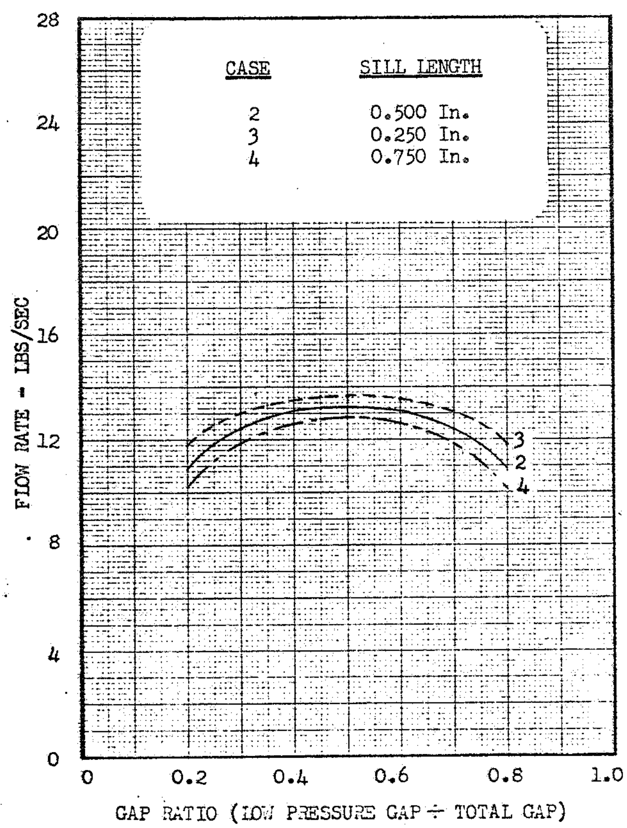


Figure 5

A COMPARISON OF TOTAL FLOW WITH VARIABLE SILL LENGTHS IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

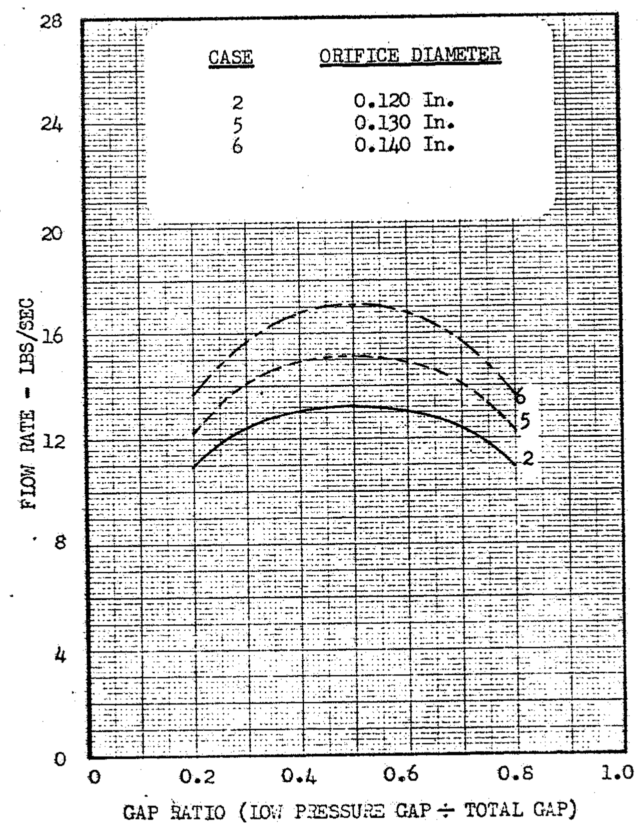


Figure 6

A COMPARISON OF TOTAL FLOW WITH VARIABLE ORIFICES IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

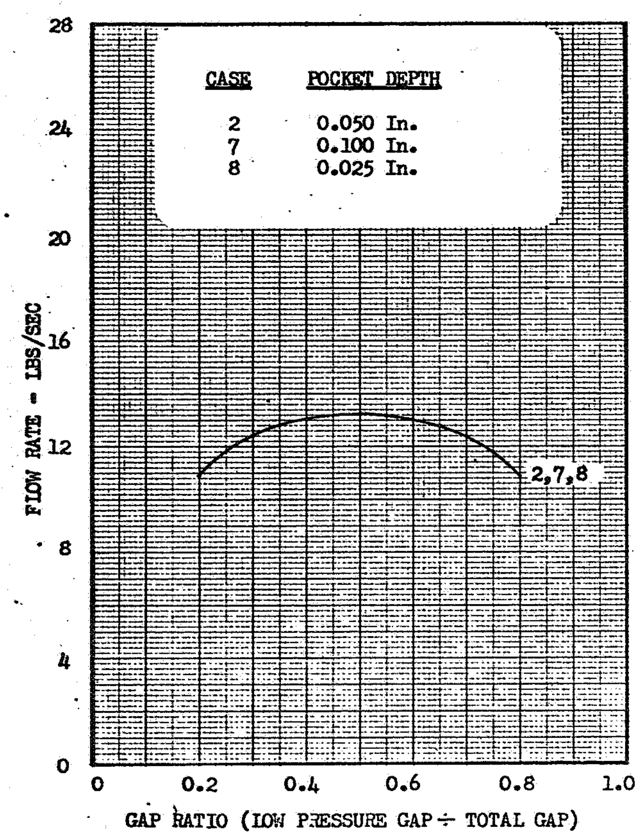


Figure 7

A COMPARISON OF TOTAL FLOW WITH VARIABLE POCKET DEPTHS IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

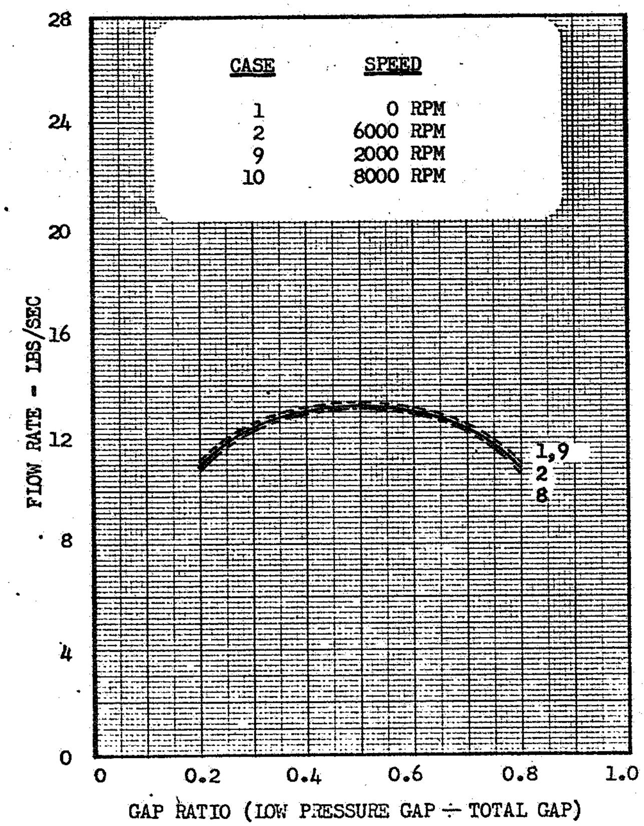


Figure 8

A COMPARISON OF TOTAL FLOW WITH VARIABLE SPEED IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

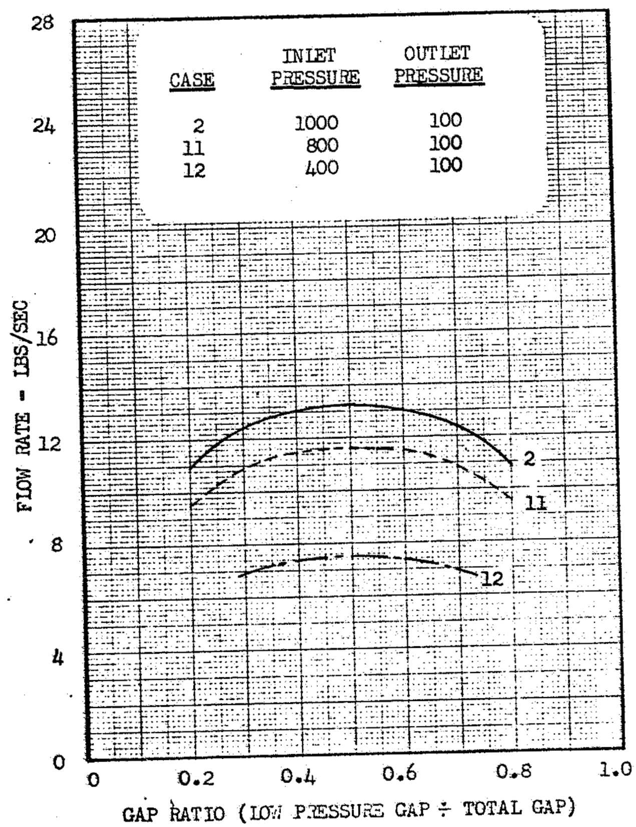


Figure 9

A COMPARISON OF TOTAL FLOW WITH VARIABLE PRESSURES
IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

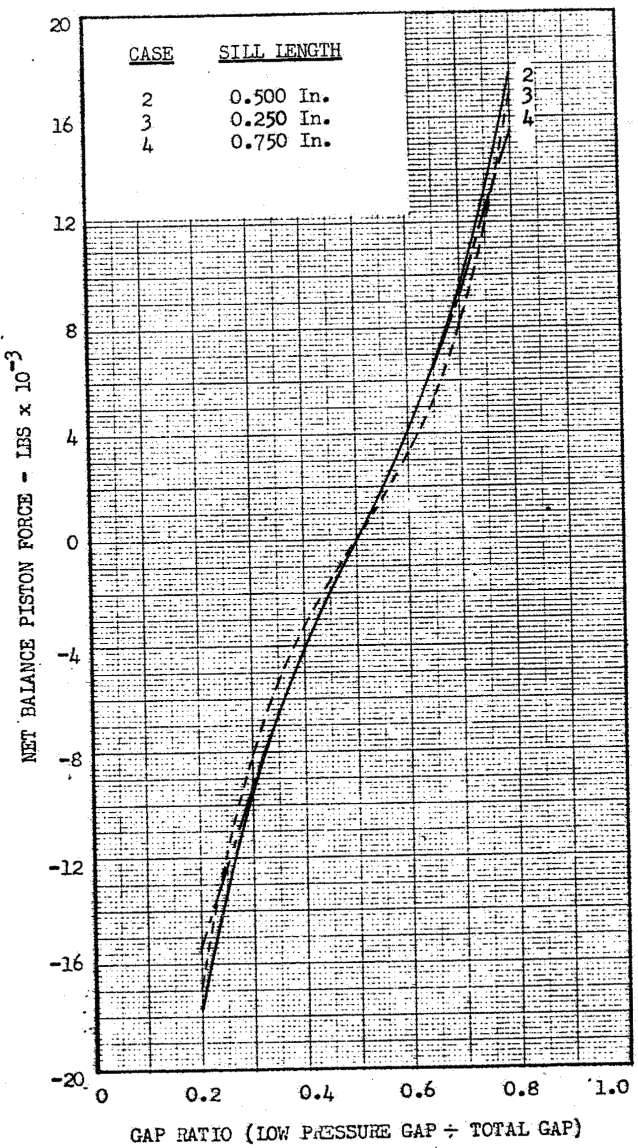


Figure 10

A COMPARISON OF FORCE WITH VARIABLE SILL LENGTHS
IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

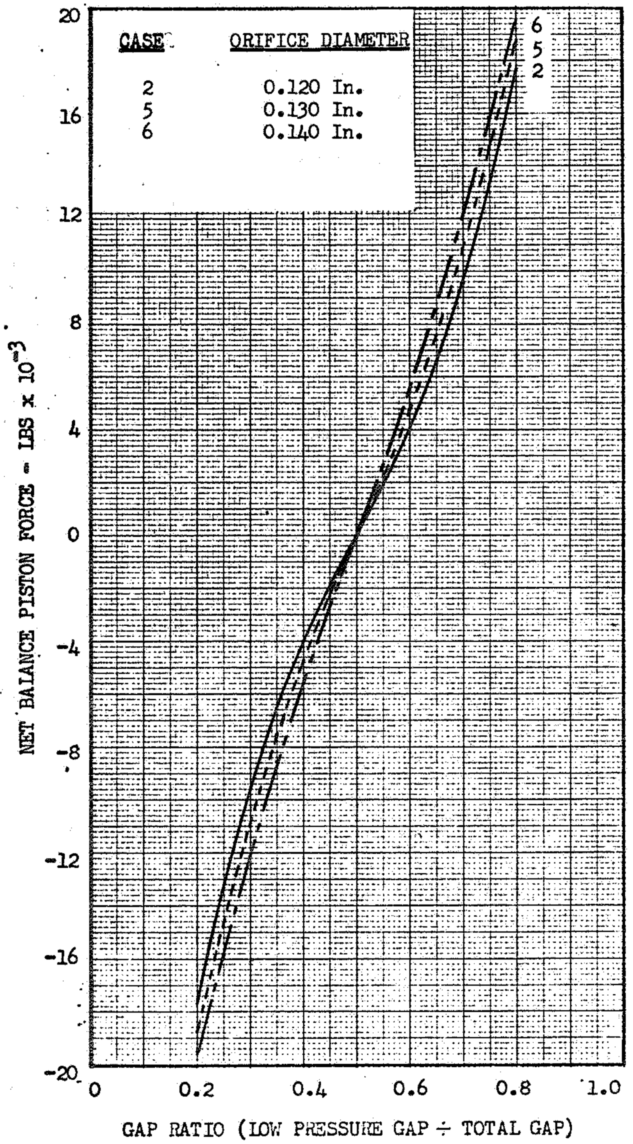


Figure 11

A COMPARISON OF FORCE WITH VARIABLE ORIFICES IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

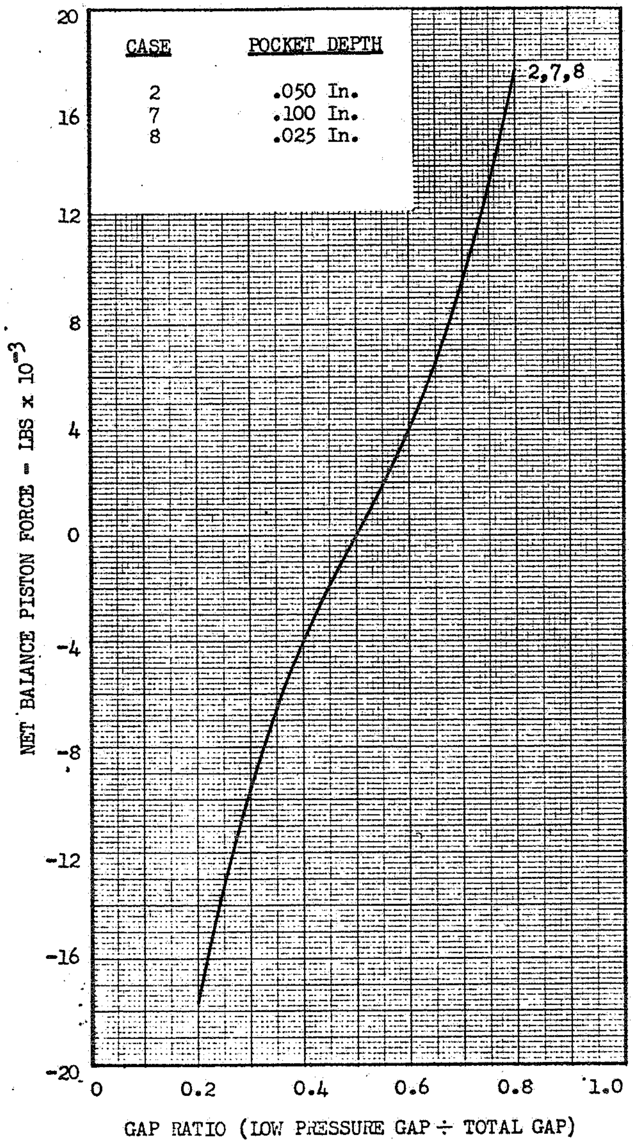


Figure 12

A COMPARISON OF FORCE WITH VARIABLE POCKET DEPTH IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

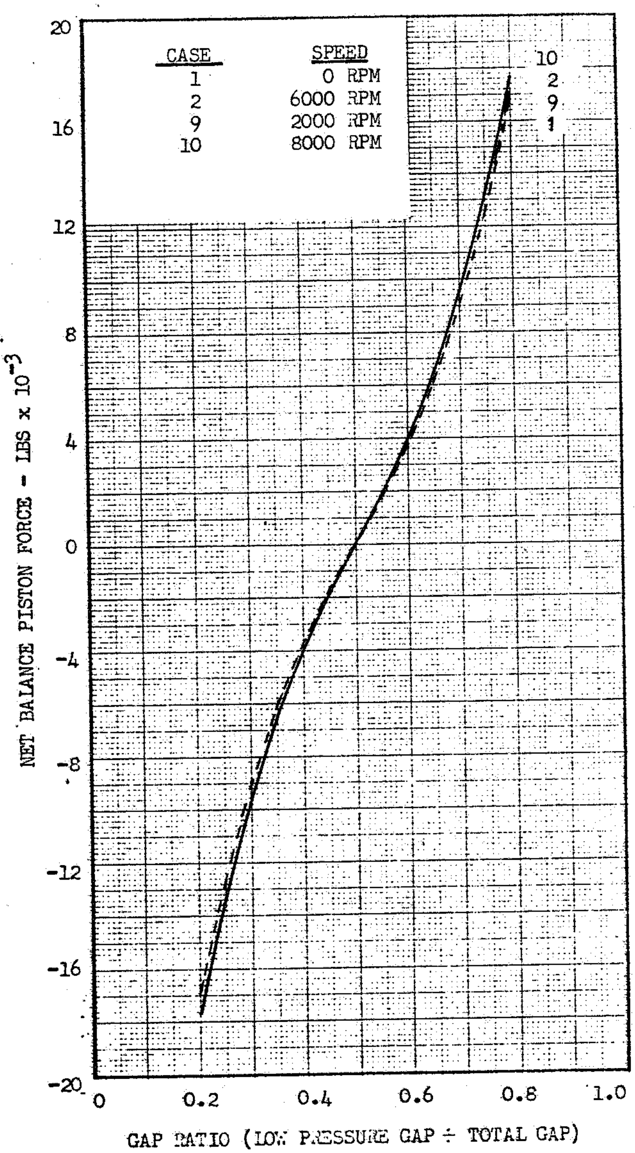


Figure 13

A COMPARISON OF FORCE WITH VARIABLE SPEED
IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

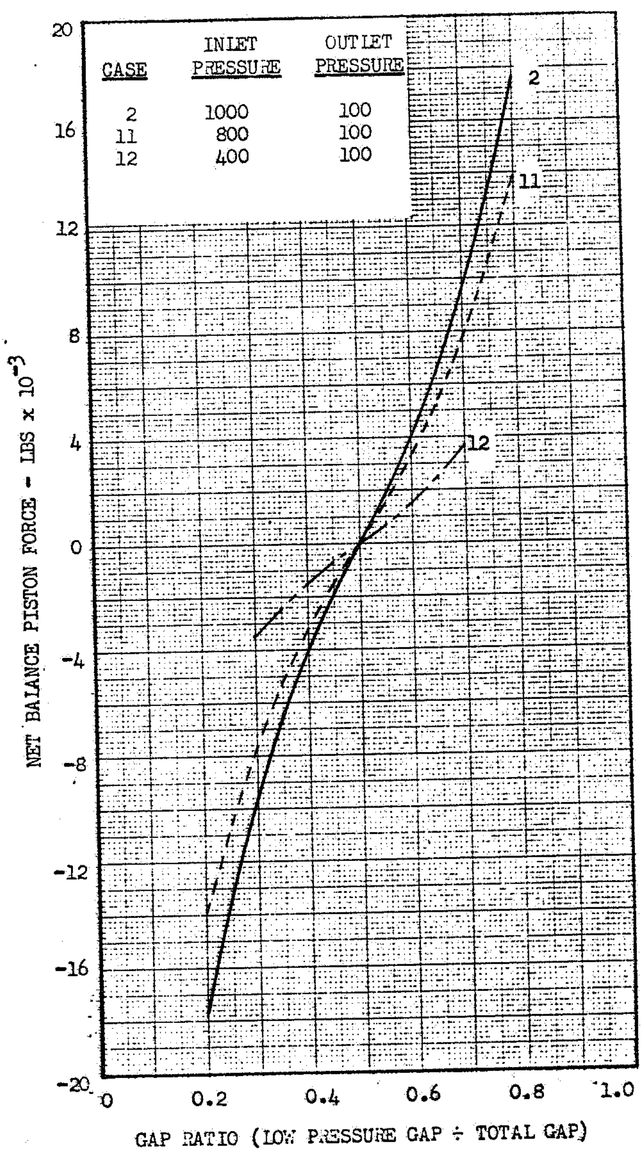


Figure 14

A COMPARISON OF FORCE WITH VARIABLE PRESSURES
IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

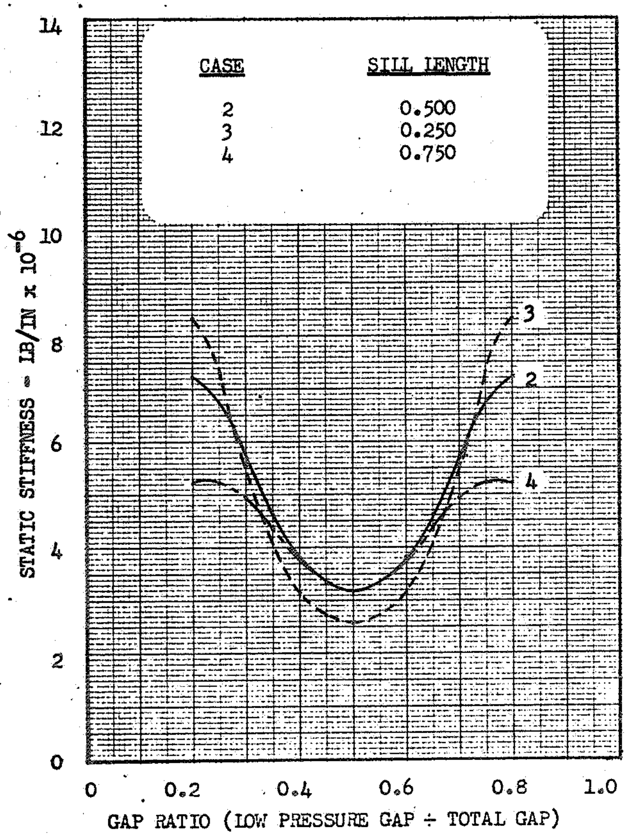


Figure 15

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SILL LENGTHS IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

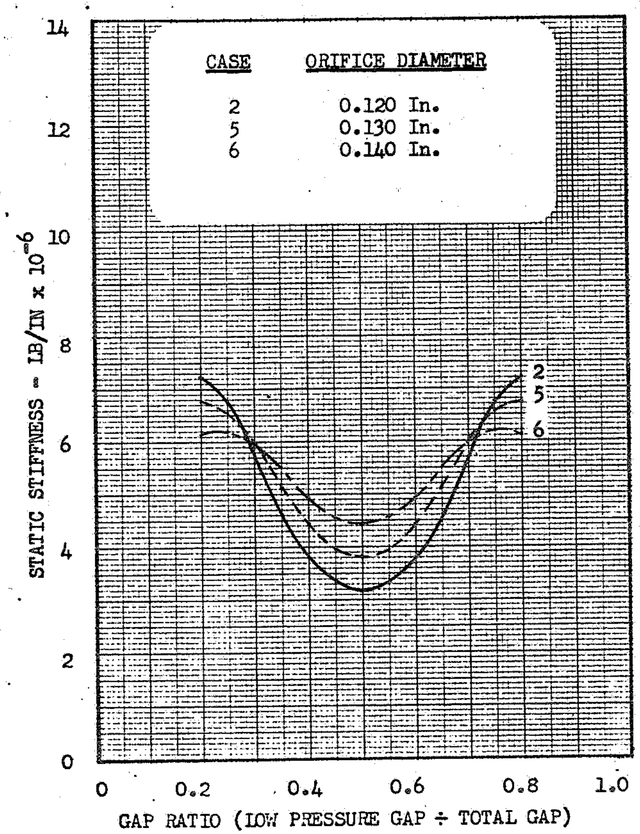


Figure 16 4

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE ORIFICES IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

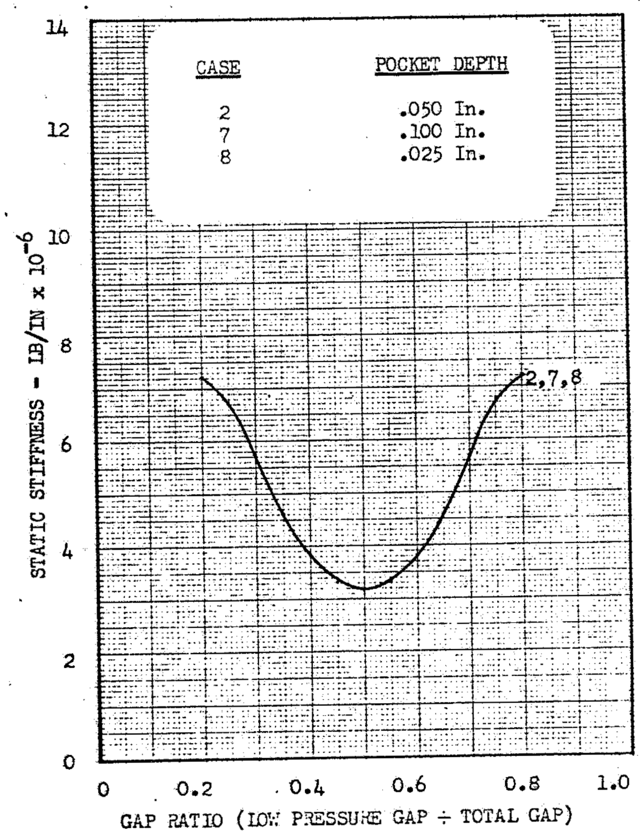


Figure 17

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE POCKET DEPTH IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

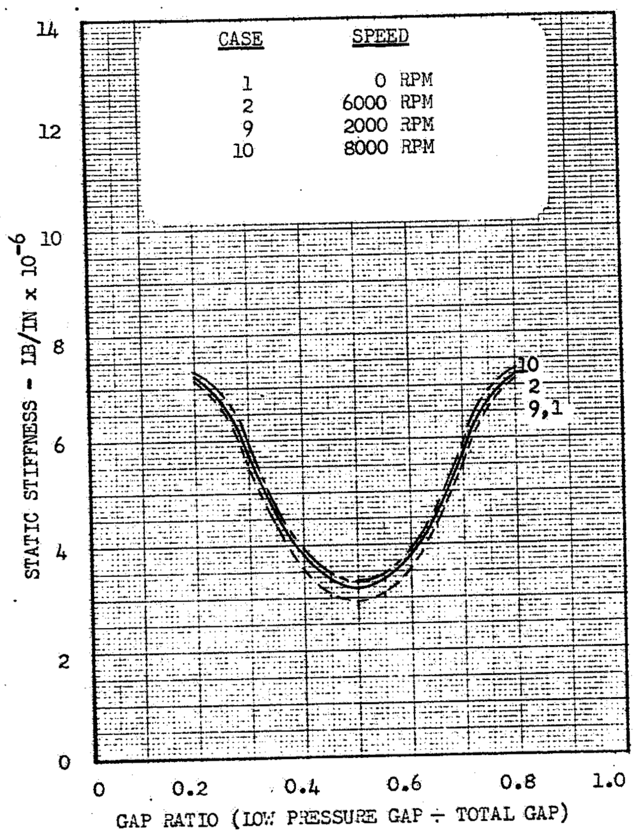


Figure 18

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SPEED IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

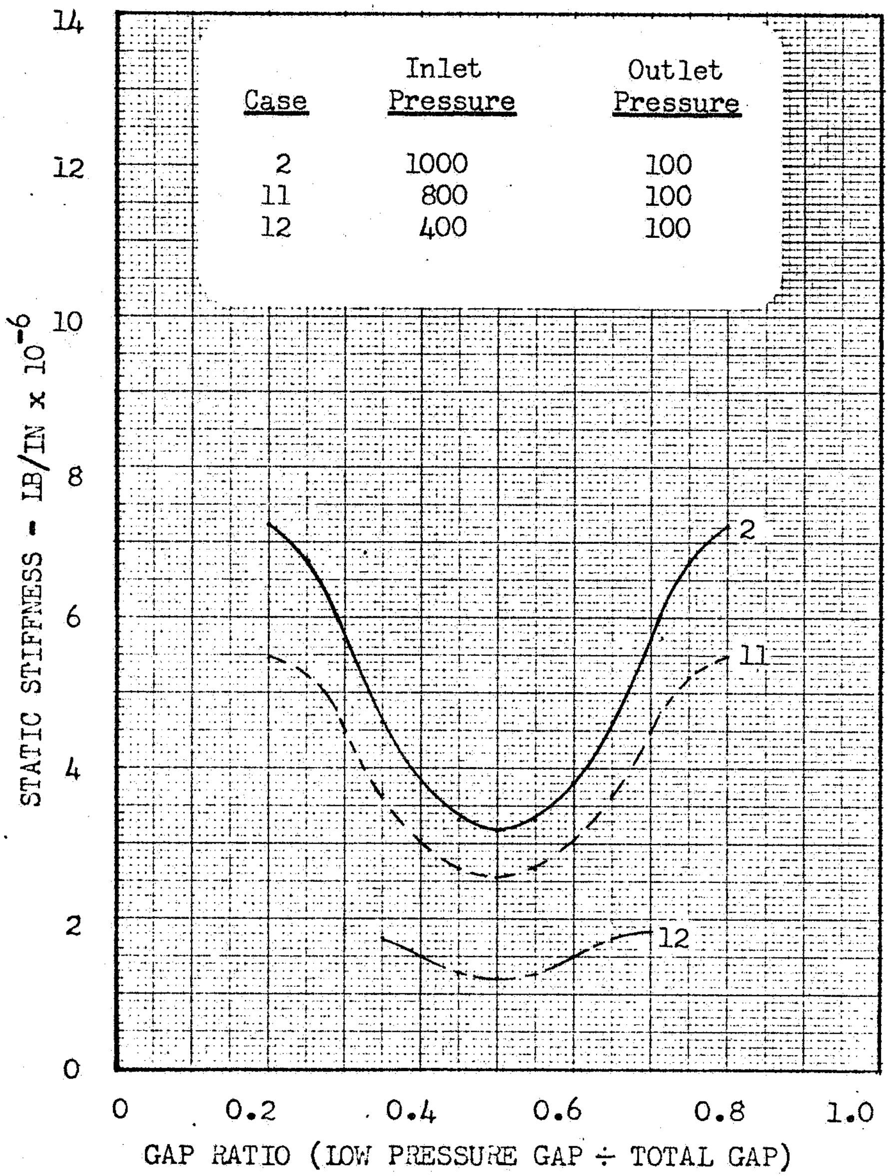


Figure 19

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE PRESSURES IN A PARALLEL FLOW BALANCE PISTON WITH WATER AS THE FLUID

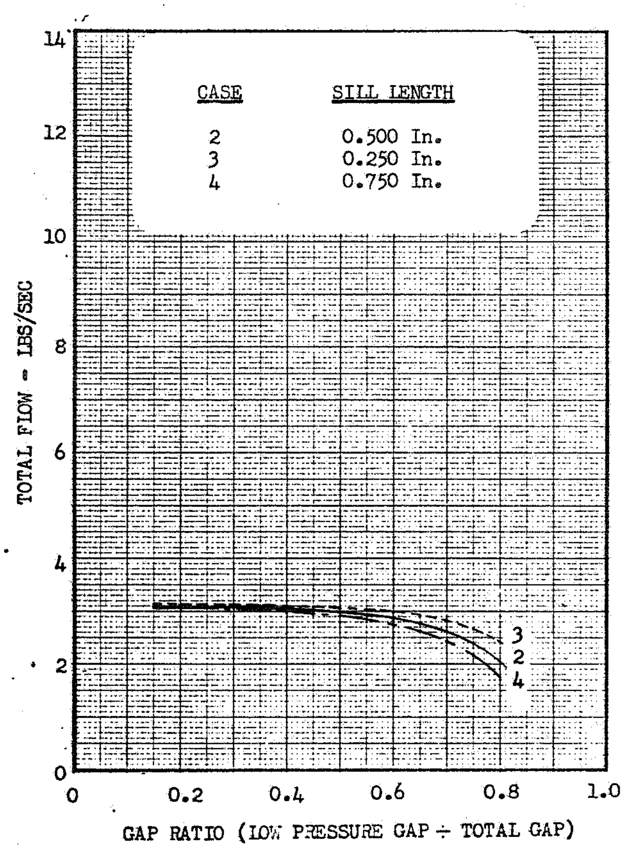


Figure 20

A COMPARISON OF FLOW WITH VARIABLE SILL LENGTH IN
A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

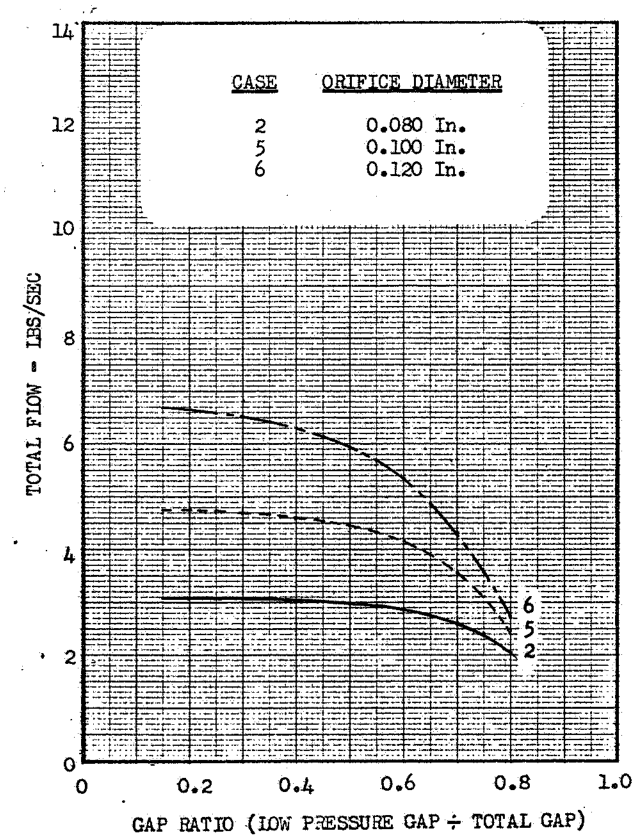


Figure 21

A COMPARISON OF FLOW WITH VARIABLE ORIFICES IN
A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

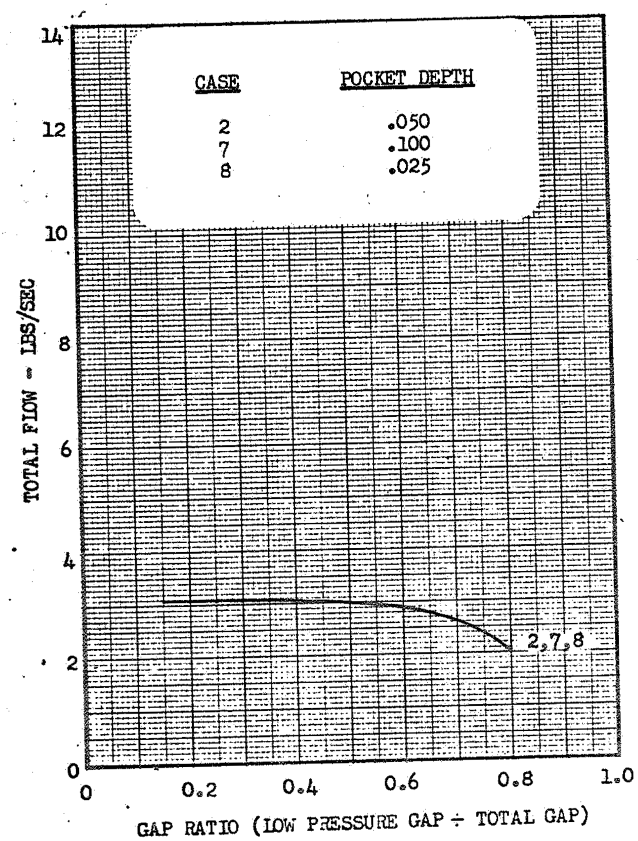


Figure 22

A COMPARISON OF FLOW WITH VARIABLE POCKET DEPTHS IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

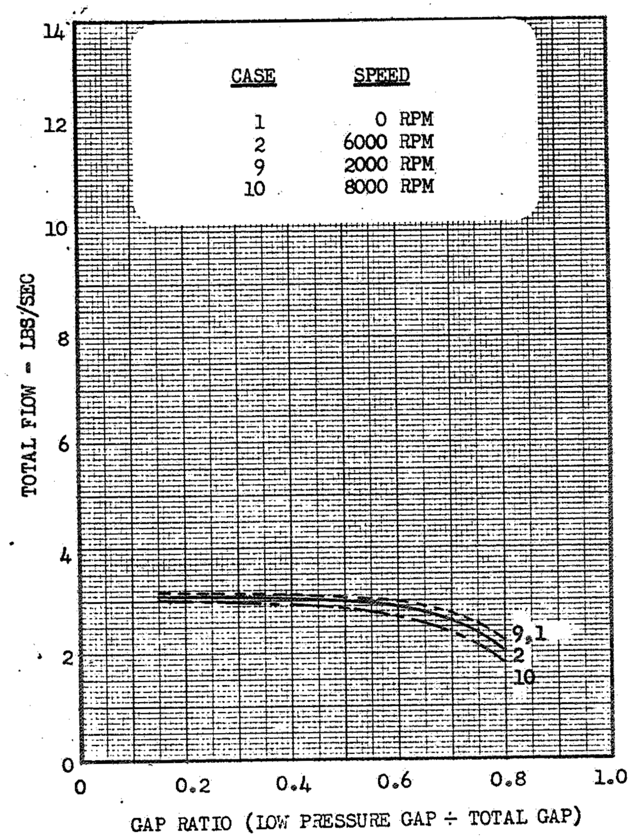


Figure 23

A COMPARISON OF FLOW WITH VARIABLE SPEED IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

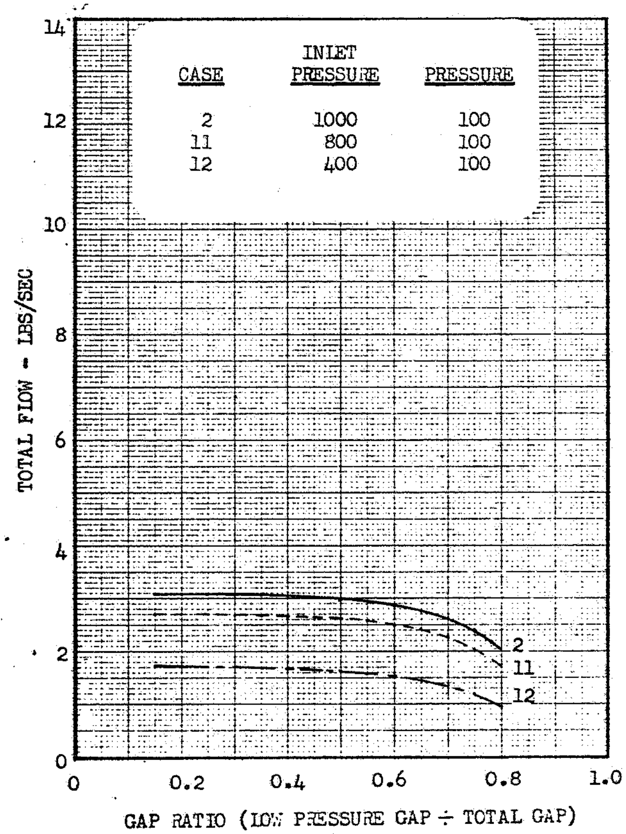


Figure 24

A COMPARION OF FLOW WITH VARIABLE PRESSURES IN
A SERIES FLOW THRUST BALANCER WITH WATER AS THE FLUID

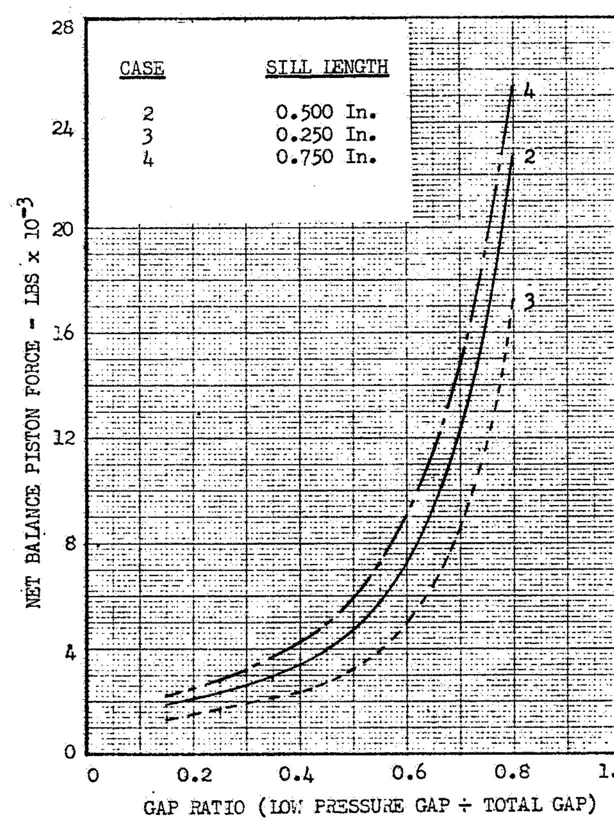


Figure 25

A COMPARISON OF FORCE WITH VARIABLE SILL LENGTH
IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

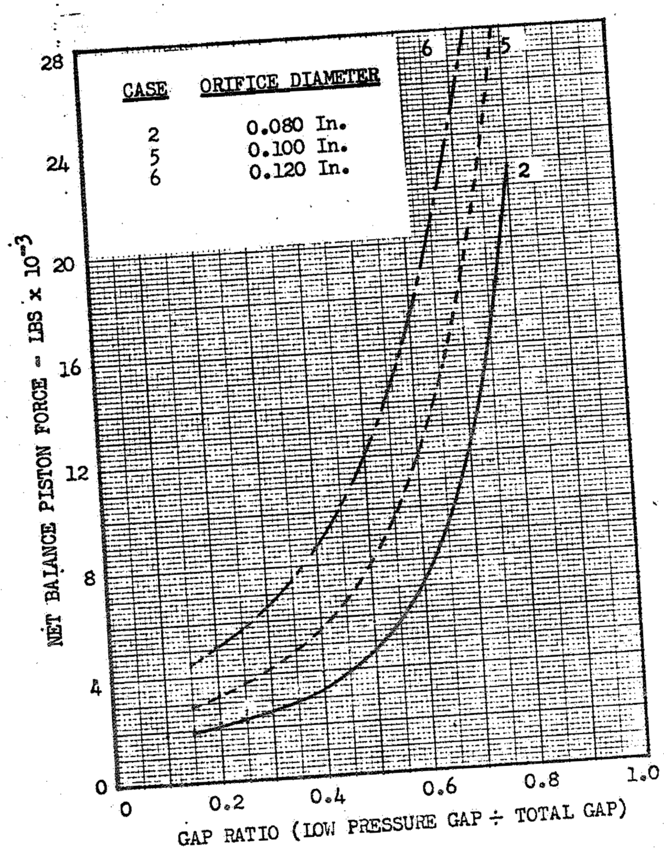


Figure 26

A COMPARISON OF FORCE WITH VARIABLE ORIFICES IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

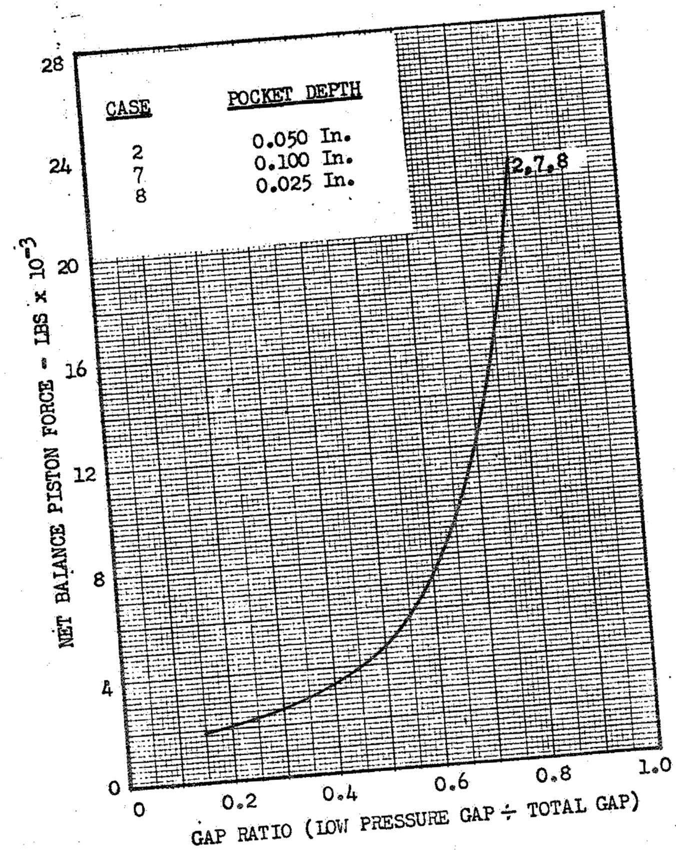


Figure 27

A COMPARISON OF FORCE WITH VARIABLE POCKET DEPTH IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

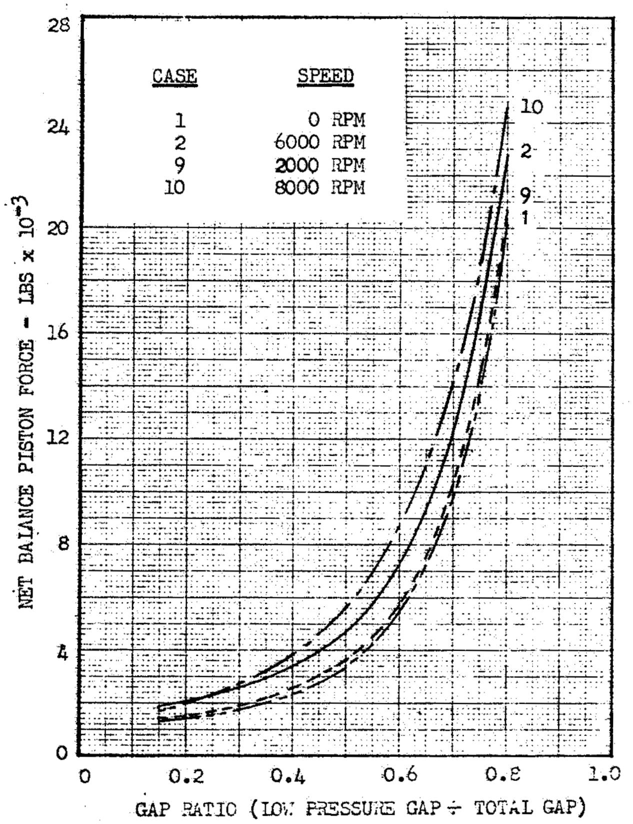


Figure 28

A COMPARISON OF FORCE WITH VARIABLE SPEED IN A SERIES FLOW BALANCE PISTON WITH WATER AS THE FLUID

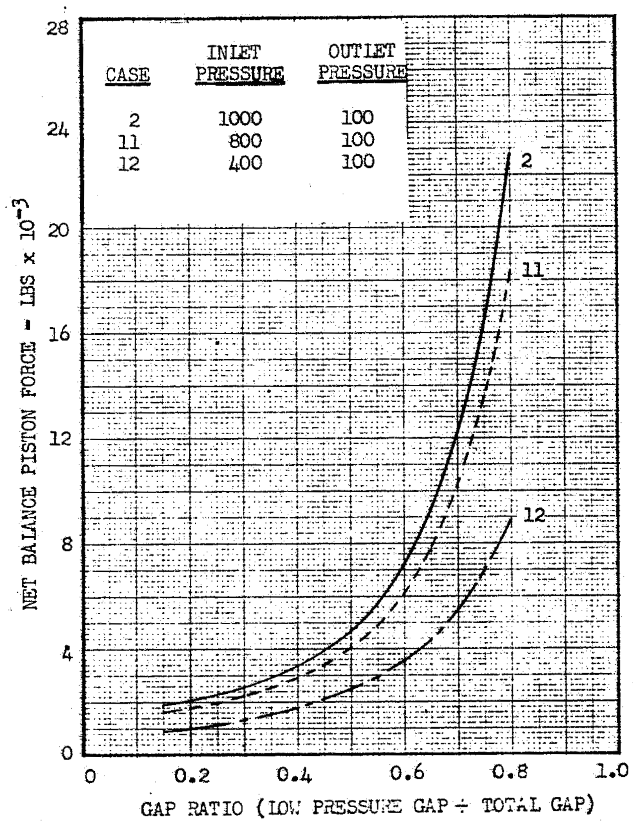


Figure 29

A COMPARISON OF FORCE WITH VARIABLE PRESSURE IN A SERIES FLOW BALANCE PISTON WITH WATER AS THE FLUID

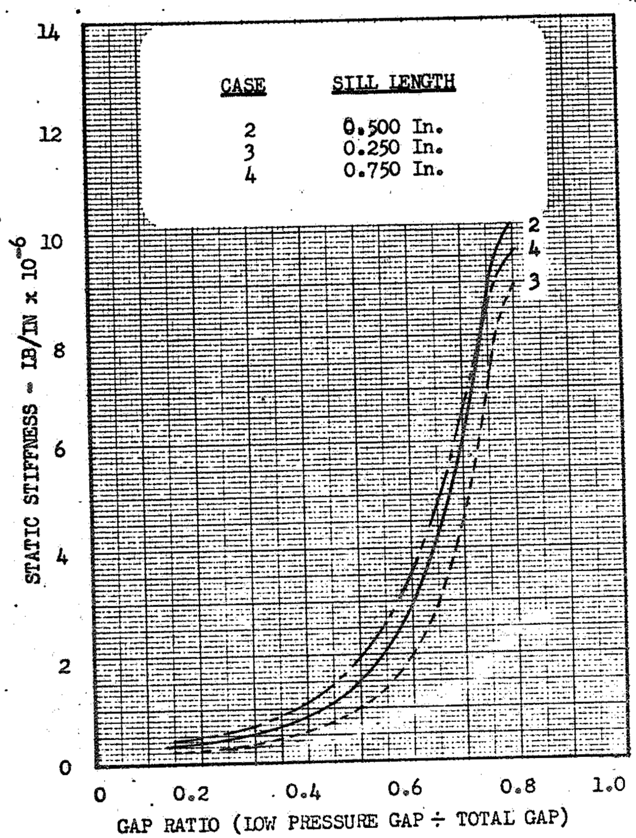


Figure 30

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SILL LENGTH IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

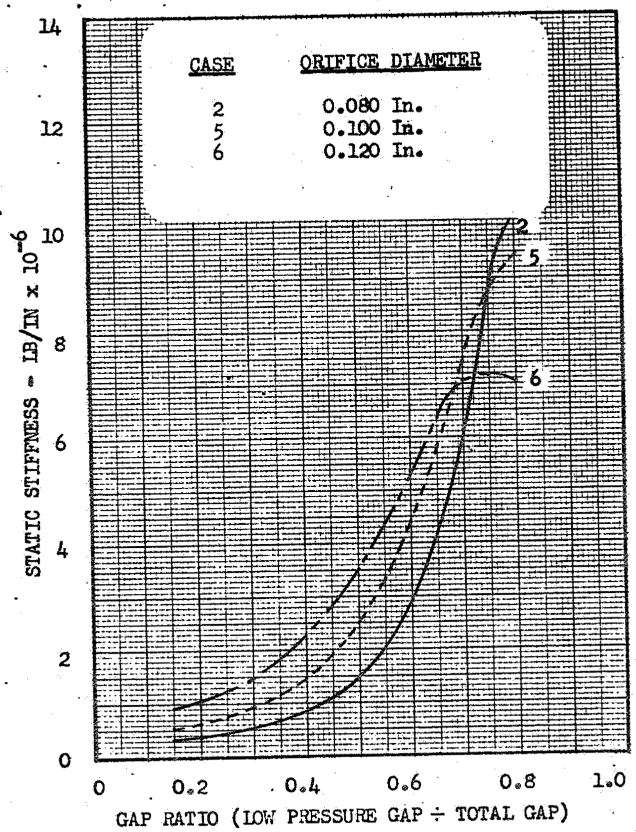


Figure 31

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE ORIFICES IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

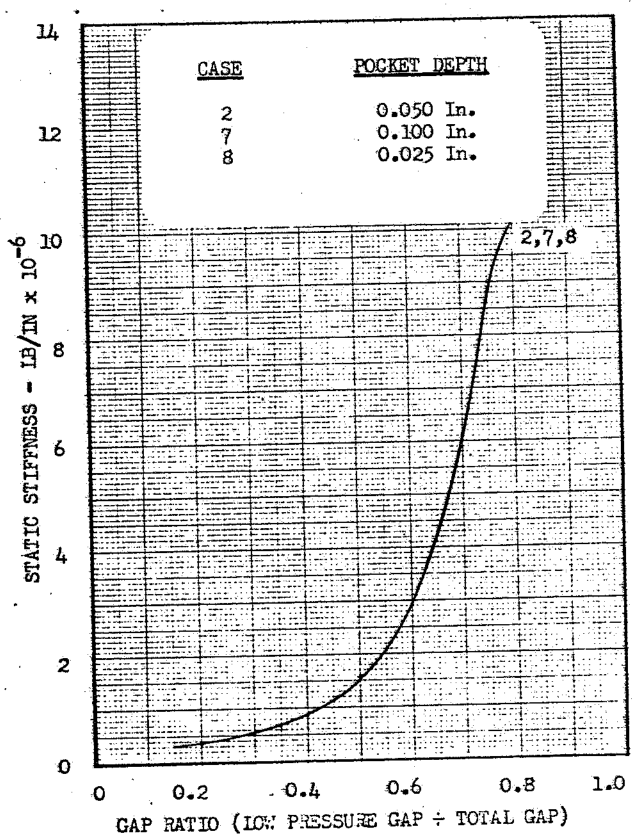


Figure 32

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE POCKET DEPTH IN A SERIES FLOW BALANCE PISTON WITH WATER AS THE FLUID

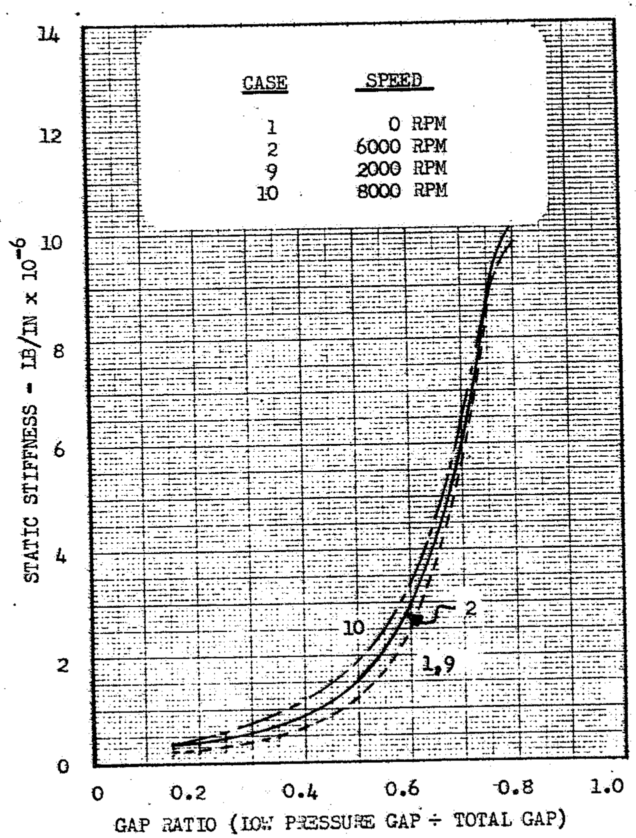


Figure 33

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SPEED IN A SERIES FLOW THRUST BALANCE PISTON WITH WATER AS THE FLUID

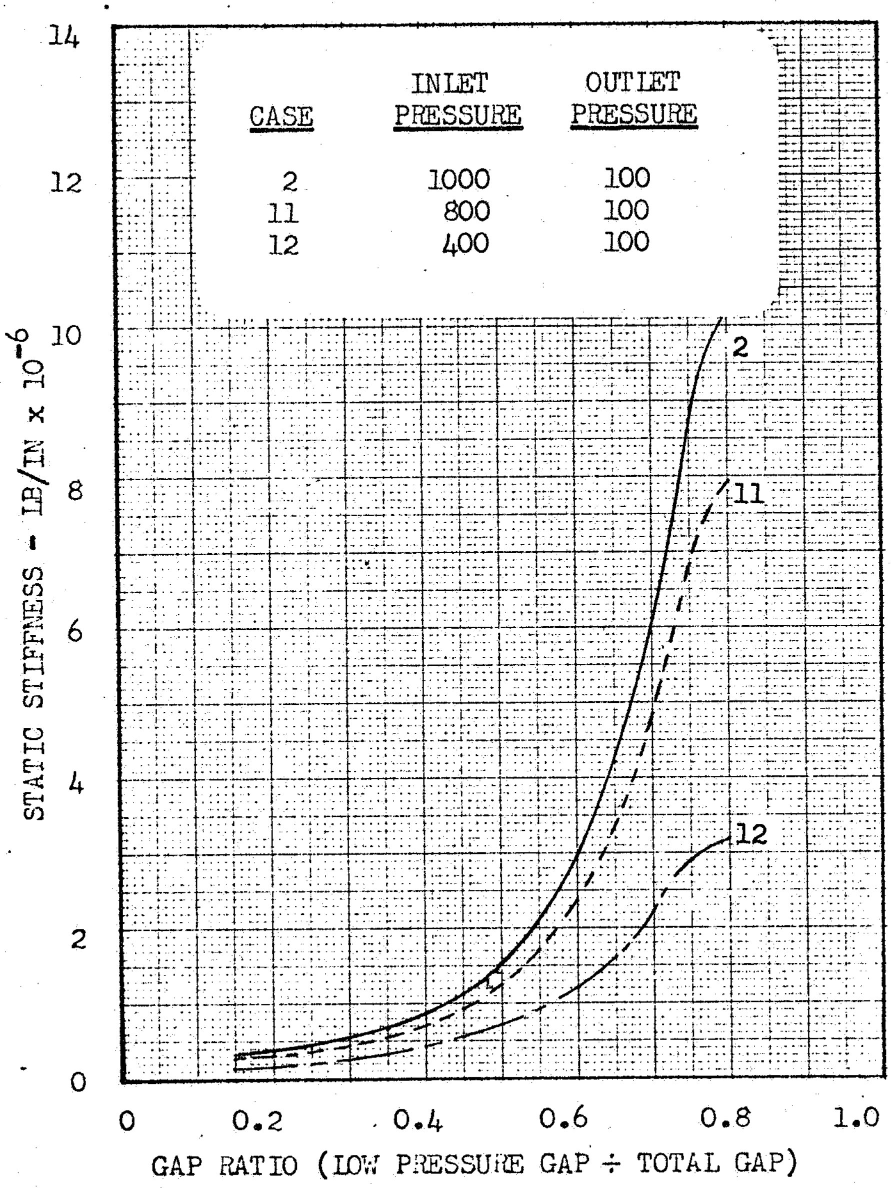


Figure 34

A COMPARISON OF STATIC STIFFNESS WITH VARIABLE PRESSURE IN A SERIES FLOW BALANCE PISTON WITH WATER AS THE FLUID

Pocket depth shows a negligible effect.

Sill length has a small effect upon flow until the piston moves close to the supply orifice side where longer sills decrease the flow. The longer sill also shows higher load capability and higher static stiffness.

The orifice diameter has a large effect upon all of the parameters studied. As the orifice size is made larger, the load capacity and static stiffness increase and there is a penalty of a greater flow rate.

The flow, load capacity, and static stiffness increase as pressure becomes greater.

Figures No. 35 through No. 49 show parametric plots of a parallel flow configuration with gaseous nitrogen as the test fluid.

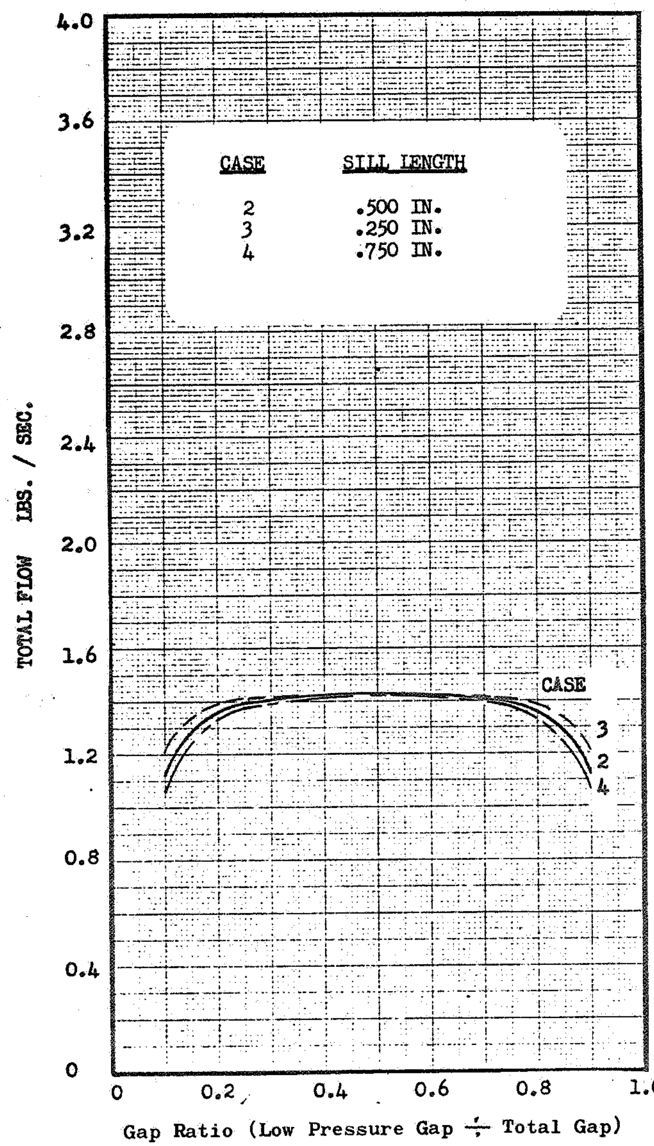
Evaluation of these parametric plots show pocket depth and speed have a negligible effect upon force, static stiffness, and flow. Of all parameters studied, orifice size and pressure level have the most effect. Larger orifices and higher pressures give greater loads and static stiffness; however, these advantages must be weighed against higher flow rates to select the best configuration for a specific application. The shape of the static stiffness curves indicates a smaller total gap would be desirable to decrease the flat curve portion observed near the mid-position. With a smaller total gap, stiffness would increase faster as the piston moved away from mid-position.

The series flow parametric plots for gaseous nitrogen are shown on Figures No. 50 through No. 64.

The results obtained in this parametric study are similar to those obtained with the parallel case except that this configuration is not symmetrical about the mid-position. The series configuration requires a constant biased load and could become unstable at low loads. Flow lessens rapidly as the gap decreases on the supply orifice side of the balance piston. This condition is present in a high-loaded case. Large orifices and higher pressures are desired to obtain high load capacity and high static stiffness. These features must be weighed against the greater flow required with larger orifices and higher pressure.

2. Dynamic

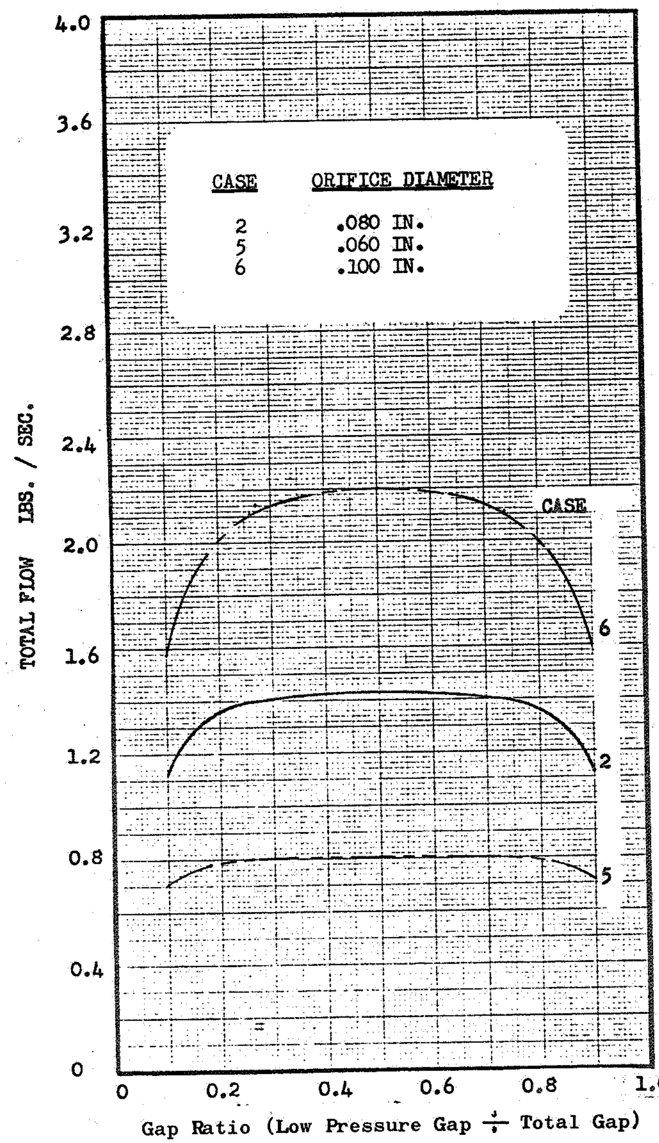
The analog computer parametric study was performed for each of the four basic thrust balancer configurations. For each of the basic configurations, the effect upon the dynamic response caused by variations in piston sill width, piston pocket depth, and inlet orifice diameter was studied. The ensuing discussion is a brief summary of the results obtained from the analog computer study. Complete details as well as the graphs of the analog recordings are included in Appendix C.



A COMPARISON OF TOTAL FLOW WITH VARIABLE SILL LENGTHS

IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

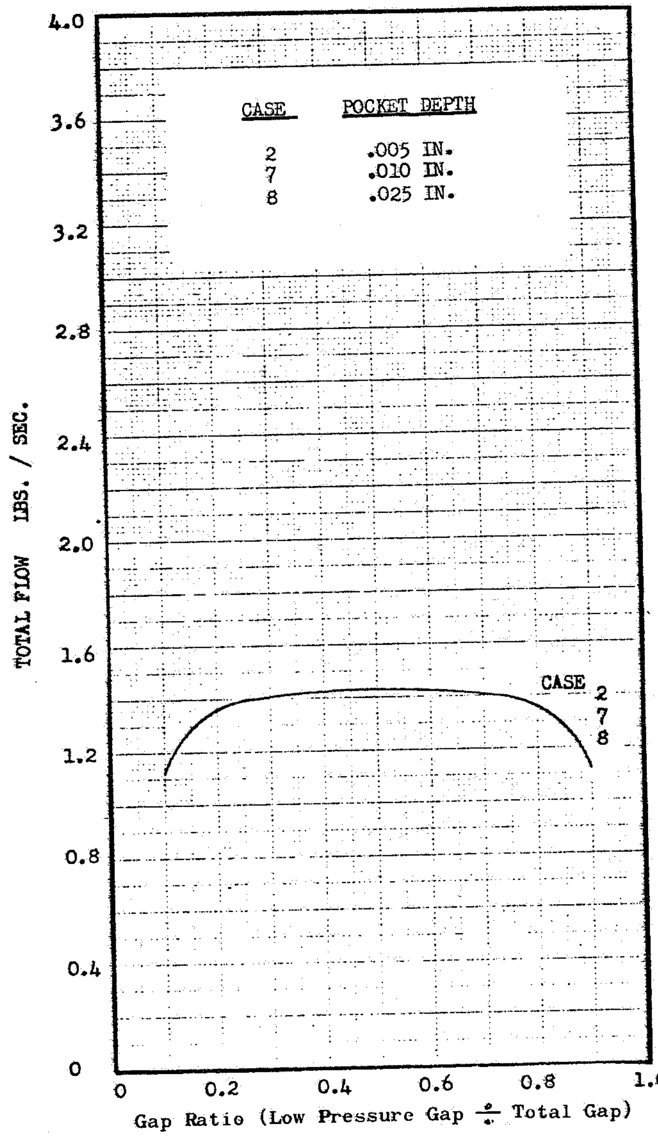
Figure 35



A COMPARISON OF TOTAL FLOW WITH VARIABLE ORIFICE SIZES

IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

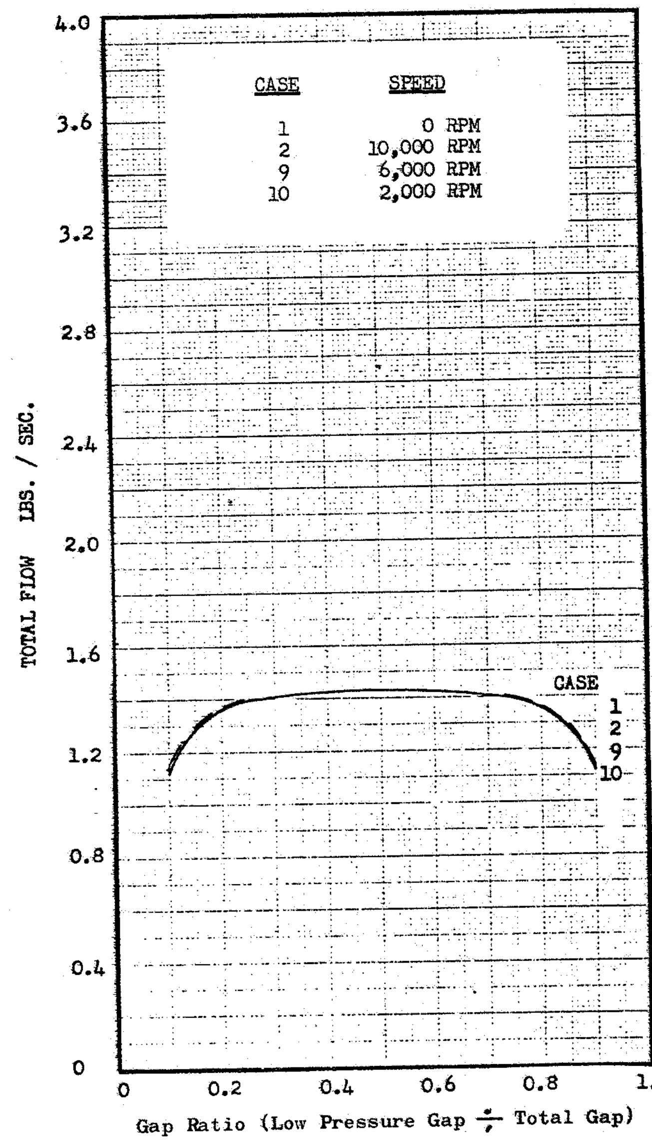
Figure 36



A COMPARISON OF TOTAL FLOW WITH VARIABLE POCKET DEPTHS

IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

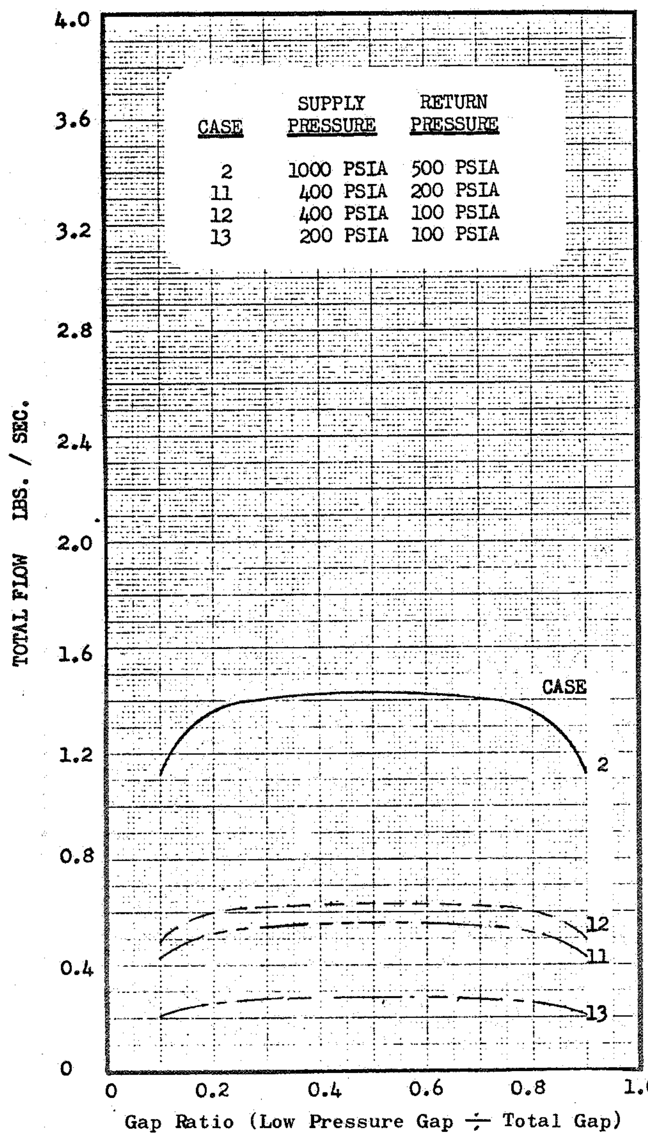
Figure 37



A COMPARISON OF TOTAL FLOW WITH VARIABLE SHAFT SPEEDS

IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

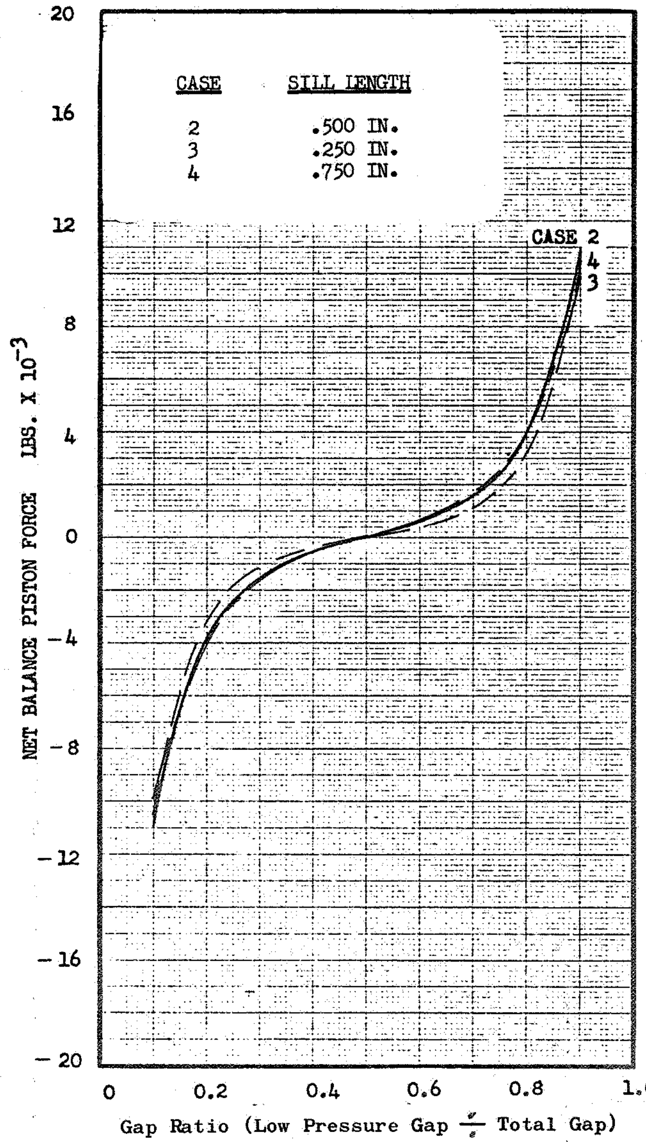
Figure 38



A COMPARISON OF TOTAL FLOW WITH VARIABLE PRESSURE LEVELS

IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

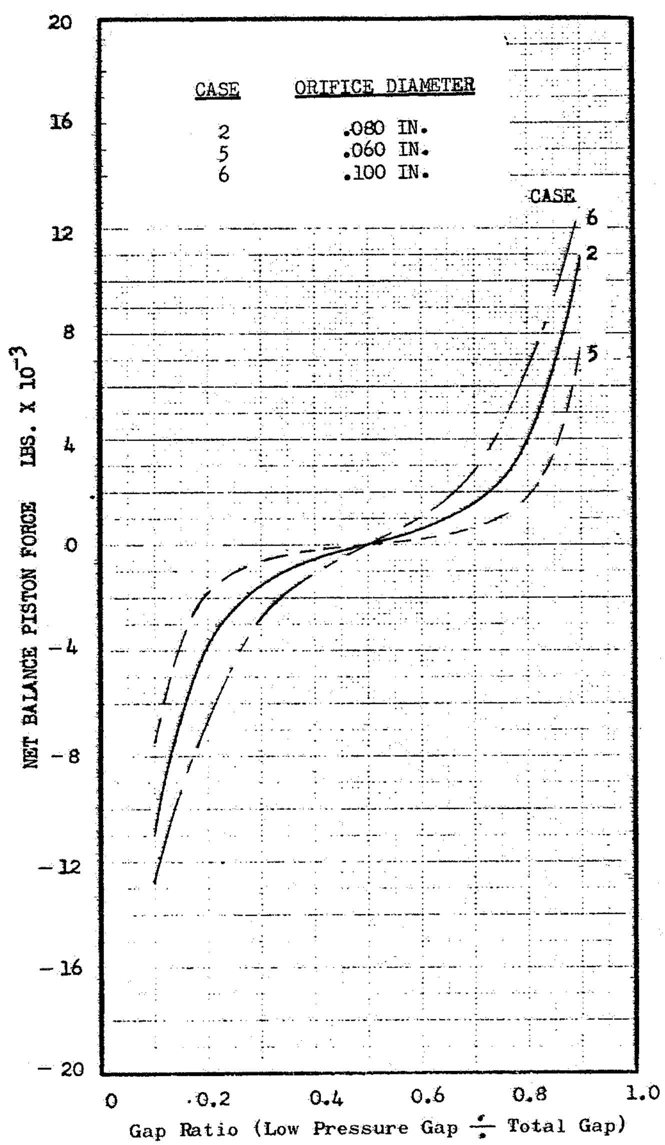
Figure 39



A COMPARISON OF FORCE WITH VARIABLE SILL LENGTHS

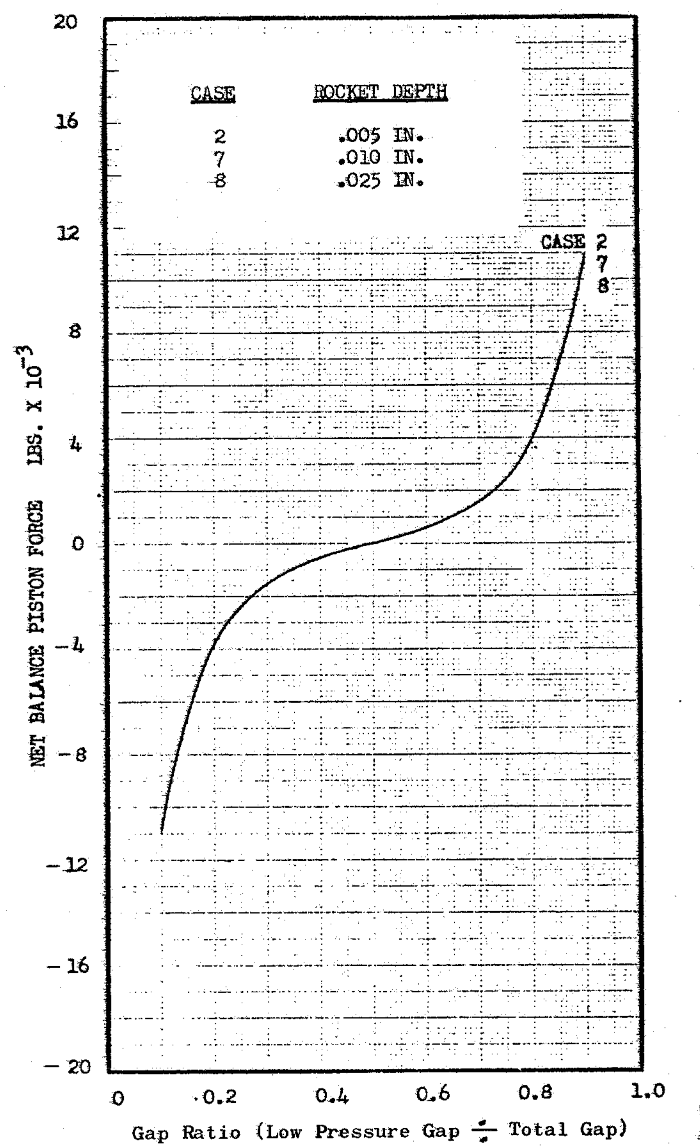
IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 40



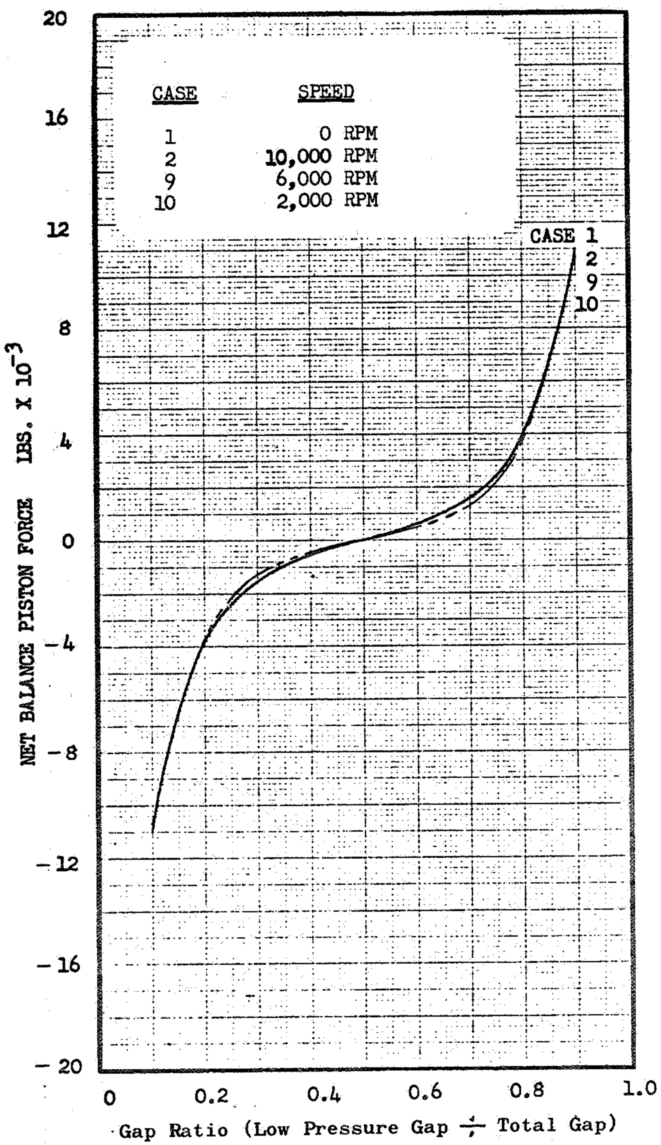
A COMPARISON OF FORCE WITH VARIABLE ORIFICE SIZES
IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 41



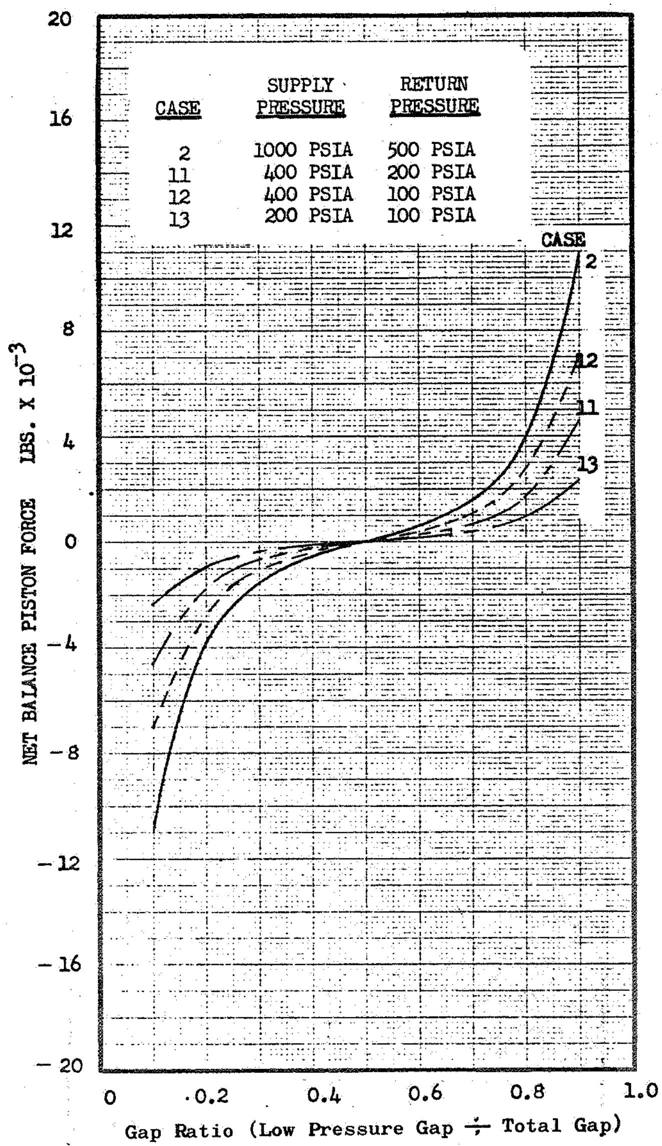
A COMPARISON OF FORCE WITH VARIABLE POCKET DEPTHS
IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 42



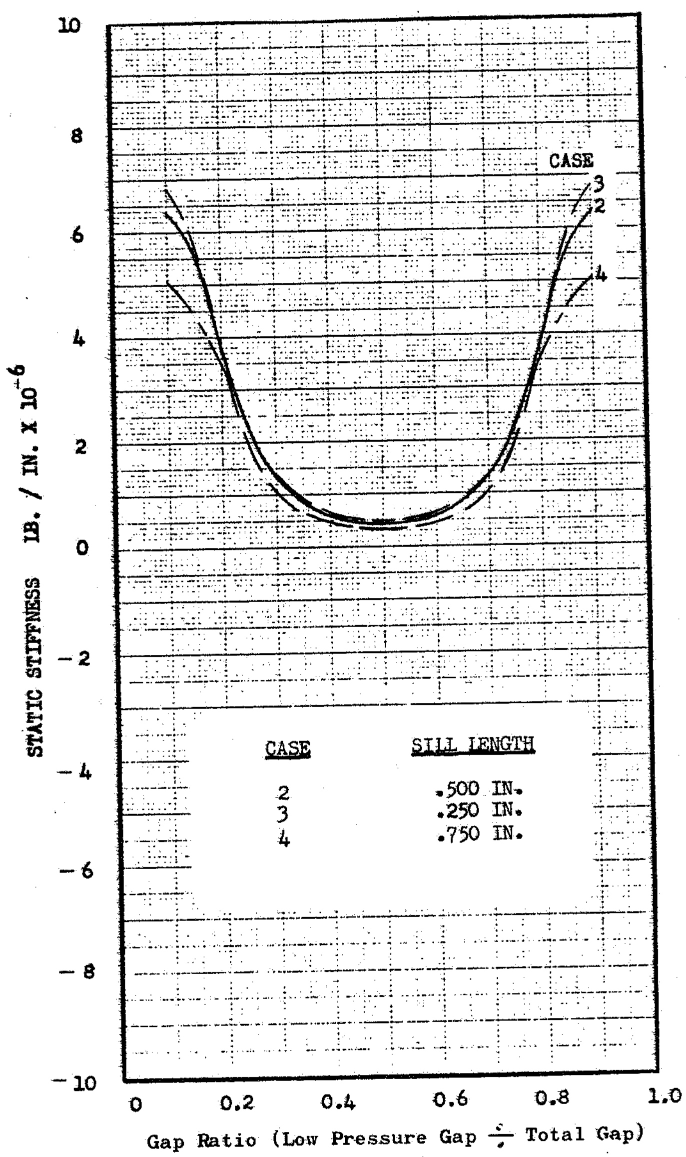
A COMPARISON OF FORCE WITH VARIABLE SHAFT SPEEDS IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 43



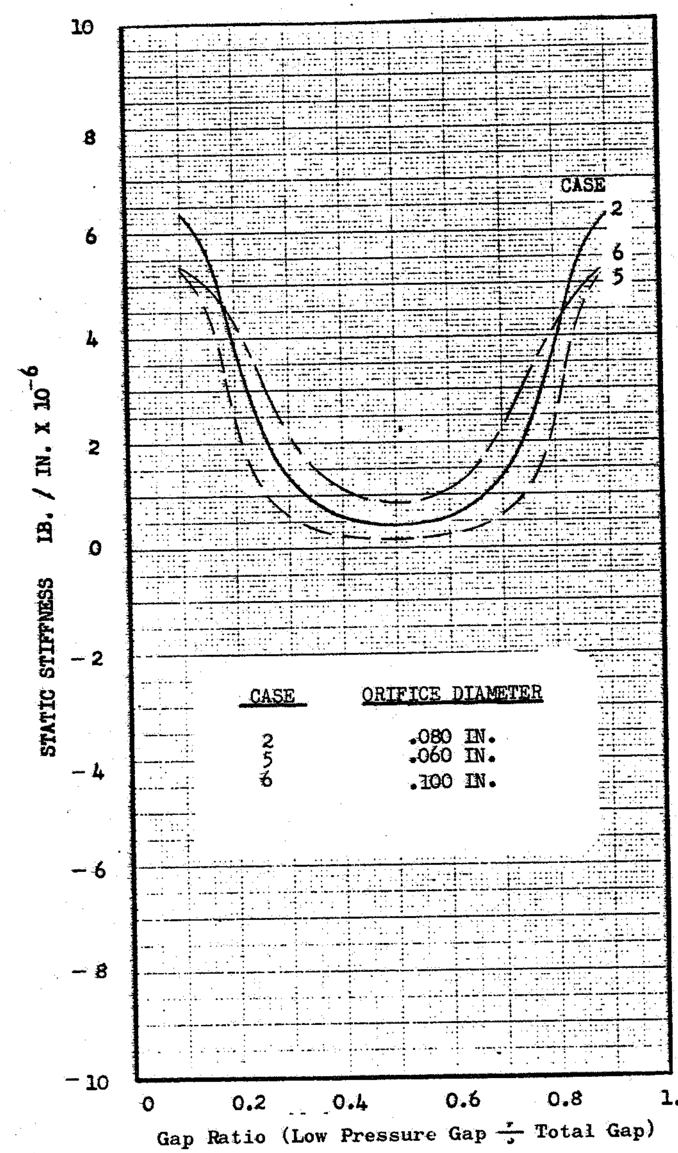
A COMPARISON OF FORCE WITH VARIABLE PRESSURE LEVELS IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 44



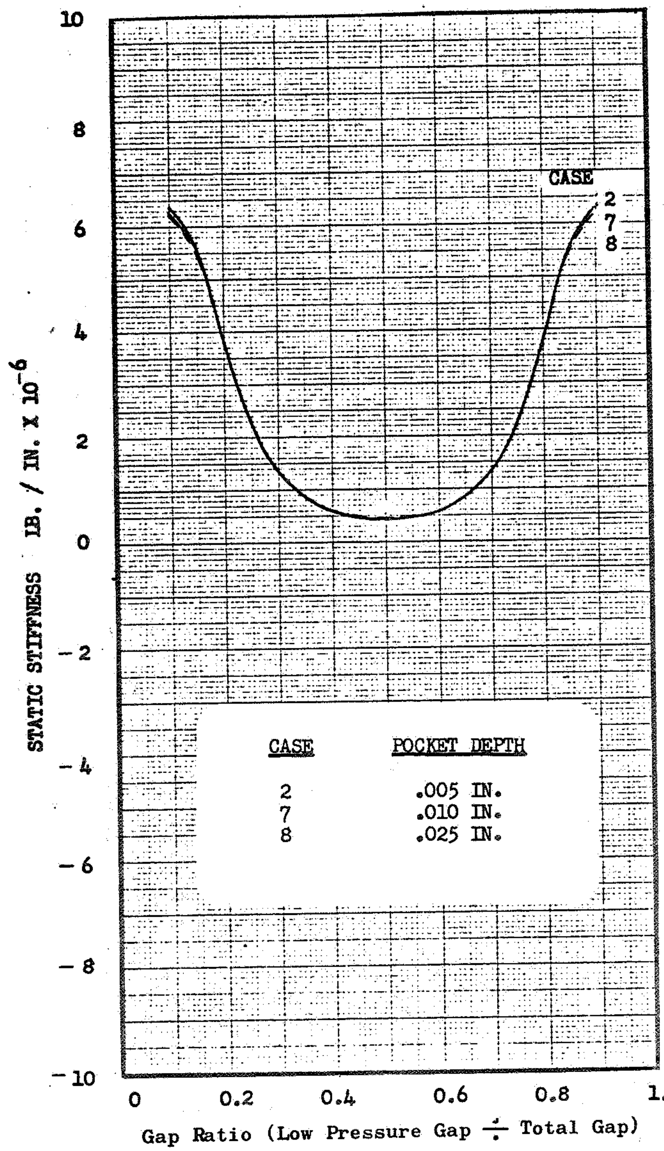
A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SILL LENGTHS
IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 45



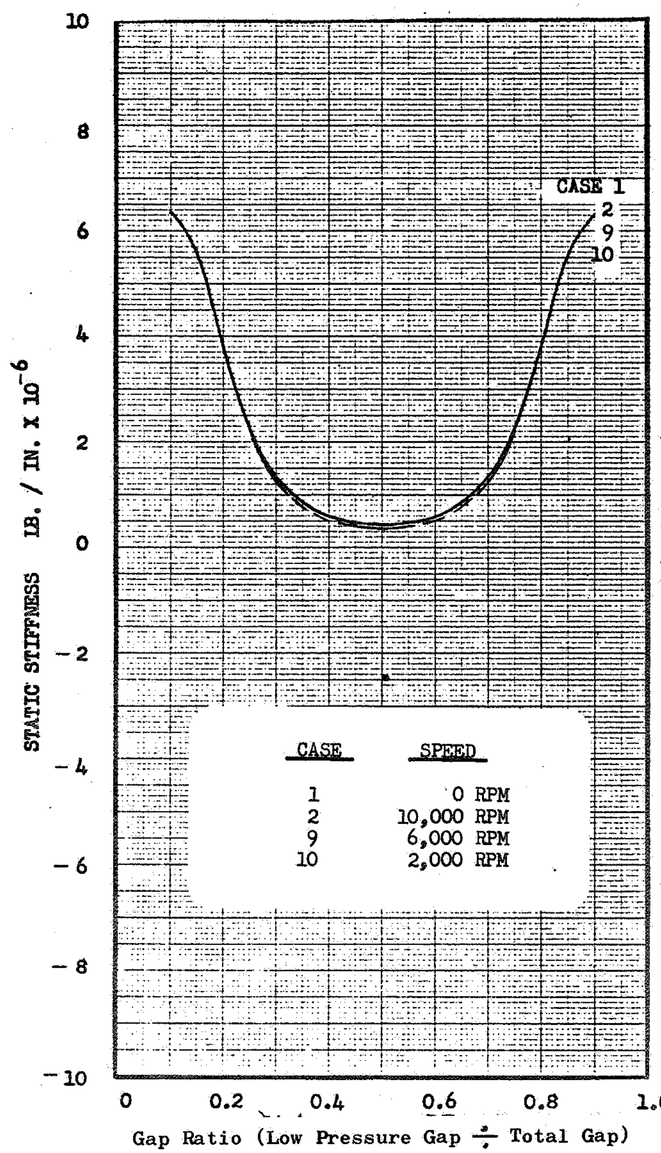
A COMPARISON OF STATIC STIFFNESS WITH VARIABLE ORIFICE SIZES
IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 46



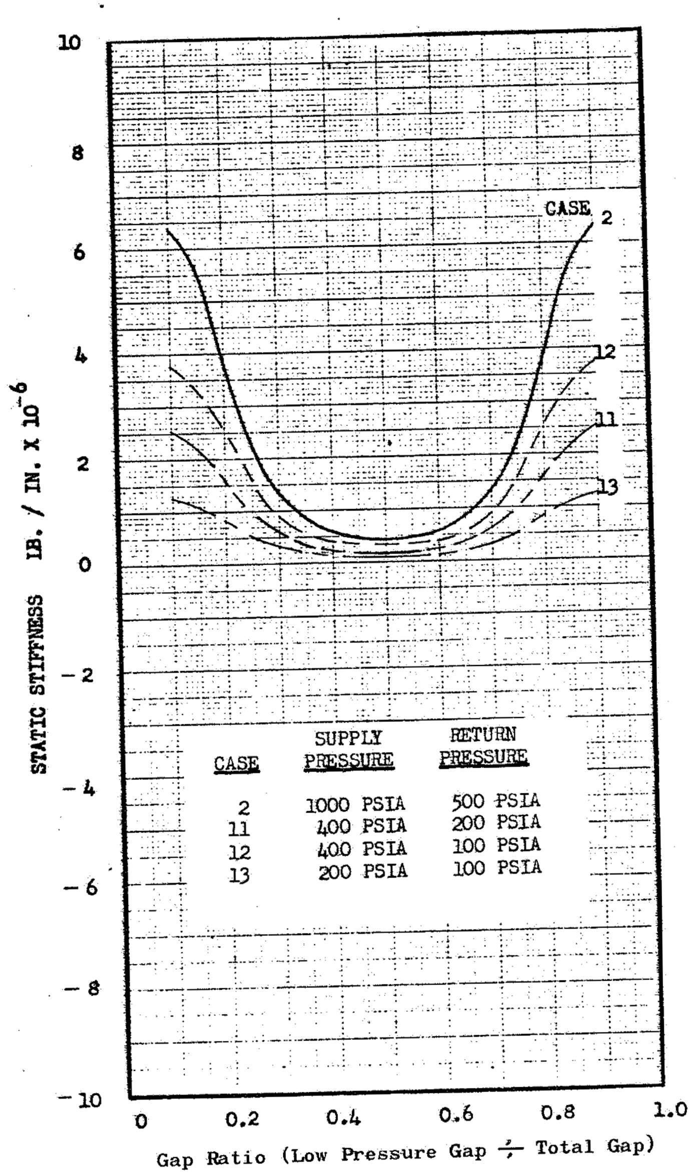
A COMPARISON OF STATIC STIFFNESS WITH VARIABLE POCKET DEPTHS IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 47



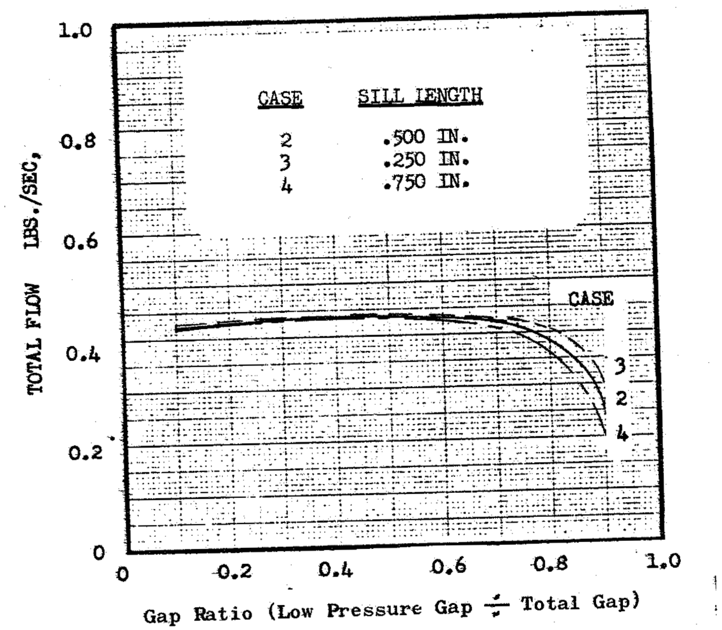
A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SHAFT SPEEDS IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 48



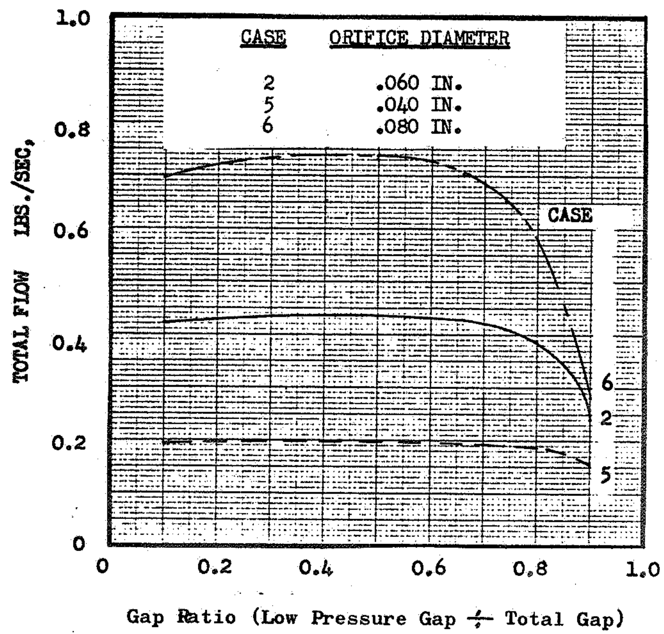
A COMPARISON OF STATIC STIFFNESS WITH VARIABLE PRESSURE LEVELS IN A PARRALLEL FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 49



A COMPARISON OF TOTAL FLOW WITH VARIABLE SILL LENGTHS IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

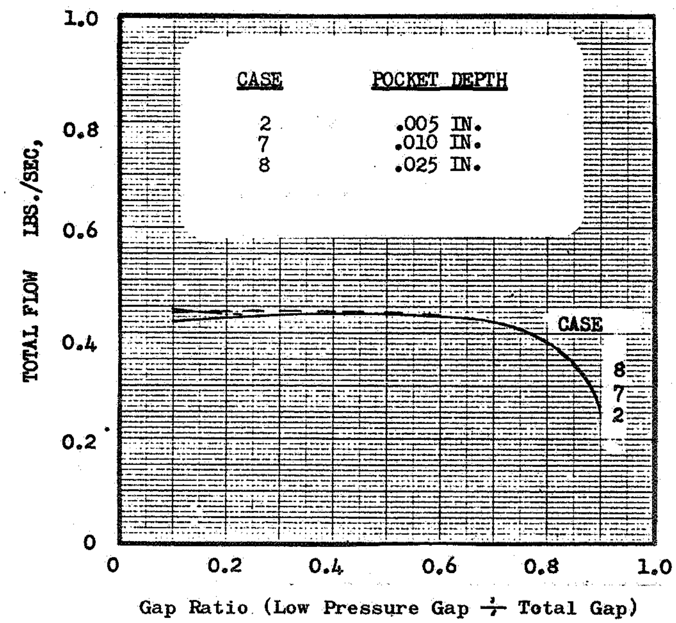
Figure 50



A COMPARISON OF TOTAL FLOW WITH VARIABLE ORIFICE SIZES

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

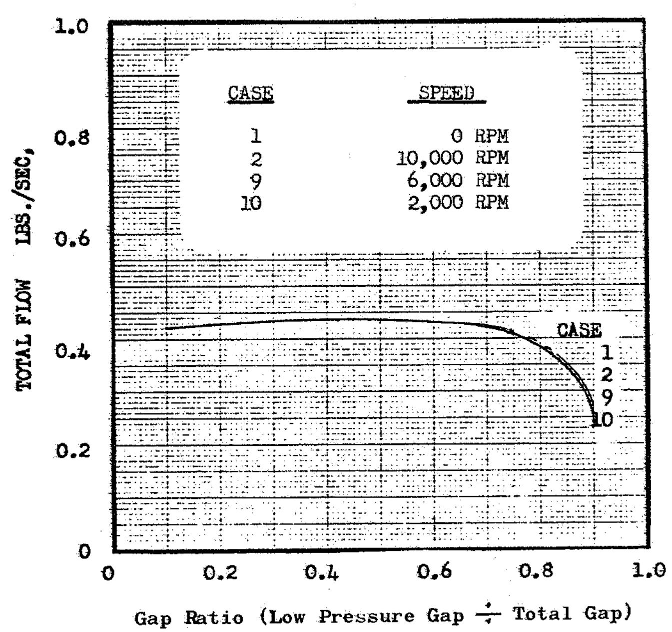
Figure 51



A COMPARISON OF TOTAL FLOW WITH VARIABLE POCKET DEPTHS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

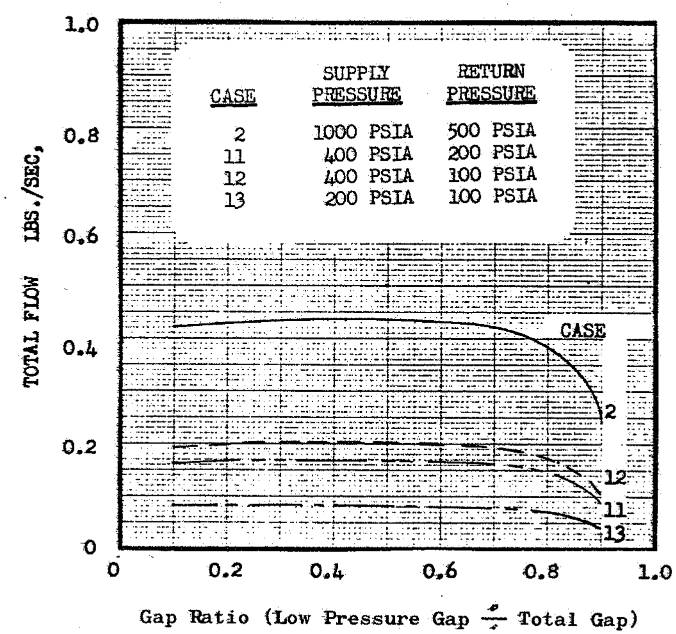
Figure 52



A COMPARISON OF TOTAL FLOW WITH VARIABLE SHAFT SPEEDS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

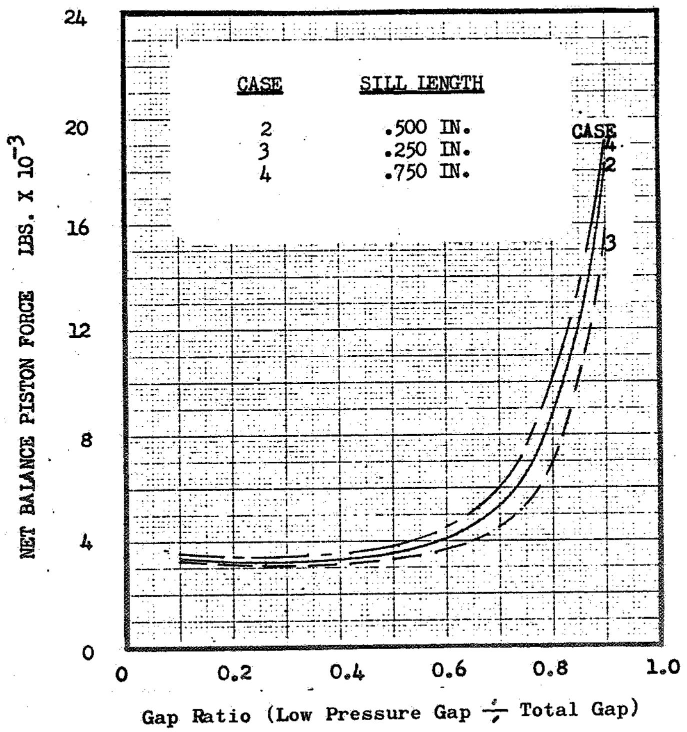
Figure 53



A COMPARISON OF TOTAL FLOW WITH VARIABLE PRESSURE LEVELS

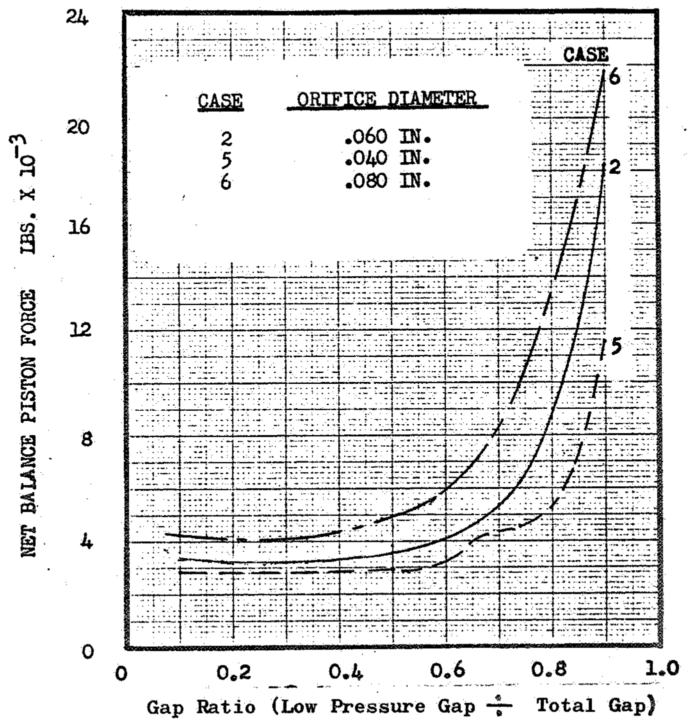
IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 54



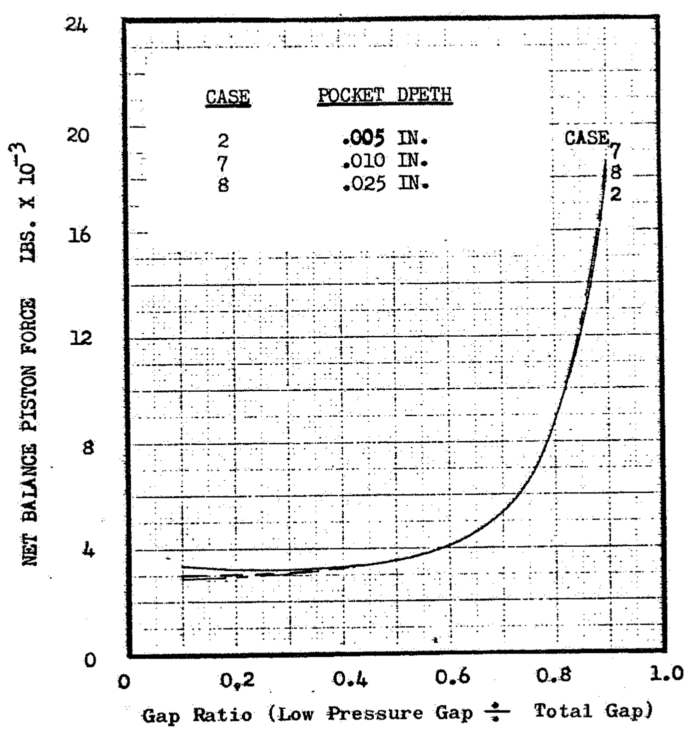
A COMPARISON OF FORCE WITH VARIABLE SILL LENGTHS
IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 55



A COMPARISON OF FORCE WITH VARIABLE ORIFICE SIZES
IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

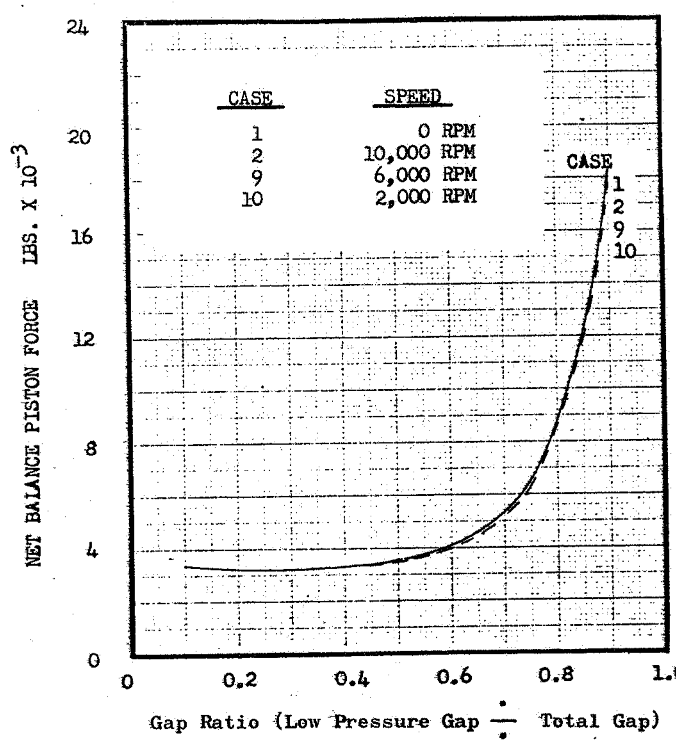
Figure 56



A COMPARISON OF FORCE WITH VARIABLE POCKET DEPTHS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

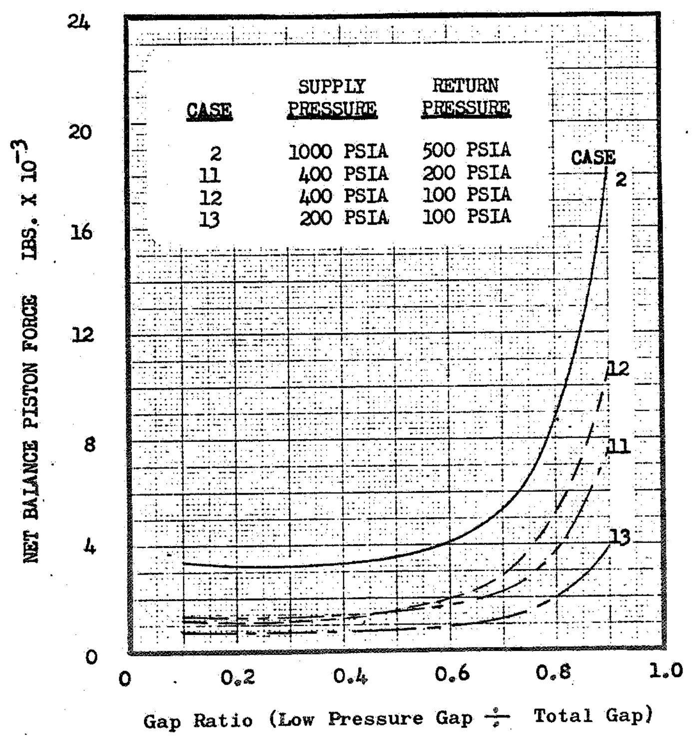
Figure 57



A COMPARISON OF FORCE WITH VARIABLE SHAFT SPEEDS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

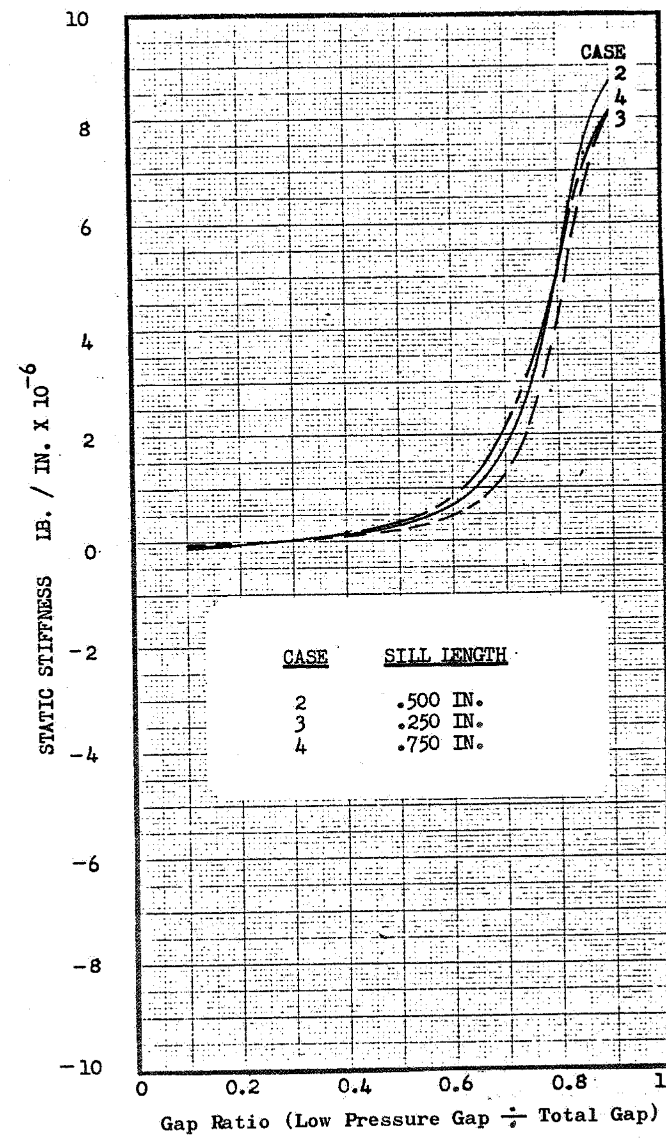
Figure 58



A COMPARISON OF FORCE WITH VARIABLE PRESSURE LEVELS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

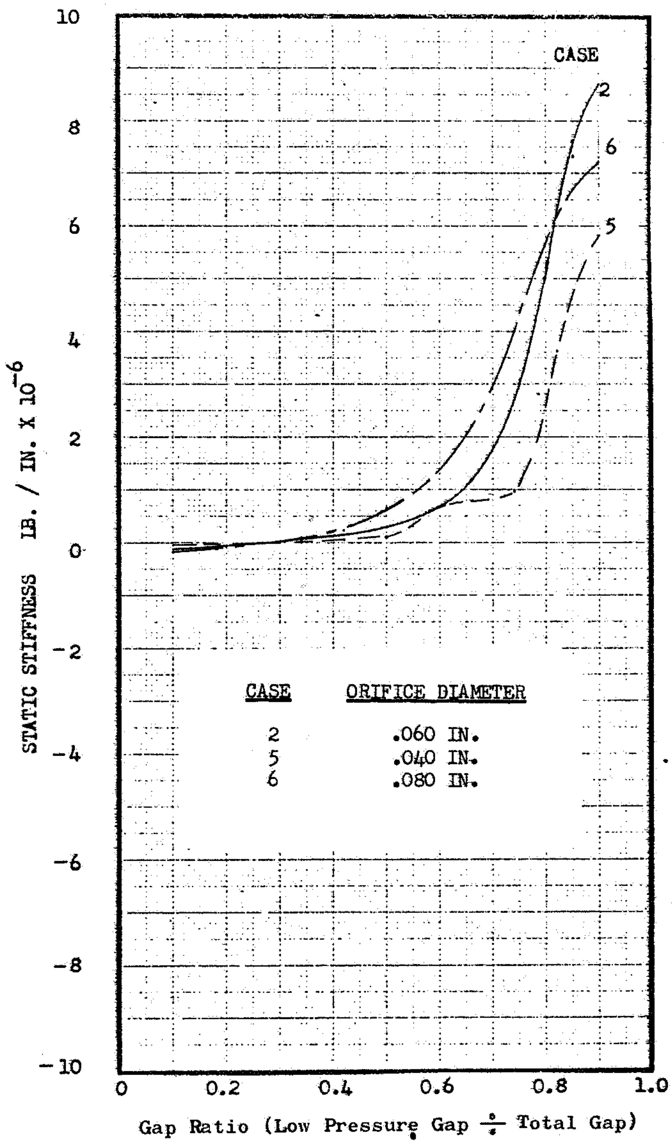
Figure 59



A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SILL LENGTHS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

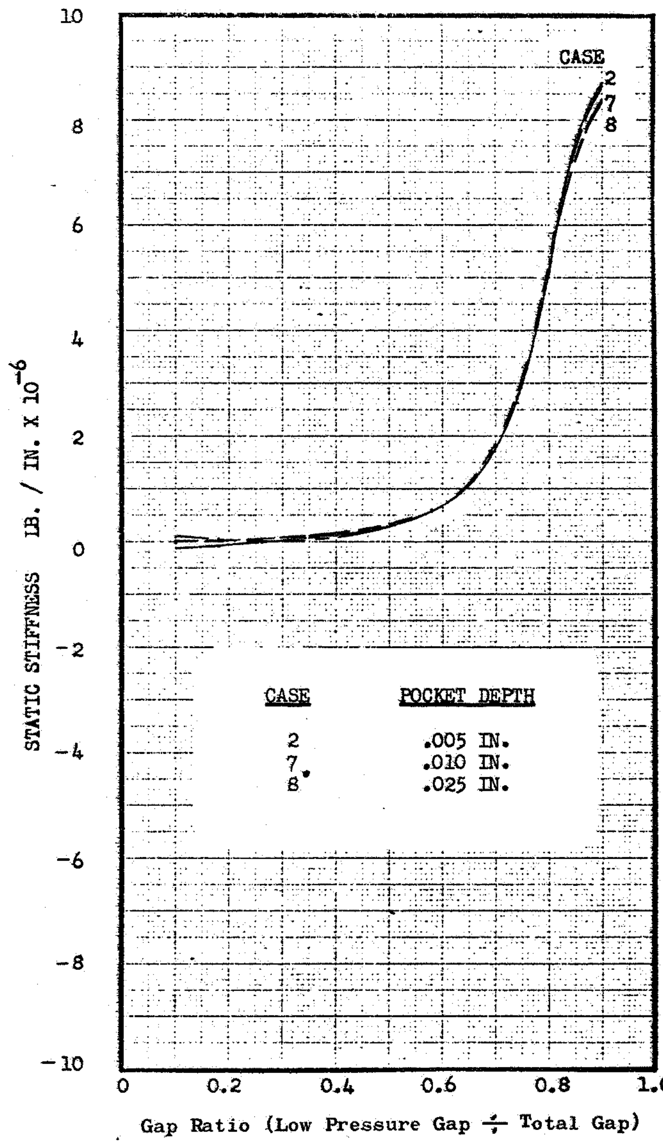
Figure 60



A COMPARISON OF STATIC STIFFNESS WITH VARIABLE ORIFICE SIZES

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

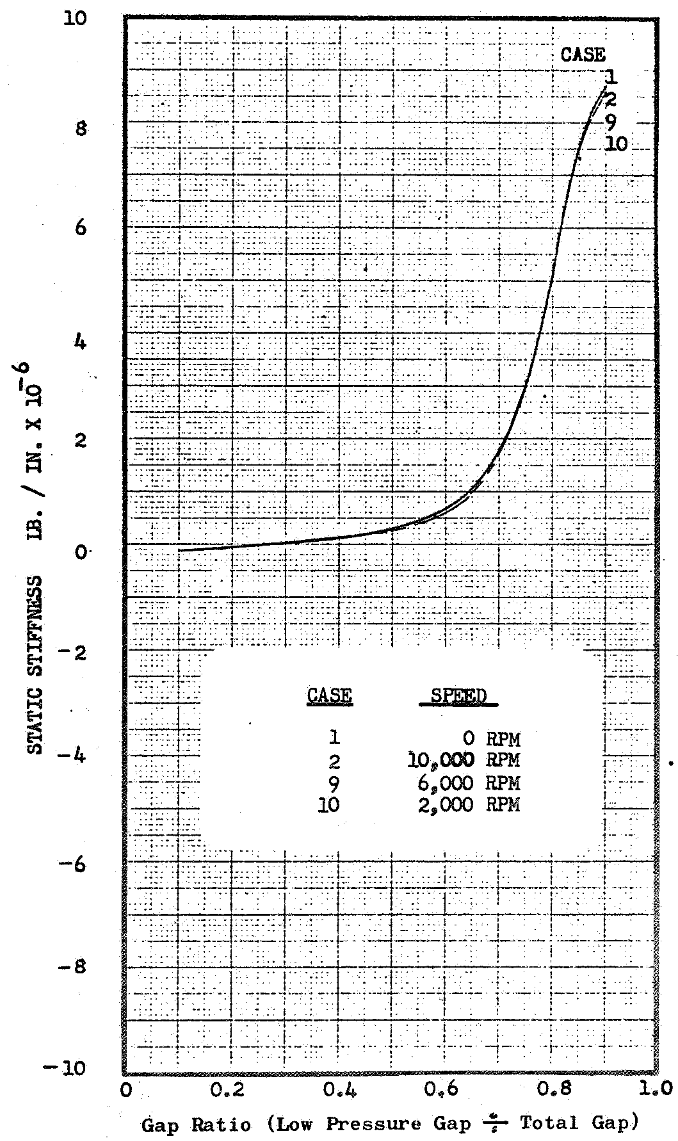
Figure 61



A COMPARISON OF STATIC STIFFNESS WITH VARIABLE POCKET DEPTHS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

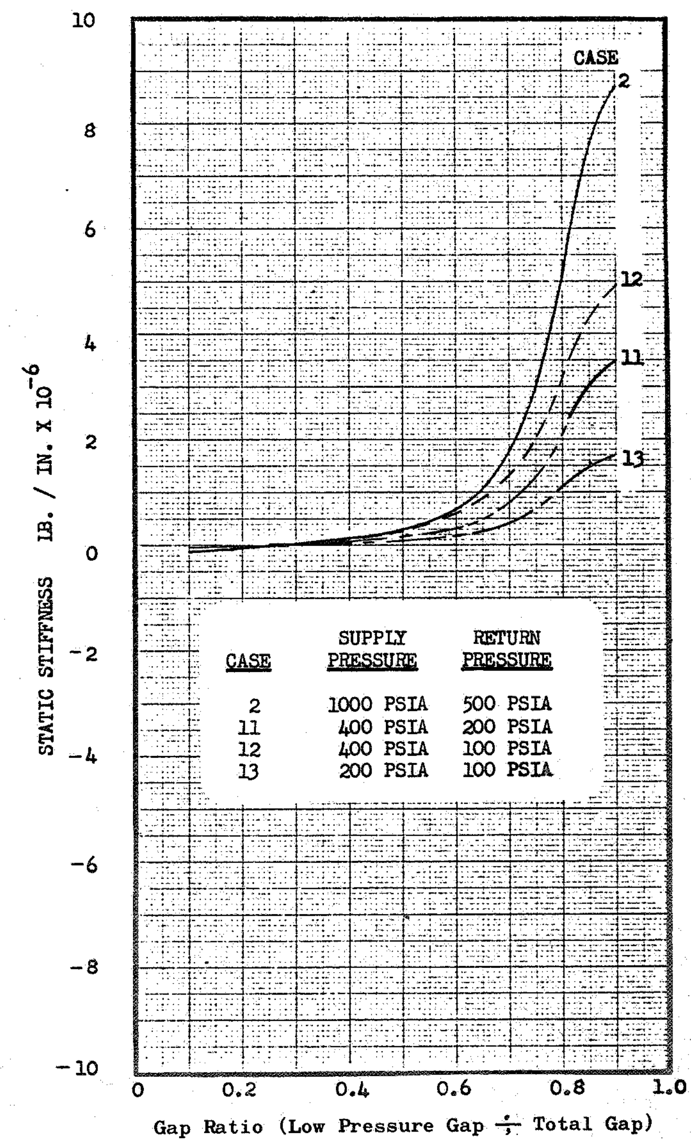
Figure 62



A COMPARISON OF STATIC STIFFNESS WITH VARIABLE SHAFT SPEEDS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 63



A COMPARISON OF STATIC STIFFNESS WITH VARIABLE PRESSURE LEVELS

IN A SERIES FLOW BALANCE PISTON USING GASEOUS NITROGEN AS THE FLUID.

Figure 64

During the incompressible parallel configuration study, the piston sill width was set at 0.25-in., 0.50-in., and 0.75-in. For each of these sill widths, the inlet orifice was varied from 0.1-in. to 0.17-in. and the piston pocket from 0.025-in. to 0.10-in. The results from this study showed the incompressible parallel balancer to be quite insensitive to parameter variations. For instance, in each case, the response to a step in force piston inlet pressure resulted in approximately a 10% overshoot in piston displacement and some damped oscillations (approximately 700 cps) of internal balancer pressures.

For the incompressible series configuration study, the nominal parameters consisted of a sill width of 0.5-in., a pocket depth of 0.05-in., and an inlet orifice diameter of 0.1-in. These parameters were then varied both higher and lower than these values. A change in inlet orifice diameter from 0.1-in. to 0.2-in. resulted in an increase in piston displacement overshoot from 0% to 25% during a step decrease in force piston inlet pressure. Changes in sill widths to 0.25-in. and 0.75-in. resulted in negligible response changes. An increase in pocket depth to 0.1-in. increased the displacement overshoot from 0% to 6%. In general, the series incompressible balancer showed no evidence of instability and appeared to be quite insensitive to parameter changes.

The compressible parallel configuration study included balancer pressure ranges of from 1000 psi to 500 psi, 400 psi to 200 psi, and 200 psi to 100 psi between inlet and discharge. However, most of the study was accomplished in the 400 psi to 200 psi range.

The brief study conducted of the balancer in the 1000 psi to 500 psi range showed the system to be stable. However, some low damped oscillations of approximately 750 cps were observed.

In the 400 psi to 200 psi range, a nominal set of parameters was prescribed as 0.5-in. sill width, 0.01-in. pocket depth, 0.1-in. orifice diameter. These nominal values resulted in a stable but lightly damped system with low damped oscillation of approximately 720 cps. Increasing the orifice diameter to 0.2-in. resulted in an instability at 740 cps. The instability resulted when the displacement was approximately 0.004-in. Changing the sill width and pocket depth produced no pronounced change in system operation.

The study of the system in the 200 psi to 100 psi range showed the system to be unstable. Stability could not be obtained during a brief parameter study.

The compressible series configuration study was carried out for a balancer pressure range of from 400 psi to 200 psi between the inlet and outlet. Approximately the same parameter variations were made as during the compressible parallel study. With a sill width of 0.5-in., a pocket depth of 0.01-in., and a 0.1-in. diameter inlet orifice, the system was found to be stable over the complete operating range. When the inlet orifice diameter was increased to 0.15-in., the systems became unstable when the piston displacement became greater than 0.003-in. from mid-point position. With an increase in inlet orifice diameter to 0.2-in., the unstable boundary moves down to a displacement value of 0.002-in.

Increasing the pocket depth from 0.01-in. to 0.02-in. with a 0.5-in. sill and a 0.1-in. inlet orifice results in an instability for displacements above 0.0045-in. from center.

The dynamic response obtained for the system with a 0.25-in. sill width was similar to that for the 0.5-in. one. Increasing the sill width to 0.75-in. resulted in some limit cycles at a piston displacement of 0.0025-in. from center.

In general, the analog computer parameter study showed the incompressible balancers to be very stable and quite insensitive to parameter changes. The compressible configurations were found to be much less stable and rather sensitive to certain parameter changes.

IV. CONCLUSIONS AND RECOMMENDATIONS

These conclusions and recommendations are preliminary ones only, based upon the results of Phase I. They remain subject to verification by the Phase II testing results.

The steady-state and analog parametric studies show the test assembly design to be quite stable with both water and gaseous nitrogen when operating at or near the design pressure of 1000 psi. Both the series and parallel configurations were extremely stable for a wide range of parameter variations using water as the fluid. Some highly damped oscillations were observed in the series configuration analog study at approximately 700 cps.

At low operating pressures and with large compensating orifices, both the series and parallel configurations showed instability with gaseous nitrogen as the fluid. Oscillations at 720 cps to 740 cps were evident in the parallel flow case with operating pressures below 400 psi and an orifice diameter of 0.2-in. This occurred when the piston was displaced 0.004-in. from mid-position.

The series flow configuration also became unstable at operating pressures below 400 psi with an inlet orifice of 0.15-in. This occurred at a displacement of 0.003-in. from the mid-position.

Verification of the results obtained from the parametric analysis will be accomplished in Phase II of this program. Tests will be conducted to verify the flow and pressure profile calculations as well as to verify the dynamic stability. It is recommended that tests be conducted for a range of speeds and pressures with varying sill lengths, pocket depths, and orifices. Both series and parallel configurations will be tested in water and gaseous nitrogen. Further, a statistical approach is recommended for parameter variations during testing to minimize the number of tests that must be conducted to verify the computer programs and parametric studies.

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3. Young, W. E., and Due, H. F., Investigation of Pressure Prediction Methods for Radial Flow Impellers, Phase II, Final Report PWA FR-1276, Contract NAS 8-5442, 8 March 1965

4. Tao, L. N., and Donovan, W. F., "Through-Flow in Concentric and Eccentric Annuli of Fine Clearance with and without Relative Motion of the Boundaries," Trans. ASME, November 1955

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APPENDICES

APPENDIX A

NOMENCLATURE

APPENDIX A

NOMENCLATURE

A - Area - in.^{2}
C - Dimensionless coefficient
C_p - Specific heat at constant pressure - Btu/lb °F
D - Diameter - in.
f - Friction factor
F - Force - lb
g - Gravitational constant - 386 in./sec^2
h - Clearance - in.
H - Head of liquid - ft
J - Mechanical equivalent of heat - 778 ft lb/Btu
K - Rotational constant - dimensionless
L - Length - in.
M - Torque - in./lb
n - Reynolds Number coefficient
N - Number of lines or lands - dimensionless or revolutions-per-minute - rpm
P - Pressure - lb/in.^{2}
Q - Volumetric flow rate - in.^{3}/sec
R - Radius - in.
R_e - Reynolds Number
T - Temperature - Degree Rankine
U - Tangential velocity - in./sec
V - Through flow velocity - in./sec
W - Weight Flow - lb/sec
μ - Absolute viscosity - lb sec/in.^{2}
ω - Angular velocity - radians/sec
γ - Weight density - lb/in.^{3}

SUBSCRIPTS

1,2,----etc.	Station Location
D	Point on Rotating Disk
avg.	Average

APPENDIX B

STEADY-STATE COMPUTER PROGRAM

The information contained in this appendix is based upon that compiled for the "Users Manual, Series and Parallel Thrust System, Program E21902" by M. J. Gerber, Aerojet-General Computing Sciences, 1 April 1968

APPENDIX B

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Program E21902 was written for the parametric analysis of the steady-state, incompressible, subsonic compressible fluid flow of series and parallel self-compensating axial thrust balance systems. The Input for Thrust Balancer Stability Program is provided as Attachment A to this appendix while the Flow Charts and Program Listing are included as Attachments B and C, respectively.

II. STATEMENT OF PROBLEM

Figure No. B-1 is a schematic flow diagram of the parallel flow self-compensating test assembly and associated circuitry to be analyzed in this program. Fluid, which is supplied to the test loop from a separate pump flow circuit, runs from an accumulator to the load piston and to both the low-pressure side and the high-pressure side of the balance piston. Flow is returned from both pistons to the pump suction circuit.

Figure No. B-2 is a schematic flow diagram of the series flow test assembly. The fluid supply and return are similar to that of the parallel flow system. However, flow to the balance piston is supplied to the high-pressure side and then, in series, from the high-pressure side to the low-pressure side before returning to the supply pump suction circuit.

Figures No. B-3 and No. B-4 are block schematic diagrams of the mathematical models for the parallel flow and series flow systems, respectively. The program considers only that portion of the circuits included between pressures PFS and pressures PFPR1 and PFC2 for the load piston; PLS and PBPR1 for the low-pressure side of the balance piston; and PHS and PBPR1 for the high-pressure side of the balance piston.

III. METHOD OF SOLUTION

Analysis of the balance system begins with the balance piston. At constant eccentricity, shaft speed, supply pressure, and return pressure, a range of clearances on the low-pressure sill are considered with the total sill clearance held constant. At each clearance, the fluid properties are calculated, based upon input property tables, the forces, and the horsepower. Then, the stiffness is calculated for the range of clearances. The force piston is calculated last with successive calculations of properties, forces, and horsepower made for a range of supply pressures.

To solve for the pressure and flow values of the balance piston, an approximation of the pressure drop across the orifice is made and the orifice equations are solved for the first flow value. Then, this flow is used to solve all pressure drops in the series flow case. For parallel flow, the orifice flow is arbitrarily split between outward and inward flow using the ratio of the average sill radius to the sum of the average radii of both sills. Pressure drops through the system are calculated to obtain a value for return

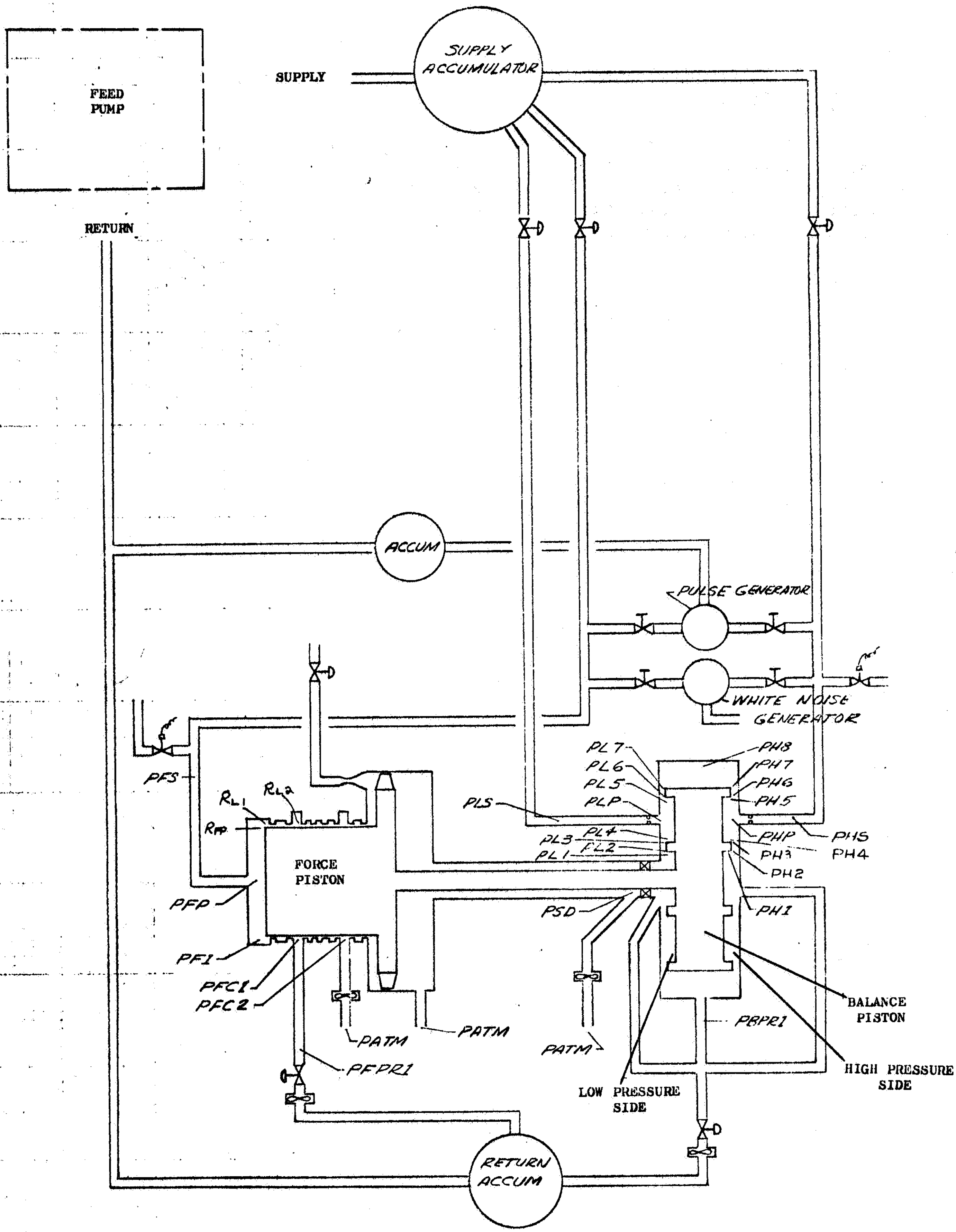


Figure B-1 System Schematic - Parallel Flow

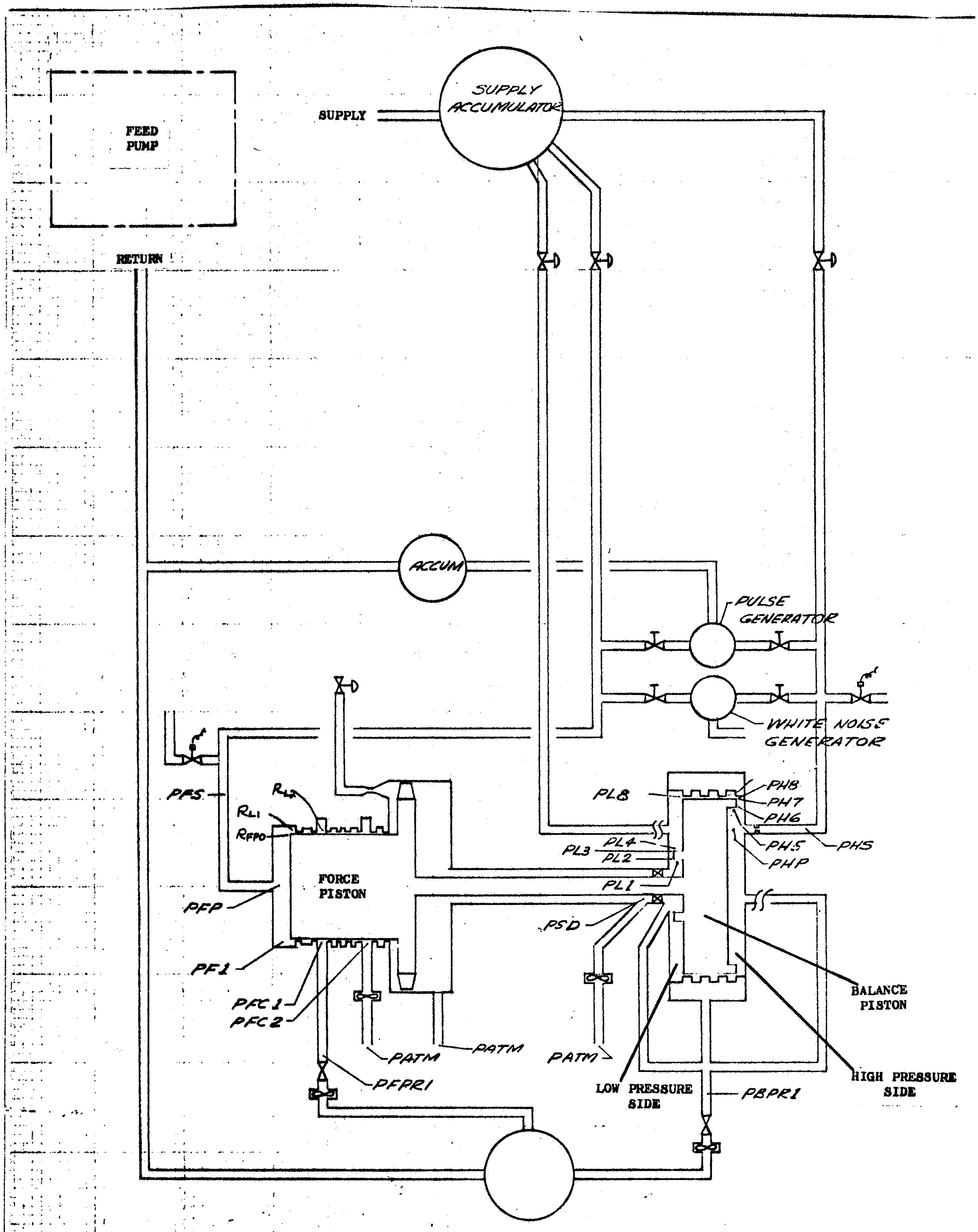


Figure B-2 System Schematic - Series Flow

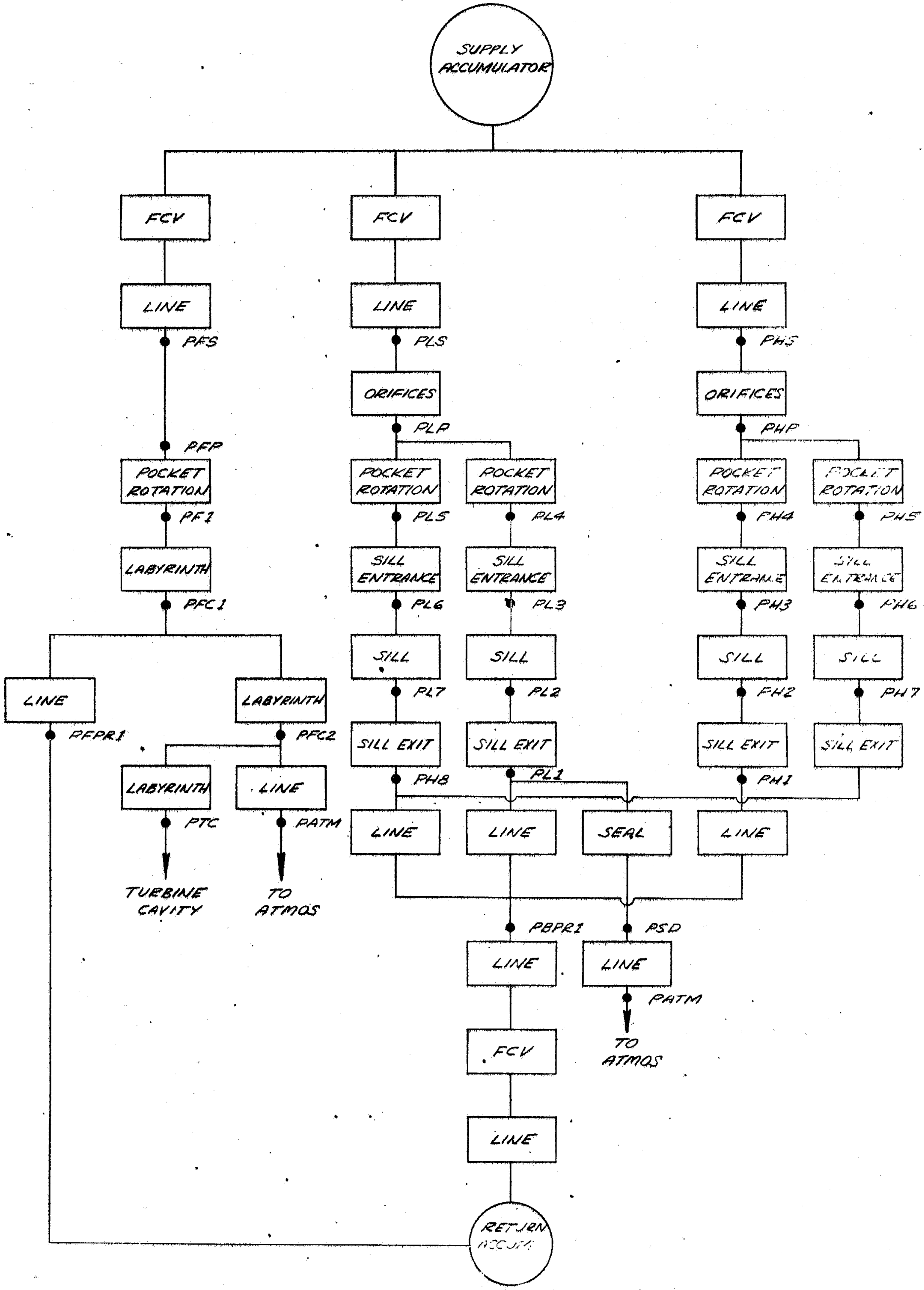


Figure B-3: System Schematic - Parallel Flow System

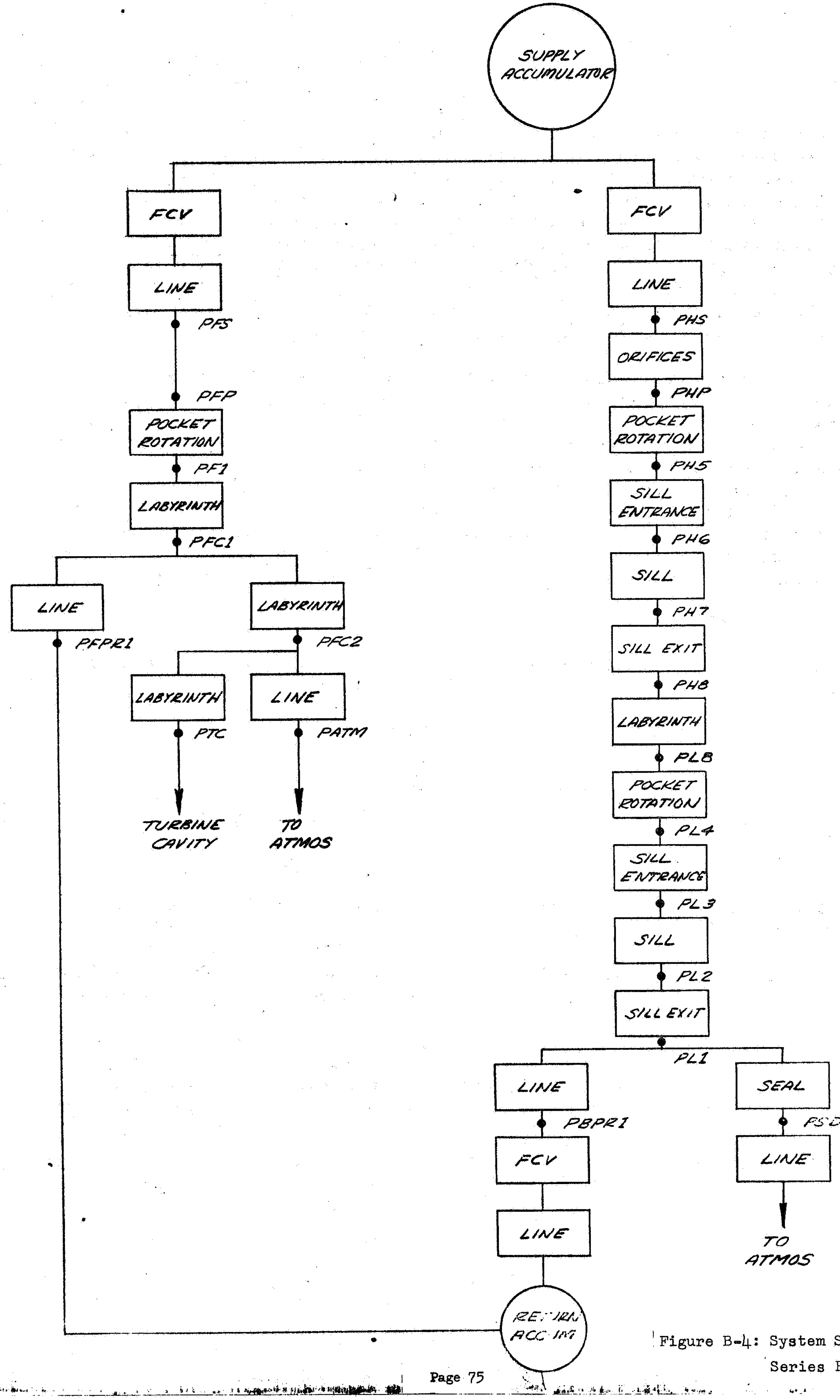


Figure B-4: System Schematic - Series Flow System pressure in each separate flow loop. The calculated pressure drop between supply pressure and return pressure is compared to input values. If any of the calculated values exceed limits set by the input data, over-all flow coefficients are calculated based upon calculated pressure drops. These coefficients are used with the actual available pressure drop to obtain the next approximation of flow in all of the flow loops. The sill lands are divided into rings to permit assuming a linear pressure gradient with the radius on each ring for the force calculations. Reynolds Number is calculated throughout the flow circuit to evaluate whether the flow is laminar or turbulent for selection of the appropriate flow equations and coefficients.

To solve for the pressure and flow values of the load piston, an approximation for the pressure drop across the orifices is again made to determine the first supply flow value. Then, this flow is used to solve the pressure drops in the pocket and piston labyrinth. The piston labyrinth pressure and the return pressures determine the return flows. The calculated supply flow value is compared with the total return flow. If the difference exceeds limits set by the input data, an approximation for the piston labyrinth pressure is calculated based upon calculated flows. Then, the supply flow coefficients are used with the labyrinth pressure approximation to calculate the next orifice pressure drop approximation.

IV. RESTRICTIONS

In Program E21902, the size of the input problem is restricted to the following:

- The number of clearance increments on the low pressure sill has a maximum of 20.
- The number of sill lands has a maximum of 20.
- The maximum table size is 30 x 30 for each fluid property.

V. ERRORS

The following errors generate an error message and the listed change of program flow:

If the interpolation routines for the fluid property tables are called with pressures or temperatures outside the table ranges, an error message is printed and

- the nearest table value is used if less than five such errors have occurred for the current clearance of the balance piston or for the current supply pressure of the load piston, or
- the current clearance or supply pressure calculation is by-passed and calculation is begun on the next clearance or supply pressure if five or more such errors have occurred.

If property pressure or flow iterations do not yield convergence in the maximum number of iterations as specified by the input, an error message is printed and the current clearance calculation of the balance piston or the current supply pressure calculation of the load piston is bypassed and calculation is begun on the next clearance or supply pressure.

VI. OPERATING INSTRUCTIONS

The program was written for the IBM 360/65. No special tapes or operating procedures are required.

VII. DECK SET-UP

Multiple input cases can be executed in one computer run by stacking the complete input card set for one case behind the previous case.

ATTACHMENT A

(APPENDIX B)

INPUT FOR THRUST BALANCER STABILITY PROGRAM

Card	Column	Format	Variable and Definition
INPUT COMMON TO ALL CASE TYPES			
1	1-72	Alphanumeric	TITLE (I) = case title
2	1-6	Integer	IPRES = 0, if compressible flow 1, if incompressible flow
	7-12	Integer	IBAL = 0, if parallel piston 1, if series piston
	13-18	Integer	NH = number of clearance increments ($\leq$20)
	19-24	Integer	ITERC = maximum number of iterations on subroutine pressure calculation
	25-30	Integer	ITERP = maximum number of iterations on properties pressure for parallel and force piston
	31-36	Integer	NTLAM = number of EL values in laminar flow rate ratio table (maximum 40)
	37-42	Integer	NTTUR = number of EL values in turbulent flow rate ratio table (maximum 40)
	43-48	Integer	ISEAL = 0, if seal, and 1, if labyrinth
	49-54	Integer	IKIN = 0, if rotation factors calculated in pockets and sills 1, if rotation factors input
	55-60	Integer	ITABLE = 0, if property tables not input (previously input property tables used) = 1, if tables input (first case of a run must input tables)
3	1-12	Decimal	HT = total clearance (in.)
	13-24	Decimal	HMIN = minimum sill clearance calculation point (in.)
	25-36	Decimal	HMAX = maximum sill clearance calculation point (in.)
	37-48	Decimal	HDLP = clearance difference between low-pressure pocket depth HLP at orifice and depth HL7 of low-pressure outer land (in.)
	49-60	Decimal	DHL = deflection on low-pressure side from inner land depth HL3 to outer land depth (in.)
	61-72	Decimal	HDHP = clearance difference between high-pressure side pocket depth HHP at orifice and outer land depth HH7 (in.)

Card	Column	Format	Variable and Definition
4	1-12	Decimal	XNRPM = rotational speed (rpm)
	13-24	Decimal	ECC = runout (in.)
	25-36	Decimal	PATM = atmospheric pressure (lb/in.**2)
	37-48	Decimal	Cl = closure on subroutine pressure calculations (relative error)
	49-60	Decimal	CLOS = closure on properties pressure
	61-72	Decimal	C11 = pocket pressure approximation factor
5	1-12	Decimal	XKRING = factor for calculating rings in sill (1/in.) (N = 2*(R2-R1/(R2+R1) XKRING +1)
	13-24	Decimal	CR = averaging constant for fluid properties
	25-36	Decimal	CMLAM = laminar moment fraction factor constant
	37-48	Decimal	NMLAM = laminar moment fraction factor exponent
6	1-12	Decimal	CMTUR = turbulent moment fraction factor constant
	13-24	Decimal	NMTUR = turbulent moment fractor factor exponent
	25-36	Decimal	CFLAM = laminar flow fraction factor constant
	37-48	Decimal	NFLAM = laminar flow fraction factor exponent
	49-60	Decimal	CFTUR = turbulent flow fraction factor constant
	61-72	Decimal	NFTUR = turbulent flow fraction factor exponent

Repeat card 7 until NTLAM values of EL and FRL have been supplied.

Card	Column	Format	Variable and Definition
7	1-12	Decimal	EL(1) = laminar eccentricity ratio table value
	13-24	Decimal	FRL(1) = laminar flowrate ratio for EL(1)
	25-36	Decimal	EL(2)
	37-48	Decimal	FRL(2)
	49-60	Decimal	EL(3)
	61-72	Decimal	FRL(3)

Repeat card 8 until NTTUR values of ET and FRT have been supplied.

Card	Column	Format	Variable and Definition
8	1-12	Decimal	ET(1) = turbulent eccentricity ratio table value
	13-24	Decimal	FRT(1) = turbulent flowrate ratio for ET(1)

Card	Column	Format	Variable and Definition
8 (cont.)			
	25-36	Decimal	ET(2)
	37-48	Decimal	FRT(2)
	49-60	Decimal	ET(3)
	61-72	Decimal	FRT(3)

INPUT OF FLUID PROPERTY TABLES

Delete Cards 9-24 if I Table (Card 2) = 0.

Card	Column	Format	Variable and Definition
9	1-6	Integer	NPDENS = number of pressure values in density table (maximum of 30)
	7-12	Integer	NTDENS = number of temperature values in density table (maximum of 30)
	13-18	Integer	NPHEAT = number of pressure values in specific heat table (30 maximum)
	19-24	Integer	NTHEAT = number of temperature values in specific heat table (30 maximum)
	25-30	Integer	NPVISC = number of pressure values in viscosity table (30 maximum)
	31-36	Integer	NTVISC = number of temperature values in viscosity table (30 maximum)
	37-42	Integer	NETEMP = number of entropy values in temperature table (maximum of 30)
	43-48	Integer	NTTEMP = number of temperature values in temperature table (maximum of 30)
	49-54	Integer	NPBULK = number of pressure values in bulk modulus table (maximum of 30)
	55-60	Integer	NTBULK = number of temperature values in bulk modulus table (maximum of 30)

Repeat card 10 until NPDENS values have been supplied.

Card	Column	Format	Variable and Definition
10	1-12	Decimal	PDENS(1) = pressure value for density table (psia)
	13-24	Decimal	PDENS(2)
	25-36	Decimal	PDENS(3)
	37-48	Decimal	PDENS(4)
	49-60	Decimal	PDENS(5)
	61-72	Decimal	PDENS(6)

Card	Column	Format	Variable and Defintion

Repeat card 11 until NTDENS values have been supplied.

Card	Column	Format	Variable and Defintion
11	1-12	Decimal	TDENS(1) = temperature value for density table (DEG R)
	13-24	Decimal	TDENS(2)
	25-36	Decimal	TDENS(3)
	37-48	Decimal	TDENS(4)
	49-60	Decimal	TDENS(5)
	61-72	Decimal	TDENS(6)

Repeat card 12 until all values of density have been supplied for the NPDENS pressures at temperature TDENS(1), and continue until all values have been supplied for the NPDENS pressures at temperatures TDENS(2) to TDENS(NTDENS).

Card	Column	Format	Variable and Defintion
12	1-12	Decimal	GDENS(1,1) = density for table at PDENS(1), and TDENS(1) (lb/in.**3)
	13-24	Decimal	GDENS(2,1) = density for table at PDENS(2) and TDENS(1)
	25-36	Decimal	GDENS
	37-48	Decimal	GDENS
	49-60	Decimal	GDENS
	61-72	Decimal	GDENS(I,J) = density for table at PDENS(I) and TDENS(J)

Repeat card 13 until NPHEAT values have been supplied.

Card	Column	Format	Variable and Defintion
13	1-12	Decimal	PHEAT(1) = pressure value for specific heat table (psia)
	13-24	Decimal	PHEAT (2)
	25-36	Decimal	PHEAT (3)
	37-48	Decimal	PHEAT (4)
	49-60	Decimal	PHEAT (5)
	61-72	Decimal	PHEAT (6)

Repeat card 14 until NTHEAT values have been supplied.

Card	Column	Format	Variable and Defintion
14	1-12	Decimal	THEAT(1) = temperature value for specific heat table (°R)
	13-24	Decimal	THEAT(2)
	25-36	Decimal	THEAT(3)

Card	Column	Format	Variable and Definition
14 (cont.)			
	37-48	Decimal	THEAT(4)
	49-60	Decimal	THEAT(5)
	61-72	Decimal	THEAT(6)

Repeat card 15 until all values of specific heat have been supplied for the NPHEAT pressures at temperature THEAT(1), and continue until all values have been supplied for the NPHEAT pressures at temperatures THEAT(2) to THEAT(NTHEAT).

Card	Column	Format	Variable and Definition
15	1-12	Decimal	CPHEAT(1,1) = specific heat for table at PHEAT(1) and THEAT(1) (Btu/lb*°R)
	13-24	Decimal	CPHEAT(2,1) at PHEAT(2) and THEAT(1)
	25-36	Decimal	
	37-48	Decimal	
	49-60	Decimal	
	61-72	Decimal	CPHEAT(I,J) = specific heat at PHEAT(I) and THEAT(J)

Repeat card 16 until NPVISC values have been supplied.

Card	Column	Format	Variable and Definition
16	1-12	Decimal	PVISC(1) = pressure value for viscosity table (psia)
	13-24	Decimal	PVISC(2)
	25-36	Decimal	PVISC(3)
	37-48	Decimal	PVISC(4)
	49-60	Decimal	PVISC(5)
	61-72	Decimal	PVISC(6)

Repeat card 17 until NTVISC values have been supplied.

Card	Column	Format	Variable and Definition
17	1-12	Decimal	TVISC(1) = temperature value for viscosity table (°R)
	13-24	Decimal	TVISC(2)
	25-36	Decimal	TVISC(3)
	37-48	Decimal	TVISC(4)
	49-60	Decimal	TVISC(5)
	61-72	Decimal	TVISC(6)

Card	Column	Format	Variable and Definition

Repeat card 18 until all values of viscosity have been supplied for the NPVISC pressures at temperature TVISC(1), and continue until all values have been supplied at temperature TVISC(2) to TVISC(NTVISC).

18	1-12	Decimal	XMVISC(1,1) = viscosity at PVISC(1) and TVISC(1) (lb*sec/in.**2)
	13-24	Decimal	XMVISC(2,1) at PVISC(2) and TVISC(1)
	25-36	Decimal	
	37-48	Decimal	
	49-60	Decimal	
	61-72	Decimal	XMVISC(I,J) = viscosity at PVISC(I) and TVISC(J)

Repeat card 19 until NETEMP values have been supplied.

19	1-12	Decimal	ETEMP(1) = entropy value for temperature table (Btu/lb*°R)
	13-24	Decimal	ETEMP(2)
	25-36	Decimal	ETEMP(3)
	37-48	Decimal	ETEMP(4)
	49-60	Decimal	ETEMP(5)
	61-72	Decimal	ETEMP(6)

Repeat card 20 until NTTEMP values have been supplied.

20	1-12	Decimal	TTEMP(1) = temperature value for temperature table (°R)
	13-24	Decimal	TTEMP(2)
	25-36	Decimal	TTEMP(3)
	37-48	Decimal	TTEMP(4)
	49-60	Decimal	TTEMP(5)
	61-72	Decimal	TTEMP(6)

Repeat card 21 until all values of pressure have been supplied for the NETEMP entropies at temperature TTEMP(1), and continue until all values have been supplied at temperature (TTEMP(2) to TTEMP(NTTEMP).

Card	Column	Format	Variable and Definition
21	1-12	Decimal	PTEMP(1,1) = pressure value at ETEMP(1) and TTEMP(1) psia
	13-24	Decimal	TTEMP(2,1)
	25-36	Decimal	TTEMP(3)
	37-48	Decimal	
	49-60	Decimal	
	61-72	Decimal	PTEMP(I,J) = pressure value at ETEMP(I) and TTEMP(J)

Repeat card 22 until NPBULK values have been supplied.

Card	Column	Format	Variable and Definition
22	1-12	Decimal	PBULK(1) = pressure value for bulk modulus table (psia)
	13-24	Decimal	PBULK(2)
	25-36	Decimal	PBULK(3)
	37-48	Decimal	PBULK(4)
	49-60	Decimal	PBULK(5)
	61-72	Decimal	PBULK(6)

Repeat card 23 until NTBULK, values have been supplied.

Card	Column	Format	Variable and Definition
23	1-12	Decimal	TBULK(1) = temperature value for bulk modulus table (°R)
	13-24	Decimal	TBULK(2)
	25-36	Decimal	TBULK(3)
	37-48	Decimal	TBULK(4)
	49-60	Decimal	TBULK(5)
	61-72	Decimal	TBULK(6)

Repeat card 24 until all values of bulk modulus have been supplied for the NPBULK pressures at temperature TBULK(1), and continue until all values have been supplied at temperature, TBULK(2) to TBULK(NTBULK).

Card	Column	Format	Variable and Definition
24	1-12	Decimal	EBULK(1,1) = bulk modulus at PBULK(1) and TBULK(1) (lb/in.**2)
	13-24	Decimal	EBULK(2,1)
	25-36	Decimal	
	37-48	Decimal	

Card	Column	Format	Variable and Definition
24 (cont.)			
	49-60	Decimal	
	61-72	Decimal	EBULK(I,J) = bulk modulus at PBULK(I) and TBULK(J)

Input for parallel piston case.

Delete cards 25-39 if IBAL = 1 indicating series piston case.

Card	Column	Format	Variable and Definition
25	1-12	Decimal	RH1 = outer radius of high-pressure side inner pocket (in.)
	13-24	Decimal	RH2 = inner radius of high-pressure side inner land (in.)
	25-36	Decimal	RH3 = outer radius of high-pressure side inner land (in.)
	37-48	Decimal	RH4 = inner radius of high-pressure side inner pocket (in.)
	49-60	Decimal	RH5 = outer radius of high-pressure side outer pocket (in.)
	61-72	Decimal	RH6 = inner radius of high-pressure side outer land (in.)
26	1-12	Decimal	RH7 = outer radius of high-pressure side outer land (in.)
	13-24	Decimal	RH8 = inner radius of high-pressure side outer annulus (in.)
	25-36	Decimal	RH9 = labyrinth outer radius on high-pressure side (in.)
	37-48	Decimal	RL1 = outer radius of low-pressure side inner pocket (in.)
	49-60	Decimal	RL2 = inner radius of low-pressure side inner land (in.)
	61-72	Decimal	RL3 = outer radius of low-pressure side inner land (in.)
27	1-12	Decimal	RL4 = inner radius of low-pressure side inner pocket (in.)
	13-24	Decimal	RL5 = outer radius of low-pressure side outer procket (in.)

Card	Column	Format	Variable and Definition
27 (cont.)			
	25-36	Decimal	RL6 = inner radius of low-pressure side outer land (in.)
	37-48	Decimal	RL7 = outer radius of low-pressure side outer land (in.)
	49-60	Decimal	RL8 = inner radius of low-pressure side outer pocket (in.)
	61-72	Decimal	RL9 = outer radius of labyrinth on low-pressure side (in.)
28	1-12	Decimal	RHP = radius of high-pressure pocket at orifice (in.)
	13-24	Decimal	RLP = radius of low-pressure pocket at orifice (in.)
	25-36	Decimal	RHANN = outer annulus radius on high-pressure side (in.)
	37-48	Decimal	RLANN = outer annulus radius on low-pressure side (in.)
	49-60	Decimal	RSD = shaft labyrinth outlet shaft radius (in.)
	61-72	Decimal	RSDH = shaft labyrinth outlet housing radius (in.)
29	1-12	Decimal	RH1S = high-pressure side shaft radius (in.)
	13-24	Decimal	RL1S = low-pressure side shaft radius (in.)
	25-36	Decimal	RR1 = return line radius of low-pressure inner land (in.)
30	1-12	Decimal	HH1S = high-pressure side shaft clearance (in.)
	13-24	Decimal	HL1S = low-pressure side shaft clearance (in.)
	25-36	Decimal	XLL8 = low-pressure cavity length (in.)
	37-48	Decimal	XLH8 = high-pressure cavity length (in.)
31	1-12	Decimal	DHSHP = high-pressure orifice diameter (in.)
	13-24	Decimal	DLSLP = low-pressure orifice diameter (in.)
	25-36	Decimal	CHSHP = high-pressure orifice discharge coefficient
	37-48	Decimal	CLSLP = low-pressure orifice discharge coefficient

Card	Column	Format	Variable and Definition
31 (cont.)			
	49-60	Decimal	DHS = diameter of high-pressure supply line (in.)
	61-72	Decimal	DLS = diameter of low-pressure supply line (in.)
32	1-12	Decimal	PHS = high-pressure supply pressure (lb/in.**2)
	13-24	Decimal	PLS = low-pressure supply pressure (lb/in.**2)
	25-36	Decimal	PB1R1 = exit pressure (lb/in.**2)
	37-48	Decimal	PSD = shaft labyrinth pressure (lb/in.**2)
	49-60	Decimal	THS = high-pressure supply temperature (°R)
	61-72	Decimal	TLS = low-pressure supply temperature (°R)
33	1-12	Decimal	XNHSHP = number of high-pressure orifices
	13-24	Decimal	XNLSLP = number of low-pressure orifices
	25-36	Decimal	CH5H6 = flow coefficient for outward flow sill entrance loss on high-pressure side
	37-48	Decimal	CH7H8 = flow coefficient for outward flow sill exit loss on high-pressure side
	49-60	Decimal	CH4H3 = flow coefficient for inward flow sill entrance loss on high-pressure side
	61-72	Decimal	CH2H1 = flow coefficient for inward flow sill exit loss on high-pressure side
34	1-12	Decimal	CL5L6 = flow coefficient for low-pressure outward flow sill entrance loss
	13-24	Decimal	CL7L8 = flow coefficient for low-pressure outward flow sill exit loss
	25-36	Decimal	CL4L3 = flow coefficient for low-pressure inward flow sill entrance loss
	37-48	Decimal	CL2L1 = flow coefficient for low-pressure inward flow sill exit loss
35	1-12	Decimal	HL1SD = shaft labyrinth tooth clearance (in.)
	13-24	Decimal	HEL1SD = shaft labyrinth valley depth (in.)
	25-36	Decimal	XLL1SD = shaft labyrinth over-all length (in.)
	37-48	Decimal	XNL1SD = number of shaft labyrinth sealing points

Card	Column	Format	Variable and Definition
35 (cont.)			
	49-60	Decimal	PL1SD = shaft labyrinth pitch (in.)
	61-72	Decimal	XL1SD = shaft labyrinth sealing point width (in.)
36	1-12	Decimal	CL1SD = shaft labyrinth discharge coefficient
	13-24	Decimal	XNH1R1 = number of high-pressure return lines
	25-36	Decimal	XLH1R1 = length of high-pressure return lines (in.)
	37-48	Decimal	XNL1R1 = number of low-pressure return lines
	49-60	Decimal	XLL1R1 = length of low-pressure return lines (in.)
37	1-12	Decimal	XNH8R1 = number of return lines of outer annulus
	13-24	Decimal	XLH8R1 = length of return lines (in.)
	25-36	Decimal	RH8R1 = radius of return lines (in.)

If IKIN (card 2) = 0, delete cards 38 and 39

Card	Column	Format	Variable and Definition
38	1-12	Decimal	XKHPH5 = fluid rotation factor between pocket at orifice and inner radius of outer pocket on high-pressure side
	13-24	Decimal	XKH6H7 = fluid rotation factor between outer land inner and outer radius on high-pressure side
	25-36	Decimal	XKHPH4 = fluid rotation factor between pocket at orifice and outer radius of inner pocket on high-pressure side
	37-48	Decimal	XKH3H2 = fluid rotation factor between inner land inner and outer radius on high-pressure side
	49-60	Decimal	XKLPL5 = fluid rotation factor between pocket at orifice and inner radius of outer pocket on low-pressure side
	61-72	Decimal	XKL6L7 = fluid rotation factor between outer land inner and outer radius on low-pressure side

Card	Column	Format	Variable and Definition
39	1-12	Decimal	XKLPL4 = fluid rotation factor between pocket at orifice and outer radius of inner pocket on low-pressure side
	13-24	Decimal	XKL3L2 = fluid rotation factor between inner land inner and outer radius on low-pressure side

SERIES PISTON CASE

Delete cards 40-50 if IBAL = 0 indicating parallel piston case

Card	Column	Format	Variable and Definition
40	1-12	Decimal	RL1 = outer radius of low-pressure side inner pocket (in.)
	13-24	Decimal	RL2 = inner radius of low-pressure side inner land (in.)
	25-36	Decimal	RL3 = outer radius of low-pressure side inner land (in.)
	37-48	Decimal	RL4 = inner radius of low-pressure side pocket (in.)
	49-60	Decimal	RL8 = outer radius of low-pressure side pocket (in.)
	61-72	Decimal	RL9 = outer radius of labyrinth on low-pressure side (in.)
41	1-12	Decimal	RH5 = outer radius of high-pressure side outer pocket (in.)
	13-24	Decimal	RH6 = inner radius of high-pressure side outer land (in.)
	25-36	Decimal	RH7 = outer radius of high-pressure side outer land (in.)
	37-48	Decimal	RH8 = inner radius of high-pressure side outer annulus (in.)
	49-60	Decimal	RH9 = labyrinth outer radius on high-pressure side (in.)
	61-72	Decimal	RSD = shaft labyrinth outlet shaft radius (in.)
42	1-12	Decimal	RHP = radius of high-pressure pocket at orifice (in.)
	13-24	Decimal	RHANN = outer annulus radius on high-pressure side (in.)

Card	Column	Format	Variable and Definition
43	1-12	Decimal	RHCL = inner radius for high-pressure inner pocket
	13-24	Decimal	RSDH = shaft labyrinth outlet housing radius (in.)
	25-36	Decimal	HH9 = high-pressure outer cavity clearance (in.)
	37-48	Decimal	HL9 = low-pressure outer cavity clearance (in.)
	49-60	Decimal	HSD = sealing discharge outlet clearance (in.)
44	1-12	Decimal	HL1S = low-pressure side shaft clearance (in.)
	13-24	Decimal	HL1SD = shaft labyrinth tooth clearance (in.)
	25-36	Decimal	HEL1SD = shaft labyrinth valley depth (in.)
	37-48	Decimal	XLL1SD = shaft labyrinth over-all length (in.)
	49-60	Decimal	XNL1SD = number of shaft labyrinth sealing points
45	1-12	Decimal	PL1SD = shaft labyrinth pitch (in.)
	13-24	Decimal	XL1SD = shaft labyrinth sealing point width (in.)
	25-36	Decimal	CL1SD = shaft labyrinth discharge coefficient
	37-48	Decimal	HH9L9 = piston labyrinth tooth clearance (in.)
	49-60	Decimal	HEH9L9 = piston labyrinth valley depth (in.)
	61-72	Decimal	XLH9L9 = piston labyrinth over-all length (in.)
46	1-12	Decimal	XNH9L9 = number of piston labyrinth sealing points
	13-24	Decimal	PH9L9 = piston labyrinth pitch (in.)
	25-36	Decimal	XH9L9 = piston labyrinth sealing point width (in.)
	37-48	Decimal	CH9L9 = piston labyrinth discharge coefficient
	49-60	Decimal	DHSHP = high-pressure orifice diameter (in.)
	61-72	Decimal	CHSHP = high-pressure orifice discharge coefficient

Card	Column	Format	Variable and Definition
47	1-12	Decimal	XNHSHP = number of high-pressure orifices
	13-24	Decimal	PHS = high-pressure supply pressure (lb/in.**2)
	25-36	Decimal	PBPR1 = exit pressure (lb/in.**2)
	37-48	Decimal	PSD = shaft labyrinth pressure (lb/in.**2)
	49-60	Decimal	DHS = high-pressure supply line diameter (in.)
48	1-12	Decimal	CH5H6 = flow coefficient for high-pressure sill entrance flow
	13-24	Decimal	CH7H8 = flow coefficient for high-pressure sill exit flow
	25-36	Decimal	CL7L8 = flow coefficient for low-pressure inner flow sill entrance loss
	37-48	Decimal	CL4L3 = flow coefficient for low-pressure inward flow sill entrance loss
	49-60	Decimal	CL2L1 = flow coefficient for low-pressure inward flow sill exit loss
49	1-12	Decimal	XNL1R1 = number of low-pressure return lines
	13-24	Decimal	XLL1R1 = length of low-pressure return lines (in.)
	25-36	Decimal	WHPH1S = high-pressure inner procket flow-rate (lb/sec)
	37-48	Decimal	THS = high-pressure supply temperature (°R)
	49-60	Decimal	HH8L8 = annulus clearance (in.)
	61-72	Decimal	XLH8L8 = annulus length (in.)

if KIN = 0 (card 2), delete card 50

Card	Column	Format	Variable and Definition
50	13-24	Decimal	XKH6H7 = fluid rotation factor between outer land and outer radius on high-pressure side
	25-36	Decimal	XKL7L4 = fluid rotation factor for inward pocket flow calculation
	37-48	Decimal	XKL3L2 = fluid rotation factor between inner land inner and outer radius on low-pressure side
	49-60	Decimal	XKHPH1 = fluid rotation factor between pocket at orifice and inner radius of inner pocket on high-pressure side

Card	Column	Format	Variable and Definition
FORCE PISTON			
51	1-12	Decimal	NFS = number of force piston supply pressure increments (maximum 20)
	13-24	Decimal	PFSMIN = minimum force piston supply pressure (lb/in.**2)
	25-36	Decimal	PFSMAX = maximum force piston supply pressure (lb/in.**2)
	37-48	Decimal	PC2 = force piston cavity pressure (lb/in.**2)
	49-60	Decimal	PEXH = force piston turbine pressure (lb/in.**2)
	61-72	Decimal	PFPR1 = force piston return pressure (lb/in.**2)
52	1-12	Decimal	XNFSFP = number of orifices
	13-24	Decimal	DFSFP = orifice diameter (in.)
	25-36	Decimal	CFSFP = orifice discharge coefficient
	37-48	Decimal	TFS = force piston supply temperature (°F)
	49-60	Decimal	DFS = supply line diameter (in.)
	61-72	Decimal	C12 = force piston pocket pressure approximation factor
53	1-12	Decimal	RFP = inner pocket radius at orifice (in.)
	13-24	Decimal	RF1 = outer pocket radius (in.)
	25-36	Decimal	RFTS = turbine radius at seal (in.)
	37-48	Decimal	HFP = axial clearance at inner pocket diameter (in.)
	49-60	Decimal	HF1 = axial clearance at outer pocket diameter (in.)
54	1-12	Decimal	HF1C1 = first labyrinth clearance (in.)
	13-24	Decimal	HEF1C1 = first labyrinth pocket depth (in.)
	25-36	Decimal	XLF1C1 = first labyrinth length (in.)
	37-48	Decimal	XNF1C1 = number of first labyrinth lands
	49-60	Decimal	PF1C1 = first labyrinth pitch (in.)
	61-72	Decimal	XF1C1 = first labyrinth land width (in.)

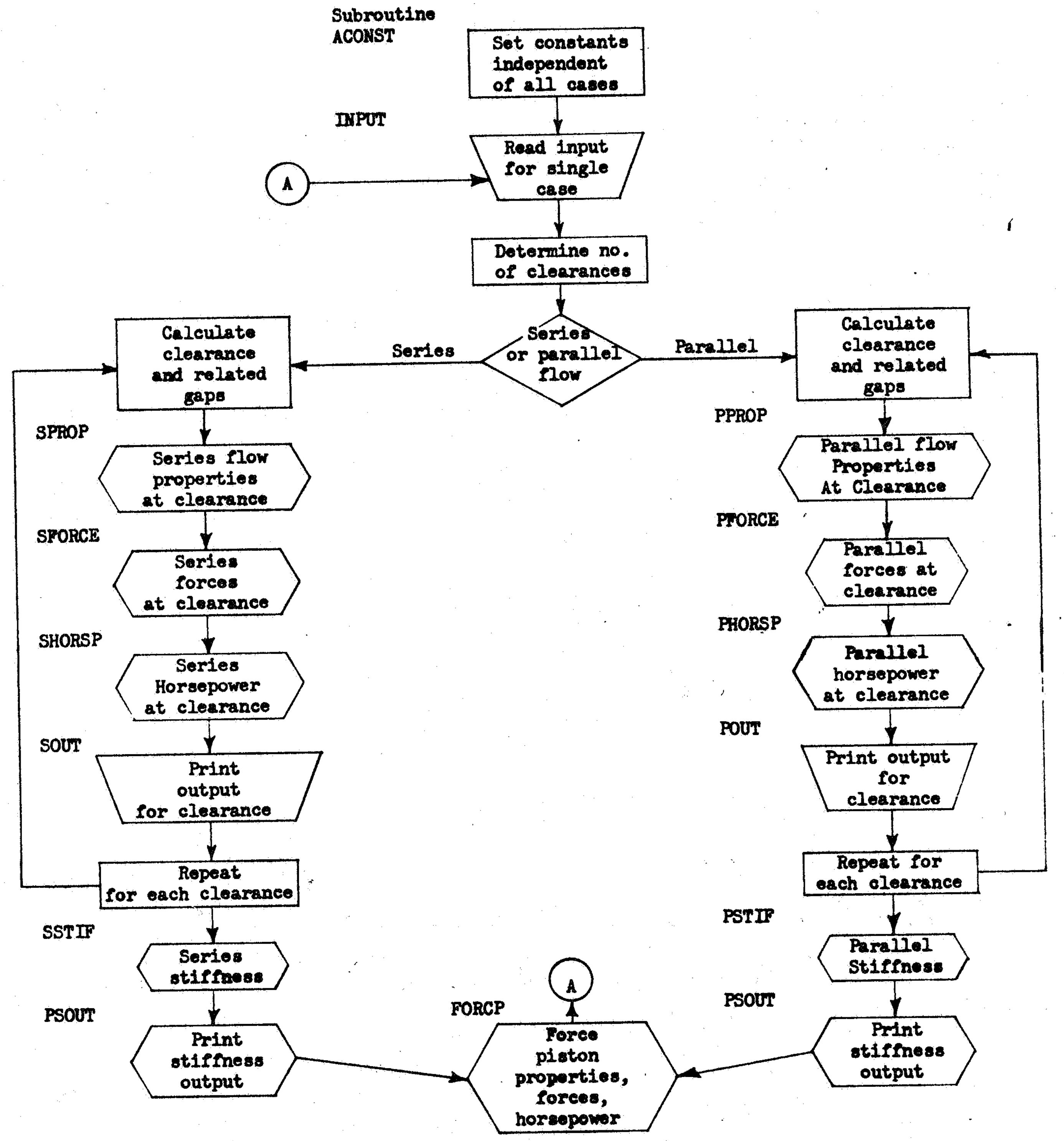
Card	Column	Format	Variable and Definition
55	1-12	Decimal	HC1C2 = second labyrinth clearance (in.)
	13-24	Decimal	HEC1C2 = second labyrinth pocket depth (in.)
	25-36	Decimal	XLC1C2 = second labyrinth length (in.)
	37-48	Decimal	XNC1C2 = number of second labyrinth lands
	49-60	Decimal	PC1C2 = second labyrinth pitch (in.)
	61-72	Decimal	XC1C2 = second labyrinth land width (in.)
56	1-12	Decimal	CF1C1 = first labyrinth discharge coefficient
	13-24	Decimal	CC1C2 = second labyrinth discharge coefficient
	25-36	Decimal	XNC1R1 = number of return lines
	37-48	Decimal	XLC1R1 = return line length (in.)
	49-60	Decimal	RC1R1 = return line radius (in.)

ATTACHMENT B

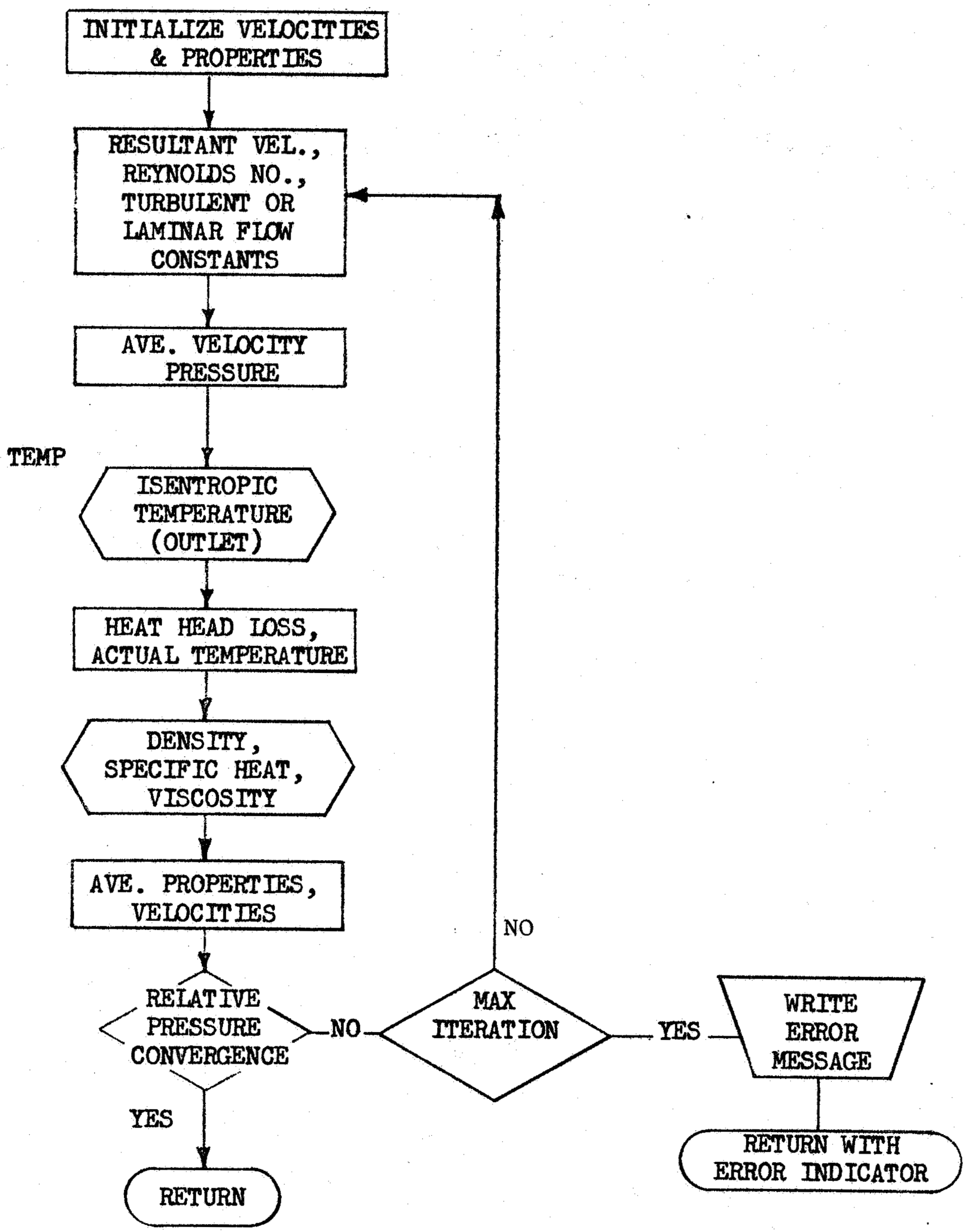
(APPENDIX B)

FLOW CHARTS

MAIN PROGRAM FOR THRUST BALANCER STABILITY PROGRAM

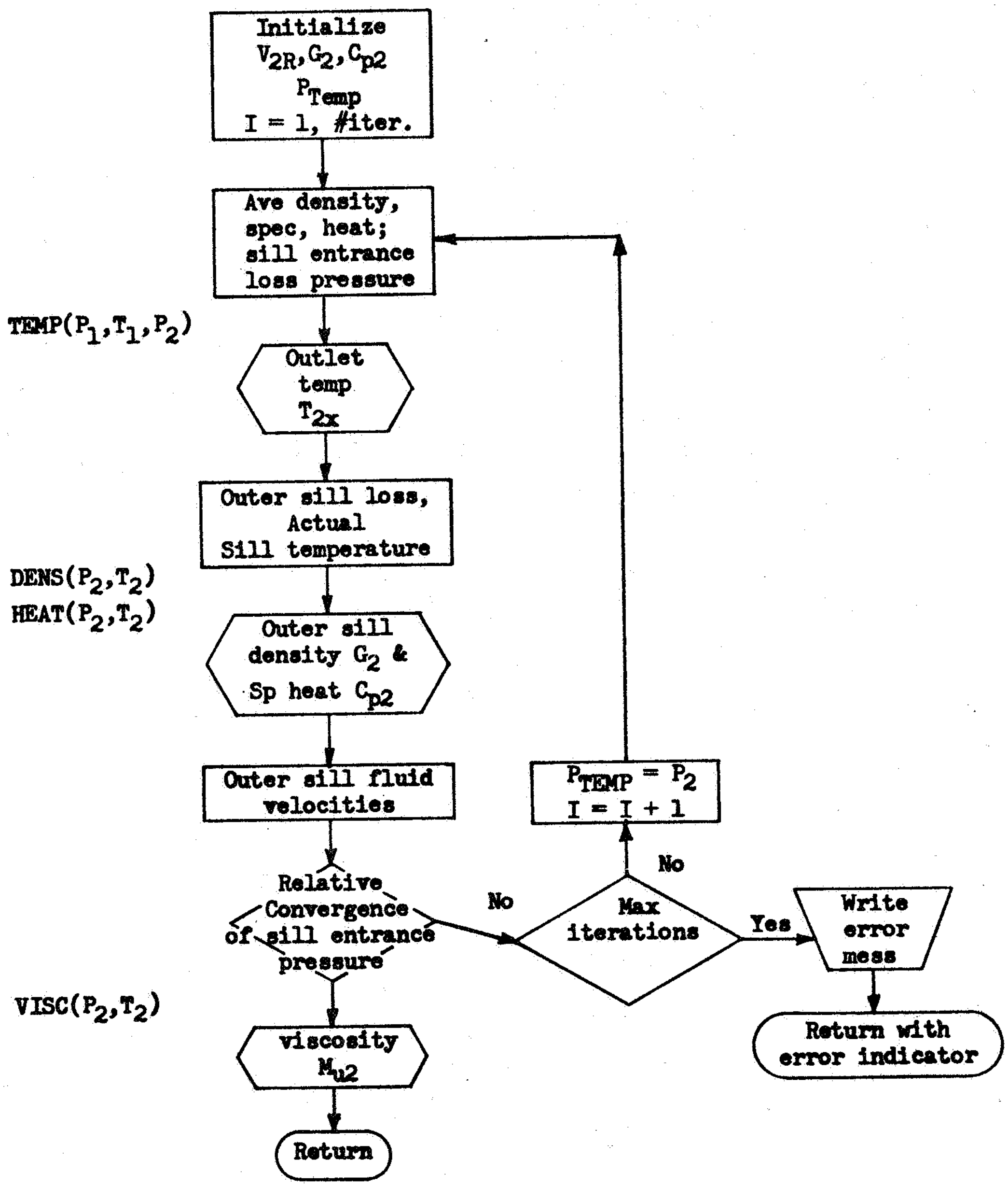


ANNP - ANNULUS FLOW OUTLET PRESSURE CALCULATION

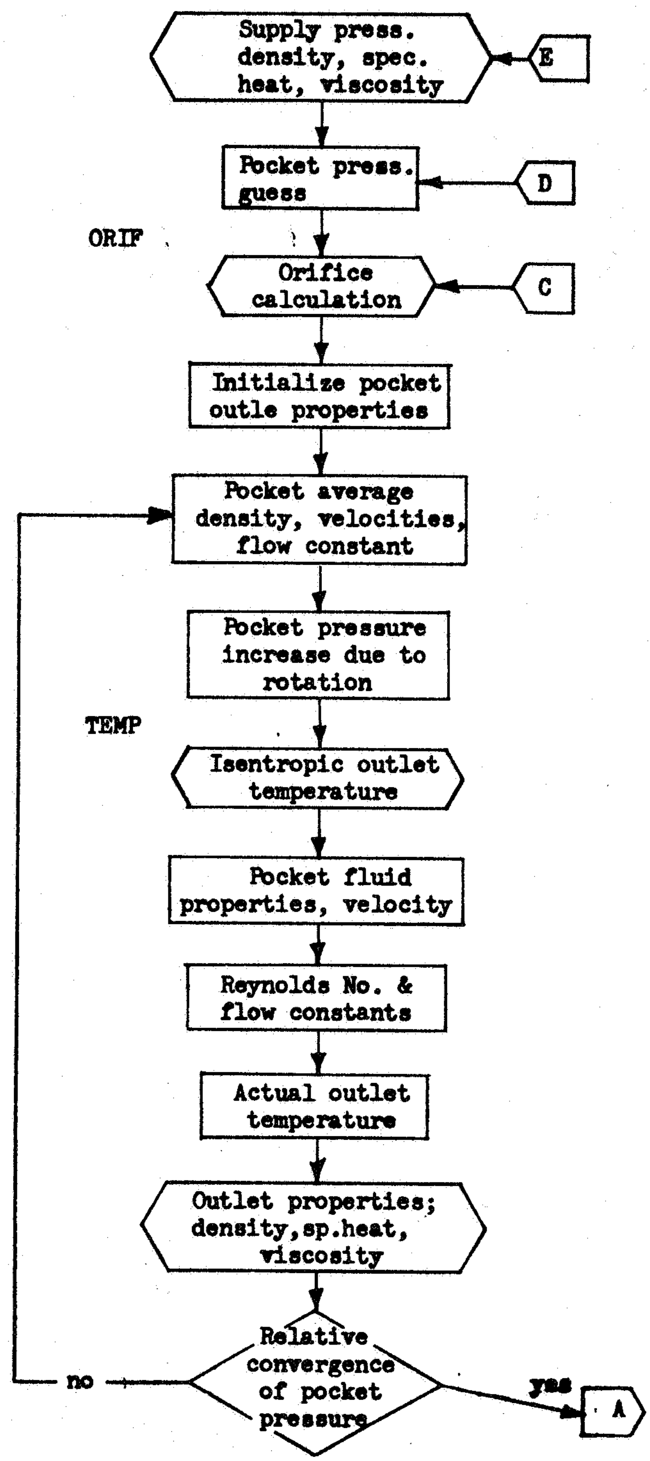


SUBROUTINE ENTS (P_1,$T_1 G_1$,C_{p1},V_{1R},H_1,W_{12}, P_2,T_2, G_2,C_{p2},V_2,V_{2R}, R_2,H_2, M_{u2}, K_1,K_{12},G_{VTY},J,U_{H6F}(=U_2?), ITERE)

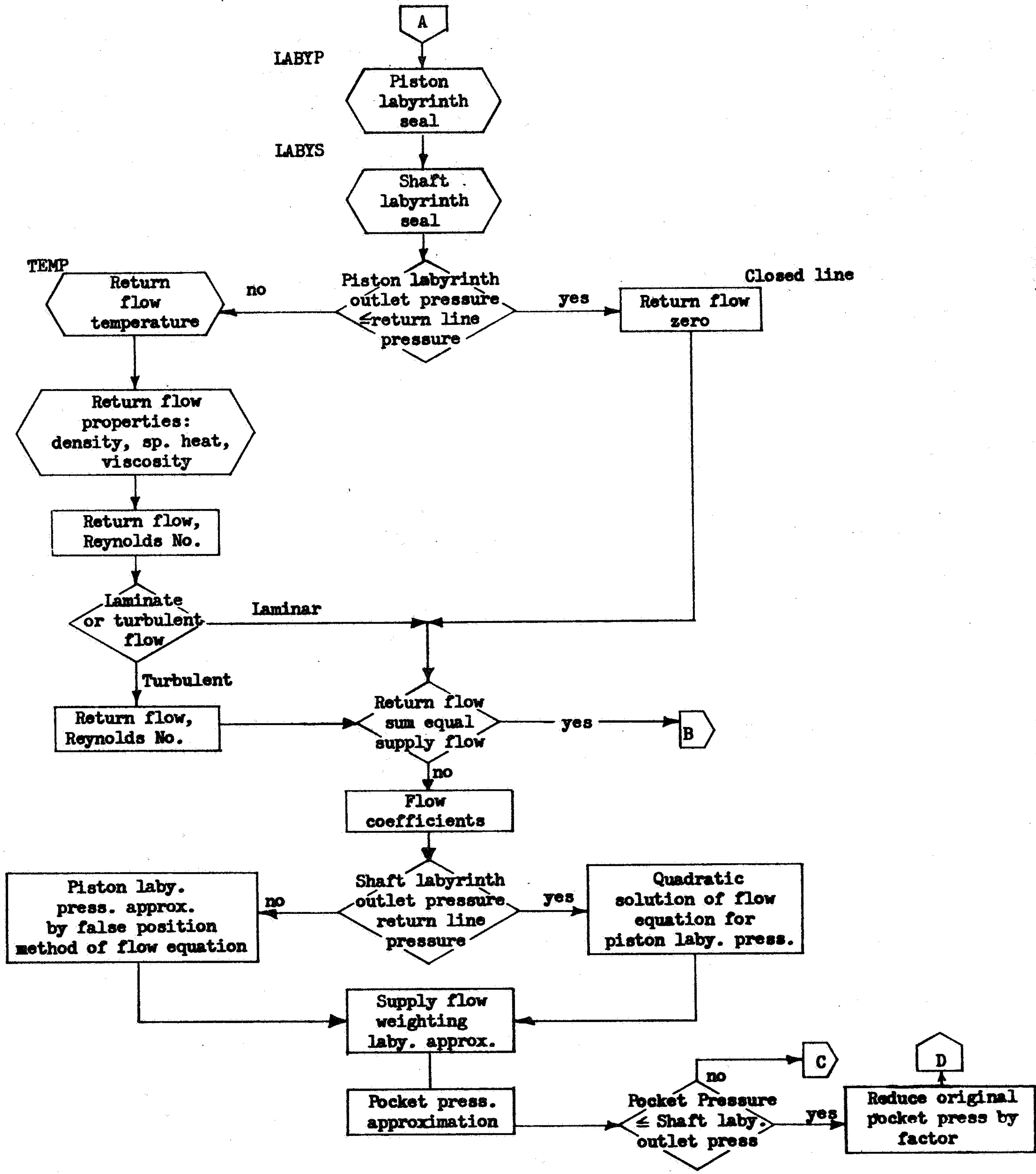
SILL ENTRANCE PRESSURE
CALCULATION



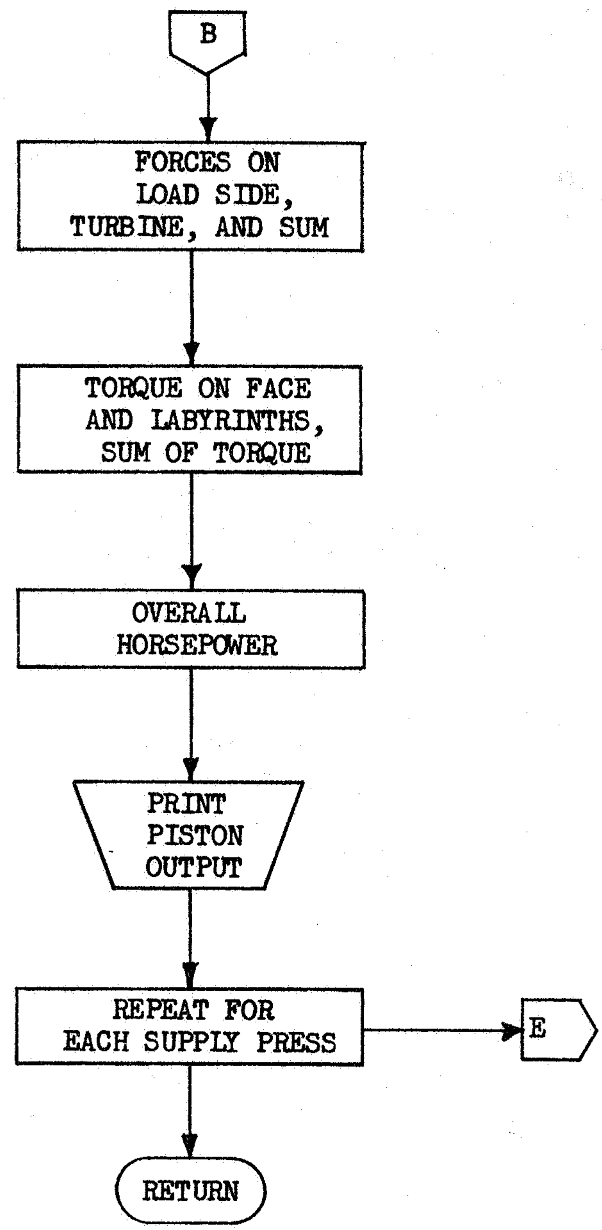
FORCP - FORCE (LOADER) PISTON

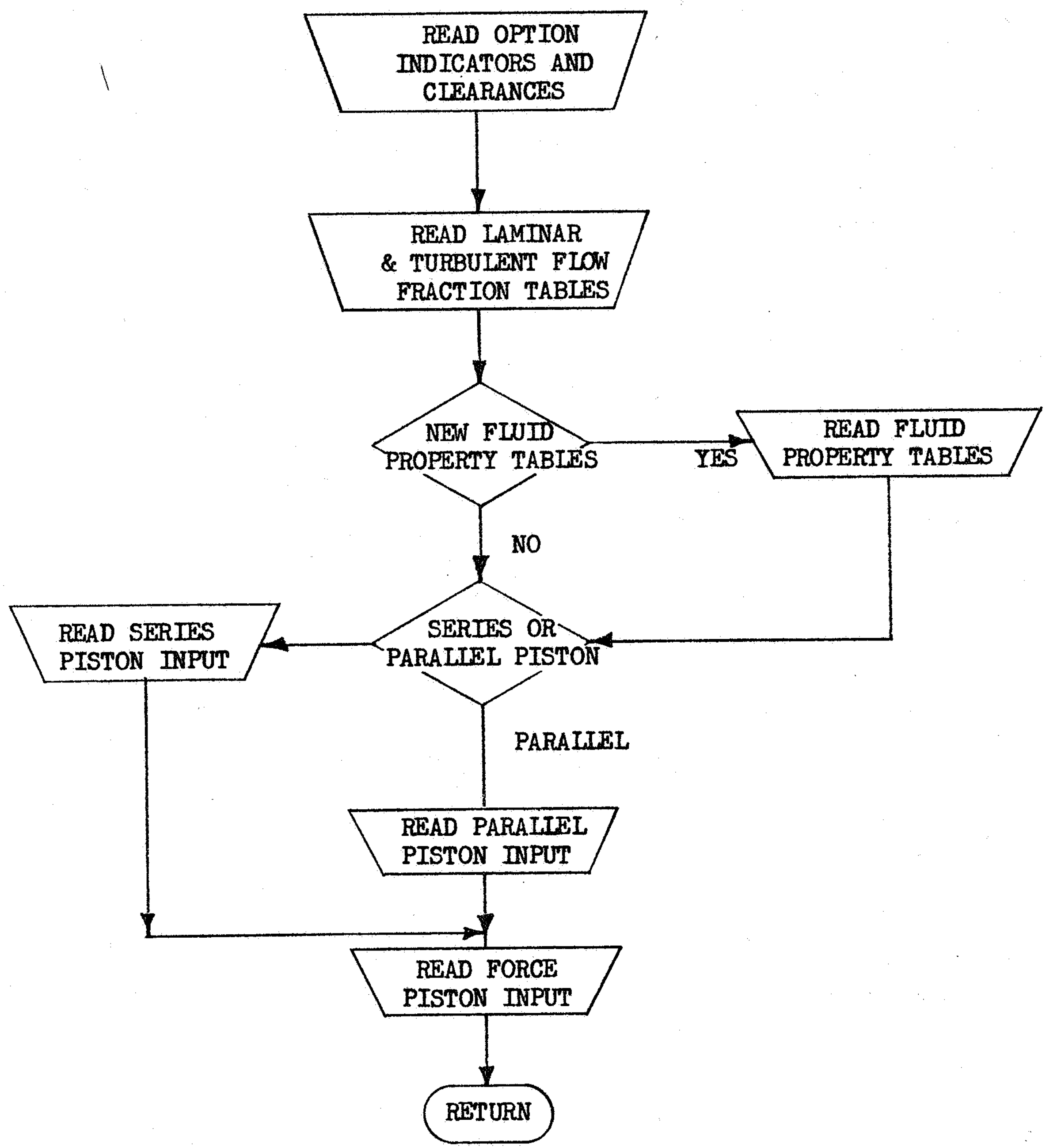


FORCP


A
LABYP
Piston labyrinth seal
LABYS
Shaft labyrinth seal
TEMP
Return flow temperature
no
Piston labyrinth outlet pressure ≤return line pressure
yes
Closed line
Return flow zero
Return flow properties: density, sp. heat, viscosity
Return flow, Reynolds No.
Laminate or turbulent flow
Laminar
Turbulent
Return flow, Reynolds No.
Return flow sum equal supply flow
yes
B
no
Flow coefficients
Piston laby. press. approx. by false position method of flow equation
no
Shaft labyrinth outlet pressure return line pressure
yes
Quadratic solution of flow equation for piston laby. press.
Supply flow weighting laby. approx.
Pocket press. approximation
no
C
Pocket Pressure ≤ Shaft laby. outlet press
yes
D
Reduce original pocket press by factor

FORCP

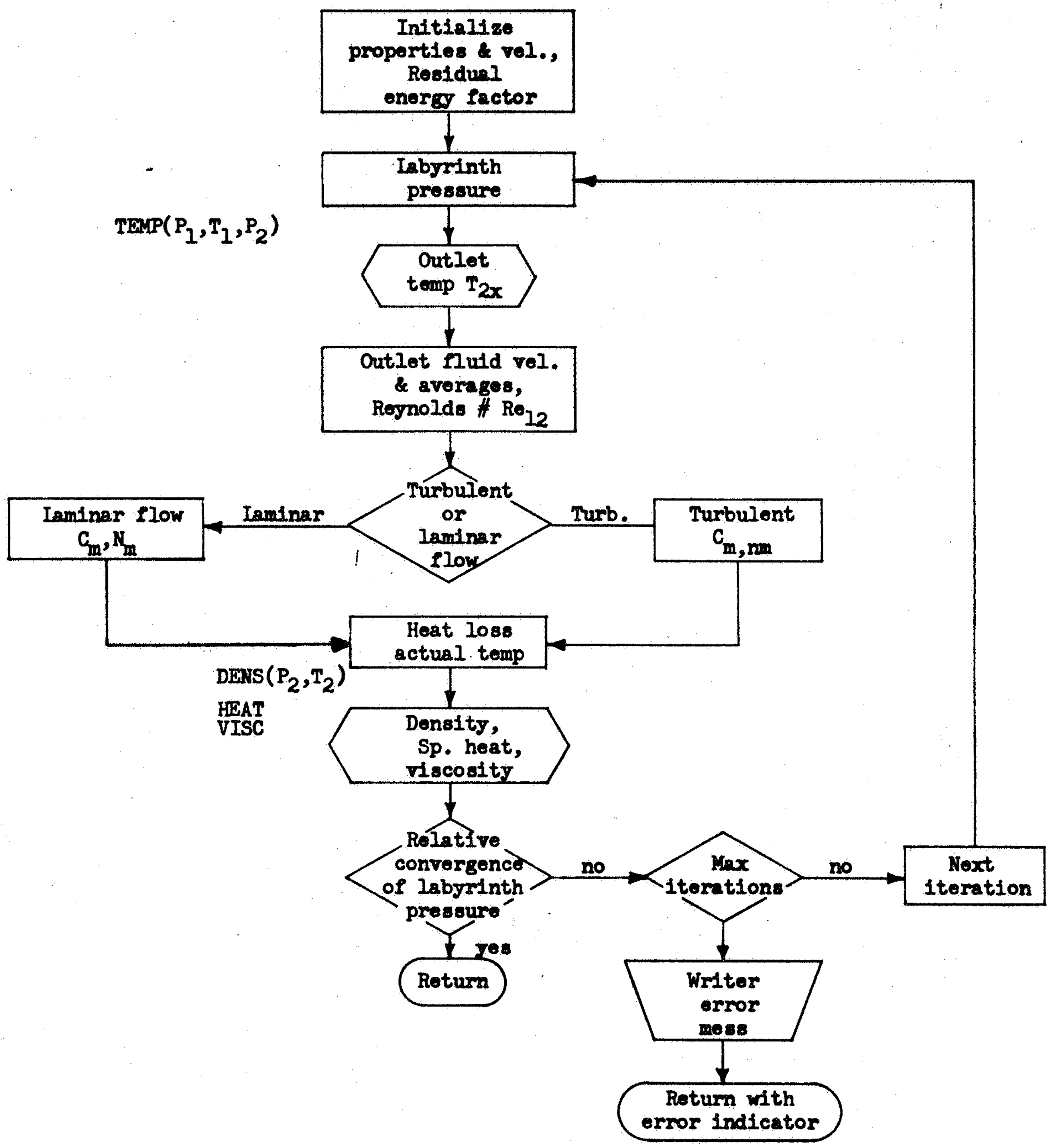

B
FORCES ON LOAD SIDE, TURBINE, AND SUM
TORQUE ON FACE AND LABYRINTHS, SUM OF TORQUE
OVERALL HORSEPOWER
PRINT PISTON OUTPUT
REPEAT FOR EACH SUPPLY PRESS
E
RETURN


READ OPTION INDICATORS AND CLEARANCES
READ LAMINAR & TURBULENT FLOW FRACTION TABLES
NEW FLUID PROPERTY TABLES
YES
READ FLUID PROPERTY TABLES
NO
SERIES OR PARALLEL PISTON
READ SERIES PISTON INPUT
PARALLEL
READ PARALLEL PISTON INPUT
READ FORCE PISTON INPUT
RETURN

SUBROUTINE LABYP ($P_1, T_1, G_1, C_{p_1}, M_{u1}, W_{12}, N_{L12}, P_{L12}, L_{L12}, H_{L121}, C_{12}, C_{MTUR}, C_{MLAM}, N_{MTUR_1}$ $N_{MLAM}, P_{-3_1} H_4$,

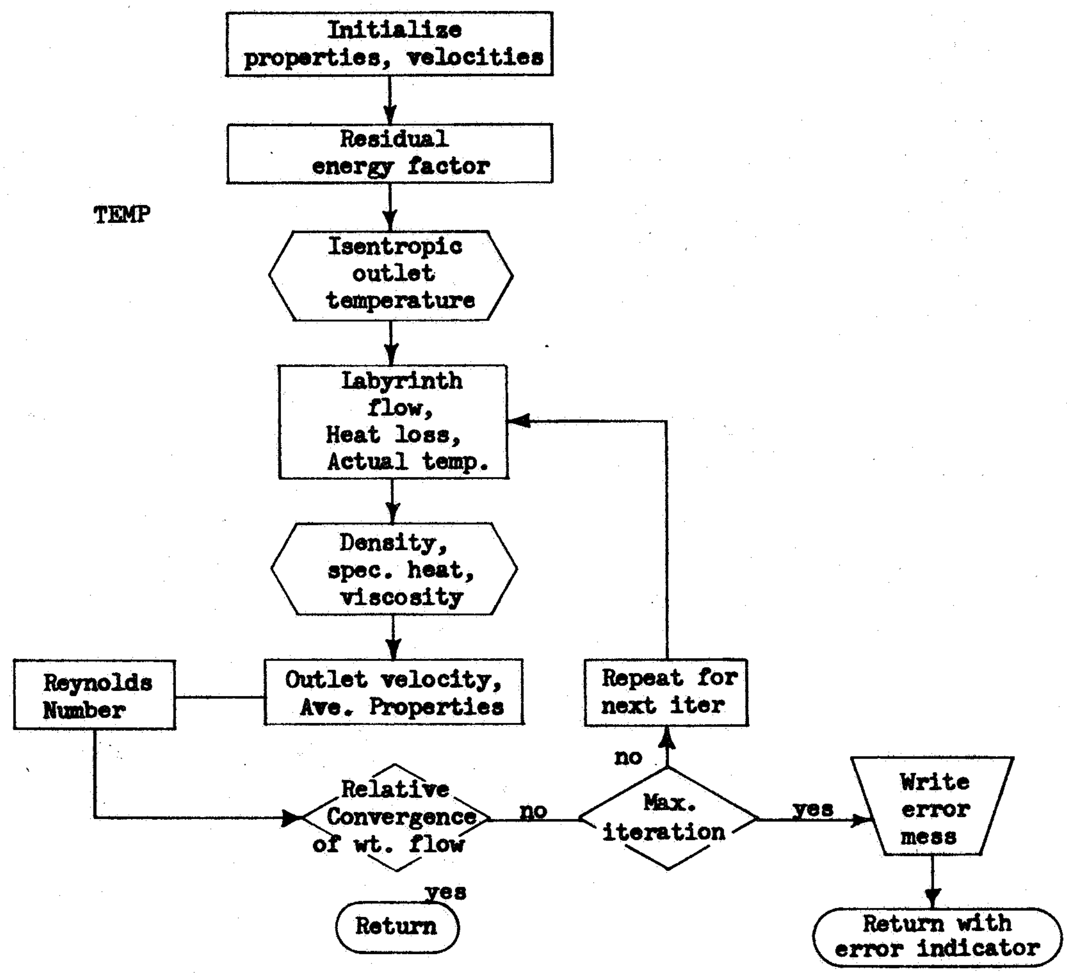
$P_2, T_2, G_2, C_{p_2}, M_{u_2}, V_{R1}, U_{3L}, U_{D3L}$, ITERP

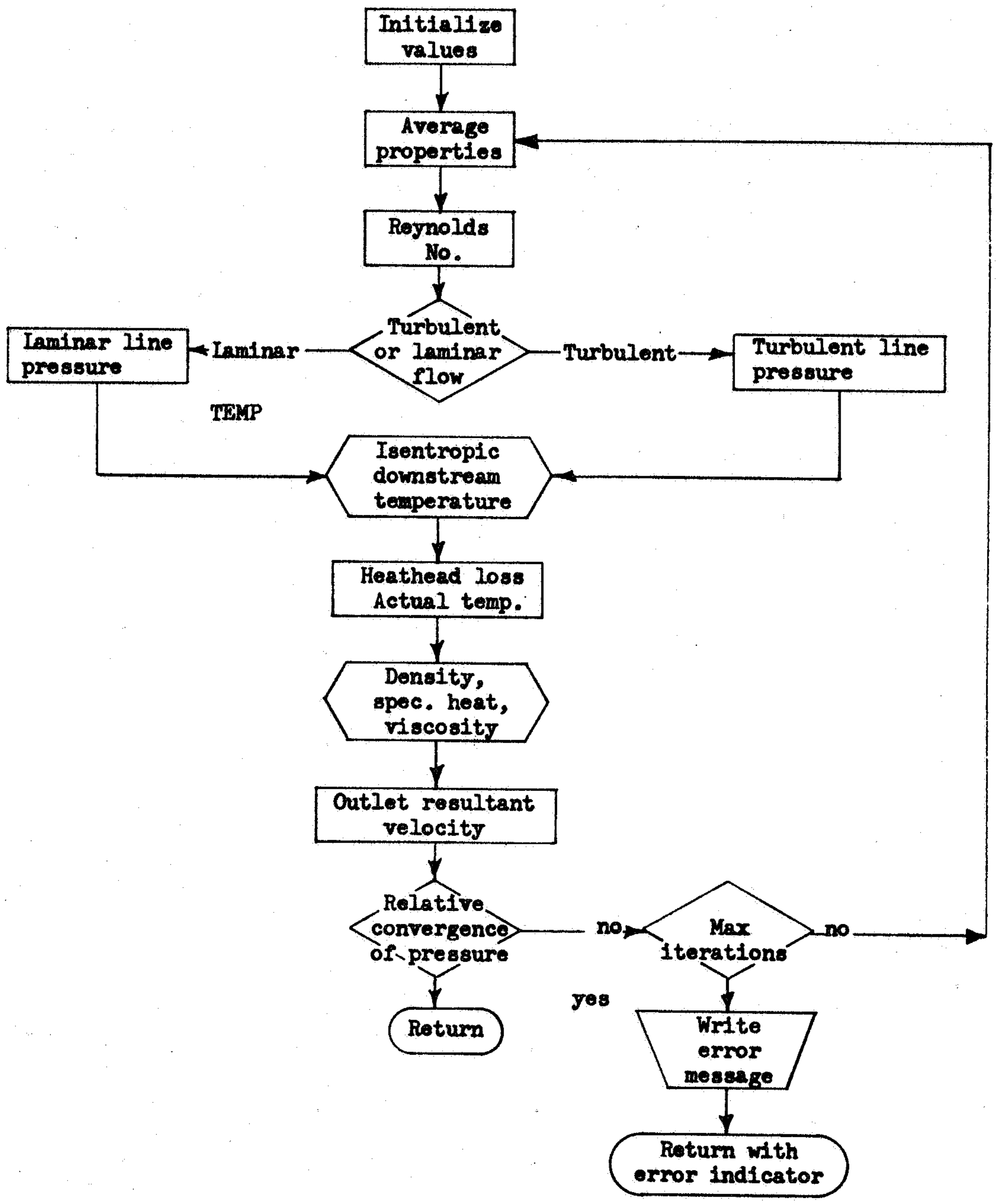
Piston labyrinth pressure calculation



JBROUTINE LABYS ($P_1, T_1, G_1, V_{R_1}, C_{p1}, P_2, T_2, G_2, V_{R_2}, C_{p_2}, W_{12}$ $P_{S12}, L_{S12}, H_{S12}, C_{12}, R_S, N_{S12}, G_{VTY}$, J, ITERL)

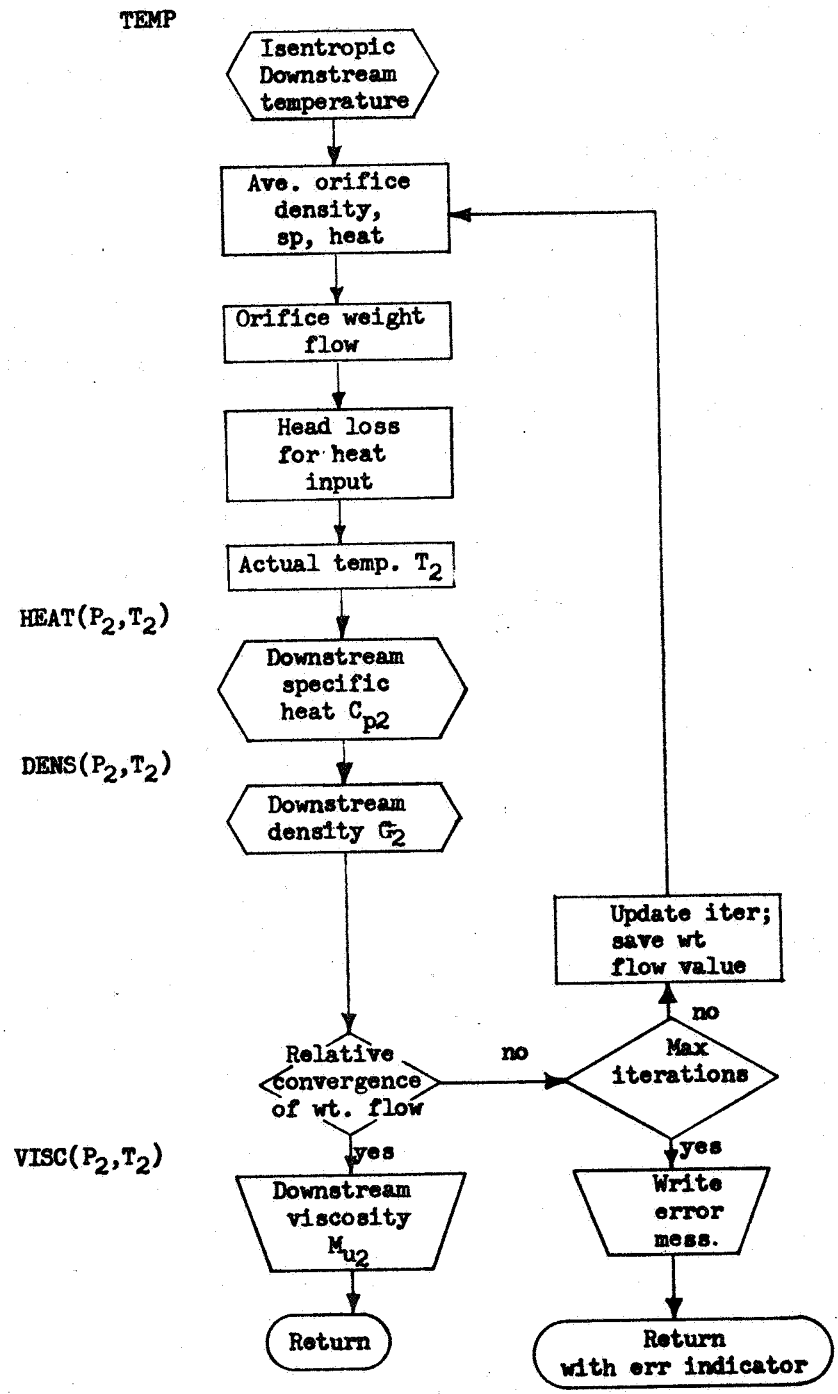
SHAFT LABYRINTH FLOW
CALCULATION GIVEN INLET &
OUTLET PRESSURES



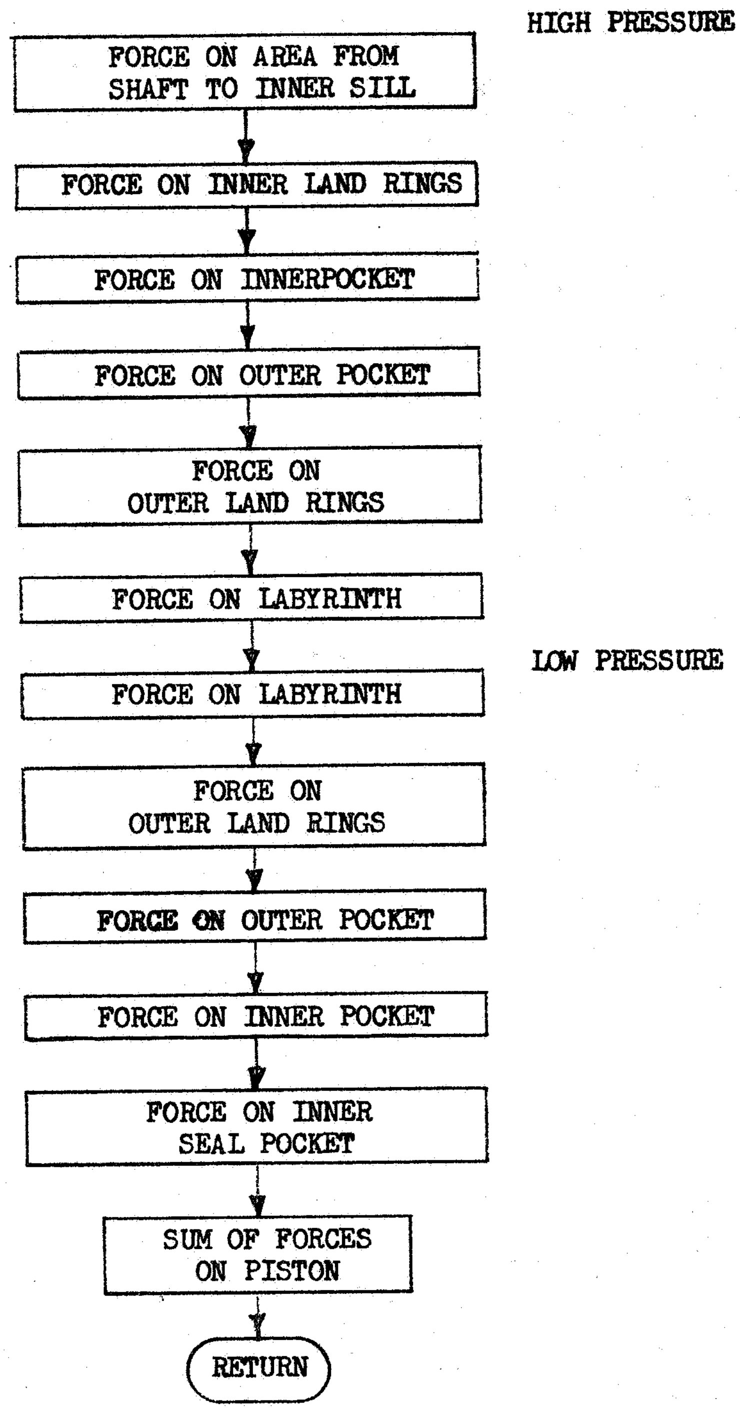

Initialize values
Average properties
Reynolds No.
Turbulent or laminar flow
Laminar
Laminar line pressure
Turbulent
Turbulent line pressure
TEMP
Isentropic downstream temperature
Heathead loss Actual temp.
Density, spec. heat, viscosity
Outlet resultant velocity
Relative convergence of pressure
no
Max iterations
no
yes
Return
Write error message
Return with error indicator

SUBROUTINE ORIF $(P_1, T_1, G_1, W_{12}, P_2, T_2, G_2, C_{p2}, M_{u_2}, N_{10}, C_1, C_2, D_{12}, D_1, R_2, H_2, G_{vty}, J, ITERO)$

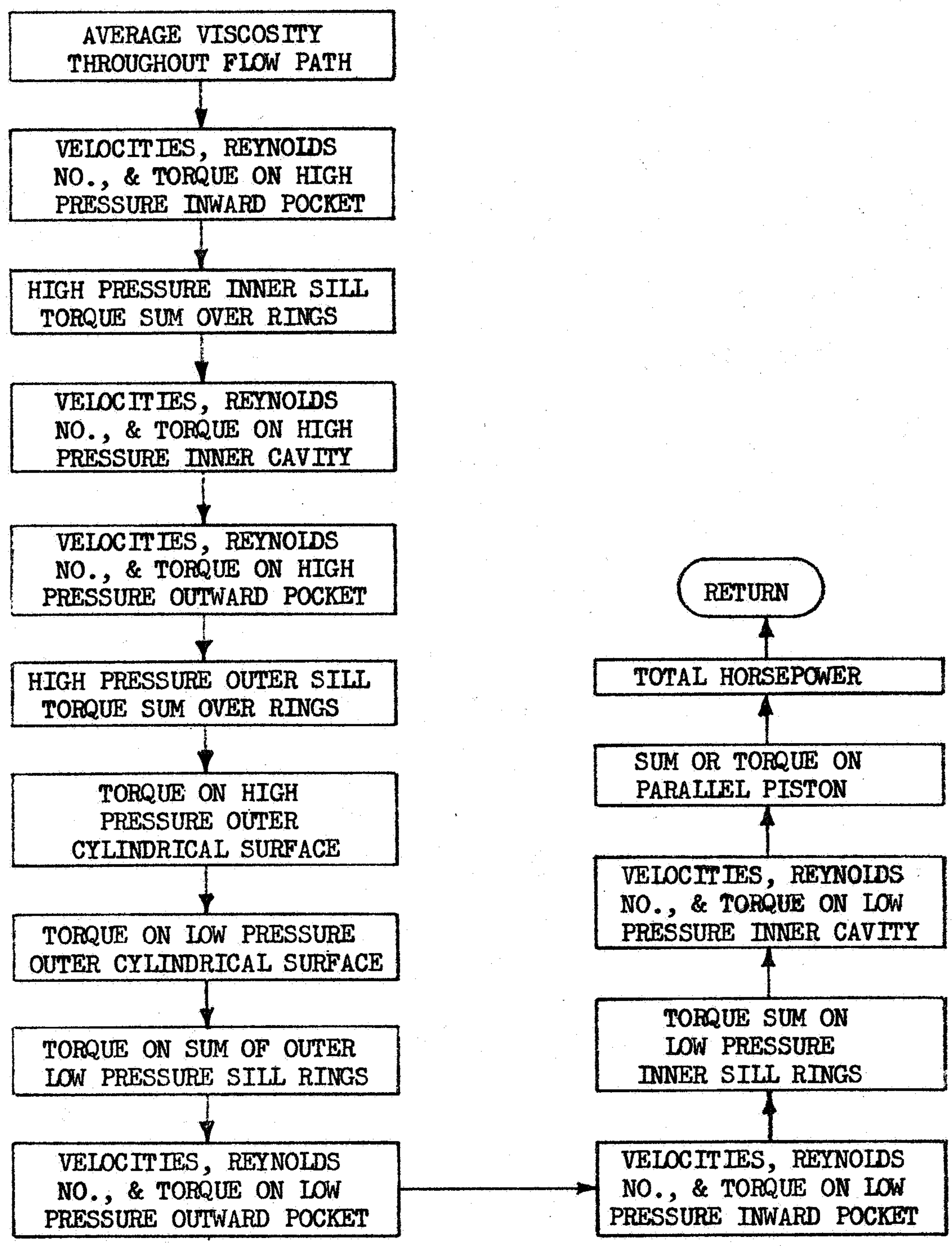
Orifice weight flow
given inlet & outlet
pressures



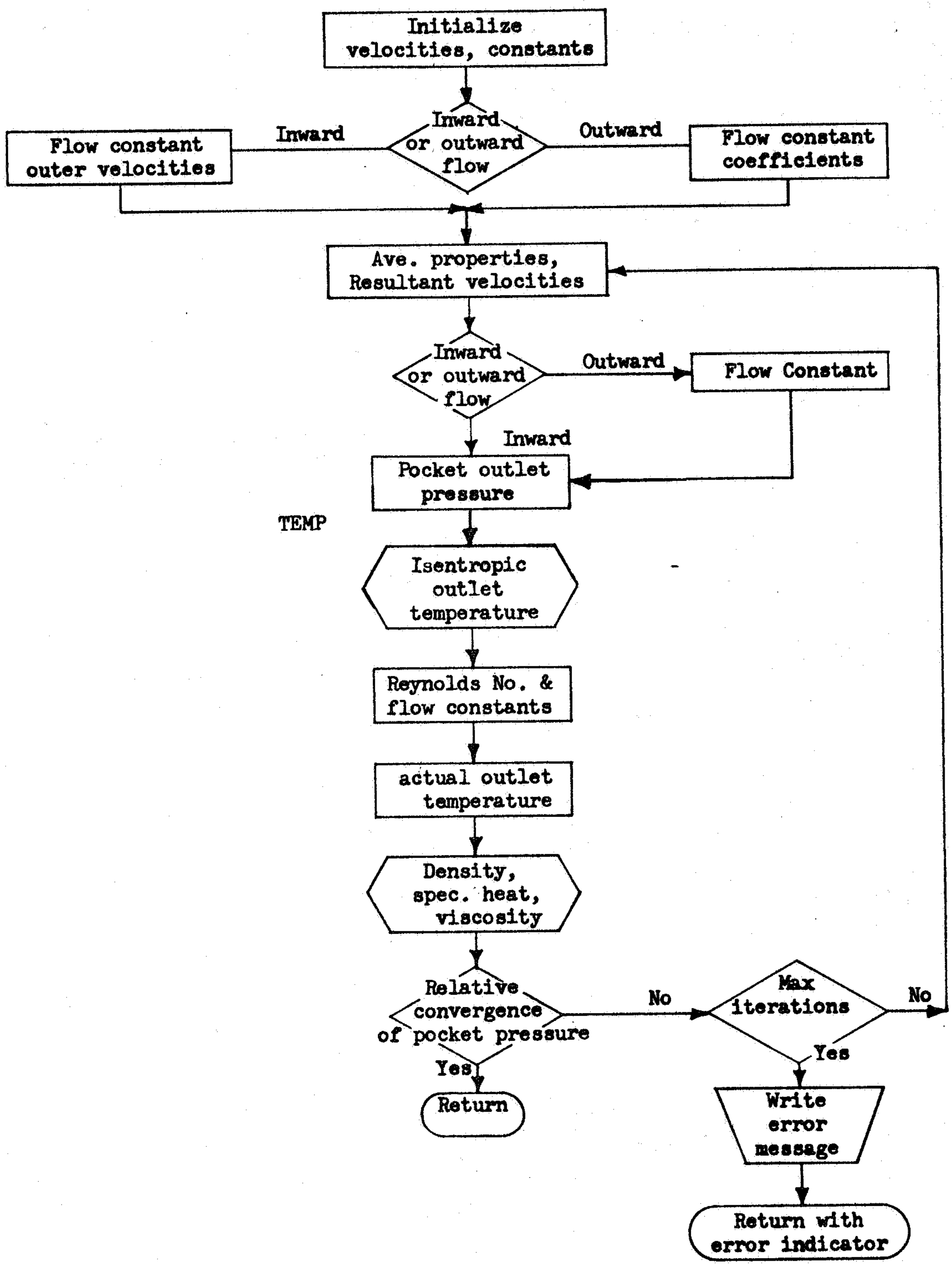
PFORCE - PARRALLEL PISTON FORCE



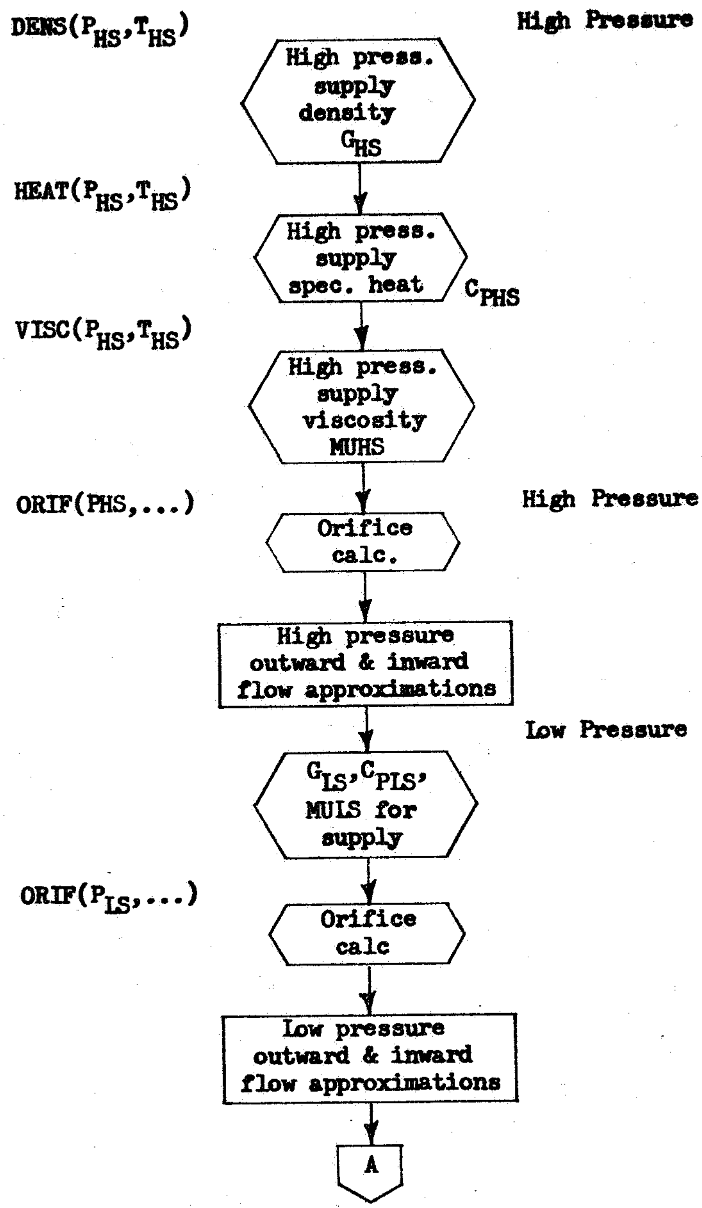
PHORSP - PARALLEL PISTON HORSEPOWER

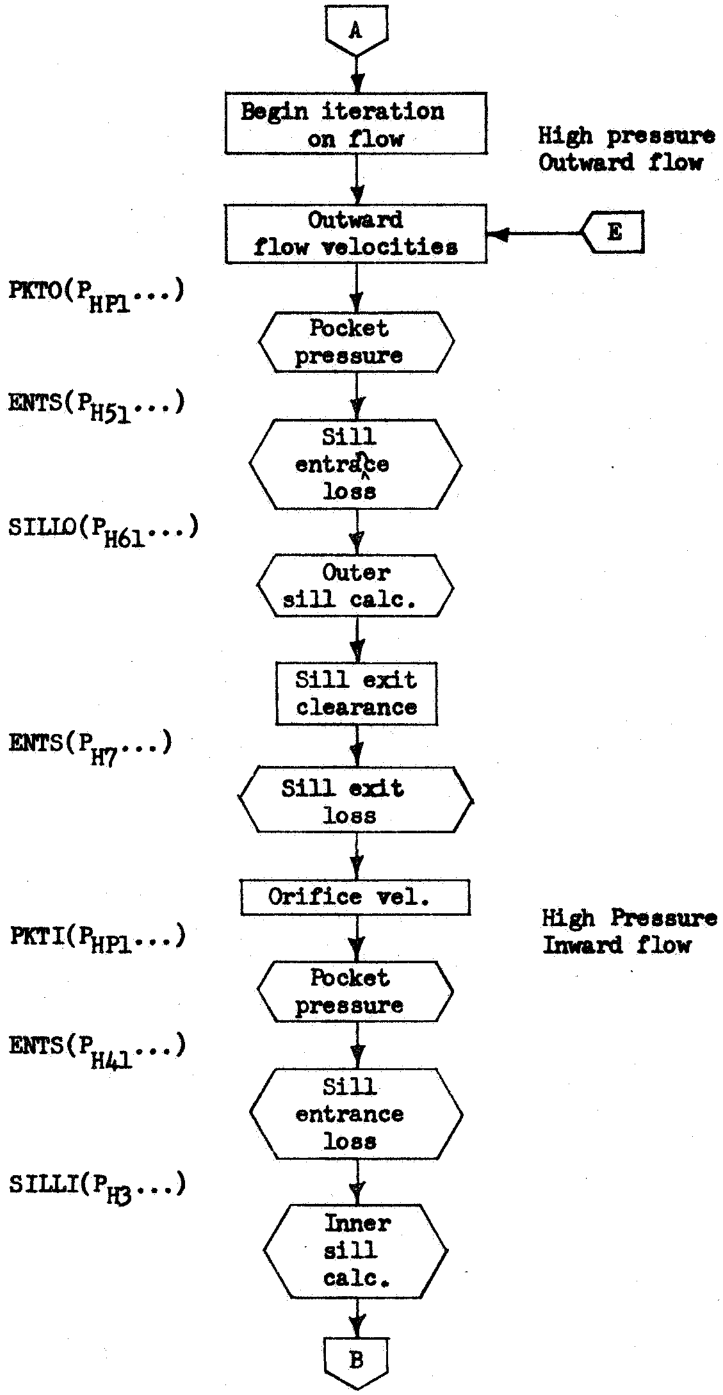


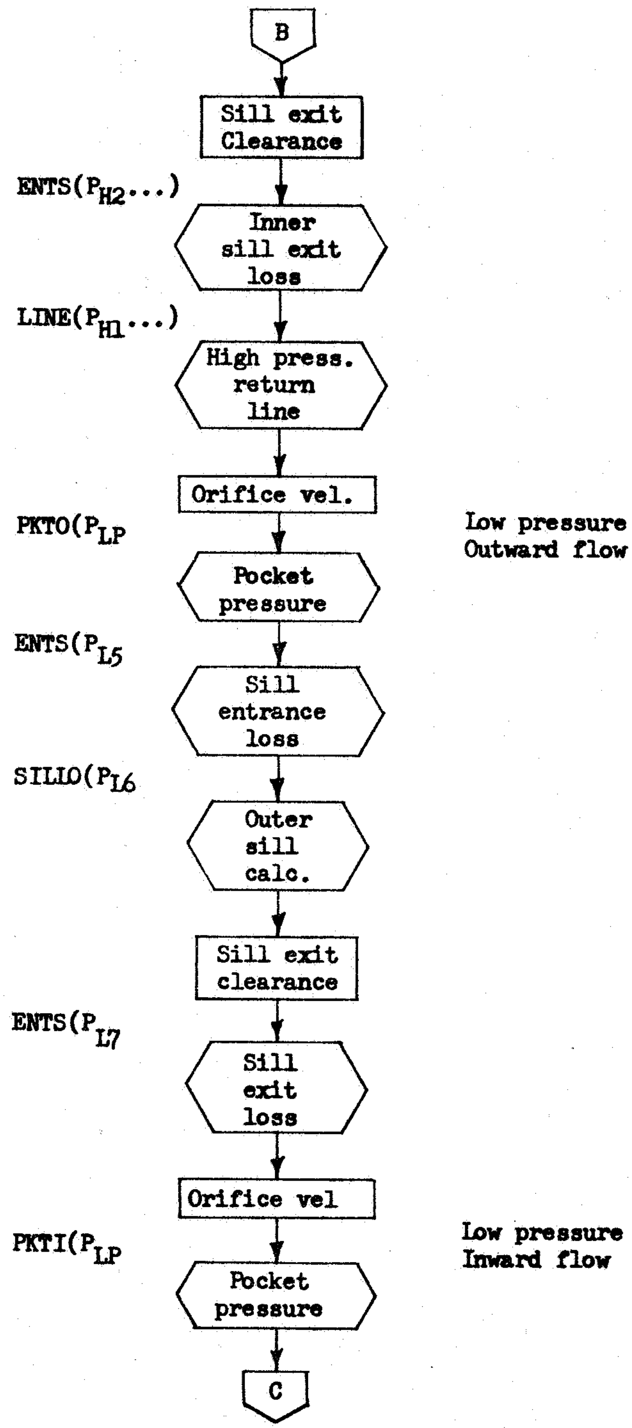
PKT - POCKET OUTLET PRESSURE CALCULATION FOR INWARD
OR OUTWARD FLOW GIVEN INLET PRESSURE AND FLOW



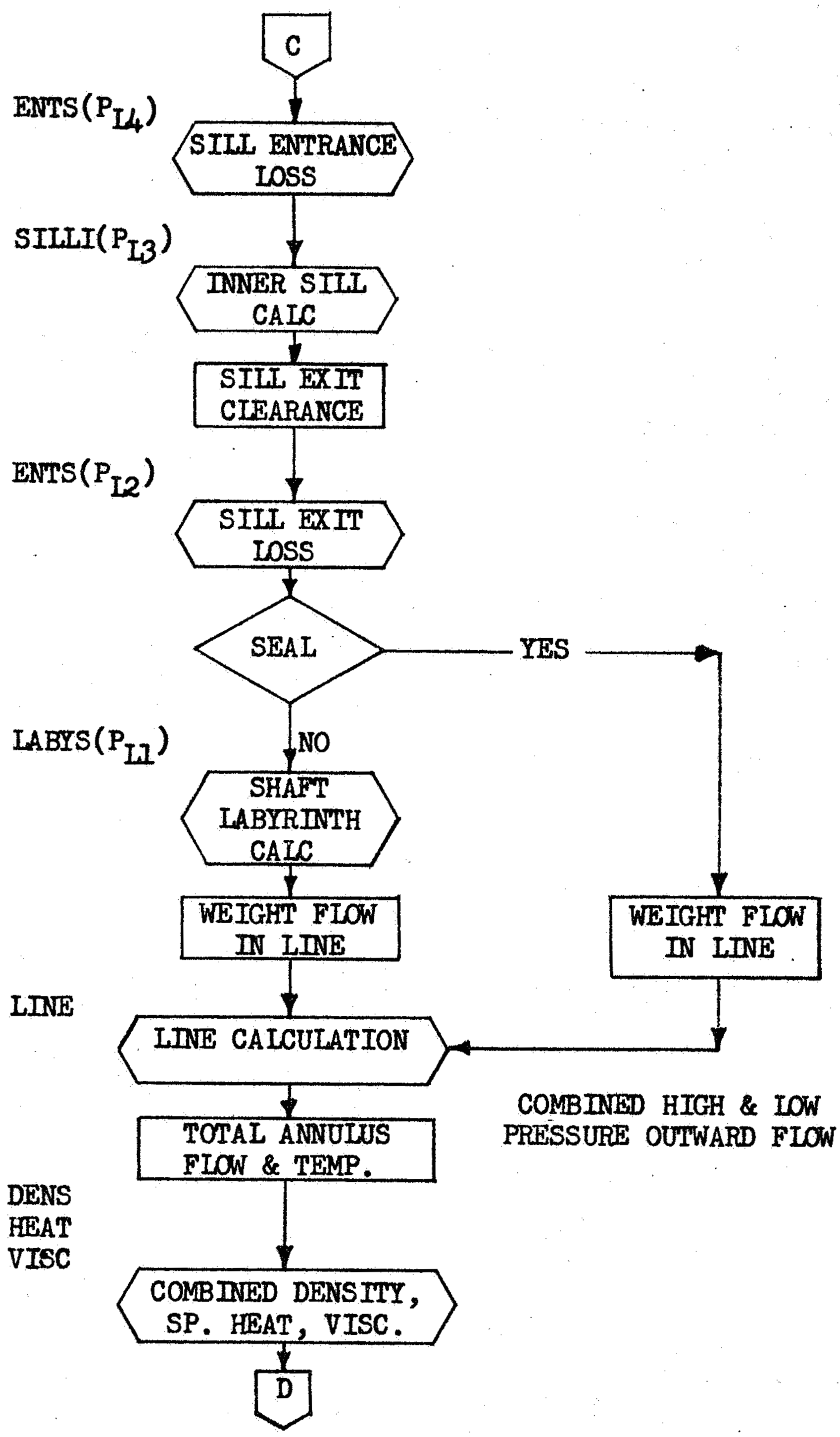
PARALLEL FLOW
PROPERTIES
PPROP

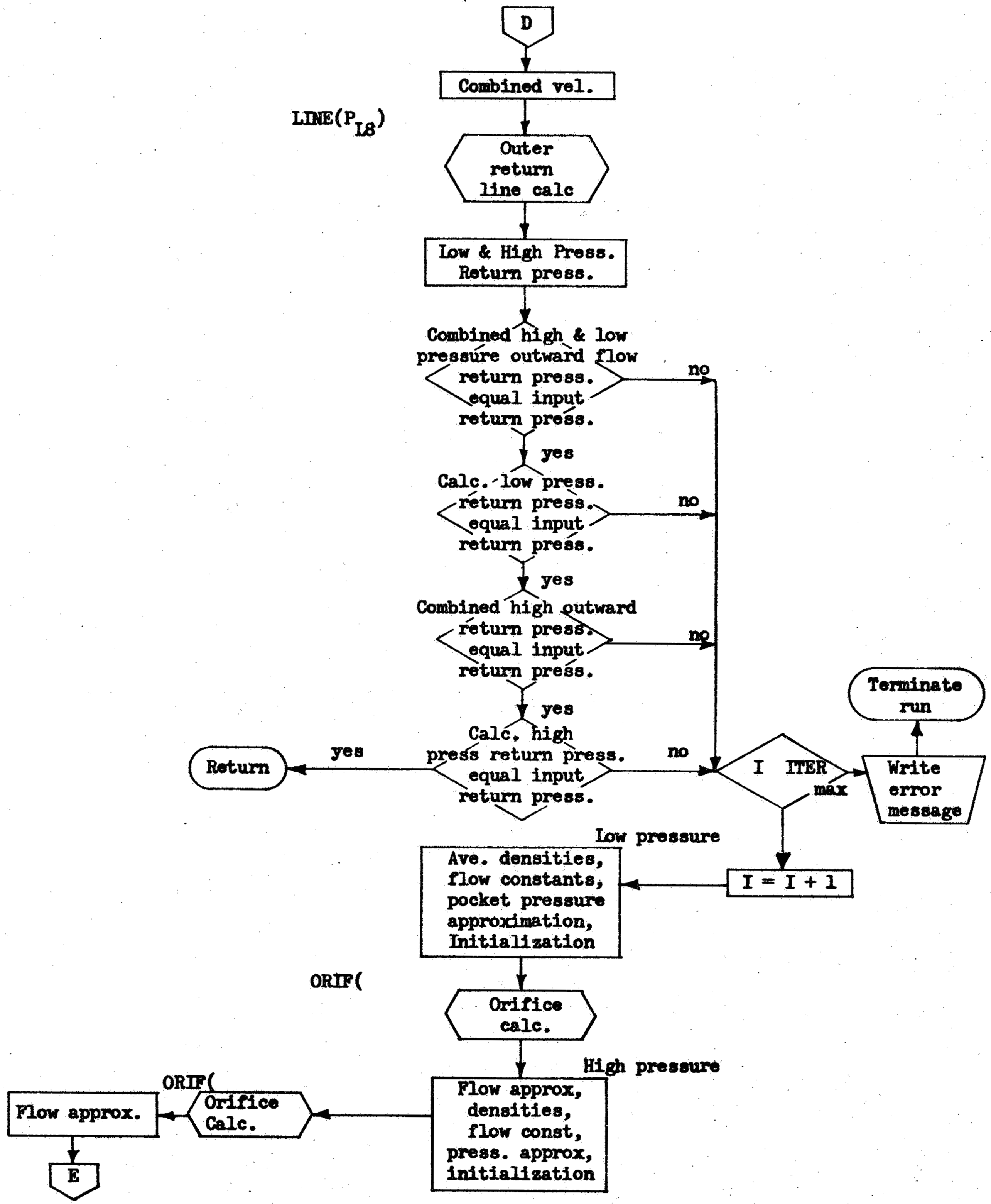



A
Begin iteration on flow
High pressure Outward flow
Outward flow velocities
E
PKTO(P_HP1...)
Pocket pressure
ENTS(P_H51...)
Sill entrance loss
SILLO(P_H61...)
Outer sill calc.
Sill exit clearance
ENTS(P_H7...)
Sill exit loss
Orifice vel.
High Pressure Inward flow
PKTI(P_HP1...)
Pocket pressure
ENTS(P_H41...)
Sill entrance loss
SILLI(P_H3...)
Inner sill calc.
B

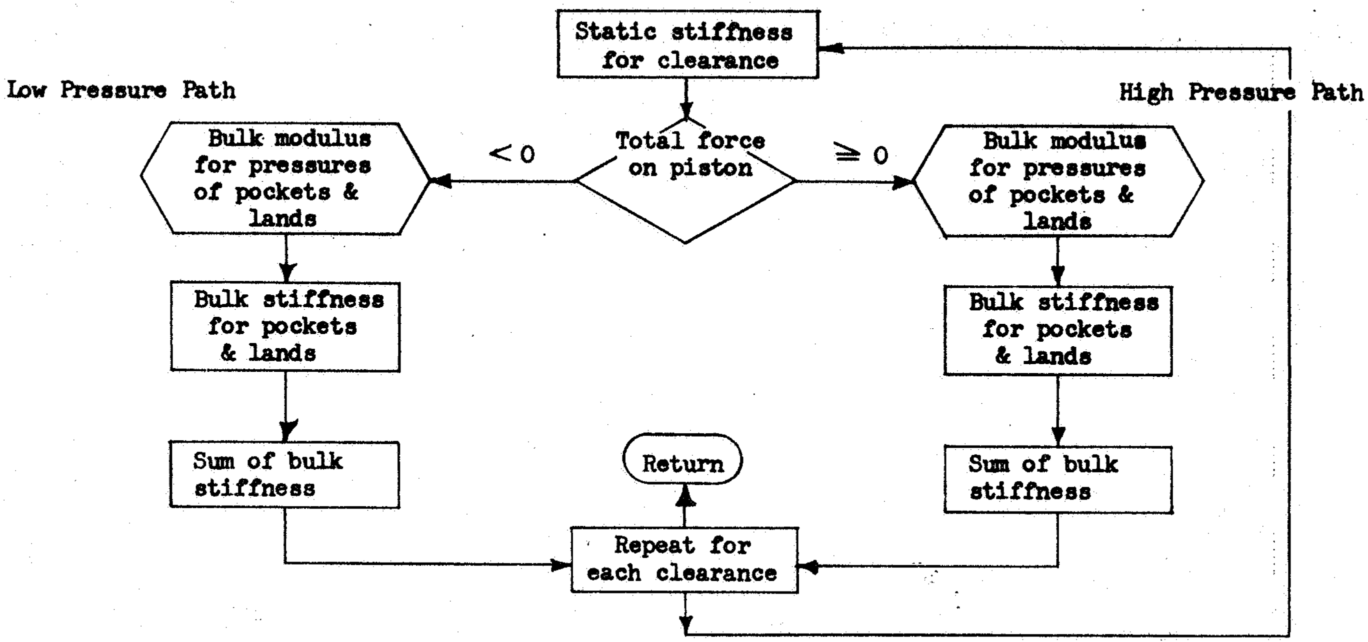

B
Sill exit
Clearance
ENTS(P_H2...)
Inner
sill exit
loss
LINE(P_H1...)
High press.
return
line
Orifice vel.
PKTO(P_LP
Low pressure
Outward flow
Pocket
pressure
ENTS(P_L5
Sill
entrance
loss
SILLO(P_L6
Outer
sill
calc.
Sill exit
clearance
ENTS(P_L7
Sill
exit
loss
Orifice vel
PKTI(P_LP
Low pressure
Inward flow
Pocket
pressure
C

PPROP

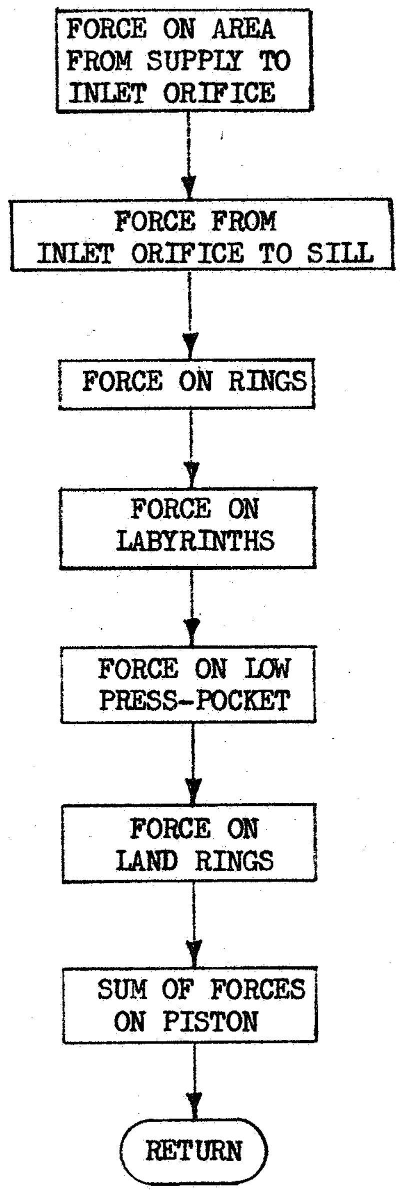

C
ENTS(P_{L4})
SILL ENTRANCE LOSS
SILLI(P_{L3})
INNER SILL CALC
SILL EXIT CLEARANCE
ENTS(P_{L2})
SILL EXIT LOSS
SEAL
YES
NO
LABYS(P_{L1})
SHAFT LABYRINTH CALC
WEIGHT FLOW IN LINE
WEIGHT FLOW IN LINE
LINE
LINE CALCULATION
COMBINED HIGH & LOW PRESSURE OUTWARD FLOW
TOTAL ANNULUS FLOW & TEMP.
DENS
HEAT
VISC
COMBINED DENSITY, SP. HEAT, VISC.
D

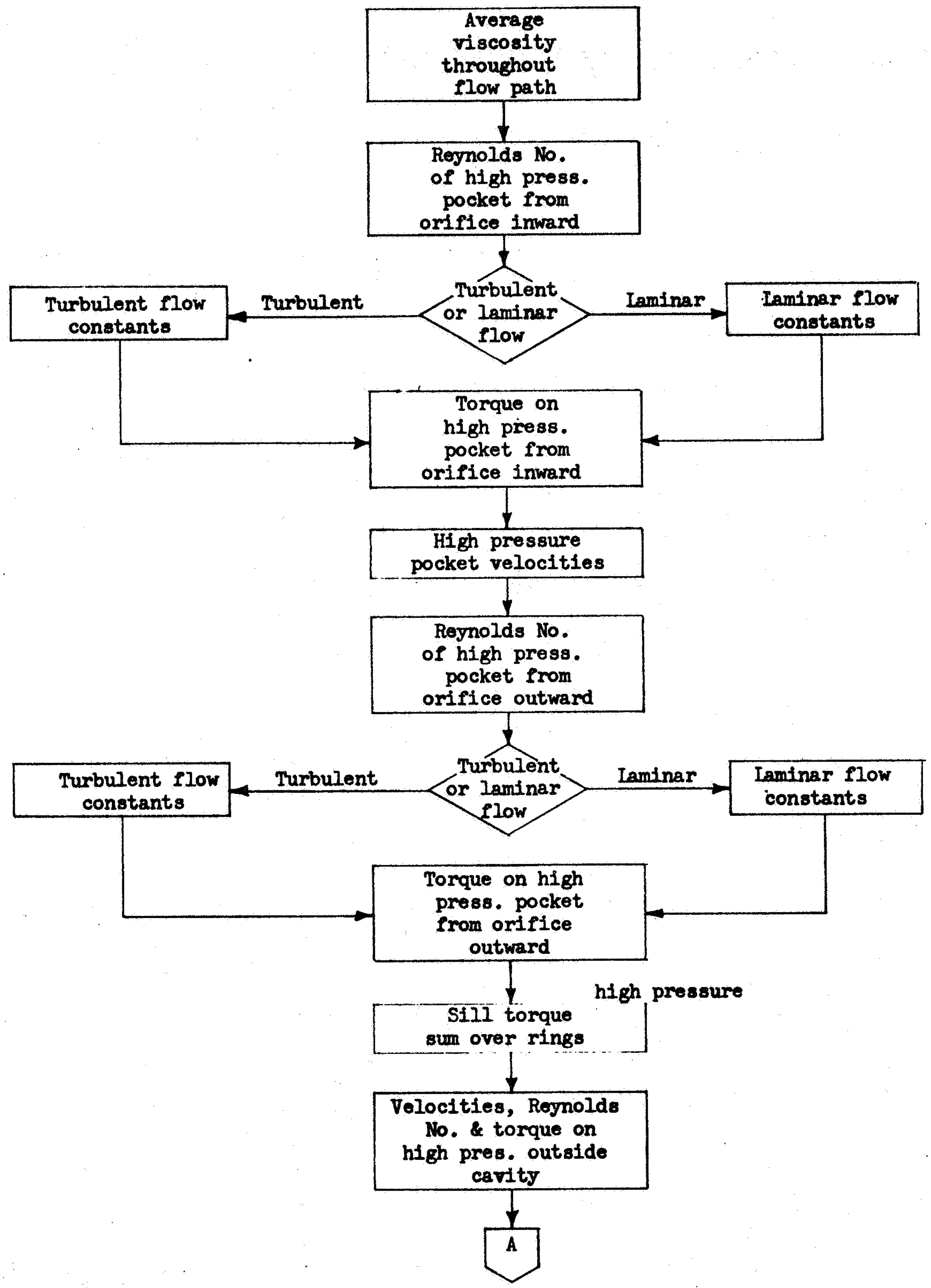

D
Combined vel.
LINE(P_{LS})
Outer return line calc
Low & High Press. Return press.
Combined high & low pressure outward flow return press. equal input return press.
no
yes
Calc. low press. return press. equal input return press.
no
yes
Combined high outward return press. equal input return press.
no
yes
Calc. high press return press. equal input return press.
yes
no
Return
I ITER max
Write error message
Terminate run
I = I + 1
Low pressure
Ave. densities, flow constants, pocket pressure approximation, Initialization
ORIF(
Orifice calc.
High pressure
Flow approx, densities, flow const, press. approx, initialization
ORIF(
Orifice Calc.
Flow approx.
E

PSTIF - Parallel piston stiffness

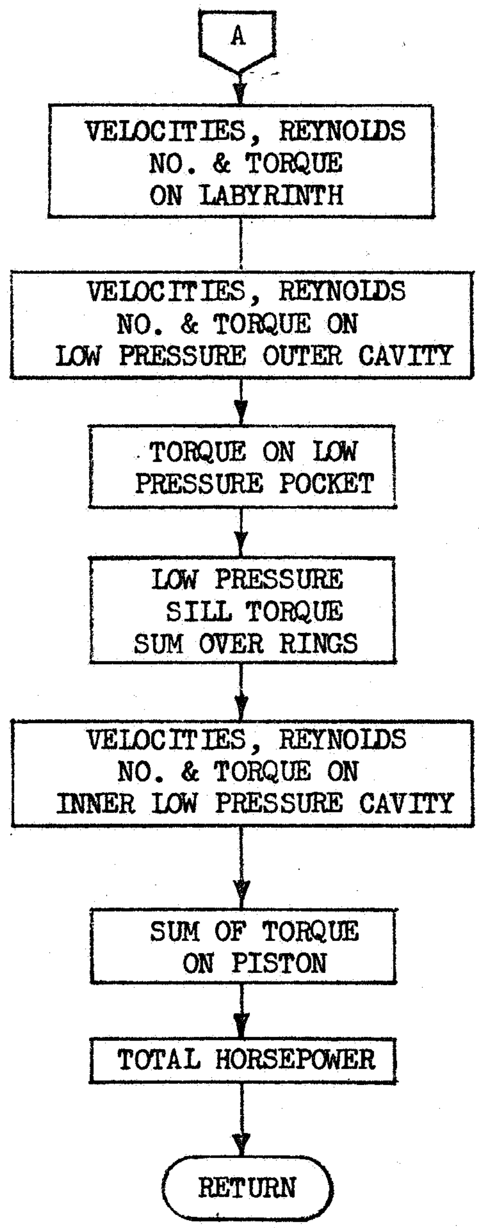


SFORCE - SERIES FORCE CALCULATION

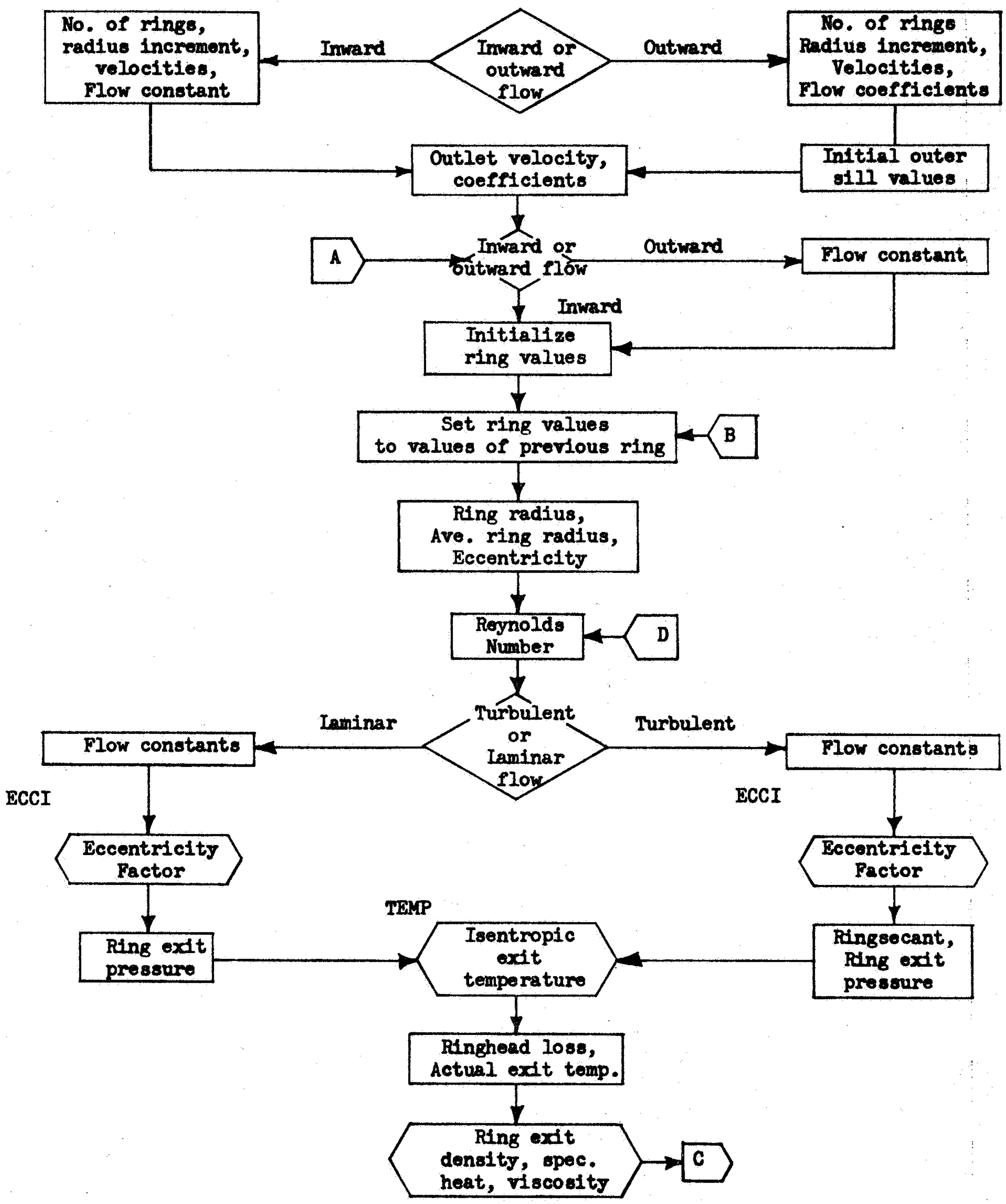


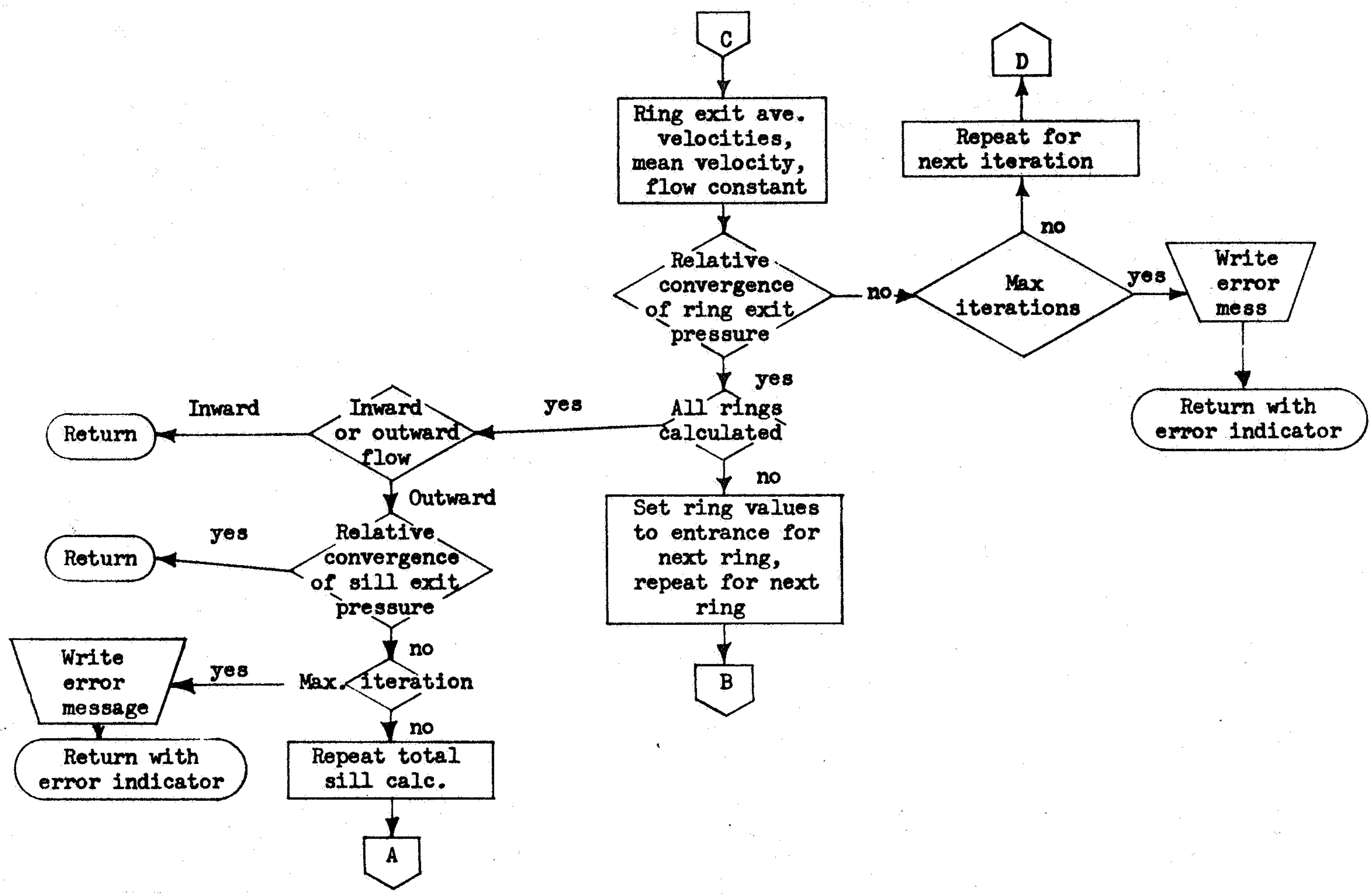

Average viscosity throughout flow path
Reynolds No. of high press. pocket from orifice inward
Turbulent or laminar flow
Turbulent
Laminar
Turbulent flow constants
Laminar flow constants
Torque on high press. pocket from orifice inward
High pressure pocket velocities
Reynolds No. of high press. pocket from orifice outward
Turbulent or laminar flow
Turbulent
Laminar
Turbulent flow constants
Laminar flow constants
Torque on high press. pocket from orifice outward
high pressure
Sill torque sum over rings
Velocities, Reynolds No. & torque on high pres. outside cavity
A

SHORSP

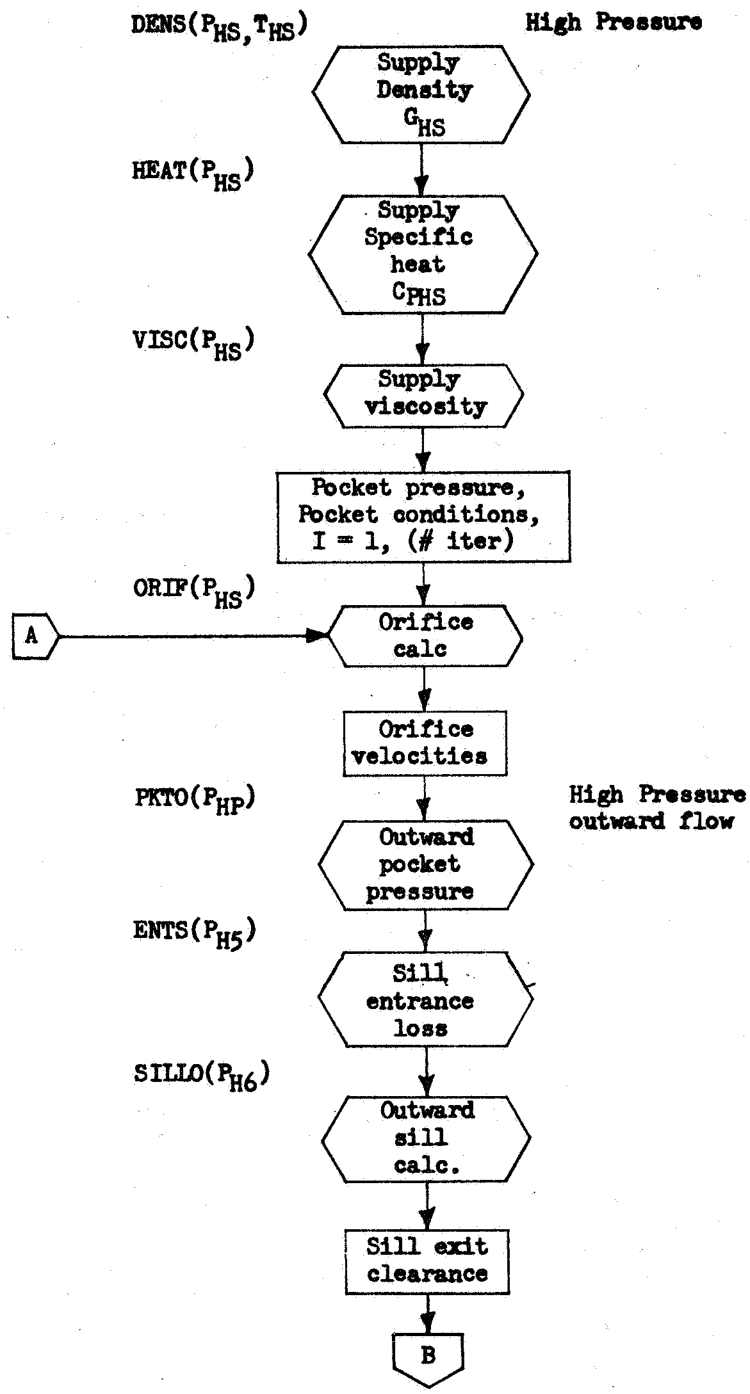

A
VELOCITIES, REYNOLDS NO. & TORQUE ON LABYRINTH
VELOCITIES, REYNOLDS NO. & TORQUE ON LOW PRESSURE OUTER CAVITY
TORQUE ON LOW PRESSURE POCKET
LOW PRESSURE SILL TORQUE SUM OVER RINGS
VELOCITIES, REYNOLDS NO. & TORQUE ON INNER LOW PRESSURE CAVITY
SUM OF TORQUE ON PISTON
TOTAL HORSEPOWER
RETURN

SILL - Sill pressure for inward or outward flow

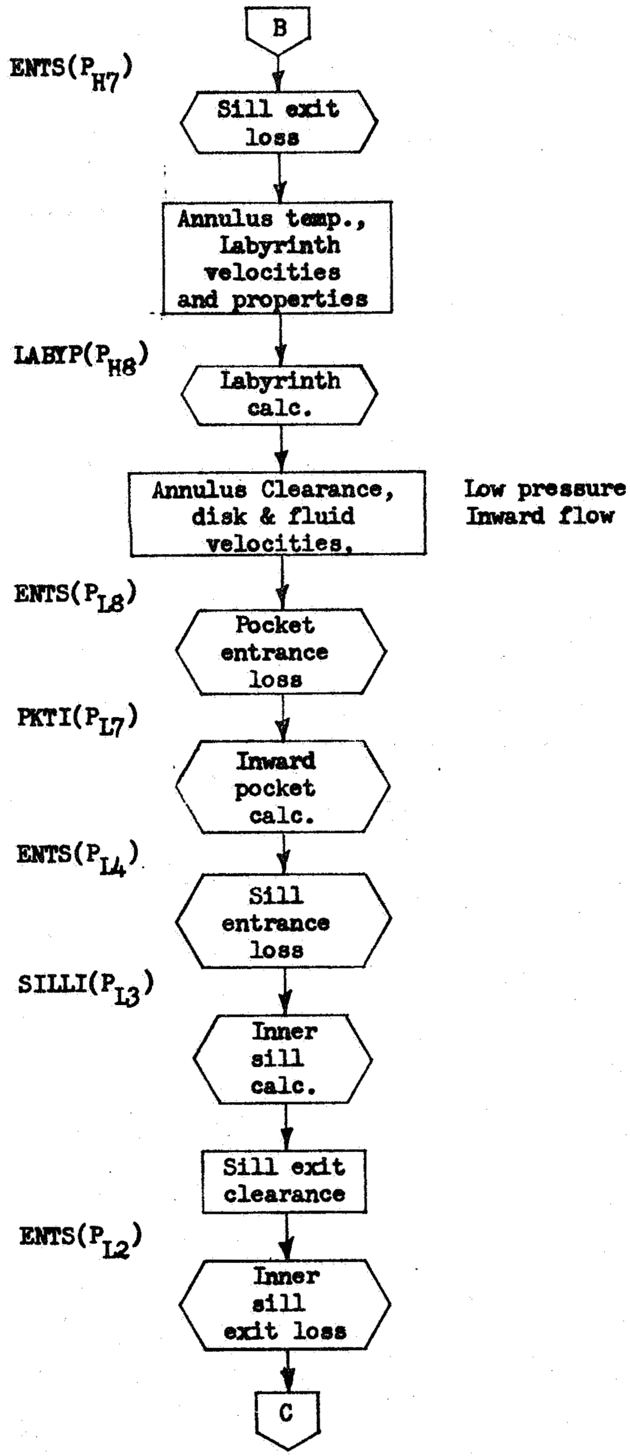



C
Ring exit ave. velocities, mean velocity, flow constant
Relative convergence of ring exit pressure
no
Max iterations
no
Repeat for next iteration
D
yes
Write error mess
Return with error indicator
yes
All rings calculated
no
Set ring values to entrance for next ring, repeat for next ring
B
yes
Inward or outward flow
Inward
Return
Outward
Relative convergence of sill exit pressure
yes
Return
no
Max. iteration
yes
Write error message
Return with error indicator
no
Repeat total sill calc.
A

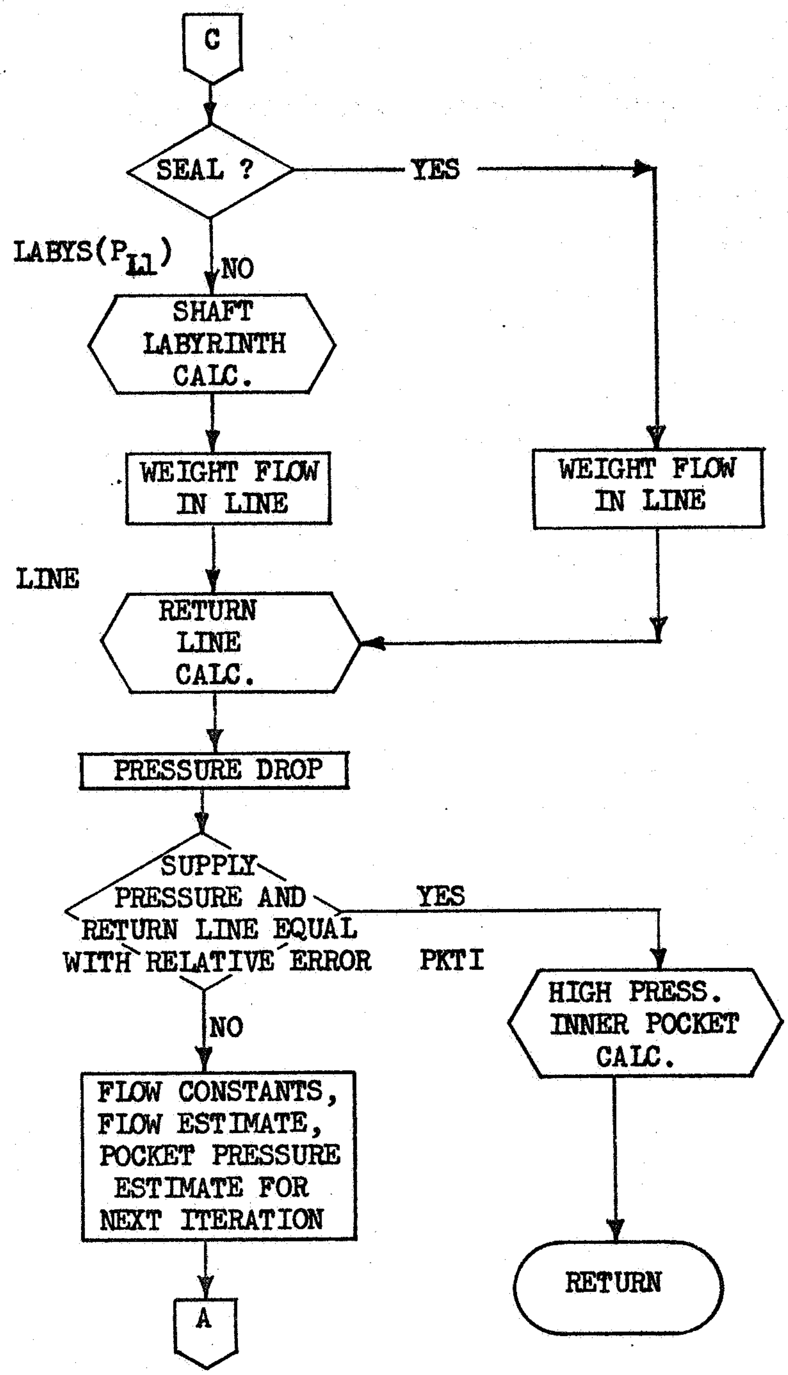
PROP - SERIES FLOW PRESSURE PROPERTIES CALCULATION



'ROP

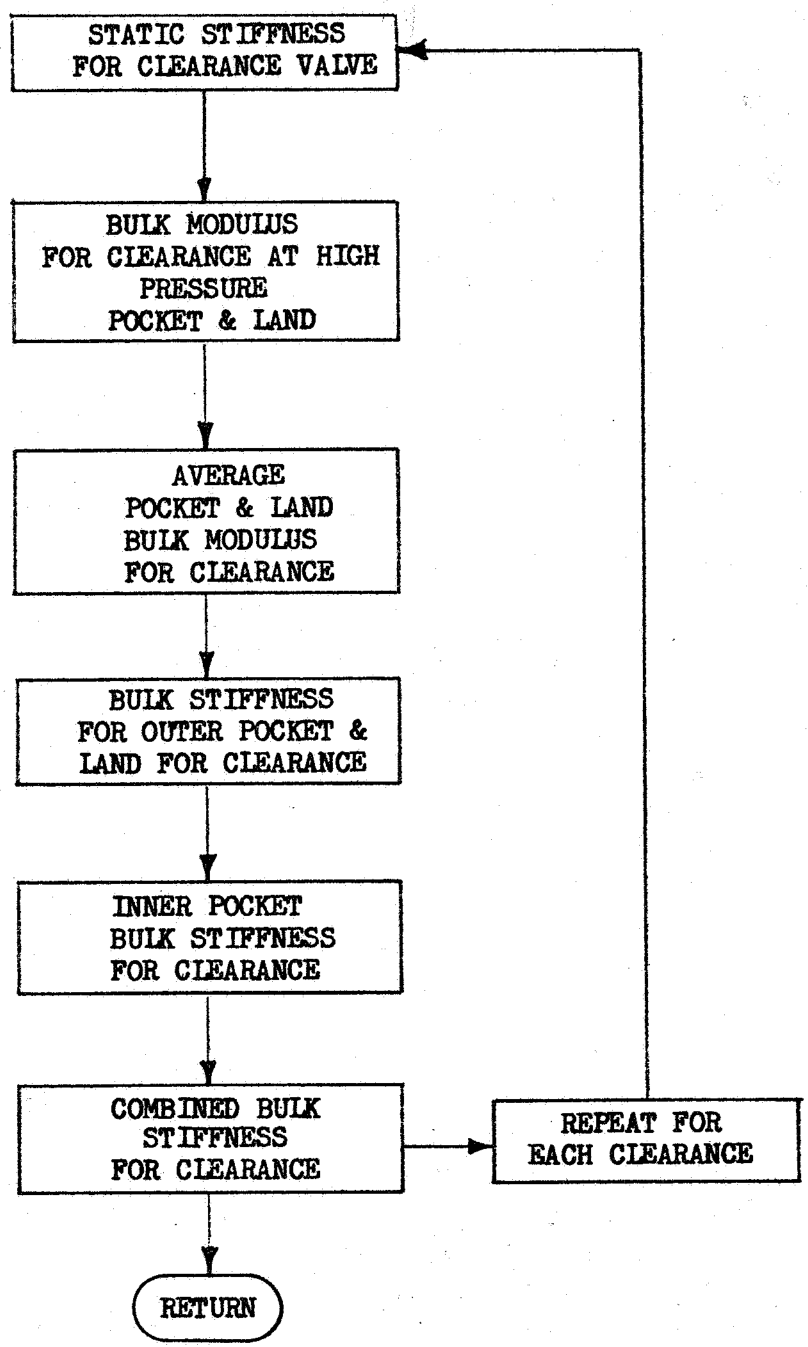

B
ENTS(P_{H7})
Sill exit loss
Annulus temp., Labyrinth velocities and properties
LABYP(P_{H8})
Labyrinth calc.
Annulus Clearance, disk & fluid velocities.
Low pressure Inward flow
ENTS(P_{L8})
Pocket entrance loss
PKTI(P_{L7})
Inward pocket calc.
ENTS(P_{L4})
Sill entrance loss
SILLI(P_{L3})
Inner sill calc.
Sill exit clearance
ENTS(P_{L2})
Inner sill exit loss
C

SPROP


C
SEAL ?
YES
LABYS(P_{L1})
NO
SHAFT LABYRINTH CALC.
WEIGHT FLOW IN LINE
WEIGHT FLOW IN LINE
LINE
RETURN LINE CALC.
PRESSURE DROP
SUPPLY PRESSURE AND RETURN LINE EQUAL WITH RELATIVE ERROR
YES
PKTI
NO
HIGH PRESS. INNER POCKET CALC.
FLOW CONSTANTS, FLOW ESTIMATE, POCKET PRESSURE ESTIMATE FOR NEXT ITERATION
RETURN
A

SSTIF - SERIES PISTON STIFFNESS

SUBROUTINE BULK



ATTACHMENT C

(APPENDIX B)

LISTING OF

PROGRAM DECK AND DATA DECK

```
./      ADD    LIST=ALL,LEVEL=00,SOURCE=0,IGNORE=EOF,NAME=E21902
./      NUMBER NEW1=00000000,INCR=00000005
//JOBLIB DD DSNAME=PRODLMOD,DISP=OLD
// EXEC HCMPLNK,PARM.COMPIL='LINECNT=44,OPT=2,NOMAP'
//COMPIL.SYSIN DD *
C
C                  PROGRAM PLACED ON PRODUCTION 23APR68
C
C      MAIN PROGRAM FOR THRUST BALANCER STABILITY PROGRAM
       IMPLICIT REAL*8 (A-H , O-Z)
       COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
       REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
       COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
       COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
       COMMON /MAIN1/ M
       COMMON /MAIN2/ HL3(20)
       COMMON /MAIN3/ HH3
       COMMON /ERPRNT/ IERRT
C
C      SET CONSTANTS INDEPENDENT OF ALL CASES
C
       CALL ACONST
C
C      READ INPUT
C
       NPDENS=0
    10 CALL INPUT
C      TEST FOR SERIES OR PARALLEL FLOW
C
       DH=(HMAX-HMIN)/DFLOAT(NH)
       NH=NH+1
       IF(IBAL.EQ.0)GO TO 70
C
C
C      SERIES PISTON CALCULATIONS FOR FLUID PROPERTIES, FORCES, AND
C      HORSEPOWER
C
       DO 60 M=1,NH
       IERRT=0
       HL3(M)=HMIN+DFLOAT(M-1)*DH
       HLP(M)=HL3(M)+HDLP+DHL*P5
       HL7(M)=HL3(M)+HDLP+DHL
       HH3=HT-HL3(M)+HDHP
```

```
      HH7(M)=HT-HL3(M)
      HHP(M)=HH7(M)+HDHP-P5*DHL
      CALL SPROP
      IF(IERRT.LT.5)GO TO 50
      IF(IERRT.EQ.10)GO TO 30
      WRITE (6,20)HH7(M)
   20 FORMAT(1H0/ 20H0THE CLEARANCE HH7 = ,1P1D12.4,1X, 60HWAS BYPASSED
     1AFTER 5 PROPERTY TABLE ARGUMENTS WERE IN ERROR.  )
      GO TO 60
   30 WRITE (6,40)HH7(M)
   40 FORMAT(1H0/ 20H0THE CLEARANCE HH7 = ,1P1D12.4,1X, 74HWAS BYPASSED
     1AFTER CONVERGENCE WAS NOT OBTAINED IN THE MAXIMUM ITERATIONS. )
      GO TO 60
   50 CONTINUE
      CALL SFORCE
      CALL SHORSP
      CALL SOUT
   60 CONTINUE
C
C     SERIES PISTON STIFFNESS AND OUTPUT
C
      CALL SSTIF
      CALL PSOUT
      GO TO 110
C
C     PARALLEL PISTON CALCULATIONS
C
   70 CONTINUE
      DO 100 M=1,NH
      IERRT=0
      HL3(M)=HMIN+DFLOAT(M-1)*DH
      HL7(M)=HL3(M)+DHL
      HLP(M)= HDLP+P5*(HL3(M)+HL7(M))
      HH3=HT-HL3(M)
      HH7(M)=HT-HL7(M)
      HHP(M)=HDHP+P5*(HH3+HH7(M))
      CALL PPROP
      IF(IERRT.LT.5)GO TO 90
      IF(IERRT.EQ.10)GO TO 80
      WRITE (6,20)HH7(M)
      GO TO 100
   80 WRITE (6,40)HH7(M)
      GO TO 100
   90 CONTINUE
      CALL PFORCE
      CALL PHORSP
      CALL POUT
  100 CONTINUE
C
      CALL PSTIF
      CALL PSOUT
C
```

```
C      FORCE PISTON CALCULATIONS
C
  110 CONTINUE
      CALL FORCP
      GO TO 10
      END
      SUBROUTINE INPUT
C
C      INPUT FOR THRUST BALANCER STABILITY PROGRAM
C
C
C      INPUT COMMON TO ALL CASE TYPES
C
C      TITLE(I) = CASE TITLE
C      IPRES = 0, IF COMPRESSIBLE FLOW AND 1, IF INCOMPRESSIBLE FLOW
C      IBAL = 0, IF PARALLEL PISTON AND 1, IF SERIES PISTON
C      ISEAL = 0, IF SEAL, AND 1, IF LABYRINTH
C      IKIN = 0, IF ROTATION FACTORS CALCULATED IN POCKETS AND SILLS
C             1, IF ROTATION FACTORS INPUT
C      ITABLE = 0, IF PROPERTY TABLES NOT INPUT IN THIS CASE
C                  (TABLES FROM PREVIOUS CASE USED)
C               1, IF PROPERTY TABLES ARE INPUT (TABLES MUST BE INPUT IN
C                  FIRST CASE OF EACH COMPUTER RUN)
C      XNRPM = ROTATIONAL SPEED (RPM)
C      HT = TOTAL CLEARANCE (IN)
C      NH = NUMBER OF CLEARANCE INCREMENTS
C      HMIN = MINIMUM SILL CLEARANCE CALCULATION POINT (IN)
C      HMAX = MAXIMUM SILL CLEARANCE CALCULATION POINT (IN)
C      ECC = RUNOUT (IN)
C      PATM = ATMOSPHERIC PRESSURE (LB/IN**2)
C      C1 = CLOSURE ON SUBROUTINE PRESSURE CALCULATIONS
C      CMLAM = LAMINAR MOMENT FRACTION FACTOR CONSTANT
C      NMLAM = LAMINAR MOMENT FRACTION FACTOR EXPONENT
C      CMTUR = TURBULENT MOMENT FRACTION FACTOR CONSTANT
C      NMTUR = TURBULENT MOMENT FRACTION FACTOR EXPONENT
C      CFLAM = LAMINAR FLOW FRACTION FACTOR CONSTANT
C      NFLAM = LAMINAR FLOW FRACTION FACTOR EXPONENT
C      CFTUR = TURBULENT FLOW FRACTION FACTOR CONSTANT
C      NFTUR = TURBULENT FLOW FRACTION FACTOR EXPONENT
C      NTLAM = NUMBER OF VALUES IN LAMINAR FLOWRATE RATIO TABLE (MAX 40)
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
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     4     ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)          00000770
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,    00000775
     1      RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,    00000780
     2      RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,                   00000785
     3      XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,00000790
     4      PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3, 00000795
     5      CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,  00000800
     6      XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R100000805
     7     ,XNH8R1, XLH8R1, RH8R1                                       00000810
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,     00000815
     1      XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8                  00000820
     2     ,WHPH1S                                                      00000825
      COMMON /IN5/ K, NFS, PFS(21), TFS, PC2, PEXH, PFPR1, XNFSFP,      00000830
     1      DFSFP, CFSFP, DFS, RFP, RF1, RFTS, HF1C1, HEF1C1, XLF1C1,   00000835
     2      XNF1C1, PF1C1, XF1C1, HC1C2, HEC1C2, XLC1C2, XNC1C2, PC1C2,00000840
     3      XC1C2, CF1C1, CC1C2, HFP, HF1, HSP, XNC1R1, XLC1R1, RC1R1   00000845
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,   00000850
     1      CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)            00000855
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN        00000860
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),   00000865
     1      GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),         00000870
     2      RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4                      00000875
      COMMON /FSER/ PH1S(20), TH1S(20), GL7L4, XKL7L4, TH9(20), PH9(20) 00000880
      COMMON /PGUES/ C11                                                00000885
      COMMON /PFGUES/ C12                                               00000890
C     EL(N) = LAMINAR ECCENTRICITY RATIO TABLE VALUE                    00000895
C     FRL(N) = LAMINAR FLOWRATE RATIO FOR EL(N)                         00000900
C     NTTUR = NUMBER OF VALUES IN TURBULENT FLOWRATE RATIO TABLE        00000905
C     ET(N) = TURBULENT ECCENTRICITY RATIO TABLE VALUE                  00000910
C     FRT(N) = TURBULENT FLOWRATE RATIO FOR ET(N)                       00000915
C     XKRING = FACTOR FOR CALCULATING RINGS IN SILL (1/IN)              00000920
C     ITERC = MAXIMUM NUMBER OF ITERATIONS ON SUBROUTINE PRESSURE CALC. 00000925
C     ITERP = MAXIMUM NUMBER OF ITERATIONS ON PROPERTIES PRESSURE FOR   00000930
C             PARALLEL AND FORCE PISTON                                 00000935
C     CLOS = CLOSURE ON PROPERTIES PRESSURE                             00000940
C     HDLP = CLEARANCE DIFFERENCE ON LOW PRESSURE SIDE BETWEEN POCKET   00000945
C            DEPTH HLP AND OUTER LAND DEPTH HL7 (IN)                    00000950
C     HDHP = CLEARANCE DIFFERENCE ON HIGH PRESSURE SIDE BETWEEN POCKET  00000955
C            DEPTH HHP AT ORIFICE AND OUTER LAND DEPTH HH7 (IN)         00000960
C     DHL = DEFLECTION FROM INNER LAND DEPTH HL3 (ON LOW PRESSURE SIDE) 00000965
C           TO OUTER LAND DEPTH HL7 (IN)                                00000970
C     CR = AVERAGING CONSTANT FOR FLUID PROPERTIES                      00000975
      READ (5,10,END=610)(TITLE(I),I=1,9)                               00000980
   10 FORMAT(9A8)                                                       00000985
      READ (5,20)IPRES,IBAL,NH,ITERC,ITERP,NTLAM,NTTUR                  00000990
     1,ISEAL,IKIN,ITABLE                                                00000995
   20 FORMAT(12I6)                                                      00001000
      READ (5,30)HT,HMIN,HMAX,HDLP,DHL,HDHP                             00001005
   30 FORMAT(6D12.6)                                                    00001010
      READ (5,30)XNRPM,ECC,PATM,C1,CLOS,C11                             00001015
      OMEGAD=PI30*XNRPM                                                 00001020
      READ (5,30)XKRING,CR,CMLAM,NMLAM                                  00001025
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      READ (5,30)CMTUR,NMTUR,CFLAM,NFLAM,CFTUR,NFTUR
      READ (5,30)(EL(N),FRL(N),N=1,NTLAM)
      READ (5,30)(ET(N),FRT(N),N=1,NTTUR)
      IF(NH.EQ.0)NH=10
      IF(PATM.EQ.0.)PATM=14.7
      IF(CR.EQ.0.)CR=.5
      IF(C1.EQ.0.)C1=.005
      IF(CLOS.EQ.0.)CLOS=.005
      IF(XKRING.EQ.0.)XKRING=.02
      IF(CMLAM.EQ.0.)CMLAM=96.
      IF(NMLAM.EQ.0.)NMLAM=1.
      IF(CMTUR.EQ.0.)CMTUR=.079
      IF(NMTUR.EQ.0.)NMTUR=.43
      IF(CFLAM.EQ.0.)CFLAM=96.
      IF(NFLAM.EQ.0.)NFLAM=1.
      IF(CFTUR.EQ.0.)CFTUR=.316
      IF(NFTUR.EQ.0.)NFTUR=.21
      IERR=0
      IF(NH.LE.20)GO TO 50
      IERR=1
      WRITE (6,40)NH
   40 FORMAT(1H0/71H0THE MAXIMUM NUMBER OF CLEARANCE INCREMENTS IS 20.
     1THE INPUT NUMBER IS , I6 )
   50 IF(NTLAM.LE.40)GO TO 70
      IERR=1
      WRITE(6,60)NTLAM
   60 FORMAT(1H0/107H0THE MAXIMUM NUMBER OF LAMINAR ECCENTRICITY RATIO -
     1 FLOWRATE RATIO TABLE VALUES IS 40.  THE INPUT NUMBER IS,1P1D13.4)
   70 IF(NTTUR.LE.40)GO TO 90
      IERR=1
      WRITE (6,80)NTTUR
   80 FORMAT(1H0/107H0THE MAXIMUM NUMBER OF TURBULENT ECCENTRICITY RATIO
     1-FLOWRATE RATIO TABLE VALUES IS 40.  THE INPUT NUMBER IS,1P1D13.4)
   90 IF(IERR.EQ.1)STOP
C
C     PRINT INPUT VALUES
C
      WRITE (6,100)(TITLE(L),L=1,9)
  100 FORMAT(1H1/1H ,45X,27HAEROJET-GENERAL CORPORATION /1H ,49X,19HPROP
     1ULSION DIVISION /1H ,47X,22HSACRAMENTO, CALIFORNIA/15H0PROGRAM E21
     2902 /1H0,9A8)
      IF(IPRES.EQ.0)GO TO 140
      IF(IBAL.EQ.0)GO TO 120
      WRITE (6,110)
  110 FORMAT(44H0INCOMPRESSIBLE, SERIES FLOW THRUST BALANCER )
      GO TO 180
  120 WRITE (6,130)
  130 FORMAT(46H0INCOMPRESSIBLE, PARALLEL FLOW THRUST BALANCER)
      GO TO 180
  140 IF(IBAL.EQ.0)GO TO 160
      WRITE (6,150)
  150 FORMAT(42H0COMPRESSIBLE, SERIES FLOW THRUST BALANCER )
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      GO TO 180
  160 WRITE (6,170)
  170 FORMAT(44H0COMPRESSIBLE, PARALLEL FLOW THRUST BALANCER )
  180 WRITE (6,190)XNRPM,ECC,PATM,C1,CMTUR,NMTUR,CMLAM,NMLAM,CFTUR,
     1 NFTUR,CFLAM,NFLAM
  190 FORMAT(1H0/19H0GENERAL INPUT DATA/27H0ANGULAR VELOCITY, N(RPM) = ,
     11P1D15.4/ 19H RUNOUT, ECC (IN) = ,D15.4 / 40H ATMOSPHERIC PRESSURE
     2, PATM (LB/IN**2) = ,D15.4 / 31H RELATIVE CLOSURE ON PRESSURE = ,
     3D15.4 / 26H FRICTION FACTOR CONSTANTS / 1H ,5X, 8HCMTURB = ,D15.4
     4,10X,8HNMTURB = ,D15.4/1H ,5X,8HCMLAM  = ,D15.4, 10X, 8HNMLAM  = ,
     5 D15.4/ 1H ,5X, 8HCFTURB = ,D15.4 ,10X, 8HNFTURB = ,D15.4/ 1H ,5X,
     6 8HCFLAM  = ,D15.4, 10X, 8HNFLAM  = ,D15.4 )
C
C      INPUT OF FLUID PROPERTY TABLES IF COMPRESSIBLE FLOW
C
C      PDENS(I) = PRESSURE VALUE FOR DENSITY TABLE
C      TDENS(J) = TEMPERATURE VALUE FOR DENSITY TABLE
C      GDENS(I,J) = DENSITY FOR TABLE AT PDENS(I) AND TDENS(J)
C      PHEAT(I) = PRESSURE VALUE FOR SPECIFIC HEAT TABLE
C      THEAT(J) = TEMPERATURE VALUE FOR SPEC. HEAT TABLE
C      CPHEAT(I,J) = SPECIFIC HEAT AT PHEAT(I) AND THEAT(J)
C      PVISC(I) = PRESSURE VALUE FOR VISCOSITY TABLE
C      TVISC(J) = TEMPERATURE VALUE FOR VISCOSITY TABLE
C      XMVISC(I,J) = VISCOSITY AT PVISC(I) AND TVISC(J)
C      NPDENS = NUMBER OF PRESSURE VALUES IN DENSITY TABLE (MAX OF 30)
C      NTDENS = NUMBER OF TEMPERATURE VALUES IN DENSITY TABLE (MAX OF 30)
C      NPHEAT = NUMBER OF PRESSURE VALUES IN SPECIFIC HEAT TABLE (30 MAX)
C      NTHEAT = NUMBER OF TEMPERATURE VALUES IN SPEC. HEAT TABLE (30 MAX)
C      NPVISC = NUMBER OF PRESSURE VALUES IN VISCOSITY TABLE (30 MAX)
C      NTVISC = NUMBER OF TEMPERATURE VALUES IN VISCOSITY TABLE (30 MAX)
C      NETEMP = NUMBER OF ENTROPY VALUES IN TEMPERATURE TABLE (MAX OF 30)
C      NTTEMP = NUMBER OF TEMPERATURE VALUES IN TEMPERATURE TABLE (30)
C      ETEMP(I) = ENTROPY VALUE FOR TEMPERATURE TABLE
C      TTEMP(J) = TEMPERATURE VALUE FOR TEMPERATURE TABLE
C      PTEMP(I,J) = PRESSURE VALUE AT ETEMP(I) AND TTEMP(J)
C      NPBULK = NUMBER OF PRESSURE VALUES IN BULK MODULUS TABLE
C      NTBULK = NUMBER OF TEMPERATURE VALUES IN BULK MODULUS TABLE
C      PBULK(I) = PRESSURE VALUE FOR BULK MODULUS TABLE
C      TBULK(J) = TEMPERATURE VALUE FOR BULK MODULUS TABLE
C      EBULK(I,J) = BULK MODULUS AT PBULK(I) AND TBULK(J)
C
      IF(ITABLE.EQ.1)GO TO 210
      IF(NPDENS.NE.0)GO TO 420
      WRITE (6,200)
  200 FORMAT(1H0/114H0VARIABLE ITABLE (INPUT ON CARD 1) INDICATES THAT N
     1O PROPERTY TABLES ARE TO BE INPUT, BUT THE TABLES MUST BE INPUT  /
     234H SINCE NONE WERE INPUT PREVIOUSLY. )
      STOP
  210 CONTINUE
      READ (5,20)NPDENS,NTDENS,NPHEAT,NTHEAT,NPVISC,NTVISC,NETEMP,
     1 NTTEMP,NPBULK,NTBULK
      IF(NPDENS.LE.30)GO TO 230
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      IERR=1                                                            00001550
      WRITE (6,220)NPDENS                                               00001555
  220 FORMAT(1H0/ 87H0THE MAXIMUM NUMBER OF PRESSURE VALUES FOR THE DENS00001560
     1ITY TABLE IS 30.  THE INPUT VALUE IS ,I6)                         00001565
  230 IF(NTDENS.LE.30)GO TO 250                                         00001570
      IERR=1                                                            00001575
      WRITE (6,240)NTDENS                                               00001580
  240 FORMAT(1H0/ 90H0THE MAXIMUM NUMBER OF TEMPERATURE VALUES IN THE DE00001585
     1NSITY TABLE IS 30.  THE INPUT NUMBER IS ,I6)                      00001590
  250 IF(NPHEAT.LE.30)GO TO 270                                         00001595
      IERR=1                                                            00001600
      WRITE(6,260)NPHEAT                                                00001605
  260 FORMAT(1H0/ 93H0THE MAXIMUM NUMBER OF PRESSURE VALUES IN THE SPECI00001610
     1FIC HEAT TABLE IS 30.  THE INPUT NUMBER IS ,I6)                   00001615
  270 IF(NTHEAT.LE.30)GO TO 290                                         00001620
      IERR=1                                                            00001625
      WRITE (6,280)NTHEAT                                               00001630
  280 FORMAT(1H0/ 96H0THE MAXIMUM NUMBER OF TEMPERATURE VALUES IN THE SP00001635
     1ECIFIC HEAT TABLE IS 30.  THE INPUT NUMBER IS ,I6)                00001640
  290 IF(NPVISC.LE.30)GO TO 310                                         00001645
      IERR=1                                                            00001650
      WRITE (6,300)NPVISC                                               00001655
  300 FORMAT(1H0/ 89H0THE MAXIMUM NUMBER OF PRESSURE VALUES IN THE VISCO00001660
     1SITY TABLE IS 30.  THE INPUT NUMBER IS ,I6)                       00001665
  310 IF(NTVISC.LE.30)GO TO 330                                         00001670
      IERR=1                                                            00001675
      WRITE (6,320)NTVISC                                               00001680
  320 FORMAT(1H0/ 92H0THE MAXIMUM NUMBER OF TEMPERATURE VALUES IN THE VI00001685
     1SCOSITY TABLE IS 30.  THE INPUT NUMBER IS , I6)                   00001690
  330 IF(NETEMP.LE.30)GO TO 350                                         00001695
      IERR=1                                                            00001700
      WRITE (6,340)NETEMP                                               00001705
  340 FORMAT(1H0/ 90H0THE MAXIMUM NUMBER OF ENTROPY VALUES IN THE TEMPER00001710
     1ATURE TABLE IS 30.  THE INPUT NUMBER IS ,I6)                      00001715
  350 IF(NTTEMP.LE.30)GO TO 370                                         00001720
      IERR=1                                                            00001725
      WRITE (6,360)NTTEMP                                               00001730
  360 FORMAT(1H0/ 94H0THE MAXIMUM NUMBER OF TEMPERATURE VALUES IN THE TE00001735
     1MPERATURE TABLE IS 30.  THE INPUT NUMBER IS ,I6)                  00001740
  370 IF(NPBULK.LE.30)GO TO 390                                         00001745
      IERR=1                                                            00001750
      WRITE (6,380)NPBULK                                               00001755
  380 FORMAT(1H0/ 92H0THE MAXIMUM NUMBER OF PRESSURE VALUES IN THE BULK 00001760
     1MODULUS TABLE IS 30.  THE INPUT NUMBER IS ,I6)                    00001765
  390 IF(NTBULK.LE.30)GO TO 410                                         00001770
      IERR=1                                                            00001775
      WRITE (6,400)NTBULK                                               00001780
  400 FORMAT(1H0/ 95H0THE MAXIMUM NUMBER OF TEMPERATURE VALUES IN THE BU00001785
     1LK MODULUS TABLE IS 30.  THE INPUT NUMBER IS ,I6)                 00001790
  410 IF(IERR.EQ.1)STOP                                                 00001795
      READ (5,30)(PDENS(I),I=1,NPDENS)                                  00001800
      READ (5,30)(TDENS(J),J=1,NTDENS)                                  00001805
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      READ (5,30)((GDENS(I,J),I=1,NPDENS),J=1,NTDENS)
      READ (5,30)(PHEAT(I),I=1,NPHEAT)
      READ (5,30)(THEAT(J),J=1,NTHEAT)
      READ (5,30)((CPHEAT(I,J),I=1,NPHEAT),J=1,NTHEAT)
      READ (5,30)(PVISC(I),I=1,NPVISC)
      READ (5,30)(TVISC(J),J=1,NTVISC)
      READ (5,30)((XMVISC(I,J),I=1,NPVISC),J=1,NTVISC)
      READ (5,30)(ETEMP(I),I=1,NETEMP)
      READ (5,30)(TTEMP(J),J=1,NTTEMP)
      READ (5,30)((PTEMP(I,J),I=1,NETEMP),J=1,NTTEMP)
      READ (5,30)(PBULK(I),I=1,NPBULK)
      READ (5,30)(TBULK(J),J=1,NTBULK)
      READ (5,30)((EBULK(I,J),I=1,NPBULK),J=1,NTBULK)
  420 CONTINUE
C
C     INPUT FOR PARALLEL PISTON CASE
C
      IF(IBAL.EQ.1)GO TO 480
C     RH1 = INNER RADIUS OF HIGH PRESSURE SIDE INNER POCKET (IN)
C     RH2 = INNER RADIUS OF HIGH PRESSURE SIDE INNER LAND (IN)
C     RH3 = OUTER RADIUS OF HIGH PRESSURE SIDE INNER LAND (IN)
C     RH4 = OUTER RADIUS OF HIGH PRESSURE SIDE INNER POCKET (IN)
C     RH5 = INNER RADIUS OF HIGH PRESSURE SIDE OUTER POCKET (IN)
C     RH6 = INNER RADIUS OF HIGH PRESSURE SIDE OUTER LAND (IN)
C     RH7 = OUTER RADIUS OF HIGH PRESSURE SIDE OUTER LAND (IN)
C     RH8 = OUTER RADIUS OF HIGH PRESSURE SIDE OUTER ANNULUS (IN)
C     RH9 = LABYRINTH OUTER RADIUS ON HIGH PRESSURE SIDE (IN)
C     RL1 = INNER RADIUS OF LOW PRESSURE SIDE INNER POCKET (IN)
C     RL2 = INNER RADIUS OF LOW PRESSURE SIDE INNER LAND (IN)
C     RL3 = OUTER RADIUS OF LOW PRESSURE SIDE INNER LAND (IN)
C     RL4 = OUTER RADIUS OF LOW PRESSURE SIDE INNER POCKET (IN)
C     RL5 = INNER RADIUS OF LOW PRESSURE SIDE OUTER POCKET (IN)
C     RL6 = INNER RADIUS OF LOW PRESSURE SIDE OUTER LAND (IN)
C     RL7 = OUTER RADIUS OF LOW PRESSURE SIDE OUTER LAND (IN)
C     RL8 = OUTER RADIUS OF LOW PRESSURE SIDE OUTER POCKET (IN)
C     RL9 = OUTER RADIUS OF LABYRINTH ON LOW PRESSURE SIDE (IN)
C     RHP = RADIUS OF HIGH PRESSURE POCKET AT ORIFICE (IN)
C     RLP = RADIUS OF LOW PRESSURE POCKET AT ORIFICE (IN)
C     RHANN = OUTER ANNULUS RADIUS ON HIGH PRESSURE SIDE (IN)
C     RLANN = OUTER ANNULUS RADIUS ON LOW PRESSURE SIDE (IN)
C     RSD = SHAFT LABYRINTH INLET RADIUS (IN)
C     RSDH = SHAFT LABYRINTH OUTLET RADIUS (IN)
C     RH1S = HIGH PRESSURE SIDE SHAFT RADIUS (IN)
C     RL1S = LOW PRESSURE SIDE SHAFT RADIUS (IN)
C     RR1 = RETURN LINE RADIUS (IN)
      READ (5,30)RH1,RH2,RH3,RH4,RH5,RH6
      READ (5,30)RH7,RH8,RH9,RL1,RL2,RL3
      READ (5,30)RL4,RL5,RL6,RL7,RL8,RL9
      READ (5,30)RHP,RLP,RHANN,RLANN,RSD,RSDH
      READ (5,30)RH1S,RL1S,RR1
C     HH1S = HIGH PRESSURE SIDE SHAFT CLEARANCE (IN)
C     HL1S = LOW PRESSURE SIDE SHAFT CLEARANCE (IN)
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C     XLL8 = LOW PRESSURE CAVITY LENGTH (IN)
C     XLH8 = HIGH PRESSURE CAVITY LENGTH (IN)
C     DHSHP = HIGH PRESSURE ORIFICE DIAMETER (IN)
C     DLSLP = LOW PRESSURE ORIFICE DIAMETER (IN)
C     CHSHP = HIGH PRESSURE ORIFICE DISCHARGE COEFFICIENT
C     CLSLP = LOW PRESSURE ORIFICE DISCHARGE COEFFICIENT
C     DHS = DIAMETER OF HIGH PRESSURE SUPPLY LINE (IN)
C     DLS = DIAMETER OF LOW PRESSURE SUPPLY LINE (IN)
C     PHS = HIGH PRESSURE SUPPLY PRESSURE (LB/IN**2)
C     PLS = LOW PRESSURE SUPPLY PRESSURE (LB/IN**2)
C     PBPR1 = EXIT PRESSURE (LB/IN**2)
C     PSD = SHAFT LABYRINTH PRESSURE (LB/IN**2)
C     THS = HIGH PRESSURE SUPPLY TEMPERATURE (DEG R)
C     TLS = LOW PRESSURE SUPPLY TEMPERATURE (DEG R)
C     XNHSHP = NUMBER OF HIGH PRESSURE ORIFICES
C     XNLSLP = NUMBER OF LOW PRESSURE ORIFICES
      READ (5,30)HH1S,HL1S,XLL8,XLH8
C     ORIFICE DIAMETER (IN), ORIFICE DISCHARGE COEF., SUPPLY LINE
C     DIAMETER (IN)
      READ (5,30)DHSHP,DLSLP,CHSHP,CLSLP,DHS,DLS
C     PRESSURES AND SUPPLY TEMPERATURES
      READ (5,30)PHS,PLS,PBPR1,PSD,THS,TLS
C     CH5H6 = FLUID ROTATION FACTOR FOR OUTWARD FLOW SILL ENTRANCE LOSS
C             ON HIGH PRESSURE SIDE
C     CH7H8 = FLUID ROTATION FACTOR FOR OUTWARD FLOW SILL EXIT LOSS
C             ON HIGH PRESSURE SIDE
C     CH4H3 = FLUID ROTATION FACTOR FOR INWARD FLOW SILL ENTRANCE LOSS
C             ON HIGH PRESSURE SIDE
C     CH2H1 = FLUID ROTATION FACTOR FOR INWARD FLOW SILL EXIT LOSS
C             ON HIGH PRESSURE SIDE
C     CL5L6 = FLUID ROTATION FACTOR FOR LOW PRESSURE OUTWARD FLOW SILL
C             ENTRANCE LOSS
C     CL7L8 = FLUID ROTATION FACTOR FOR LOW PRESSURE OUTWARD FLOW SILL
C             EXIT LOSS
C     CL4L3 = FLUID ROTATION FACTOR FOR LOW PRESSURE INWARD FLOW SILL
C             ENTRANCE LOSS
C     CL2L1 = FLUID ROTATION FACTOR FOR LOW PRESSURE INWARD FLOW SILL
C             EXIT LOSS
      READ (5,30)XNHSHP,XNLSLP,CH5H6,CH7H8,CH4H3,CH2H1
      READ (5,30)CL5L6,CL7L8,CL4L3,CL2L1
C     HL1SD = SHAFT LABYRINTH TOOTH CLEARANCE (IN)
C     HEL1SD = SHAFT LABYRINTH VALLEY DEPTH (IN)
C     XLL1SD = SHAFT LABYRINTH OVERALL LENTH (IN)
C     XNL1SD = NUMBER OF SHAFT LABYRINTH SEALING POINTS
C     PL1SD = SHAFT LABYRINTH PITCH (IN)
C     XL1SD = SHAFT LABYRINTH SEALING POINT WIDTH (IN)
C     CL1SD = SHAFT LABYRINTH DISCHARGE COEFFICIENT
C     XNH1R1 = NUMBER OF HIGH PRESSURE RETURN LINES
C     XLH1R1 = LENGTH OF HIGH PRESSURE RETURN LINES (IN)
C     XNL1R1 = NUMBER OF LOW PRESSURE RETURN LINES
C     XLL1R1 = LENGTH OF LOW PRESSURE RETURN LINES (IN)
C     XNH8R1 = NUMBER OF RETURN LINES
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C     XLH8R1 = LENGTH OF RETURN LINES (IN)
C     RH8R1 = RADIUS OF RETURN LINES (IN)
      READ (5,30)HL1SD,HEL1SD,XLL1SD,XNL1SD,PL1SD,XL1SD
C     SHAFT LABYRINTH DISCHARGE COEF. AND RETURN LINES
      READ (5,30)CL1SD,XNH1R1,XLH1R1,XNL1R1,XLL1R1
C     ANNULUS LINE
      READ (5,30)XNH8R1,XLH8R1,RH8R1
C     PRINT INPUT DATA FOR PARALLEL BALANCER
      WRITE (6,430)PHS,PLS,PBPR1,RH1,RH5,RL1,RL5,RH2,RH6,RL2,RL6,RH3,
     1RH7,RL3,RL7,RH4,RH8,RL4,RL8,RHP,RLP,RL1S
  430 FORMAT(1H0/29H0PARALLEL BALANCER INPUT DATA /21H0PRESSURES (LB/IN*
     1*2) /1H ,5X, 5HPHS = ,1P1D15.4,10X, 5HPLS = ,D15.4, 10X,  7HPBPR1
     2= ,D13.4/11H RADII (IN) / 1H ,5X, 5HRH1 = ,D15.4, 10X, 5HRH5 = ,
     3D15.4, 10X, 5HRL1 = ,D15.4,10X, 5HRL5 = ,D15.4/ 1H ,5X, 5HRH2 = ,
     4D15.4,10X, 5HRH6 = ,D15.4,10X, 5HRL2 = ,D15.4,10X, 5HRL6 = ,D15.4/
     5 1H , 5X, 5HRH3 = ,D15.4,10X, 5HRH7 = ,D15.4, 10X, 5HRL3 = ,D15.4,
     6  10X, 5HRL7 = ,D15.4/ 1H , 5X, 5HRH4 = ,D15.4,10X, 5HRH8 = ,D15.4
     7 ,10X, 5HRL4 = ,D15.4,10X,5HRL8 = ,D15.4 / 1H ,5X, 5HRHP = ,D15.4
     8 ,40X, 5HRLP = ,D15.4, 10X, 6HRL1S = ,D14.4)
      WRITE (6,440)HT,HDHP,HDLP,HH1S,HL1S,XLH8,XLL8,DHSHP,DLSLP,CHSHP,
     1 CLSLP,HL1SD,HEL1SD,XLL1SD,PL1SD,XL1SD,XNL1SD,CL1SD
  440 FORMAT(16H CLEARANCES (IN) /1H ,5X, 4HHT = ,1P1D16.4,10X,  6HHDHP
     1= ,D14.4,10X,6HHDLP = ,D14.4,10X,6HHH1S = ,D14.4/ 1H ,5X ,6HHL1S =
     2 ,D14.4,10X,5HLH8 = ,D15.4,10X, 5HLL8 = ,D15.4/21H ORIFICE COMPENS
     3ATION / 1H ,5X,13HDIAMETER (IN) , 57X,21HDISCHARGE COEFFICIENT /
     41H ,5X,7HDHSHP =,D13.4, 10X,7HDLSLP = ,D13.4,10X, 7HCHSHP = , D13.
     54,10X, 7HCLSLP = ,D13.4/16H SHAFT LABYRINTH /1H ,5X, 29HTOOTH CLEA
     6RANCE, HL1SD (IN) = ,D15.4/ 1H , 5X,27HVALLEY DEPTH, HEL1SD (IN) =
     7 ,D15.4/ 1H ,5X,28HOVERALL LENGTH, LL1SD (IN) = ,D15.4/ 1H , 5X,
     819HPITCH, PL1SD (IN) = ,D15.4/ 1H ,5X,25HPOINT WIDTH, XL1SD (IN) =
     9,D15.4 /                       1H ,5X,25HNUMBER OF POINTS, NL1SD =
     A,D15.4 / 1H ,5X,29HDISCHARGE COEFFICIENT CL1SD = ,D15.4)
      WRITE (6,450)CH5H6,CH7H8,CH4H3,CH2H1,CL5L6,CL7L8,CL4L3,CL2L1
  450 FORMAT(18H FLOW COEFFICIENTS          / 1H ,5X, 7HCH5H6 = ,D15.4,  8X
     1, 7HCH7H8 = ,D15.4 , 8X, 7HCH4H3 = ,D15.4, 8X, 7HCH2H1 = ,D15.4/
     21H ,5X, 7HCL5L6 = ,D15.4, 8X, 7HCL7L8 = ,D15.4 , 8X, 7HCL4L3 = ,
     3D15.4, 8X, 7HCL2L1 = ,D15.4)
C     ROTATION FACTORS FOR SILL AND POCKET SUBROUTINES
      IF(IKIN.EQ.0)GO TO 470
C     XKHPH5 = FLUID ROTATION FACTOR BETWEEN POCKET AT ORIFICE AND INNER
C              RADIUS OF OUTER POCKET ON HIGH PRESSURE SIDE
C     XKH6H7 = FLUID ROTATION FACTOR BETWEEN OUTER LAND INNER AND OUTER
C              RADIUS ON HIGH PRESSURE SIDE
C     XKHPH4 = FLUID ROTATION FACTOR BETWEEN POCKET AT ORIFICE AND OUTER
C              RADIUS OF INNER POCKET ON HIGH PRESSURE SIDE
C     XKH3H2 = FLUID ROTATION FACTOR BETWEEN INNER LAND INNER AND OUTER
C              RADIUS ON HIGH PRESSURE SIDE
C     XKLPL5 = FLUID ROTATION FACTOR BETWEEN POCKET AT ORIFICE AND INNER
C              RADIUS OF OUTER POCKET ON LOW PRESSURE SIDE
C     XKL6L7 = FLUID ROTATION FACTOR BETWEEN OUTER LAND INNER AND OUTER
C              RADIUS ON LOW PRESSURE SIDE
C     XKLPL4 = FLUID ROTATION FACTOR BETWEEN POCKET AT ORIFICE AND OUTER
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C               RADIUS OF INNER POCKET ON LOW PRESSURE SIDE
C        XKL3L2 = FLUID ROTATION FACTOR BETWEEN INNER LAND INNER AND OUTER
C               RADIUS ON LOW PRESSURE SIDE
         READ (5,30)XKHPH5,XKH6H7,XKHPH4,XKH3H2,XKLPL5,XKL6L7
         READ (5,30)XKLPL4,XKL3L2
         WRITE (6,460)XKHPH5,XKH6H7,XKHPH4,XKH3H2,XKLPL5,XKL6L7,XKLPL4,
        1 XKL3L2
  460    FORMAT(1H ,5X, 7HKHPH5 = ,1P1D15.4, 8X,7HKH6H7 = ,D15.4, 8X, 7HKHP
        1H4 = ,D15.4, 8X, 7HKH3H2 = ,D15.4/1H , 5X, 7HKLPL5 = ,D15.4, 8X,
        2 7HKL6L7 = ,D15.4, 8X, 7HKLPL4 = ,D15.4,8X,7HKL3L2 = ,D15.4)
         GO TO 550
  470    IF(XNRPM.NE.0.)GO TO 550
         IKIN=1
         XKHPH5=0.
         XKH6H7=0.
         XKHPH4=0.
         XKH3H2=0.
         XKLPL5=0.
         XKL6L7=0.
         XKLPL4=0.
         XKL3L2=0.
         GO TO 550
C
C        SERIES PISTON CASE
C
  480    CONTINUE
C        RADII (IN)
C        RHCL = CENTERLINE INNER RADIUS FOR HIGH PRESSURE INNER POCKET (IN)
C        HH9 = HIGH PRESSURE OUTER CAVITY CLEARANCE (IN)
         READ (5,30)RL1,RL2,RL3,RL4,RL8,RL9
         READ (5,30)RH5,RH6,RH7,RH8,RH9,RSD
         READ (5,30)RHP,RHANN,RLANN,RR1,RL1S,RL7
C        HL9 = LOW PRESSURE OUTER CAVITY CLEARANCE (IN)
C        HSD = SEALING DISCHARGE CLEARANCE (IN)
C        HH9L9 = PISTON LABYRINTH TOOTH CLEARANCE (IN)
C        HEH9L9 = PISTON LABYRINTH VALLEY DEPTH (IN)
C        XLH9L9 = PISTON LABYRINTH OVERALL LENGTH (IN)
C        XNH9L9 = NUMBER OF PISTON LABYRINTH SEALING POINTS
C        PH9L9 = PISTON LABYRINTH PITCH (IN)
C        XH9L9 = PISTON LABYRINTH SEALING POINT WIDTH (IN)
C        CH9L9 = PISTON LABYRINTH DISCHARGE COEFFICIENT
C        WHPH1S = HIGH PRESSURE INNER POCKET FLOWRATE (LB/SEC)
C        HH8L8 = ANNULUS CLEARANCE (IN)
C        XLH8L8 = ANNULUS LENGTH (IN)
C        XKHPH1 = FLUID ROTATION FACTOR BETWEEN POCKET AT ORIFICE AND INNER
C               RADIUS OF INNER POCKET ON HIGH PRESSURE SIDE
         READ (5,30)RHCL,RSDH,HH9,HL9,HSD
C        CLEARANCES AND SHAFT LABYRINTH
         READ (5,30)HL1S,HL1SD,HEL1SD,XLL1SD,XNL1SD
C        PISTON LABYRINTH AND ORIFICE DIAMETER (IN)
         READ (5,30)PL1SD,XL1SD,CL1SD,HH9L9,HEH9L9,XLH9L9
C        SHAFT LABYRINTH AND PISTON LABYRINTH
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      READ (5,30)XNH9L9,PH9L9,XH9L9,CH9L9,DHSHP,CHSHP
C     ORIFICE DISCHARGE COEF., NUMBER OF ORIFICES, AND PRESSURES
      READ (5,30)XNHSHP,PHS,PBPR1,PSD,DHS
C     FLUID ROTATION FACTORS AND RETURN LINE
      READ (5,30)CH5H6,CH7H8,CL7L8,CL4L3,CL2L1
C     SUPPLY TEMPERATURE
      READ (5,30)XNL1R1,XLL1R1,WHPH1S,THS,HH8L8,XLH8L8
C     PRINT INPUT DATA FOR SERIES BALANCER
      WRITE (6,490)PHS,PBPR1,RSD,RL4,RHP,RH7,RL1,RL8,RH5,RH8,RL2,RL9,
     1 RH6,RH9,RL3
  490 FORMAT(1H0/ 27H0SERIES BALANCER INPUT DATA /21H0PRESSURES (LB/IN**
     12) /1H ,5X, 5HPHS = ,1P1D15.4,10X, 7HPBPR1 = ,D13.4/11H RADII (IN)
     2 / 1H ,5X, 5HRSD = ,D15.4,10X,5HRL4 = ,D15.4, 10X, 5HRHP = ,D15.4,
     3 10X, 5HRH7 = ,D15.4 /1H ,5X,5HRL1 = ,D15.4,10X,5HRL8 = ,D15.4,10X
     4, 5HRH5 = ,D15.4,10X, 5HRH8 = ,D15.4/1H ,5X,5HRL2 = ,D15.4,10X,
     5 5HRL9 = ,D15.4, 10X, 5HRH6 = ,D15.4, 10X, 5HRH9 = ,D15.4 /1H ,5X,
     6 5HRL3 = ,D15.4)
      WRITE (6,500)HT,HDHP,HDLP,HH9,HL9,HL1S,DHSHP,CHSHP
  500 FORMAT(16H CLEARANCES (IN) /1H ,5X 4HHT = ,1P1D16.4,10X,6HHDHP = ,
     1 D14.4,10X, 6HHDLP = ,D14.4,10X, 5HHH9 = ,D15.4/1H ,5X, 5HRL9 = ,
     2 D15.4,10X, 6HHL1S = ,D14.4/21H ORIFICE COMPENSATION /1H ,5X,13HDI
     3AMETER (IN), 27X, 21HDISCHARGE COEFFICIENT /1H ,5X,7HDHSHP = ,
     4D13.4,10X, 7HCHSHP = ,D13.4)
      WRITE (6,510)HH9L9,HL1SD,HEH9L9,HEL1SD,XLH9L9,XLL1SD,PH9L9,PL1SD,
     1 XH9L9,XL1SD,XNH9L9,XNL1SD,CH9L9,CL1SD
  510 FORMAT(11H LABYRINTHS ,21X, 6HPISTON ,26X, 5HSHAFT /1H ,5X,21HTOOT
     1H CLEARANCE (IN),,5X, 7HHH9L9 = ,1P1D15.4,10X,7HHL1SD = ,D15.4 /
     2 1H ,5X,18HVALLEY DEPTH (IN), ,8X,8HHEH9L9 = ,D14.4,10X,8HHEL1SD =
     3 ,D14.4/ 1H ,5X, 20H0VERALL LENGTH (IN), ,6X, 7HLH9L9 = ,D15.4,10X
     4,7HLL1SD = ,D15.4/ 1H ,5X, 11HPITCH (IN), ,15X, 7HPH9L9 = ,D15.4,
     5 10X, 7HPL1SD = ,D15.4/ 1H ,5X, 17HPOINT WIDTH (IN), ,9X, 7HXH9L9
     6= ,D15.4,10X, 7HXL1SD = ,D15.4/ 1H ,5X, 17HNUMBER OF POINTS, ,9X,
     7 7HNH9L9 = ,D15.4,10X, 7HNL1SD = ,D15.4/ 1H ,5X, 22HDISCHARGE COEF
     8FICIENT, ,4X, 7HCH9L9 = ,D15.4,10X, 7HCL1SD = ,D15.4)
      WRITE (6,520)CH5H6,CH7H8,CL7L8,CL4L3,CL2L1
  520 FORMAT(18H FLOW COEFFICIENTS      /1H ,5X,7HCH5H6 = ,1P1D15.4,8X,
     1 7HCH7H8 = ,D15.4, 8X, 7HCL7L8 = ,D15.4,8X, 7HCL4L3 = ,D15.4/1H
     2 5X, 7HCL2L1 = ,D15.4)
C     ROTATION FACTORS FOR SILL AND POCKET SUBROUTINES
      IF(IKIN.EQ.0)GO TO 540
C     XKL7L4 = FLUID ROTATION FACTOR FOR INWARD POCKET FLOW CALCULATION
C              ON LOW PRESSURE SIDE
      READ (5,30)XKHPH5,XKH6H7,XKL7L4,XKL3L2,XKHPH1
      WRITE(6,530)XKHPH5,XKH6H7,XKL7L4,XKL3L2,XKHPH1
  530 FORMAT(1H ,5X, 7HKHPH5 = ,1P1D15.4, 8X, 7HKH6H7 = ,D15.4,8X, 7HKL7
     1L4 = ,D15.4, 8X, 7HKL3L2 = ,D15.4/1H ,5X, 7HKHPH1 = ,D15.4)
      GO TO 550
  540 IF(XNRPM.NE.0.)GO TO 550
      IKIN=1
      XKHPH5=0.
      XKH6H7=0.
      XKL7L4=0.
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      XKL3L2=0.
      XKHPH1=0.
C
C     FORCE PISTON
C
  550 CONTINUE
C     PRESSURES
C     NFS  = NUMBER OF FORCE PISTON SUPPLY PRESSURE INCREMENTS (MAX 20)
C     PFSMIN = MINIMUM FORCE PISTON SUPPLY PRESSURE (LB/IN**2)
C     PFSMAX = MAXIMUM FORCE PISTON SUPPLY PRESSURE (LB/IN**2)
C     PFS(N) = FORCE PISTON SUPPLY PRESSURE (LB/IN**2)
C     PC2 = FORCE PISTON CAVITY PRESSURE (LB/IN**2)
C     PEXH = FORCE PISTON TURBINE PRESSURE (LB/IN**2)
C     PFPR1 = FORCE PISTON RETURN PRESSURE (LB/IN**2)
C     XNFSFP = NUMBER OF ORIFICES
C     DFSFP = ORIFICE DIAMETER (IN)
C     CFSFP = ORIFICE DISCHARGE COEFFICIENT
C     TFS = FORCE PISTON SUPPLY TEMPERATURE (DEG F)
C     DFS = SUPPLY LINE DIAMETER (IN)
C     RFP = INNER POCKET RADIUS AT ORIFICE (IN)
C     RF1 = OUTER POCKET RADIUS (IN)
C     RFTS = TURBINE RADIUS (IN)
C     HFP = AXIAL CLEARANCE AT INNER POCKET DIAMETER (IN)
C     HF1 = AXIAL CLEARANCE AT OUTER POCKET DIAMETER (IN)
C     HF1C1 = FIRST LABYRINTH CLEARANCE (IN)
C     HEF1C1 = FIRST LABYRINTH POCKET DEPTH (IN)
C     XLF1C1 = FIRST LABYRINTH LENGTH (IN)
C     XNF1C1 = NUMBER OF FIRST LABYRINTH LANDS
C     PF1C1 = FIRST LABYRINTH PITCH (IN)
C     XF1C1 = FIRST LABYRINTH LAND WIDTH (IN)
C     HC1C2 = SECOND LABYRINTH CLEARANCE (IN)
C     HEC1C2 = SECOND LABYRINTH POCKET DEPTH (IN)
C     XLC1C2 = SECOND LABYRINTH LENGTH (IN)
C     XNC1C2 = NUMBER OF SECOND LABYRINTH LANDS
C     PC1C2 = SECOND LABYRINTH PITCH (IN)
C     XC1C2 = SECOND LABYRINTH LAND WIDTH (IN)
C     CF1C1 = FIRST LABYRINTH DISCHARGE COEFFICIENT
C     CC1C2 = SECOND LABYRINTH DISCHARGE COEFFICIENT
C     XNC1R1 = NUMBER OF RETURN LINES
C     XLC1R1 = RETURN LINE LENGTH (IN)
C     RC1R1 = RETURN LINE RADIUS (IN)
      READ (5,30) XNFS,PFSMIN,PFSMAX,PC2,PEXH,PFPR1
      NFS=XNFS+.1
      IF(NFS.LE.20)GO TO 570
      WRITE (6,560)NFS
  560 FORMAT(1H0/ 89H0THE MAXIMUM NUMBER OF FORCE PISTON SUPPL PRESSURE
     1INCREMENTS IS 20.  THE INPUT NUMBER IS ,I6)
      STOP
  570 CONTINUE
C     FORCE PISTON PRESSURE
      IF(NFS.NE.0)GO TO 580
      DFS=0.D0
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      GO TO 590
  580 CONTINUE
      DFS=(PFSMAX-PFSMIN)/DFLOAT(NFS)
  590 CONTINUE
      NFS=NFS+1
      DO 600 N=1,NFS
      PFS(N)=PFSMIN+DFLOAT(N-1)*DFS
  600 CONTINUE
C     ORIFICE VALUES, SUPPLY TEMPERATURE AND LINE DIAMETER
      READ (5,30)XNFSFP,DFSFP,CFSFP,TFS,DFS,C12
C     RADII AND CLEARANCES
      READ (5,30)RFP,RF1,RFTS,HFP,HF1
C     FIRST LABYRINTH
      READ (5,30)HF1C1,HEF1C1,XLF1C1,XNF1C1,PF1C1,XF1C1
C     SECOND LABYRINTH
      READ (5,30)HC1C2,HEC1C2,XLC1C2,XNC1C2,PC1C2,XC1C2
C     LABYRINTH COEF. AND LINE VALUES
      READ (5,30)CF1C1,CC1C2,XNC1R1,XLC1R1,RC1R1
      RETURN
  610 STOP
      END
      SUBROUTINE SPROP
C
C     SERIES FLOW PRESSURE PROPERTIES
C
C     M = SILL CLEARANCE SUBSCRIPT
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL1
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,
     5 GL2(21), CPL2(21), XMUL2(21)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4       ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1        NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2        NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3        NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4       ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1        RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2        RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3        XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4        PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5        CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6        XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
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     7       ,XNH8R1, XLH8R1, RH8R1
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,
     1        XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8
     2       ,WHPHIS
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /MAIN1/ M
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1       ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2        PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3                 PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4       ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5        PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1        XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2        REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, DUM1 , GH6H7(21),
     3        CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4        REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5        NML7(21), WLPL8, DUM2 , GL3L2(21), CML2(21), UDL2(21),
     6        REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1        GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2        RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /SPARL/ XKP(20), XKBP(20)
      COMMON /SHP/ VRL1, VRSD, GH8L8, UDH8L8, GH9L9
      COMMON /FSER/ PH1S(20), TH1S(20), GL7L4, XKL7L4, TH9(20),PH9(20)
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /OUTP2/ GH9,CPH9, XMUH9, REL7L4, REH8L8, REH9L9, REH8H9
      COMMON /PGUES/ C11
      COMMON /GTRAN/ GHPH1S
      COMMON /ERPRNT/ IERRT
      DIMENSION VRH7(21), VH7(21), VRL2(21),VL2(21)
      EQUIVALENCE (WHSHP,WHPH8,WHPH1,WLPL1)
C
C     HIGH PRESSURE SIDE
C
C     HIGH PRESSURE SUPPLY VALUES
      CALL DBLIN(PHS,THS,GHS,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 150
   10 CONTINUE
      CALL  DBLIN(PHS,THS,CPHS,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 190
   20 CONTINUE
      CALL DBLIN(PHS,THS,XMUHS,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 210
   30 CONTINUE
      PDENH=PHS-PBPR1
      DPDENH=DSQRT(PDENH)
C     HIGH PRESSURE POCKET CONDITIONS
      PHP(M)=PHS+C11*(PBPR1-PHS)*((HH7(M)/HT)**1.5)
      CALL ORIF(PHS,THS,GHS,CPHS,PHP(M),XNHSHP,CHSHP,DHSHP,DHS,RHP,HHP(M
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     1),WHSHP,THP(M),GHP,CPHP,XMUHP)
      IF(IERRT.GE.5)RETURN
C     SILL RADII
C
C     FLOW APPROXIMATIONS
C
C     VELOCITY CONSTANTS
C
      CVHP=PI2*RHP*HHP(M)
      UHP=PI60*RHP*XNRPM
      UHP2=UHP*UHP
      HH8=(RHANN*RHANN/RH7-RH7)*P5
      HL8=(RLANN*RLANN/RL7-RL7)*P5
      HL1=P5*(RL1S+RL2)*HL1S/RL2
      CTH9=(RH9*RH9-RH8*RH8)*PI/(CHL*CT2)
      RH9L9=RH9-HEH9L9
      CVH9=PI2*HEH9L9*RH9L9
      UH9=PI60*RH9L9*XNRPM
      UH92=UH9*UH9
      UL8=PI60*RL8*XNRPM
      CVL8=PI2*RL8*HL8
      UL82=UL8*UL8
C
C     ITERATION ON PRESSURES - HIGH PRESSURE INWARD AND OUTWARD RETURN
C                              LOW PRESSURE INWARD AND OUTWARD RETURN
C
      DO 120 N=1,ITERP
C
C     OUTWARD FLOW
C
      VHPO=WHPH8/(CVHP*GHP)
      VRHPO=DSQRT(VHPO*VHPO+UHP2)
      CALL PKT(PHP(M),THP(M),GHP,CPHP,WHPH8,RHP,HHP(M),RH5,VRHPO,XMUHP,
     1 PH5(M),TH5(M),GH5,CPH5,VH5,UH5,XMUH5,VRH5,REHPH5,GHPH5,XKHPH5,0)
      IF(IERRT.GE.5)RETURN
      CALL ENTS(PH5(M),TH5(M),GH5,CPH5,VRH5,HHP(M),WHPH8,RH6,HH7(M),
     1 CH5H6,PH6(M),TH6(M),GH6,CPH6,VH6,VRH6,XMUH6,UH6)
      IF(IERRT.GE.5)RETURN
C     VELOCITIES
C     POCKET PRESSURE
C     SILL ENTRANCE LOSS
C     OUTER SILL
      CALL SILL(PH6(M),TH6(M),GH6,CPH6,XMUH6,RH6,VRH6,WHPH8,RH7,HH7(M),
     1 VH6,DUM,PH7(1,M),TH7(1,M),GH7,CPH7,XMUH7,XKH6H7,RH7I,REH7,VH7,
     2 VRH7,UDH7,GH6H7,CMH7,NMH7,NH7I,0)
      IF(IERRT.GE.5)RETURN
C     SILL EXIT LOSS
      CALL ENTS(PH7(NH7I,M),TH7(NH7I,M),GH7(NH7I),CPH7(NH7I),VRH7(NH7I),
     1 HH7(M),WHPH8,RH8,HH8,CH7H8,PH8(M),TH8(M),GH8,CPH8,VH8,VRH8,XMUH8,
     2 UH8)
      IF(IERRT.GE.5)RETURN
C     CHECK IF LABYRINTH
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      IF(XNH9L9.NE.0.)GO TO 40
C     ANNULUS CALCULATION
      CALL ANNP(PH8(M),TH8(M),GH8,CPH8,XMUH8,WHSHP,VH8,VRH8,RH8,HH8L8,
     1 XLH8L8,RL8,PL8(M),TL8(M),GL8,CPL8,XMUL8,UH8L8,UDH8L8,VL8,VRL8,
     2 REH8L8,GH8L8)
      IF(IERRT.GE.5)RETURN
      GO TO 100
C
C     ANNULUS TEMPERATURE RISE
   40 CONTINUE
      REH8H9=GH8*VRH8*HH8/(GVTY*XMUH8)
      IF(REH8H9.GT.2000.)GO TO 50
      CM=CMLAM
      NM=NMLAM
      GO TO 60
   50 CM=CMTUR
      NM=NMTUR
   60 CONTINUE
      UDH8=UH8*2.
      TH9(M)=TH8(M)+CTH9*CM*GH8*(UDH8**3)/(CPH8*WHSHP*(REH8H9**NM))
C     LABYRINTH VELOCITIES
      VH9=WHSHP/(GH8*CVH9)
      VRH9=DSQRT(UH92+VH9*VH9)
C     LABYRINTH CALCULATIONS
      PH9(M)=PH8(M)
      CALL DBLIN(PH9(M),TH9(M),GH9,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 230
   70 CONTINUE
      CALL DBLIN(PH9(M),TH9(M),CPH9,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,
     1 IERR)
      IF(IERR.EQ.1)GO TO 260
   80 CONTINUE
      CALL DBLIN(PH9(M),TH9(M),XMUH9,PVISC,TVISC,XMVISC,NPVISC,NTVISC,
     1 IERR)
      IF(IERR.EQ.1)GO TO 280
   90 CONTINUE
      CALL LABYP(PH9(M),TH9(M),GH9,CPH9,XMUH9,WHSHP,XNH9L9,PH9L9,XH9L9,
     1 HH9L9,CH9L9,HEH9L9,RH9,VRH9,PL8(M),TL8(M),GL8,CPL8,XMUL8,UH9,UDH9
     2 ,VL9,VRL9,REH9L9,GH9L9)
      IF(IERRT.GE.5)RETURN
C
C     LOW PRESSURE SIDE
C
C     ANNULUS CALCULATIONS
      VL8=WHSHP/(CVL8*GL8)
      VRL8=DSQRT(VL8*VL8+UL82)
C     POCKET CALCULATION
  100 CONTINUE
      CALL ENTS(PL8(M),TL8(M),GL8,CPL8,VRL8,HL8,WHSHP,RL7,HL7(M),CL7L8,
     1 PL7(1,M),TL7(1,M),GL7,CPL7,VL7,VRL7,XMUL7,UL7)
      IF(IERRT.GE.5)RETURN
      CALL PKT(PL7(1,M),TL7(1,M),GL7,CPL7,WHSHP,RL7,HL7(M),RL4,VRL7,
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      1 XMUL7,PL4(M),TL4(M),GL4,CPL4,VL4,UL4,XMUL4,VRL4,REL7L4,GL7L4,
      2 XKL7L4,1)
        IF(IERRT.GE.5)RETURN
        CALL ENTS(PL4(M),TL4(M),GL4,CPL4,VRL4,HLP(M),WLPL1,RL3,HL7(M),
      1 CL4L3,PL3(M),TL3(M),GL3,CPL3,VL3,VRL3,XMUL3,UL3)
        IF(IERRT.GE.5)RETURN
        CALL SILL(PL3(M),TL3(M),GL3,CPL3,XMUL3,RL3,VRL3,WLPL1,RL2,HLP(M),
      1 VL3,RL7,PL2(1,M),TL2(1,M),GL2,CPL2,XMUL2,XKL3L2,RL2I,REL2,VL2,
      2 VRL2,UDL2,GL3L2,CML2,NML2,NL2I,1)
        IF(IERRT.GE.5)RETURN
        CALL ENTS(PL2(NL2I,M),TL2(NL2I,M),GL2(NL2I),CPL2(NL2I),VRL2(NL2I),
      1 HL7(M),WLPL1,RL1,HL1,CL2L1,PL1(M),TL1(M),GL1,CPL1,VL1,VRL1,XMUL1,
      2 UL1)
        IF(IERRT.GE.5)RETURN
C
C       CHECK FOR SEAL OR LABYRINTH
C
        WL1R1=WLPL1
        IF(ISEAL.EQ.0)GO TO 110
C       SHAFT LABYRINTH
        CALL LABYS(PL1(M),TL1(M),GL1,VRL1,CPL1,PSD,PL1SD,XL1SD,HL1SD,
      1 XNL1SD,CL1SD,RSD,RSDH,TSD,GSD,VRSD,CPSD,WL1SD,XMUL1S,GL1SD,
      2 REL1SD,XMUL1)
        WL1R1=WL1R1-WL1SD
        IF(IERRT.GE.5)RETURN
C       RETURN LINE
  110   CONTINUE
        CALL LINE(PL1(M),TL1(M),GL1,CPL1,XMUL1,VRL1,XNL1R1,XLL1R1,WL1R1,
      1 RR1,PL1R1,TL1R1,GL1R1,CPL1R1,XMUL1R,VRL1R1,REL1R1)
        IF(IERRT.GE.5)RETURN
        IF(DABS(1.-(PHS-PL1R1)/PDENH).LE.CLOS)GO TO 140
C
C       CALCULATE NEXT FLOW APPROXIMATIONS
C
        XKBPS=WHSHP/DSQRT(PHS-PL1R1)
        XKORF=WHSHP/DSQRT(PHS-PHP(M))
        WHSHP=XKBPS*DPDENH
C       HIGH PRESSURE APPROXIMATIONS
        PHP(M)=PHS-(WHSHP/XKORF)**2
  120   CONTINUE
        WRITE (6,130)ITERP,PHP(M)
  130   FORMAT(1H0/ 79H0THE SERIES PROPERTIES PRESSURE CALCULATIONS DID NO
      1T CONVERGE IN THE MAXIMUM OF ,I4,1X,11HITERATIONS. /42H THE FINAL
      2HIGH PRESSURE POCKET PRESSURE = ,1P1D15.4)
        IERRT=10
        RETURN
  140   CONTINUE
C       HIGH PRESSURE INNER POCKET
        VHPI=WHPH1S/(CVHP*GHP)
        VRHPI=DSQRT(VHPI*VHPI+UHP2)
        CALL PKT(PHP(M),THP(M),GHP,CPHP,WHPH1S,RHP,HHP(M),RHCL,VRHPI,XMUHP
      1,PH1S(M),TH1S(M),GH1S,CPH1S,VH1S,UH1S,XMUH1S,VRH1S,REH1S,GHPH1S,
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    2 XKHPH1,1)
      RETURN
  150 WRITE (6,160)
  160 FORMAT(1H0/ 94H0THE HIGH PRESSURE SUPPLY VALUES FOR DENSITY TABLE
     1INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
  170 WRITE (6,180)PHS,THS
  180 FORMAT(11H PRESSURE = ,1P1D15.4 /14HTEMPERATURE = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 10
  190 WRITE (6,200)
  200 FORMAT(1H0/100H0THE HIGH PRESSURE SUPPLY VALUES FOR SPECIFIC HEAT
     1TABLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE.  )
      WRITE (6,180)PHS,THS
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 20
  210 WRITE (6,220)
  220 FORMAT(1H0/ 96H0THE HIGH PRESSURE SUPPLY VALUES FOR VISCOSITY TABL
     1E INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,180)PHS,THS
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 30
  230 WRITE (6,240)
  240 FORMAT(1H0/ 90H0THE SERIES LABYRINTH VALUES FOR DENSITY TABLE INTE
     1RPOLATION WERE OUTSIDE THE TABLE RANGE.  )
  250 WRITE (6,180)PH9(M),TH9(M)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 70
  260 WRITE (6,270)
  270 FORMAT(1H0/ 96H0THE SERIES LABYRINTH VALUES FOR SPECIFIC HEAT TABL
     1E INTERPOLATION WERE OUTSIDE THE TABLE RANGE.  )
      WRITE (6,180)PH9(M),TH9(M)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 80
  280 WRITE (6,290)
  290 FORMAT(1H0/ 92H0THE SERIES LABYRINTH VALUES FOR VISCOSITY TABLE IN
     1TERPOLATION WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,180)PH9(M),TH9(M)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 90
      END
      SUBROUTINE SFORCE
C
C     SERIES PISTON FORCE CALCULATION
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
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     1      NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2      NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3      ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1      RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2      RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3      XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4      PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5      CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6      XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7      ,XNH8R1, XLH8R1, RH8R1
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,
     1      XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8
     2      ,WHPH1S
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1      CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /MAIN1/ M
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1      ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2      PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3              PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4      ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5      PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1      GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2      RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /FSER/ PH1S(20), TH1S(20), GL7L4, XKL7L4, TH9(20),PH9(20)
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /GTRAN/ GHPH1S
      RHP2=RHP*RHP
      PI40=PI4/GVTY*OMEGAD*OMEGAD
C     HIGH PRESSURE SIDE
      FP(1)=PH1S(M)*PI*RHP2+PI40*GHPH1S*(XKHPH1*(RHP2-RHCL*RHCL))**2
      RD=RH5*RH5-RHP2
      FP(2)=RD*(PI*PHP(M)+RD*PI40*GHPH5*XKHPH5*XKHPH5)
      RHM=RH6
      RHM2=RH6*RH6
      PHM=PH6(M)
      FP(3)=0.
      DO 10 I=1,NH7I
      RH22=RH7I(I)*RH7I(I)
      FP(3)=FP(3)+PI*(PHM*(RH22-RHM2)+(PH7(I,M)-PHM)*(2.*RH22-RH7I(I)*
     1 RHM -RHM2)/3.)
      RHM=RH7I(I)
      RHM2=RH22
      PHM=PH7(I,M)
   10 CONTINUE
      FP(4)=PH8(M)*PI*(RH9*RH9-RH7*RH7)
      FP(5)=PL8(M)*PI*(RL9*RL9-RL7*RL7)
      FP(5)=-FP(5)
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      RD=RL7*RL7-RL4*RL4
      FP(6)=RD*(-PI*PL4(M)-RD*PI40*GL7L4*XKL7L4*XKL7L4)
      RHM=RL3
      RHM2=RL3*RL3
      PHM=PL3(M)
      FP(7)=0.
      DO 20 I=1,NL2I
      RH22=RL2I(I)*RL2I(I)
      FP(7)=FP(7)+PI*(PL2(I,M)*(RH22-RHM2)+(PL2(I,M)-PHM)*(2.*RHM2-RHM*
     1 RL2I(I)-RH22)/3.)
      RHM=RL2I(I)
      RHM2=RH22
      PHM=PL2(I,M)
   20 CONTINUE
      FP(8)=-PI*PL1(M)*(RL1*RL1-RL1S*RL1S)
      FPP(M)=0.
      DO 30 I=1,8
      FPP(M)=FPP(M)+FP(I)
   30 CONTINUE
      RETURN
      END
      SUBROUTINE SHORSP
C
C     SERIES FLOW BALANCER HORSEPOWER
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL1
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,
     5 GL2(21), CPL2(21), XMUL2(21)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1       RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2       RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3       XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4       PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5       CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6       XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7      ,XNH8R1, XLH8R1, RH8R1
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,
     1       XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8
     2      ,WHPH1S
      REAL*8 NM
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
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      COMMON /MAIN1/ M
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1       ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2       PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3               PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4       ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5       PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1       XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2       REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),
     3       CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4       REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5       NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),
     6       REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1       GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2       RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /OUTP2/ GH9,CPH9, XMUH9, REL7L4, REH8L8, REH9L9, REH8H9
      COMMON /SHP/ VRL1, VRSD, GH8L8, UDH8L8, GH9L9
      COMMON /FSER/ PH1S(20), TH1S(20), GL7L4, XKL7L4, TH9(20),PH9(20)
      DIMENSION TM(9), XMP(20)
      EQUIVALENCE (WHSHP,WHPH1), (GL8L4,GL7L4), (XMUL9,XMUL8)
C     AVERAGE VISCOSITIES
      XMHPH5=XMUHP+CR*(XMUH5-XMUHP)
C     HIGH PRESSURE POCKET INWARD VELOCITY
      VHP=WHSHP/(PI*HHP(M)*RHP*GHP)
      UHP=PI60*XNRPM*RHP
      UDHP=2.*UHP
      VRHP=DSQRT(UHP*UHP+VHP*VHP)
      REHP=GHP*VRHP*HHP(M)/(XMUHP*GVTY)
      IF(REHP.GT.2000.)GO TO 10
      CM=CMLAM
      NM=NMLAM
      GO TO 20
   10 CM=CMTUR
      NM=NMTUR
   20 CONTINUE
      TM(1)=GHP*CM*PI4G*(UDHP**2)*(RHP**3)/(REHP**NM)
      RHPH5=RHP+RH5
      UDHPH5=PI60*XNRPM*RHPH5
      UHPH5=UDHPH5*.5
      VHPH5=WHSHP/(PI*HHP(M)*RHPH5*GHPH5)
      VRHPH5=DSQRT(UHPH5*UHPH5+VHPH5*VHPH5)
      REHPH5=GHPH5*VRHPH5*HHP(M)/(GVTY*XMHPH5)
      IF(REHPH5.GT.2000.)GO TO 30
      CM=CMLAM
      NM=NMLAM
      GO TO 40
   30 CM=CMTUR
      NM=NMTUR
   40 CONTINUE
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      TM(2)=GHPH5*XKHPH5*PI4G*((UDHPH5*RHPH5)**2)*(RH5-RHP)
     1 /(REHPH5**NM)
C     SILL TORQUE
      TM(3)=0.
      RHM=RH6
      DO 50 I=1,NH7I
      TM(3)=TM(3)+GH6H7(I)*CMH7(I)*((UDH7(I)*(RHM+RH7I(I)))**2)*(-RHM+
     1 RH7I(I))/(REH7(I)**(NMH7(I)))*PI4G
      RHM=RH7I(I)
   50 CONTINUE
C     HIGH PRESSURE OUTSIDE CAVITY
C     CHECK IF LABYRINTH
      IF(XNH9L9.NE.0.)GO TO 80
C     ANNULUS
      XMH8L8=XMUH8+CR*(XMUL8-XMUH8)
      IF(REH8L8.GT.2000.)GO TO 60
      CM=CMLAM
      NM=NMLAM
      GO TO 70
   60 CM=CMTUR
      NM=NMTUR
   70 CONTINUE
      TM(4)=0.
      TM(5)=0.
      TM(6)=GH8L8*CM*PI*((UDH8L8*RL8)**2)*XLH8L8/((REH8L8**NM)*GVTY)
      GO TO 150
   80 CONTINUE
      RH8H9=RH8+RH9
      VH8H9=WHSHP/(PI*HH9*RH8H9*GH8)
      UDH8H9=PI60*XNRPM*RH8H9
      VRH8H9=DSQRT(UDH8H9*UDH8H9*.25+VH8H9*VH8H9)
      REH8H9=GH8*VRH8H9*HH9/(GVTY*XMUH8)
      IF(REH8H9.GT.2000.)GO TO 90
      CM=CMLAM
      NM=NMLAM
      GO TO 100
   90 CM=CMTUR
      NM=NMTUR
  100 CONTINUE
      TM(4)=GH8*CM*PI4G*((UDH8H9*RH8H9)**2)*(RH9-RH8)/(REH8H9**NM)
      VH9L9=WHSHP/(PI2*RH9*GH9L9*HEH9L9)
      UDH9=2.*PI60*XNRPM*RH9
      VRH9L9=DSQRT(VH9L9*VH9L9+.25*UDH9*UDH9)
      XMH9L9=XMUH9+CR*(XMUL9-XMUH9)
      REH9L9=GH9L9*VRH9L9*HEH9L9/(GVTY*XMH9L9)
      IF(REH9L9.GT.2000.)GO TO 110
      CM=CMLAM
      NM=NMLAM
      GO TO 120
  110 CM=CMTUR
      NM=NMTUR
  120 CONTINUE
```

```
      TM(5)=GH9L9*CM*PI4G*((UDH9*RH9)**2)*XLH9L9/(REH9L9**NM)
C     LOW PRESSURE OUTER CAVITY
      RL9L8=RL9+RL8
      VL9L8=WHSHP/(PI*HL9*RL9L8*GL8)
      UDL9L8=PI60*XNRPM*RL9L8
      VRL9L8=DSQRT(VL9L8*VL9L8+.25*UDL9L8*UDL9L8)
      REL9L8=GL8*VRL9L8*HL9/(GVTY*XMUL8)
      IF(REL9L8.GT.2000.)GO TO 130
      CM=CMLAM
      NM=NMLAM
      GO TO 140
  130 CM=CMTUR
      NM=NMTUR
  140 CONTINUE
      TM(6)=GL8*CM*PI4G*(RL9-RL8)*((UDL9L8*RL9L8)**2)/(REL9L8**NM)
C     LOW PRESSURE POCKET
  150 CONTINUE
      RL7L4=RL7+RL4
      UDL7L4=PI60*XNRPM*RL7L4
      IF(REL7L4.GT.2000.)GO TO 160
      CM=CMLAM
      NM=NMLAM
      GO TO 170
  160 CM=CMTUR
      NM=NMTUR
  170 CONTINUE
      TM(7)=GL7L4*CM*PI4G*(RL7-RL4)*((UDL7L4*RL7L4)**2)/(REL7L4**NM)
C     LOW PRESSURE SILL
      TM(8)=0.
      RHM=RL3
      DO 180 I=1,NL2I
      TM(8)=TM(8)+GL3L2(I)*CML2(I)*PI4G*((UDL2(I)*(RHM+RL2I(I))) **2)*
     1 (RL2I(I)-RHM)/(REL2(I)**(NML2(I)))
      RHM=RL2I(I)
  180 CONTINUE
C     LOW PRESSURE INNER CAVITY
      VRL1SD=.5*(VRL1+VRSD)
      REL1SD=GL1*VRL1SD*HSD/(GVTY*XMUL1)
      IF(REL1SD.GT.2000.)GO TO 190
      CM=CMLAM
      NM=NMLAM
      GO TO 200
  190 CM=CMTUR
      NM=NMTUR
  200 CONTINUE
      UDL1SD=OMEGAD*RSD
      TM(9)=GL1*CM*PI4G*(RL1-RSD)*((UDL1SD*(RL1+RSD))**2)/(REL1SD**NM)
C     TOTAL TORQUE AND HORSEPOWER ON SERIES PISTON
      XMP(M)=0.
      DO 210 I=1,9
      XMP(M)=XMP(M)+TM(I)
  210 CONTINUE
```

```
      HPP(M)=XMP(M)*XNRPM/63000.
      RETURN
      END
      SUBROUTINE SOUT
C
C     SERIES PISTON OUTPUT OF FLUID PROPERTIES, FORCES, AND HORSEPOWER
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,
     1             XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8
     2            ,WHPH1S
      COMMON /IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1             CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /MAIN1/ M
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL1
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,
     5 GL2(21), CPL2(21), XMUL2(21)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1             NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2             NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3             ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4            ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1             RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2             RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3             XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4             PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5             CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6             XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7            ,XNH8R1, XLH8R1, RH8R1
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1            ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2             PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3                    PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4            ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5             PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1             XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2             REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, DUM1 , GH6H7(21),
     3             CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4             REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5             NML7(21), WLPL8, DUM2 , GL3L2(21), CML2(21), UDL2(21),
     6             REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1             GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2             RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
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      COMMON /FSER/ PH1S(20), TH1S(20), GL7L4, XKL7L4, TH9(20),PH9(20)
      COMMCN /OUTP1/ WT(20), WHSHP, WLSLP
      COMMON /OUTP2/ GH9,CPH9, XMUH9, REL7L4, REH8L8, REH9L9, REH8H9
      COMMON /MAIN2/ HL3(20)
      WRITE (6,10)(TITLE(I),I=1,9)
   10 FORMAT(1H1/1H ,45X,27HAEROJET-GENERAL CORPORATION /1H ,49X,19HPROP
     1ULSION DIVISION /1H ,47X,22HSACRAMENTO, CALIFORNIA/15H0PROGRAM E21
     2902 /1H0,9A8)
      BTU=.7073*HPP(M)
      WT(M)=WHPH1
      WRITE (6,20)HL1,HH7(M),WHPH1,BTU
   20 FORMAT( 39H0FLUID STATE - SERIES FLOW            /1H0/17H CLEARA
     1NANCE (IN) , 51X,18HFLOW RATE (LB/SEC) , 10X,25HHEAT GENERATION (B
     2TU/SEC) / 1H ,5X, 5HHL1 = ,1P1D15.4,10X, 5HHH7 = ,D15.4,15X, D15.4
     3,15X,D15.4 )
      WRITE (6,30)
   30 FORMAT(1H ,6X, 8HLOCATION ,7X, 8HPRESSURE , 4X, 11HTEMPERATURE ,8X
     1,7HDENSITY , 2X,13HSPECIFIC HEAT , 6X, 9HVISCOSITY ,7X, 8HREYNOLDS
     2, 7X, 8HROTATION /1H ,19X,10H(LB/IN**2) , 8X, 7H(DEG R) ,5X,10H(LB
     3/IN**3) , 2X,13H(BTU/LB*DEGR) ,1X, 14H(LB*SEC/IN**2) , 9X, 6HNUMBE
     4R , 9X, 6HFACTOR  )
      WRITE (6,40)RL1,PL1(M),TL1(M),GL1,CPL1,XMUL1,REL1R1
   40 FORMAT(4H RL1 ,1P1D11.4, 6D15.4)
      WRITE(6,50)RL2,PL2(NL2I,M),TL2(NL2I,M),GL2(NL2I),CPL2(NL2I),
     1XMUL2(NL2I)
   50 FORMAT(4H RL2 ,1P1D11.4,5D15.4)
      IF(NL2I.EQ.1)GO TO 80
      I=NL2I
      NHM=NL2I-1
      DO 70 IP=1,NHM
      IM=I
      I=NL2I-IP
      WRITE (6,60)PL2(I,M),TL2(I,M),GL2(I),CPL2(I),XMUL2(I),REL2(IM)
   60 FORMAT(1H ,14X,1P6D15.4)
   70 CONTINUE
   80 CONTINUE
      WRITE (6,90)RL3,PL3(M),TL3(M),GL3,CPL3,XMUL3,REL2(1),XKL3L2
   90 FORMAT(4H RL3 ,1P1D11.4,7D15.4)
      WRITE (6,100)RL4,PL4(M),TL4(M),GL4,CPL4,XMUL4
  100 FORMAT(4H RL4 ,1P1D11.4,5D15.4)
      WRITE (6,110)RL7,PL7(1,M),TL7(1,M),GL7(1),CPL7(1),XMUL7(1),REL7L4
     1,XKL7L4
  110 FORMAT(4H RL7 ,1P1D11.4,7D15.4)
      IF(XNH9L9.EQ.0.)GO TO 120
      RE8=REH9L9
      GO TO 130
  120 RE8=REH8L8
  130 CONTINUE
      WRITE (6,140)RL8,PL8(M),TL8(M),GL8,CPL8,XMUL8,RE8
  140 FORMAT(4H RL8 ,1P1D11.4,6D15.4)
      WRITE (6,150)RHP,PHP(M),THP(M),GHP,CPHP,XMUHP
  150 FORMAT(4H RHP ,1P1D11.4,5D15.4)
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      WRITE (6,160)RH5,PH5(M),TH5(M),GH5,CPH5,XMUH5,REHPH5,XKHPH5
  160 FORMAT(4H RH5 ,1P1D11.4,7D15.4)
      WRITE (6,170)RH6,PH6(M),TH6(M),GH6,CPH6,XMUH6
  170 FORMAT(4H RH6 ,1P1D11.4,5D15.4)
      WRITE (6,180)RH7I(1),PH7(1,M),TH7(1,M),GH7(1),CPH7(1),XMUH7(1),
     1 REH7(1),XKH6H7
  180 FORMAT(4H RH7 ,1P1D11.4,7D15.4)
      IF(NH7I.GT.1)WRITE (6,60)(PH7(I,M),TH7(I,M),GH7(I),CPH7(I),
     1XMUH7(I),REH7(I),I=2,NH7I)
      WRITE (6,190)RH8,PH8(M),TH8(M),GH8,CPH8,XMUH8
  190 FORMAT(4H RH8 ,1P1D11.4,5D15.4)
      IF(XNH9L9.NE.0)WRITE (6,200)RH9,PH9(M),TH9(M),GH9,CPH9,XMUH9,
     1 REH8H9
  200 FORMAT(4H RH9 ,1P1D11.4,6D15.4)
      WRITE (6,10)(TITLE(I),I=1,9)
      WRITE (6,210)FPP(M),FP(1),FP(3),FP(5),FP(7),FP(2),FP(4),FP(6),
     1 FP(8)
  210 FORMAT(16HOSERIES BALANCER  /1H0/12H FORCES (LB) , 1P1D15.4/1H  ,5X
     1,5HFS1 = ,D15.4, 10X, 5HFS3 = ,D15.4,10X, 5HFS5 = ,D15.4,10X, 5HFS
     27 = ,D15.4 /1H , 5X, 5HFS2 = ,D15.4,10X, 5HFS4 = ,D15.4,10X, 5HFS6
     3 = ,D15.4,10X, 5HFS8 = ,D15.4)
      RETURN
      END
      SUBROUTINE SSTIF
C
C     SERIES PISTON STIFFNESS
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1             NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2             NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3             ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4            ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1             NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2             NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3             NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4            ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1             RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2             RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3             XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4             PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5             CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6             XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7            ,XNH8R1, XLH8R1, RH8R1
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,
     1             XNH9L9, PH9L9, XH9L9, CH9L9, HH8L8, XLH8L8
     2            ,WHPH1S
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1             CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
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      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1      ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2       PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3              PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4      ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5       PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1       XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2       REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),
     3       CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4       REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5       NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),
     6       REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1       GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2       RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /SPARL/ XKP(20), XKBP(20)
      DIMENSION EBH5(20), EBH6(20), EBH7(20), EBHP(20), EBHPH5(20),
     1 EBH6H7(20), BHPH5(20), BH6H7(20), BHP(20)
      DO 80 M=1,NH
      IF(M.EQ.NH)GO TO 10
      IF(M.NE.1)GO TO 20
      XKP(1)=(FPP(2)-FPP(1))/(HH7(2)-HH7(1))
      GO TO 30
   10 XKP(NH)=(FPP(NH)-FPP(NH-1))/(HH7(NH)-HH7(NH-1))
      GO TO 30
   20 XKP(M)=(FPP(M+1)-FPP(M-1))/(HH7(M+1)-HH7(M-1))
   30 CONTINUE
      XKP(M)=-XKP(M)
      CALL DBLIN(PH5(M),TH5(M),EBH5(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 90
   40 CONTINUE
      CALL DBLIN(PH6(M),TH6(M),EBH6(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 110
   50 CONTINUE
      CALL DBLIN(PH7(NH7I,M),TH7(NH7I,M),EBH7(M),PBULK,TBULK,EBULK,
     1 NPBULK,NTBULK,IERR)
      IF(IERR.EQ.1)GO TO 120
   60 CONTINUE
      CALL DBLIN(PHP(M),THP(M),EBHP(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 130
   70 CONTINUE
      EBHPH5(M)=P5*(EBHP(M)+EBH5(M))
      EBH6H7(M)=P5*(EBH6(M)+EBH7(M))
C     BULK STIFFNESS
      PI7=PI/HH7(M)
      PI7P=PI/(HH7(M)+HHP(M))
      RHP2=RHP*RHP
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      BHPH5(M)=PI7P*EBHPH5(M)*(RH5*RH5-RHP2)                           00007270
      BH6H7(M)=PI7*EBH6H7(M)*(RH7*RH7-RH6*RH6)                         00007275
      BHP(M)=PI7P*RHP2*EBHP(M)                                         00007280
      XKBP(M)=BHPH5(M)+BH6H7(M)+BHP(M)                                 00007285
   80 CONTINUE                                                         00007290
      RETURN                                                           00007295
   90 WRITE (6,100)PH6(M),TH6(M),M                                     00007300
  100 FORMAT(1H0/ 88H0THE STIFFNESS VALVES FOR BULK MODULUS TABLE INTERP00007305
     1OLATION WERE OUTSIDE THE TABLE RANGE. /11H PRESSURE = ,1P1D15.4/ 00007310
     2 14H TEMPERATURE = ,1P1D15.4/29H SILL CLEARANCE SUBSCRIPT M = ,I4)00007315
      GO TO 40                                                         00007320
  110 WRITE (6,100)PH6(M),TH6(M),M                                     00007325
      GO TO 50                                                         00007330
  120 WRITE (6,100)PH7(NH7I,M),TH7(NH7I,M),M                           00007335
      GO TO 60                                                         00007340
  130 WRITE (6,100)PHP(M),THP(M),M                                     00007345
      GO TO 70                                                         00007350
      END                                                              00007355
      SUBROUTINE PPROP                                                 00007360
C                                                                      00007365
C     PARALLEL FLOW PRESSURE PROPERTIES                                00007370
C                                                                      00007375
C     M = SILL CLEARANCE SUBSCRIPT                                     00007380
      IMPLICIT REAL*8 (A-H , O-Z)                                      00007385
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,     00007390
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,   00007395
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,   00007400
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL        00007405
     4      ,XNRPM                                                     00007410
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR                                   00007415
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30), 00007420
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),      00007425
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),      00007430
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)        00007435
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)        00007440
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,   00007445
     1       RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,  00007450
     2       RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,                 00007455
     3       XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,00007460
     4       PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3, 00007465
     5       CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD, 00007470
     6       XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R100007475
     7      ,XNH8R1, XLH8R1, RH8R1                                     00007480
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,    00007485
     1       XNH9L9, PH9L9, XH9L9, CH9L9                               00007490
     2      ,WHPH1S                                                    00007495
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,  00007500
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)          00007505
      COMMON /MAIN1/ M                                                 00007510
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)00007515
     1      ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),00007520
     2       PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),00007525
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     3              PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)00007530
     4        ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),00007535
     5         PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20) 00007540
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),    00007545
     1         GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),        00007550
     2         RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4                     00007555
      REAL*8  NMH2, NMH7, NML7, NML2                                      00007560
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),00007565
     1         XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21), 00007570
     2         REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),00007575
     3         CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,    00007580
     4         REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),   00007585
     5         NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),     00007590
     6         REL2(21), NML2(21), HL1, GL1SD, XMUL1S                     00007595
      COMMON /SPARL/ XKP(20), XKBP(20)                                    00007600
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN          00007605
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),    00007610
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,      00007615
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL100007620
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,        00007625
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,    00007630
     5 GL2(21), CPL2(21), XMUL2(21)                                       00007635
      COMMON /MAIN2/ HL3(20)                                              00007640
      COMMON /MAIN3/ HH3                                                  00007645
      COMMON /PGUES/ C11                                                  00007650
      COMMON /OUTP1/ WT(20), WHSHP, WLSLP                                 00007655
      COMMON /ERPRNT/ IERRT                                               00007660
      COMMON /CLOW/ CVLP,ULP2, HL8,      VRL8, PL1R1                      00007665
      DIMENSION VRH7(21), VH7(21), VRH2(21), VH2(21)                      00007670
      REAL*8 NM                                                           00007675
C                                                                         00007680
C     HIGH PRESSURE SIDE                                                  00007685
C                                                                         00007690
C     HIGH PRESSURE SUPPLY VALUES                                         00007695
      CALL DBLIN(PHS,THS,GHS,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)        00007700
      IF(IERR.EQ.1)GO TO 200                                              00007705
   10 CONTINUE                                                            00007710
      CALL DBLIN(PHS,THS,CPHS,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)      00007715
      IF(IERR.EQ.1)GO TO 240                                              00007720
   20 CONTINUE                                                            00007725
      CALL DBLIN(PHS,THS,XMUHS,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)     00007730
      IF(IERR.EQ.1)GO TO 260                                              00007735
   30 CONTINUE                                                            00007740
      PDENH=PHS-PBPR1                                                     00007745
C     HIGH PRESSURE POCKET CONDITIONS                                     00007750
      PHP(M)=PHS+C11*(PBPR1-PHS)*((HH7(M)/HT)**1.5)                       00007755
      CALL ORIF(PHS,THS,GHS,CPHS,PHP(M),XNHSHP,CHSHP,DHSHP,DHS,RHP,HHP(M00007760
     1),WHSHP,THP(M),GHP,CPHP,XMUHP)                                      00007765
      IF(IERRT.GE.5)RETURN                                                00007770
C     SILL RADII                                                          00007775
      RH6H7=P5*(RH6+RH7)                                                  00007780
      RH2H3=P5*(RH2+RH3)                                                  00007785
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C     FLOW APPROXIMATIONS
      CWHPH8=RH6H7/(RH6H7+RH2H3)
      WHPH8=CWHPH8*WHSHP
      WHPH1=WHSHP-WHPH8
C
C     LOW PRESSURE SIDE
C
      CALL DBLIN(PLS,TLS,GLS,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 280
   40 CONTINUE
      CALL DBLIN(PLS,TLS,CPLS,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 310
   50 CONTINUE
      CALL DBLIN(PLS,TLS,XMULS,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 330
   60 CONTINUE
C     POCKET CONDITIONS
      PDENL=PLS-PBPR1
      PLP(M)=PLS+C11*(PBPR1-PLS)*((HL3(M)/HT)**1.5)
      CALL ORIF(PLS,TLS,GLS,CPLS,PLP(M),XNLSLP,CLSLP,DLSLP,DLS,RLP,HLP(M
     1),WLSLP,TLP(M),GLP,CPLP,XMULP)
      IF(IERRT.GE.5)RETURN
      RL6L7=P5*(RL6+RL7)
      RL2L3=P5*(RL2+RL3)
      CWLPL8=RL6L7/(RL6L7+RL2L3)
      WLPL8=CWLPL8*WLSLP
      WLPL1=WLSLP-WLPL8
C     FLOW APPROXIMATIONS
C
C     VELOCITY CONSTANTS
C
      CVHP=PI2*RHP*HHP(M)
      UHP=PI60*RHP*XNRPM
      UHP2=UHP*UHP
      HH8=(RHANN*RHANN/RH7-RH7)*P5
      HH1=P5*(RH1S+RH2)*HH1S/RH2
      CVLP=PI2*RLP*HLP(M)
      ULP=PI60*RLP*XNRPM
      ULP2=ULP*ULP
      HL8=(RLANN*RLANN/RL7-RL7)*P5
      HL1=P5*(RL1S+RL2)*HL1S/RL2
C
C     ITERATION ON PRESSURES - HIGH PRESSURE INWARD AND OUTWARD RETURN
C                              LOW PRESSURE INWARD AND OUTWARD RETURN
C
      INDW=0
      DO 180 N=1,ITERP
      IF(INDW.EQ.1)GO TO 70
C
C     OUTWARD FLOW
C
      VHPO=WHPH8/(CVHP*GHP)
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      VRHPO=DSQRT(VHPO*VHPO+UHP2)
      CALL PKT(PHP(M),THP(M),GHP,CPHP,WHPH8,RHP,HHP(M),RH5,VRHPO,XMUHP,
     1 PH5(M),TH5(M),GH5,CPH5,VH5,UH5,XMUH5,VRH5,REHPH5,GHPH5,XKHPH5,0)
      IF(IERRT.GE.5)RETURN
      IF(XKHPH5.LT..5)XKHPH5=.5
      CALL ENTS(PH5(M),TH5(M),GH5,CPH5,VRH5,HHP(M),WHPH8,RH6,HH7(M),
     1 CH5H6,PH6(M),TH6(M),GH6,CPH6,VH6,VRH6,XMUH6,UH6)
      IF(IERRT.GE.5)RETURN
C     VELOCITIES
C     POCKET PRESSURE
C     SILL ENTRANCE LOSS
C     OUTER SILL
      CALL SILL(PH6(M),TH6(M),GH6,CPH6,XMUH6,RH6,VRH6,WHPH8,RH7,HH7(M),
     1 VH6,DUM,PH7(1,M),TH7(1,M),GH7,CPH7,XMUH7,XKH6H7,RH7I,REH7,VH7,
     2 VRH7,UDH7,GH6H7,CMH7,NMH7,NH7I,0)
      IF(IERRT.GE.5)RETURN
C     SILL EXIT LOSS
      CALL ENTS(PH7(NH7I,M),TH7(NH7I,M),GH7(NH7I),CPH7(NH7I),VRH7(NH7I),
     1 HH7(M),WHPH8,RH8,HH8,CH7H8,PH8(M),TH8(M),GH8,CPH8,VH8,VRH8,XMUH8,
     2 UH8)
      IF(IERRT.GE.5)RETURN
      REH8=GH8*VRH8*HH8/(GVTY*XMUH8)
C
C     INWARD FLOW
C
C     VELOCITIES
      VHPI=WHPH1/(CVHP*GHP)
      VRHPI=DSQRT(VHPI*VHPI+UHP2)
C     POCKET PRESSURE
      CALL PKT(PHP(M),THP(M),GHP,CPHP,WHPH1,RHP,HHP(M),RH4,VRHPI,XMUHP,
     1 PH4(M),TH4(M),GH4,CPH4,VH4,UH4,XMUH4,VRH4,REHPH4,GHPH4,XKHPH4,1)
      IF(IERRT.GE.5)RETURN
      IF(XKHPH4.LT..5)XKHPH4=.5
C     SILL ENTRANCE LOSS
      CALL ENTS(PH4(M),TH4(M),GH4,CPH4,VRH4,HHP(M),WHPH1,RH3,HH7(M),
     1 CH4H3,PH3(M),TH3(M),GH3,CPH3,VH3,VRH3,XMUH3,UH3)
      IF(IERRT.GE.5)RETURN
C     INNER SILL
      CALL SILL(PH3(M),TH3(M),GH3,CPH3,XMUH3,RH3,VRH3,WHPH1,RH2,HH7(M),
     1 VH3,RH7,PH2(1,M),TH2(1,M),GH2,CPH2,XMUH2,XKH3H2,RH2I,REH2,VH2,
     2 VRH2,UDH2,GH3H2,CMH2,NMH2,NH2I,1)
      IF(IERRT.GE.5)RETURN
C     SILL EXIT LOSS
      CALL ENTS(PH2(NH2I,M),TH2(NH2I,M),GH2(NH2I),CPH2(NH2I),VRH2(NH2I),
     1 HH3,WHPH1,RH1,HH1,CH2H1,PH1(M),TH1(M),GH1,CPH1,VH1,VRH1,XMUH1,
     2 UH1)
      IF(IERRT.GE.5)RETURN
C     INWARD FLOW HIGH PRESSURE RETURN LINE
      CALL LINE(PH1(M),TH1(M),GH1,CPH1,XMUH1,VRH1,XNH1R1,XLH1R1,WHPH1,
     1 RR1,PH1R1,TH1R1,GH1R1,CPH1R1,XMUH1R,VRH1R1,REH1R1)
      IF(IERRT.GE.5)RETURN
C
```

```
C       LOW PRESSURE SIDE
C
   70 CONTINUE
      CALL PLOW
      IF(IERRT.GE.5)RETURN
C
C       COMBINED HIGH AND LOW PRESSURE OUTWARD FLOW
C
C       ANNULUS VALUES
      WH8R1=WHPH8+WLPL8
      TL8H8=(WHPH8*CPH8*TH8(M)+WLPL8*CPL8*TL8(M))/(WH8R1*P5*(CPH8+CPL8))
      CALL DBLIN(PL8(M),TL8H8,GL8H8,PDENS,TDENS,GDENS,NPDENS,NTDENS,
     1 IERR)
      IF(IERR.EQ.1)GO TO 350
   80 CONTINUE
      CALL DBLIN(PL8(M),TL8H8,CPL8H8,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,
     1 IERR)
      IF(IERR.EQ.1)GO TO 380
   90 CONTINUE
      CALL DBLIN(PL8(M),TL8H8,XMUL8H ,PVISC,TVISC,XMVISC,NPVISC,NTVISC,
     1 IERR)
      IF(IERR.EQ.1)GO TO 400
  100 CONTINUE
      VRL8H8=P5*(VRL8+VRH8)
      CALL LINE(PL8(M),TL8H8,GL8H8,CPL8H8,XMUL8H,VRL8H8,XNH8R1,XLH8R1,
     1 WH8R1,RH8R1,PLBPR1,TLBPR1,GLBPR1,CPLBPR,XMULBP,VRLBPR ,RELBPR )
      IF(IERRT.GE.5)RETURN
C       OUTWARD RETURN PRESSURES
      PHOR1=PH8(M)-PL8(M)+PLBPR1
C
C       CONVERGENCE TEST ON RETUR PRESSURES
C
      IF(DABS(1.-(PLS-PLBPR1)/PDENL).GT.CLOS)GO TO 110
      IF(DABS(1.-(PLS-PL1R1)/PDENL).GT.CLOS)GO TO 110
      IF(DABS(1.-(PHS-PHOR1)/PDENH).GT.CLOS)GO TO 110
      IF(DABS(1.-(PHS-PH1R1)/PDENH).LE.CLOS)RETURN
C       ADJUSTMENT OF OUTWARD FLOW APPROXIMATION
  110 CONTINUE
      INDW=0
      IF(PLP(M).GE.PLBPR1)GO TO 120
      WLPL8=WLPL8*1.1
      INDW=1
      GO TO 180
  120 IF(PHP(M).GE.PHOR1)GO TO 130
      WHPH8=WHPH8*1.1
      GO TO 180
C
C       CALCULATE NEXT FLOW APPROXIMATIONS
C
C       FLOW CONSTANTS
  130 CONTINUE
      XKLORF=WLSLP/DSQRT(PLS-PLP(M))
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      XKLOUT=WLPL8/DSQRT(PLP(M)-PLBPR1)
      XKLIN=WLPL1/DSQRT(PLP(M)-PLIR1)
C     LOW PRESSURE ESTIMATE
      WOLD=WLSLP
  140 CONTINUE
      XKBAR=((XKLOUT+XKLIN)/XKLORF)**2
      PLP(M)=(PLS+XKBAR*PBPR1)/(XKBAR+1.)
      CALL ORIF(PLS,TLS,GLS,CPLS,PLP(M),XNLSLP,CLSLP,DLSLP,DLS,RLP,HLP(M
     1),WLSLP,TLP(M),GLP,CPLP,XMULP)
      IF(IERRT.GE.5)RETURN
      IF(DABS((WLSLP-WOLD)/WOLD).LE..2 )GO TO 150
      XKLOUT=.9*XKLOUT
      XKLIN=.9*XKLIN
      GO TO 140
  150 CONTINUE
      WLPL8=XKLOUT*DSQRT(PLP(M)-PBPR1)
      WLPL1=WLSLP-WLPL8
C     FLOW CONSTANTS
      XKHORF=WHSHP/DSQRT(PHS-PHP(M))
      XKHOUT=WHPH8/DSQRT(PHP(M)-PHOR1)
      XKHIN=WHPH1/DSQRT(PHP(M)-PH1R1)
C     HIGH PRESSURE APPROXIMATIONS
      WOLD=WHSHP
  160 CONTINUE
      XKBAR=((XKHOUT+XKHIN)/XKHORF)**2
      PHP(M)=(PHS+XKBAR*PBPR1)/(XKBAR+1.)
      CALL ORIF(PHS,THS,GHS,CPHS,PHP(M),XNHSHP,CHSHP,DHSHP,DHS,RHP,HHP(M
     1),WHSHP,THP(M),GHP,CPHP,XMUHP)
      IF(IERRT.GE.5)RETURN
      IF(DABS((WHSHP-WOLD)/WOLD).LE..2 )GO TO 170
      XKHOUT=.9*XKHOUT
      XKHIN=.9*XKHIN
      GO TO 160
  170 CONTINUE
      WHPH8=XKHOUT*DSQRT(PHP(M)-PBPR1)
      WHPH1=WHSHP-WHPH8
  180 CONTINUE
      WRITE (6,190)ITERP,PHP(M),PLP(M)
  190 FORMAT(1H0/ 81HOTHE PARALLEL PROPERTIES PRESSURE CALCULATIONS DID
     1NOT CONVERGE IN THE MAXIMUM OF ,I4,1X, 11HITERATIONS. /42H THE FIN
     2AL HIGH PRESSURE POCKET PRESSURE = ,1P1D15.4 /41H THE FINAL LOW PR
     3ESSURE POCKET PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
  200 WRITE (6,210)
  210 FORMAT(1H0/ 94HOTHE HIGH PRESSURE SUPPLY VALUES FOR DENSITY TABLE
     1INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
  220 WRITE (6,230)PHS,THS
  230 FORMAT(11H PRESSURE = ,1P1D15.4/14H TEMPERATURE = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 10
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240 WRITE (6,250)
250 FORMAT(1H0/100H0THE HIGH PRESSURE SUPPLY VALUES FOR SPECIFIC HEAT
   1TABLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,230)PHS,THS
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 20
260 WRITE (6,270)
270 FORMAT(1H0/ 96H0THE HIGH PRESSURE SUPPLY VALUES FOR VISCOSITY TABL
   1E INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,230)PHS,THS
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 30
280 WRITE (6,290)
290 FORMAT(1H0/ 93H0THE LOW PRESSURE SUPPLY VALUES FOR DENSITY TABLE I
   1NTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
300 WRITE (6,230)PLS,TLS
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 40
310 WRITE (6,320)
320 FORMAT(1H0/ 99H0THE LOW PRESSURE SUPPLY VALUES FOR SPECIFIC HEAT T
   1ABLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,230)PLS,TLS
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 50
330 WRITE (6,340)
340 FORMAT(1H0/ 95H0THE LOW PRESSURE SUPPLY VALUES FOR VISCOSITY TABLE
   1 INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,230)PLS,TLS
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 60
350 WRITE (6,360)
360 FORMAT(1H0/ 81H0THE ANNULUS VALUES FOR DENSITY TABLE INTERPOLATION
   1 WERE OUTSIDE THE TABLE RANGE. )
370 WRITE (6,230)PL8(M),TL8H8
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 80
380 WRITE (6,390)
390 FORMAT(1H0/ 87H0THE ANNULUS VALUES FOR SPECIFIC HEAT TABLE INTERPO
   1LATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,230)PL8(M),TL8H8
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 90
400 WRITE (6,410)
410 FORMAT(1H0/ 83H0THE ANNULUS VALUES FOR VISCOSITY TABLE INTERPOLATI
   1ON WERE OUTSIDE THE TABLE RANGE. )
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      WRITE (6,230)PL8(M),TL8H8                                         00009090
      IERRT=IERRT+1                                                     00009095
      IF(IERRT.GE.5)RETURN                                              00009100
      GO TO 100                                                         00009105
      END                                                               00009110
      SUBROUTINE PLOW                                                   00009115
C                                                                       00009120
C     LOW PRESSURE SIDE CALCULATIONS FOR PARALLEL PISTON PROPERTIES     00009125
C                                                                       00009130
      IMPLICIT REAL*8 (A-H , O-Z)                                       00009135
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,      00009140
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,    00009145
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,    00009150
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL         00009155
     4      ,XNRPM                                                      00009160
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR                                    00009165
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),  00009170
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),       00009175
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),       00009180
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)         00009185
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)         00009190
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,    00009195
     1       RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,   00009200
     2       RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,                  00009205
     3       XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,00009210
     4       PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3, 00009215
     5       CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,  00009220
     6      ,XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R100009225
     7      ,XNH8R1, XLH8R1, RH8R1                                      00009230
      COMMON /IN4/ RR1, RHCL, HH9, HL9, HSD, HH9L9, HEH9L9, XLH9L9,     00009235
     1       XNH9L9, PH9L9, XH9L9, CH9L9                                00009240
     2      ,WHPH1S                                                     00009245
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,   00009250
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)           00009255
      COMMON /MAIN1/ M                                                  00009260
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)00009265
     1      ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),00009270
     2       PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),00009275
     3               PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)00009280
     4      ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),00009285
     5       PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20) 00009290
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),   00009295
     1       GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),        00009300
     2       RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4                     00009305
      REAL*8 NMH2, NMH7, NML7, NML2                                     00009310
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),00009315
     1       XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21), 00009320
     2       REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),00009325
     3       CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,    00009330
     4       REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),   00009335
     5       NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),     00009340
     6       REL2(21), NML2(21), HL1, GL1SD, XMUL1S                     00009345
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      COMMON /SPARL/ XKP(20), XKBP(20)
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL1
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,
     5 GL2(21), CPL2(21), XMUL2(21)
      COMMON /MAIN2/ HL3(20)
      COMMON /MAIN3/ HH3
      COMMON /PGUES/ C11
      COMMON /OUTP1/ WT(20), WHSHP, WLSLP
      COMMON /ERPRNT/ IERRT
      COMMON /CLOW/ CVLP,ULP2, HL8,      VRL8, PL1R1
      DIMENSION VRL2(21), VL2(21), VRL7(21), VL7(21)
C
C     OUTWARD FLOW
C
      VLPO=WLPL8/(CVLP*GLP)
      VRLPO=DSQRT(VLPO*VLPO+ULP2)
      CALL PKT(PLP(M),TLP(M),GLP,CPLP,WLPL8,RLP,HLP(M),RL5,VRLPO,XMULP,
     1 PL5(M),TL5(M),GL5,CPL5,VL5,UL5,XMUL5,VRL5,RELPL5,GLPL5,XKLPL5,0)
      IF(IERRT.GE.5)RETURN
      IF(XKLPL5.LT..5)XKLPL5=.5
      CALL ENTS(PL5(M),TL5(M),GL5,CPL5,VRL5,HLP(M),WLPL8,RL6,HL7(M),
     1 CL5L6,PL6(M),TL6(M),GL6,CPL6,VL6,VRL6,XMUL6,UL6)
      IF(IERRT.GE.5)RETURN
      CALL SILL(PL6(M),TL6(M),GL6,CPL6,XMUL6,RL6,VRL6,WLPL8,RL7,HL7(M),
     1 VL6,DUM,PL7(1,M),TL7(1,M),GL7,CPL7,XMUL7,XKL6L7,RL7I,REL7,VL7,
     2 VRL7,UDL7,GL6L7,CML7,NML7,NL7I,0)
      IF(IERRT.GE.5)RETURN
      CALL ENTS(PL7(NL7I,M),TL7(NL7I,M),GL7(NL7I),CPL7(NL7I),VRL7(NL7I),
     1 HL7(M),WLPL8,RL8,HL8,CL7L8,PL8(M),TL8(M),GL8,CPL8,VL8,VRL8,XMUL8,
     2 UL8)
      IF(IERRT.GE.5)RETURN
      REL8=GL8*VRL8*HL8/(GVTY*XMUL8)
C
C     INWARD FLOW
C
      VLPI=WLPL1/(GLP*CVLP)
      VRLPI=DSQRT(VLPI*VLPI+ULP2)
      CALL PKT(PLP(M),TLP(M),GLP,CPLP,WLPL1,RLP,HLP(M),RL4,VRLPI,XMULP,
     1 PL4(M),TL4(M),GL4,CPL4,VL4,UL4,XMUL4,VRL4,RELPL4,GLPL4,XKLPL4,1)
      IF(IERRT.GE.5)RETURN
      IF(XKLPL4.LT..5)XKLPL4=.5
      CALL ENTS(PL4(M),TL4(M),GL4,CPL4,VRL4,HLP(M),WLPL1,RL3,HL7(M),
     1 CL4L3,PL3(M),TL3(M),GL3,CPL3,VL3,VRL3,XMUL3,UL3)
      IF(IERRT.GE.5)RETURN
      CALL SILL(PL3(M),TL3(M),GL3,CPL3,XMUL3,RL3,VRL3,WLPL1,RL2,HL7(M),
     1 VL3,RL7,PL2(1,M),TL2(1,M),GL2,CPL2,XMUL2,XKL3L2,RL2I,REL2,VL2,
     2 VRL2,UDL2,GL3L2,CML2,NML2,NL2I,1)
      IF(IERRT.GE.5)RETURN
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```
      CALL ENTS(PL2(NL2I,M),TL2(NL2I,M),GL2(NL2I),CPL2(NL2I),VRL2(NL2I),
     1 HL7(M),WLPL1,RL1,HL1,CL2L1,PL1(M),TL1(M),GL1,CPL1,VL1,VRL1,XMUL1,
     2 UL1)
      IF(IERRT.GE.5)RETURN
C
C     CHECK FOR SEAL OR LABYRINTH
C
      WL1R1=WLPL1
      IF(ISEAL.EQ.0)GO TO 10
C     SHAFT LABYRINTH
      CALL LABYS(PL1(M),TL1(M),GL1,VRL1,CPL1,PSD,PL1SD,XL1SD,HL1SD,
     1 XNL1SD,CL1SD,RSD,RSDH,TSD,GSD,VRSD,CPSD,WL1SD,XMUL1S,GL1SD,
     2 REL1SD,XMUL1)
      IF(IERRT.GE.5)RETURN
      WL1R1=WL1R1-WL1SD
C     RETURN LINE
   10 CONTINUE
      CALL LINE(PL1(M),TL1(M),GL1,CPL1,XMUL1,VRL1,XNL1R1,XLL1R1,WL1R1,
     1 RR1,PL1R1,TL1R1,GL1R1,CPL1R1,XMUL1R,VRL1R1,REL1R1)
      RETURN
      END
      SUBROUTINE PFORCE
C
C     PARALLEL PISTON FORCE CALCULATION
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAN, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4       ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1        RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2        RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3        XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4        PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5        CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6        XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7       ,XNH8R1, XLH8R1, RH8R1
      COMMON /MAIN1/ M
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1       ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2        PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3                PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4       ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5        PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1        GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2        RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
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      REAL*8 NM
      RLP2=RLP*RLP
      PI40=PI4/GVTY*OMEGAD*OMEGAD
      RHP2=RHP*RHP
C     HIGH PRESSURE SIDE
      FP(1)=PH1(M)*PI*(RH1*RH1-RH1S*RH1S)
      RHM=RH3
      RHM2=RH3*RH3
      PHM=PH3(M)
      FP(2)=0.
      DO 10 I=1,NH2I
      RH22=RH2I(I)*RH2I(I)
      FP(2)=FP(2)+PI*(PH2(I,M)*(RHM2-RH22)+(PHM-PH2(I,M))*(2.*RHM2-RH2I(
     1I)*RHM-RH22)/3.)
      RHM=RH2I(I)
      RHM2=RH22
      PHM=PH2(I,M)
   10 CONTINUE
      RD=RHP2-RH4*RH4
      FP(3)=RD*(PI*PH4(M)+RD*PI40*GHPH4*XKHPH4*XKHPH4)
      RD=RH5*RH5-RHP2
      FP(4)=RD*(PI*PHP(M)+RD*PI40*GHPH5*XKHPH5*XKHPH5)
      RHM=RH6
      RHM2=RH6*RH6
      PHM=PH6(M)
      FP(5)=0.
      DO 20 I=1,NH7I
      RH22=RH7I(I)*RH7I(I)
      FP(5)=FP(5)+PI*(PHM*(RH22-RHM2)+(PH7(I,M)-PHM)*(2.*RH22-RH7I(I)*
     1 RHM-RHM2)/3.)
      RHM=RH7I(I)
      RHM2=RH22
      PHM=PH7(I,M)
   20 CONTINUE
      FP(6)=PI*PH8(M)*(RH9*RH9-RHM2)
C     LOW PRESSURE SIDE
      FP(7)=-PI*PL8(M)*(RL9*RL9-RL7I(NL7I)**2)
      RHM=RL6
      RHM2=RL6*RL6
      PHM=PL6(M)
      FP(8)=0.
      DO 30 I=1,NL7I
      RH22=RL7I(I)*RL7I(I)
      FP(8)=FP(8)+PI*(PHM*(RHM2-RH22)+(PHM-PL7(I,M))*(2.*RH22-RHM*
     1 RL7I(I)-RHM2)/3.)
      RHM=RL7I(I)
      RHM2=RH22
      PHM=PL7(I,M)
   30 CONTINUE
      RD=RL5*RL5-RLP2
      FP(9)=-RD*(PLP(M)*PI+RD*GLPL5*XKLPL5*XKLPL5*PI40)
      RD=RLP2-RL4*RL4
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      FP(10)=-RD*(PL4(M)*PI+RD*GLPL4*XKLPL4*XKLPL4*PI40)
      FP(11)=0.
      RHM=RL3
      RHM2=RL3*RL3
      PHM=PL3(M)
      DO 40 I=1,NL2I
      RH22=RL2I(I)*RL2I(I)
      FP(11)=FP(11)+PI*(PL2(I,M)*(RH22-RHM2)+(PL2(I,M)-PHM)*(2.*RHM2
     1-RHM*RL2I(I)-RH22)/3.)
      RHM=RL2I(I)
      RHM2=RH22
      PHM=PL2(I,M)
   40 CONTINUE
      FP(12)=PL1(M)*PI*(RL1S*RL1S-RL1*RL1)
      FPP(M)=0.
      DO 50 I=1,12
      FPP(M)=FPP(M)+FP(I)
   50 CONTINUE
      RETURN
      END
      SUBROUTINE PHORSP
C
C     PARALLEL FLOW BALANCER HORSEPOWER
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, CI, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1       RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2       RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3       XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4       PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5       CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6       XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7      ,XNH8R1, XLH8R1, RH8R1
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /MAIN1/ M
      DIMENSION TM(12), XMP(20)
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1       GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2       RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1       XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2       REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),
     3       CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4       REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
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     5        NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),
     6        REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      REAL*8 NM
C
C     AVERAGE VISCOSITIES
C
      XMHPH4=XMUHP+CR*(XMUH4-XMUHP)
      XMHPH5=XMUHP+CR*(XMUH5-XMUHP)
      XMH7L7=XMUH7(NH7I)+CR*(XMUL7(NL7I)-XMUH7(NH7I))
      XMLPL5=XMULP+CR*(XMUL5-XMULP)
      XMLPL4=XMULP+CR*(XMUL4-XMULP)
C     CONSTANTS
      PIU=PI60*XNRPM
C     HIGH PRESSURE POCKET INWARD RADIAL VELOCITY
      RHPH4=RHP+RH4
      VHPH4=WHPH1/(PI*HHP(M)*RHPH4)
      VHPH4=VHPH4/GHPH4
      UDHPH4=PIU*RHPH4
      VRHPH4=DSQRT(VHPH4*VHPH4+.25*UDHPH4*UDHPH4)
      REHPH4=GHPH4*VRHPH4*HHP(M)/(GVTY*XMHPH4)
      IF(REHPH4.GT.2000.)GO TO 10
      CM=CMLAM
      NM=NMLAM
      GO TO 20
   10 CM=CMTUR
      NM=NMTUR
   20 CONTINUE
      TM(1)= GHPH4*CM*PI4G*RHPH4*UDHPH4*UDHPH4*(RHP*RHP-RH4*RH4) /(REHPH
     14**NM)
C     INNER HIGH PRESSURE SILL
      TM(2)=0.
      RM=RH3
      RM2=RH3*RH3
      DO 30 I=1,NH2I
      R2=RH2I(I)*RH2I(I)
      TM(2)=TM(2)+GH3H2(I)*CMH2(I)*PI4G*UDH2(I)*UDH2(I)*(R2-RM2)*(RM+
     1 RH2I(I))/(REH2(I)**(NMH2(I)))
      RM=RH2I(I)
      RM2=R2
   30 CONTINUE
C     HIGH PRESSURE INNER CAVITY
      VH1=WHPH1/(PI*HH1*RH1)
      VH1=VH1/GH1
      VRH1=DSQRT(UH1*UH1+VH1*VH1)
      REH1=GH1*VRH1*HH1/(GVTY*XMUH1)
      IF(REH1.GT.2000.)GO TO 40
      CM=CMLAM
      NM=NMLAM
      GO TO 50
   40 CONTINUE
      CM=CMTUR
      NM=NMTUR
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   50 CONTINUE
      UDH1=2.*UH1
      TM(3)=GH1*CM*PI4G*UDH1*UDH1*(RH1**3)/(REH1**NM)
C     HIGH PRESSURE POCKET OUTWARD RADIAL VELOCITY
      RHPH5=RHP+RH5
      VHPH5=WHPH8/(PI*HHP(M)*RHPH5)
      VHPH5=VHPH5/GHPH5
      UDHPH5=PIU*RHPH5
      VRHPH5=DSQRT(VHPH5*VHPH5+.25*UDHPH5*UDHPH5)
      REHPH5=GHPH5*VRHPH5*HHP(M)/(GVTY*XMHPH5)
      IF(REHPH5.GT.2000.)GO TO 60
      CM=CMLAM
      NM=NMLAM
      GO TO 70
   60 CM=CMTUR
      NM=NMTUR
   70 CONTINUE
      TM(4)=GHPH5*CM*PI4G*UDHPH5*UDHPH5*RHPH5*(RH5*RH5-RHP*RHP)/(REHPH5*
     1*NM)
C     OUTER HIGH PRESSURE SILL
      RM=RH6
      RM2=RH6*RH6
      TM(5)=0.
      DO 80 I=1,NH7I
      R2=RH7I(I)*RH7I(I)
      TM(5)=TM(5)+GH6H7(I)*CMH7(I)*PI4G*UDH7(I)*UDH7(I)*(R2-RM2)*(RM+
     1 RH7I(I))/(REH7(I)**(NMH7(I)))
      RM=RH7I(I)
      RM2=R2
   80 CONTINUE
C     OUTER CYLINDRICAL PISTON SURFACE, HIGH PRESSURE SIDE
      IF(REH8.GT.2000.)GO TO 90
      CM=CMLAM
      NM=NMLAM
      GO TO 100
   90 CM=CMTUR
      NM=NMTUR
  100 CONTINUE
      TM(6)=GH8*CM*PI*XLH8*(UH8*2.*RH8)**2/(GVTY*(REH8**NM))
C     OUTER CYLINDRICAL PISTON SURFACE, LOW PRESSURE SIDE
      IF(REL8.GT.2000.)GO TO 110
      CM=CMLAM
      NM=NMLAM
      GO TO 120
  110 CM=CMTUR
      NM=NMTUR
  120 CONTINUE
      TM(7)=GL8*CM*PI*XLL8*(UL8*2.*RL8)**2/(GVTY*(REL8**NM))
C     OUTER LOW PRESSURE SILL
      RM=RL6
      RM2=RL6*RL6
      TM(8)=0.
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      DO 130 I=1,NL7I
      R2=RL7I(I)*RL7I(I)
      TM(8)=TM(8)+GL6L7(I)*CML7(I)*PI4G*UDL7(I)*UDL7(I)*(R2-RM2)*(RM+
     1 RL7I(I))/(REL7(I)**(NML7(I)))
      RM=RL7I(I)
      RM2=R2
  130 CONTINUE
C     LOW PRESSURE POCKET OUTWARD RADIAL VELOCITY
      RLPL5=RLP+RL5
      VLPL5=WLPL8/(PI*HLP(M)*RLPL5)
      VLPL5=VLPL5/GLPL5
      UDLPL5=PIU*RLPL5
      VRLPL5=DSQRT(VLPL5*VLPL5+.25*UDLPL5*UDLPL5)
      RELPL5=GLPL5*VRLPL5*HLP(M)/(GVTY*XMLPL5)
      IF(RELPL5.GT.2000.)GO TO 140
      CM=CMLAM
      NM=NMLAM
      GO TO 150
  140 CM=CMTUR
      NM=NMTUR
  150 CONTINUE
      TM(9)=GLPL5*CM*PI4G*UDLPL5*UDLPL5*(RL5*RL5-RLP*RLP)*RLPL5/(RELPL5*
     1*NM)
C     LOW PRESSURE POCKET INWARD RADIAL VELOCITY
      RLPL4=RLP+RL4
      VLPL4=WLPL1/(PI*HLP(M)*RLPL4)
      VLPL4=VLPL4/GLPL4
      UDLPL4=PIU*RLPL4
      VRLPL4=DSQRT(.25*UDLPL4*UDLPL4+VLPL4*VLPL4)
      RELPL4=GLPL4*VRLPL4*HLP(M)/(GVTY*XMLPL4)
      IF(RELPL4.GT.2000.)GO TO 160
      CM=CMLAM
      NM=NMLAM
      GO TO 170
  160 CM=CMTUR
      NM=NMTUR
  170 CONTINUE
      TM(10)=GLPL4*CM*PI4G*UDLPL4*UDLPL4*(RLP*RLP-RL4*RL4)*RLPL4/(
     1RELPL4**NM)
C     INNER LOW PRESSURE SILL
      RM=RL3
      RM2=RL3*RL3
      TM(11)=0.
      DO 180 I=1,NL2I
      R2=RL2I(I)*RL2I(I)
      TM(11)=TM(11)+GL3L2(I)*CML2(I)*PI4G*UDL2(I)*UDL2(I)*(R2-RM2)*(RM+
     1RL2I(I))/(REL2(I)**(NML2(I)))
      RM=RL2I(I)
      RM2=R2
  180 CONTINUE
C     LOW PRESSURE INNER CAVITY
      TM(12)=0.
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      IF(ISEAL.EQ.0)GO TO 210
      RL1SD=RSD+RL1
      VL1SD=WLPL1/(PI*HL1*RL1SD)
      VL1SD=VL1SD/GL1SD
      UDL1SD=PIU*RL1SD
      VRL1SD=DSQRT(VL1SD*VL1SD+.25*UDL1SD*UDL1SD)
      REL1SD=GL1SD*VRL1SD*HL1/(GVTY*XMUL1S)
      IF(REL1SD.GT.2000.)GO TO 190
      CM=CMLAM
      NM=NMLAM
      GO TO 200
  190 CM=CMTUR
      NM=NMTUR
  200 CONTINUE
      TM(12)=GL1SD*CM*PI4G*UDL1SD*UDL1SD*RL1SD*(RL1*RL1-RSD*RSD)/(
     1 REL1SD**NM)
C     TOTAL TORQUE AND HORSEPOWER ON PARALLEL PISTON
  210 CONTINUE
      XMP(M)=0.
      DO 220 I=1,12
      XMP(M)=XMP(M)+TM(I)
  220 CONTINUE
      HPP(M)=XMP(M)*XNRPM/63000.
      RETURN
      END
      SUBROUTINE POUT
C
C     PARALLEL PISTON OUTPUT OF FLUID PROPERTIES, FORCES, AND HORSEPOWER
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4       ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1        XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2        REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),
     3        CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4        REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5        NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),
     6        REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /MAIN1/ M
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1        RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2        RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3        XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4        PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5        CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
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     6       XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7      ,XNH8R1, XLH8R1, RH8R1
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1      ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2       PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3               PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6( 20)
     4      ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5       PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1       GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2       RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /OUTP1/ WT(20), WHSHP, WLSLP
      COMMON /CPROP/ CPH1, REH1R1, GH2(21), XMUH2(21), GH3, CPH2(21),
     1 CPH3, XMUH3, GH4, CPH4, GHP, CPHP, REHPH4, GH5, CPH5, REHPH5,
     2 GH6, CPH6, XMUH6, GH7(21), CPH7(21), CPH8, XMUH8, GL1,CPL1, XMUL1
     3,REL1R1, GL3, CPL3, XMUL3,GL4, CPL4, GLP, CPLP, RELPL4, GL5,
     4 CPL5, RELPL5, GL6, CPL6, XMUL6, GL7(21), CPL7(21), CPL8, XMUL8,
     5 GL2(21), CPL2(21), XMUL2(21)
      WRITE (6,10)(TITLE(I),I=1,9)
   10 FORMAT(1H1/1H ,45X,27HAEROJET-GENERAL CORPORATION /1H ,49X,19HPROP
     1ULSION DIVISION /1H ,47X,22HSACRAMENTO, CALIFORNIA/15H0PROGRAM E21
     2902 /1H0,9A8)
      BTU=.7073*HPP(M)
      WT(M)=WHSHP+WLSLP
      WRITE (6,20)HL7(M),HH7(M),BTU,WT(M),WHSHP,WHPH8,WHPH1,WLSLP,
     1 WLPL8,WLPL1
   20 FORMAT( 41H0FLUID STATE - PARALLEL FLOW             /1H0/15H CLEA
     1RANCE (IN) ,71X,25HHEAT GENERATION (BTU/SEC) /1H ,5X, 5HHL7 = ,1P1
     2D15.4,10X, 5HHH7 = ,D15.4, 30X,D15.4/24H FLOW RATES - W (LB/SEC)/
     3 1H ,5X,4HWT = ,D15.4,11X, 7HWHSHP = ,D15.4, 8X, 7HWHPH8 = ,D15.4,
     4 8X, 7HWHPH1 = ,D15.4/1H , 5X, 7HWLSLP = ,D12.4 ,11X, 7HWLPL8 = ,
     5 D15.4, 8X, 7HWLPL1 = ,D15.4)
      WRITE (6,30)
   30 FORMAT( 1H0,6X,8HLOCATION ,7X, 8HPRESSURE , 4X, 11HTEMPERATURE ,
     1 8X, 7HDENSITY ,2X, 13HSPECIFIC HEAT , 6X, 9HVISCOSITY , 7X, 8HREY
     2NOLDS , 7X, 8HROTATION /1H ,19X, 10H(LB/IN**2) ,8X, 7H(DEG R) ,5X,
     3 10H(LB/IN**3) ,2X,13H(BTU/LB*DEGR) ,1X,14H(LB*SEC/IN**2) ,9X,6HNU
     4MBER , 9X, 6HFACTOR )
      WRITE (6,40)RH1,PH1(M),TH1(M),GH1,CPH1,XMUH1,REH1R1
   40 FORMAT(4H RH1 ,1P1D11.4,6D15.4)
      WRITE (6,50)RH2I(NH2I),PH2(NH2I,M),TH2(NH2I,M),GH2(NH2I),CPH2(
     1 NH2I),XMUH2(NH2I)
   50 FORMAT(4H RH2 ,1P1D11.4,5D15.4)
      IF(NH2I.EQ.1)GO TO 80
      I=NH2I
      NHM=NH2I-1
      DO 70 IP=1,NHM
      IM=I
      I=NH2I-IP
      WRITE (6,60)RH2I(I),PH2(I,M),TH2(I,M),GH2(I),CPH2(I),XMUH2(I)
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    1 ,REH2(IM)
 60 FORMAT(1H ,1P1D14.4,6D15.4)
 70 CONTINUE
 80 CONTINUE
    WRITE (6,90)RH3,PH3(M),TH3(M),GH3,CPH3,XMUH3,REH2(1),XKH3H2
 90 FORMAT(4H RH3,1P1D11.4,7D15.4)
    WRITE (6,100)RH4,PH4(M),TH4(M),GH4,CPH4,XMUH4
100 FORMAT(4H RH4 ,1P1D11.4,5D15.4)
    WRITE (6,110)RHP,PHP(M),THP(M),GHP,CPHP,XMUHP,REHPH4,XKHPH4
110 FORMAT(4H RHP ,1P1D11.4,7D15.4)
    WRITE (6,120)RH5,PH5(M),TH5(M),GH5,CPH5,XMUH5,REHPH5,XKHPH5
120 FORMAT(4H RH5 ,1P1D11.4,7D15.4)
    WRITE (6,130)RH6,PH6(M),TH6(M),GH6,CPH6,XMUH6
130 FORMAT(4H RH6 ,1P1D11.4,5D15.4)
    WRITE (6,140) RH7I(1),PH7(1,M),TH7(1,M),GH7(1),CPH7(1),XMUH7(1),
    1 REH7(1),XKH6H7
140 FORMAT(4H RH7, 1P1D11.4,7D15.4)
    IF(NH7I.GT.1)WRITE (6,150)(RH7I(I),PH7(I,M),TH7(I,M),GH7(I),CPH7(
    1I),XMUH7(I),REH7(I),I=2,NH7I)
150 FORMAT(1H ,1P1D14.4,6D15.4)
    WRITE (6,160)RH8,PH8(M),TH8(M),GH8,CPH8,XMUH8
160 FORMAT(4H RH8 ,1P1D11.4,5D15.4)
    WRITE (6,170)RL1,PL1(M),TL1(M),GL1,CPL1,XMUL1,REL1R1
170 FORMAT(4H RL1 ,1P1D11.4,6D15.4)
    WRITE (6,180)RL2I(NL2I),PL2(NL2I,M),TL2(NL2I,M),GL2(NL2I),CPL2(
    1 NL2I),XMUL2(NL2I)
180 FORMAT(4H RL2 ,1P1D11.4,5D15.4)
    IF(NL2I.EQ.1)GO TO 200
    I=NL2I
    NHM=NL2I-1
    DO 190 IP=1,NHM
    IM=I
    I=NL2I-IP
    WRITE (6,60)RL2I(I),PL2(I,M),TL2(I,M),GL2(I),CPL2(I),XMUL2(I)
    1 ,REL2(IM)
190 CONTINUE
200 CONTINUE
    WRITE (6,210)RL3,PL3(M),TL3(M),GL3,CPL3,XMUL3,REL2(1),XKL3L2
210 FORMAT(4H RL3 ,1P1D11.4, 7D15.4)
    WRITE (6,220)RL4,PL4(M), TL4(M),GL4,CPL4,XMUL4
220 FORMAT(4H RL4 ,1P1D11.4,5D15.4)
    WRITE (6,230)RLP,PLP(M),TLP(M),GLP, CPLP ,XMULP,RELPL4,XKLPL4
230 FORMAT(4H RLP ,1P1D11.4,7D15.4)
    WRITE (6,240)RL5,PL5(M),TL5(M),GL5,CPL5,XMUL5,RELPL5,XKLPL5
240 FORMAT(4H RL5 ,1P1D11.4,7D15.4)
    WRITE (6,250)RL6,PL6(M),TL6(M),GL6,CPL6,XMUL6
250 FORMAT(4H RL6 ,1P1D11.4,5D15.4)
    WRITE (6,260)RL7I(1),PL7(1,M),TL7(1,M),GL7(1),CPL7(1),XMUL7(1),
    1 REL7(1),XKL6L7
260 FORMAT(4H RL7 ,1P1D11.4,7D15.4)
    IF(NL7I.GT.1)WRITE (6,150)(RL7I(I),PL7(I,M),TL7(I,M),GL7(I),CPL7(
    1I),XMUL7(I),REL7(I),I=2,NL7I)
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      WRITE (6,270)RL8,PL8(M),TL8(M),GL8,CPL8,XMUL8
  270 FORMAT(4H RL8 ,1P1D11.4,5D15.4)
      WRITE (6,10)(TITLE(I),I=1,9)
      WRITE (6,280)FPP(M),FP(1),FP(4),FP(7),FP(10),FP(2),FP(5),FP(8),
     1 FP(11),FP(3),FP(6),FP(9),FP(12)
  280 FORMAT(18HOPARALLEL BALANCER /1H0/12H FORCES (LB) ,1P1D15.4/1H ,5X
     1, 5HFP1 = ,D15.4,10X, 5HFP4 = ,D15.4,10X, 5HFP7 = ,D15.4,10X,
     2 6HFP10 = ,D15.4/1H ,5X, 5HFP2 = ,D15.4,10X, 5HFP5 = ,D15.4,10X,
     3 5HFP8 = ,D15.4,10X, 6HFP11 = ,D15.4 /1H , 5X, 5HFP3 = ,D15.4,10X,
     4 5HFP6 = ,D15.4,10X, 5HFP9 = ,D15.4, 10X, 6HFP12 = ,D15.4)
      RETURN
      END
      SUBROUTINE PSTIF
C
C     PARALLEL PISTON STIFFNESS
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4       ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1        NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2        NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3        NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4       ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /IN3/ RH1, RH2, RH3, RH4, RH5, RH6, RH7, RH8, RH9, RL1,
     1        RL2, RL3, RL4, RL5, RL6, RL7, RL8, RL9, RSD, RL1S, RH1S,
     2        RLP, RHP, RHANN, RLANN, RSDH, HH1S, HL1S,
     3        XLL8, XLH8, DHSHP, DLSLP, CHSHP, CLSLP, DHS, DLS, PHS, PLS,
     4        PBPR1, PSD, THS, TLS, XNHSHP, XNLSLP, CH5H6, CH7H8, CH4H3,
     5        CH2H1, CL5L6, CL7L8, CL4L3, CL2L1, HL1SD, HEL1SD, XLL1SD,
     6        XNL1SD, PL1SD, XL1SD, CL1SD, XNH1R1, XLH1R1, XNL1R1, XLL1R1
     7       ,XNH8R1, XLH8R1, RH8R1
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /PARL/ PHP(20), THP(20), PH5(20), TH5(20), PH6(20), TH6(20)
     1       ,PH7(21,20), TH7(21,20), PH8(20), TH8(20), PH4(20), TH4(20),
     2        PH3(20), TH3(20), PH2(21,20), TH2(21,20), PH1(20), TH1(20),
     3                PLP(20), TLP(20), PL5(20), TL5(20), PL6(20), TL6(20)
     4       ,PL7(21,20), TL7(21,20), PL8(20), TL8(20), PL4(20), TL4(20),
     5        PL3(20), TL3(20), PL2(21,20), TL2(21,20), PL1(20), TL1(20)
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
     1        GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2        RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /SPARL/ XKP(20), XKBP(20)
      DIMENSION          EBH2(20), EBH3(20), EBH4(20), EBH5(20),
     1 EBH6(20), EBH7(20), EBHP(20), EBH2H3(20), EBH4HP(20), EBHPH5(20),
     2 EBH6H7(20), BH2H3(20), BH4HP(20), BHPH5(20), BH6H7(20), EBL2(20),
     3 EBL3(20), EBL4(20), EBL5(20), EBL6(20), EBL7(20), EBLP(20),
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     4 EBL2L3(20), EBL4LP(20), EBLPL5(20), EBL6L7(20), BL2L3(20),
     5 BL4LP(20), BLPL5(20), BL6L7(20)
      EQUIVALENCE (EBH2(1),EBL2(1)),(EBH3(1),EBL3(1)),(EBH4(1),EBL4(1)),
     1 (EBH5(1),EBL5(1)),(EBH6(1),EBL6(1)),(EBH7(1),EBL7(1)),
     2 (EBHP(1),EBLP(1)),(EBH2H3(1),EBL2L3(1)),(EBH4HP(1),EBL4LP(1)),
     3 (EBHPH5(1),EBLPL5(1)),(EBH6H7(1),EBL6L7(1)),(BH2H3(1),BL2L3(1)),
     4 (BH4HP(1),BL4LP(1)),(BHPH5(1),BLPL5(1)),(BH6H7(1),BL6L7(1))
      DO 190 M=1,NH
      IF(M.EQ.NH)GO TO 10
      IF(M.NE.1)GO TO 20
      XKP(1)=(FPP(2)-FPP(1))/(HH7(2)-HH7(1))
      GO TO 30
   10 XKP(NH)=(FPP(NH)-FPP(NH-1))/(HH7(NH)-HH7(NH-1))
      GO TO 30
   20 XKP(M)=(FPP(M+1)-FPP(M-1))/(HH7(M+1)-HH7(M-1))
   30 CONTINUE
      XKP(M)=-XKP(M)
      P5=.5
      PI=3.1415927
      IF(FPP(M).LT.0.)GO TO 110
C     HIGH PRESSURE PATH
C     BULK MODULUS AND AVERAGE BULK MODULUS
      CALL DBLIN(PH2(NH2I,M),TH2(NH2I,M),EBH2(M),PBULK,TBULK,EBULK,
     1 NPBULK,NTBULK,IERR)
      IF(IERR.EQ.1)GO TO 200
   40 CONTINUE
      CALL DBLIN(PH3(M),TH3(M),EBH3(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 220
   50 CONTINUE
      CALL DBLIN(PH4(M),TH4(M),EBH4(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 230
   60 CONTINUE
      CALL DBLIN(PH5(M),TH5(M),EBH5(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1IERR)
      IF(IERR.EQ.1)GO TO 240
   70 CONTINUE
      CALL DBLIN(PH6(M),TH6(M),EBH6(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 250
   80 CONTINUE
      CALL DBLIN(PH7(NH7I,M),TH7(NH7I,M),EBH7(M),PBULK,TBULK,EBULK,
     1 NPBULK,NTBULK,IERR)
      IF(IERR.EQ.1)GO TO 260
   90 CONTINUE
      CALL DBLIN(PHP(M),THP(M),EBHP(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 270
  100 CONTINUE
      EBH2H3(M)=P5*(EBH2(M)+EBH3(M))
      EBH4HP(M)=P5*(EBH4(M)+EBHP(M))
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      EBHPH5(M)=P5*(EBHP(M)+EBH5(M))
      EBH6H7(M)=P5*(EBH6(M)+EBH7(M))
C     BULK STIFFNESS
      PI7=PI/HH7(M)
      PI7P=PI/HHP(M)
      RHP2=RHP*RHP
      BH2H3(M)=PI7*EBH2H3(M)*(RH3*RH3-RH2*RH2)
      BH4HP(M)=PI7P*EBH4HP(M)*(RHP2-RH4*RH4)
      BHPH5(M)=PI7P*EBHPH5(M)*(RH5*RH5-RHP2)
      BH6H7(M)=PI7*EBH6H7(M)*(RH7*RH7-RH6*RH6)
      XKBP(M)=BH2H3(M)+BH4HP(M)+BHPH5(M)+BH6H7(M)
      GO TO 190
C     LOW PRESSURE PATH
C     BULK MODULUS AND AVERAGE BULK MODULUS
  110 CONTINUE
      CALL DBLIN(PL2(NL2I,M),TL2(NL2I,M),EBL2(M),PBULK,TBULK,EBULK,
     1 NPBULK,NTBULK,IERR)
      IF(IERR.EQ.1)GO TO 280
  120 CONTINUE
      CALL DBLIN(PL3(M),TL3(M),EBL3(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 290
  130 CONTINUE
      CALL DBLIN(PL4(M),TL4(M),EBL4(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 300
  140 CONTINUE
      CALL DBLIN(PL5(M),TL5(M),EBL5(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 310
  150 CONTINUE
      CALL DBLIN(PL6(M),TL6(M),EBL6(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 320
  160 CONTINUE
      CALL DBLIN(PL7(NL7I,M),TL7(NL7I,M),EBL7(M),PBULK,TBULK,EBULK,
     1 NPBULK,NTBULK,IERR)
      IF(IERR.EQ.1)GO TO 330
  170 CONTINUE
      CALL DBLIN(PLP(M),TLP(M),EBLP(M),PBULK,TBULK,EBULK,NPBULK,NTBULK,
     1 IERR)
      IF(IERR.EQ.1)GO TO 340
  180 CONTINUE
      PI7=PI/HL7(M)
      PI7P=PI/HLP(M)
      EBL2L3(M)=P5*(EBL2(M)+EBL3(M))
      EBL4LP(M)=P5*(EBL4(M)+EBLP(M))
      EBLPL5(M)=P5*(EBLP(M)+EBL5(M))
      EBL6L7(M)=P5*(EBL6(M)+EBL7(M))
C     BULK STIFFNESS
      RLP2=RLP*RLP
      BL2L3(M)=PI7*EBL2L3(M)*(RL3*RL3-RL2*RL2)
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      BL4LP(M)=PI7P*EBL4LP(M)*(RLP2-RL4*RL4)
      BLPL5(M)=PI7P*EBLPL5(M)*(RL5*RL5-RLP2)
      BL6L7(M)=PI7*EBL6L7(M)*(RL7*RL7-RL6*RL6)
      XKBP(M)=BL2L3(M)+BL4LP(M)+BLPL5(M)+BL6L7(M)
  190 CONTINUE
      RETURN
  200 WRITE (6,210)PH2(NH2I,M),TH2(NH2I,M),M
  210 FORMAT(1H0/115H0THE VALUES FOR BULK MODULUS TABLE INTERPOLATION IN
     1 THE PARALLEL STIFFNESS SUBROUTINE WERE OUTSIDE THE TABLE RANGE.
     2/11H PRESSURE = ,1P1D15.4/14H TEMPERATURE = ,1P1D15.4/29H SILL CLE
     3ARANCE SUBSCRIPT M = ,I4)
      GO TO 40
  220 WRITE (6,210)PH3(M),TH3(M),M
      GO TO 50
  230 WRITE (6,210)PH4(M),TH4(M),M
      GO TO 60
  240 WRITE (6,210)PH5(M),TH5(M),M
      GO TO 70
  250 WRITE (6,210)PH6(M),TH6(M),M
      GO TO 80
  260 WRITE (6,210)PH7(NH7I,M),TH7(NH7I,M),M
      GO TO 90
  270 WRITE (6,210)PHP(M),THP(M),M
      GO TO 100
  280 WRITE (6,210)PL2(NL2I,M),TL2(NL2I,M),M
      GO TO 120
  290 WRITE (6,210)PL3(M),TL3(M),M
      GO TO 130
  300 WRITE (6,210)PL4(M),TL4(M),M
      GO TO 140
  310 WRITE (6,210)PL5(M),TL5(M),M
      GO TO 150
  320 WRITE (6,210)PL6(M),TL6(M),M
      GO TO 160
  330 WRITE (6,210)PL7(NL7I,M),TL7(NL7I,M),M
      GO TO 170
  340 WRITE (6,210)PLP(M),TLP(M),M
      GO TO 180
      END
      SUBROUTINE PSOUT
C
C     PARALLEL PISTON STIFFNESS OUTPUT
C     SERIES PISTON OUTPUT OF STIFFNESS
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /FPARL/ FP(12), FPP(20), NH2I, NH7I, RH2I(20), RH7I(21),
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     1          GHPH4, XKHPH4, GHPH5, XKHPH5, NL7I, NL2I, RL7I(20),
     2          RL2I(21), GLPL5, XKLPL5, GLPL4, XKLPL4
      COMMON /SPARL/ XKP(20), XKBP(20)
      REAL*8 NMH2, NMH7, NML7, NML2
      COMMON /HPARL/ HPP(20), XMUHP, XMUH4, XMUH5, XMUH7(21), XMUL7(21),
     1          XMULP, XMUL5, XMUL4, WHPH1, GH3H2(21), CMH2(21), UDH2(21),
     2          REH2(21), NMH2(21), HH1, UH1, GH1, XMUH1, WHPH8, GH6H7(21),
     3          CMH7(21), UDH7(21), REH7(21), NMH7(21), REH8, GH8, UH8,
     4          REL8, GL8, UL8, GL6L7(21), CML7(21), UDL7(21), REL7(21),
     5          NML7(21), WLPL8, WLPL1, GL3L2(21), CML2(21), UDL2(21),
     6          REL2(21), NML2(21), HL1, GL1SD, XMUL1S
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1          CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /OUTP1/ WT(20), WHSHP, WLSLP
      COMMON /MAIN2/ HL3(20)
      WRITE (6,10)(TITLE(I),I=1,9)
   10 FORMAT(1H1/1H ,45X,27HAEROJET-GENERAL CORPORATION /1H ,49X,19HPROP
     1ULSION DIVISION /1H ,47X,22HSACRAMENTO, CALIFORNIA/15H0PROGRAM E21
     2902 /1H0,9A8)
      WRITE (6,20)(HL3(M),HH7(M),WT(M),FPP(M),XKP(M),XKBP(M),HPP(M),
     1M=1,NH)
   20 FORMAT(33H0PERFORMANCE OVER CLEARANCE RANGE  /1H0/ 11H  LOW PRES.
     1,7X, 10HHIGH PRES. , 8X, 9HFLOW RATE ,9X, 8HBALANCER ,11X, 6HSTATI
     2C ,13X,4HBULK          ,6X,11HHORSEPOWER /11H  CLEARANCE ,8X, 9HCLEA
     3RANGE ,30X, 4HLOAD ,8X, 9HSTIFFNESS ,8X,      9HSTIFFNESS /1H ,
     4 6X,4H(IN) ,13X, 4H(IN) ,9X, 8H(LB/SEC) ,13X, 4H(LB) ,10X, 7H(LB/I
     5N) ,10X, 7H(LB/IN) ,13X, 4H(HP) /1H /(1H ,1P1D10.4,6D17.4))
      RETURN
      END
      SUBROUTINE FORCP
C
C     FORCE (LOADER) PISTON
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1          NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2          NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3          ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4         ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1          NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2          NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3          NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4         ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /IN5/ K, NFS, PFS(21), TFS, PC2, PEXH, PFPR1, XNFSFP,
     1          DFSFP, CFSFP, DFS, RFP, RF1, RFTS, HF1C1, HEF1C1, XLF1C1,
     2          XNF1C1, PF1C1, XF1C1, HC1C2, HEC1C2, XLC1C2, XNC1C2, PC1C2,
     3          XC1C2, CF1C1, CC1C2, HFP, HF1, HSP, XNC1R1, XLC1R1, RC1R1
      REAL*8 NM
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1          CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
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```
      COMMON /FORCL/ PFP(20), TFP(20), PF1(20), TF1(20), PC1(20),
     1               TC1(20),          TC2(20), PR1(20), TR1(20),
     2               FFP(20), HPFP(20)
      COMMON /FORCC/ N, NDUM, WFSFP, WC1C2, WC1R1, GFP, CPFP, XMUFP, GF1
     1       ,CPF1,XMUF1, REFPF1, RF1HE, GC1, CPC1, XMUC1, REF1C1,REC1R1
      COMMON /PFGUES/ C12
      COMMON /PGUES/ C11
      COMMON /ERPRNT/ IERRT
      DIMENSIONTM(3)
      CVF1=PI2*RF1*HF1
      UDF1=OMEGAD*RF1
      UDF12=UDF1*UDF1*.25
      CK=.578-1.67*HF1
      IF(UDF1.NE.0.)CK1=4.11/UDF1
      RFD=RF1*RF1-RFP*RFP
      CPF1C=OMEGAD*OMEGAD*RFD/CHL
      CRE=2.*HF1/GVTY
      CTF1=UDF12*RFD*PI/(CHL*CT2)
      RF1HE=RF1+HEF1C1
      RF1HE2=RF1+HEC1C2
C     CALCULATION OF FORCE PISTON VALUES FOR EACH SUPPLY PRESSURE
      DO 330 N=1,NFS
      IERRT=0
      PDEN=PFS(N)-PFPR1
C     SUPPLY VALUES
      CALL DBLIN(PFS(N),TFS    ,GFS,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 340
   10 CONTINUE
      CALL DBLIN(PFS(N),TFS,CPFS,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 380
   20 CONTINUE
      CALL DBLIN(PFS(N),TFS,XMUFS,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 400
   30 CONTINUE
C     POCKET PRESSURE
   40 CONTINUE
      PFP(N)=PFS(N)-C12*(PFS(N)-PFPR1)
      WFSFP=0.
C
C     ITERATION ON POCKET PRESSURE
C
      DO 280 IP=1,ITERP
C     ORIFICE CALCULATION
      CALL ORIF(PFS(N),TFS,GFS,CPFS,PFP(N),XNFSFP,CFSFP,DFSFP,DFS,RFP,
     1 HFP,WFSFP,TFP(N),GFP,CPFP,XMUFP)
      IF(IERRT.GE.5)GO TO 300
      PF1(N)=0.
      GF1=GFP
      CPF1=CPFP
      XMUF1=XMUFP
C     ITERATION ON POCKET PRESSURE INCREASE DUE TO ROTATION
      DO 130 I=1,ITERC
```

```
      PTEM=PF1(N)
      GFPF1=GFP+CR*(GF1-GFP)
      VF1=WFSFP/(CVF1*GF1)
      IF(VF1.GT.UDF1*.07)GO TO 50
      XK=CK-CK1*VF1
      GO TO 60
   50 XK=0.
   60 CONTINUE
      PF1(N)=PFP(N)+GFPF1*XK*XK*CPF1C
C     ISENTROPIC OUTLET TEMPERATURE
      CALL TEMP(PFP(N),TFP(N),PF1(N),TF1X,IERR)
      IF(IERR.EQ.1)GO TO 420
   70 CONTINUE
C     FLUID PROPERTIES
      VRFPF1=P5*DSQRT(VF1*VF1+UDF12)
      CPFPF1=P5*(CPFP+CPF1)
      XMFPF1=P5*(XMUFP+XMUF1)
C     POCKET REYNOLDS NUMBER
      REFPF1=CRE*GFPF1*VRFPF1/XMFPF1
      IF(REFPF1.GT.2000.)GO TO 80
      CM=CMLAM
      NM=NMLAM
      GO TO 90
   80 CM=CMTUR
      NM=NMTUR
   90 CONTINUE
C     ACTUAL OUTLET TEMPERATURE
      TF1(N)=TF1X+CTF1*CM*GFPF1/(WFSFP*CPFPF1*(REFPF1**NM))
C     OUTLET PROPERTIES
      CALL DBLIN(PF1(N),TF1(N),GF1,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 440
  100 CONTINUE
      CALL DBLIN(PF1(N),TF1(N),CPF1,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,
     1IERR)
      IF(IERR.EQ.1)GO TO 470
  110 CONTINUE
      CALL DBLIN(PF1(N),TF1(N),XMUF1,PVISC,TVISC,XMVISC,NPVISC,NTVISC,
     1IERR)
      IF(IERR.EQ.1)GO TO 490
  120 CONTINUE
      IF(DABS((PF1(N)-PTEM)/PF1(N)).LE.C1)GO TO 160
  130 CONTINUE
      WRITE (6,140)ITERC,PF1(N),PTEM
  140 FORMAT(1H0/106H0THE FORCE PISTON ITERATION ON POCKET PRESSURE INCR
     1EASE DUE TO ROTATION DID NOT CONVERGE IN THE MAXIMUM OF ,I4 /
     212H ITERATIONS. / 28H THE FINAL POCKET PRESSURE = ,1P1D15.4/
     3 34H THE PREVIOUS ITERATION PRESSURE= ,1P1D15.4)
      WRITE (6,150)PFS(N)
  150 FORMAT( 22H SUPPLY PRESSURE PFS = ,1P1D15.4)
      GO TO 330
C     CONVERGENCE OF POCKET PRESSURE DUE TO ROTATION
  160 VR1=2.*VRFPF1
```

```
C     LABYRINTH SEAL CALCULATIONS
      CALL LABYP(PF1(N),TF1(N),GF1,CPF1,XMUF1,WFSFP,XNF1C1,PF1C1,XF1C1,
     1 HF1C1,CF1C1,HEF1C1,RF1HE,VR1,PC1(N),TC1(N),GC1,CPC1,XMUC1,UF1,
     2 UDF1,VC1,VRC1,REF1C1,GF1C1)
      IF(IERRT.GE.5)GO TO 300
      CALL LABYS(PC1(N),TC1(N),GC1,VRC1,CPC1,PC2    ,PC1C2,XC1C2,HC1C2,
     1 XNC1C2,CC1C2,RF1,RF1HE2,TC2(N),GC2,VRC2,CPC2,WC1C2,XMUC2,GC1C2,
     2 REC1C2,XMUC1)
      IF(IERRT.GE.5)GO TO 300
C     RETURN FLOW
      IF(PC1(N).GT.PFPR1)GO TO 170
      WC1R1=0.D0
      GO TO 210
  170 CONTINUE
      CALL TEMP(PC1(N),TC1(N),PFPR1,TFPR1,IERR)
      IF(IERR.EQ.0)GO TO 180
      WRITE (6,510)PC1(N),TC1(N),PFPR1
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
  180 CONTINUE
      CALL DBLIN(PFPR1,TFPR1,GFPR1,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.0)GO TO 190
      WRITE (6,520)
      WRITE (6,370)PFPR1,TFPR1
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
  190 CONTINUE
      CALL DBLIN(PFPR1,TFPR1,XMFPR1,PVISC,TVISC,XMVISC,NPVISC,NTVISC,
     1IERR)
      IF(IERR.EQ.0)GO TO 200
      WRITE (6,530)
      WRITE (6,370)PFPR1,TFPR1
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
  200 CONTINUE
      GC1R1=GC1+CR*(GFPR1-GC1)
      XMC1R1=XMUC1+CR*(XMFPR1-XMUC1)
C     LAMINAR FLOW IN LINE
      WC1R1=P5*PI4*(PC1(N)-PFPR1)*(RC1R1**4)*XNC1R1/(XMC1R1*XLC1R1)
      REC1R1=2.*WC1R1/(PI*GVTY*XMC1R1*RC1R1*XNC1R1)
      IF(REC1R1.LE.2000.)GO TO 210
      WC1R1=PI*XNC1R1*((PC1(N)-PFPR1)*GC1R1/(CFTUR*XLC1R1)*(2.0**(2.0+
     1 NFTUR))*(GVTY**(1.0-NFTUR))*(RC1R1**(5.0-NFTUR))/(XMC1R1**NFTUR)
     2)**(1.0/(2.0-NFTUR))
      REC1R1=2.*WC1R1/(PI*GVTY*XMC1R1*RC1R1*XNC1R1)
  210 CONTINUE
      WR1C1=WC1R1+WC1C2
      IF(DABS((WR1C1-WFSFP)/WFSFP).LE.C1)GO TO 320
C
C     TEST FOR CONVERGENCE OF FLOW VALUES
C
C     ADJUST INLET FLOW
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```
      XKFSFP=WFSFP/DSQRT(PFS(N)-PFP(N))
      XKFSC1=WFSFP/DSQRT(PFS(N)-PC1(N))
      XKC1C2=WC1C2/DSQRT(PC1(N)-PC2)
C
C     CALCULATE NEW PC1(N) USING Y FLOW NET
C     WITH METHOD OF FALSE POSITION
C
      IF(PC1(N).LE.PFPR1)GO TO 250
      XKC1R1=WC1R1/DSQRT(PC1(N)-PFPR1)
      ICOUNT=0
      ZNEG=WFSFP-WR1C1
      IF(ZNEG.LT.0.D0)GO TO 220
C     WFSFP-WR1C1 POSITIVE
      ZPOS=ZNEG
      XPOS=PC1(N)
      XNEG=PFS(N)
      ZNEG=-XKC1R1*DSQRT(XNEG-PFPR1)-XKC1C2*DSQRT(XNEG-PC2)
      GO TO 230
C     WFSFP-WR1C1 NEGATIVE
  220 XNEG=PC1(N)
      XPOS=PFPR1
      ZPOS=XKFSC1*DSQRT(PFS(N)-XPOS)-XKC1C2*DSQRT(XPOS-PC2)
      IF(ZPOS.LE.0.D0)GO TO 250
C     CALCULATE NEXT PC1(N) GUESS
  230 PC1TEM=XPOS-(XPOS-XNEG)*ZPOS/(ZPOS-ZNEG)
      WFSFP=XKFSC1*DSQRT(PFS(N)-PC1TEM)
      WR1C1=XKC1R1*DSQRT(PC1TEM-PFPR1)+XKC1C2*DSQRT(PC1TEM-PC2)
      ZPC1=WFSFP-WR1C1
      IF(DABS(ZPC1/WFSFP).LE.C1)GO TO 260
      ICOUNT=ICOUNT+1
      IF(ICOUNT.GE.ITERP)GO TO 260
      IF(ZPC1.LT.0.D0)GO TO 240
      XPOS=PC1TEM
      ZPOS=ZPC1
      GO TO 230
  240 XNEG=PC1TEM
      ZNEG=ZPC1
      GO TO 230
  250 CONTINUE
      XKA=XKFSC1*XKFSC1
      XKC=XKC1C2*XKC1C2
      PC1TEM=(XKA*PFS(N)+XKC*PC2)/(XKA+XKC)
  260 CONTINUE
      WFSFP=XKFSC1*DSQRT(PFS(N)-(PC1TEM+PC1(N)+PC1TEM)/3.D0)
C     ADJUST POCKET PRESSURE
      PFP(N)=PFS(N)-(WFSFP/XKFSFP)**2
      IF(PFP(N).GT.PC2)GO TO 280
      C12=C12*2.D0
      WRITE(6,270)
  270 FORMAT(79H0THE INITIAL FORCE PISTON POCKET PRESSURE WAS TOO LARGE.
     1  C12 HAS BEEN DOUBLED.   )
      GO TO 40
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```
  280 CONTINUE
      WRITE (6,290)ITERP,WR1C1,WFSFP,PFP(N)
  290 FORMAT(1H0/ 64H0THE FORCE PISTON RETURN FLOW DID NOT CONVERGE IN T
     1HE MAXIMUM OF ,I4, 1X, 11HITERATIONS. /14H RETURN FLOW =,1P1D15.4/
     2 13H INLET FLOW= ,D15.4/ 24H FINAL POCKET PRESSURE = ,D15.4)
      WRITE (6,150)PFS(N)
      GO TO 330
  300 WRITE (6,310)PFS(N)
  310 FORMAT(1H0/ 39H0THE FORCE PISTON SUPPLY PRESSURE PFS = ,1P1D12.4,
     11X, 60HWAS BYPASSED AFTER 5 PROPERTY TABLE ARGUMENTS WERE IN ERROR
     2. )
      GO TO 330
  320 CONTINUE
C
C     FORCE CALCULATIONS
C
      RF12=RF1*RF1
      FFP1=PI*RF12*(-PFP(N)+.25*GFPF1/GVTY*RF12*(XK    *OMEGAD)**2)
      FFP2=PEXH*PI*(RF12-RFTS*RFTS)
      FFP(N)=FFP1+FFP2
C
C     HORSEPOWER CALCULATIONS
C
      CTM=CM*PI4G*((UDF1*RF1)**2)
      TM(1)=GFP*CTM*RF1/(REFPF1**NM)
      TM(2)=GF1C1*CTM*XLF1C1/(REF1C1**NM)
      TM(3)=GC1C2*CTM*XLC1C2/(REC1C2**NM)
      XMFPR=TM(1)+TM(2)+TM(3)
      HPFP(N)=XMFPR*XNRPM/63000.
      CALL LOUT
  330 CONTINUE
      RETURN
  340 WRITE (6,350)
  350 FORMAT(1H0/ 93H0THE FORCE PISTON SUPPLY VALUES FOR DENSITY TABLE I
     1NTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
  360 WRITE (6,370)PFS(N),TFS
  370 FORMAT(11H PRESSURE = ,1P1D15.4/14H TEMPERATURE = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 10
  380 WRITE (6,390)
  390 FORMAT(1H0/ 98H0THE FORCE PISTON SUPPLY VALUES FOR SPECIIC HEAT TA
     1BLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,370)PFS(N),TFS
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 20
  400 WRITE (6,410)
  410 FORMAT(1H0/ 95H0THE FORCE PISTON SUPPLY VALUES FOR VISCOSITY TABLE
     1 INTERPOLATION WERE OUTSIDE THE TABLE RANGE.  )
      WRITE (6,370)PFS(N),TFS
      IERRT=IERRT+1
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```
      IF(IERRT.GE.5)GO TO 300
      GO TO 30
  420 WRITE (6,430)PFP(N),TFP(N),PF1(N)
  430 FORMAT(1H0/ 97H0THE FORCE PISTON OUTLET VALUES FOR TEMPERATURE TAB
     1LE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. /19H ORIFICE PRESSU
     2RE = ,1P1D15.4/22H ORIFICE TEMPERATURE = ,1P1D15.4/25H POCKET OUTL
     3ET PRESSURE = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 70
  440 WRITE (6,450)
  450 FORMAT(1H0/ 93H0THE FORCE PISTON POCKET VALUES FOR DENSITY TABLE I
     1NTERPOLATION WERE OUTSIDE THE TABLE RANGE.  )
  460 WRITE (6,370)PF1(N),TF1(N)
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 100
  470 WRITE (6,480)
  480 FORMAT(1H0/ 99H0THE FORCE PISTON POCKET VALUES FOR SPECIFIC HEAT T
     1ABLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,370)PF1(N),TF1(N)
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 110
  490 WRITE (6,500)
  500 FORMAT(1H0/ 95H0THE FORCE PISTON POCKET VALUES FOR VISCOSITY TABLE
     1 INTERPOLATION WERE OUTSIDE THE TABLE RANGE.       )
      WRITE (6,370)PF1(N),TF1(N)
      IERRT=IERRT+1
      IF(IERRT.GE.5)GO TO 300
      GO TO 120
  510 FORMAT(1H0/102H0THE FORCE PISTON RETURN LINE VALUES FOR TEMPERATUR
     1E TABLE INTERPOLATION WERE OUTSIDE THE TABLE RANGE. /27H FIRST LAB
     2YRINTH PRESSURE =,1P1D15.4/ 30H FIRST LABYRINTH TEMPERATURE = ,
     3 D15.4/18H RETURN PRESSURE = ,D15.4)
  520 FORMAT(1H0/ 93H0THE FORCE PISTON RETURN VALUES FOR DENSITY TABLE I
     1NTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
  530 FORMAT(1H0/ 95H0THE FORCE PISTON RETURN VALUES FOR VISCOSITY TABLE
     1 INTERPOLATION WERE OUTSIDE THE TABLE RANGE. )
      END
      SUBROUTINE LOUT
C
C     FORCE PISTON OUTPUT
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN5/ K, NFS, PFS(21), TFS, PC2, PEXH, PFPR1, XNFSFP,
     1         DFSFP, CFSFP, DFS, RFP, RF1, RFTS, HF1C1, HEF1C1, XLF1C1,
     2         XNF1C1, PF1C1, XF1C1, HC1C2, HEC1C2, XLC1C2, XNC1C2, PC1C2,
     3         XC1C2, CF1C1, CC1C2, HFP, HF1, HSP, XNC1R1, XLC1R1, RC1R1
      COMMON /FORCL/ PFP(20), TFP(20), PF1(20), TF1(20), PC1(20),
     1               TC1(20),           TC2(20), PR1(20), TR1(20),
     2               FFP(20), HPFP(20)
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```
      COMMON /FORCC/ N, NDUM, WFSFP, WC1C2, WC1R1, GFP, CPFP, XMUFP, GF1
     1     ,CPF1,XMUF1, REFPF1, RF1HE, GC1, CPC1, XMUC1, REF1C1,REC1R1
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4        ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      WRITE (6,10)(TITLE(I),I=1,9)
   10 FORMAT(1H1/1H ,45X,27HAEROJET-GENERAL CORPORATION /1H ,49X,19HPROP
     1ULSION DIVISION /1H ,47X,22HSACRAMENTO, CALIFORNIA/15H0PROGRAM E21
     2902 /1H0,9A8)
      WRITE (6,20)PFS(N),PFPR1,PC2,RF1
   20 FORMAT(12H0LOAD PISTON /1H0/21H PRESSURES (LB/IN**2) /1H ,5X,5HPFS
     1 = ,1P1D15.4,10X, 7HPFPR1 = ,D15.4, 8X, 6HPFC2 = ,D15.4/ 19H RADIU
     2S (IN), RF1 = ,D15.4 )
      WRITE (6,30)HF1C1,HC1C2,HEF1C1,HEC1C2,XLF1C1,XLC1C2,PF1C1,PC1C2,
     1 XF1C1,XC1C2,XNF1C1,XNC1C2,CF1C1,CC1C2
   30 FORMAT(11H LABYRINTHS /1H ,5X,21HTOOTH CLEARANCE (IN),,5X,7HHF1C1
     1= ,1P1D15.4,10X, 7HHC1C2 = ,D15.4/1H ,5X, 18HVALLEY DEPTH (IN), ,
     2 8X, 8HHEF1C1 = ,D14.4,10X, 8HHEC1C2 = ,D14.4/1H ,5X, 20HOVERALL L
     3ENGTH (IN), ,6X,7HLF1C1 =,D15.4,10X, 7HLC1C2 = ,D15.4/1H , 5X, 11H
     4PITCH (IN), ,15X, 7HPF1C1 = ,D15.4,10X, 7HPC1C2 = ,D15.4/1H ,5X,
     5 17HPOINT WIDTH (IN), ,9X, 7HXF1C1 = ,D15.4,10X, 7HXC1C2 = ,D15.4/
     61H ,5X, 17HNUMBER OF POINTS, ,9X, 7HNF1C1 = ,D15.4, 10X,7HNC1C2 =
     7 ,D15.4/ 1H ,5X,22HDISCHARGE COEFFICIENT, 4X,7HCF1C1 = ,D15.4,10X,
     8 7HCC1C2 = ,D15.4)
      BTU=.7073*HPFP(N)
      WRITE (6,40)WFSFP,WC1C2,WC1R1,BTU
   40 FORMAT(19H0FLOW RATE (LB/SEC) ,74X, 25HHEAT GENERATION (BTU/SEC)/
     11H ,5X, 7HWFSFP = ,1P1D15.4, 8X, 7HWC1C2 = ,D15.4, 8X, 7HWC1R1 = ,
     2 D15.4,10X, D15.4)
      WRITE (6,50)RFP,PFP(N),TFP(N),GFP,CPFP,XMUFP,RF1,PF1(N),TF1(N),
     1 GF1,CPF1,XMUF1,REFPF1,RF1HE,PC1(N),TC1(N),GC1,CPC1,XMUC1,REF1C1,
     2 REC1R1,FFP(N),HPFP(N)
   50 FORMAT(1H0,7X, 8HLOCATION ,9X, 8HPRESSURE ,6X, 11HTEMPERATURE ,
     1 10X, 7HDENSITY , 4X, 13HSPECIFIC HEAT , 8X, 9HVISCOSITY , 2X,15HR
     2EYNOLDS NUMBER /1H ,22X, 10H(LB/IN**2) ,10X, 7H(DEG R) ,4X, 13H(B
     3TU/LB*DEGR) ,3X, 14H(LB*SEC/IN**2) / 4H RFP ,1P1D12.4,5D17.4/4H RF
     41 ,D12.4,6D17.4/ 5H RFC1 ,D11.4,6D17.4/1H ,100X,D17.4/25H0LOAD PIS
     5TON FORCE (LB) = ,D15.4/ 18H HORSEPOWER (HP) =  ,D15.4)
      RETURN
      END
      SUBROUTINE ORIF(P1,T1,G1,CP1,P2,XN,C12,D12,D1,R2,H2,W12,T2,G2,CP2,
     1 XMU2)
C
C     ORIFICE CALCULATIONS
C
C     INPUT NEEDED
C
C     P1 = INITIAL PRESSURE
C     T1 = INITIAL TEMPERATURE
```

```
C     G1 = INITIAL DENSITY
C     CP1 = INITIAL SPECIFIC HEAT
C     P2 = DOWNSTREAM PRESSURE
C     XN = NUMBER OF ORIFICES
C     C12 = FLUID ROTATION FACTOR
C     D12 = ORIFICE DIAMETER
C     D1 = SUPPLY LINE DIAMETER
C     R2 = RADIUS
C     H2 = CLEARANCE
C
C     CONSTANTS NEEDED - GVTY, XJ, ITERC, CR, C1
C
C     OUTPUT RETURNED
C
C     W12 = ORIFICE WEIGHT FLOW
C     T2 = DOWNSTREAM TEMPERATURE
C     G2 = DOWNSTREAM DENSITY
C     CP2 = DOWNSTREAM SPECIFIC HEAT
C     XMU2 = DOWNSTREAM VISCOSITY
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /ERPRNT/ IERRT
C
C     CONSTANT CALCULATIONS AND INITIALIZATION
C
      G2=G1
      CP2=CP1
      CW12=XN*PI4*C12*D12*D12*DSQRT(CHL*(P1-P2))
      CHL1=P1/G1
      CHL2=.8105696/(((G1*D1*D1)**2)*GVTY)
      CHL3=.01266515/(GVTY*(R2*H2)**2)
      W12=0.
C     ISENTROPIC DOWNSTREAM TEMPERATURE T2X
      CALL TEMP(P1,T1,P2,T2X,IERR)
      IF(IERR.EQ.1)GO TO 80
   10 CONTINUE
C
C     ITERATION ON ORIFICE WEIGHT FLOW W12
C
```

```
      DO 40 N=1,ITERC                                                   00015330
C     AVERAGES                                                          00015335
      G12=G1+CR*(G2-G1)                                                 00015340
      CP12=CP1+CR*(CP2-CP1)                                             00015345
C     ORIFICE WEIGHT FLOW                                               00015350
      WTEMP=W12                                                         00015355
      W12=CW12*DSQRT(G12)                                               00015360
C     HEAD LOSS FOR HEAT INPUT                                          00015365
      HL=CHL1-P2/G2+W12*W12*(CHL2-CHL3/(G2*G2))                         00015370
C                                                                       00015375
C     ACTUAL DOWNSTREAM VALUES                                          00015380
      T2=HL/(CT2*CP12)+T2X                                              00015385
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)       00015390
      IF(IERR.EQ.1)GO TO 100                                            00015395
   20 CONTINUE                                                          00015400
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)         00015405
      IF(IERR.EQ.1)GO TO 120                                            00015410
   30 CONTINUE                                                          00015415
C     TEST FOR CONVERGENCE                                              00015420
      IF(DABS((W12-WTEMP)/W12).LE.C1)GO TO 60                           00015425
   40 CONTINUE                                                          00015430
      WRITE (6,50)ITERC,W12,WTEMP                                       00015435
   50 FORMAT(1H0/ 57H0THE ORIFICE ITERATION DID NOT CONVERGE IN THE MAXI00015440
     1MUM OF ,I4,1X,11HITERATIONS. /32H THE FINAL ORIFICE WEIGHT FLOW = 00015445
     2,1P1D15.4 /45H THE PREVIOUS ITERATION ORIFICE WEIGHT FLOW = ,     00015450
     31P1D15.4)                                                         00015455
      IERRT=10                                                          00015460
      RETURN                                                            00015465
   60 CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)      00015470
      IF(IERR.EQ.0)RETURN                                               00015475
      WRITE (6,70)P2,T2,R2                                              00015480
   70 FORMAT(1H0/101H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH00015485
     1E ORIFICE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.  /14H PRESSURE 00015490
     2P2 = ,1P1D15.4 /17H TEMPERATURE T2 = ,1P1D15.4 /20H ORIFICE RADIUS00015495
     3 R2 = ,1P1D15.4)                                                  00015500
      IERRT=IERRT+1                                                     00015505
      RETURN                                                            00015510
   80 WRITE (6,90)P1,T1,P2,R2                                           00015515
   90 FORMAT(1H0/109H0THE VALUES FOR INTERPOLATION ON THE TEMPERATURE TA00015520
     1BLE VALUES WERE OUTSIDE THE TABLE RANGE IN SUBOUTINE ORIF. /      00015525
     214H PRESSURE P1 = ,1P1D15.4/17H TEMPERATURE T1 = ,1P1D15.4/       00015530
     314H PRESSURE P2 = ,1P1D15.4/20H ORIFICE RADIUS R2 = ,1P1D15.4 )   00015535
      IERRT=IERRT+1                                                     00015540
      IF(IERRT.GE.5)RETURN                                              00015545
      GO TO 10                                                          00015550
  100 WRITE(6,110)P2,T2,R2                                              00015555
  110 FORMAT(1H0/105H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I00015560
     1N THE ORIFICE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.  /14H PRESS00015565
     2URE P2 = ,1P1D15.4/ 17H TEMPERATURE T2 = ,1P1D15.4/20H ORIFICE RAD00015570
     3IUS R2 = ,1P1D15.4)                                               00015575
      IERRT=IERRT+1                                                     00015580
      IF(IERRT.GE.5)RETURN                                              00015585
```

```
      GO TO 20
  120 WRITE(6,130)P2,T2,R2
  130 FORMAT(1H0/ 99H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
     1ORIFICE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.   /14H PRESSURE P2
     2 = ,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4 /20H ORIFICE RADIUS R2
     3 = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 30
      END
      SUBROUTINE  PKT(P1,T1,G1,CP1,W12,R1,H1,R2,VR1,XMU1,P2,T2,G2,CP2,
     1 V2,U2,XMU2,VR2,RE12,G12,XK12,IN)
C
C     POCKET OUTWARD FLOW CALCULATIONS, IF IN=0
C     POCKET INWARD FLOW CALCULATIONS, IF IN=1
C
C     INPUT NEEDED
C
C     P1 = INITIAL PRESSURE
C     T1 = INITIAL TEMPERATURE
C     G1 = INITIAL POCKET DENSITY
C     CP1 = INITIAL SPECIFIC HEAT
C     W12 = WEIGHT FLOW
C     R1 = INITIAL RADIUS
C     H1 = INITIAL CLEARANCE
C     R2 = FINAL RADIUS
C     VR1 = INITIAL POCKET VELOCITY
C     XMU1 = INITIAL VISCOSITY
C
C
C
C     INPUT CONSTANTS - XNRPM, OMEGAD, CR, C1, XJ, GVTY, NMLAM, CMLAM,
C                       NMTUR, CMTUR, ITERC
C
C     OUTPUT RETURNED
C
C     P2 = INCREASED  ROTATIONAL POCKET PRESSURE, IF IN=0
C     P2 = DECREASED POCKET PRESSURE, IF IN=1
C     T2 = OUTLET TEMPERATURE
C     G2 = OUTLET DENSITY
C     CP2 = OUTLET SPECIFIC HEAT
C     V2 = POCKET OUTER RADIAL VELOCITY
C     U2 = OUTER TANGENTIAL VELOCITY
C     XMU2 = OUTLET VISCOSITY
C     VR2 = RESULTANT POCKET OUTER VELOCITY
C     RE12 = POCKET REYNOLDS NUMBER
C     G12 = AVERAGE POCKET DENSITY
C     XK12 = FLOW CONSTANT
C     XK12 = INWARD FLOW CONSTANT, IF IN=1
      IMPLICIT REAL*8 (A-H , O-Z)
      REAL*8 NM
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
```

```
     1          NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2          NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3          ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4         ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1          NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2          NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3          NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4         ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1          CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /ERPRNT/ IERRT
C
C     CONSTANT CALCULATION AND INITIALIZATION
C
      P2=0.
      G2=G1
      XMU2=XMU1
      CP2=CP1
      CV2=W12/(PI2*R2*H1)
      UD2=R2*OMEGAD
      U2=UD2*.5
      U2SQ=U2*U2
      UD12=P5*OMEGAD*(R1+R2)
      UD123=UD12**3
      RR2=(R2*R2-R1*R1)/CHL
      CP2C=OMEGAD*OMEGAD*RR2
      CRE12=2.*H1/GVTY
      IF(IN.EQ.0)GO TO 20
C     INLET OUTER VELOCITIES AND INWARD FLOW CONSTANT
      RR2=-RR2
      IF(IKIN.EQ.1)GO TO 30
      V1=W12/(PI2*R1*H1*G1)
      UD1=R1*OMEGAD
      IF(V1.GT.UD1*.07)GO TO 10
      V1U1D=V1/UD1
      R2R1=R2/R1
      H1R1=H1/R1
      H1R2=H1R1*R2R1*R2R1
      XK12=H1R2*(27.8+H1R2*(-2750.+65100.*H1R2))+V1U1D*(-917000.*H1R1**3
     1-12.6*R2R1+95.3*V1U1D)+.3865+2.13*DSQRT(V1U1D)-6.59*H1R1
      GO TO 30
   10 CONTINUE
      XK12=0.
      GO TO 30
   20 CONTINUE
      IF(IKIN.EQ.1)GO TO 30
      CK12=.578-1.67*H1
      CK122=4.11/UD2
   30 CONTINUE
```

```
      CT22=RR2*PI/(CT2*W12)*UD123
C
C     ITERATION ON INCREASED ROTATIONAL POCKET PRESSURE P2, IF IN=0
C     ITERATION ON DECREASED POCKET PRESSURE P2
C
      DO 120 N=1,ITERC
      PTEM =P2
C     AVERAGES
      G12=G1+CR*(G2-G1)
      CP12=CP1+CR*(CP2-CP1)
      XMU12=XMU1+CR*(XMU2-XMU2)
C     OUTER RESULTANT VELOCITY AND AVERAGE
      V2=CV2/G2
      VR2=DSQRT(U2SQ+V2*V2)
      VR12=.5*(VR1+VR2)
C     OUTWARD FLOW CONSTANT, IF IN=0
      IF(IN.EQ.1)GO TO 50
      IF(IKIN.EQ.1)GO TO 50
      IF(V2.GT.U2*.14) GO TO 40
      XK12=CK12-CK122*V2
      GO TO 50
   40 CONTINUE
      XK12=0.
   50 CONTINUE
      P2=G12*XK12*XK12*CP2C+P1
C     ISENTROPIC OUTLET TEMPERATURE
      CALL TEMP(P1,T1,P2,T2X,IERR)
      IF(IERR.EQ.1)GO TO 170
   60 CONTINUE
C     REYNOLDS NUMBER TO DETERMINE LAMINAR OR TURBULENT FLOW
      RE12=G12*VR12*CRE12/XMU12
      IF(RE12.GT.2000.)GO TO 70
      CM=CMLAM
      NM=NMLAM
      GO TO 80
   70 CM=CMTUR
      NM=NMTUR
   80 CONTINUE
C     OUTLET TEMPERATURE
      T2=T2X+CM*CT22*G12/(CP12*(RE12**NM))
C     DOWNSTREAM PROPERTIES
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 190
   90 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 210
  100 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 230
  110 CONTINUE
C     TEST CONVERGENCE OF P2
      IF(DABS((P2-PTEM )/P2).LE.C1)GO TO 160
```

```
120 CONTINUE
    IF(IN.EQ.1)GO TO 140
    WRITE (6,130)ITERC,P2,PTEM
130 FORMAT(1H0/ 95H0THE INCREASED POCKET ROTATIONAL PRESSURE FOR OUTWA
   1RD FLOW WAS NOT DETERMINED IN THE MAXIMUM OF ,I4,1X, 11HITERATIONS
   2. /21H THE FINAL PRESSURE = ,1P1D15.4/ 34H THE PREVIOUS ITERATION
   3PRESSURE = ,1P1D15.4 )
    IERRT=10
    RETURN
140 WRITE (6,150)ITERC,P2,PTEM
150 FORMAT(1H0/  94H0THE DECREASED POCKET ROTATIONAL PRESSURE FOR INWA
   1RD FLOW WAS NOT DETERMINED IN THE MAXIMUM OF ,I4,1X, 11HITERATIONS
   2. /21H THE FINAL PRESSURE = ,1P1D15.4/ 34H THE PREVIOUS ITERATION
   3PRESSURE = ,1P1D15.4 )
    IERRT=10
    RETURN
160 CONTINUE
    RETURN
170 WRITE (6,180)P1,T1,P2,R1,R2
180 FORMAT(1H0/117H0THE VALUES FOR INTERPOLATION ON THE TEMPERATURE TA
   1BLE VALUES WERE OUTSIDE THE TABLE RANGE FOR THE POCKET SUBROUTINE.
   2 /14H PRESSURE P1 = ,1P1D15.4/17H TEMPERATURE T1 = ,1P1D15.4/14H P
   3RESSURE P2 = ,1P1D15.4/ 12H RADIUS R1 = ,1P1D15.4/ 12H RADIUS R2 =
   4 ,1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 60
190 WRITE (6,200)P2,T2,R1,R2
200 FORMAT(1H0/ 99H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
   1 POCKET SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H PRESSURE P2
   2= ,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4/12H RADIUS R1 = ,1P1D15
   3.4/12H RADIUS R2 = ,1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 90
210 WRITE (6,220)P2,T2,R1,R2
220 FORMAT(1H0/104H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
   1N THE POCKET SUBROUTINE WERE OUTSIDE THE TABLE RANGE.  /14H PRESSU
   2RE P2 =,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4/12H RADIUS R1 = ,
   31P1D15.4/12H RADIUS R2 = ,1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 100
230 WRITE (6,240)P2,T2,R1,R2
240 FORMAT(1H0/100H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH
   1E POCKET SUBROUTINE WERE OUTSIDE THE TABLE RANGE.  /14H PRESSURE P
   22 = ,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4/12H RADIUS R1 = ,1P1D
   315.4/12H RADIUS R2 = ,1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 110
    END
```

```
      SUBROUTINE ENTS(P1,T1,G1,CP1,VR1,H1,W12,R2,H2,C2,P2,T2,G2,CP2,V2,
     1 VR2,XMU2,U2)
C
C     SILL ENTRANCE CALCULATIONS
C
C     INPUT NEEDED
C
C     P1 = INITIAL PRESSURE
C     T1 = INITIAL TEMPERATURE
C     G1 = INITIAL DENSITY
C     CP1 = INITIAL SPECIFIC HEAT
C     VR1 = INITIAL FLUID RESULTANT VELOCITY
C     H1 = INITIAL CLEARANCE
C     W12 = SILL ENTRANCE WEIGHT FLOW
C     R2 = RADIUS
C     H2 = OUTLET CLEARANCE
C     C2 = FLUID ROTATION FACTOR
C
C     CONSTANTS INPUT - CR, C1, ITERC, GVTY, XJ, XNRPM
C
C     OUTPUT RETURNED
C
C     P2 = SILL ENTRANCE DECREASED PRESSURE
C     T2 = OUTER ENTRANCE TEMPERATURE
C     G2 = OUTLET DENSITY
C     CP2 = OUTLET SPECIFIC HEAT
C     V2 = OUTER ENTRANCE FLUID RADIAL VELOCITY
C     VR2 = OUTER FLUID RESULTANT VELOCITY
C     XMU2 = OUTLET VISCOSITY
C     U2 = OUTER FLUID TANGENTIAL VELOCITY
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /ERPRNT/ IERRT
C
C     INITIALIZATION AND CONSTANT CALCULATION
C
      VR2=VR1
      G2=G1
      CP2=CP1
```

```
      P2=0.
      U2=P5*R2*OMEGAD
      U22=U2*U2
      CP2C=C2*((W12/R2*(1./H1-1./H2))**2)/(GVTY*78.956835)
      CHL2=P1/G1+VR1*VR1/CHL
      CV2=W12/(PI2*R2*H2)
C
C     ITERATION ON DECREASED SILL ENTRANCE PRESSURE
C
      DO 40 N=1,ITERC
      PTEM =P2
      G12=G1+CR*(G2-G1)
      CP12=CP1+CR*(CP2-CP1)
      P2=P1-CP2C/G12
      CALL TEMP(P1,T1,P2,T2X,IERR)
      IF(IERR.EQ.1)GO TO 80
   10 CONTINUE
      HL=CHL2-P2/G2-VR2*VR2/CHL
      T2=T2X+HL/(CP12*CT2)
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 100
   20 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 140
   30 CONTINUE
      V2=CV2/G2
      VR2=DSQRT(U22+V2*V2)
C
C     TEST ON PRESSURE FOR CONVERGENCE
C
      IF(DABS((P2-PTEM )/P2).LT.C1)GO TO 60
   40 CONTINUE
      WRITE (6,50)ITERC,P2,PTEM
   50 FORMAT(1H0/ 63H0THE SILL ENTRANCE ITERATION DID NOT CONVERGE IN TH
     1E MAXIMUM OF ,I3,1X, 11HITERATIONS. /21H THE FINAL PRESSURE = ,
     2 1P1D15.4 / 34H THE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
   60 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.0)RETURN
      WRITE (6,70)
   70 FORMAT(1H0/107H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH
     1E SILL ENTRANCE SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,130)P2,T2,R2
      IERRT=IERRT+1
      RETURN
   80 WRITE (6,90)P1,T1,P2,R2
   90 FORMAT(1H0/109H0THE VALUES FOR TEMPERATURE TABLE INTERPOLATION IN 
     1THE SILL ENTRANCE SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H PR
     2ESSURE P1 = ,1P1D15.4/17H TEMPERATURE T1 = ,1P1D15.4/14H PRESSURE 
     3P2 = ,1P1D15.4/12H RADIUS R2 = ,1P1D15.4)
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```
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 10
  100 WRITE (6,110)
  110 FORMAT(1H0/104H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
     1SILL ENTRANCE SUBROUTINE ARE OUTSIDE THE TABLE RANGE. )
  120 WRITE (6,130)P2,T2,R2
  130 FORMAT(14H PRESSURE P2 = ,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4/
     1 12H RADIUS R2 = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 20
  140 WRITE (6,150)
  150 FORMAT(1H0/111H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
     1N THE SILL ENTRANCE SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,130)P2,T2,R2
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 30
      END
      SUBROUTINE SILL(P1,T1,G1,CP1,XMU1,R1,VR1,W13,R3,H3,V1,R4,P2,T2,G2,
     1 CP2,XMU2,XK13,R2,RE12,V2,VR2,UD12,G12,CM,NM,NR,IN)
C
C     INPUT NEEDED
C
C     P1 = INITIAL PRESSURE
C     T1 = INITIAL TEMPERATURE
C     G1 = INITIAL DENSITY
C     CP1 = INITIAL SPECIFIC HEAT
C     XMU1 = INITIAL VISCOSITY
C     R1 = INITIAL RADIUS
C     VR1 = INITIAL RING FLUID RESULTANT VELOCITY
C     W13 = WEIGHT FLOW
C     R3 = EXIT RADIUS
C     H3 = EXIT CLEARANCE
C     V1 = INLET FLUID RADIAL VELOCITY
C     R4 = RADIUS FOR ECCENTRICITY CALCULATION IF INWARD FLOW
C
C     CONSTANTS NEEDED - XKRING, OMEGAD, XNRPM, ECC, GVTY, CFLAM, NFLAM,
C       CFTUR, NFTUR, CMLAM, NMLAM, CMTUR, NMTUR, XJ, CR, C1, ITERC
C
C     OUTPUT RETURNED
C
C     P2(I) = OUTLET PRESSURE FOR RING I
C     T2(I) = OUTLET TEMPERATURE FOR RING I
C     G2(I) = OUTLET DENSITY FOR RING I
C     CP2(I) = OUTLET SPECIFIC HEAT FOR RING I
C     XMU2(I) = OUTLET VISCOSITY FOR RING I
C     XK13 = ROTATING DISK FLOW CONSTANT
C     R2(I) = OUTLET RADIUS FOR RING I
C     RE12(I) = REYNOLDS NUMBER FOR RING I
C     V2(I) = RING OUTLET FLUID RADIAL VELOCITY
```

```
C     VR2(I) = RING OUTLET FLUID RESULTANT VELOCITY
C     UD12(I) = RING AVERAGE DISK TANGENTIAL VELOCITY
C     NR = NUMBER OF RINGS
C
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON / IN6/ XKH6H7, XKH3H2, XKL6L7, XKL3L2, XKHPH1, IKIN
      COMMON /ERPRNT/ IERRT
      REAL*8 NM, NF, NF1
      DIMENSION P2(1), T2(1), G2(1), CP2(1), XMU2(1), R2(1), RE12(1),
     1 V2(1),VR2(1),UD12(1), G12(1), CM(1), NM(1), VR12(20), XMU12(20),
     2 CP12(20), ER2(20), S2(20), R12(20), ECC2(20), U2(20)
C
C     CONSTANTS AND INITIALIZATION INDEPENDENT OF RING VALUES
C
      IF(IN.EQ.1)GO TO 20
C
C     OUTWARD FLOW
C
      NR=2.*(R3-R1)/(XKRING*(R3+R1))+1
      DR=(R3-R1)/DFLOAT(NR)
C     FLUIDVELOCITIES
      UD3=OMEGAD*R3
      IF(IKIN.EQ.1)GO TO 10
      CK13=.578-1.67*H3
      CK132=4.11/UD3
   10 CONTINUE
C     INITIAL VALUES FOR OUTER SILL
      G2(NR)=G1
      P3TEMP=0.
      RIN=R3
      GO TO 40
C
C     INWARD FLOW
C
   20 NR=2.*(R1-R3)/(XKRING*(R3+R1))+1
      DR=(R1-R3)/DFLOAT(NR)
      DR=-DR
C     DISK TANGENTIAL VELOCITY AND FLOW CONSTANT
      RIN=R4
```

```
      IF(IKIN.EQ.1)GO TO 40
      UD1=P5*OMEGAD*R1
      IF(V1.GT.UD1*.07) GO TO 30
      H3R1=H3/R1
      R3R1=R3/R1
      H3R3=H3R1*R3R1*R3R1
      V1UD1=V1/UD1
      XK13=H3R3*(27.8+H3R3*(-2750.+65100.*H3R3))+V1UD1*(-917000.*H3R1**3
     1-12.6*R3R1+95.3*V1UD1)+.3865+2.13*DSQRT(V1UD1)-6.59*H3R1
      GO TO 40
   30 XK13=0.
C
   40 CONTINUE
      IF(NR.LE.20)GO TO 60
      WRITE (6,50)NR,R1,R3
   50 FORMAT(1H0/ 58H0IN THE SILL SUBROUTINE THE MAXIMUM NUMBER OF RINGS
     1 IS 20. / 25H THE CALCULATED NUMBER IS ,I6 /12H RADIUS R1 = ,
     2 1P1D15.4 /12H RADIUS R3= ,1P1D15.4 /32H THE NUMBER OF RINGS USED
     3IS 20.  )
      NR=20
   60 CONTINUE
      CRE12=2.*H3/GVTY
      CP2C=OMEGAD*OMEGAD/CHL
      CP2L2=1.9098594*W13/(H3**3)
      CHL2=P1/G1+VR1*VR1/CHL
      CT22=PI/(CT2*W13*CHL)
      CV2=W13/(PI2*H3)
      CU2=P5*OMEGAD
C
C     ITERATION ON OUTER SILL PRESSURE
C     (FOR INWARD FLOW ONLY ONE ITERATION IS NECESSARY)
C
      V2(NR)=CV2/(G1*R3)
      P3TEMP=0.
      I3=1
   70 IF(IN.EQ.1)GO TO 90
      IF(IKIN.EQ.1)GO TO 90
      IF(V2(NR).GT.UD3*.07) GO TO 80
      XK13=CK13-CK132*V2(NR)
      GO TO 90
   80 XK13=0.
   90 CONTINUE
C
      VR1R=VR1
      G1R=G1
      XMU1R=XMU1
      V1R=V1
      CP1R=CP1
      P1R=P1
      T1R=T1
      R1R=R1
C
```

```
C     CALCULATION FOR EACH RING
C
      DO 270 I=1,NR
C
C     CONSTANTS AND INITIALIZATION FOR RING
C
      VR12(I)=VR1R
      G12(I)=G1R
      XMU12(I)=XMU1R
      V2(I)=V1R
      VR2(I)=VR1R
      G2(I)=G1R
      CP12(I)=CP1R
C
  100 PTEM =0.
      IRENU=0
      R2(I)=R1R+DR
      R12(I)=.5*(R1R+R2(I))
      ECC2(I)=R12(I)*ECC/RIN
      ER2(I)=ECC2(I)/H3
      U2(I)=CU2*R2(I)
      U22=U2(I)*U2(I)
      UD12(I)=CU2*(R1R+R2(I))
      UD123=UD12(I)**3
      RR2=R2(I)*R2(I)-R1R*R1R
      CP2CI=CP2C*RR2*XK13*XK13
      CP2L2I=CP2L2*DLOG(R2(I)/R1R)
      CT22I=CT22*RR2
      IF(IN.EQ.0)GO TO 110
      CT22I=-CT22I
      CP2L2I=-CP2L2I
  110 CONTINUE
C
C     ITERATION ON RING EXIT PRESSURE
C
      DO 220 N=1,ITERC
      AVE=0.0D0
      RE12(I)=CRE12*G12(I)*VR12(I)/XMU12(I)
C     REYNODS NUMBER TO DETERMINE LAMINAR OR TURBULENT FLOW
      IF(RE12(I).GT.2000.)GO TO 130
      IF(IRENU.EQ.2)AVE=P5
      IRENU=1
      CM(I)=CMLAM
      NM(I)=NMLAM
      CF=CFLAM
      NF=NFLAM
      CALL ECCI(ER2(I),CECC,EL,FRL,NTLAM,IERR)
      IF(IERR.EQ.1)GO TO 300
  120 CONTINUE
      P2(I)=P1R+G12(I)*CP2CI-CP2L2I/CECC*XMU12(I)/G12(I)
      GO TO 170
C
```

```
  130 CONTINUE
      IF(IRENU.EQ.1)AVE=P5
      IRENU=2
      CM(I)=CMTUR
      NM(I)=NMTUR
      CF=CFTUR
      NF=NFTUR
      NF1=1.-NF
      RR2E=R2(I)**NF1-R1R**NF1
      CALL ECCI(ER2(I),CECC,ET,FRT,NTTUR,IERR)
      IF(IERR.EQ.1)GO TO 340
  140 CONTINUE
      IF(IN.EQ.0)GO TO 150
      RR2E=-RR2E
      S2(I)=VR1R/V1R
      GO TO 160
  150 S2(I)=VR2(I)/V2(I)
  160 CONTINUE
      IF(S2(I).GT.3.8637)S2(I)=3.8637
      P2(I)=P1R-.25*CF/(G12(I)*(H3**3))*((W13/(CECC*PI))**(2.-NF))*(
     1 XMU12(I)**NF)*((S2(I)/(R1R*R2(I)*GVTY))**NF1)*RR2E/NF1+G12(I)*
     2 CP2CI
  170 CONTINUE
      P2(I)=P2(I)+AVE*(PTEM-P2(I))
      CALL TEMP(P1R,T1R,P2(I),T2X,IERR)
      IF(IERR.EQ.1)GO TO 360
  180 CONTINUE
      HL=CHL2-VR2(I)*VR2(I)/CHL-P2(I)/G2(I)
      T2(I)=T2X+HL/(CP12(I)*CT2)+CT22I*CM(I)*G12(I)*UD123/(CP12(I)*(RE12
     1(I)**NM(I)))
C     RING OUTLET PROPERTIES AND AVERAGES
      CALL DBLIN(P2(I),T2(I),G2(I),PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 380
  190 CONTINUE
      CALL DBLIN(P2(I),T2(I),CP2(I),PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IER
     1R)
      IF(IERR.EQ.1)GO TO 400
  200 CONTINUE
      CALL DBLIN(P2(I),T2(I),XMU2(I),PVISC,TVISC,XMVISC,NPVISC,NTVISC,
     1 IERR)
      IF(IERR.EQ.1)GO TO 420
  210 CONTINUE
      G12(I)=G1R+CR*(G2(I)-G1R)
      XMU12(I)=XMU1R+CR*(XMU2(I)-XMU1R)
      CP12(I)=CP1R+CR*(CP2(I)-CP1R)
C     RING FLUID VELOCITIES
      V2(I)=CV2/(R2(I)*G2(I))
      VR2(I)=DSQRT(V2(I)**2+U22)
      VR12(I)=.5*(VR1R+VR2(I))
      IF(DABS((P2(I)-PTEM )/P2(I)).LT.C1)GO TO 260
      PTEM =P2(I)
  220 CONTINUE
```

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      IF(IN.EQ.1)GO TO 240
      WRITE (6,230)I3,R2(I),ITERC,P2(I),PTEM
  230 FORMAT(1H0/35H0FOR SILL OUTWARD FLOW IN ITERATION,I3,1X,  81HON FI
     1NAL SILL OUTLET PRESSURE OVER ALL RINGS, THE OUTLET PRESSURE FOR T
     2HE RING OF/14H OUTLET RADIUS,1P1D15.4,1X,31HDID NOT CONVERGE IN TH
     3E MAXIMUM,I3,1X,11HITERATIONS. /21H THE FINAL PRESSURE = ,1P1D15.4
     4 /34H THE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
  240 WRITE (6,250)R2(I),ITERC,P2(I),PTEM
  250 FORMAT(1H0/ 71H0FOR SILL INWARD FLOW THE OUTLET PRESSURE FOR THE R
     1ING OF OUTLET RADIUS , 1P1D15.4,1X, 23HDID NOT CONVERGE IN THE  /
     2 8H MAXIMUM ,I3,1X,11HITERATIONS. /31H THE FINAL PRESSURE = ,1P1D1
     35.4/ 34H THE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
  260 CONTINUE
      VR1R=VR2(I)
      V1R=V2(I)
      G1R=G2(I)
      XMU1R=XMU2(I)
      CP1R=CP2(I)
      P1R=P2(I)
      T1R=T2(I)
      R1R=R2(I)
  270 CONTINUE
      IF(IN.EQ.1)RETURN
      IF(DABS((P2(NR)-P3TEMP)/P2(NR)).LT.C1)RETURN
      IF(I3.GE.ITERC)GO TO 280
      I3=I3+1
      P3TEMP=P2(NR)
      GO TO 70
C
  280 WRITE (6,290)ITERC,P2(NR),P3TEMP
  290 FORMAT(1H0/ 85H0FOR SILL OUTWARD FLOW THE FINAL SILL OUTLET PRESSU
     1RE DID NOT CONVERGE IN THE MAXIMUM,I3,1X,11HITERATIONS. /22H THE
     2FINAL PRESSURE = ,1P1D15.4 /34H THE PREVIOUS ITERATION PRESSURE =
     3 ,1P1D15.4)
      IERRT=10
      RETURN
  300 WRITE (6,310)ER2(I)
  310 FORMAT(1H0/ 86H0THE VALUE FOR LAMINAR FLOWRATE RATIO TABLE INTERPO
     1LATION WAS OUTSIDE THE TABLE RANGE. /21H ECCENTRICITY RATIO = ,
     21P1D15.4)
  320 WRITE (6,330)R1,R3
  330 FORMAT(12H RADIUS R1 = ,1P1D15.4/12H RADIUS R3 = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 120
  340 WRITE(6,350)ER2(I)
  350 FORMAT(1H0/ 88H0THE VALUE FOR TURBULENT FLOWRATE RATIO TABLE INTER
     1POLATION WAS OUTSIDE THE TABLE RANGE. /21H ECCENTRICITY RATIO = ,
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```
      2 1P1D15.4)
       WRITE (6,330)R1,R3
       IERRT=IERRT+1
       IF(IERRT.GE.5)RETURN
       GO TO 140
   360 WRITE (6,370)P1R,T1R,P2(I)
   370 FORMAT(1H0/100H0THE VALUES FOR TEMPERATURE TABLE INTERPOLATION WER
      1E OUTSIDE THE TABLE RANGE IN THE SILL SUBROUTINE. /14H PRESSURE P1
      2 = ,1P1D15.4 /17H TEMPERATURE T1 = ,1P1D15.4/14H PRESSURE P2 = ,
      3 1P1D15.4)
       WRITE (6,330)R1,R3
       IERRT=IERRT+1
       IF(IERRT.GE.5)RETURN
       GO TO 180
   380 WRITE (6,390)P2(I),T2(I)
   390 FORMAT(1H0/ 96H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
      1SILL SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H PRESSURE P2 = ,
      2 1P1D15.4/ 17H TEMPERATURE T2 = ,1P1D15.4)
       WRITE (6,330)R1,R3
       IERRT=IERRT+1
       IF(IERRT.GE.5)RETURN
       GO TO 190
   400 WRITE (6,410)P2(I),T2(I)
   410 FORMAT(1H0/102H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
      1N THE SILL SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H PRESSURE
      2P2 = ,1P1D15.4 /17H TEMPERATURE T2 = ,1P1D15.4)
       WRITE (6,330)R1,R3
       IERRT=IERRT+1
       IF(IERRT.GE.5)RETURN
       GO TO 200
   420 WRITE (6,430)P2(I),T2(I)
   430 FORMAT(1H0/ 98H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TA
      1E SILL SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H PRESSURE P2 =
      2 ,1P1D15.4/17H TEMPERATURE T2 = ,1P1D15.4)
       WRITE (6,330)R1,R3
       IERRT=IERRT+1
       IF(IERRT.GE.5)RETURN
       GO TO 210
       END
       SUBROUTINE LABYS(P1,T1,G1,VR1,CP1,P2,P12,X12,H12,XN12,C2,RS,RH,T2,
      1 G2,VR2,CP2,W12,XMU2,G12,RE12,XMU1)
C
C      SHAFT LABYRINTH CALCULATIONS
C
C
C      INPUT NEEDED
C
C      P1 = INITIAL PRESSURE
C      T1 = INITIAL TEMPERATURE
C      G1 = INITIAL DENSITY
C      VR1 = INITIAL FLUID VELOCITY
C      CP1 = INITIAL SPECIFIC HEAT
```

```
C      P2 = OUTLET PRESSURE
C      P12 = LABYRINTH PITCH
C      X12 = SEALING POINT WIDTH
C      H12 = TOTAL LABYRINTH CLEARANCE
C      XN12 = NUMBER OF SEALING POINTS
C      C2 = FLUID ROTATION FACTOR
C      RS = RADIUS
C      RH = RADIUS
C
C      CONSTANTS - CR, C1, ITERC, GVTY, XJ
C
C      OUTPUT RETURNED
C
C      T2 = OUTLET TEMPERATURE
C      G2 = OUTLET DENSITY
C      VR2 = OUTLET VELOCITY
C      CP2 = OUTLET SPECIFIC HEAT
C      W12 = LABYRINTH WEIGHT FLOW
C      XMU2 = OUTLET VISCOSITY
C      G12 = AVERAGE LABYRINTH DENSITY
C
       IMPLICIT REAL*8 (A-H , O-Z)
       COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
      1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
      2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
      3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
      4      ,XNRPM
       REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
       COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
      1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
      2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
      3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
      4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
       COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
      1       CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
       COMMON /ERPRNT/ IERRT
C
C      INITIALIZATION AND CONSTANT CALCULATION
C
       W12=0.
       G2=G1
       CP2=CP1
       VR2=VR1
       U2=(PI60*XNRPM*RS)**2
       ELRE=8.52/((P12-X12)/H12+7.23)
       ELRE=1.0-ELRE
       CW12=PI*RS*H12
       PDP=P1-P2
       CW22=8.*GVTY*PDP/(XN12*ELRE)*C2
       CHL2=VR1*VR1/CHL
       CALL TEMP(P1,T1,P2,T2X,IERR)
       IF(IERR.EQ.1)GO TO 90
```

```
   10 CONTINUE
      CVR2=PI*(RH*RH-RS*RS)
      G12=G1
C
C     ITERATION ON LABYRINTH FLOW W12
C
      DO 60 N=1,ITERC
      WTEMP=W12
      CP12=CP1+CR*(CP2-CP1)
      W12=CW12*DSQRT(G12*CW22)
      HL=PDP/G12+CHL2-VR2*VR2/CHL
      T2=T2X+HL/(CT2*CP12)
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 110
   20 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 130
   30 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.0)GO TO 50
      WRITE (6,40)
   40 FORMAT(1H0/109H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH
     1E SHAFT LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,160)P2,T2
      WRITE (6,180)RS,RH
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
   50 CONTINUE
      V2=W12/(CVR2*G2)
      VR2=DSQRT(V2*V2+U2)
      VR12=P5*(VR2+VR1)
      XMU12=XMU1+CR*(XMU2-XMU1)
      G12=G1+CR*(G2-G1)
      RE12=G12*VR12*H12/(GVTY*XMU12)
      IF(DABS((W12-WTEMP)/W12).LT.C1)GO TO 80
   60 CONTINUE
      WRITE (6,70)ITERC,W12,WTEMP
   70 FORMAT(1H0/ 65H0THE SHAFT LABYRINTH ITERATION DID NOT CONVERGE IN 
     1THE MAXIMUM OF ,I4,1X, 11HITERATIONS. /27H THE FINAL LABYRINTH FLO
     2W = ,1P1D15.4 /30H THE PREVIOUS ITERATION FLOW = ,1P1D15.4)
      IERRT=10
      RETURN
   80 CONTINUE
      RETURN
   90 WRITE (6,100)P1,T1,P2
  100 FORMAT(1H0/111H0THE VALUES FOR TEMPERATURE TABLE INTERPOLATION IN 
     1THE SHAFT LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H 
     2PRESSURE P1 = ,1P1D15.4/17H TEMPERATURE T1 = , 1P1D15.4/14H PRESSU
     3RE P2 = , 1P1D15.4)
      WRITE (6,180)RS,RH
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
```

```
      GO TO 10
  110 WRITE (6,120)
  120 FORMAT(1H0/107H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
     1SHAFT LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,160)P2,T2
      WRITE (6,180)RS,RH
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 20
  130 WRITE (6,140)
  140 FORMAT(1H0/113H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
     1N THE SHAFT LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
  150 WRITE (6,160)P2,T2
  160 FORMAT(14H PRESSURE P2 = ,1P1D15.4/17H TEMPERATURE T2 =,1P1D15.4)
  170 WRITE (6,180)RS,RH
  180 FORMAT(12H RADIUS RS = ,1P1D15.4/ 12H RADIUS RH = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 30
      END
      SUBROUTINE LABYP(P1,T1,G1,CP1,XMU1,W12,XN12,P12,X12,H12,C12,HE12,
     1R3,VR1,P2, T2,G2,CP2,XMU2,U3,UD3,V2,VR2,RE12,G12)
C
C     PISTON LABYRINTH CALCULATION
C
C     INPUT NEEDED
C
C     P1 = INITIAL PRESSURE
C     T1 = INITIAL TEMPERATURE
C     G1 = INITIAL DENSITY
C     CP1 = INITIAL SPECIFIC HEAT
C     XMU1 = INITIAL VISCOSITY
C     W12 = WEIGHT FLOW
C     XN12 = NUMBER OF SEALING POINTS
C     P12 = LABYRINTH PITCH
C     X12 = SEALING POINT WIDTH
C     H12 = TOOTH CLEARANCE
C     C12 = DISCHARGE COEFFICIENT
C     HE12 = VALLEY DEPTH
C     VR1 = INITIAL FLUID VELOCITY
C     R3 = OUTLET RADIUS
C
C     INPUT CONSTANTS - CR, C1, ITERC, GVTY, XNRPM, XJ, CMLAM,NMLAM,
C                       CMTUR, NMTUR
C
C     OUTPUT RETURNED
C
C     P2 = OUTLET PRESSURE
C     T2 = OUTLET TEMPERATURE
C     G2 = OUTLET DENSITY
C     CP2 = OUTLET PRESSURE
C     XMU2 = OUTLET VISCOSITY
```

```
C     U3 = FLUID TANGENTIAL VELOCITY
C     UD3 = DISK TANGENTIAL VELOCITY
C     V2 = OUTLET FLUID AXIAL VELOCITY
C     VR2 = OUTLET FLUID RESULTANT VELOCITY
C     RE12 = LABYRINTH REYNOLDS NUMBER
C     G12 = AVERAGE DENSITY
      IMPLICIT REAL*8 (A-H , O-Z)
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4       ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1        NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2        NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3        NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4       ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /ERPRNT/ IERRT
      REAL*8 NM
C
C     INITIALIZATION AND CONSTANTS
C
      P2=0.
      G2=G1
      VR2=VR1
      XMU2=XMU1
      CP2=CP1
      G12=G1
C     RESIDUAL ENERGY FACTOR
      ELRE=8.52/((P12-X12)/H12+7.23)
      ELRE=1.0-ELRE
      CP2C=XN12*ELRE/(78.956835*C12*GVTY)*(W12/(R3*H12))**2
      U3=P5*OMEGAD*R3
      UD3=U3*2.
      U32=U3*U3
      RHE=HE12*(R3-HE12)
      CV2=W12/(PI2*RHE)
      CRE12=HE12/GVTY
      CHL2=P1/G1+VR1*VR1/CHL
      CT22=PI*RHE*(UD3**3)/(CT2*CHL*W12)
C
C     ITERATION ON LABYRINTH DECREASED PRESSURE
C
      DO 70 N=1,ITERC
      PTEM =P2
      P2=P1-CP2C/G12
      CALL TEMP(P1,T1,P2,T2X,IERR)
      IF(IERR.EQ.1)GO TO 90
   10 CONTINUE
```

```
      V2=CV2/G2
      VR2=DSQRT(V2*V2+U32)
      VR12=.5*(VR1+VR2)
      XMU12=XMU1+CR*(XMU2-XMU1)
      RE12=G12*VR12*CRE12/XMU12
      IF(RE12.GT.2000.)GO TO 20
      CM=CMLAM
      NM=NMLAM
      GO TO 30
   20 CM=CMTUR
      NM=NMTUR
   30 CONTINUE
      HL=CHL2-P2/G2-VR2*VR2/CHL
      CP12=CP1+CR*(CP2-CP1)
      T2=T2X+HL/(CT2*CP12)+CT22*G12*CM/((RE12**NM)*CP12)
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 110
   40 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 130
   50 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 190
   60 CONTINUE
      G12=G1+CR*(G2-G1)
      IF(DABS((P2-PTEM )/P2).LE.C1)RETURN
   70 CONTINUE
      WRITE (6,80)ITERC,P2,PTEM
   80 FORMAT(1H0/75H0THE PISTON LABYRINTH PRESSURE ITERATION DID NOT CON
     1VERGE IN THE MAXIMUM OF , I4,1X, 11HITERATIONS. /21H THE FINAL PRE
     2SSURE = ,1P1D15.4/33HTHE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
   90 WRITE (6,100)P1,T1,P2
  100 FORMAT(1H0/112H0THE VALUES FOR TEMPERATURE TABLE INTERPOLATION IN
     1THE PISTON LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. /14H
     2 PRESSURE P1 =,1P1D15.4/17H TEMPERATURE T1 = , 1P1D15.4/14H PRESSU
     3RE P2 = , 1P1D15.4)
      WRITE (6,180)R3
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 10
  110 WRITE (6,120)
  120 FORMAT(1H0/108H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
     1PISTON LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
      WRITE (6,160)P2,T2
      WRITE (6,180)R3
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 40
  130 WRITE (6,140)
  140 FORMAT(1H0/114H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
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```
     1N THE PISTON LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
 150 WRITE (6,160)P2,T2
 160 FORMAT(14H PRESSURE P2 = ,1P1D15.4/17H TEMPERATURE T2 =,1P1D15.4)
 170 WRITE (6,180)R3
 180 FORMAT(12H RADIUS R3 = ,1P1D15.4)
     IERRT=IERRT+1
     IF(IERRT.GE.5)RETURN
     GO TO 50
 190 WRITE (6,200)
 200 FORMAT(1H0/110H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH
    1E PISTON LABYRINTH SUBROUTINE WERE OUTSIDE THE TABLE RANGE. )
     WRITE (6,160)P2,T2
     WRITE (6,180)R3
     IERRT=IERRT+1
     IF(IERRT.GE.5)RETURN
     GO TO 60
     END
     SUBROUTINE LINE(P1,T1,G1,CP1,XMU1,VR1,XN12,XL12,W12,R1,P2,T2,G2,
    1 CP2,XMU2,VR2,RE12)
C
C    RETURN LINE CALCULATIONS
C
C    INPUT NEEDED
C
C    P1 = INITIAL PRESSURE
C    T1 = INITIAL TEMPERATURE
C    G1 = INITIAL DENSITY
C    CP1 = INITIAL SPECIFIC HEAT
C    XMU1 = INITIAL VISCOSITY
C    VR1 = INITIAL FLUID VELOCITY
C    XN12 = NUMBER OF RETURN LINES
C    XL12 = RETURN LINE LENGTH
C    W12 = WEIGHT FLOW
C    R1 = RADIUS
C
C    CONSTANTS - CR, C1, ITERC, GVTY, XJ, CFTUR, NFTUR
C
C    OUTPUT RETURNED
C
C    P2 = LINE FLOW PRESSURE
C    T2 = OUTLET TEMPERATURE
C    G2 = OUTLET DENSITY
C    CP2 = OUTLET SPECIFIC HEAT
C    XMU2 = OUTLET VISCOSITY
C    VR2 = OUTLET RESULTANT VELOCITY
C    RE12 = REYNOLDS NUMBER FOR LINES
     IMPLICIT REAL*8 (A-H , O-Z)
     COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
    1      NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
    2      NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
    3      ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
    4     ,XNRPM
```

```
      REAL*8  NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1        NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2        NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3        NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4       ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
     1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
      COMMON /ERPRNT/ IERRT
C
C     INITIALIZATION AND CONSTANT CALCULATION
C
      P2=0.
      G2=G1
      XMU2=XMU1
      VR2=VR1
      CP2=CP1
      CRE12=.6366198*W12/(GVTY*R1*XN12)
      CP2C=2.546479*W12*XL12/(XN12*(R1**4))
      CHL2=P1/G1+VR1*VR1/CHL
      CVR2=W12/(PI*R1*R1*XN12)
C
C     ITERATION ON LINE FLOW PRESSURE
C
      DO 70 N=1,ITERC
      PTEM =P2
      G12=G1+CR*(G2-G1)
      XMU12=XMU1+CR*(XMU2-XMU1)
      CP12=CP1+CR*(CP2-CP1)
      RE12=CRE12/XMU12
      IF(RE12.GT.2000.)GO TO 10
      P2=P1-XMU12*CP2C
      GO TO 20
   10 P2=P1-CFTUR*XL12*(XMU12**NFTUR)*((W12/(PI*XN12))**(2.-NFTUR))/
     1((2.**(NFTUR+2.))*G12*(R1**(5.-NFTUR))*(GVTY**(1.-NFTUR)))
   20 CONTINUE
      CALL TEMP(P1,T1,P2,T2X, IERR)
      IF(IERR.EQ.1)GO TO 90
   30 CONTINUE
      HL=CHL2-P2/G2-VR2*VR2/CHL
      T2=T2X+HL/(CT2*CP12)
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 110
   40 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 130
   50 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 190
   60 CONTINUE
      VR2=CVR2/G2
      IF(DABS((P2-PTEM )/P2).LE.C1)RETURN
```

```
   70 CONTINUE
      WRITE (5,30)ITERC,P2,PTEM
   80 FORMAT(1H0/68H0THE LINE FLOW PRESSURE ITERATION DID NOT CONVERGE I
     1N THE MAXIMUM OF ,I4,1X,11HITERATIONS. /21H THE FINAL PRESSURE = ,
     2 1P1D15.4/34H THE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
   90 WRITE (6,100)P1,T1,P2
  100 FORMAT(1H0/100H0THE VALUES FOR TEMPERATURE TABLE INTERPOLATION IN
     1THE LINE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.  /           14H
     2PRESSURE P1 = ,1P1D15.4/17H TEMPERATURE T1 = , 1P1D15.4/14H PRESSU
     3RE P2 = , 1P1D15.4)
      WRITE (6,180)R1
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 30
  110 WRITE (6,120)
  120 FORMAT(1H0/ 97H0THE VALUES FOR DENSITY TABLE INTERPOLATION IN THE
     1LINE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.    )
      WRITE (6,160)P2,T2
      WRITE (6,180)R1
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 40
  130 WRITE (6,140)
  140 FORMAT(1H0/103H0THE VALUES FOR SPECIFIC HEAT TABLE INTERPOLATION I
     1N THE LINE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.    )
  150 WRITE (6,160)P2,T2
  160 FORMAT(14H PRESSURE P2 = ,1P1D15.4/17H TEMPERATURE T2 =,1P1D15.4)
  170 WRITE (6,180)R1
  180 FORMAT(12H RADIUS R1 = ,1P1D15.4)
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 50
  190 WRITE (6,200)
  200 FORMAT(1H0/ 99H0THE VALUES FOR VISCOSITY TABLE INTERPOLATION IN TH
     1E LINE SUBROUTINE WERE OUTSIDE THE TABLE RANGE.    )
      WRITE (6,160)P2,T2
      WRITE (6,180)R1
      IERRT=IERRT+1
      IF(IERRT.GE.5)RETURN
      GO TO 60
      END
      SUBROUTINE ANNP(P1,T1,G1,CP1,XMU1,W12,V1,VR1,R1,H12,XL12,R2,P2,T2,
     1 G2,CP2,XMU2,U12,UD12,V2,VR2,RE12,G12)
C
C     ANNULUS FLOW CALCULATION
C
C     INPUT ARGUMENTS
C     P1 = INLET PRESSURE
C     T1 = INLET TEMPERATURE
C     G1 = INLET DENSITY
```

```
C      CP1 = INLET SPECIFIC HEAT
C      XMU1 = INLET VISCOSITY
C      W12 = INWARD FLOW
C      V1 = INLET FLOW VELOCITY
C      VR1 = INLET RESULTANT VELOCITY
C      R1 = INLET RADIUS
C      H12 = ANNULUS CLEARANCE
C      XL12 = ANNULUS LENGTH
C      R2 = OUTLET RADIUS
C
C      INPUT CONSTANTS REQUIRED - CR,C1,XJ,GVTY,CMLAM,NMLAM,CMTUR,NMTUR,
C                                 XNRPM,CFLAM,NFLAM,CFTUR,NFTUR
C
C      OUTPUT ARGUMENTS
C      P2 = OUTLET PRESSURE
C      T2 = OUTLET TEMPERATURE
C      G2 = OUTLET DENSITY
C      CP2 = OUTLET SPECIFIC HEAT
C      XMU2= OUTLET VISCOSITY
C      U12 = TANGENTIAL VELOCITY
C      UD12 = DISK TANGENTIAL VELOCITY
C      V2 = OUTLET FLOW VELOCITY
C      VR2 = OUTLET RESULTANT VELOCITY
C      RE12 = REYNOLDS NUMBER
C      G12 = AVERAGE DENSITY
       IMPLICIT REAL*8 (A-H , O-Z)
       COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
      1        NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
      2        NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
      3        ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
      4       ,XNRPM
       REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
       COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
      1        NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
      2        NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
      3        NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
      4       ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
       COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
      1        CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
       COMMON /ERPRNT/ IERRT
       REAL*8 NM,NF
C
C      INITIALIZE
       P2=0.
       UD12=P5*OMEGAD*R1
       CRE=2.*H12/GVTY
       CP2C=XL12/(4.*H12*GVTY)
       CHL2=P1/G1+VR1*VR1/CHL
       CT22=PI*(UD12**3)*R1*H12/(CHL*CT2*W12)
       CV2=W12/(PI2*H12*R2)
       U12=P5*OMEGAD*R2
       U22=U12*U12
       G12=G1
```

```
      VR2=VR1
      XMU12=XMU1
      CP12=CP1
      G2=G1
      V2=V1
C
C     ITERATION ON OUTLET PRESSURE
C
      DO 70 N=1,ITERC
      PTEM=P2
      VR12=P5*(VR1+VR2)
      RE12=CRE*VR12*G12/XMU12
      IF(RE12.GT.2000.)GO TO 10
      CM=CMLAM
      NM=NMLAM
      CF=CFLAM
      NF=NFLAM
      GO TO 20
   10 CM=CMTUR
      NM=NMTUR
      CF=CFTUR
      NF=NFTUR
   20 CONTINUE
      V12=P5*(V1+V2)
      P2= P1-CF*G12*V12*V12*CP2C/(RE12**NF)
      CALL TEMP(P1,T1,P2,T2X,IERR)
      IF(IERR.EQ.1)GO TO 90
   30 CONTINUE
      HL=CHL2-P2/G2-VR2*VR2/CHL
      T2=T2X+HL/(CT2*CP12)+CM*G12*CT22/(CP12*(RE12**NM))
      CALL DBLIN(P2,T2,G2,PDENS,TDENS,GDENS,NPDENS,NTDENS,IERR)
      IF(IERR.EQ.1)GO TO 110
   40 CONTINUE
      CALL DBLIN(P2,T2,CP2,PHEAT,THEAT,CPHEAT,NPHEAT,NTHEAT,IERR)
      IF(IERR.EQ.1)GO TO 150
   50 CONTINUE
      CALL DBLIN(P2,T2,XMU2,PVISC,TVISC,XMVISC,NPVISC,NTVISC,IERR)
      IF(IERR.EQ.1)GO TO 170
   60 CONTINUE
      G12=G1+CR*(G2-G1)
      XMU12=XMU1+CR*(XMU2-XMU1)
      CP12=CP1+CR*(CP2-CP1)
      V2=CV2/G2
      VR2=DSQRT(V2*V2+U22)
      IF(DABS((P2-PTEM)/P2).LE.C1)RETURN
   70 CONTINUE
      WRITE (6,80)ITERC,P2,PTEM
   80 FORMAT(1H0/ 66H0THE ANNULUS OUTLET PRESSURE WAS NOT DETERMINED IN
     1 THE MAXIMUM OF ,I4,1X,11HITERATIONS. /21H THE FINAL PRESSURE = ,
     21P1D15.4/ 34H THE PREVIOUS ITERATION PRESSURE = ,1P1D15.4)
      IERRT=10
      RETURN
```

```
 90 WRITE (6,100)P1,T1,P2
100 FORMAT(1H0/ 85H0THE ANNULUS VALUES FOR TEMPERATURE TABLE INTERPOLA
   1TION WERE OUTSIDE THE TABLE RANGE. /14H PRESSURE P1 = ,1P1D15.4/
   217H TEMPERATURE T1 = ,1P1D15.4/14H PRESSURE P2 = 1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 30
110 WRITE (6,120)
120 FORMAT(1H0/ 88H0THE ANNULUS OUTLET VALUES FOR DENSITY TABLE INTERP
   1OLATION WERE OUTSIDE THE TABLE RANGE. )
130 WRITE (6,140)P2,T2
140 FORMAT(11H PRESSURE = ,1P1D15.4/14H TEMPERATURE = ,1P1D15.4)
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 40
150 WRITE(6,160)
160 FORMAT(1H0/ 94H0THE ANNULUS OUTLET VALUES FOR SPECIFIC HEAT TABLE
   1INTERPOLATION WERE OUTSIDE THE TABLE RANGE.  )
    WRITE (6,140)P2,T2
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 50
170 WRITE (6,180)
180 FORMAT(1H0/ 90H0THE ANNULUS OUTLET VALUES FOR VISCOSITY TABLE INTE
   1RPOLATION WERE OUTSIDE THE TABLE RANGE. )
    WRITE (6,140)P2,T2
    IERRT=IERRT+1
    IF(IERRT.GE.5)RETURN
    GO TO 60
    END
    SUBROUTINE ACONST
C
C     SET CONSTANTS THAT ARE INDEPENDENT OF ALL INPUT CASES
C
C     XJ = MECHANICAL EQUIVALENT OF HEAT
C     GVTY = GRAVITATIONAL CONSTANT
    IMPLICIT REAL*8 (A-H , O-Z)
    COMMON /CONS/ PI, PI2, PI4, PI4G, PI30, PI60, OMEGAD, XJ, GVTY,
   1         CHL, CT2, P5, HL7(21), HLP(21), HH7(21), HHP(21)
    PI=3.1415927
    PI2=6.2831854
    PI4=.7853982
    GVTY=386.088
    PI4G=PI4/GVTY
    PI30=.10471976
    PI60=.05235988
    XJ=777.5
    CHL=2.*GVTY
    CT2=12.*XJ
    P5=.5
    RETURN
    END
```

```
      SUBROUTINE ECCI(ER,C,ERA,CA,NC,IERR)
C
C     LINEAR INTERPOLATION TO DETERMINE C
C
      IMPLICIT REAL*8 (A-H , O-Z)
      DIMENSION ERA(1), CA(1)
C
      IERR=0
      IF(ER.EQ.ERA(1))GO TO 20
      IF(ER.GT.ERA(1))GO TO 30
   10 IERR=1
   20 CONTINUE
      C=CA(1)
      RETURN
   30 IF(NC.EQ.1)GO TO 10
      DO 40 I=2,NC
      IF(ER.EQ.ERA(I))GO TO 60
      IF(ER.GT.ERA(I))GO TO 70
   40 CONTINUE
   50 IERR=1
      I=NC
   60 C=CA(I)
      RETURN
   70 C=CA(I-1)+(CA(I)-CA(I-1))*(ER-ERA(I-1))/(ERA(I)-ERA(I-1))
      RETURN
      END
      SUBROUTINE DBLIN (P,T,V,PA,TA,VA,NP,NT,IERR)
C
C     DOUBLE INTERPOLATION ROUTINE
C
      IMPLICIT REAL*8 (A-H , O-Z)
      DIMENSION PA(30), TA(30), VA(30,30)
C
C     BRACKET P AND T IN PA AND TA ARRAYS
      IERR=0
      IF(P.EQ.PA(1))GO TO 40
      IF(P.GT.PA(1))GO TO 20
   10 IERR=1
      GO TO 40
   20 IF(NP.EQ.1)GO TO 10
      DO 30 I=2,NP
      IF(P.EQ.PA(I))GO TO 50
      IF(P.LT.PA(I))GO TO 60
   30 CONTINUE
      IERR=1
      IERR=1
      I=NP
      GO TO 50
   40 I=1
   50 IM=I
      GO TO 70
   60 IM=I-1
```

```
   70 IF(T.LT.TA(1))GO TO 90
      IF(T.EQ.TA(1))GO TO 100
      IF(NT.EQ.1)GO TO 90
      DO 80 J=2,NT
      IF(T.EQ.TA(J))GO TO 110
      IF(T.LT.TA(J))GO TO 120
   80 CONTINUE
      IERR=1
      J=NT
      GO TO 110
   90 IERR=1
  100 J=1
  110 JM=J
      GO TO 130
  120 JM=J-1
  130 CONTINUE
C
C     INTERPOLATE ON V AS A FUNCTION OF P FOR EACH BRACKETING T
C
      IF(I.NE.IM)GO TO 150
C     P = PA(I)
      IF(J.NE.JM)GO TO 140
      V=VA(I,J)
      RETURN
  140 CONTINUE
      VJ=VA(I,J)
      VJM=VA(I,JM)
      GO TO 170
C     P BRACKETED
  150 CONTINUE
      IF(J.NE.JM)GO TO 160
C     T = TA(J)
      V=VA(IM,J)+(VA(I,J)-VA(IM,J))*(P-PA(IM))/(PA(I)-PA(IM))
      RETURN
C     T BRACKETED
  160 CONTINUE
      RATIO=(P-PA(IM))/(PA(I)-PA(IM))
      VJ=VA(IM,J)+(VA(I,J)-VA(IM,J))*RATIO
      VJM=VA(IM,JM)+(VA(I,JM)-VA(IM,JM))*RATIO
C
C     INTERPOLATE ON V AS A FUNCTION OF T
C
  170 RATIO=(T-TA(JM))/(TA(J)-TA(JM))
      V=VJM+(VJ-VJM)*RATIO
      RETURN
      END
      SUBROUTINE TEMP(P1,T1,P2,T2,IERR)
C
C     DETERMINE ENTROPY AT P1 AND T1 BY INTERPOLATION
C     DETERMINE TEMPERATURE T2 USING P2 AND DETERMINED ENTROPY
C
      IMPLICIT REAL*8 (A-H , O-Z)
```

```
      COMMON /IN1/ IPRES, IBAL, NH, ISEAL ,HT, ECC, C1, CMLAM, CR,
     1       NMLAM, CMTUR, NMTUR, CFLAM, NFLAM, CFTUR, NFTUR, NTLAM,
     2       NTTUR, EL(40), FRL(40), ET(40), FRT(40), XKRING, ITERC,
     3       ITERP, CLOS, TITLE(9), HMIN, HMAX, HDLP, HDHP ,DHL
     4      ,XNRPM
      REAL*8 NMLAM,NMTUR,NFLAM,NFTUR
      COMMON /IN2/ NPDENS, NTDENS, PDENS(30), TDENS(30), GDENS(30,30),
     1       NPHEAT, NTHEAT, PHEAT(30), THEAT(30), CPHEAT(30,30),
     2       NPVISC, NTVISC, PVISC(30), TVISC(30), XMVISC(30,30),
     3       NETEMP, NTTEMP, ETEMP(30), TTEMP(30), PTEMP(30,30)
     4      ,NPBULK, NTBULK, PBULK(30), TBULK(30), EBULK(30,30)
      DIMENSION VJ(2)
      DIMENSION PJ(30)
      IERR=0
      IF(IPRES.EQ.1)GO TO 10
      IF(P1.NE.P2) GO TO 20
   10 CONTINUE
      T2=T1
      RETURN
   20 CONTINUE
C
C     BRACKET T1 IN TTEMP ARRAY AND P1 IN EACH PTEMP(1,J) ARRAY TO
C     CALCULATE E FROM ETEMP ARRAY
C
      IF(T1.EQ.TTEMP(1))GO TO 60
      IF(T1.GT.TTEMP(1))GO TO 40
   30 IERR=1
      GO TO 60
   40 IF(NTTEMP.EQ.1)GO TO 30
      DO 50 J=2,NTTEMP
      IF(T1.EQ.TTEMP(J))GO TO 70
      IF(T1.LT.TTEMP(J))GO TO 80
   50 CONTINUE
      J=NTTEMP
      GO TO 70
   60 J=1
   70 JM=J
      GO TO 90
   80 JM=J-1
   90 JMM=JM-1
      DO  190 J2=JM,J
      DO 100 I=1,NETEMP
      IF(PTEMP(I,J2).NE.0.)GO TO 110
  100 CONTINUE
  110 I1=I
      IF(P1.LT.PTEMP(I1,J2))GO TO 140
      IF(P1.EQ.PTEMP(I1,J2))GO TO 130
  120 IERR=1
  130 CONTINUE
      VJ(J2-JMM)=ETEMP(I1)
      GO TO 190
  140 IF(NETEMP.EQ.1)GO TO 120
```

```
      I1=I1+1
      DO 150 I=I1,NETEMP
      IF(PTEMP(I,J2).EQ.0.)GO TO 160
      IF(P1.EQ.PTEMP(I,J2))GO TO 170
      IF(P1.GT.PTEMP(I,J2))GO TO 180
  150 CONTINUE
      I=NETEMP
      GO TO 170
  160 IERR=1
      I=I-1
  170 VJ(J2-JMM)=ETEMP(I)
      GO TO 190
  180 VJ(J2-JMM)=ETEMP(I-1)+(ETEMP(I)-ETEMP(I-1))*(P1-PTEMP(I-1,J2))/(
     1PTEMP(I,J2)-PTEMP(I-1,J2))
  190 CONTINUE
      IF(J.EQ.JM)GO TO 200
      E=VJ(1)+(VJ(2)-VJ(1))*(T1-TTEMP(JM))/(TTEMP(J)-TTEMP(JM))
      GO TO 210
  200 E=VJ(1)
C
C     CALCULATE PRESSURE ARRAY PJ AT E FOR EACH TEMPERATURE TTEMP(J) BY
C     INTERPOLATION OF PTEMP(I,J) ARRAY (J FIXED).
C     INTERPOLATE OVER PRESSURE ARRAY PJ AT E TO DETERMINE T2 FOR
C     PRESSURE P2
C
  210 CONTINUE
      IF(E.EQ.ETEMP(1))GO TO 240
      IF(E.GT.ETEMP(1))GO TO 220
      IERR=1
      GO TO 240
  220 CONTINUE
      DO 230 I=2,NETEMP
      IF(E.EQ.ETEMP(I))GO TO 250
      IF(E.LT.ETEMP(I))GO TO 270
  230 CONTINUE
      IERR=1
      I=NETEMP
      GO TO 250
  240 I=1
  250 CONTINUE
      DO 260 J=1,NTTEMP
      PJ(J)=PTEMP(I,J)
  260 CONTINUE
      GO TO 310
  270 IM=I-1
      DO 300 J=1,NTTEMP
      IF(PTEMP(IM,J).NE.0.)GO TO 280
      PJ(J)=0.
      GO TO 300
  280 IF(PTEMP(I,J).NE.0.)GO TO 290
      PJ(J)=0.
      GO TO 300
```

```
 290 PJ(J)=PTEMP(IM,J)+(PTEMP(I,J)-PTEMP(IM,J))*(E-ETEMP(IM))/(ETEMP(I)00022870
    1 -ETEMP(IM))                                                      00022875
 300 CONTINUE                                                          00022880
 310 DO 320 J=1,NTTEMP                                                 00022885
     IF(PJ(J).NE.0.)GO TO 330                                          00022890
 320 CONTINUE                                                          00022895
 330 JJ=J                                                              00022900
     IF(P2.EQ.PJ(JJ))GO TO 350                                         00022905
     IF(P2.GT.PJ(JJ))GO TO 360                                         00022910
 340 IERR=1                                                            00022915
 350 T2=TTEMP(JJ)                                                      00022920
     RETURN                                                            00022925
 360 IF(JJ.EQ.NTTEMP)GO TO 340                                         00022930
     J=J+1                                                             00022935
     DO 370 JJ=J,NTTEMP                                                00022940
     IF(PJ(JJ).EQ.0.)GO TO 380                                         00022945
     IF(P2.GT.PJ(JJ))GO TO 370                                         00022950
     T2=TTEMP(JJ-1)+(TTEMP(JJ)-TTEMP(JJ-1))*(P2-PJ(JJ-1))/(PJ(JJ)-     00022955
    1 PJ(JJ-1))                                                        00022960
     RETURN                                                            00022965
 370 CONTINUE                                                          00022970
     JJ=NTTEMP                                                         00022975
     GO TO 340                                                         00022980
 380 JJ=JJ-1                                                           00022985
     GO TO 340                                                         00022990
     END                                                               00022995
/*                                                                     00023000
//LINK.SYSLMOD DD DSNAME=PRODLMOD(E21902),DISP=(OLD,KEEP)              00023005
/*                                                                     00023010
// EXEC PGM=E21902                                                     00023015
//SYSABEND DD SYSOUT=A,DCB=(RECFM=VBA,BLKSIZE=730,LRECL=138)           00023020
//FT06F001 DD SYSOUT=A,DCB=(RECFM=VBA,BLKSIZE=730,LRECL=138)           00023025
//FT07F001 DD DSNAME=PCHOUT,DISP=OLD                                   00023030
//FT05F001 DD *                                                        00023035
INCOMPRESSIBLE FLOW - PARALLEL PISTON  - TEST CASE                     00023040
     1      0     5    25    25     6     6     0     1     1          00023045
       .012       .0054        .0084        .050          0.       .05000023050
     10000.          0.         14.7         .02        .005        .800023055
         0.          .5          96.          1.                      00023060
       .079         .43          96.          1.        .079        .2100023065
         0.          1.           .2       1.061          .4     1.24300023070
         .6       1.529           .8       1.929          .1     2.49600023075
         0.          1.           .2       1.007          .4     1.04300023080
         .6         1.1           .8       1.186          1.     1.28600023085
     2      4     3     5     2     5     1     1     2     2          00023090
       14.7       1500.                                               00023095
       492.        560.         660.        760.                      00023100
     .03612      .03631       .03588      .03604      .03479    .034960023105
     .03316      .03336                                               00023110
       14.7        735.        1470.                                  00023115
       492.        560.         660.        760.        860.          00023120
      1.008       1.005        1.003        .997        .995       .99300023125
```

```
      1.005       1.003        .999       1.027       1.025       1.02100023130
      1.079       1.077       1.069                                   00023135
       14.7       1500.                                               00023140
       492.        560.        660.        760.        860.           00023145
 2.6013D-07  2.6013D-07   .9888D-07   .9888D-07   .4420D-07   .4420D-0700023150
  .2695D-07   .2695D-07   .1881D-07   .1881D-07                       00023155
                                                                      00023160
                                                                      00023165
                                                                      00023170
       14.7       1500.                                               00023175
       492.        760.                                               00023180
    291178.     295648.     210958.     248286.                       00023185
      1.750       1.750       2.250       2.250       3.500       3.50000023190
         4.          4.          4.       1.750       1.750       2.25000023195
      2.250       3.500       3.500          4.          4.          4.00023200
      2.875       2.875       4.575       4.575       1.175       1.40000023205
      1.313       1.313        .422                                   00023210
       .225        .225       1.250       1.250                       00023215
       .120        .120         .67         .67        .609        .60900023220
      1000.       1000.        100.         20.        520.        520.00023225
         6.          6.          .5          1.          .5          1.00023230
         .5          1.          .5          1.                       00023235
         0.          0.          0.          0.          0.          0.00023240
       .719          2.         36.          4.         36.           00023245
         4.         36.        .305                                   00023250
         .5          .5          .5          .5          .5         .500023255
         .5          .5                                               00023260
         4.        200.       1000.         20.         20.        100.00023265
         1.        .400         .67        520.        .844         .100023270
       .010       3.625       1.175        .875        .313         .200023275
       .008        .050       .3075          7.        .050       .007500023280
       .008        .050       .4075          9.        .050       .007500023285
       .719        .719          2.         36.        .422           00023290
INCOMPRESSIBLE FLOW - SERIES PISTON - TEST CASE                       00023295
          1       1     13     25     25     6      6     0     1    0  00023300
       .012       .0018       .0096        .050          0.       .05000023305
      6000.          0.        14.7         .02        .005         .300023310
         0.          .5         96.          1.                       00023315
       .079         .43         96.          1.        .079        .2100023320
         0.          1.          .2       1.061          .4       1.24300023325
         .6       1.529          .8       1.929          1.       2.49600023330
         0.          1.          .2       1.007          .4       1.04300023335
         .6         1.1          .8       1.186          1.       1.28600023340
      1.750       1.750       2.250       2.250          4.          4.00023345
        3.5         3.5          4.          4.          4.       1.17500023350
      2.875       4.575       4.575        .422       1.313          4.00023355
      1.313       1.400        .575        .575        .225           00023360
       .234          0.          0.          0.          0.           00023365
         0.          0.        .719          0.          0.          0.00023370
         0.          0.          0.        .719        .080        .6700023375
         6.        400.        100.         20.        .609           00023380
         .5          1.          .5          .5          1.           00023385
```

```
                                        4.        36.       .01      520.      .575     2.500023390
                                        .5        .5        .5       .5        .5          00023395
                                        4.       200.     1000.      20.       20.      100.00023400
                                        1.       .400       .67     520.      .844       .100023405
                                      .010      3.625     1.175     .875      .313       .200023410
                                      .008       .050     .3075       7.      .050    .007500023415
                                      .008       .050     .4075       9.      .050    .007500023420
                                      .719       .719        2.      36.      .422        00023425
                                 /*                                                       00023430
      ./        ENDUP
IEB517I MEMBER NAME (E21902  ) NOT FOUND IN NM DIRECTORY.  STOWED WITH TTR.
IEB518I HIGHEST CONDITION CODE WAS 00000000
IEB519I END OF JOB IEBUPDTE.
```

APPENDIX C

DYNAMIC MODEL FORMULATION

AND

ANALOG PARAMETRIC STUDIES

APPENDIX C

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I. SUMMARY

This appendix is subdivided into two major sections. The first section describes the dynamic models and analog computer simulations of the self-compensating thrust balance systems. The second section describes the parameter study conducted for these systems.

Dynamic models were simulated on an electronic analog computer. Four separate simulations were necessary to describe incompressible and compressible flow through both the parallel and series flow configurations.

The dynamic models and analog computer simulations described in the first section of this appendix were used in the parameter study. A separate study was conducted for each of the four thrust balancer systems. The parameters selected for study are associated with the principal elements of the balance piston flow path.

II. TECHNICAL DISCUSSION

A. DYNAMIC MODEL FORMULATION

1. General System Description

Schematics of the parallel and series flow balancer systems are shown on Figures No. C-1 and No. C-2, respectively. The load piston and its flow circuit are identical for the two systems. In the development of the dynamic model, it was assumed that the supply and return accumulators are maintained at a constant pressure and offer zero impedance to flow.

In the actual system, the load and balance pistons will be fed and discharged through manifolds consisting of a number of paths as represented by the schematic of Figure No. C-3. In developing the model, it was assumed that all of the paths of each manifold are of equal geometry so that pressure and flow symmetry about the piston and manifold will exist. Referring to Figure No. C-3, it can be assumed that:

$$\begin{aligned} P_{i1} &= P_{i2} = \dots\dots = P_{ik} \\ \dot{W}_{i1} &= \dot{W}_{i2} = \dots\dots = \dot{W}_{ik} \\ P_{o1} &= P_{o2} = \dots\dots = P_{on} \\ \dot{W}_{o1} &= \dot{W}_{o2} = \dots\dots = \dot{W}_{on} \end{aligned} \qquad \text{Eq. (1)}$$

Then, all of the paths of each manifold can be represented by a single path as shown in the schematics of Figures No. C-1 and No. C-2.

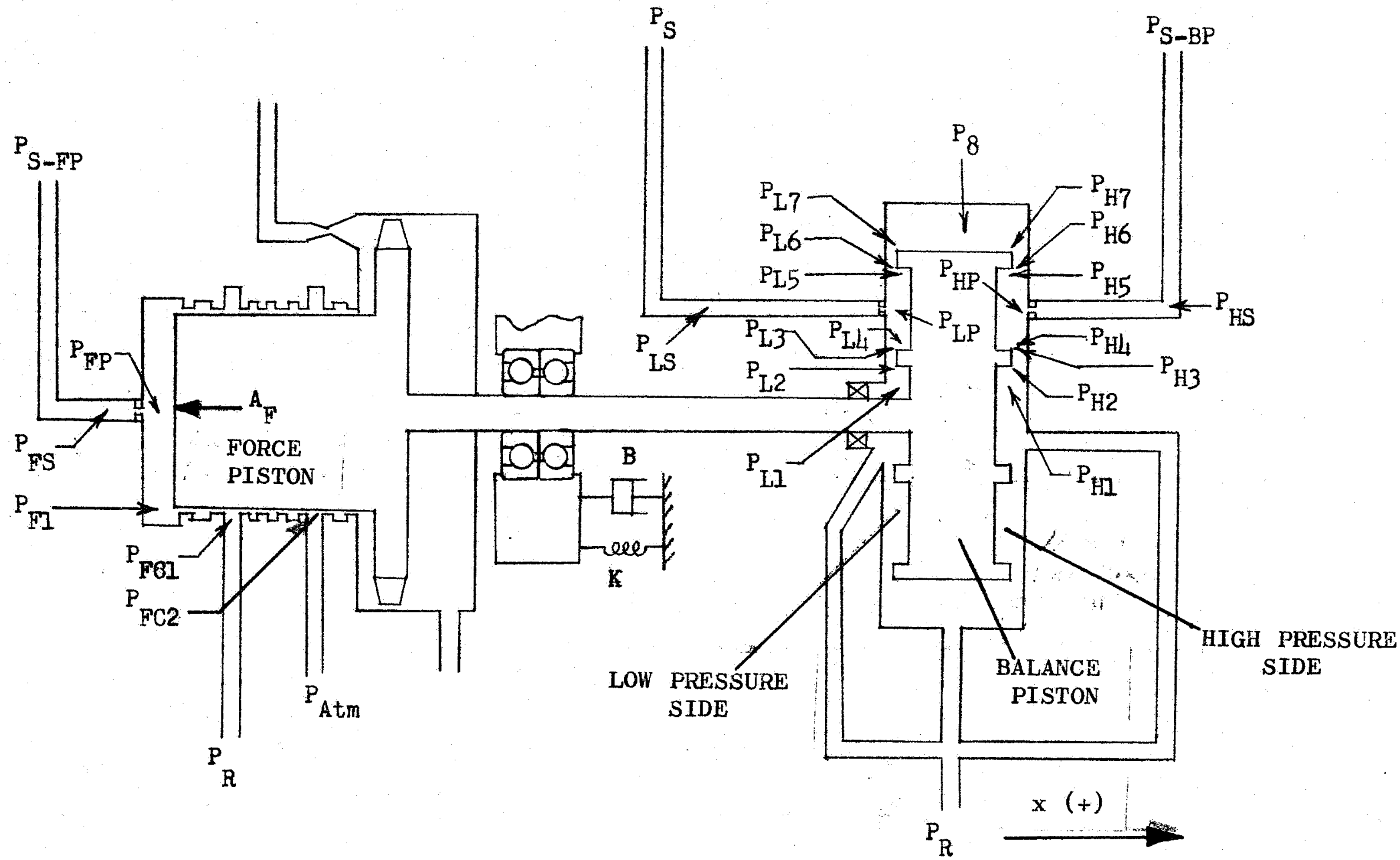

Figure C-1 System Schematic - Parallel Flow

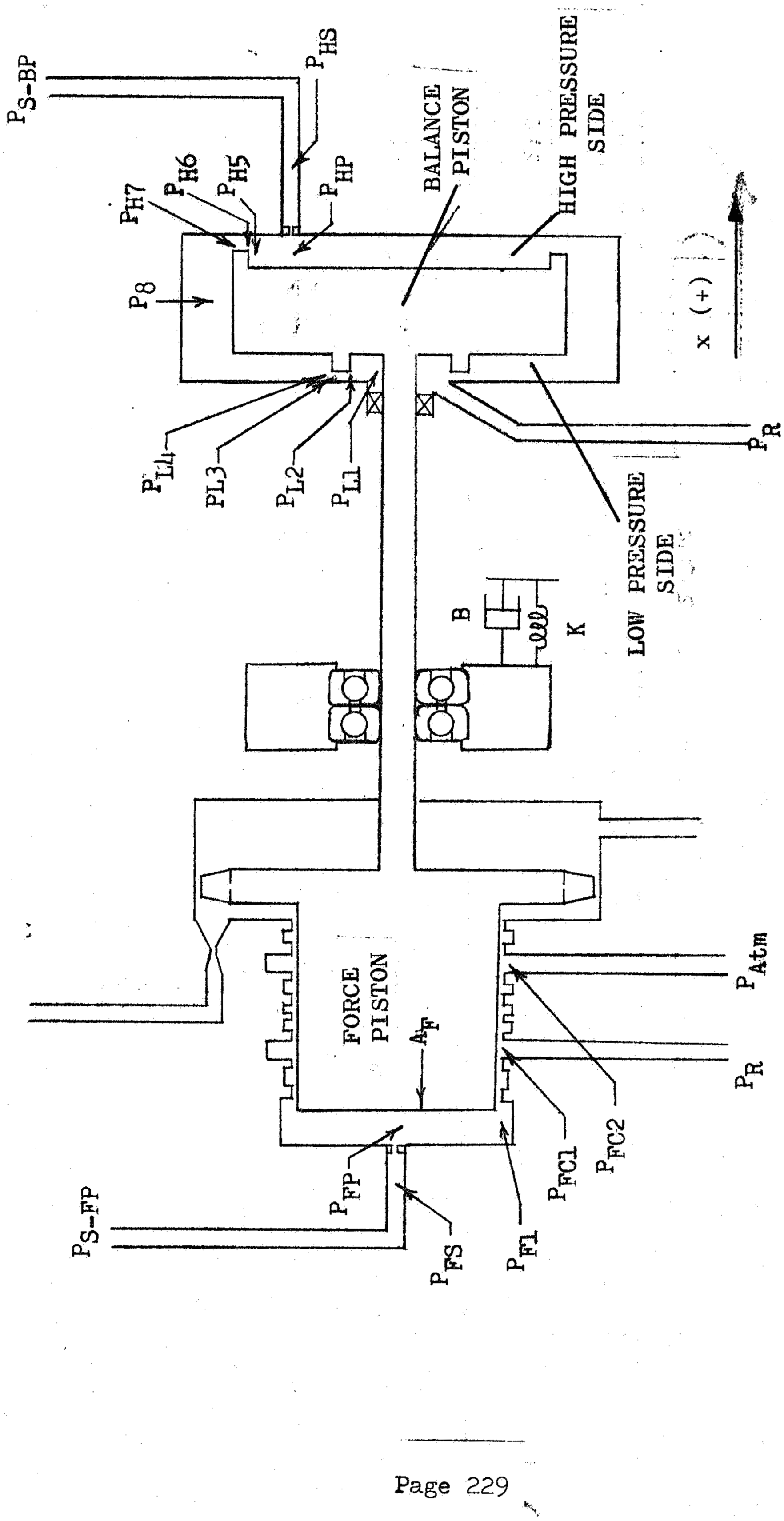

Figure C-2 System Schematic - Series Flow

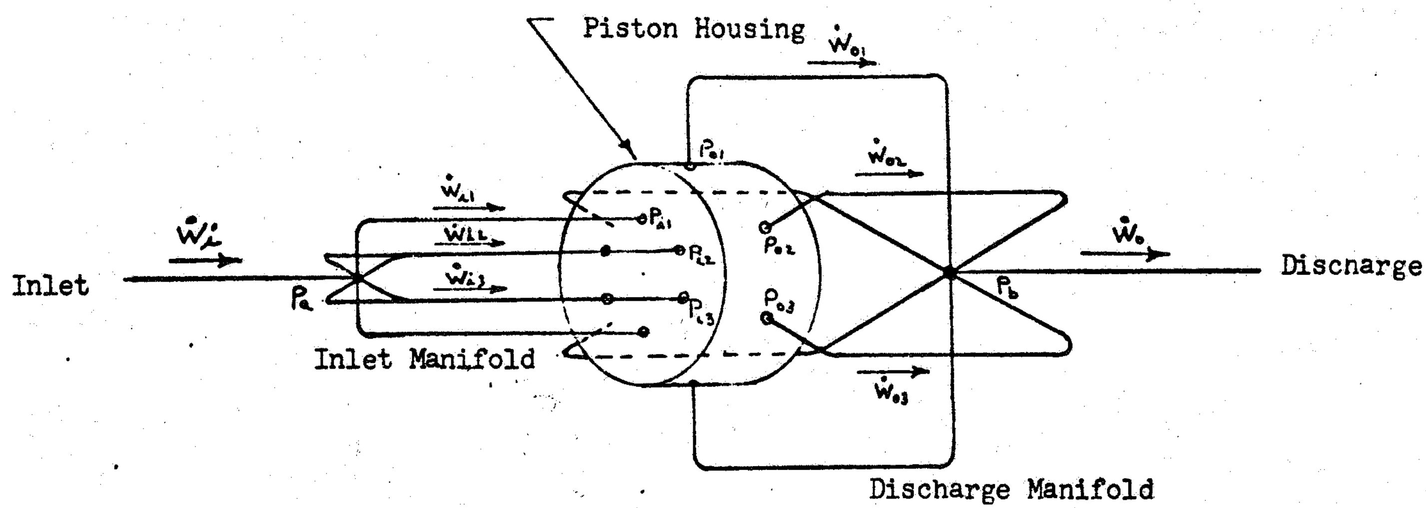

Figure C-3 Thrust Balancer Manifolds

The characteristics of the single line will be those of the parallel combination of all the paths of the manifold. All paths are identical; therefore,

$$L_e = \frac{L_i}{K}, \quad R_e = \frac{R_i}{K}, \quad C_e = KC_i \qquad \text{Eq. (2)}$$

where: Li, Ri, and Ci are individual path parameters.
Le, Re, and Ce are equivalent single path parameters.
K is the number of paths.

Also, by the argument of symmetry, the flow about the piston can be represented by a single path.

2. Modeling Philosophy

It was necessary to develop analytical models which would describe the dynamic behavior of the thrust balancer system for both incompressible water flow and the compressible flow of a perfect gas. These models must represent the fluid transmission line dynamics of the supply and discharge lines, the lumped fluid parameters of the balance and load piston circuits, the rotor mass, and the mechanical stiffness as well as damping of the rotor supports. The modeling techniques used are those described by Alexander and Bailey(1).

In this study, the analytical model for compressible flow was limited to flows in the subsonic region. Except for some minor modifications, compressible flow was described by the same basic model as incompressible flow.

The compressible model was developed from the incompressible flow model by adding the capability for varying the density and the bulk modulus of the fluid as a function of the fluid state. An important aspect of using the same basic model for both incompressible and compressible flow, aside from the obvious one of reducing the number of required models from two to one, is the possibility of extending its use to other fluids.

With certain exceptions, the sequence of the derivation of the dynamic equations which describe the various sections of the thrust balancer system follow the flow path through the balancer. Following the derivation of the system dynamic equations, consideration is given to approximations and modifications required for their simulation on a computer. Because of the nonlinear nature of the system and the number of required parameter changes, an electronic analog computer was selected for simulating the dynamic model.

3. Fluid Lines

The fluid supply and discharge lines of the system can be classified as uniform transmission lines, which are distributed parameter

(1) Alexander, J. E. and Bailey, J. M., Systems Engineering Mathematics, Prentice-Hall, 1962

elements that are described by partial differential equations. However, if the length of the line is less than one-sixth of an acoustic wavelength at the frequency of interest, then the lines can be approximated with sufficient accuracy by a lumped-parameter element. The lumped-parameter representation will be used in the formulation of the thrust balancer model. Each line will be divided into short sections which are analogous to the electrical network of Figure No. C-4.

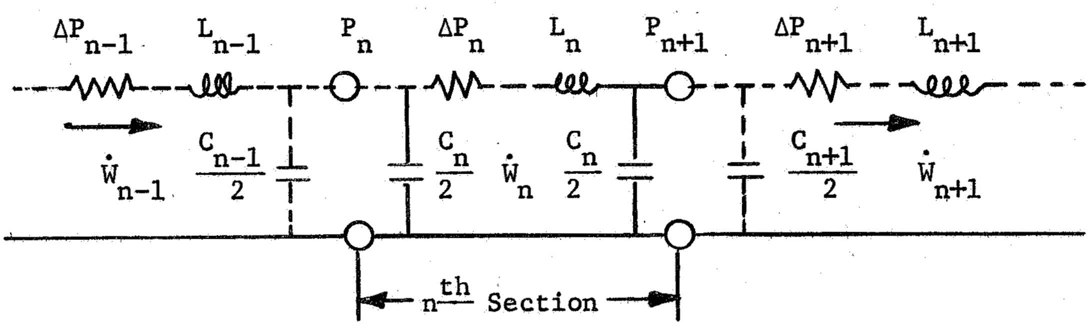

Figure C-4

Lumped Parameter Line Section

The n^{th} section is described by the following integral-differential equations,

$$P_n - \Delta P_n - L_n \frac{d\dot{W}_n}{dt} \; P_{(n+1)} = 0 \qquad \text{Eq. (3)}$$

$$P_n = \frac{2}{C_{n-1} + C_n} \int_o^t (\dot{W}_{n-1} - \dot{W}_n)\, dt \qquad \text{Eq. (4)}$$

where

$$L_n = \frac{\ell}{Ag} \; \frac{sec^2}{in.^2}, \text{ inertance} \qquad \text{Eq. (5)}$$

$$C_n = \ell Ag \left[\frac{1}{C^2} + \frac{\gamma d}{gEb} \right] in.^2, \text{ capacitance} \qquad \text{Eq. (6)}$$

For laminar flow

$$\Delta P_n = R_n \dot{W}_n$$

where:

$$R_n = \frac{128}{\pi} \; \frac{u\ell}{\gamma d^4} \; \frac{sec}{in.^2}, \text{ resistance} \qquad \text{Eq. (7)}$$

For turbulent flow

$$\Delta P_n = K_n(\dot{W}_n)^2$$

$$\text{where: } K_n = \frac{8}{\pi 2} f \frac{\ell}{g\gamma d^5} \frac{\text{sec}^2}{\text{lb in.}^2} \qquad \text{Eq. (8)}$$

The flow loss terms are those of Binder(2).

For the incompressible fluid flow simulation, the fluid flow through the lines was known to be of sufficient magnitude to produce turbulent flow. As a result, no provision was made for laminar flow.

With compressible flow, the density and bulk modulus of the fluid (hence, the capacitance of the line sections) were dependent upon the state of the fluid. By using the compressible relations developed in Attachment A of this appendix, it was possible to determine the capacitance of each line section. However, the line pressures are not expected to vary over a great range; therefore, a nominal value of capacitance was used which achieved a considerable reduction in simulation complexity.

A modification of the pressure drop equations also was made for the compressible line simulation. In this case, the pressure drop (ΔP) was assumed to be a linear function of weight flow where:

$$\Delta P_n = K_n \dot{W}_n$$

and:

$$K_n = \frac{16}{\pi 2} f \frac{\ell}{g\gamma d^5} \dot{W}_n \qquad \text{Eq. (9)}$$

4. Balance Piston Circuit - Parallel Flow

The following equations describe the flow through the parallel flow balance piston. A schematic of the parallel flow configuration is shown on Figure No. C-1. Flow enters on each side of the piston where it splits, flowing through the outer and inner radial orifices to the outer and inner discharge lines.

The load piston can exert force in one direction only; therefore, it will always tend to displace the balance piston to the right as viewed on Figure No. C-1. This displacement produces a flow restriction and a higher pressure on the right side of the balance piston. For convenience, the right side of the balance piston, as viewed on Figure No. C-1, will be referred to

(2) Binder, R. C., Fluid Mechanics, Prentice-Hall, 1955

as the high-pressure side and the left side of the balance piston as the low-pressure side.

a. Inlet Flow - High-Pressure Side

Flow through the high-pressure side will be described by the following equations beginning at the inlet:

(1) Inlet Pressure

$$\frac{dP_{HS}}{dt} = \frac{2}{C_{hi}} (\dot{W}_{hi} - \dot{W}_{HO}) \qquad \text{Eq. (10)}$$

The line capacitance C_{hi} will be assumed constant for both incompressible and compressible flow.

(2) Inlet Orifice

$$P_{HS} - K_{HO} (\dot{W}_{HO})^2 - L_{HO} \frac{d\dot{W}_{HO}}{dt} - P_{HP} = 0 \qquad \text{Eq. (11)}$$

where

$$K_{HO} = \frac{1}{2g\gamma_{HO} C_D^2 A_{HO}^2} = \frac{K_{HO}}{\gamma_{HO}} \qquad \text{Eq. (12)}$$

and

$$L_{HO} = \frac{\ell_{HO}}{gA_{HO}} \qquad \text{Eq. (13)}$$

For the compressible case, the density (γ_{HO}) was simulated by

$$\gamma_{HO} = K_k + K_\gamma P_{HP} \qquad \text{Eq. (14a)}$$

which is a linear approximation of

$$\gamma_{HO} = \frac{P_s^{\left(\frac{k-1}{k}\right)}}{RT_s} P_{HP}^{\frac{1}{k}} \qquad \text{Eq. (14b)}$$

as developed in Attachment A of this appendix.

(3) Pocket Pressure

$$\frac{dP_{HP}}{dt} = \frac{1}{V_H} \left(\frac{\beta}{\gamma}\right)_H \left(\dot{W}_{HO} + \gamma_H A_H \frac{dx}{dt} - \dot{W}_{H4} - \dot{W}_{H5}\right) \qquad \text{Eq. (15)}$$

$$V_H = V_{HO} - A_H X \qquad \text{Eq. (16)}$$

For compressible flow, the ratio of bulk modulus to density is given by:

$$\left(\frac{\beta}{\gamma}\right)_H = K_c + K_T P_{HP} \qquad \text{Eq. (17a)}$$

which is a linear approximation of the expression

$$\left(\frac{\beta}{\gamma}\right)_H = \frac{kRTs}{P_s^{\left(\frac{k-1}{k}\right)}} P_{HP}^{\left(\frac{k-1}{k}\right)} \qquad \text{Eq. (17b)}$$

as developed in Attachment A of this appendix.

The coefficient $(\gamma_H A_H)$ will be assumed a constant in the simulation.

b. Outward Flow - High-Pressure Side

The following equations describe the flow from the high-pressure inlet outward past the outer radial orifice to the outer discharge line.

(1) Pocket Rotational Pressure

$$P_{H5} = P_{HP} + P_{H\omega5} \qquad \text{Eq. (18)}$$

where

$$P_{H\omega5} = \frac{\gamma_H K}{2g} {}_{out}^{2} \omega_r^2 (R_{H6}^2 - R_{HP}^2) \qquad \text{Eq. 19)}$$

For the compressible case where the density is low, $P_{H\omega5}$ is small and is neglected in the computer simulation.

(2) Outer Radial Orifice

The radial orifice equations and their method of simulation are defined in Attachment B of this appendix. The outer radial orifice on the high-pressure side is described by:

$$P_{H5} - \Delta P_{H58} - \frac{1}{J_{H67}(h_s - x)} \frac{d\dot{W}H5}{dt} - P_8 = 0 \qquad \text{Eq. (20)}$$

where

$$\Delta P_{H58} = \frac{\gamma N}{\gamma H58} f(\dot{W}_{H5}) f(h - x) \qquad \text{Eq. (21)}$$

and

$$\frac{\gamma H58}{\gamma N} = 1 \quad \text{(incompressible flow)}$$

or

$$\frac{\gamma H58}{\gamma N} = \frac{K_k}{\gamma N} + \frac{K\gamma}{\gamma N}\left(\frac{P_H + P_8}{2}\right) \text{(compressible flow)} \qquad \text{Eq. (22)}$$

The inertance is a function of sill gap where the coefficient J_{H67} is given by:

$$J_{H67} = \frac{g\pi(R_{H7} + R_{H6})}{(R_{H7} - R_{H6})} \qquad \text{Eq. (23)}$$

(3) Outer Discharge Cavity

$$\frac{dP_{HS}}{dt} = \frac{1}{C_8 + \frac{C_o}{2}} (\dot{W}_{H5} + \dot{W}_{L5} - \dot{W}_o) \qquad \text{Eq. (24)}$$

where

$$C_8 = \frac{\gamma 8\ 8}{\beta 8} = \text{pocket capacitance}$$

$$C_o = \text{return line section capacitance}$$

The capacitance $(C_8 + \frac{C_o}{2})$ is assumed constant for both the incompressible and compressible computer simulations.

c. Inward Flow - High-Pressure Side

The following equations describe the flow from the high pressure inlet inward past the inner radial orifice and out the inner discharge line.

(1) Pocket Rotational Pressure

$$P_{H4} = P_{HP} - P_{H\omega 4} \qquad \text{Eq. (25)}$$

where

$$P_{H\omega 4} = \frac{\gamma_H}{2g} K_{in}^2 \omega_r^2 (R_{HP}^2 - R_{H3}^2) \qquad \text{Eq. (26)}$$

For the compressible case where the density is low, $P_{H\omega_4}$ is small and is neglected in the computer simulation.

(2) Inner Radial Orifice

The inner radial orifice equation, as developed in Attachment B of this appendix, is expressed by

$$P_{H4} - \Delta P_{H41} - \frac{1}{J_{H32(h_s - x)}} \frac{d\dot{W}_{H4}}{dt} - P_{H1} = 0 \qquad \text{Eq. (27)}$$

where

$$\Delta P_{H41} = \frac{\gamma_N}{\gamma_{H41}} f(\dot{W}_{H4}) f(h_s - x) \qquad \text{Eq. (28)}$$

and

$$\frac{\gamma_{H41}}{\gamma N} = 1 \quad \text{(incompressible flow)}$$

or

$$\frac{\gamma H41}{\gamma N} = \frac{K_k}{\gamma_N} + \frac{K_\gamma}{\gamma_N} \frac{(P_{H4} + P_{H1})}{2} \quad \text{(compressible flow)}$$

Eq. (29)

Orifice inertance coefficient J_{H32} is given by

$$J_{H32} = \frac{g\pi(R_{H3} + R_{H2})}{R_{H3} - R_{H2}} \qquad \text{Eq. (30)}$$

(3) Inner Discharge Cavity

$$\frac{dP_{H1}}{dt} = \frac{1}{\left(C_{H1} + \frac{C_{ho}}{2}\right)} \quad \dot{W}_{H4} + \gamma_{H1} A_{H1} \frac{dx}{dt} - \dot{W}_{ho}$$

Eq. (31)

$$C_{H1} = \left(\frac{\gamma}{\beta}\right)_{H1} V_{H1} \quad \text{(pocket capacitance)}$$

$$C_{ho} = \text{line section capacitance}$$

The capacitance $(C_{H1} + \frac{C_{ho}}{2})$ and the coefficient $(\gamma_{H1}A_{H1})$ are assumed constant for both the incompressible and compressible computer simulations.

d. Inlet Flow - Low-Pressure Side

Beginning at the inlet on the low pressure side:

(1) Inlet Pressure

$$\frac{dP_{LS}}{dt} = \frac{2}{C_{\ell i}} (W_{\ell i} - W_{LO}) \qquad \text{Eq. (32)}$$

The line capacitance $C_{\ell i}$ will be assumed constant for both the incompressible and compressible flow conditions.

(2) Inlet Orifice

$$P_{LS} - K_{LO}\dot{W}_{LO}^{2} - L_{LO}\frac{d\dot{W}_{LO}}{dt} - P_{LP} = 0 \qquad \text{Eq. (33)}$$

where

$$K_{LO} = \frac{1}{2g\ \gamma_{LO}C_D^{2}\ A_{LO}^{2}} = \frac{K'_{LO}}{\gamma_{LO}} \qquad \text{Eq. (34)}$$

and

$$L_{LO} = \frac{\ell LO}{gA_{LO}} \qquad \text{Eq. (35)}$$

For the compressible case, the density γ_{LO} is given by $\gamma_{LO} = K_k + K\ P_{LP}$ Eq. (36)

(3) Pocket Pressure

$$\frac{dP_{LP}}{dt} = \frac{1}{V_L}\left(\frac{\beta}{\gamma}\right)_L (\dot{W}_{LO} - \gamma_L A\frac{dx}{Ldt} - \dot{W}_{L4} - \dot{W}_{L5})$$

Eq. (37)

$$V_L = V_{Lo} + A_L X \qquad \text{Eq. (38)}$$

and for the compressible flow case

$$\left(\frac{\beta}{\gamma}\right)_L = K_c + K_T\ P_{LP} \qquad \text{Eq. (39)}$$

The coefficient $(\gamma_L A_L)$ will be assumed constant.

e. Outward Flow - Low-Pressure Side

The following equations describe the flow path dynamics from the low pressure inlet outward past the outer radial orifice to the outer discharge line.

(1) Pocket Rotational Pressure

$$P_{L5} = P_{LP} + P_{L\omega 5} \qquad \text{Eq. (40)}$$

where for incompressible flow

$$P_{L\omega 5} = \frac{\gamma L}{2g} K_{out}^{2} \, \omega r^{2} \, (R_{L6}^{2} - R_{LP}^{2}) \qquad \text{Eq. (41)}$$

For the compressible flow case where the density is low, $P_{L\omega 5}$ is small and is neglected.

(2) Outer Radial Orifice

The outer radial orifice on the low pressure side is described by:

$$P_{L5} - \Delta P_{L58} - \frac{1}{J_{L56}(h_s + x)} \frac{d\dot{W}_{L5}}{dt} - P_8 = 0 \qquad \text{Eq. (42)}$$

where

$$\Delta P_{L58} = \frac{\gamma_N}{\gamma_{L58}} f(\dot{W}_{L5}) f(h_s + x) \qquad \text{Eq. (43)}$$

and

$$\frac{\gamma_{L58}}{\gamma_N} = 1 \text{ (incompressible flow)}$$

or

$$\frac{\gamma_{L58}}{\gamma_N} = \frac{K_k}{\gamma_N} + \frac{K}{\gamma_N} \frac{(P_{L5} + P_8)}{2} \text{ (compressible flow)} \qquad \text{Eq. (44)}$$

The orifice inertance coefficient J_{L67} is given by

$$J_{L67} = \frac{g\pi(R_{L7} + RL_6)}{R_{L7} - R_{L6}} \qquad \text{Eq. (45)}$$

(3) Outer Discharge Cavity

The outer pocket is common to both the high and low pressure sides of the balance piston so that the pressure is described by Equation (24).

f. Inward Flow - Low-Pressure Side

The following equations describe the flow path dynamics from the low pressure inlet inward past the inner radial orifice to the inner discharge line.

(1) Pocket Rotational Pressure

$$P_{L4} = P_{LP} - P_{L\omega 4} \qquad \text{Eq. (46)}$$

where

$$P_{L\omega 4} = \frac{\gamma_L}{2g} K_{in} \; \omega^2 r^2 (R_{LP}^2 - R_{L3}^2) \qquad \text{Eq. (47)}$$

For the compressible case where the density is low, $P_{L\omega 4}$ is assumed to be zero.

(2) Inner Radial Orifice

$$P_{L4} - \Delta P_{L41} - \frac{1}{J_{L32}(h_s + x)} \frac{d\dot{W}_{L4}}{dt} - P_{L1} = 0 \qquad \text{Eq. (48)}$$

where

$$\Delta P_{L41} = \frac{\gamma_N}{\gamma_{L41}} f(\dot{W}_{L4}) \; f\,(h_s + x) \qquad \text{Eq. (49)}$$

and

$$\frac{\gamma_{L41}}{\gamma_N} = 1 \quad \text{(incompressible flow)}$$

or

$$\frac{\gamma_{L41}}{\gamma_N} = \frac{K_k}{\gamma_N} + \frac{K_\gamma}{\gamma_N} \; \frac{(P_{L4} + P_{L1})}{2} \quad \text{(compressible flow)} \qquad \text{Eq. (50)}$$

The orifice inertance coefficient, J_{L32}, is given by:

$$J_{L32} = \frac{g\,\pi(R_{L3} + R_{L2})}{(R_{L3} - R_{L2})} \qquad \text{Eq. (51)}$$

(3) Inner Discharge Cavity

$$\frac{dP_{L1}}{dt} = \frac{1}{C_{L1} + \frac{C_{\ell o}}{2}} \; \dot{W}_{L3} + \gamma_{L1} A_{L1} \frac{dx}{dt} - \dot{W}_{\ell o} \qquad \text{Eq. (52)}$$

where

$$C_{L1} = \frac{\gamma_{L1} V_{H1}}{\beta_{H1}} = \text{pocket capacitance}$$

$$C_{\ell o} = \text{line section capacitance}$$

The capacitance $(C_{L1} + \frac{C_{\ell o}}{2})$ and the coefficient $(\gamma_{L1} A_{L1})$ are assumed constant for both the compressible and incompressible computer simulations.

5. Balance Piston Circuit-Series Flow

The following set of equations describes the flow through the series balance piston circuit. As shown on the schematic of Figure No. C-2, flow enters on the right side of the balance piston, flows outward through an outer radial orifice, then flows inward on the left side of the piston through an inner radial orifice to the discharge line. As the flow direction would indicate, the pocket on the right side of the balance piston will be at a higher pressure than the pocket on the left side. For convenience, the inlet or right side of the balance piston will be referred to as the high-pressure side and the left side as the low-pressure side.

a. Inlet Flow - High-Pressure Side

Beginning at the inlet:

(1) Inlet Pressure

$$\frac{dP_{HS}}{dt} = \frac{2}{C_{hi}} (\dot{W}_{hi} - \dot{W}_{Ho}) \qquad \text{Eq. (53)}$$

The line capacitance C_{hi} will be assumed constant for both incompressible and compressible flow.

(2) Inlet Orifice

$$P_{HS} - K_{HO} (W_{HO})^2 - L_{HO} \frac{W_{HO}}{dt} - P_{Hp} = 0 \qquad \text{Eq. (54)}$$

where

$$K_{HO} = \frac{1}{2g\ \gamma_{HO}\ C_D^2 A_{HO}^2} = \frac{K_{HO}'}{\gamma_{HO}} \qquad \text{Eq. (55)}$$

and

$$L_{HO} = \frac{\ell_{HO}}{gA_{HO}} \qquad \text{Eq. (56)}$$

For the compressible case, the density γ_{HO} is simulated by

$$\gamma_{HO} = K_k + K_\gamma P_{HP} \qquad \text{Eq. (57)}$$

which is a linear approximation of

$$\gamma_{HO} = \frac{P_s^{\left(\frac{k-1}{k}\right)}}{RTs} P_{HP}^{\left(\frac{1}{k}\right)} \qquad \text{Eq. (58)}$$

as developed in Attachment A of this appendix.

(3) Pocket Pressure - High-Pressure Side

$$\frac{dP_{HP}}{dt} = \frac{1}{V_H}\left(\frac{\beta}{\gamma}\right)_H (\dot{W}_{HO} + \gamma_H A_H \frac{dx}{dt} - \dot{W}_{H5}) \qquad \text{Eq. (59)}$$

where

$$V_H = V_{Ho} - A_H X \qquad \text{Eq. (60)}$$

For compressible flow, the ratio of bulk modulus to density is given by

$$\left(\frac{\beta}{\gamma}\right)_H = K_c + K_T P_{HP} \qquad \text{Eq. (61)}$$

which is a linearized approximation of

$$\left(\frac{\beta}{\gamma}\right)_H = \frac{kRT_s}{P_s^{\left(\frac{k-1}{k}\right)}} P_{HP}^{\left(\frac{k-1}{k}\right)} \qquad \text{Eq. (62)}$$

which is developed in Attachment A of this appendix. The coefficient $(\gamma_H A_H)$ is assumed constant

b. Outward Flow - High-Pressure Side

(1) Pocket Rotational Pressure

$$P_{H5} = P_{HP} + P_{H\omega 5} \qquad \text{Eq. (63)}$$

where

$$P_{H\omega 5} = \frac{\gamma_H}{2g} K_{out}{}^2 {}_{\omega r}{}^2 (R_{H6}{}^2 - R_{HP}{}^2) \qquad \text{Eq. (64)}$$

For the compressible case where the density is low, $P_{H\omega 5}$ is small and is neglected.

(2) Outer Radial Orifice

The radial orifice equations are defined in Attachment B of this appendix. The outer radial orifice on the high pressure side is described by

$$P_{H5} - \Delta P_{H58} - \frac{1}{J_{H67}(h_s - x)} \frac{d\dot{W}_{H5}}{dt} - P_{H8} = 0 \qquad \text{Eq. (65)}$$

where

$$\Delta P_{H58} = \frac{\gamma_N}{\gamma_{H58}} f\,(\dot{W}_{H5})\; f(h_s - x) \qquad \text{Eq. (66)}$$

and

$$\frac{\gamma_{H58}}{\gamma_N} = 1 \text{ (incompressible flow)}$$

or

$$\frac{\gamma_{H58}}{\gamma_N} = \frac{K_k}{\gamma_N} + \frac{K}{\gamma_N}\left(\frac{P_{H5} + P_{H8}}{2}\right) \text{ (compressible flow)} \qquad \text{Eq. (67)}$$

The orifice inertance coefficient is given by

$$J_{H67} = \frac{g\pi(R_{H7} + R_{H6})}{(R_{H7} - R_{H6})} \qquad \text{Eq. (68)}$$

c. Piston Axial Flow

After flowing through the outer radial orifice, the flow passes axially between the outer piston circumference and the housing to the low-pressure side of the piston. The flow path between the piston circumference and housing can consist of either an annulus or a labyrinth. In general, the flow is described by:

$$P_{H8} - K_{BPL}\,(\dot{W}_{H5})^2 - L_{BPL}\frac{d\dot{W}_{H5}}{dt} - P_{L8} = 0 \qquad \text{Eq. (69)}$$

For the annulus flow path, the loss coefficient K_{BPL} and the inertance L_{BPL} are small which yields the approximation

$$P_{H8} \approx P_{L8}$$

For the labyrinth flow path, the loss coefficient and inertance are significant.

d. Inlet Flow - Low-Pressure Side

Pocket Pressure

$$\frac{dP_{LS}}{dt} = \frac{1}{V_L} \left(\frac{\beta}{\gamma}\right)_L (\dot{W}_{H5} - \gamma_L A_L \frac{dx}{dt} - \dot{W}_{L4}) \qquad \text{Eq. (70)}$$

where

$$V_L = V_{Lo} + A_L X \qquad \text{Eq. (71)}$$

and for the compressible flow case

$$\left(\frac{\beta}{\gamma}\right)_L = K_c + K_T P_{L8} \qquad \text{Eq. (72)}$$

The coefficient $(\gamma_L A_L)$ is assumed constant.

e. Inward Flow - Low-Pressure Side

(1) Pocket Rotational Pressure

$$P_{L4} = P_{L8} - P_{L\omega 4} \qquad \text{Eq. (73)}$$

where

$$P_{L\omega 4} = \frac{\gamma_L}{2g} K_{in}^2 \omega_r^2 (R_{L7}^2 - R_{L3}^2) \qquad \text{Eq. (74)}$$

For the compressible case where the density is low, $P_{L\omega 4}$ is small and neglected.

(2) Inner Radial Orifice

$$P_{L4} - \Delta P_{L41} - \frac{1}{J_{L32} (h_s + x)} \frac{dW_{L4}}{dt} - P_{L1} = 0 \qquad \text{Eq. (75)}$$

where

$$\Delta P_{L41} = \frac{\gamma_N}{\gamma_{L41}} f(\dot{W}_{L4}) f(h_s + x) \qquad \text{Eq. (76)}$$

and

$$\frac{\gamma_{L41}}{\gamma_N} = 1 \text{ (incompressible flow)}$$

$$\frac{\gamma_{L41}}{\gamma_N} = \frac{K_k}{\gamma_N} + \frac{K_\gamma}{\gamma_N}\left(\frac{P_{L4} + P_{L1}}{2}\right) \text{ (compressible flow)} \qquad \text{Eq. (77)}$$

The orifice inertance coefficient, J_{L32}, is given by

$$J_{L32} = \frac{g\pi(R_{L3} + R_{L2})}{R_{L3} - R_{L2}} \qquad \text{Eq. (78)}$$

(3) Inner Discharge Cavity

$$\frac{dP_{L1}}{dt} = \frac{1}{(C_{L1} + C_{\ell o/2})}\left(\dot{W}_{L4} + \gamma_{L1}A_{L1}\frac{dx}{dt} - \dot{W}_{\ell o}\right) \qquad \text{Eq. (79)}$$

where

$$C_{L1} = \frac{\gamma_{L1} V_{L1}}{\beta_{L1}} \text{ (pocket capacitance)}$$

$$C_{\ell o} = \text{line section capacitance}$$

The capacitance $(C_{L1} + \frac{C_{\ell o}}{2})$ and the coefficient $(\gamma_{L1}A_{L1})$ are assumed constant for both the compressible and incompressible computer simulations.

6. Load Piston Flow Circuit

The following equations describe the flow through the load piston circuit. Referring to the schematic of either Figure No. C-1 or No. C-2, the load piston circuit consists of an inlet orifice, a piston cavity, and labyrinth passages between the outer piston circumference and the housing. Beginning at the load piston inlet, the circuit dynamic equations are defined in the following sections.

a. Inlet Pressure

$$\frac{dP_{FS}}{dt} = \frac{2}{C_{fi}}(\dot{W}_{fi} - \dot{W}_{FO}) \qquad \text{Eq. (80)}$$

The line capacitance C_{fi} is assumed constant.

b. Inlet Orifice

$$P_{FS} - K_{FO}\dot{W}_{FO}^{2} - L_{FO}\frac{d\dot{W}_{FO}}{dt} - P_{FP} = 0 \qquad \text{Eq. (81)}$$

where

$$K_{Fo} = \frac{1}{2g\ \gamma_{FP}\ C_D^2\ A_{FO}^{2}} \qquad \text{Eq. (82)}$$

$$L_{Fo} = \frac{\ell_{FO}}{g A_{FO}} \qquad \text{Eq. (83)}$$

For the compressible case, the density γ_{FP} is given by either

$$\gamma_{FP} = \frac{P_S^{\left(\frac{k-1}{k}\right)}}{RT_S}\ P_{Fp}^{\left(\frac{1}{k}\right)} \qquad \text{Eq. (84)}$$

or its linearized approximation as defined in Attachment A of this appendix. However, in the simulation of the force piston inlet orifice, the density is assumed constant. This is done as a simplification to conserve computing equipment for more critical portions of the computer model and will have a small affect upon computer model accuracy.

c. Cavity Pressure

$$\frac{dP_{FP}}{dt} = \frac{1}{V_F}\left(\frac{\beta}{\gamma}\right)_F\left(\dot{W}_{FO} - \dot{W}_{F1} - \gamma_F A_F\frac{dx}{dt}\right) \qquad \text{Eq. (85)}$$

The variation of the volume, V_F, with piston displacement, x, is negligible when compared to the nominal or steady-state value. Therefore, the volume, V_F, is assumed constant. For the compressible flow analog simulation, the ratio of bulk modulus to density $\left(\frac{\beta}{\gamma}\right)_F$ is given by

$$\left(\frac{\beta}{\gamma}\right)_F = \frac{kRT_S}{P_S^{\left(\frac{k-1}{k}\right)}}\ P_{FP}^{\left(\frac{k-1}{1}\right)} \qquad \text{Eq. (86)}$$

or a linearized approximation given by

$$\left(\frac{\beta}{\gamma}\right)_F = K_c + K_T\ P_{FP} \qquad \text{Eq. (87)}$$

as developed in Attachment A of this appendix. The coefficient ($\gamma_F A_F$) of the piston rate $\frac{(dx)}{dt}$ is assumed constant in the compressible simulation.

d. Cavity Rotational Pressure

$$P_{F1} = P_{FP} + P_{F\omega} \qquad \text{Eq. (88)}$$

where

$$P_{F\omega} = \frac{\gamma_F}{2g} K_{FP}^2 \omega_r^2 R_{FP}^2 \qquad \text{Eq. (89)}$$

The equation for $P_{F\omega}$ gives the pressure distribution in the cavity caused by rotation. This equation is not included in the computer simulation for compressible flow because the gas density is very low and the pressure increase, $P_{F\omega}$, is negligible.

e. First Labyrinth Seal

The flow through the labyrinth seal between the cavity and discharge line is given by

$$P_{F1} - K_{F1} \dot{W}_{F1}^2 - L_{F1} \frac{dW_{F1}}{dt} - P_{FC1} = 0 \qquad \text{Eq. (90)}$$

where the flow loss coefficient, K_{F1}, is best obtained by test. The inertance, L_{F1}, is given by

$$L_{F1} = \frac{\ell_L}{g\pi(R_L^2 - R_{FP}^2)} \qquad \text{Eq. (91)}$$

f. Discharge Pressure

$$\frac{dP_{FC1}}{dt} = \frac{2}{C_{fi}} (\dot{W}_{F1} - \dot{W}_{fo} - \dot{W}_{FC2}) \qquad \text{Eq. (92)}$$

The line section capacitance (C_{fi}) is assumed constant.

g. Second Labyrinth Seal

$$P_{FC1} - K_{F2} \dot{W}_{F2}^2 - L_{F2} \frac{dW_{F2}}{dt} - P_{FC2} = 0 \qquad \text{Eq. (93)}$$

h. Vent Line Pressure

$$\frac{dP_{FC2}}{dt} = \frac{2}{C_{fo}} (\dot{W}_{F2} - \dot{W}_{fo}) \qquad \text{Eq. (94)}$$

The line capacitance, C_{fo}, is assumed constant.

With compressible gas flow, the discharge line is assumed to be closed, and the total flow is assumed to be discharging at the vent. Therefore, the discharge pressure, Equation (92), is not included in the compressible flow computer simulation and the two labyrinth Equations, (90) and (93), are combined to obtain the total labyrinth flow.

7. Piston Forces

The piston forces are obtained from an integration of the pressures over the face of the piston. The integration over the various areas of the force and balance pistons is described in Attachment C of this appendix. In addition, the forces on the lands or sills resulting from squeeze film effects also are described in Attachment C. However, the equations of Attachment C, which define sill forces in terms of sill pressures, are not used in the computer simulation.

As explained in the development of the radial orifice equations of Attachment B of this appendix, to reduce simulation complexity, the sill flow loss was lumped together with the sill entrance and exit losses. Therefore, the pressures within the sills which are needed to use the sill force equations of Attachment C are not obtained in the simulation. For this reason, approximate sill forces were developed by assuming that the inner half of the sill diameter is acted upon by the inner pressure and the outer half of the sill diameter is acted upon by the outer pressure. The major component of force is generated by the pocket pressure across the pocket area; therefore, the sill approximation does not result in an appreciable error.

a. Balance Piston Force - Parallel Flow

(1) High-Pressure Side

The total force on the high-pressure side of the parallel flow balance piston is given by

$$F_H = A_{H1} P_{H1} + A_{H4} P_{H4} + A_{HP} P_{HP} + F_H + A_{H5} P_{H5}$$

$$+ A_{H8} P_{H8} + K_{H5} \frac{f_H(\dot{x})}{(h_s - x)^3} \qquad \text{Eq. (95)}$$

where

$$A_{H1} = \pi\left(\frac{R_{H2} + R_{H3}}{2}\right)^2 \qquad \text{Eq. (96)}$$

$$A_{H4} = \pi\left[R_{H3}^{\;2} - \left(\frac{R_{H2} + R_{H3}}{2}\right)^2\right] \qquad \text{Eq. (97)}$$

$$A_{HP} = \pi\left(R_{H6}^{\;2} - R_{H3}^{\;2}\right) \qquad \text{Eq. (98)}$$

$$F_{HW} = \frac{\pi\gamma}{4g} W_r^2 \left[K_{out}^{\;2}\left(R_{H6}^{\;2} - R_{HP}^{\;2}\right)^2 - K_{in}^{\;2}\left(R_{HP}^{\;2} - R_{H3}^{\;2}\right)^2\right] \qquad \text{Eq. (99)}$$

$$A_{H5} = \pi\left[\left(\frac{R_{H7} + R_{H6}}{2}\right)^2 - R_{H6}^{\;2}\right] \qquad \text{Eq. (100)}$$

$$A_{H8} = \pi\left[R_{H7}^{\;2} - \left(\frac{R_{H7} + R_{H6}}{2}\right)^2\right] \qquad \text{Eq. (101)}$$

$$K_{HS} = \frac{(.079)\pi\mu^n\gamma^{1-n}}{2g^{1-n}} \left\{ (\sec\,\alpha)_{H32}^{1-n} \int_{R_{H2}}^{R_{H3}} r \int_{R_{H2}}^{r} \frac{1}{B}, \frac{dP}{dg}\, dydr \right.$$

$$\left. + (\sec\,\alpha)_{H67}^{1-n} \int_{R_{H6}}^{R_{H7}} r \int_{R_{H6}}^{r} \frac{1}{B}\frac{dP}{dy}\, dy\; dr \right\} \qquad \text{Eq. (102)}$$

$$f_H(x) = \begin{cases} \left(\dfrac{dx}{dt}\right)^2 & \cdot \quad \dfrac{dx}{dt} > 0 \\ 0 & \cdot \quad \dfrac{dx}{dt} \leq 0 \end{cases} \qquad \text{Eq. (103)}$$

The double integral terms in Equation (102) are evaluated in Attachment C of this appendix.

(2) Low-Pressure Side

The total force on the low-pressure side of the parallel flow balance piston is given by

$$F_L = A_{L1} P_{L1} + A_{L4} P_{L4} + A_{LP} P_{LP} + F_L + A_{L5} P_{L5}$$

$$+ A_{L8} P_{L8} + K_{HS} \frac{f_L(\dot{x})}{(hs + X)^3} \qquad \text{Eq. (104)}$$

and

$$A_{L1} = \pi\left[\left(\frac{R_{L3} + R_{L2}}{2}\right)^2 - R_{LS}^{\ 2}\right] \qquad \text{Eq. (105)}$$

$$A_{L4} = \pi\left[R_{L3}^{\ 2} - \left(\frac{R_{L2} + R_{L3}}{2}\right)^2\right] \qquad \text{Eq. (106)}$$

$$A_{LP} = \pi\left(R_{L6}^{\ 2} - R_{L3}^{\ 2}\right) \qquad \text{Eq. (107)}$$

$$F_{LW} = \frac{\pi\gamma}{4g}\,\omega_r^2\left[K_{out}^{\ 2}\left(R_{L6}^{\ 2} - R_{LP}^{\ 2}\right)^2 - K_{in}^{\ 2}\left(R_{LP}^{\ 2} - R_{L3}^{\ 2}\right)^2\right] \qquad \text{Eq. (108)}$$

$$A_{L5} = \pi\left[\left(\frac{R_{L7} + R_{L6}}{2}\right)^2 - R_{L6}^{\ 2}\right] \qquad \text{Eq. (109)}$$

$$A_{L8} = \pi\left[R_{L7}^{\ 2} - \left(\frac{R_{L7} + R_{L6}}{2}\right)^2\right] \qquad \text{Eq. (110)}$$

$$K_{HS} = \frac{(0.079)\pi \quad \mu^n(1-n)}{2\ g^{1-n}}\left\{(\sec\alpha)^{1-n}_{L32}\int_{R_{L2}}^{R_{L3}} r \int_{R_{L2}}^{r} \frac{1}{B'}\frac{dP}{dy}\,dy\,dr\right.$$

$$\left.+ (\sec\alpha)^{1-n}_{L67}\int_{R_{L6}}^{R_{L7}} r \int_{R_{L6}}^{r} \frac{1}{B'}\frac{dP}{dy}\,dy\,dr\right\} \qquad \text{Eq. (111)}$$

$$f_L(x) = \begin{cases} 0 & \cdot \quad \frac{dx}{dt} \geq 0 \\ \left(\frac{dx}{dt}\right)^2 & \cdot \quad \frac{dx}{dt} < 0 \end{cases} \qquad \text{Eq. (112)}$$

The double integrals in Equation (111) are evaluated in Attachment C of this appendix.

Although the "sec α" terms of Equations (102) and (111) are variables which are dependent upon weight flow and sill gap width, they were evaluated at nominal conditions and assumed constant in the computer simulation. The square exponent on the velocity terms of Equations (103) and (112) are an approximation of the exponent (2-n) as developed in Attachment C. The squeeze film terms are neglected in the compressible flow case because of the low values of gas density and viscosity. The rotational force terms ($F_{H\omega}$) and ($F_{L\omega}$) also are neglected for the compressible case because the gas density is low.

b. Balance Piston Force - Series Flow

(1) High-Pressure Side

The total force on the high-pressure side of the series flow balance piston is given by

$$F_H = A_H P_{HP} + F_H + A_{H5} P_{H5} + A_{H8} P_{H8} + K_{HS} \frac{f_H(\dot{X})}{(h_s - x)^3} \qquad \text{Eq. (113)}$$

where

$$A_{HP} = \pi R_{H6}^2 \qquad \text{Eq. (114)}$$

$$F_{HW} = \frac{\pi\gamma}{4g} \omega_r^2 \left[K_{out}^2 \left(R_{H6}^2 - R_{HP}^2\right)^2 - K_{in}^2 R_{HP}^4\right] \qquad \text{Eq. (115)}$$

$$A_{H5} = \pi\left[\left(\frac{R_{H6} + R_{H7}}{2}\right)^2 - R_{H6}^2\right] \qquad \text{Eq. (116)}$$

$$A_{H8} = \pi\left[R_{H7}^2 - \left(\frac{R_{H6} + R_{H7}}{2}\right)^2\right] \qquad \text{Eq. (117)}$$

$$K_{HS} = \frac{(0.079)\pi\ \mu^n\ \gamma^{1-n}}{2\ g^{1-n}} (\sec\ \alpha)^{1-n}_{H67} \int_{R_{H6}}^{R_{H7}} r \int_{R_{H6}}^{r} \frac{1}{B'} \frac{dP}{dy}\, dy\, dr$$

Eq. (118)

$$f_H(x) = \begin{cases} \left(\frac{dx}{dt}\right)^2 & \cdot \quad \frac{dx}{dt} > 0 \\ 0 & \cdot \quad \frac{dx}{dt} \leq 0 \end{cases}$$

Eq. (119)

The double integral term in Equation (118) is evaluated in Attachment C of this appendix.

(2) Low-Pressure Side

The total force on the low-pressure side of the series flow balance piston is given by

$$F_L = A_{L1}P_{L1} + A_{L4}P_{L4} + A_L P_{L8} - F_{L\omega} + K_{LS} \frac{f_{L(\dot{x})}}{(h_s + x)^3}$$

Eq. (120)

where

$$A_{L1} = \pi\left[\left(\frac{R_{L3} + R_{L2}}{2}\right)^2 - R_{L5}{}^2\right]$$

Eq. (121)

$$A_{L4} = \pi\left[R_{L3}{}^2 - \left(\frac{R_{L3} + R_{L2}}{2}\right)^2\right]$$

Eq. (122)

$$A_L = \pi(R_{L7}{}^2 - R_{L3}{}^2)$$

Eq. (123)

$$F_{LW} = \frac{\pi\gamma}{4g}\ K_{in}^2\ \omega_r^2 \left(R_{L7}^2 - R_{L3}^2\right)$$

Eq. (124)

$$K_{LS} = \frac{(0.079)\pi\ \mu^n\ \gamma^{1-n}}{2g^{1-n}} (\sec\ \alpha)^{1-n}_{L32} \int_{R_{L2}}^{R_{L3}} r \int_{R_{L2}}^{r} \frac{1}{B'} \frac{dP}{dy}\, dy\, dr$$

Eq. (125)

$$f_L(x) = \begin{cases} 0 & , \quad \frac{dx}{dt} \geq 0 \\ \left(\frac{dx}{dt}\right)^2 & , \quad \frac{dx}{dt} < 0 \end{cases}$$ Eq. (126)

The double integral term in Equation (125) is evaluated in Attachment C of this appendix.

The "sec α" terms of Equations (118) and (125) were evaluated at nominal conditions and assumed constant. The square of the velocity Equations (119) and (126) is an approximation of the velocity raised to the power of (2-n) developed in Attachment C. For compressible flow where the gas density and viscosity are low, the squeeze film terms are neglected. The rotational force terms ($F_{H\omega}$) and ($F_{L\omega}$) also are neglected for the compressible case.

c. Load Piston Force

The force on the load piston is given by

$$F_{FP} = A_F P_{FP} + F_{F\omega}$$ Eq. (127)

where

$$A_F = \pi R_{FP}^2$$ Eq. (128)

$$F_{F\omega} = \frac{\pi \gamma FP}{4g} K_{FP}^2 \omega_r^2 R_{FP}^4$$ Eq. (129)

The force term attributable to rotation, $F_{F\omega}$, will be neglected for the compressible flow case where the gas density is low.

8. Piston Motion

A diagram of the piston and its supports is shown on Figures No. C-1 and No. C-2. The positive displacement of the piston is in the direction which would result from an increase in load piston pressure which is to the right in Figures No. C-1 and No. C-2. Piston motion is described by

$$F_{FP} + F_L - F_H = M\ddot{X} + B\dot{x} + Kx$$ Eq. (130)

9. Analog Computer Simulation

The following discussions describe the electronic analog computer simulations of the thrust balancer mathematical models developed in the previous sections. The analog computing equipment used in this study consisted of a PACE Model 24-D and a PACE Model 131-R with 120 and 60 operational amplifiers, respectively. The series flow balancer was completely simulated on the Model 24-D computer, while both computers were required for the more complex parallel flow system. A discussion of analog computing techniques is given by Johnson(3).

Although the incompressible and compressible models are very similar, both were simulated separately to make the most efficient use of the computing equipment. Therefore, four separate simulations were required for all of the balancer configurations. All four simulations are composed of similar basic elements or blocks and a complete description of each simulation would be redundant. The computer simulation of the incompressible parallel flow model was selected to be described in depth while only the different or special features of the other simulations are discussed. However, the schematics of all four simulations are included in this appendix.

a. Parallel Flow Balancer - Incompressible Flow

Simulation diagrams for the incompressible parallel flow balancer are given as Figures No. C-5 through No. C-16. Each major section of the simulation is labeled as to the element of the thrust balancer model which it represents. The following paragraphs explain each section of the simulation.

Simulation diagrams of the inlet and return lines are shown on Figures No. C-5 and No. C-6. Each line is simulated as two lumped-parameter sections. The length of line that each lumped-parameter section represents is approximately equal to one-sixth a wave-length at the maximum frequency of interest. With a maximum frequency of interest of 1000 cps, two lumped sections represent a total line length of approximately 20-in. for the water flow case and 4-in. for the gaseous nitrogen flow case.

From the lines, flow passes through the inlet orifice into the piston cavity. The simulation section which represents these elements for the high-pressure and low-pressure side of the piston are shown on Figures No. C-7 and No. C-8, respectively. These figures also include the summation of force components to obtain the total force on each side of the piston.

The simulation of the outward flow through the outer radial orifice on the high-pressure side of the piston is shown on Figure No. C-9. The pressure drop through the radial orifice is obtained as a function of both the weight flow and piston gap as described in Attachment B of this appendix. The function of weight flow is obtained from a second order polynomial involving weight flow while the sill gap function is obtained from a third order polynomial for the inverse of the sill gap. Although the functions also could have been obtained from a function generator, the polynomial method of function generations was selected to facilitate parameter changes.

(3) Johnson, C. L., Analog Computer Techniques, McGraw-Hill, 1956

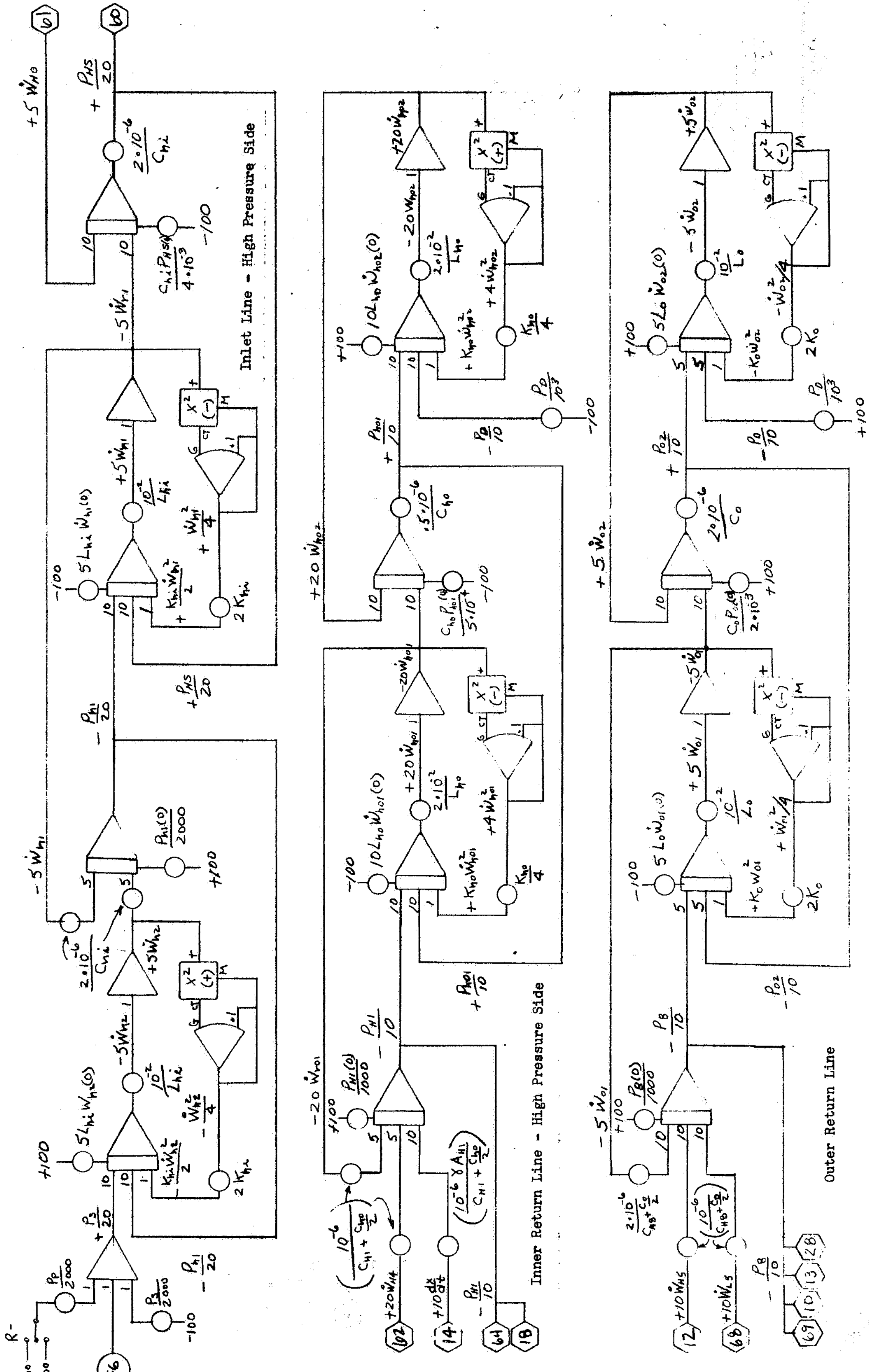

Figure C-5 Incompressible, Parallel Flow Simulation - Balance Piston Lines

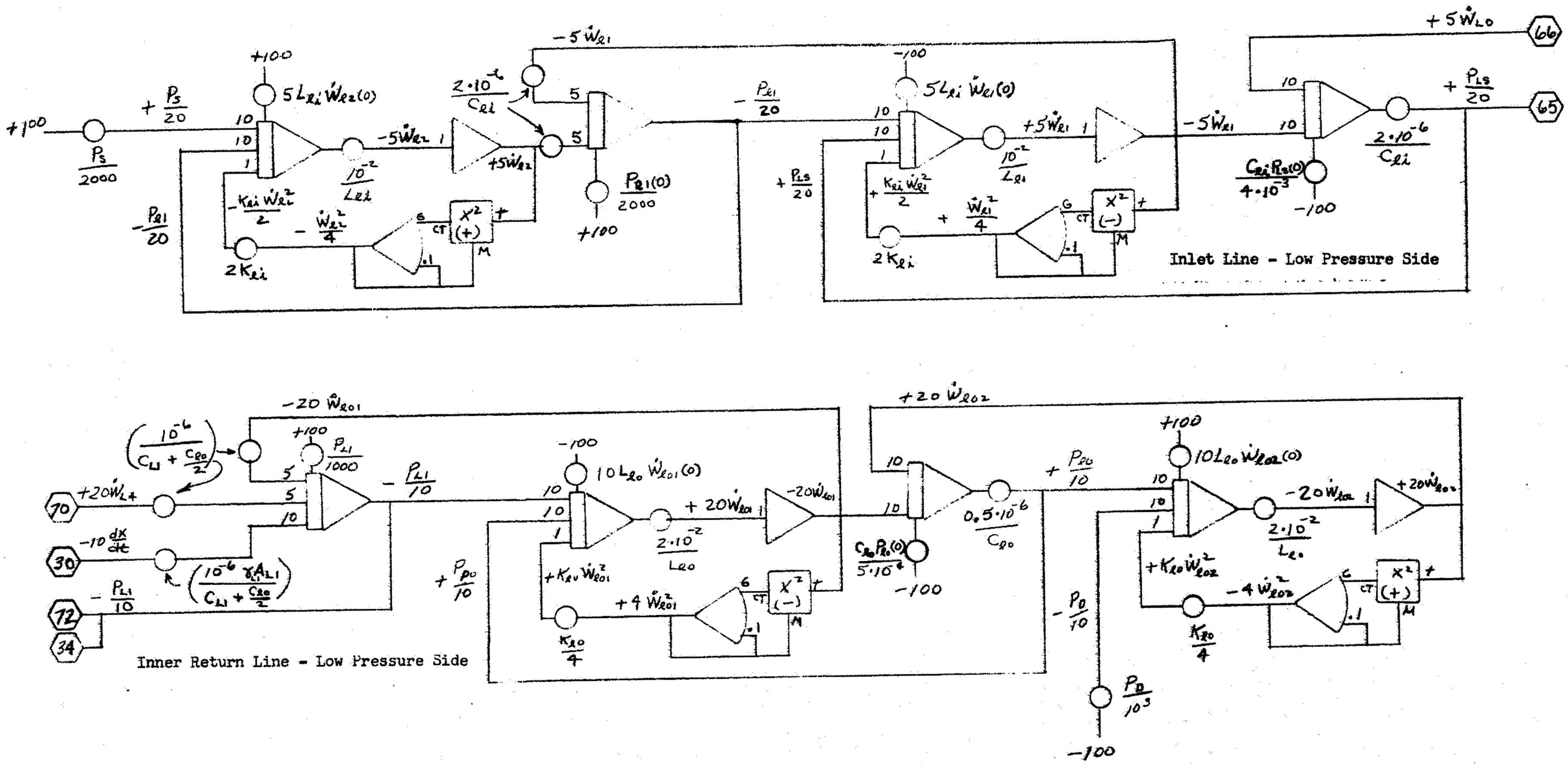

Figure C-6 Incompressible, Parallel Flow Simulation - Balance Piston Lines

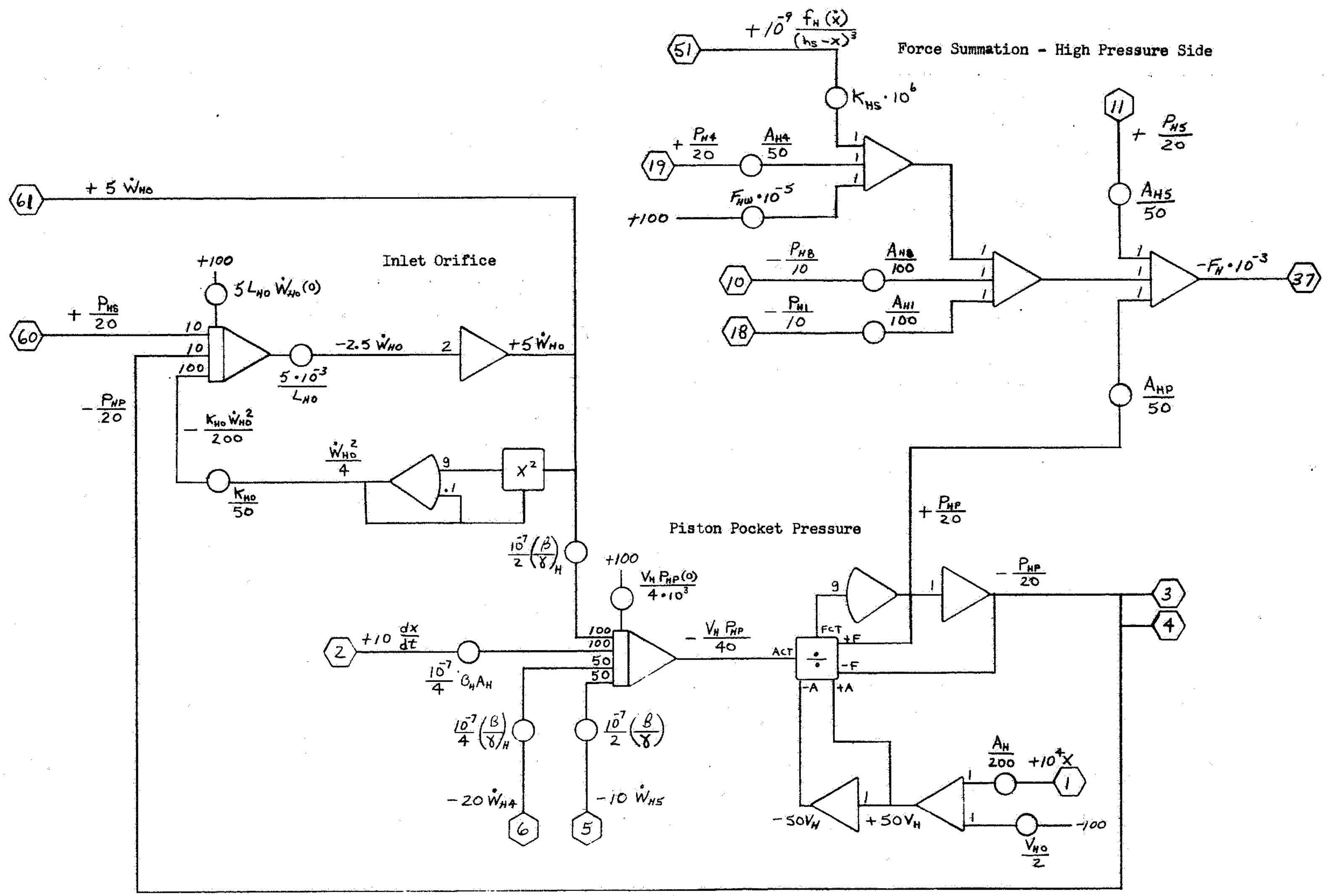

Figure C-7 Incompressible, Parallel Flow Simulation - Balance Piston Inlet - High Pressure Side

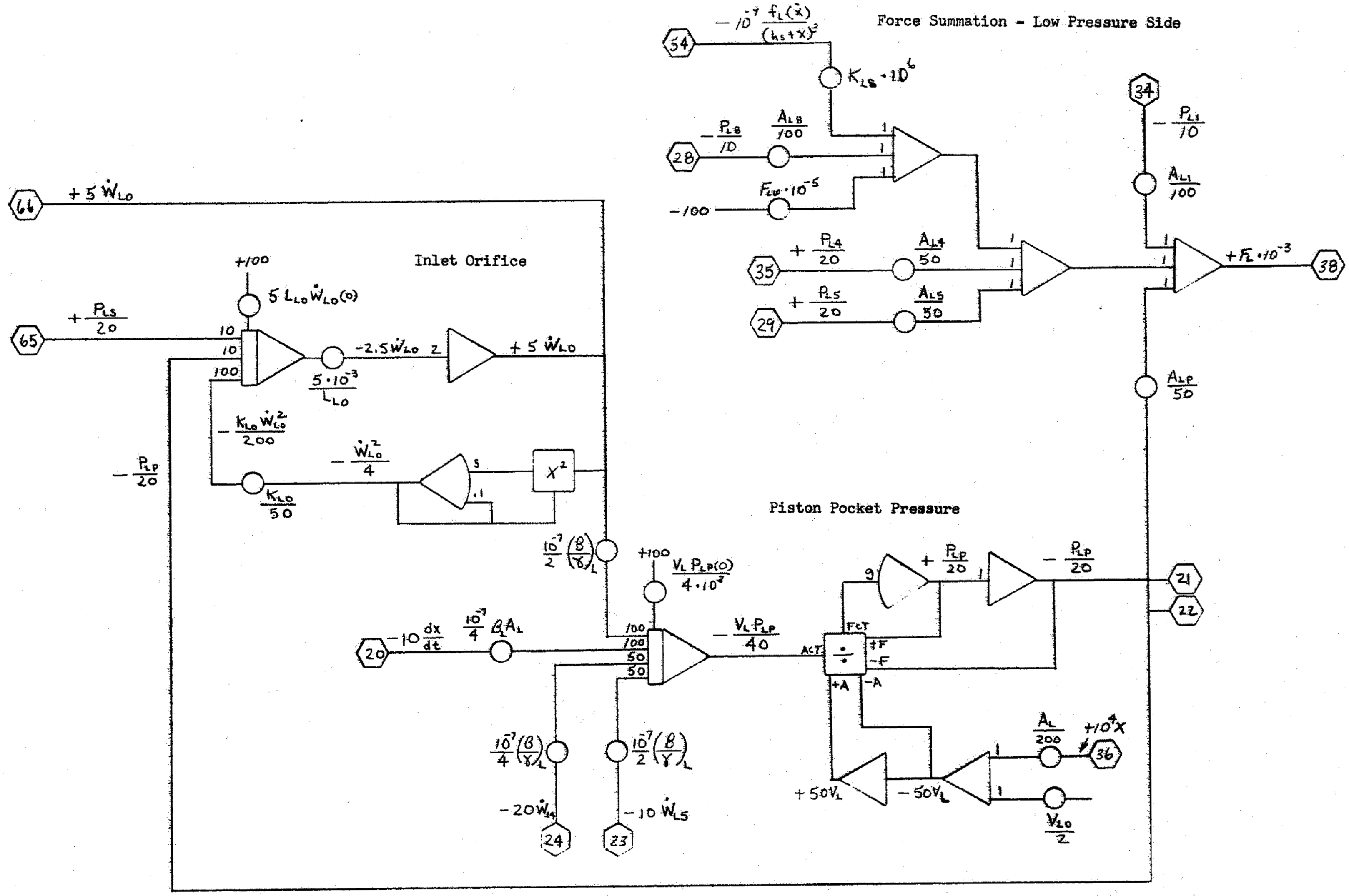

Figure C-8 Incompressible, Parallel Flow Simulation - B lance Piston Inlet - Low Pressure Side

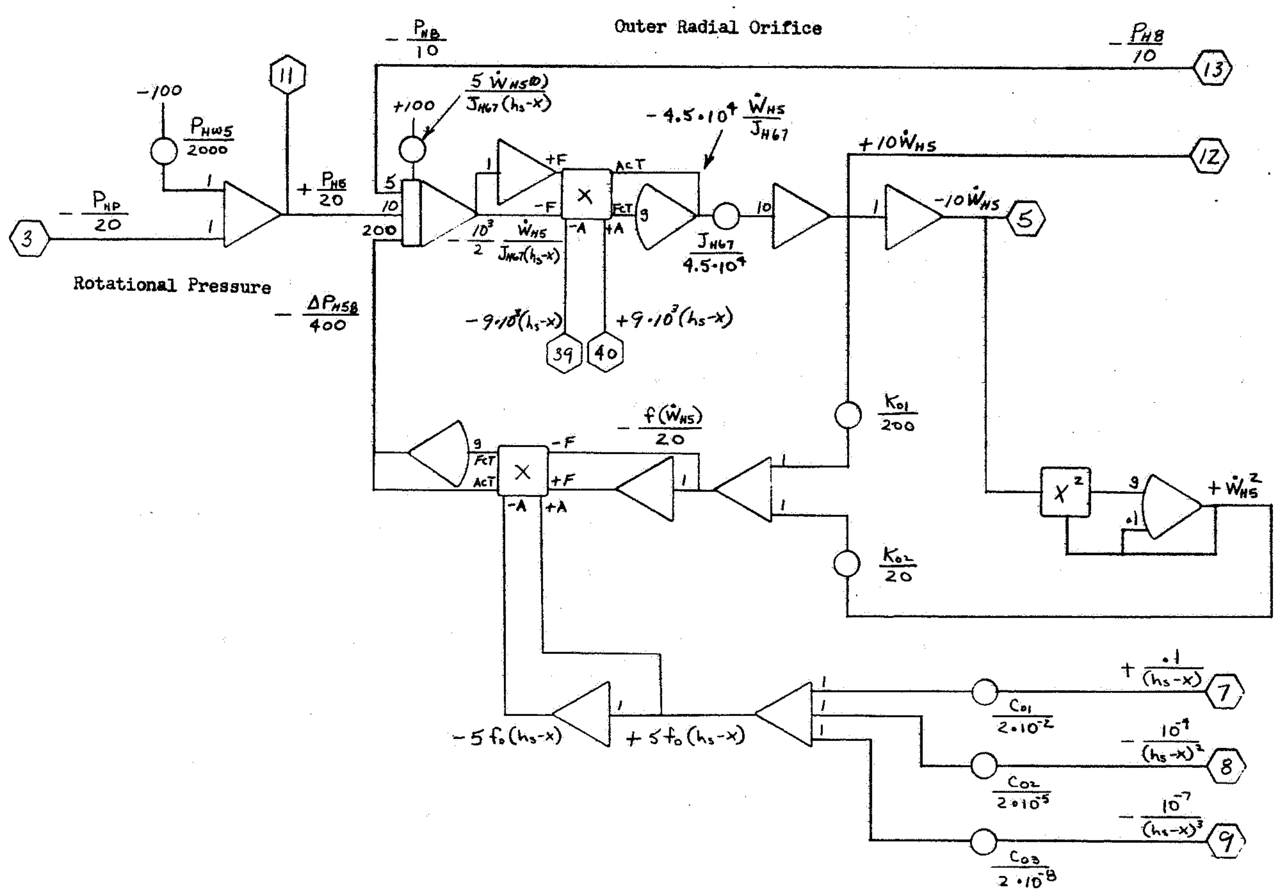

Figure C-9 Incompressible, Parallel Flow Simulation -
Balance Piston Outward Flow-High Pressure Side

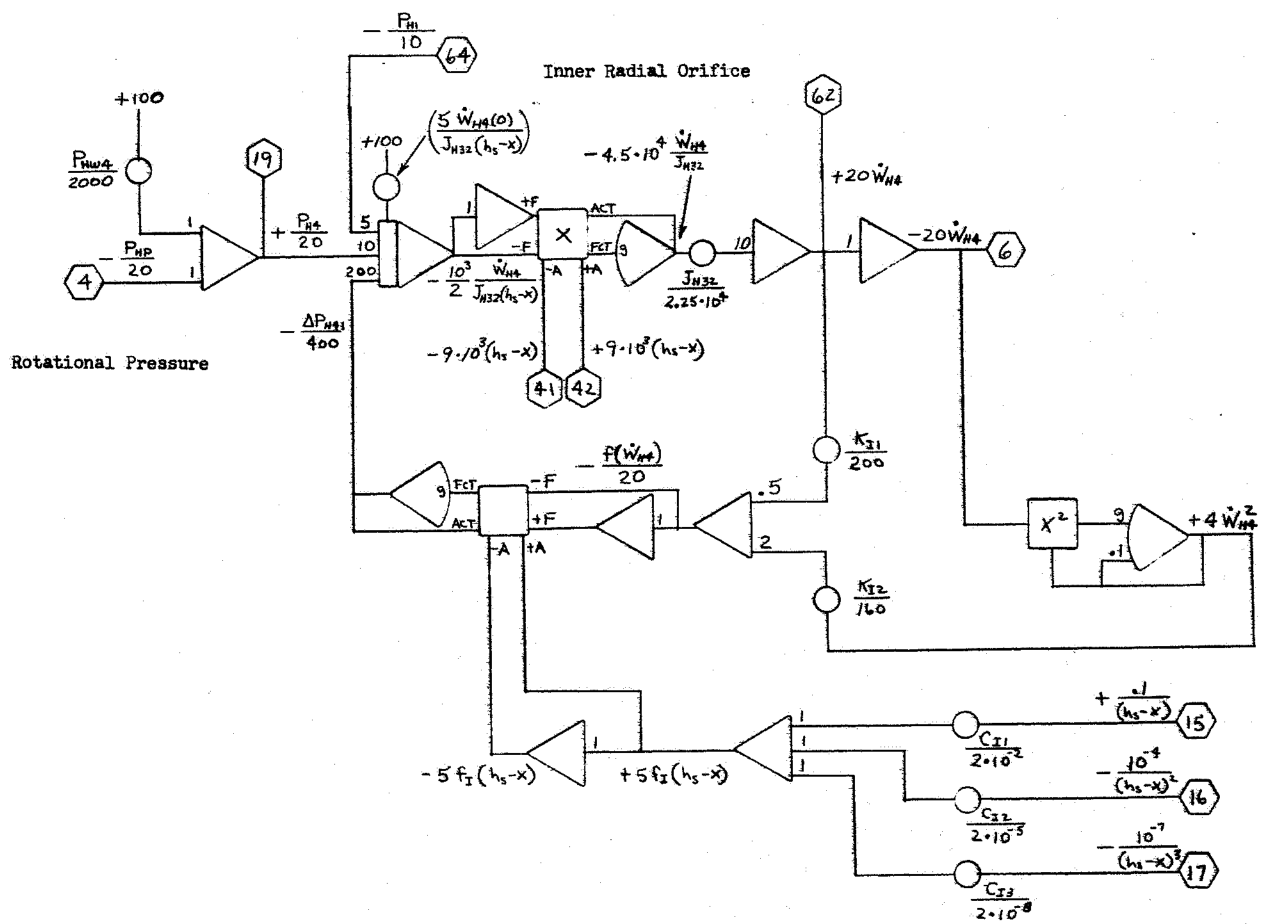

Figure C-10 Incompressible, Parallel Flow Simulation - Balance Piston Inward Flow-High Pressure Side

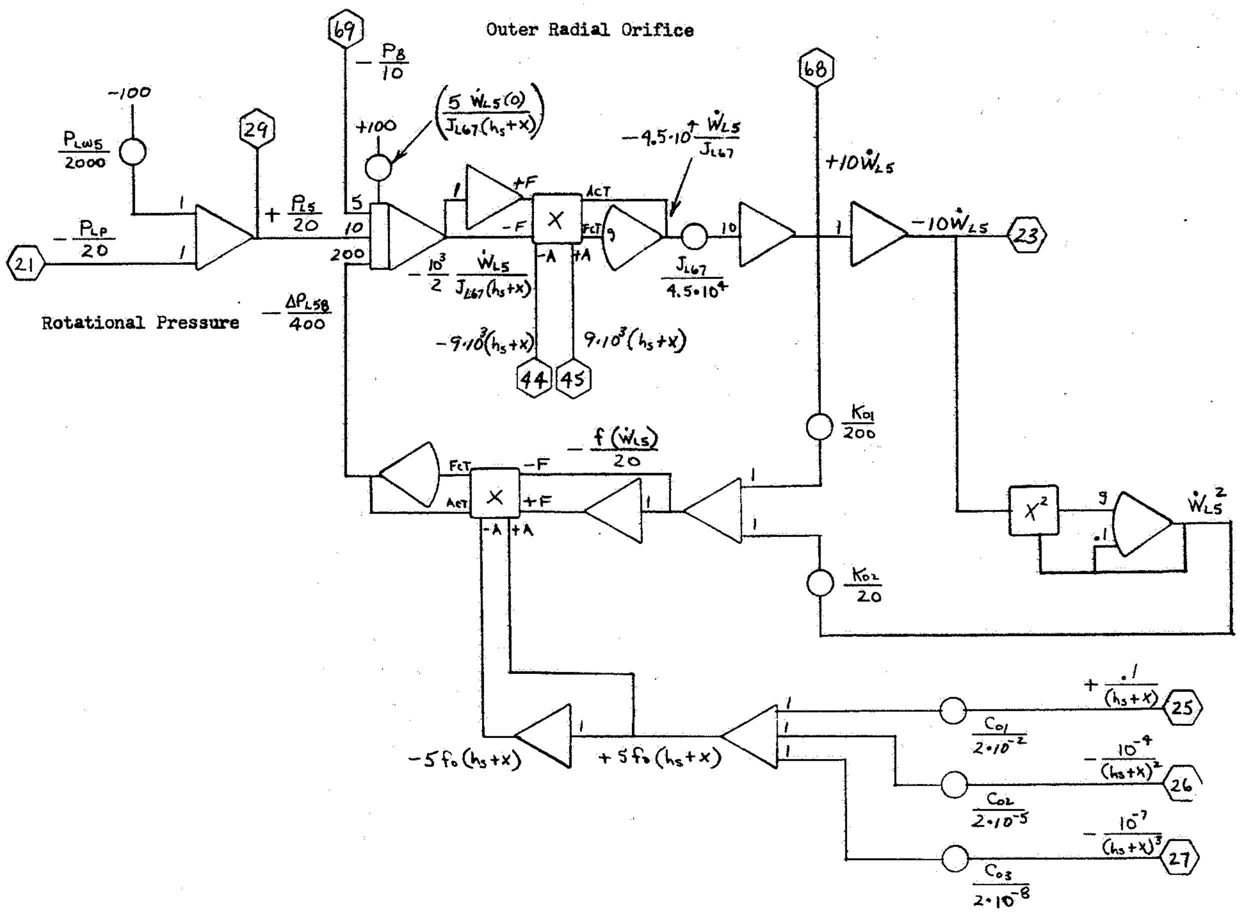

Figure C-11 Incompressible, Parallel Flow Simulation - Balance Piston Outward Flow-Low Pressure Side

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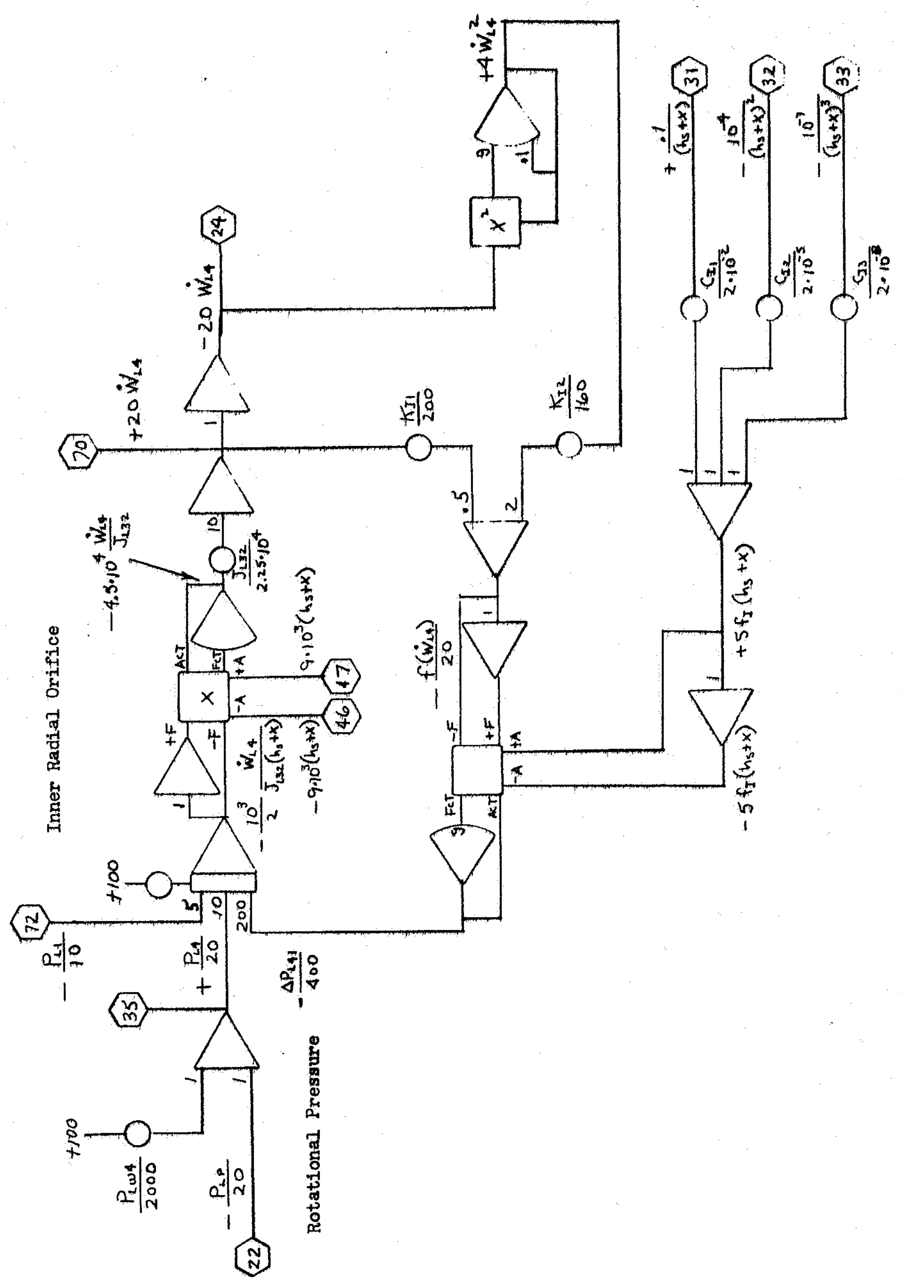
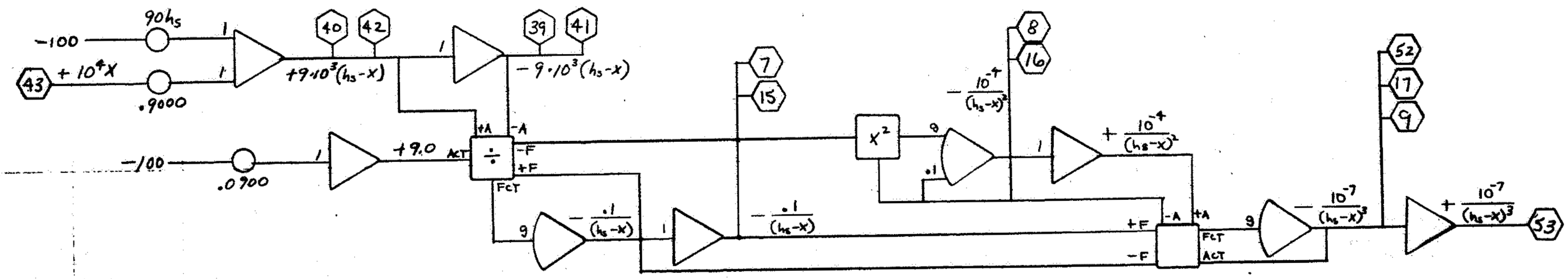


Figure G-12 Incompressible, Parallel Flow Simulation - Balance Piston Inward Flow-Low Pressure Side f(h) Generation - High Pressure Side



f(h) Generation - Low Pressure Side

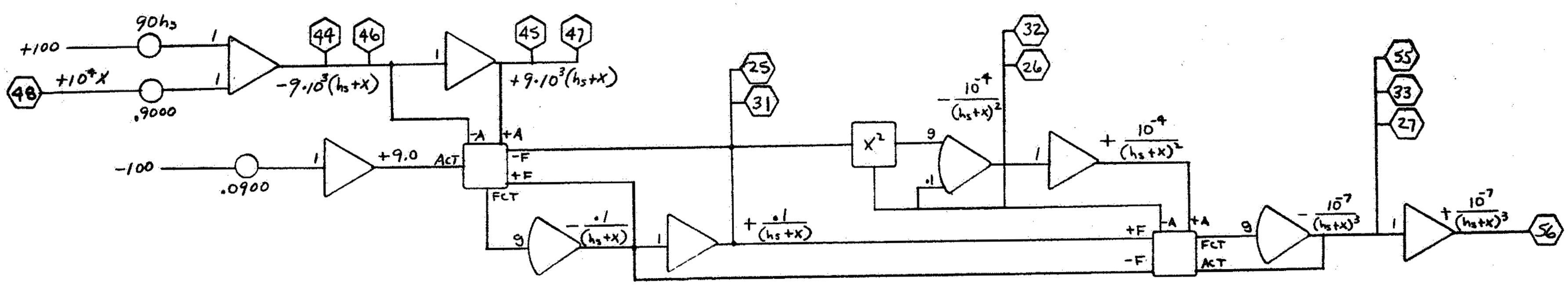


Figure C-13 Incompressible, Parallel Flow Simulation - Sill Gap Functions

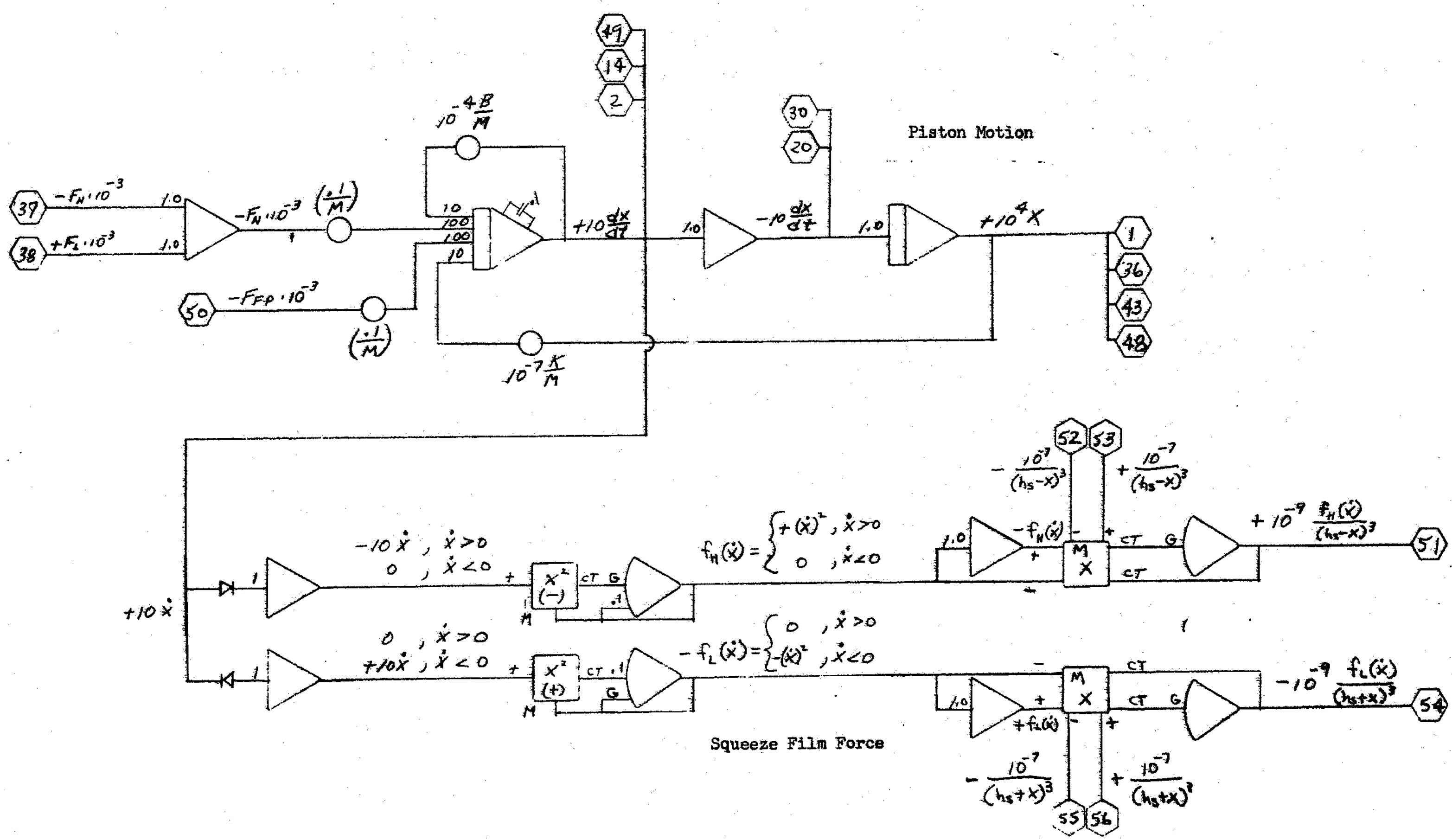


Figure C-14 Incompressible, Parallel Flow Simulation - Piston Motion and Squeeze Film Force

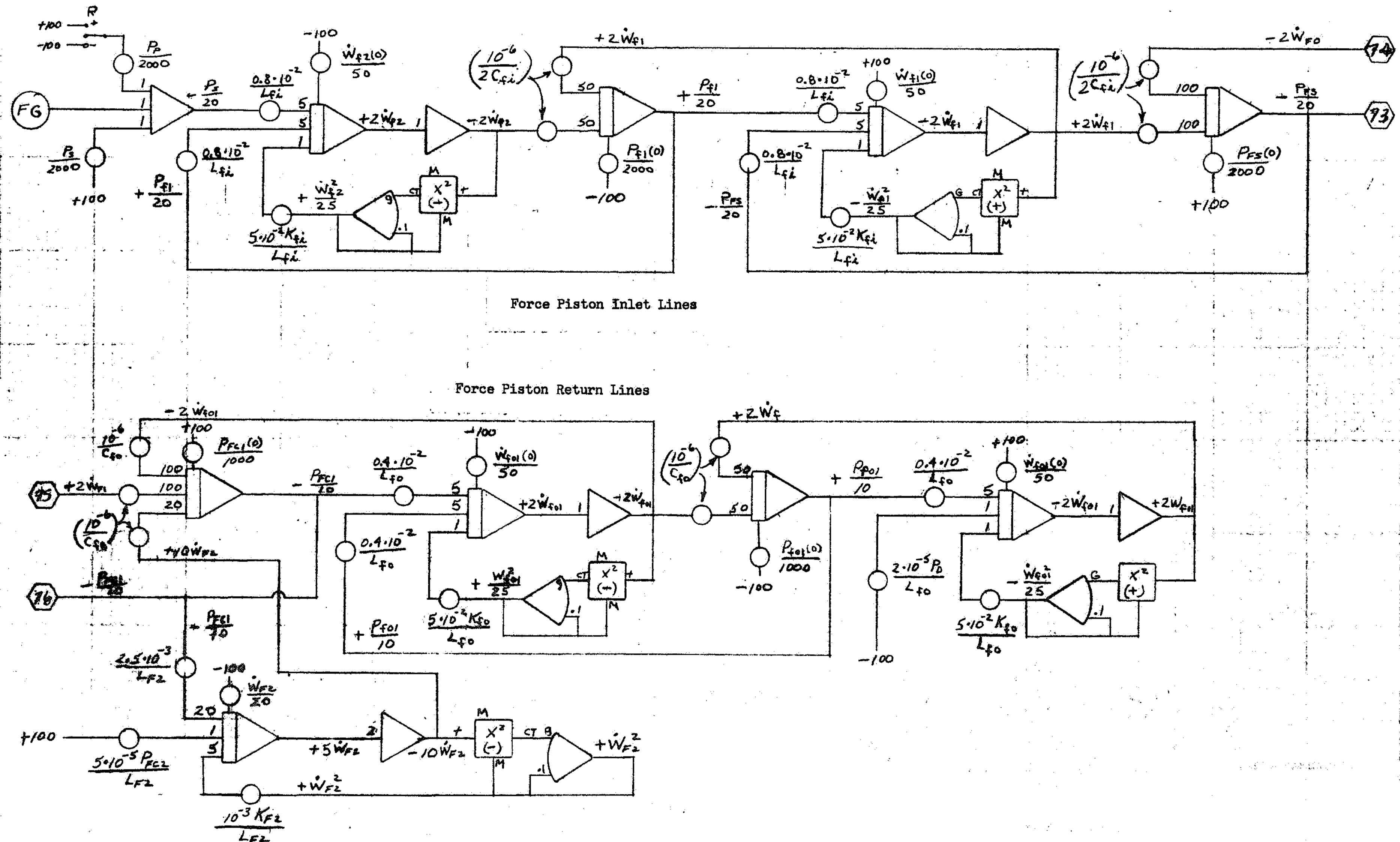


Figure C-15 Incompressible, Parallel Flow Simulation - Force Piston Lines

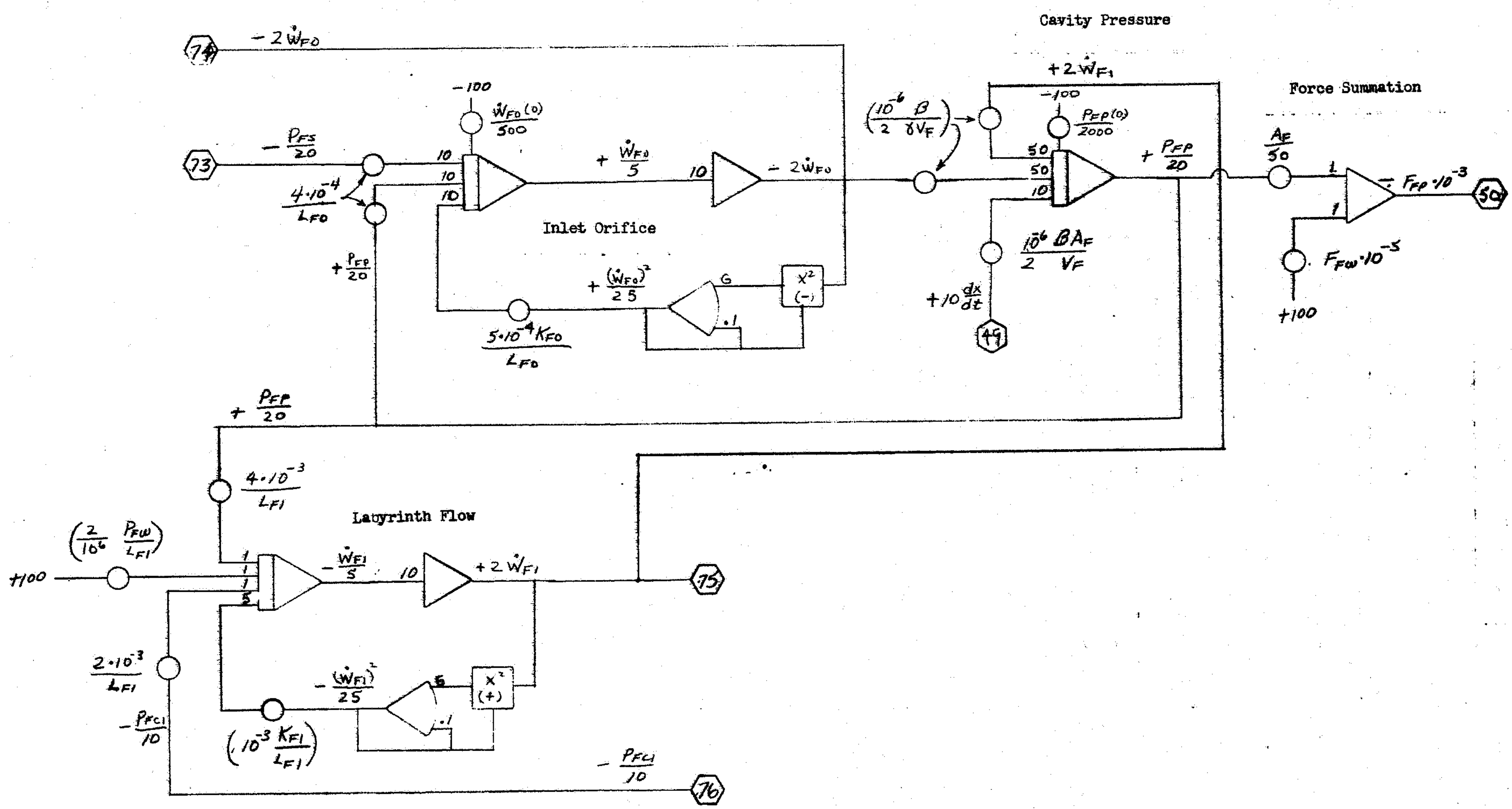


Figure G-16 Incompressible, Parallel Flow Simulation - Force Piston Flow Circuit

The simulations which describe the flow through the other radial orifices are similar to that described for the high-pressure outer orifice. The simulation schematics are shown on Figures No. C-10 through No. C-12.

The simulation section shown on Figure No. C-13 generates the first, second, and third power of the inverse of the sill gap for each side of the piston. These values are used in the generation of the radial orifice characteristics and the squeeze film forces.

The mechanical characteristics of the piston and its supports are represented by a portion of the simulation shown on Figure No. C-14. The spring and friction forces are linear functions of displacement and velocity.

The simulation of the equations which describe the forces resulting from squeeze film effects also is shown on Figure No. C-14. The force is simulated as a nonlinear function of velocity and sill gap.

The inlet and return lines of the force piston circuit are simulated as shown on Figure No. C-15. This simulation is similar to that for the balance piston lines previously described. Simulation of the second labyrinth section of the force piston circuit also is included on Figure No. C-15. The force piston flow circuit from inlet orifice through the first labyrinth is shown on Figure No. C-16.

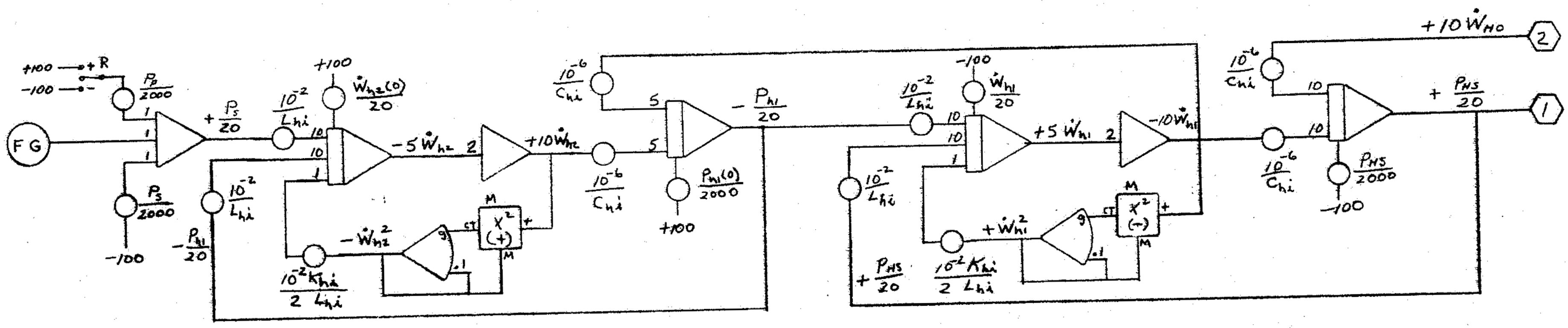
b. Series Flow Balancer - Incompressible Flow

Simulation diagrams for the incompressible series flow balancer are shown on Figures No. C-17 through No. C-24. The simulation of the series flow balancer is very similar to that previously described for the parallel flow case. The principal difference is a rearrangement of the basic elements and a reduction in complexity. The only additional element in the series flow balancer circuit is the flow path around the piston circumference. This element is simulated on Figure No. C-19 so that either an annulus or a labyrinth can be represented.

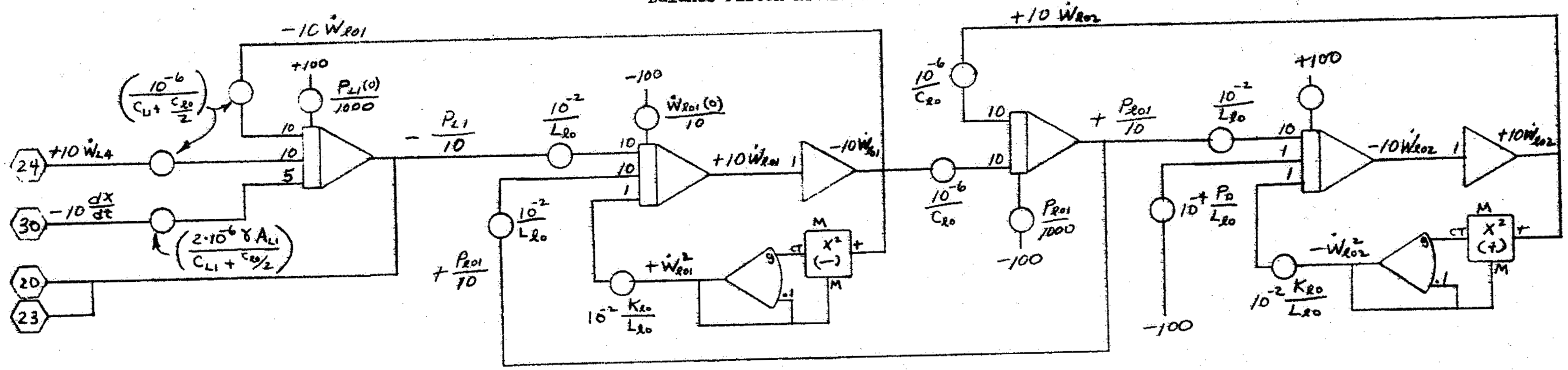
c. Parallel Flow Balancer - Compressible Flow

Simulation diagrams for the compressible parallel flow balancer are shown on Figures No. C-25 through No. C-35. The simulation shown is scaled for the 400 psi to 200 psi pressure range. The principal difference between the simulation of the compressible model and the previously described incompressible model is the addition of variable values of fluid density and bulk modulus.

The simulation of the balance piston inlet and return lines is shown on Figures No. C-25 and No. C-26. The line simulation is



Balance Piston Inlet Lines



Balance Piston Return Lines

Figure C-17 Incompressible, Series Flow Simulation - Balance Piston Lines

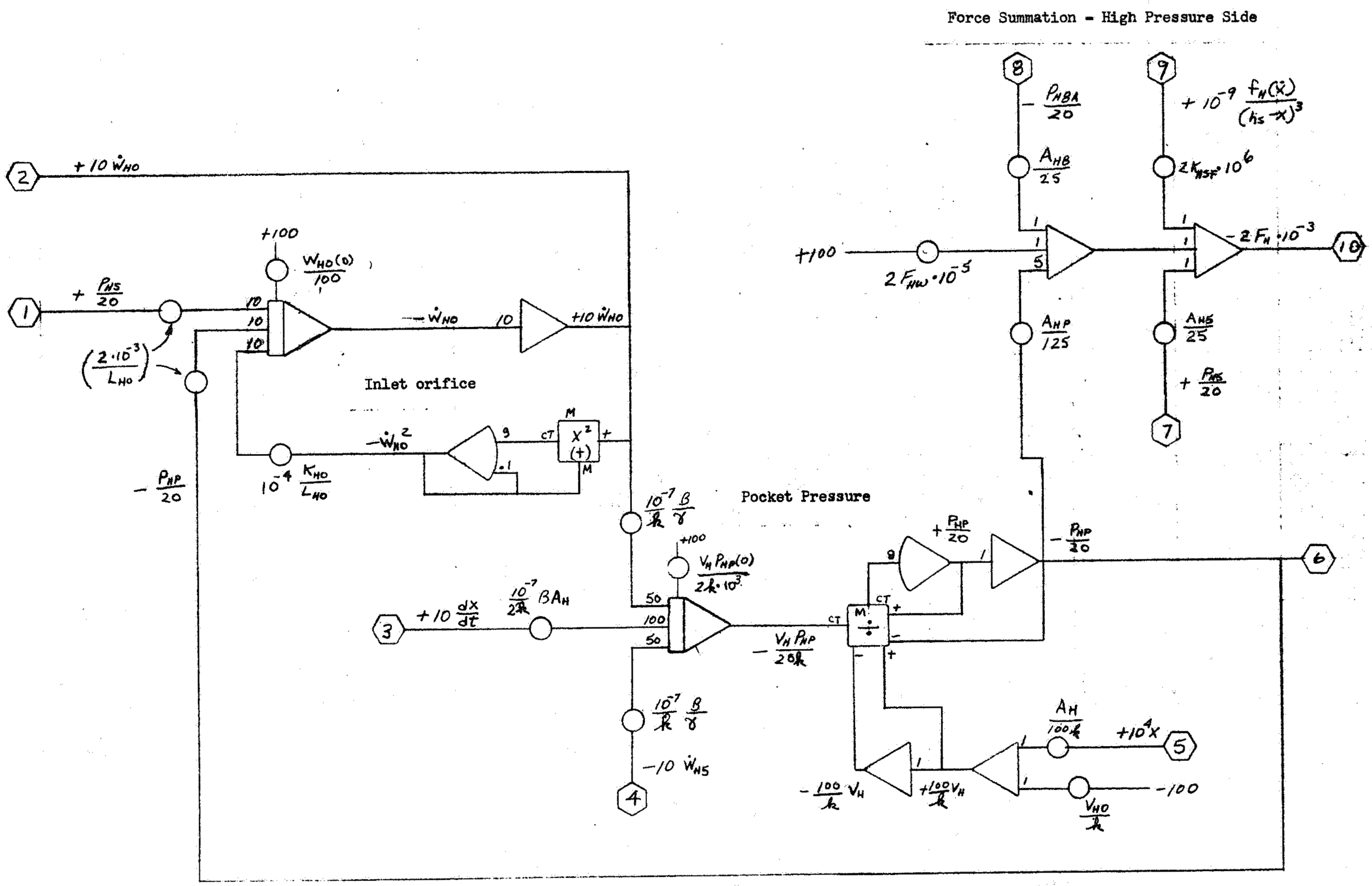


Figure C-18 Incompressible, Series Flow Simulation - Balance Piston Inlet

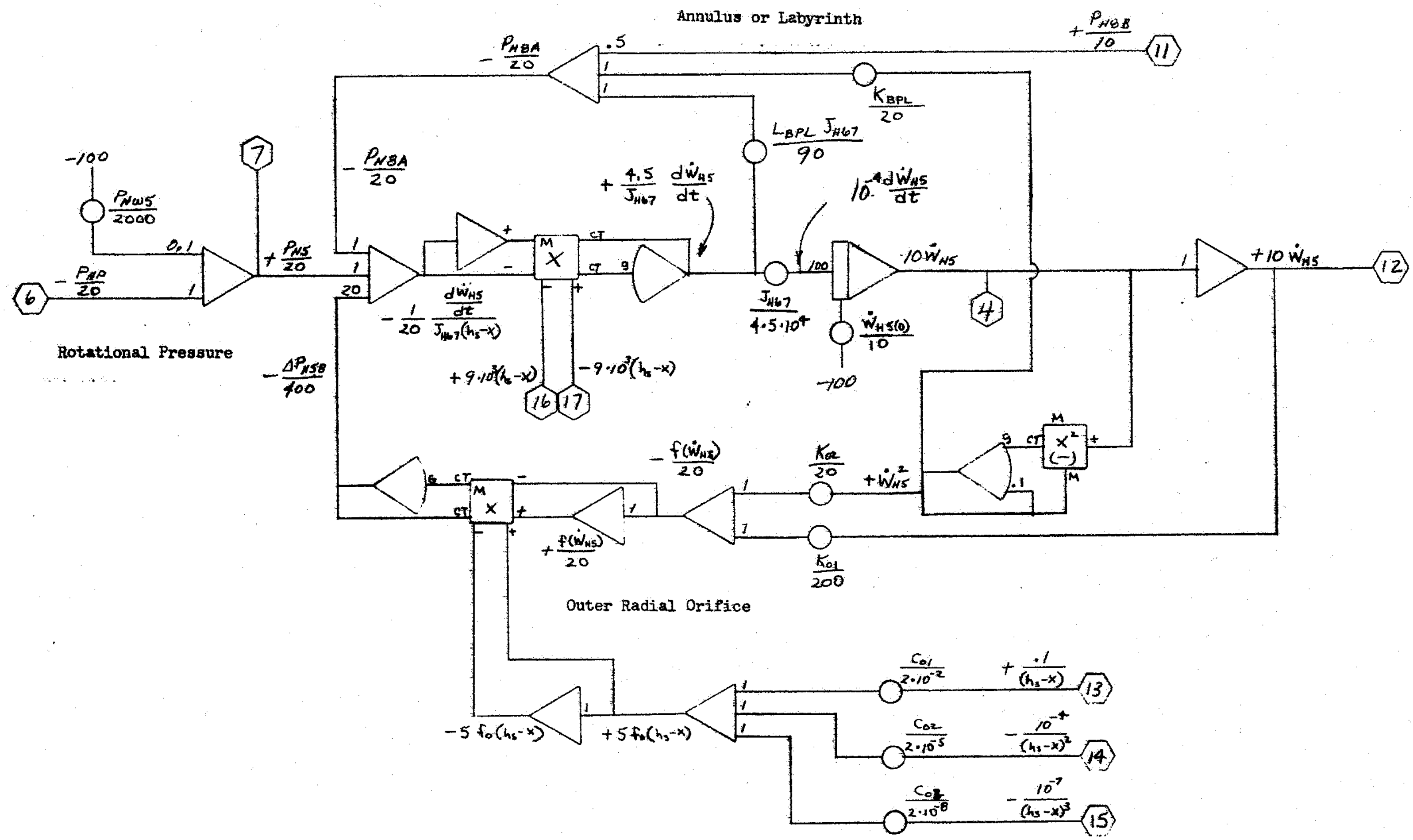


Figure C-19 Incompressible, Series Flow Simulation - Balance Piston Outward Flow-High Pressure Side

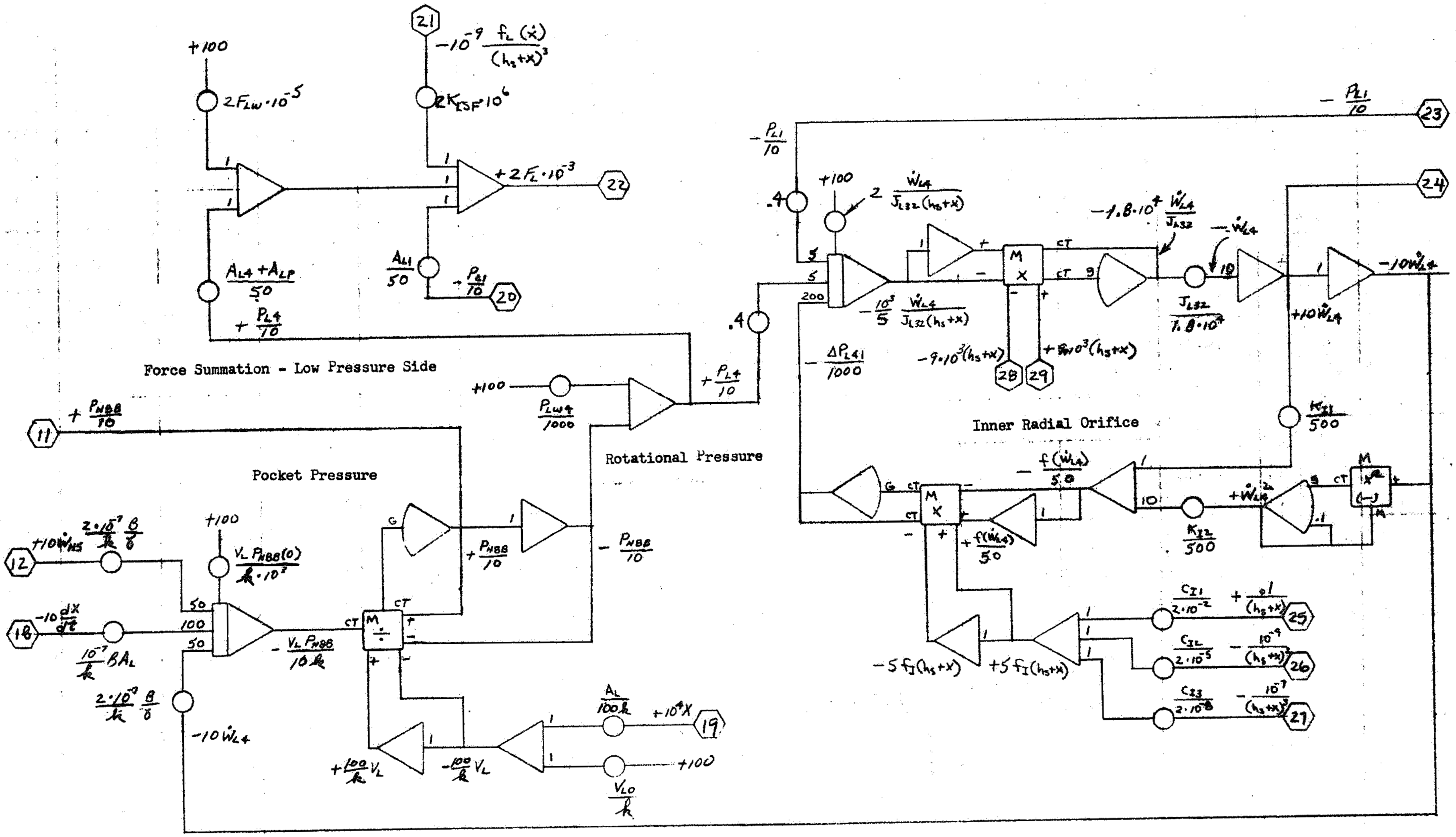
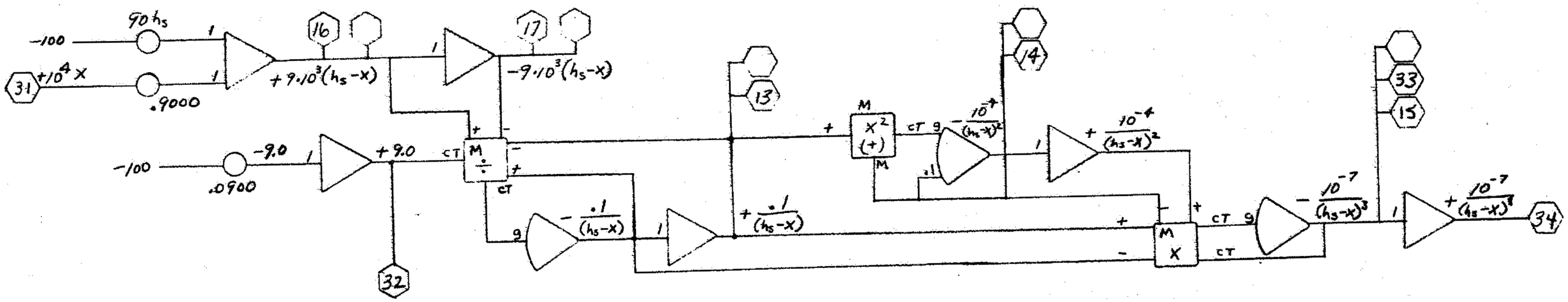


Figure C-20 Incompressible, Series Flow Simulation - Balance Piston Inward Flow-Low Pressure Side



f(h) Generation - High Pressure Side

f(h) Generation - Low Pressure Side

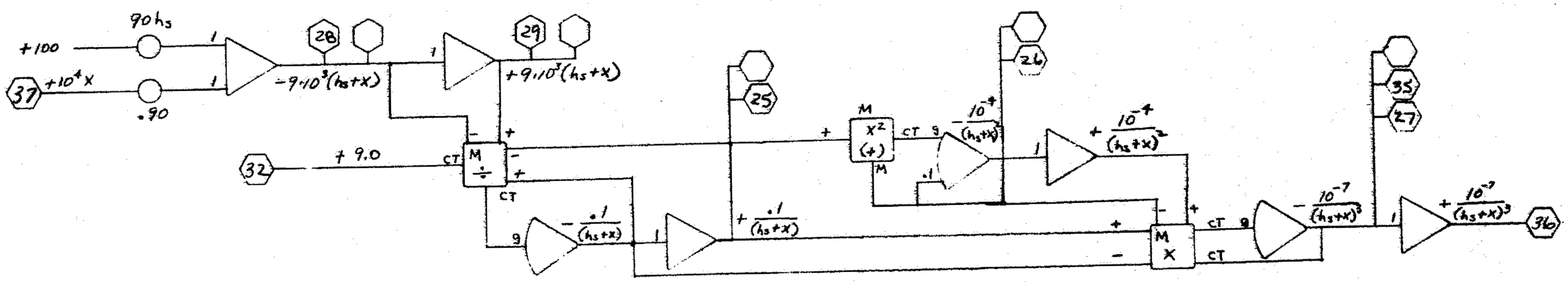


Figure C-21 Incompressible, Series Flow Simulation - Sill Gap Functions

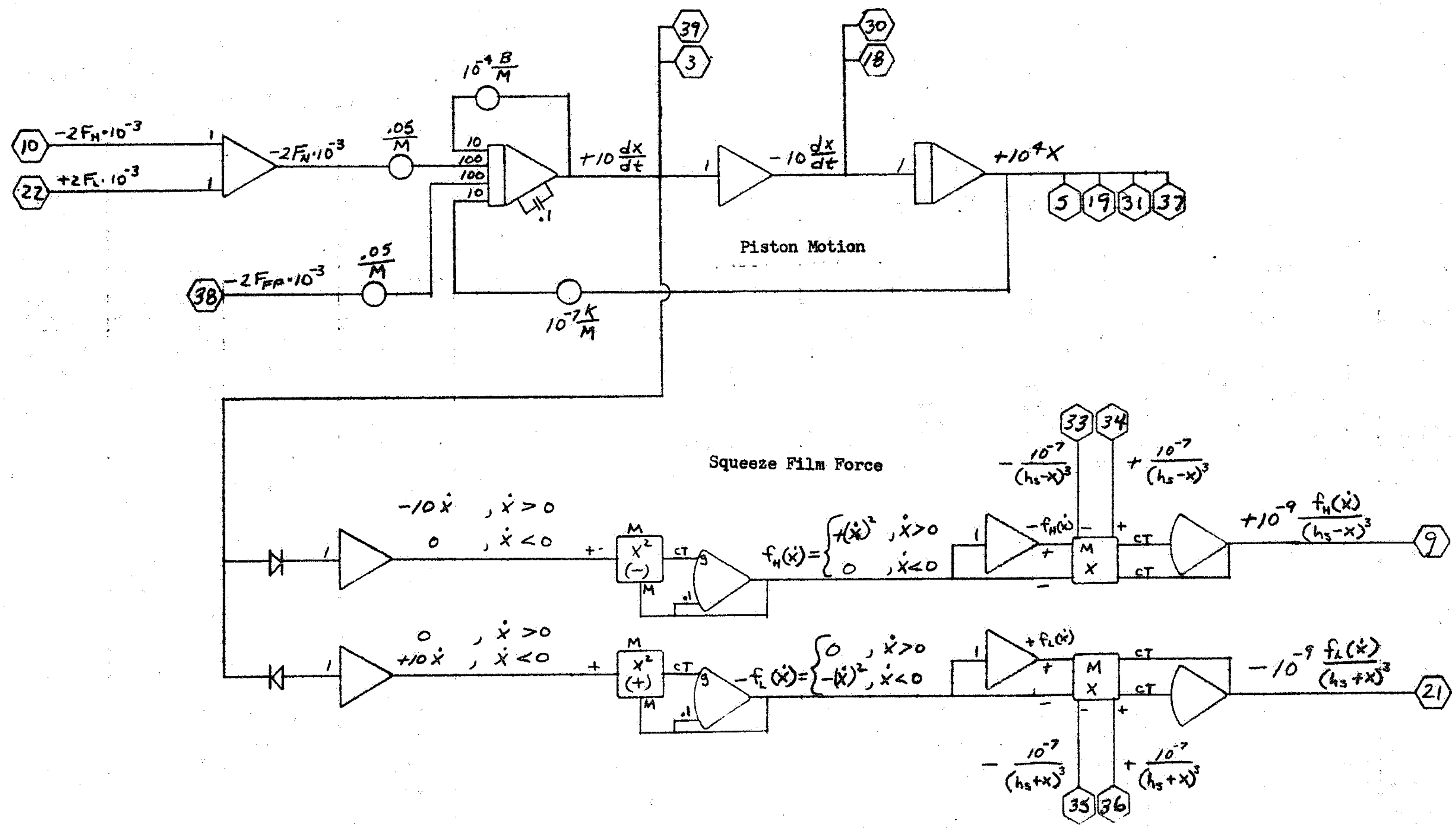
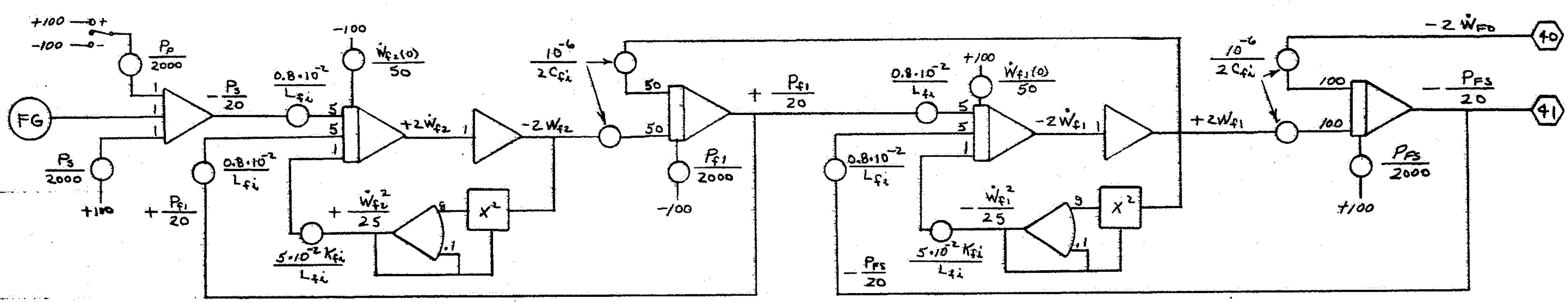


Figure C-22 Incompressible, Series Flow Simulation - Piston Motion and Squeeze Film Force



Force Piston Inlet Line

Force Piston Return Line

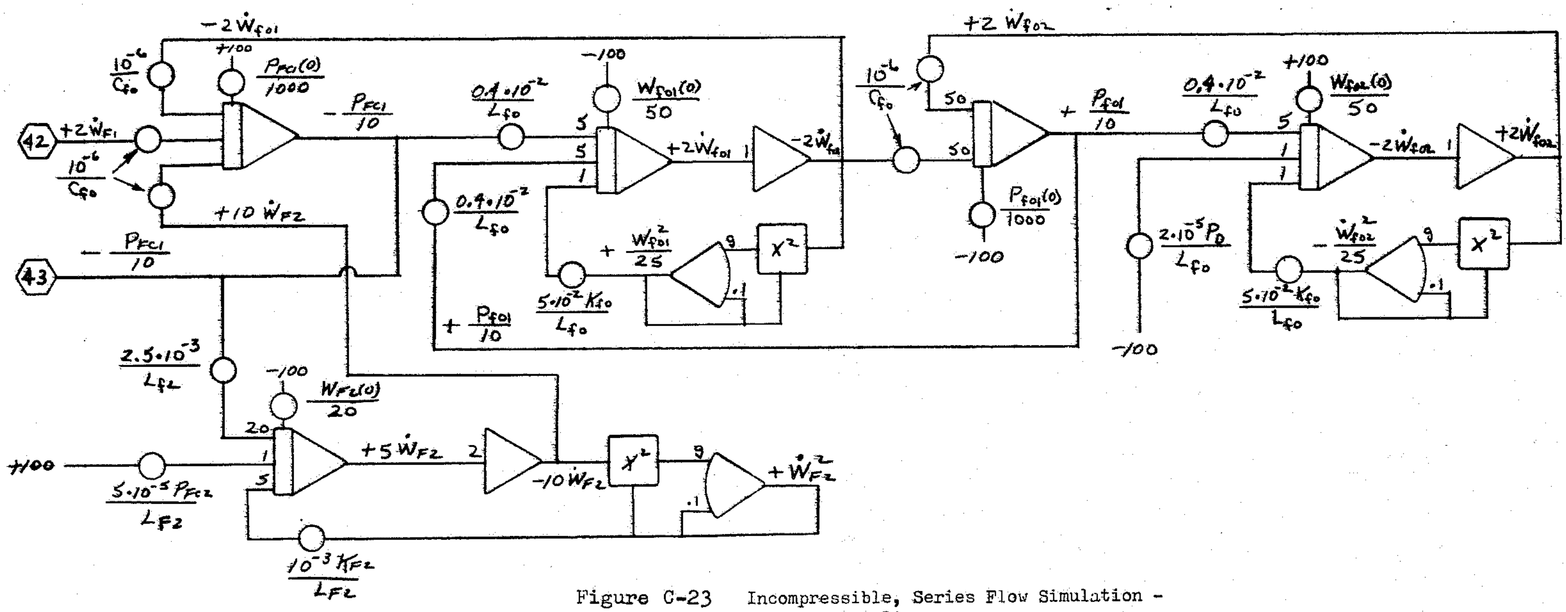


Figure C-23 Incompressible, Series Flow Simulation - Force Piston Lines

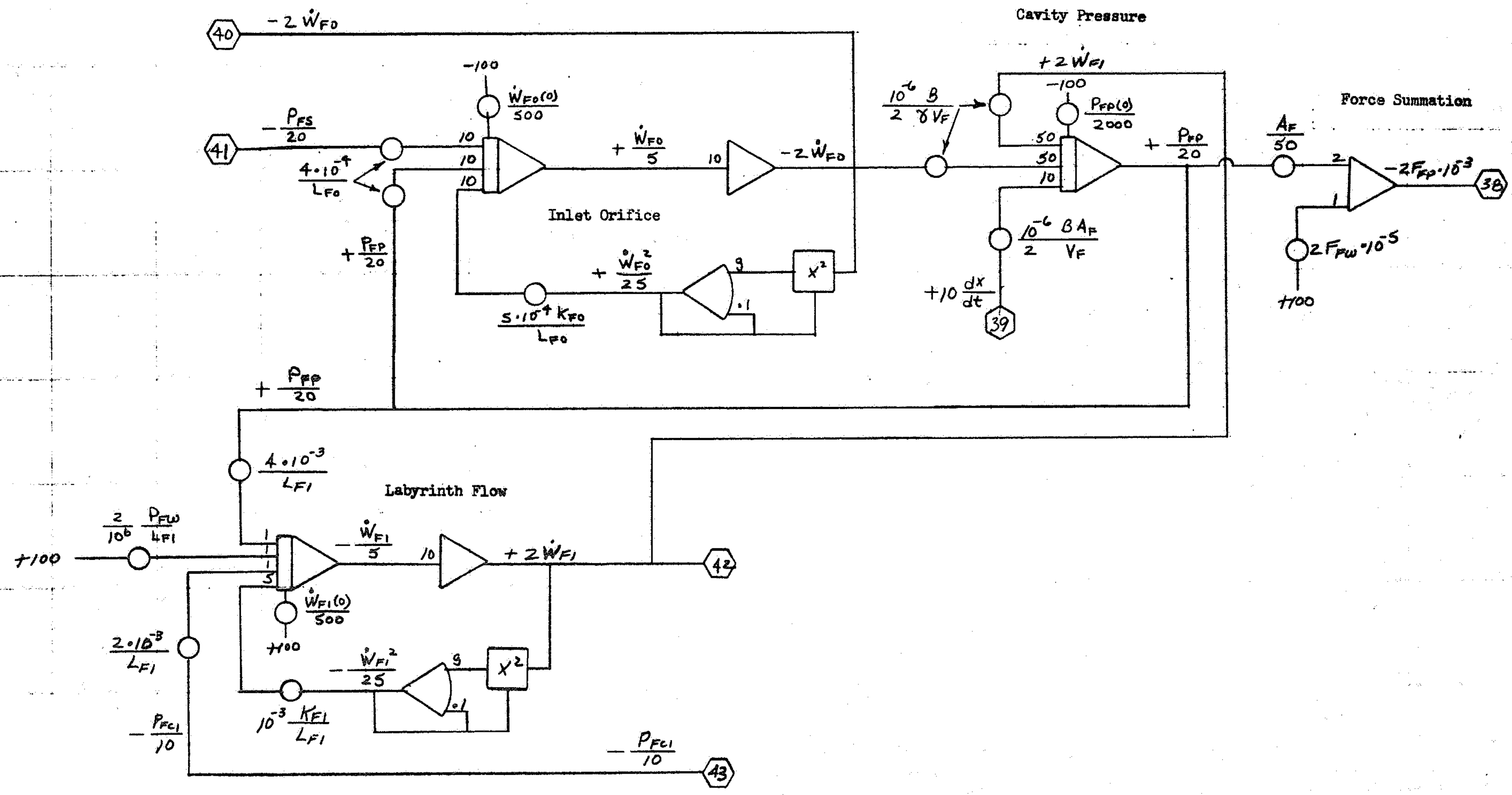
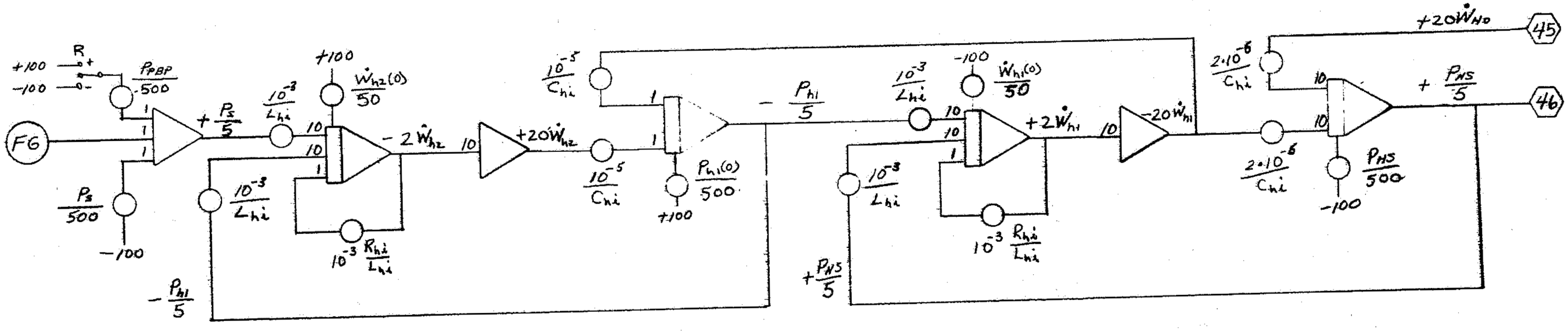


Figure C-24 Incompressible, Series Flow Simulation - Force Piston Flow Circuit



Inlet Lines - High Pressure Side

Inlet Lines - Low Pressure Side

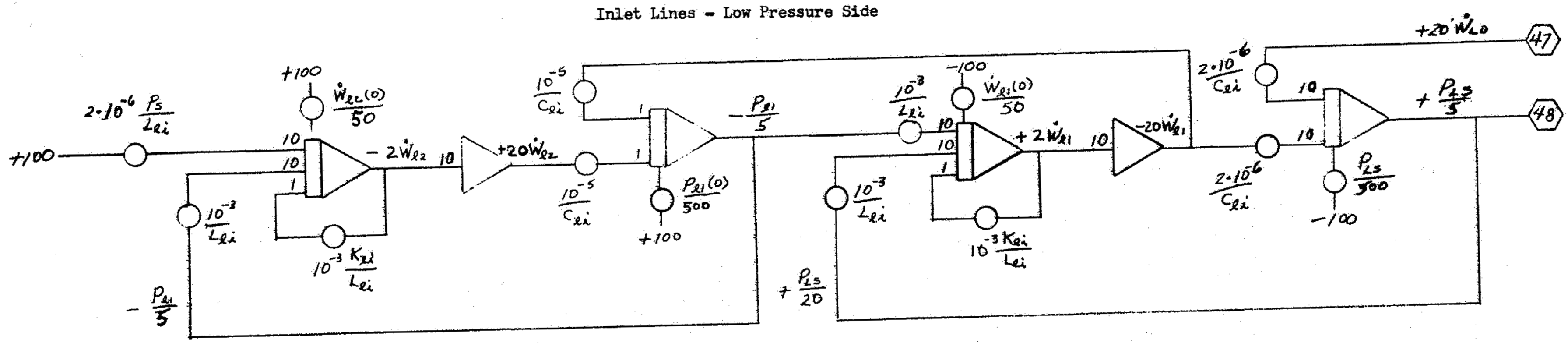


Figure C-25 Compressible, Parallel Flow Simulation - Balance Piston Inlet Lines

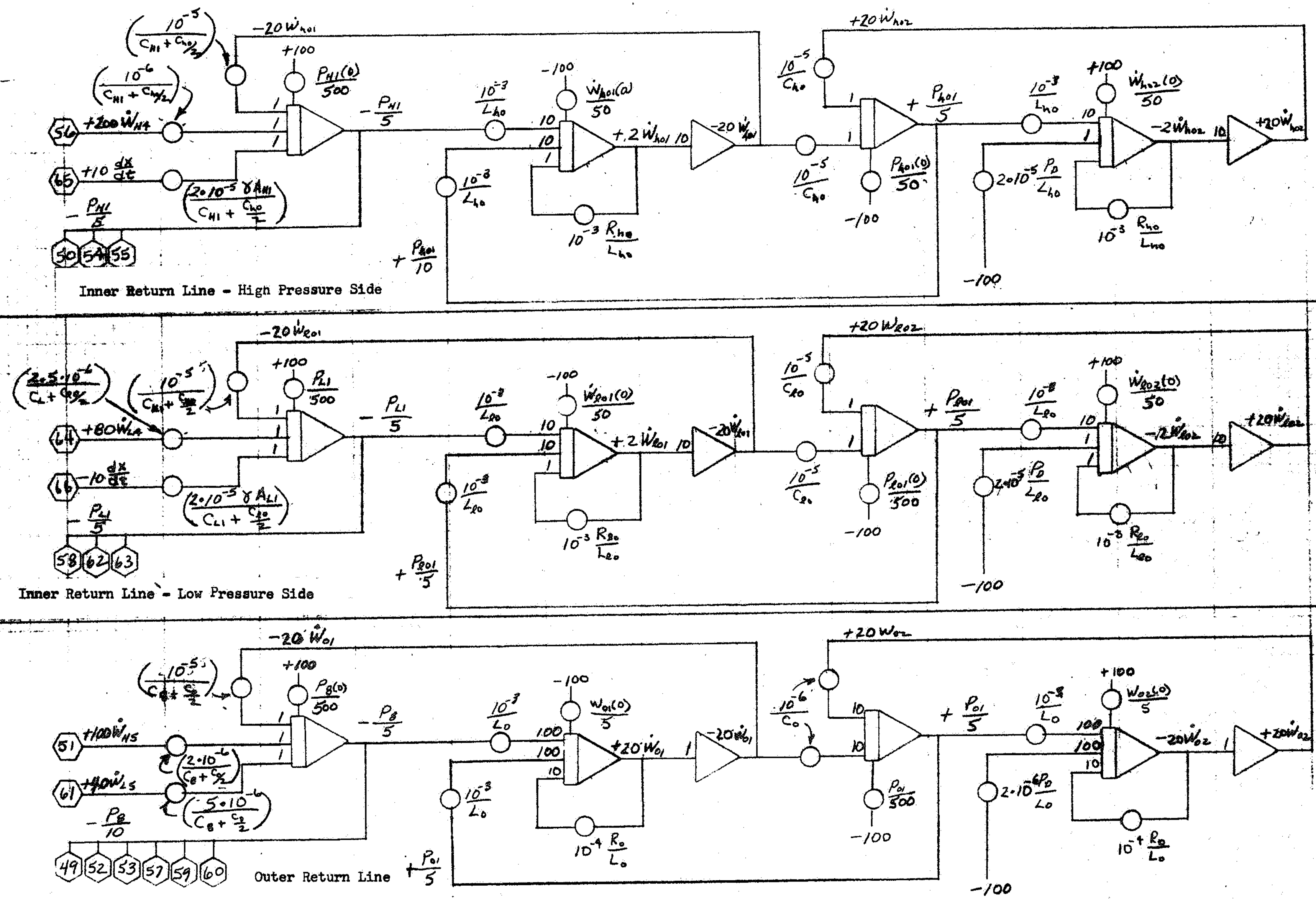


Figure C-26 Compressible, Parallel Flow Simulation - Balance Piston Return Lines similar in form to that for the incompressible case except that the loss term was made a linear function of weight flow. This simplification was made to conserve computing equipment required for the addition of the variable fluid density.

Figures No. C-27 and No. C-28 are the simulation diagrams of the inlet orifice, piston cavity, and the force simulation of the high-pressure and low-pressure sides of the piston, respectively. The orifice pressure drop is a function of a variable fluid density. The ratio of the fluid bulk modulus to density in the cavity also is a variable.

The simulation of the radial orifices is shown in Figures No. C-29 through No. C-32. The orifice pressure loss also is a function of density. The rotational effects of the fluid in the piston pocket are neglected in the compressible case.

The squeeze film effects were not included in the compressible flow simulation.

d. Series Flow Balancer - Compressible Flow

Simulation diagrams for the compressible series flow balancer are shown as Figures No. C-36 through No. C-43. This simulation is a rearrangement of the basic sections of the parallel compressible simulation.

10. <u>Linearized Digital Computer Analysis</u>

Although the system dynamic study was conducted on the analog computer, it was considered prudent to verify the predicted dynamic behavior by means of a digital computer program. Aerojet-General Computer Program E32205 computes the Eigenvalues, λ, and the sensitivity is defined by $\frac{\partial \lambda}{\partial A}$. A discussion of this technique is given by Van Ness, et al(4).

The system selected for the application of this dynamic verification was the combination of the load piston circuit, series flow balance piston circuit, and the piston mechanical circuit for compressible flow. Following the system selection, the system equations were reduced to a set of simultaneous, linear, first-order, differential equations which constitute the state vector form. The results of this study are described in the discussion of parametric studies.

a. Load Piston Circuit

The load piston fluid circuit equations for compressible flow were linearized for small perturbations and expressed in the following state vector form.

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(4) Van Ness, J. E., Boyle, J. M., and Imad, E. P., "Sensitivities of Large Multi-Loop Control Systems," <u>IEEE Transactions on Automatic Control</u>, Vol. AC-10, No. 3, July 1965

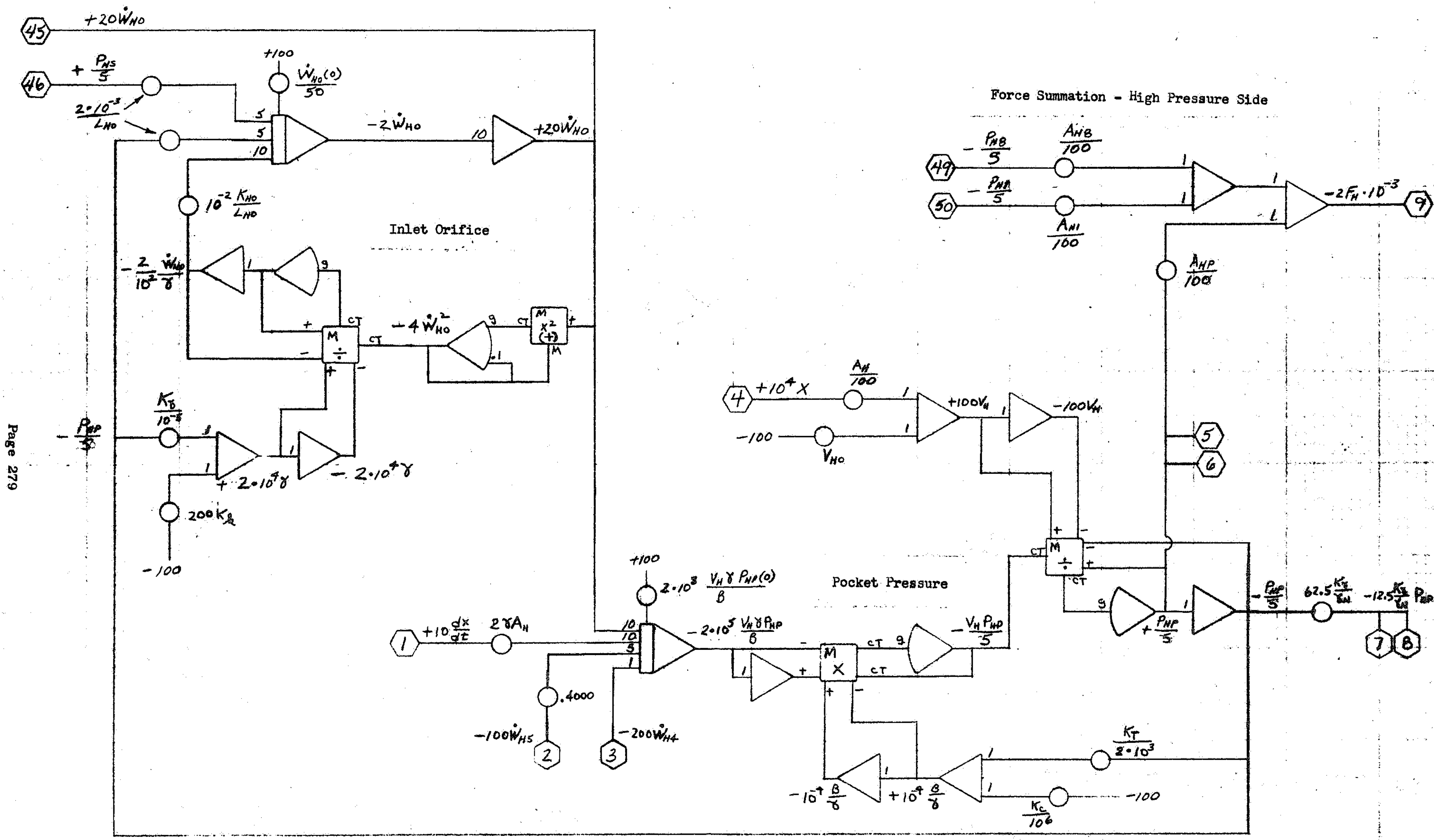

Figure C-27 Compressible, Parallel Flow Simulation - Balance Piston Inlet-High Pressure Side

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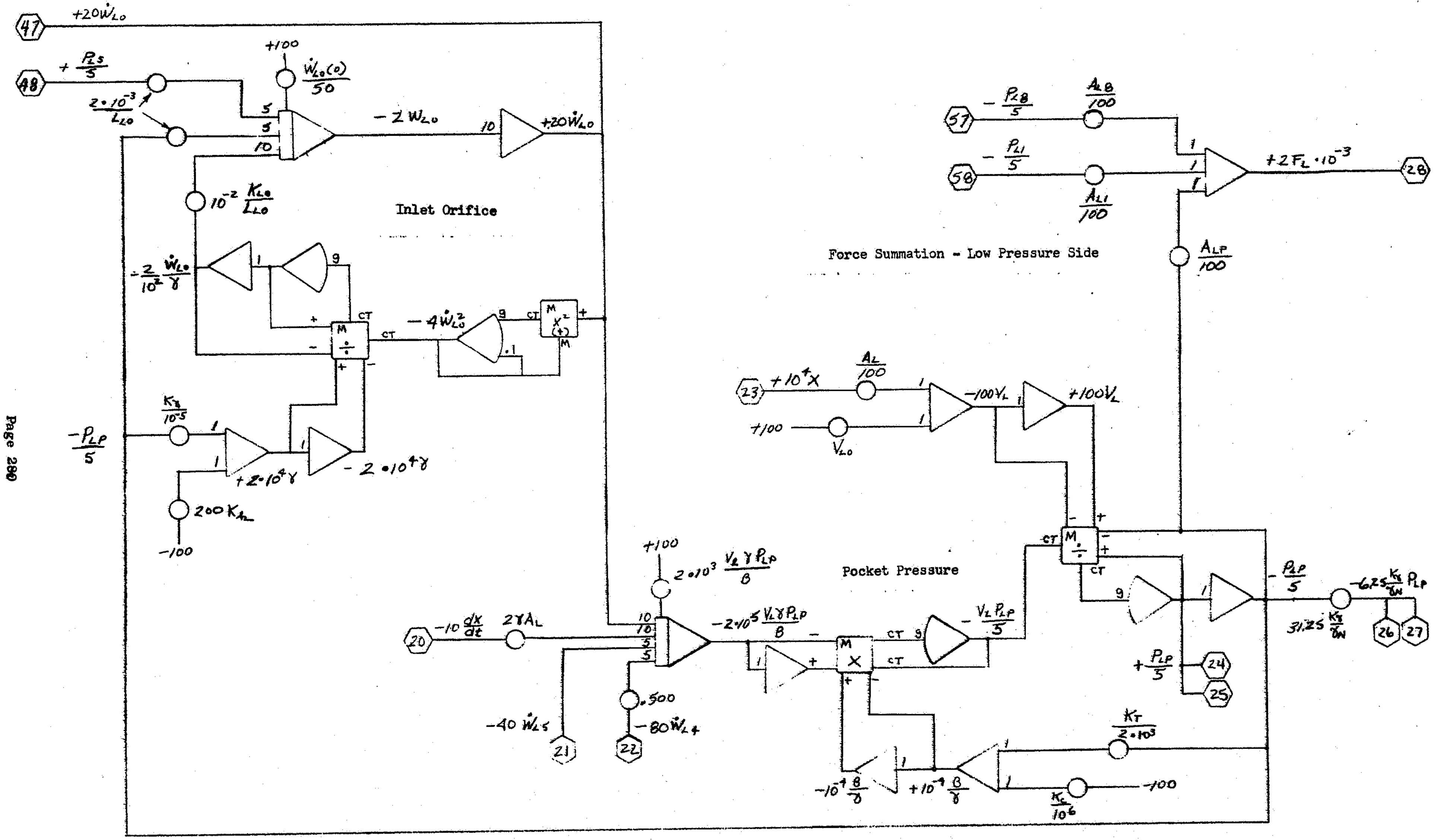


Figure C-28 Compressible, Parallel Flow Simulation - Balance Piston Inlet - Low Pressure Side

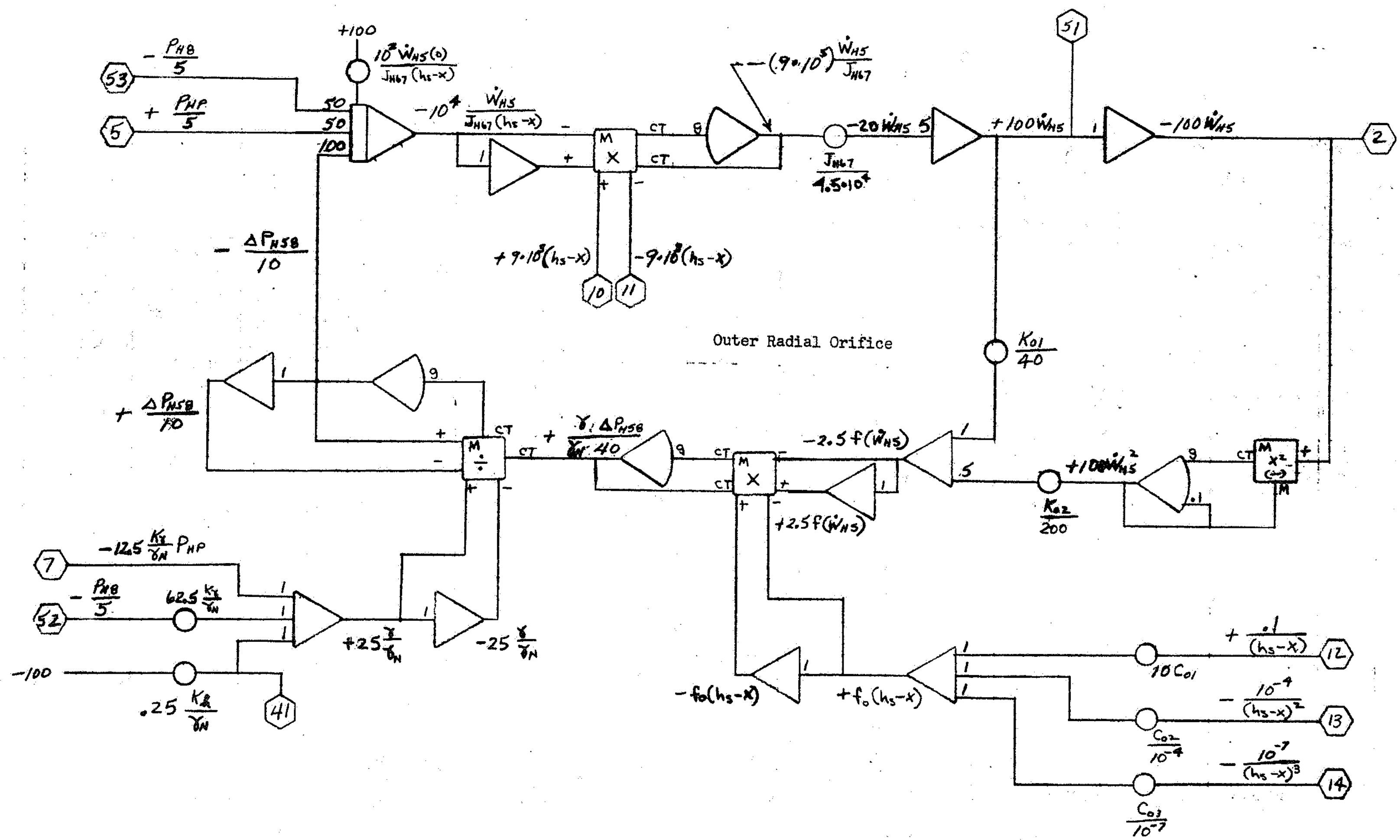


Figure C-29 Compressible, Parallel Flow Simulation - Balance Piston Outward Flow-High Pressure Side

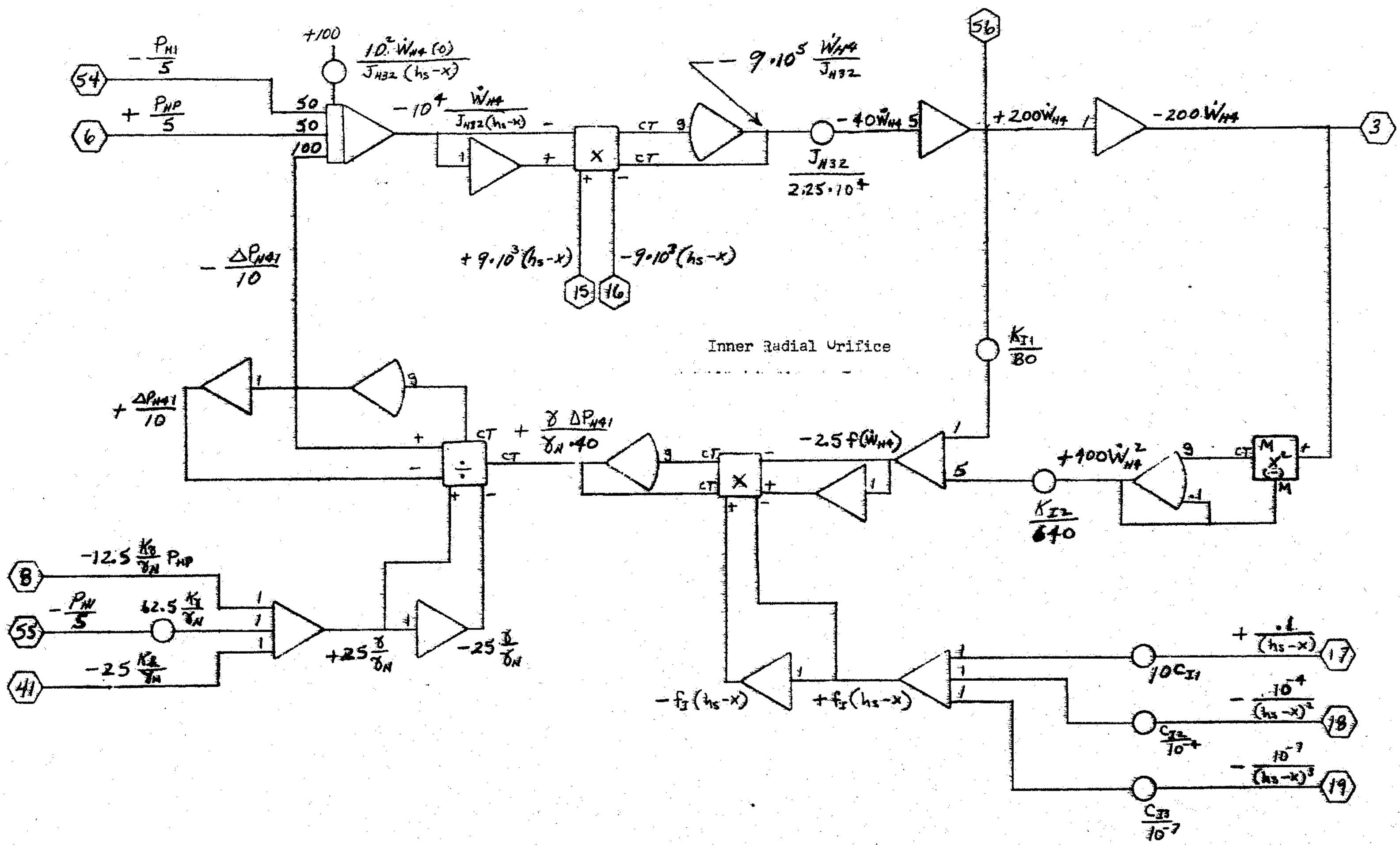


Figure G-30 Compressible, Parallel Flow Simulation - Balance Piston Inward Flow-High Pressure Side

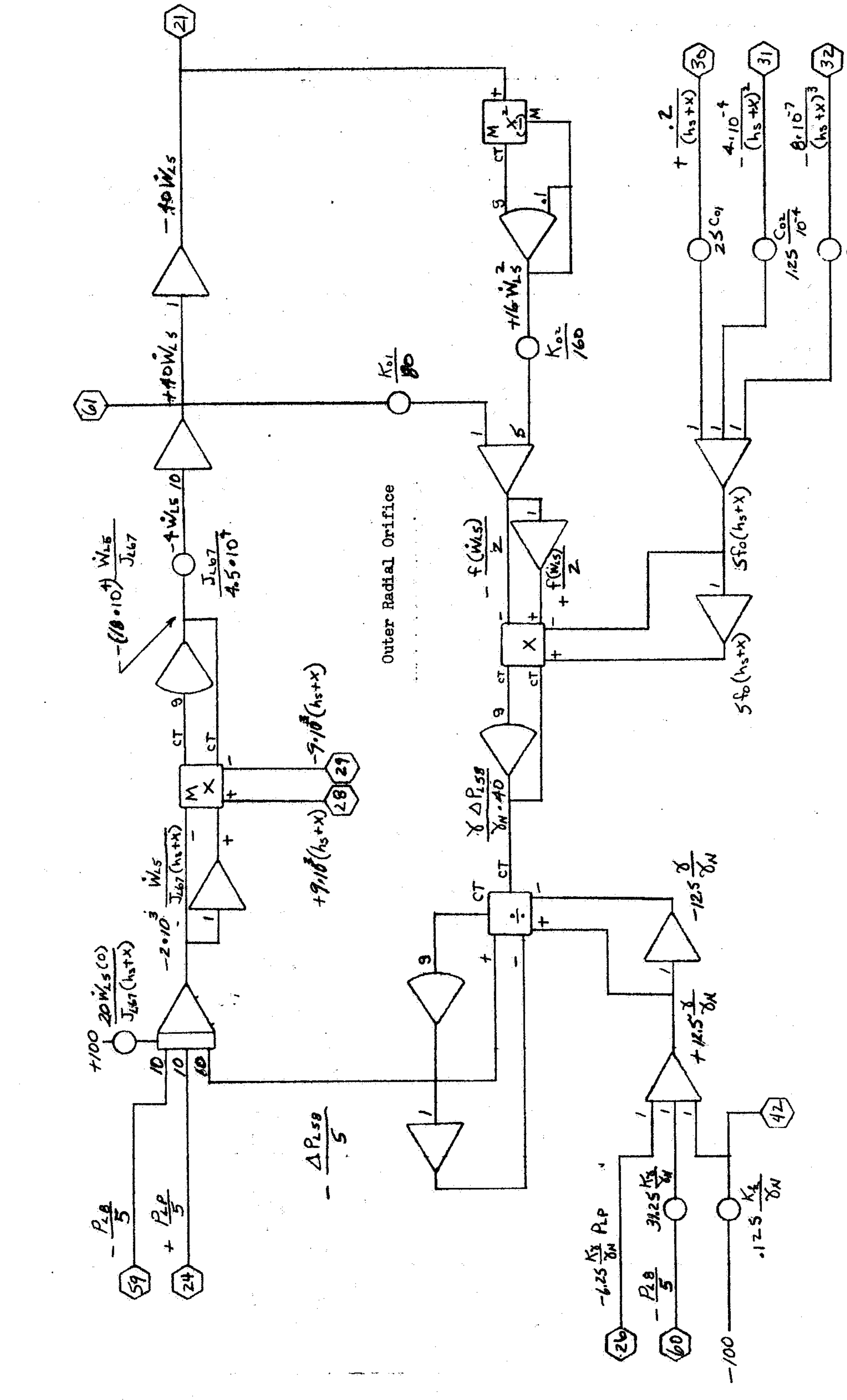


Figure C-31 Compressible, Parallel Flow Simulation - Balance Piston Outward Flow-Low Pressure Side

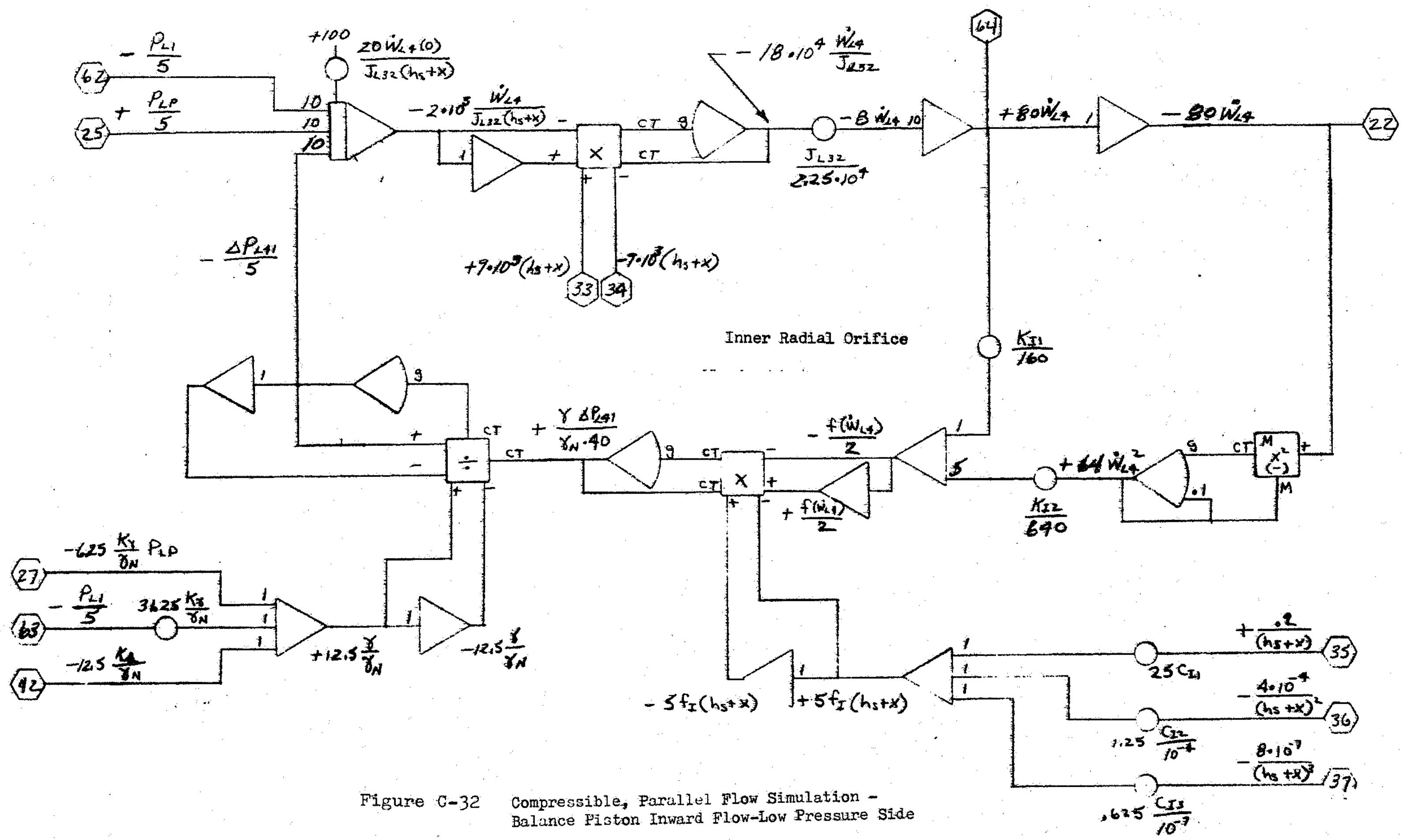
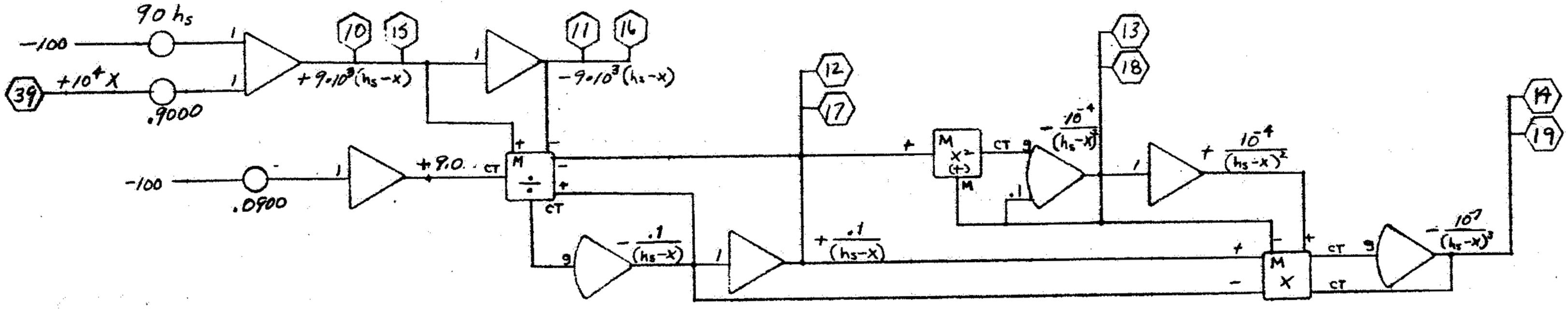


Figure C-32 Compressible, Parallel Flow Simulation - Balance Piston Inward Flow-Low Pressure Side



f(n) Generation - Hign Pressure Side

f(h) Generation - Low Pressure Side

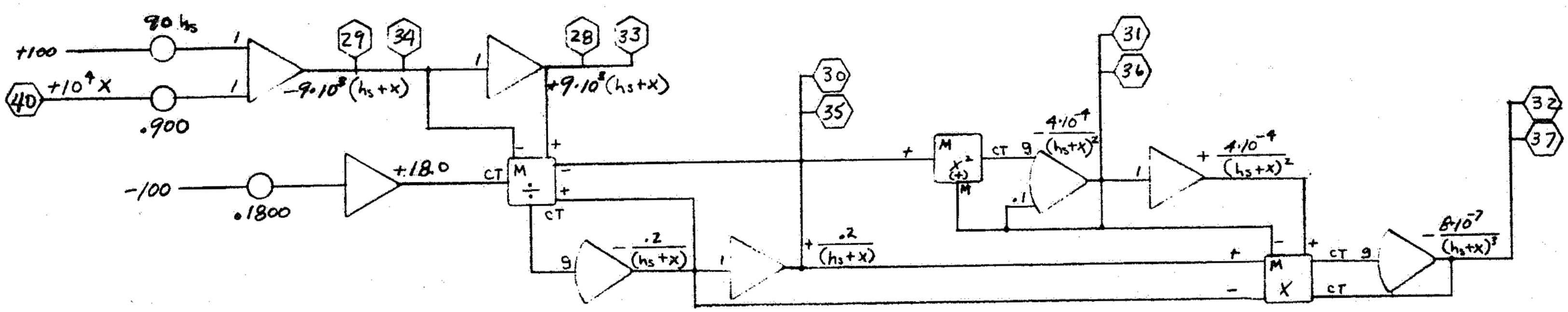


Figure C-33 Compressible, Parallel Flow Simulation - Sill Gap Functions

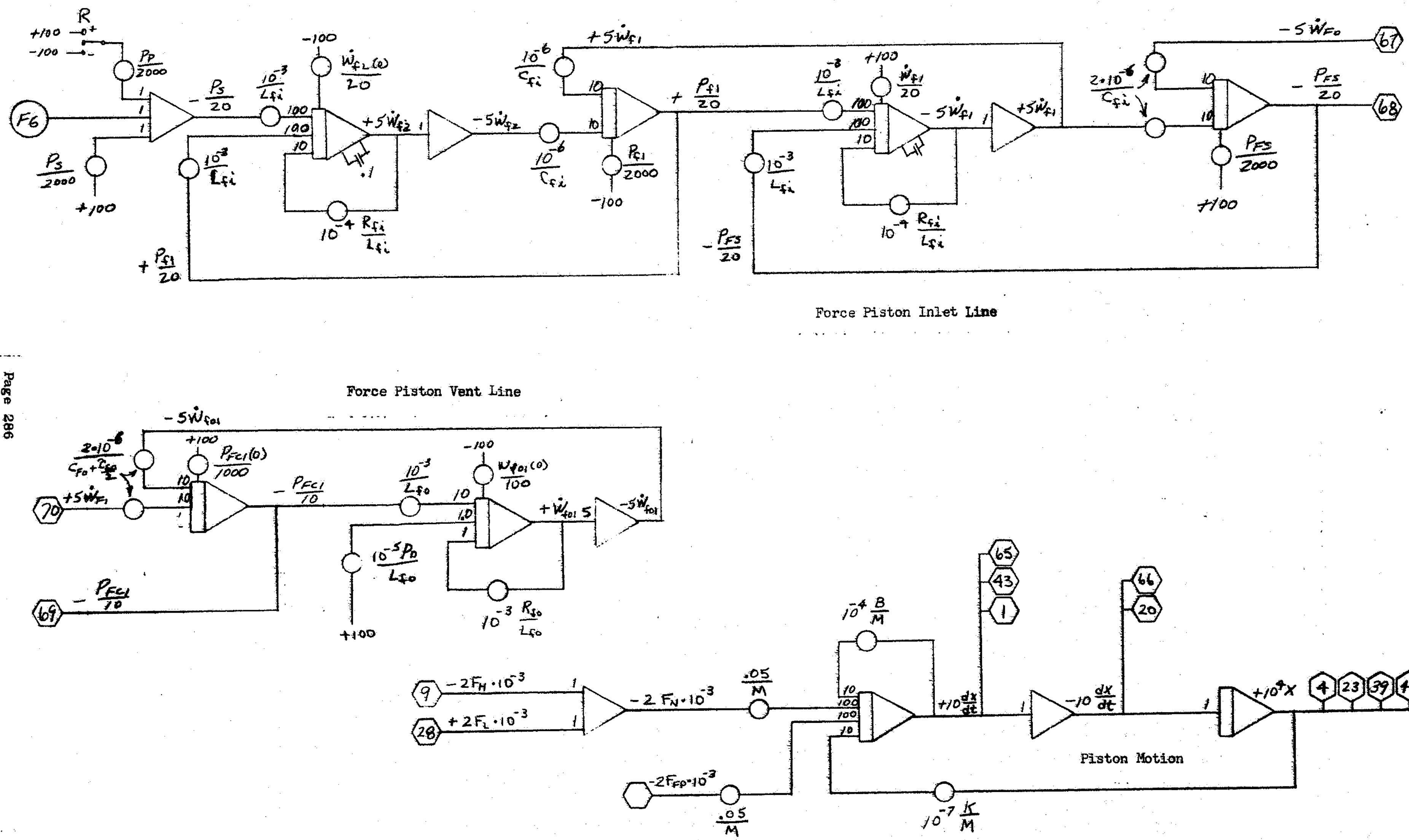


Figure C-34 Compressible, Parallel Flow Simulation - Piston Motion and Force Piston Lines

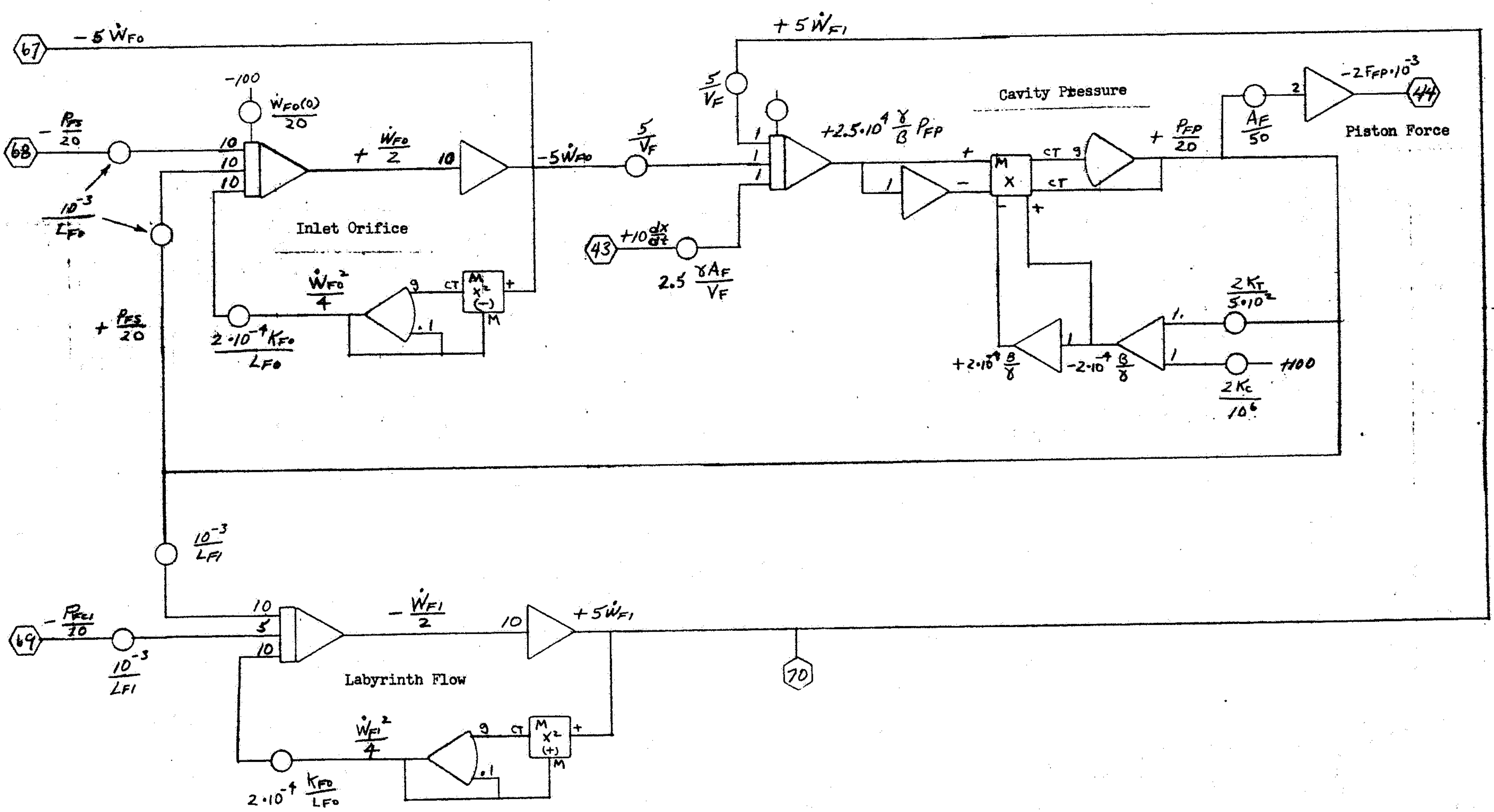
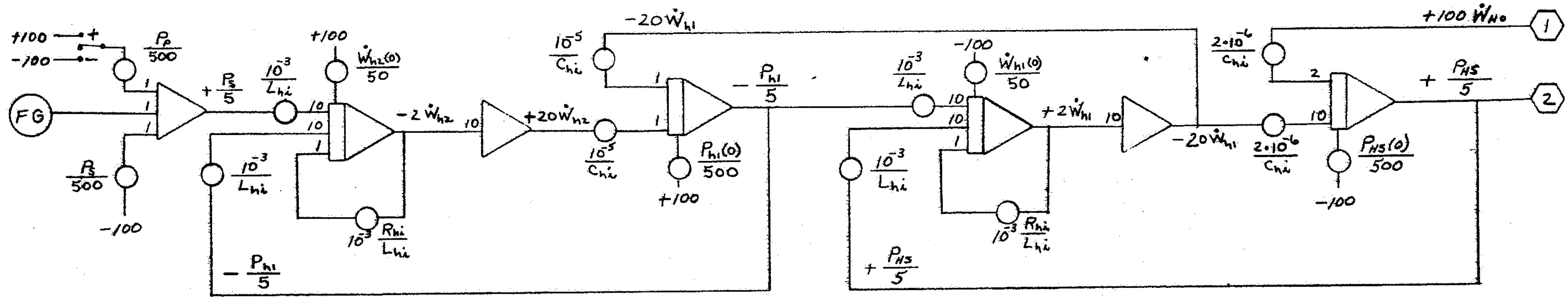


Figure C-35 Compressible, Parallel Flow Simulation - Force Piston Flow Circuit



Balance Piston Inlet Line

Balance Piston Return Line

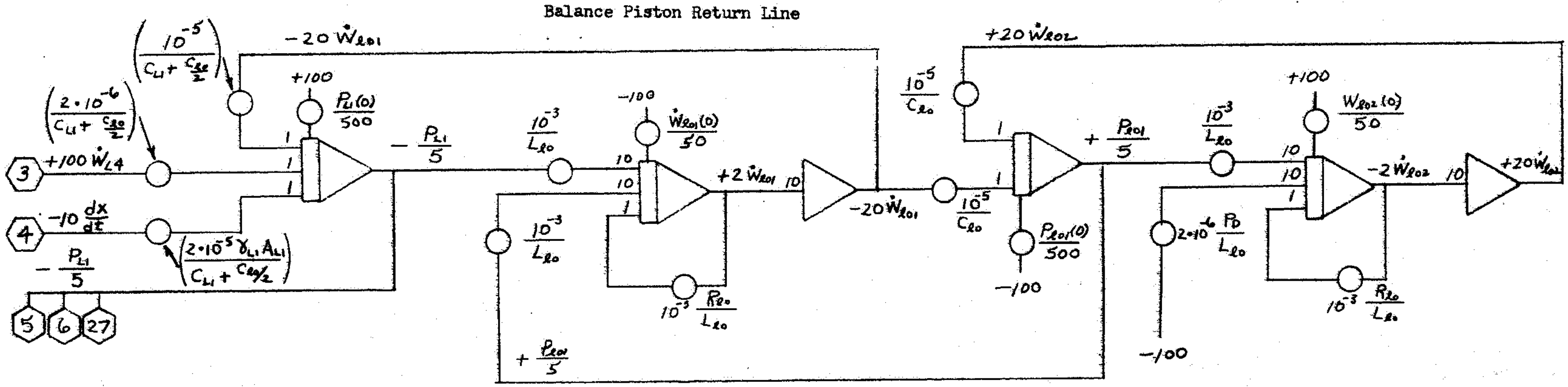


Figure C-36 Compressible, Series Flow Simulation - Balance Piston Lines

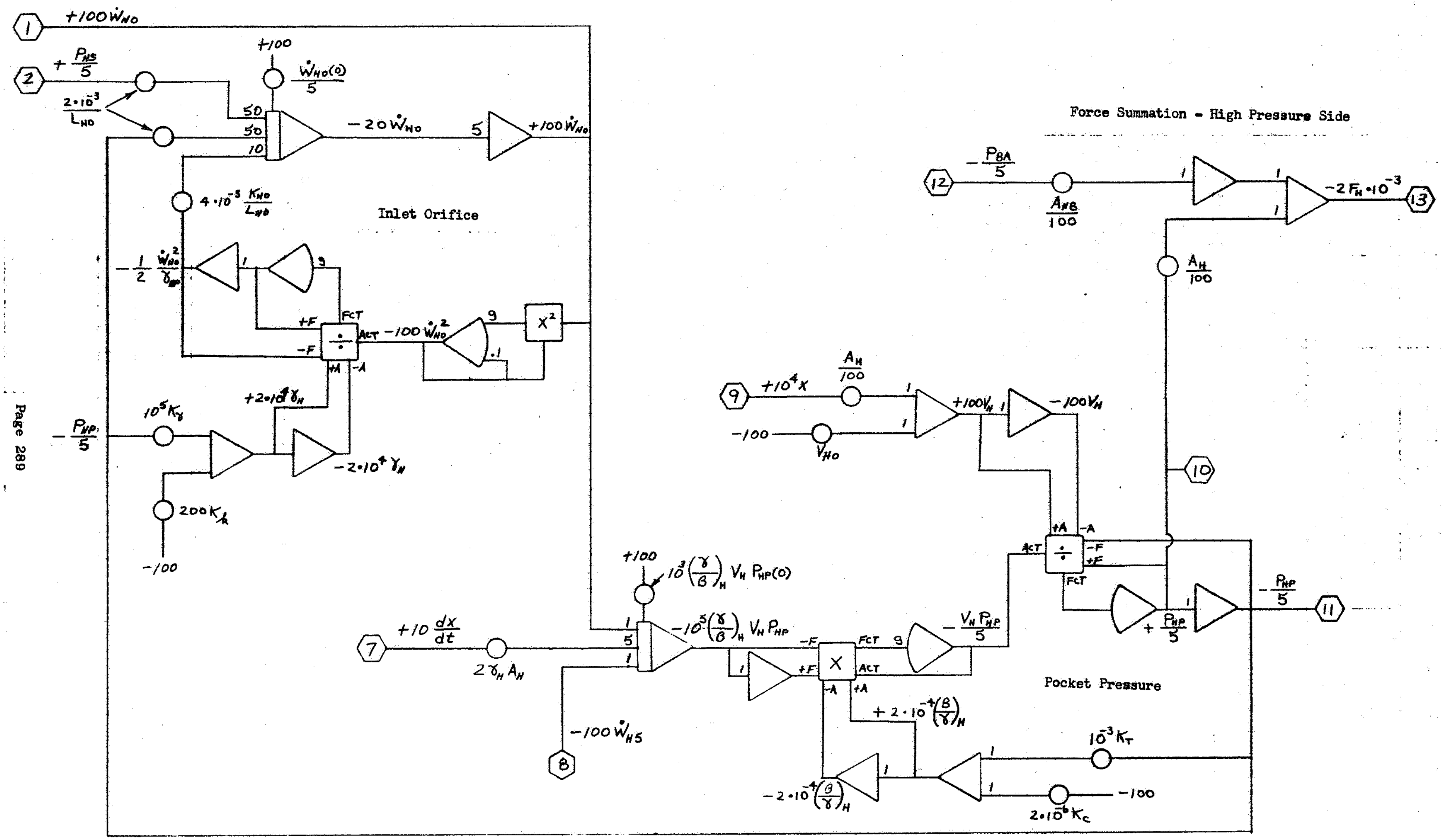


Figure C-37 Compressible, Series Flow Simulation - Balance Piston Inlet

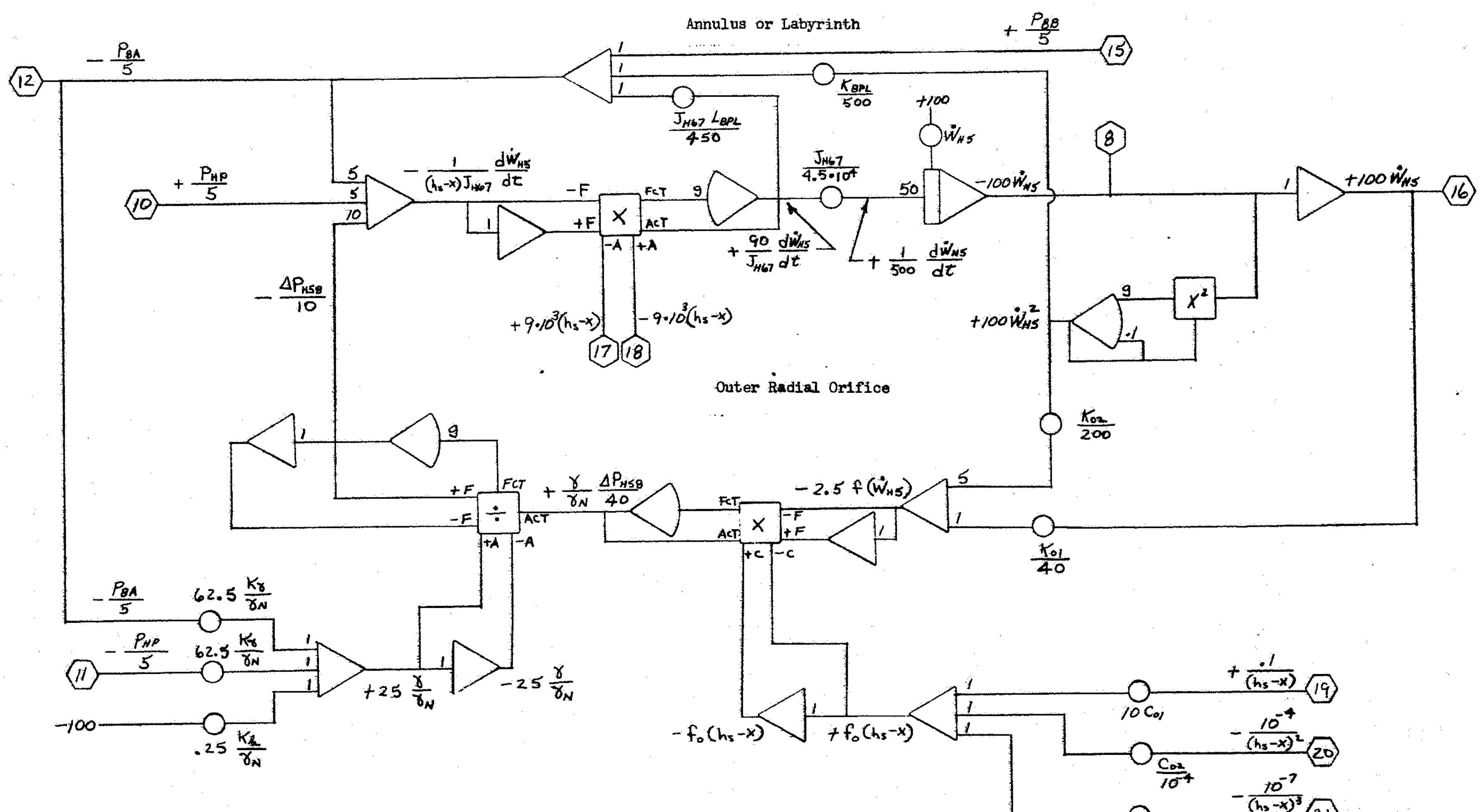


Figure C-38 Compressible, Series Flow Simulation - Balance Piston Outward Flow-High Pressure Side

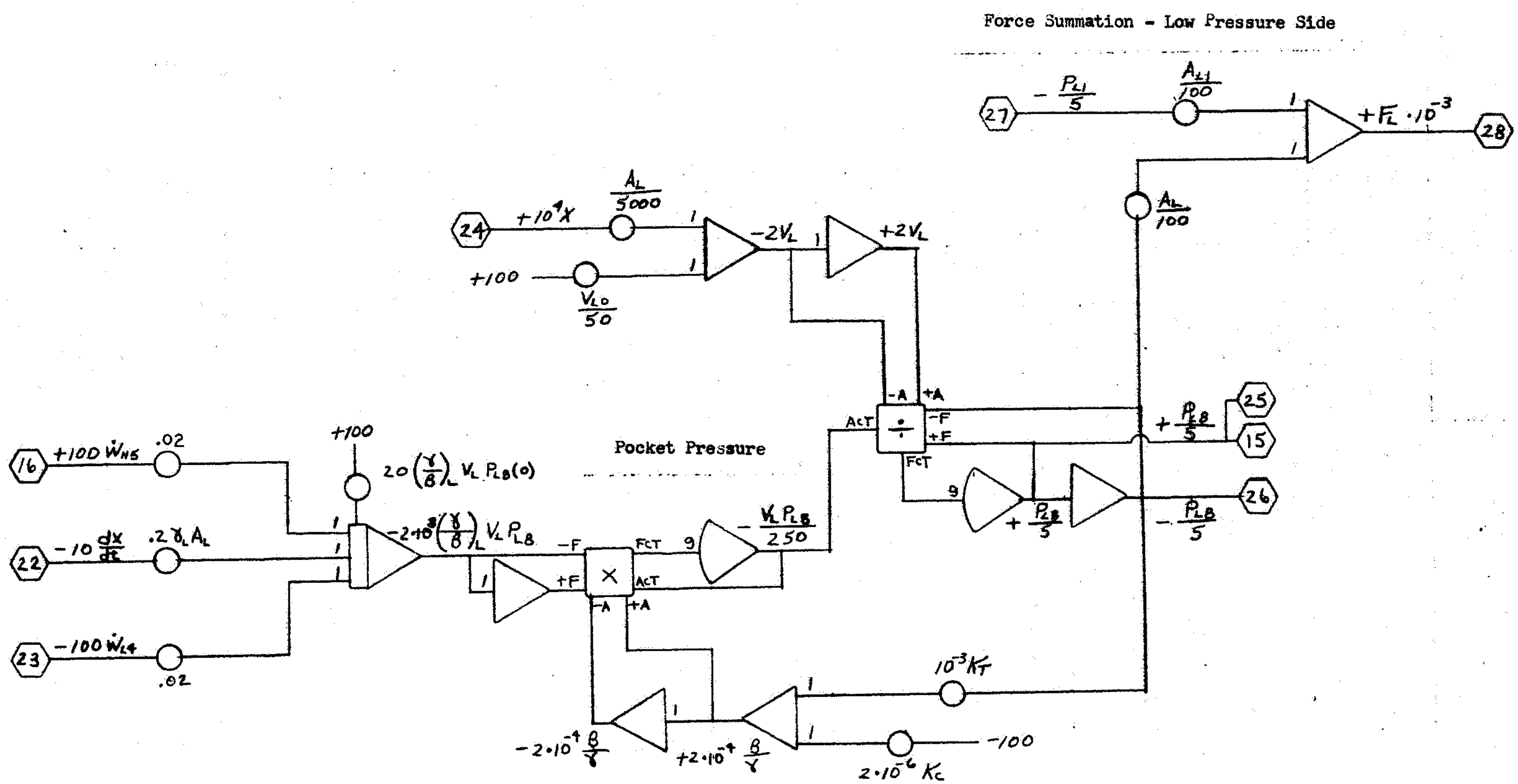


Figure C-39 Compressible, Series Flow Simulation - Balance Piston Inlet Flow-Low Pressure Side

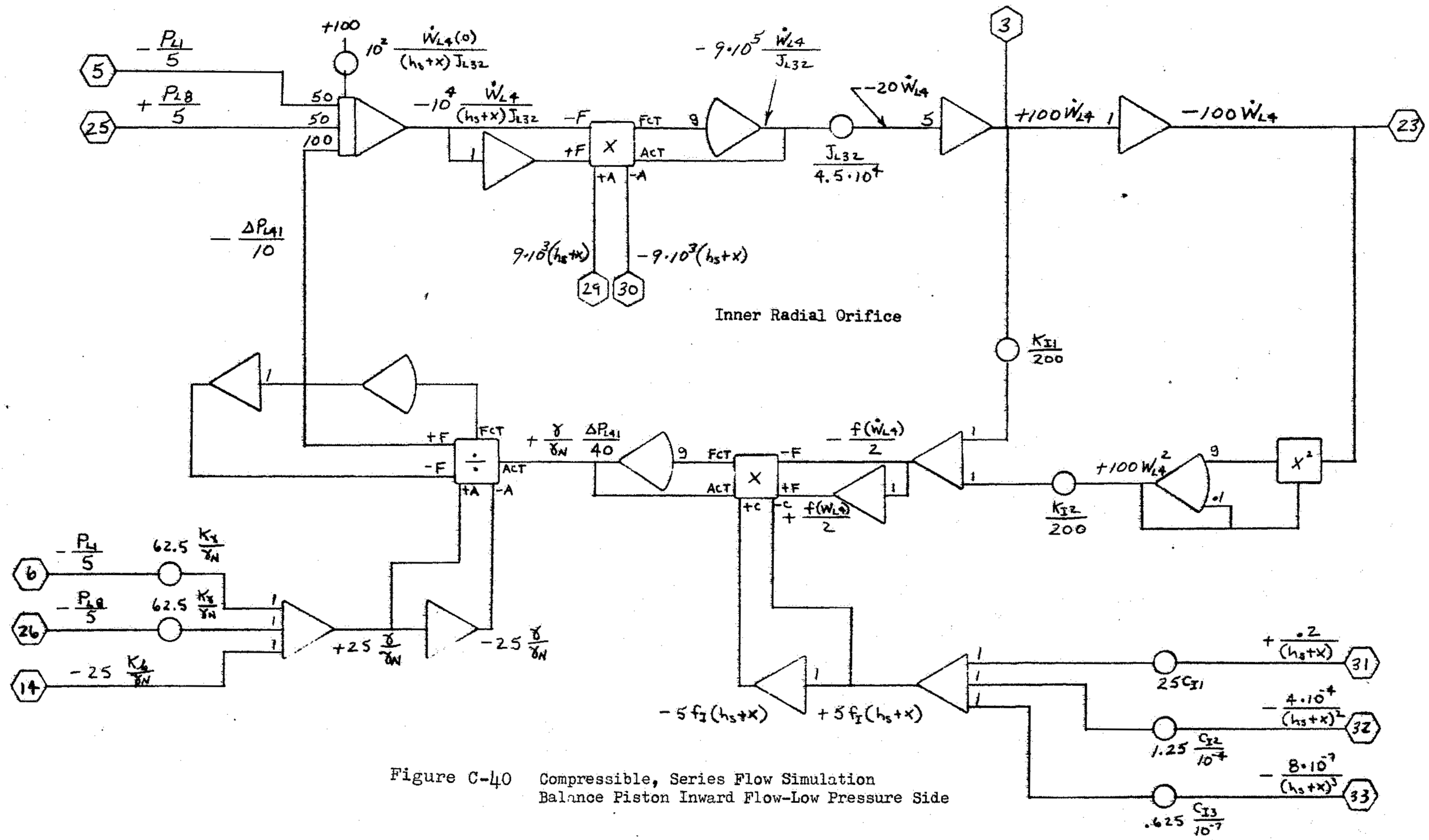
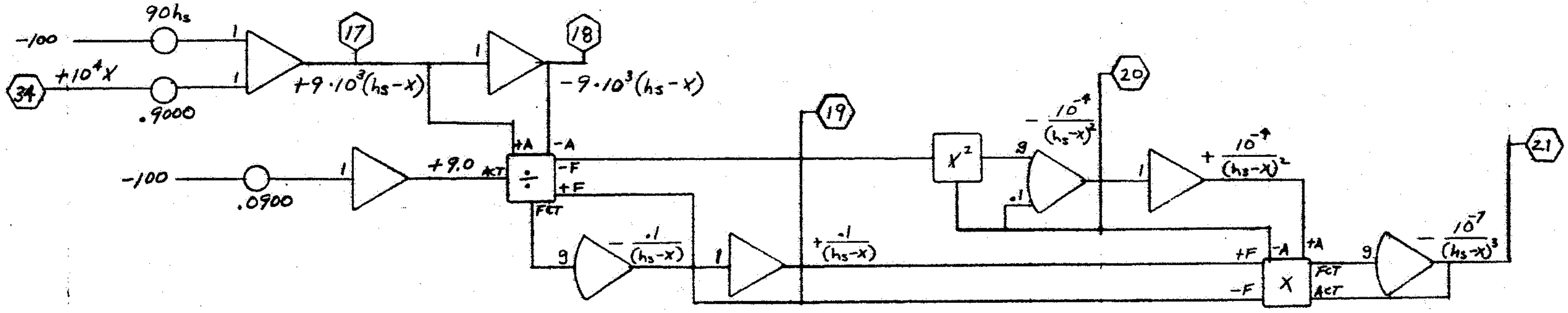


Figure C-40 Compressible, Series Flow Simulation
Balance Piston Inward Flow-Low Pressure Side



f(h) Generation - High Pressure Side

f(h) Generation - Low Pressure Side

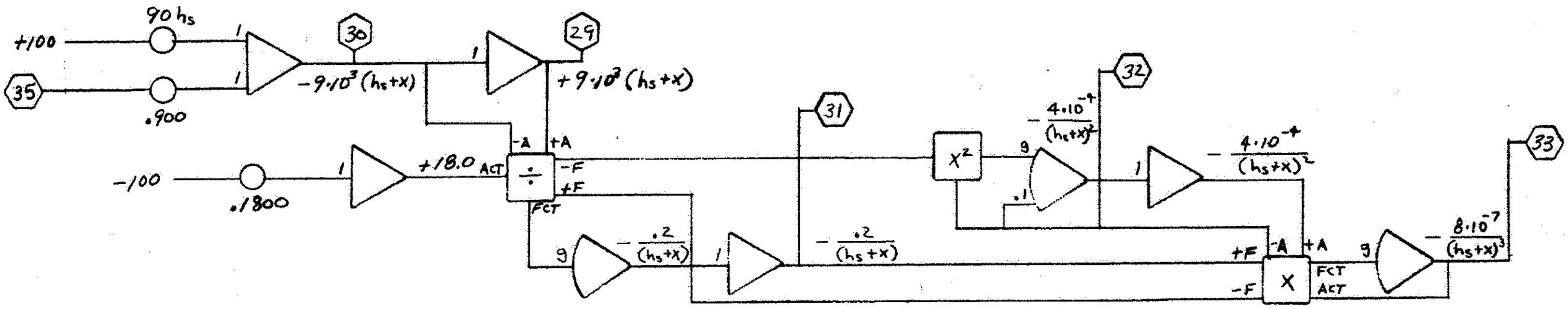


Figure C-41 Compressible, Series Flow Simulation - Sill Gap Functions

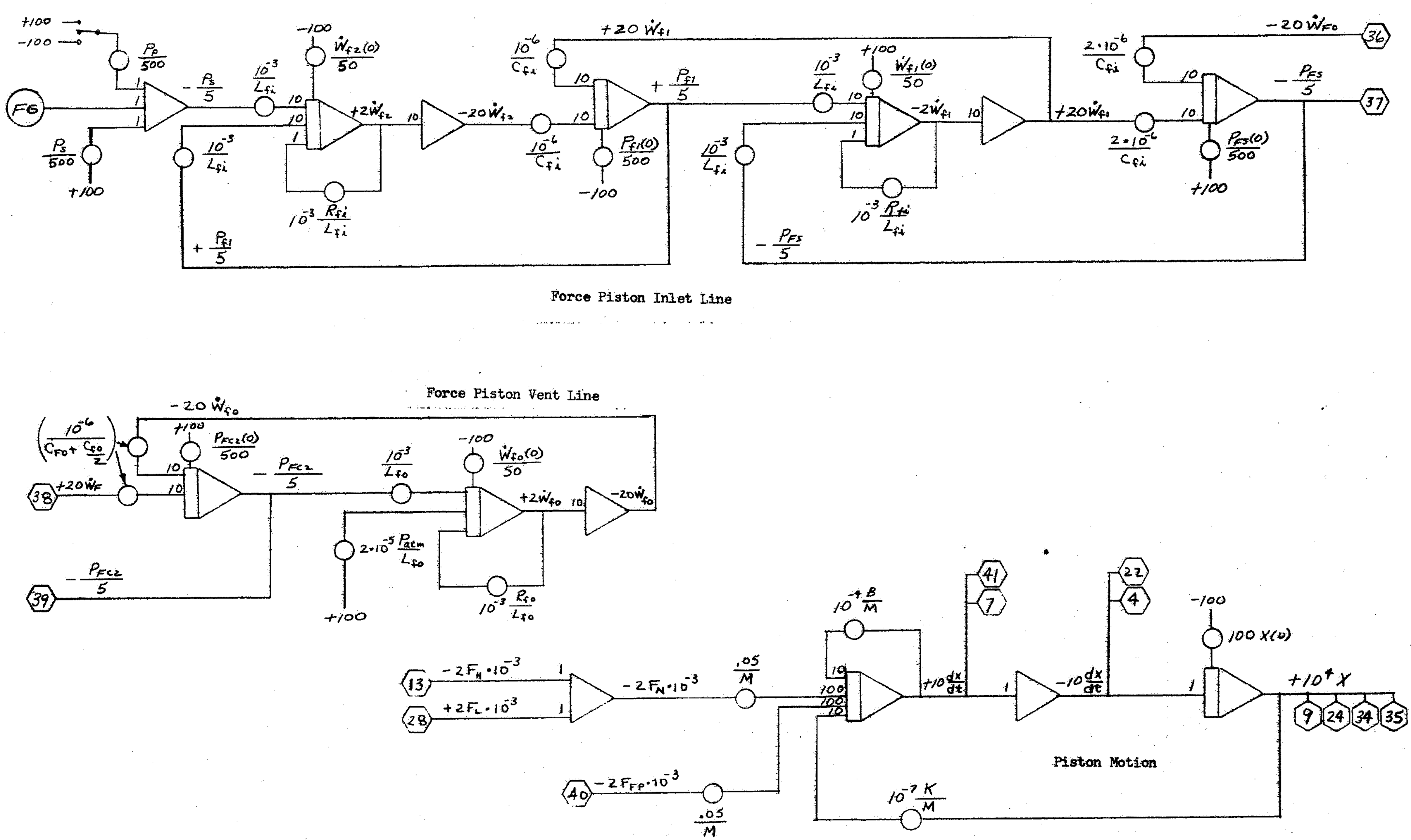


Figure C-42 Compressible, Series Flow Simulation - Piston Motion and Force Piston Lines

2

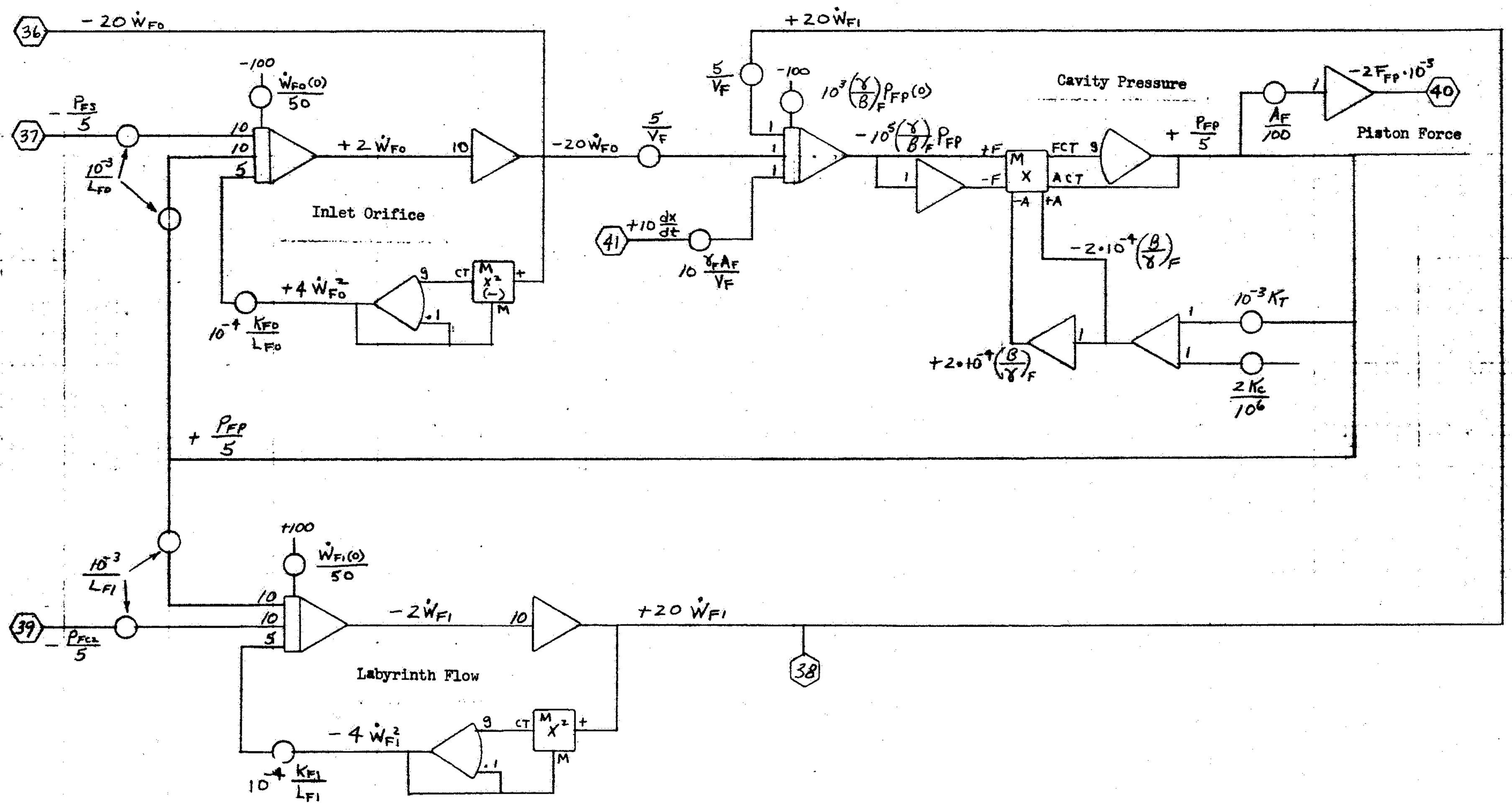


Figure C-43 Compressible, Series Flow Simulation - Force Piston Flow Circuit

First Line Section

$$\frac{d\dot{W}_{f2}}{dt} = \frac{R_{f1}}{L_{fi}} \dot{W}_{f2} - \frac{1}{L_{fi}} P_{fi}$$

Line Pressure

$$\frac{dP_{fi}}{dt} \quad \frac{1}{C_{fi}} \dot{W}_{f2} - \frac{1}{C_{fi}} \dot{W}_{fi}$$

Second Line Section

$$\frac{d\dot{W}_{fi}}{dt} = \frac{1}{L_{fi}} P_{fi} - \frac{R_{fi}}{L_{fi}} \dot{W}_{fi} - \frac{1}{L_{fi}} P_{FS}$$

Inlet Pressure

$$\frac{dP_{FS}}{dt} = \frac{2}{C_{fi}} \dot{W}_{fi} - \frac{2}{C_{fi}} \dot{W}_{FO}$$

Inlet Orifice

$$\frac{d\dot{W}_{FO}}{dt} = \frac{1}{L_{FO}} P_{FS} - \frac{R_{FO}}{L_{FO}} \dot{W}_{FO} - \frac{1}{L_{FO}} P_{FP}$$

Cavity Pressure

$$\frac{dP_{FP}}{dt} = \frac{\beta}{V_F} \dot{W}_{FO} - \frac{\beta}{V_F} \dot{W}_F - \frac{\beta A_F}{V_F} \dot{X}$$

Labyrinth Flow

$$\frac{d\dot{W}_F}{dt} = \frac{1}{L_F} P_{FP} - \frac{R_F}{L_F} \dot{W}_F - \frac{1}{L_F} P_{FC2}$$

Discharge Pressure

$$\frac{dP_{FC2}}{dt} = \frac{1}{C_{Fi} + \frac{C_{FO}}{2}} \dot{W}_F - \frac{1}{C_{Fi} + \frac{C_{fo}}{2}} \dot{W}_{fo}$$

Discharge Line

$$\frac{d\dot{W}_{fo}}{dt} = \frac{1}{L_{fo}} P_{FC2} - \frac{R_{fo}}{L_{fo}} \dot{W}_{fo}$$

b. Balance Piston - Series Flow Circuit

Arranging the compressible series flow balance piston equations in linearized state vector form yields

First Inlet Line Section

$$\frac{d\dot{W}_{h2}}{dt} = \frac{R_{hi}}{L_{hi}} \dot{W}_{h2} - \frac{1}{L_{hi}} P_{hi}$$

Line Pressure

$$\frac{dP_{hi}}{dt} = \frac{1}{C_{hi}} \dot{W}_{h2} - \frac{1}{C_{hi}} \dot{W}_{hi}$$

Second Inlet Line Section

$$\frac{d\dot{W}_{hi}}{dt} = \frac{1}{L_{hi}} P_{hi} - \frac{R_{hi}}{L_{hi}} \dot{W}_{hi} - \frac{1}{L_{hi}} P_{HS}$$

Inlet Pressure

$$\frac{dP_{HS}}{dt} = \frac{2}{C_{hi}} \dot{W}_{hi} - \frac{2}{C_{hi}} \dot{W}_{HO}$$

Inlet Orifice

$$\frac{d\dot{W}_{HO}}{dt} = \frac{1}{L_{HO}} P_{HS} - \frac{R_{HO}}{L_{HO}} \dot{W}_{HO} - \frac{1}{L_{HO}} P_{HP}$$

Pocket Pressure

$$\frac{dP_{HP}}{dt} = \frac{\beta A_H}{V_H} \dot{X} + \frac{\beta}{\gamma V_H} \dot{W}_{HO} - \frac{\beta}{\gamma V_H} \dot{W}_{H5}$$

Outer Piston Sill

$$\frac{d\dot{W}_{H5}}{dt} = -\frac{1}{L_{H67}} \frac{\partial\overline{\Delta P}_{H58}}{\partial\overline{X}} X + \frac{1}{L_{H67}} P_{HP} - \frac{1}{L_{H67}} \frac{\partial\overline{\Delta P}_{H58}}{\partial\overline{\dot{W}}_{H5}} \dot{W}_{H5} - \frac{1}{L_{H67}} P_8$$

Pocket Pressure (Low-Pressure Side)

$$\frac{dP_8}{dt} = -\frac{\beta A_L}{V_L} \dot{X} + \frac{\beta}{\gamma V_L} \dot{W}_{H5} - \frac{\beta}{\gamma V_L} \dot{W}_{L4}$$

Inner Piston Sill

$$\frac{d\dot{W}_{L4}}{dt} = -\frac{1}{L_{L32}} \frac{\partial\overline{\Delta P}_{L41}}{\partial\overline{X}} X - \frac{1}{L_{L32}} P_8 \frac{1}{L_{L32}} \frac{\partial\overline{\Delta P}_{L41}}{\partial\overline{\dot{W}}_{L4}} \dot{W}_4 - \frac{1}{L_{L32}} P_{Li}$$

Discharge Pressure

$$\frac{dP_{Li}}{dt} = -\frac{\gamma A_{Li}}{C_{Li} + \frac{C_{\ell o}}{2}} \dot{X} - \frac{1}{C_{Li} + \frac{C_{\ell o}}{2}} \dot{W}_{L4} - \frac{1}{C_{Li} + \frac{C_{\ell o}}{2}} \dot{W}_{\ell oi}$$

First Discharge Line Section

$$\frac{d\dot{W}_{\ell oi}}{dt} = \frac{1}{L_{\ell o}} P_{Li} - \frac{R_{\ell o}}{L_{\ell o}} \dot{W}_{\ell oi} - \frac{1}{L_{\ell o}} P_{\ell oi}$$

Line Pressure

$$\frac{dP_{\ell oi}}{dt} = \frac{1}{C_{\ell o}} \dot{W}_{\ell oi} - \frac{1}{C_{\ell o}} \dot{W}_{\ell o2}$$

Second Discharge Line Section

$$\frac{d\dot{W}_{\ell o2}}{dt} = \frac{1}{L_{\ell o}} P_{\ell oi} - \frac{R_{\ell o}}{L_{\ell o}} \dot{W}_{\ell o2}$$

c. Mechanical System

Arranging the mechanical equations in state vector form yields

$$\frac{dx}{dt} = \dot{X}$$

$$\frac{d\dot{X}}{dt} = \frac{A_F}{M} P_{FP} - \frac{A_H}{M} P_{HP} - \frac{(A_L - A_8)}{M} P_8 - \frac{A_{Li}}{M} P_{Li} - \frac{\beta}{M} \dot{X} - \frac{K}{M} X$$

B. PARAMETRIC STUDY

A study was conducted to determine the effects of variations in principal parameters upon system operation and stability. The mathematical models and analog computer simulations described in the previous discussion were used in the parameter study. A separate study was conducted for each of the four thrust balance systems. For each system, a nominal set of parameters was selected, about which variations in certain parameters were made. Records of system response were obtained from the analog computer simulation for each parameter variation.

The parameters selected to be included in the study are associated with the principal elements of the balance piston flow path. The selected parameters include the diameter of the balance piston inlet orifices, the depth of the piston pocket, and the width of the piston sills.

Records of the response of the system to both step and sinusoidal excitation were obtained. The system excitation was introduced in the pressure source associated with either the load piston or the high-pressure side of the balance piston. The results obtained from the sinusoidal tests were reduced to frequency response information consisting of the amplitude ratio and phase angle of the peak-to-peak piston displacement to the peak-to-peak sinusoidal source pressure.

1. Parallel Flow Balancer - Incompressible Flow

A list of the nominal parameters used in the study of the incompressible, parallel flow balancer is shown on Table C-I. The nominal configuration has a sill width of 0.5-in., an inlet orifice of 0.1-in., and a piston pocket depth of 0.05-in.

Frequency response plots obtained from the simulation of the nominal system are shown on Figures No. C-44 and No. C-45. Figure No. C-44 shows the amplitude ratio and phase angle of piston displacement with respect to a sinusoidal excitation at the load piston pressure source. Amplitude ratio is given in decibels and phase angle in degrees. The plot on Figure No. C-44 shows a low damped anti-resonance and resonance at approximately 450 cps and 600 cps, respectively. The ratio of piston displacement to balance piston pressure excitation given on Figure No. C-45 shows similar characteristics except the frequencies at which they occur are different.

The response of the system to a pressure step from 1000 psi to 200 psi at the load piston source is shown on Figures No. C-46 and No. C-47. The piston displacement shows an overshoot of approximately 14% after which, the response quickly dampens out. Some small, low damped oscillations of approximately 1400 cps are noted in the pressure and weight flow traces. A modification of the feed line parameters resulted in changes

TABLE C-I

PARAMETER VALUES - INCOMPRESSIBLE FLOW

	Parallel Balancer	Series Balancer	Units
B	100	100	lb-sec/in.
C_{fi}	$3.0x10^{-6}$	$8.0x10^{-7}$	$in.^2$
C_{fo}	$2.08x10^{-6}$	$1.6x10^{-6}$	$in.^2$
C_{hi}, C_{li}	$2.18x10^{6}$	$2.48x10^{-6}$	$in.^2$
C_{ho}, C_{lo}	$1.05x10^{-6}$	$3.2x10^{-6}$	$in.^2$
C_o	$2.08x10^{-6}$	-	$in.^2$
D	0.05	0.05	in.
d_{FO}	1.0	0.5	in.
d_{HO}, d_{LO}	0.1	0.1	in.
h_s	0.0006	0.006	in.
K	500,000	250,000	lb/in.
K_{FO}	0.1185	1.9	$sec^2/lb-in.^2$
K_{F1}	0.40	2.45	$sec^2/lb-in.^2$
K_{F2}	2.0	2.45	$sec^2/lb-in.^2$
K_{fi}	$7.05x10^{-4}$	$3.2x10^{-2}$	$sec^2/lb-in.^2$
K_{fo}	$1.59x10^{-2}$	$2.78x10^{-2}$	$sec^2/lb-in.^2$
K_{HSF}	$3.0x10^{-7}$	$2.1x10^{-7}$	-
K_{LSF}	$3.0x10^{-7}$	$9.4x10^{-8}$	-
K_{HO}, K_{LO}	32.9	32.9	$sec^2/lb-in.^2$
K_{hi}, K_{li}	$3.54x10^{-2}$	$4.74x10^{-2}$	$sec^2/lb-in.^2$
K_{ho}, K_{lo}	$5.1x10^{-2}$	$1.73x10^{-2}$	$sec^2/lb-in.^2$
K_{out}, K_{in}	0.5	0.5	$sec^2/lb-in.^2$
K_o	$2.2x10^{-2}$	-	$sec^2/lb-in.^2$

TABLE C-I (cont.)

	Parallel Balancer	Series Balancer	Units
L_{FO}	8.25×10^{-4}	3.3×10^{-3}	$sec^2/lb\text{-}in.^2$
L_{F1}	9.5×10^{-3}	5.0×10^{-3}	$sec^2/lb\text{-}in.^2$
L_{F2}	1.0×10^{-2}	5.0×10^{-3}	$sec^2/lb\text{-}in.^2$
L_{fi}	1.08×10^{2}	5.56×10^{-2}	$sec^2/lb\text{-}in.^2$
L_{fo}	1.47×10^{-2}	2.78×10^{-2}	$sec^2/lb\text{-}in.^2$
L_{HO}, L_{LO}	1.375×10^{-3}	1.375×10^{-3}	$sec^2/lb\text{-}in.^2$
L_{hi}, L_{li}	1.41×10^{-2}	1.78×10^{-2}	$sec^2/lb\text{-}in.^2$
L_{ho}, L_{lo}	2.94×10^{-2}	1.39×10^{-2}	$sec^2/lb\text{-}in.^2$
L_o	1.47×10^{-2}	–	$sec^2/lb\text{-}in.^2$
M	.103	.103	$lb\text{-}sec^2/in.$
N_{RPM}	10,000	10,000	RPM
R_{FP}	3.625	3.625	in.
R_{HP}	2.75	2.875	in.
R_{H2}, R_{L2}	1.5	1.75	in.
R_{H3}, R_{L3}	2.0	2.25	in.
R_{H6}, R_{L6}	3.5	3.5	in.
R_{H7}, R_{L7}	4.0	4.0	in.
R_{HS}, R_{LS}	0.8	1.5	in.
V_F	17.62	17.62	$in.^3$
V_{H1}, V_{L1}	5.05	5.05	$in.^3$
V_8	26.4	–	$in.^3$
β	3.26×10^{5}	3.26×10^{5}	psi
γ	3.62×10^{-2}	3.62×10^{-2}	$lb/in.^3$

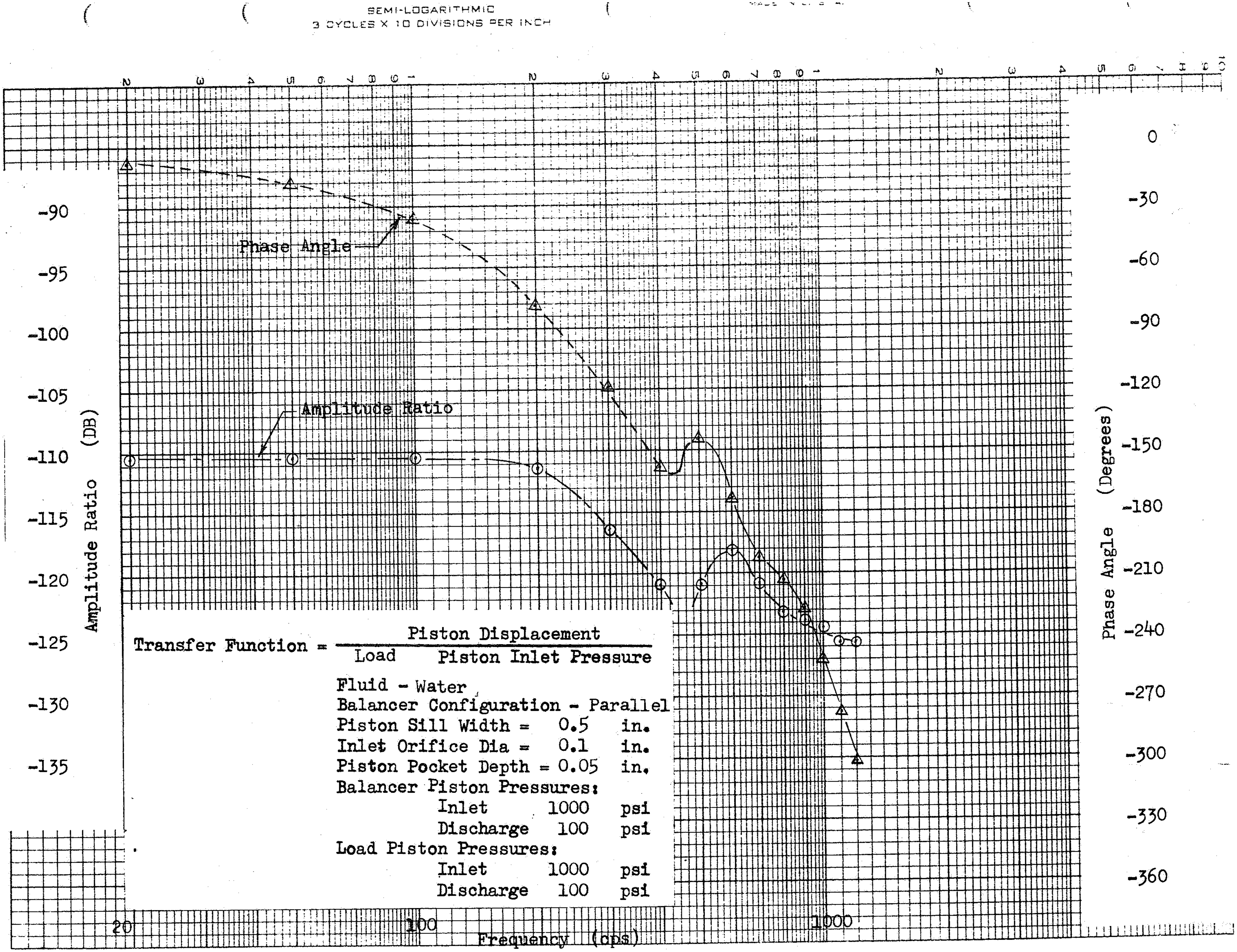


Figure C-44 Frequency Response - Incompressible, Parallel Balancer

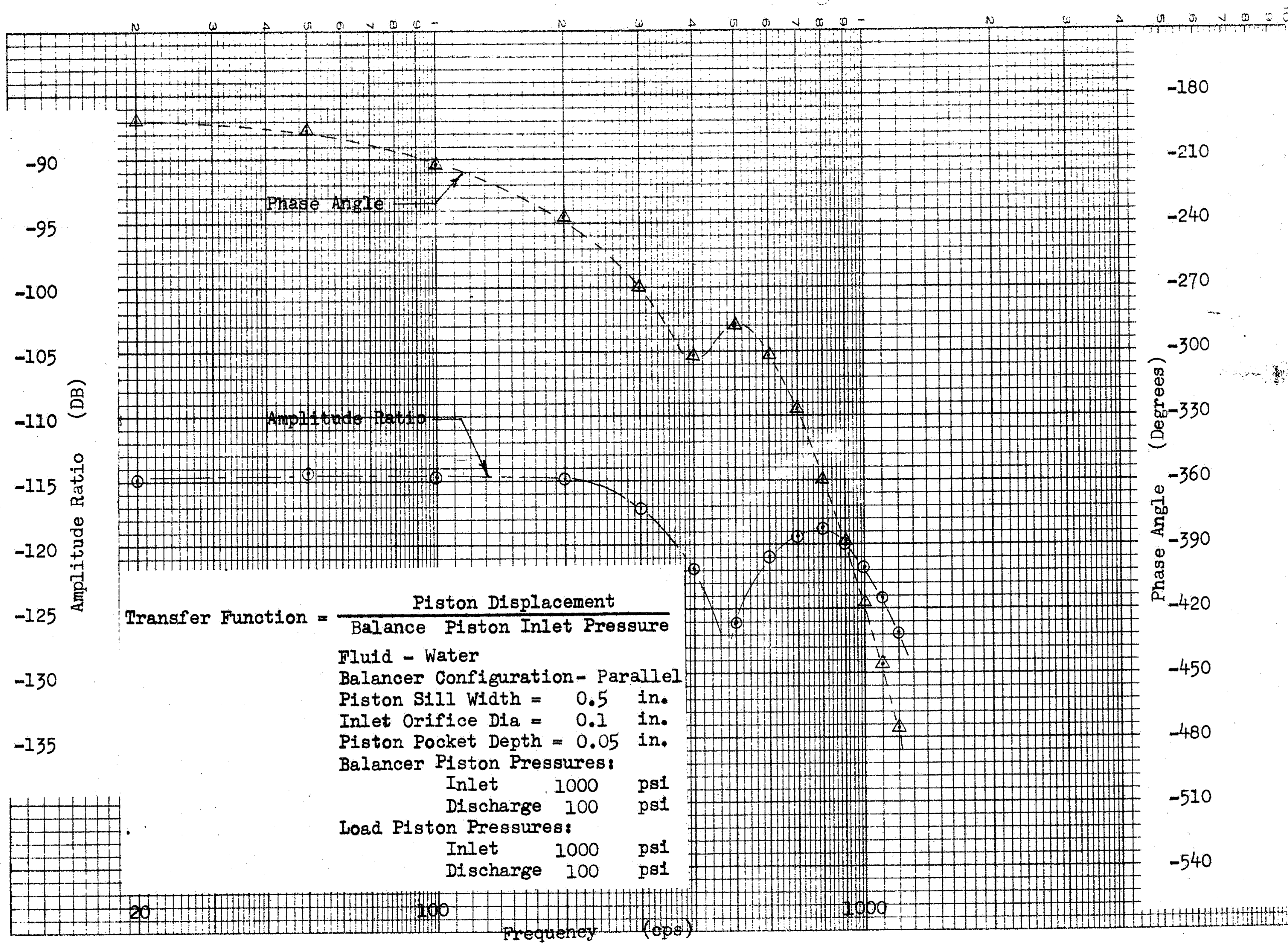


Figure C-45 Frequency Response - Incompressible, Parallel Balancer

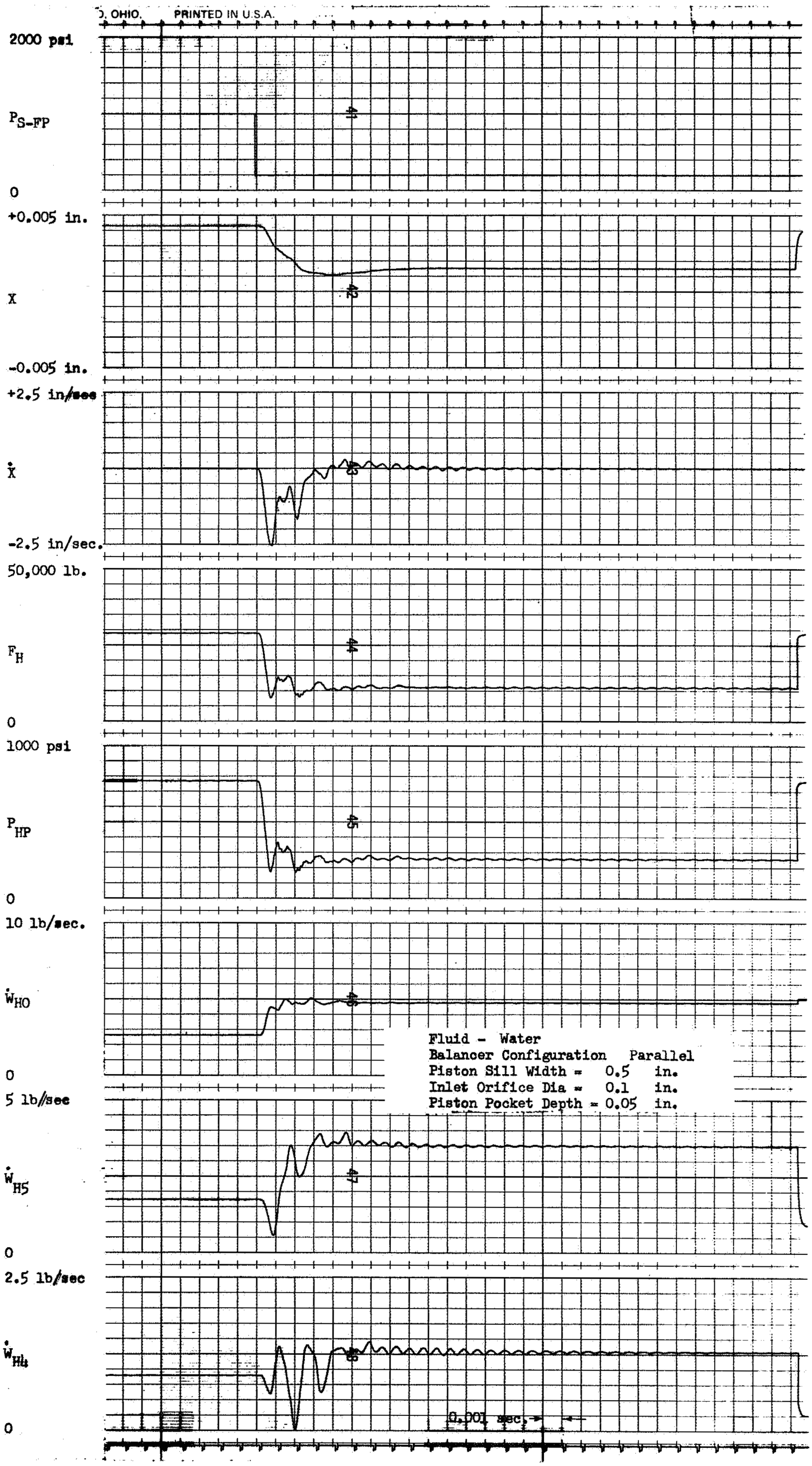


Figure C-46 : Step Response - Incompressible, Parallel Balancer

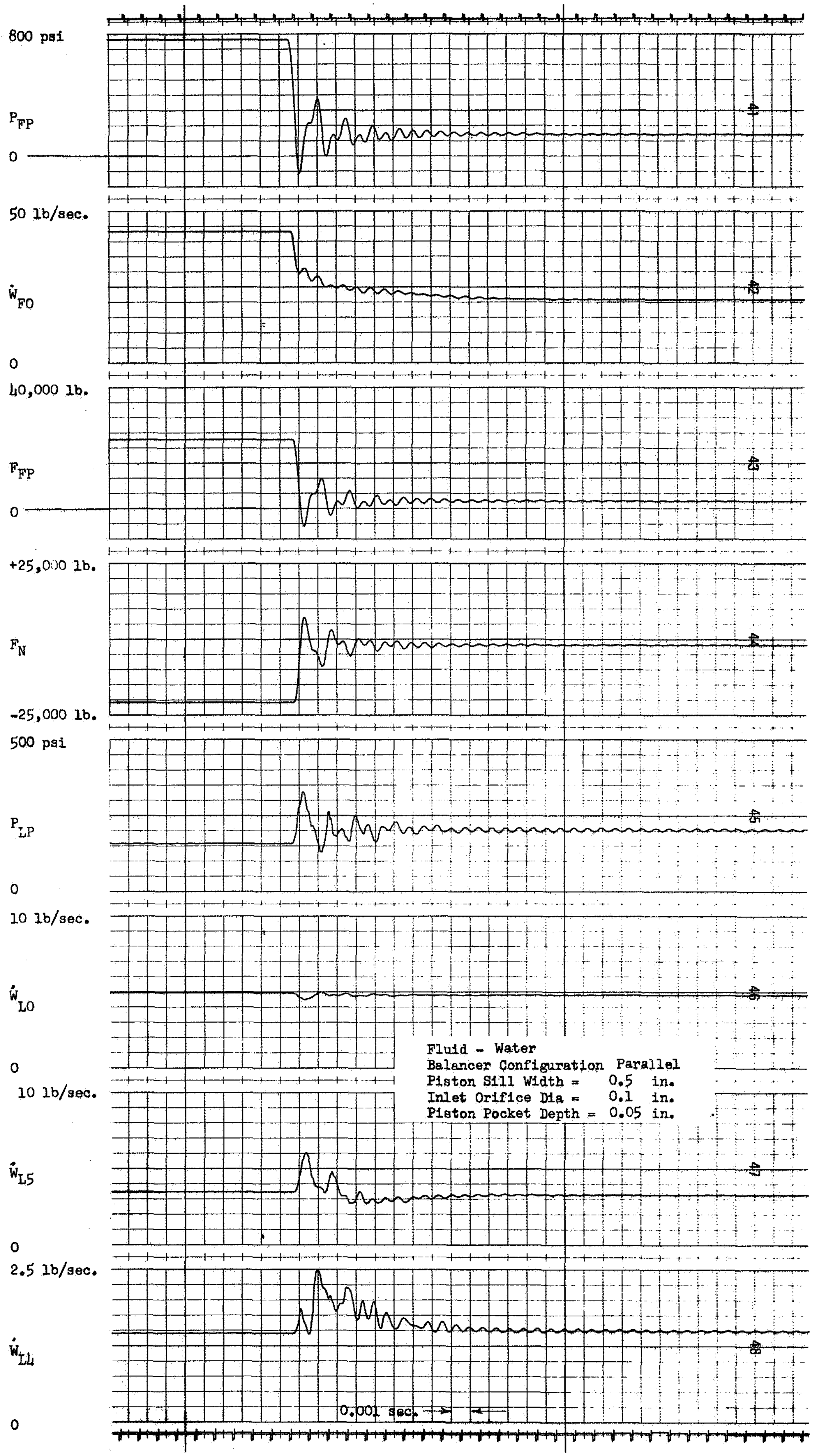


Figure C-47 Step Response - Incompressible, Parallel Balancer

in these oscillations which indicates that they are associated with the feed lines. Oscillations at the beginning of the transient in the range of 700 cps to 750 cps also are noted in the pressure and weight flows. This frequency corresponds approximately with the resonant frequency noted in the frequency response of Figure No. C-45.

Weight flow to the high-pressure side increases considerably after the force piston pressure is decreased while the weight flow to the low-pressure side remains nearly constant. This indicates that the low-pressure flow is determined principally by the inlet orifice for the resulting piston positions.

During the response to a step in load piston inlet pressure, the traces of load piston cavity pressure and force become momentarily negative during the transient. However, this is not possible in the actual case; therefore, the results of the test are not completely valid. The negative portion is so small that it is not expected to alter the results significantly.

The system response to a step from 1000 psi to 400 psi in balance piston source pressure is shown on Figures No. C-48 and No. C-49. The piston response shows negligible overshoot while the pressures and weight flows show transient oscillations of approximately 475 cps.

During the parameter study, sill widths were set at 0.25-in., 0.50-in., and 0.75-in. For each of these sill widths, the inlet orifice was varied from 0.1-in. to 0.17-in. and the piston pocket depth from 0.025-in. to 0.10-in. Although response records from all of these configurations are not illustrated, they are discussed in general and representative cases shown.

Figures No. C-50 and No. C-51 show the resulting response of the system to a step in load piston pressure with the inlet orifice diameter increased to 0.17-in. A comparison of these results with those obtained with a 0.1-in. orifice shows no great change. The overshoot in piston displacement is slightly greater while the oscillations in pressure and weight flows are less. With the larger orifice, the apparent stiffness of the system is increased and the piston displacement is less. The decrease in pressure and weight flow oscillations with the larger balance piston orifices indicate that the oscillations are associated with the load piston. The stiffening effect of the balance piston dampens the oscillations out more quickly.

An increase in sill width to 0.75-in. with other parameters nominal results in the response shown on Figures No. C-52 and No. C-53. Examination of the response of piston displacement shows a slight amount of ringing which was not present in the nominal case. Although records for the 0.25-in. sill are not shown, the resulting piston displacement transient was a damped response without any overshoot. Although the difference is small, the records indicate a more oscillatory and less stable system with the wider sill.

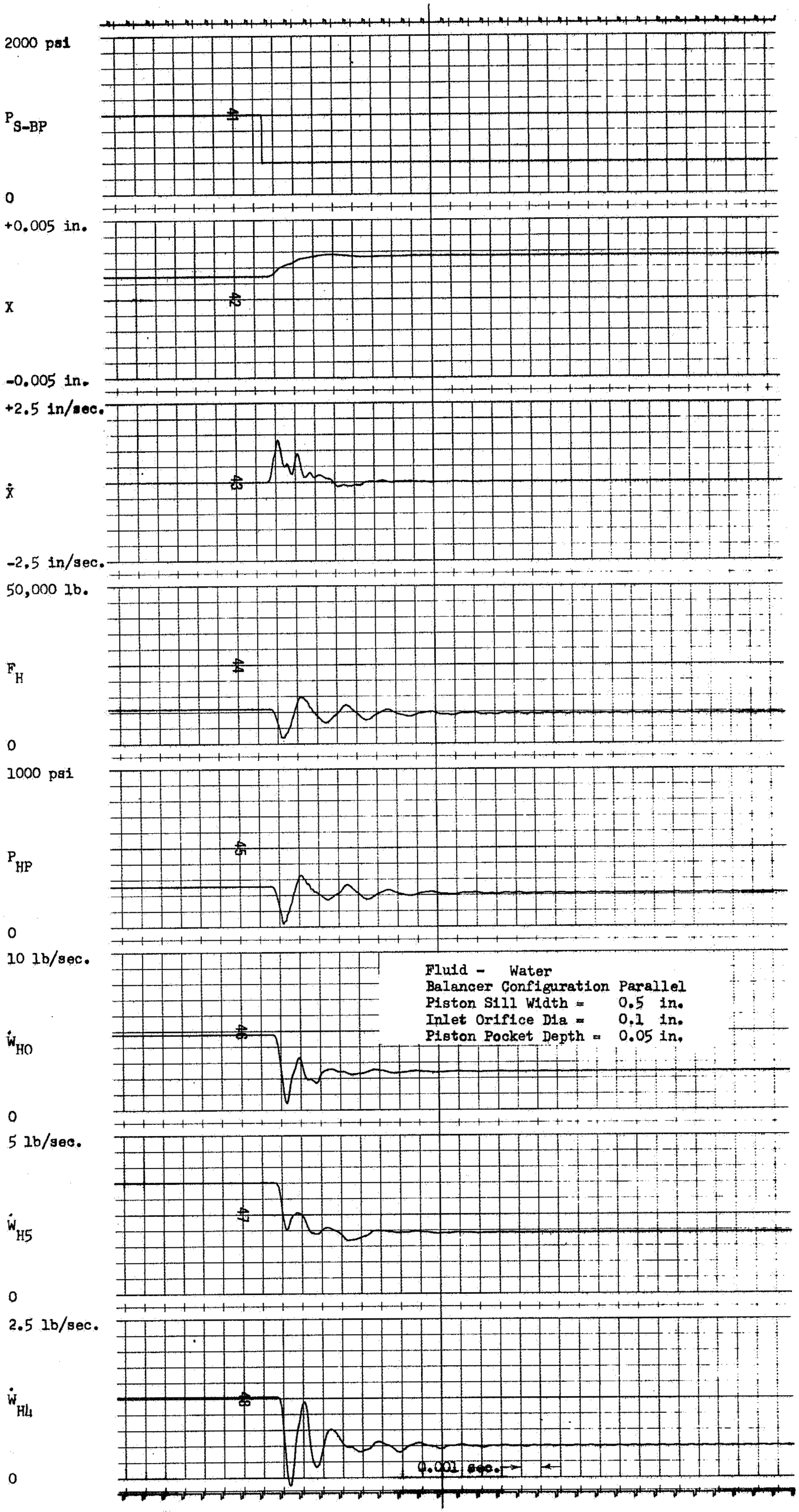


Figure C-48 Step Response - Incompressible, Parallel Balancer

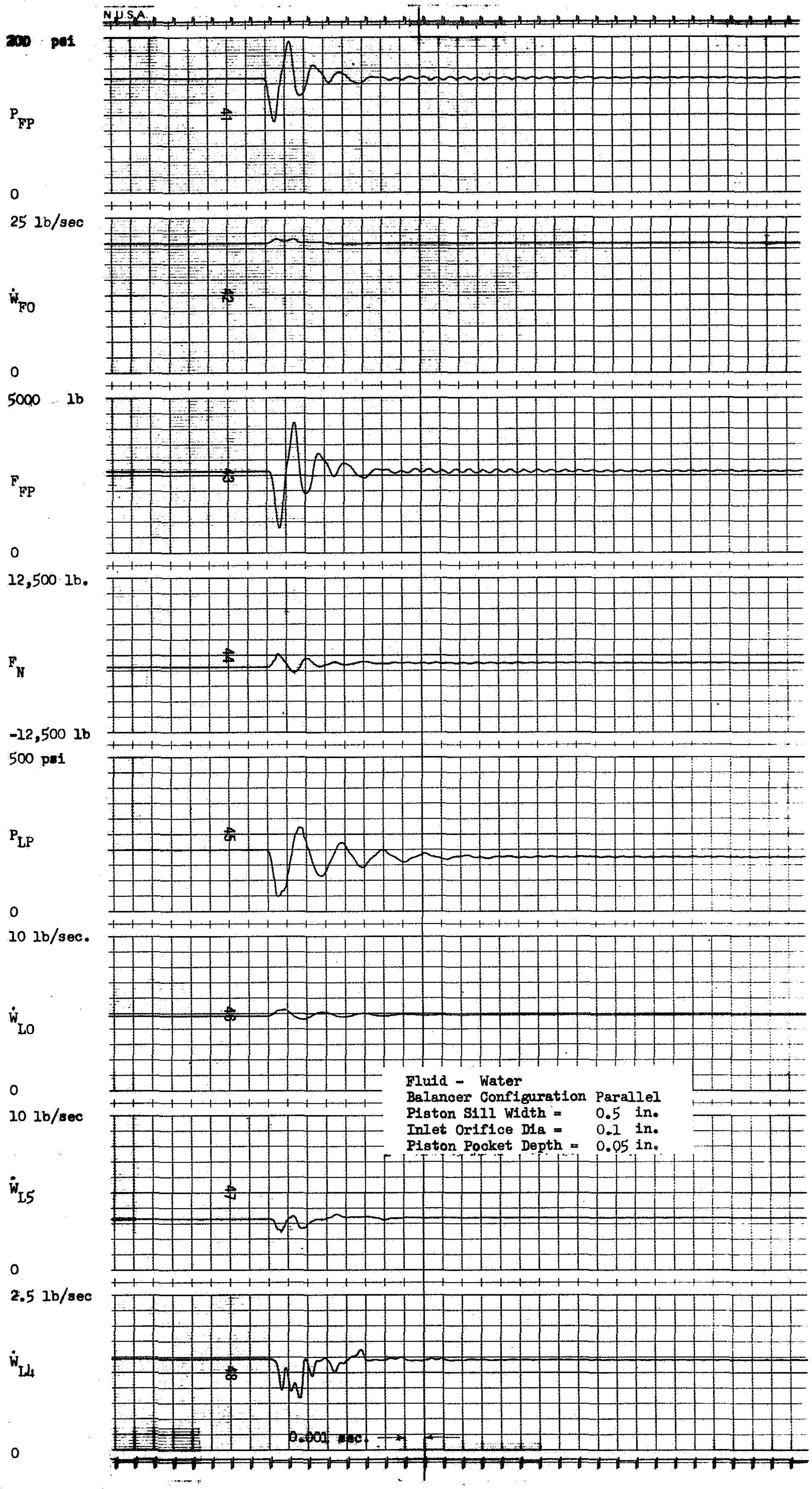


Figure C-49 Step Response - Incompressible, Parallel Balancer

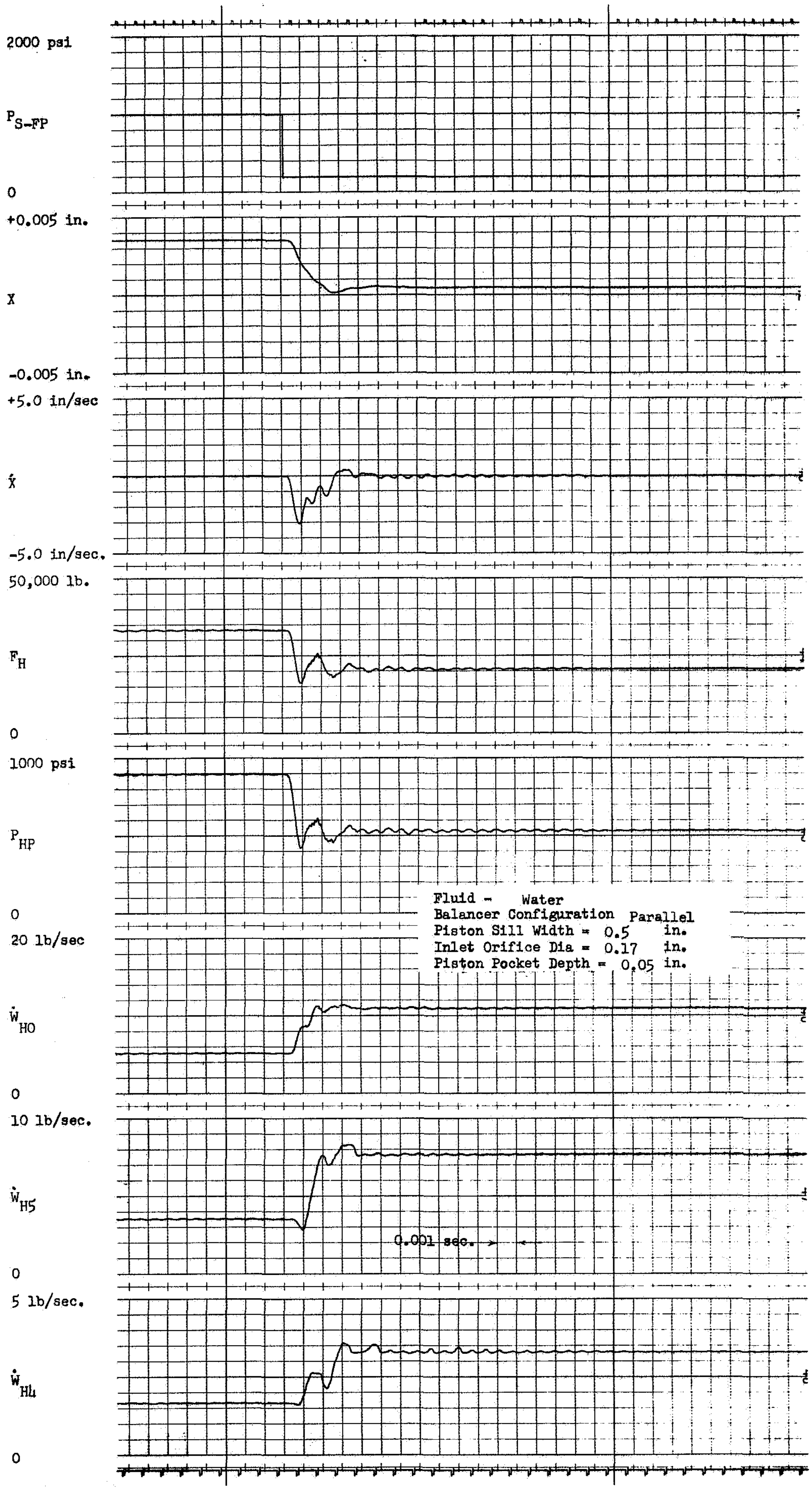


Figure C-50 Step Response - Incompressible, Parallel Balancer

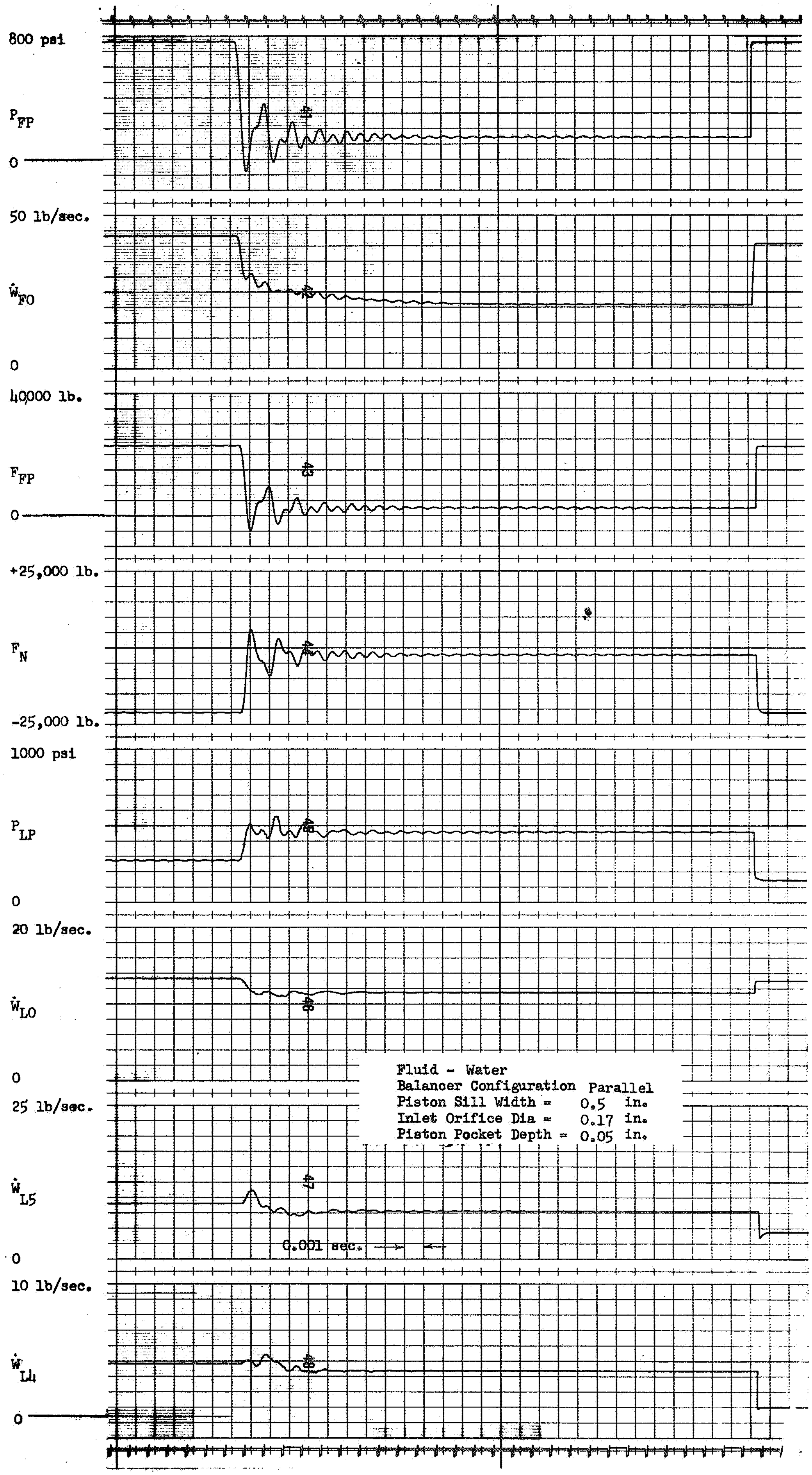


Figure C-51 Step Response - Incompressible, Parallel Balancer

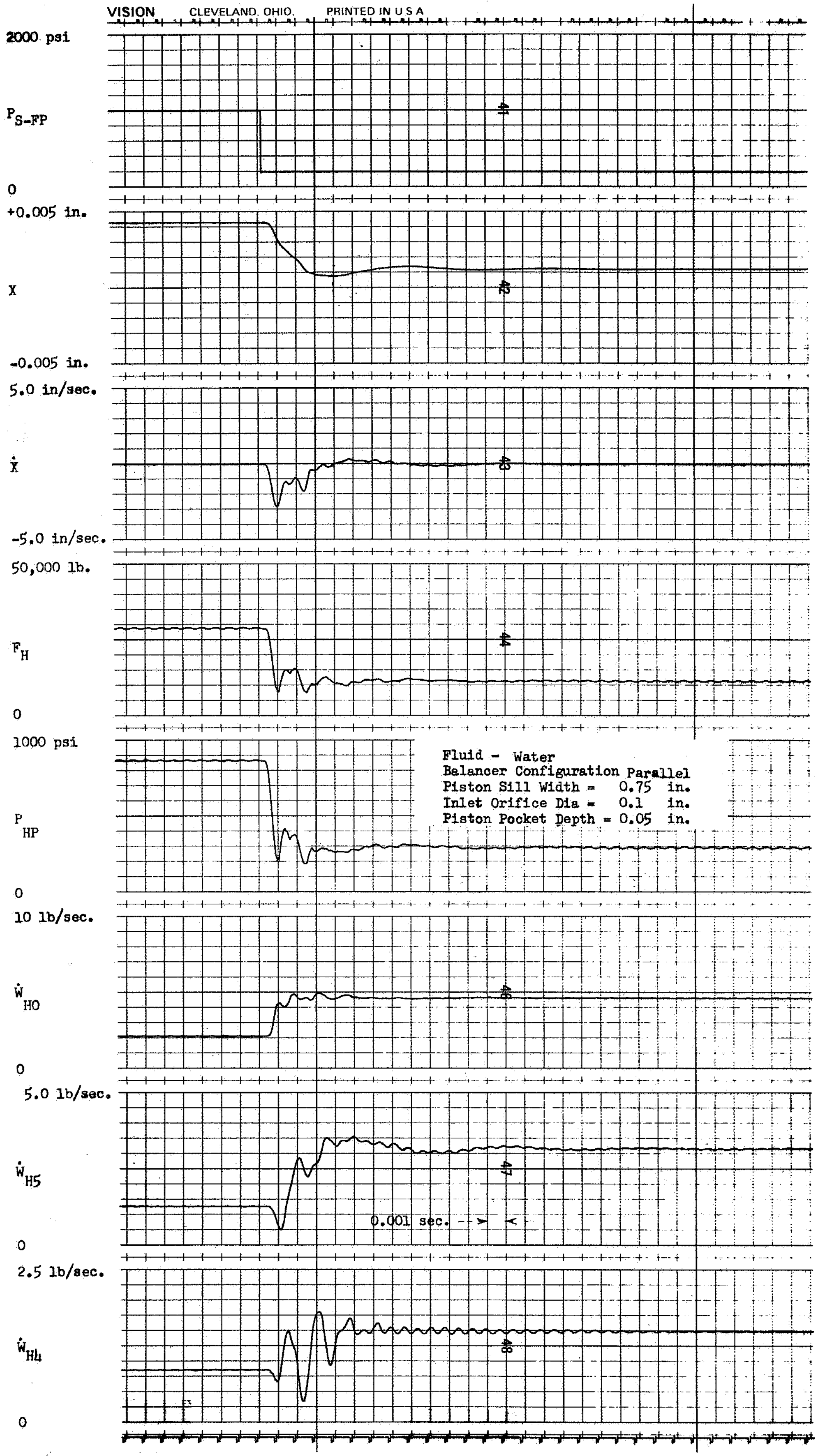


Figure C-52 Step Response - Incompressible, Parallel Balancer

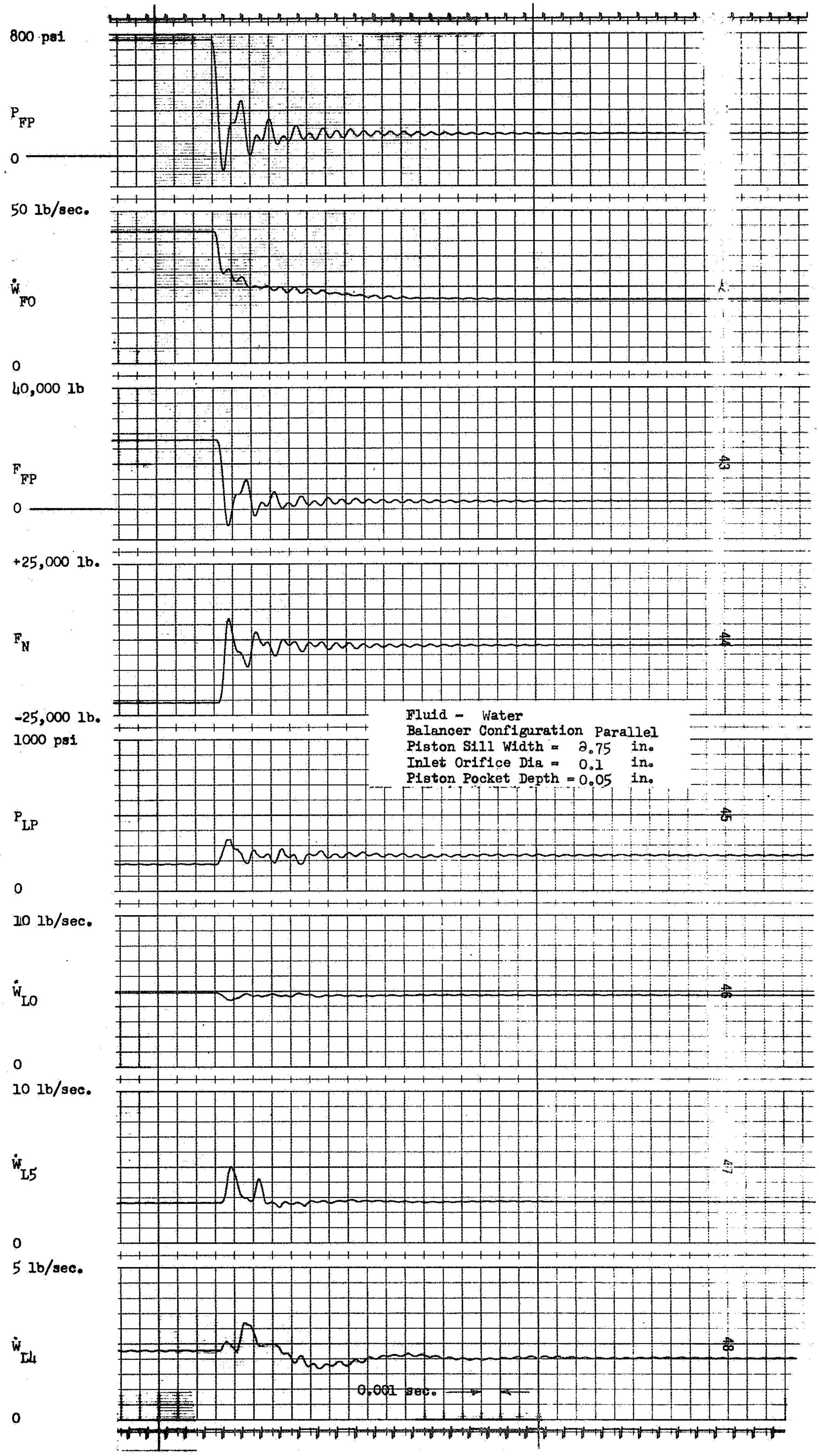


Figure C-53 Step Response - Incompressible, Parallel Balancer

A comparison of records with pocket depths of 0.025-in., 0.050-in., and 0.1-in. indicate nearly identical results. Therefore, the sensitivity of pocket depth upon system operation is small.

The results of the parametric study showed that the parallel incompressible flow balancer is quite insensitive to parameter changes. Increasing the sill width results in a slightly more oscillatory system while variations in inlet orifice and pocket depth produced no great change.

2. Series Flow Balancer - Incompressible Flow

A list of the nominal parameters used in the incompressible series flow case is provided as Table C-II. As with the parallel case, the nominal configuration has a sill width of 0.5-in., an inlet orifice of 0.1-in., and a piston pocket depth of 0.05-in.

Frequency response data for the nominal case is shown on Figures No. C-54 and No. C-55. Records of the nominal system response to a pressure step at the load piston and balance piston sources are shown on Figures No. C-56 and No. C-57, respectively. These records are used for comparison of the nominal response with those obtained with parameter variations.

With the inlet orifice diameter increased to 0.2-in., the frequency response functions change to that of Figures No. C-58 and No. C-59. Comparing these responses with those for the nominal orifice, it is evident that the resonant peaks become higher as the orifice diameter is increased. The higher resonant peaks indicate that the system Eigenvalues or closed-loop poles have moved toward the unstable region. The response to a step in load piston source pressure (Figure No. C-60) also is more underdamped than it previously was in the nominal case. This substantiates the relative decrease in stability noted in the frequency response records. The difference in response to a step in balance piston source pressure (Figure No. C-61) is less pronounced.

Figures No. C-62 and No. C-63 show the resulting frequency response records of the system with the pocket depth increased to 0.1-in. A comparison of these records with those obtained for the nominal case shows only minor differences. Although the step response records are not shown, they also reflect very minor differences from those of the nominal. The system appears quite insensitive to changes in pocket depth.

The frequency response records for the system with a sill width of 0.25-in. and 0.75-in. are shown on Figures No. C-64 and No. C-65, and Figures No. C-66 and No. C-67, respectively. A comparison of these records with those obtained with a 0.5-in. sill shows them all to be very similar. Some variation in low frequency gain is noted, which indicates a variation in system stiffness. The anti-resonance or zero of the frequency response of

TABLE C-II

PARAMETER VALUES - COMPRESSIBLE FLOW

Parameter	Parallel Balancer	Series Balancer	Units
B	50	50	lb-sec/in.
C_{fi}	4.15×10^{-6}	4.15×10^{-6}	$in.^2$
C_f	7.14×10^{-6}	7.14×10^{-6}	$in.^2$
C_{hi}, C_{li}	1.04×10^{-5}	1.04×10^{-5}	$in.^2$
C_{ho}, C_{lo}	1.62×10^{-5}	1.62×10^{-5}	$in.^2$
C_o	8.4×10^{-6}	-	$in.^2$
C	.01	.01	in.
d_{FO}	0.7	0.7	in.
d_{HO}, d_{LO}	0.1	0.1	in.
h_s	0.006	0.006	in.
K	250,000	250,000	lb/in.
K_c	2.4×10^{-5}	2.4×10^{-5}	in.
K_{FO}	11.2	11.2	$sec^2/lb\text{-}in.^2$
K_{F1}	20	20	$sec^2/lb\text{-}in.^2$
K_{HO}', K_{LO}'	1.195	1.195	$sec^2\text{-}in./lb^2$
K_k	3.36×10^{-4}	3.36×10^{-4}	$lb/in.^3$
K_T	333	333	$in.^3/lb$
K_γ	2.98×10^{-6}	2.98×10^{-6}	1/in.
L_{FO}	1.68×10^{-3}	1.68×10^{-3}	$sec^2/in.^2$
L_{F1}	5×10^{-3}	5×10^{-3}	$sec^2/in.^2$
L_{fi}	9.26×10^{-3}	9.26×10^{-3}	$sec^2/in.^2$
L_{fo}	4.64×10^{-3}	4.64×10^{-3}	$sec^2/in.^2$

TABLE C-II (cont.)

Parameter	Parallel Balancer	Series Balancer	Units
L_{HO}, L_{LO}	1.375×10^{-3}	1.375×10^{-3}	$sec^2/in.^2$
L_{hi}, L_{li}	3.0×10^{-3}	3.0×10^{-3}	$sec^2/in.^2$
L_{ho}, L_{lo}	2.3×10^{-3}	2.3×10^{-3}	$sec^2/in.^2$
L_o	4.5×10^{-3}	-	$sec^2/in.^2$
M	.103	.103	$lb\text{-}sec^2/in.$
N_{RPM}	10,000	10,000	RPM
R_{FP}	3.625	3.625	$in.^2$
R_{HP}	2.875	2.875	in.
R_{H2}, R_{L2}	1.75	1.75	in.
R_{H3}, R_{L3}	2.25	2.25	in.
R_{H6}, R_{L6}	3.5	3.5	in.
R_{H7}, R_{L7}	4.0	4.0	in.
R_s	1.5	1.5	in.
V_F	17.62	17.62	$in.^3$
V_{H1}, V_{L1}	5.05	5.05	$in.^3$
V_8	26.4	-	$in.^2$

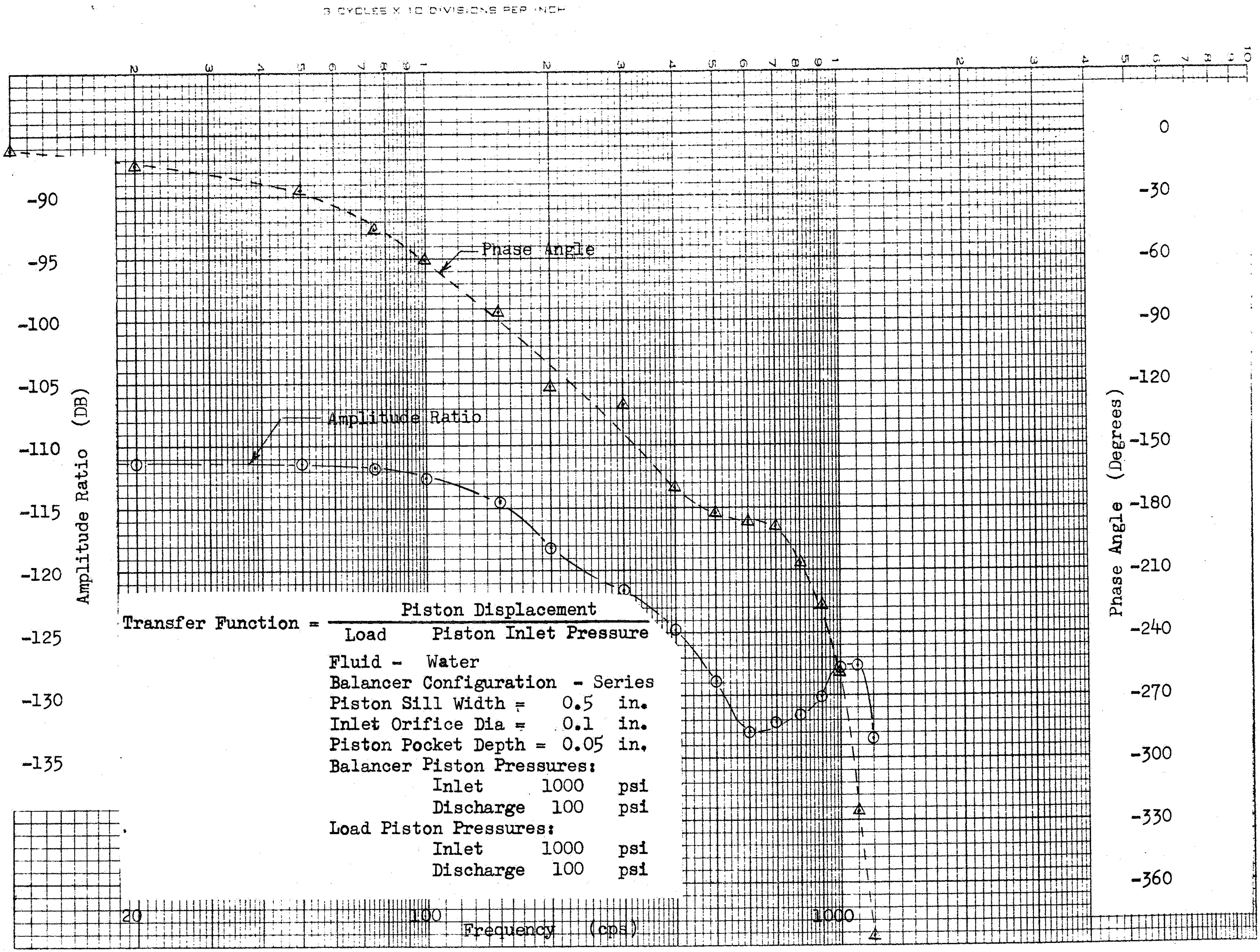


Figure C-54 Frequency Response - Incompressible, Series Balancer

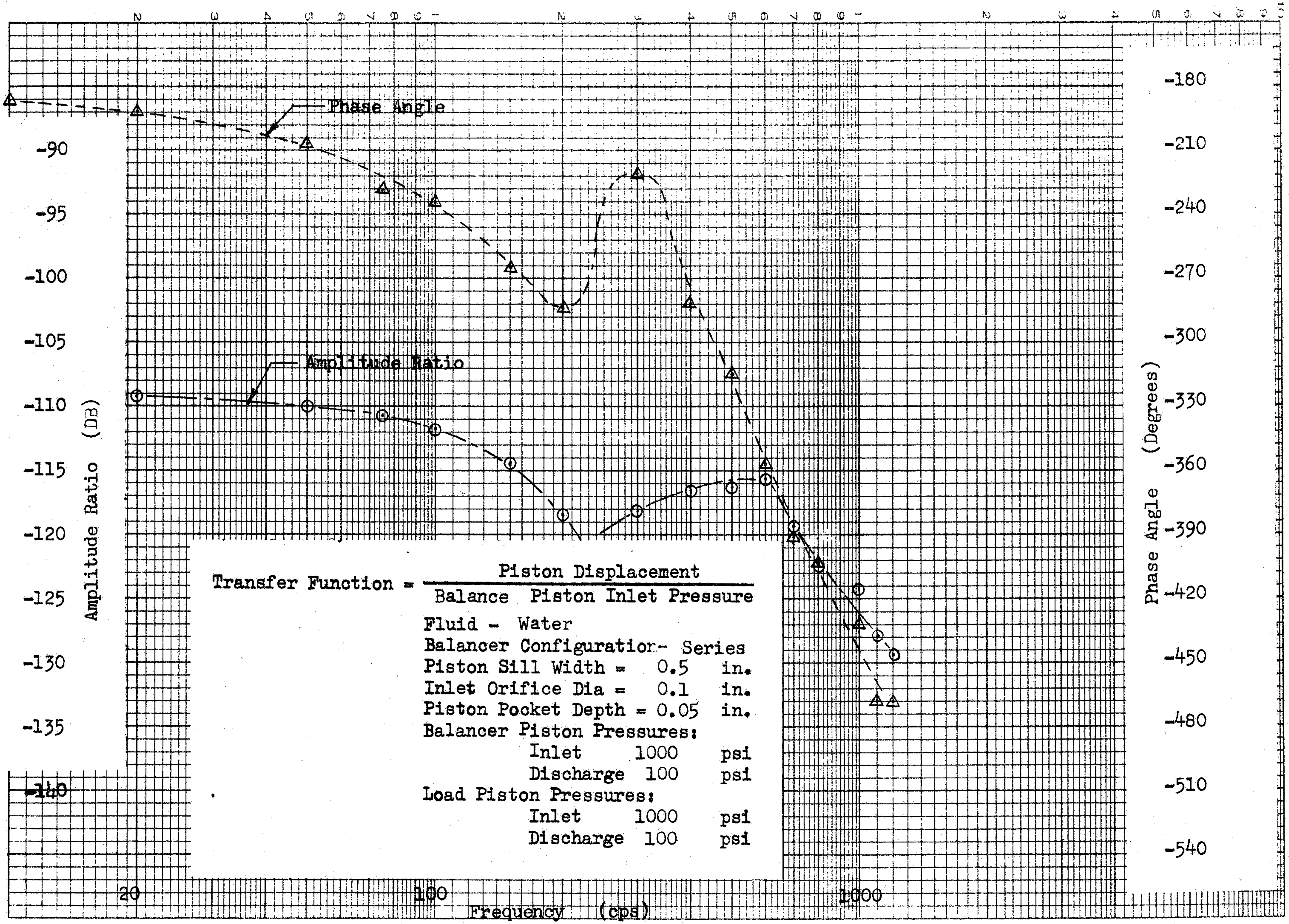


Figure C-55 Frequency Response - Incompressible, Series Balancer

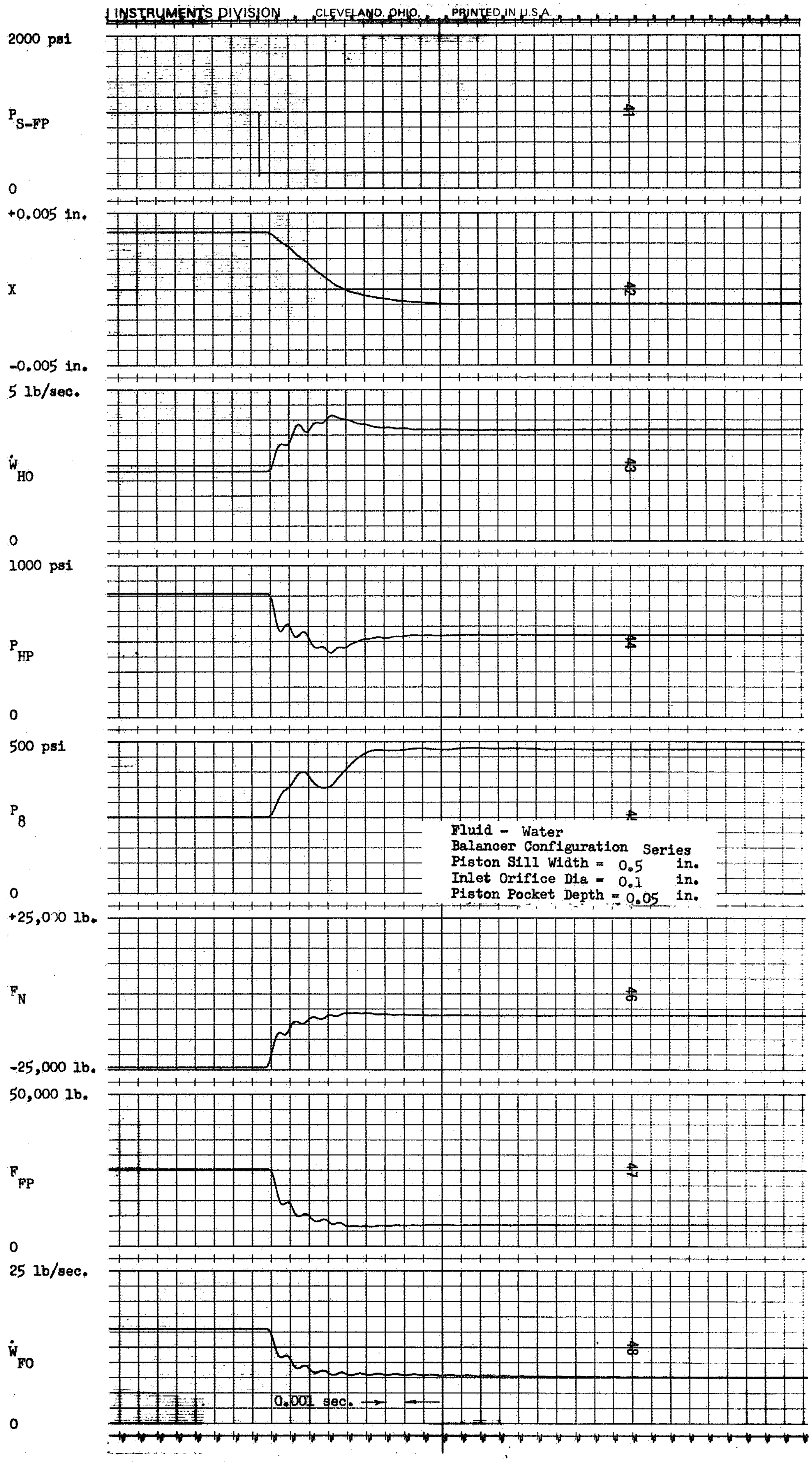


Figure C-56 Step Response - Incompressible, Series Balancer

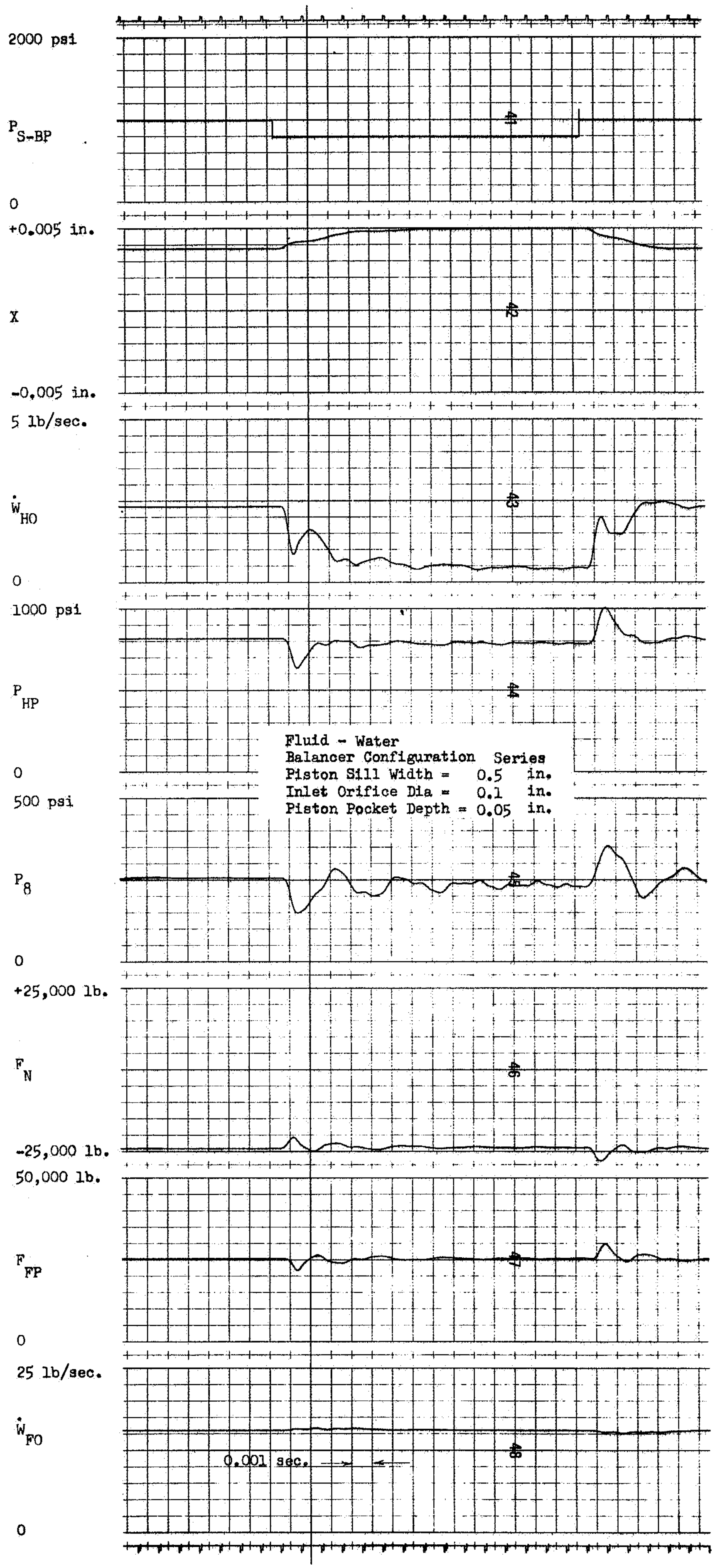


Figure C-57 Step Response - Incompressible, Series Balancer

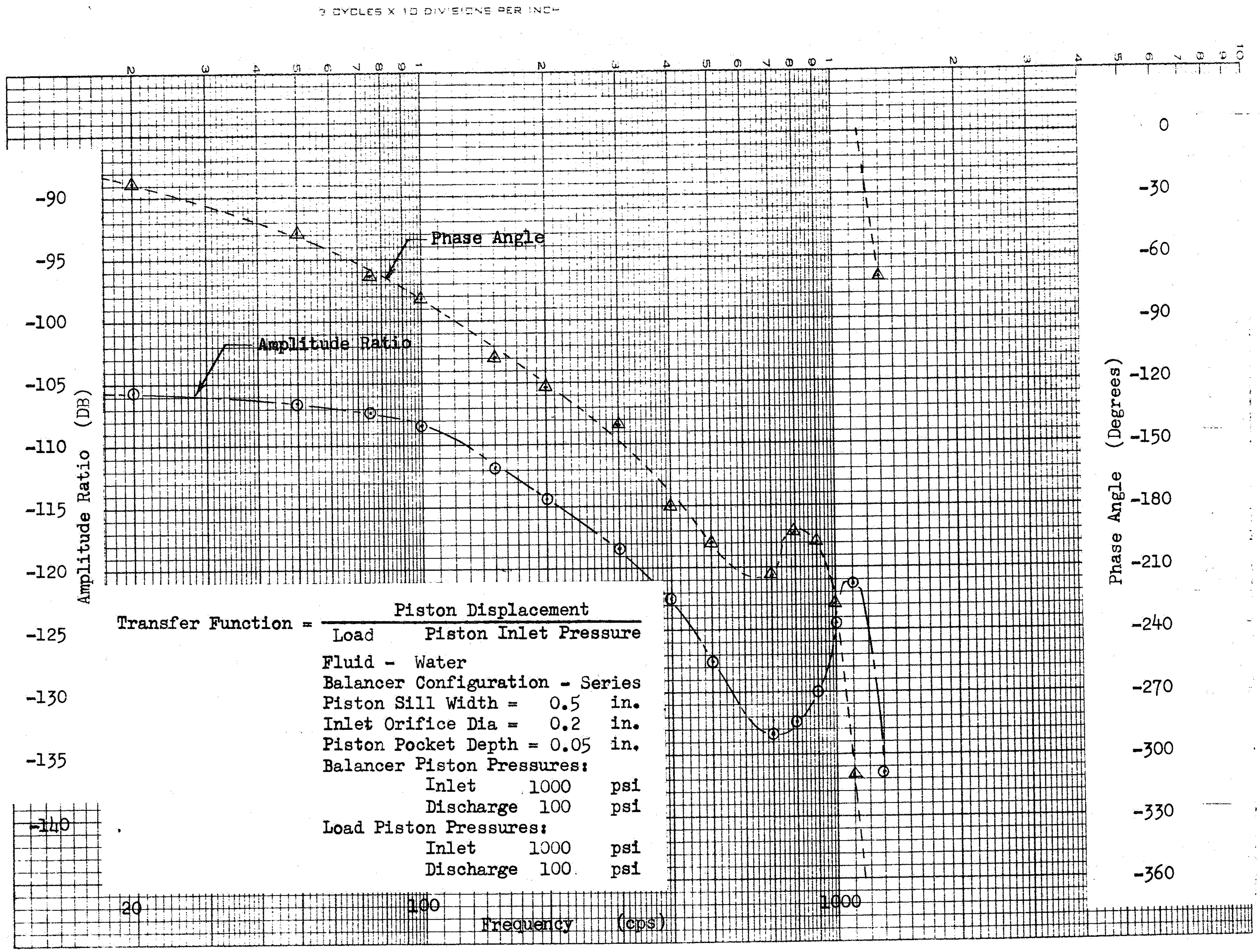


Figure C-58 Frequency Response - Incompressible, Series Balancer

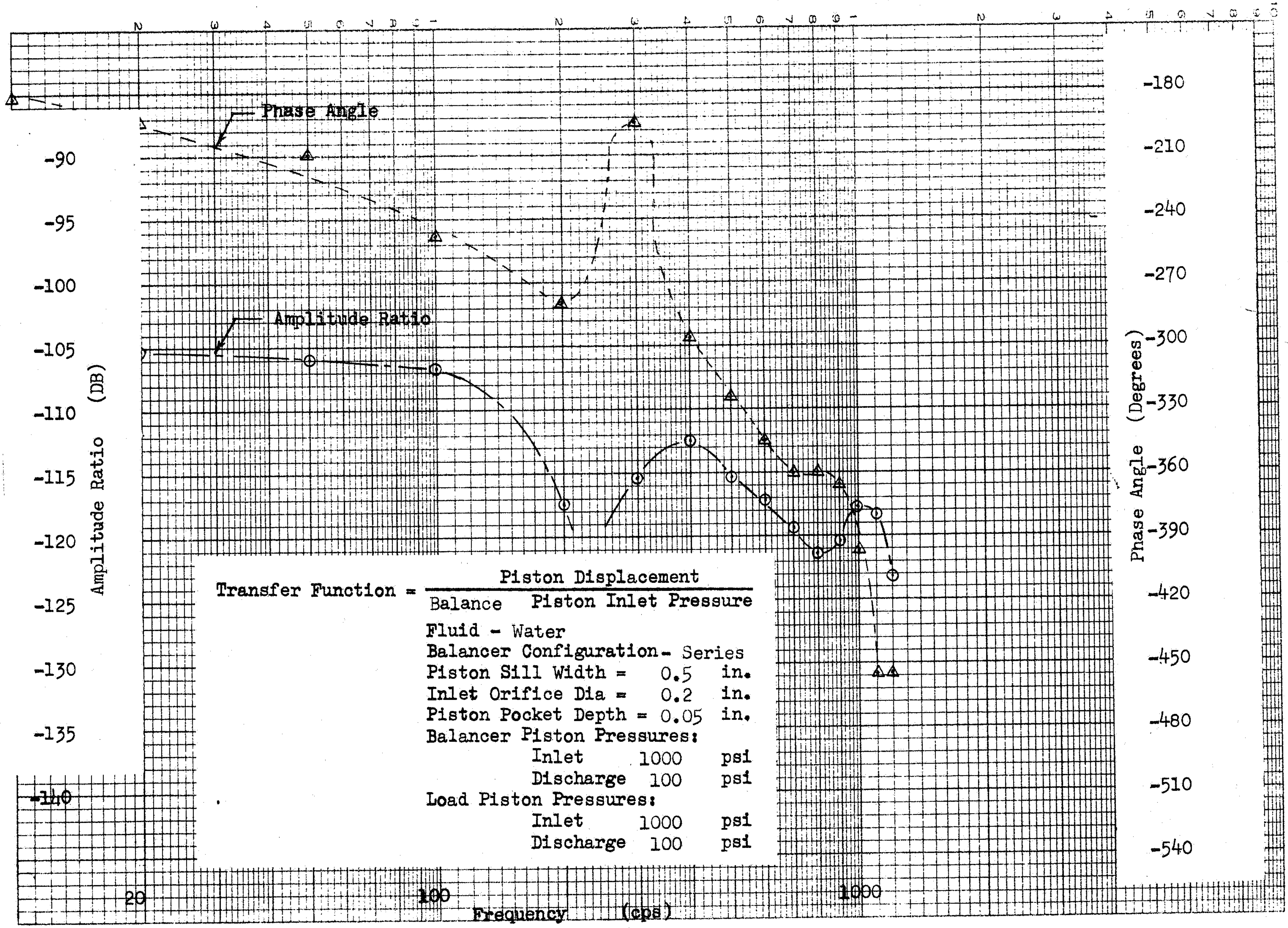


Figure C-59 Frequency Response - Incompressible, Series Balancer

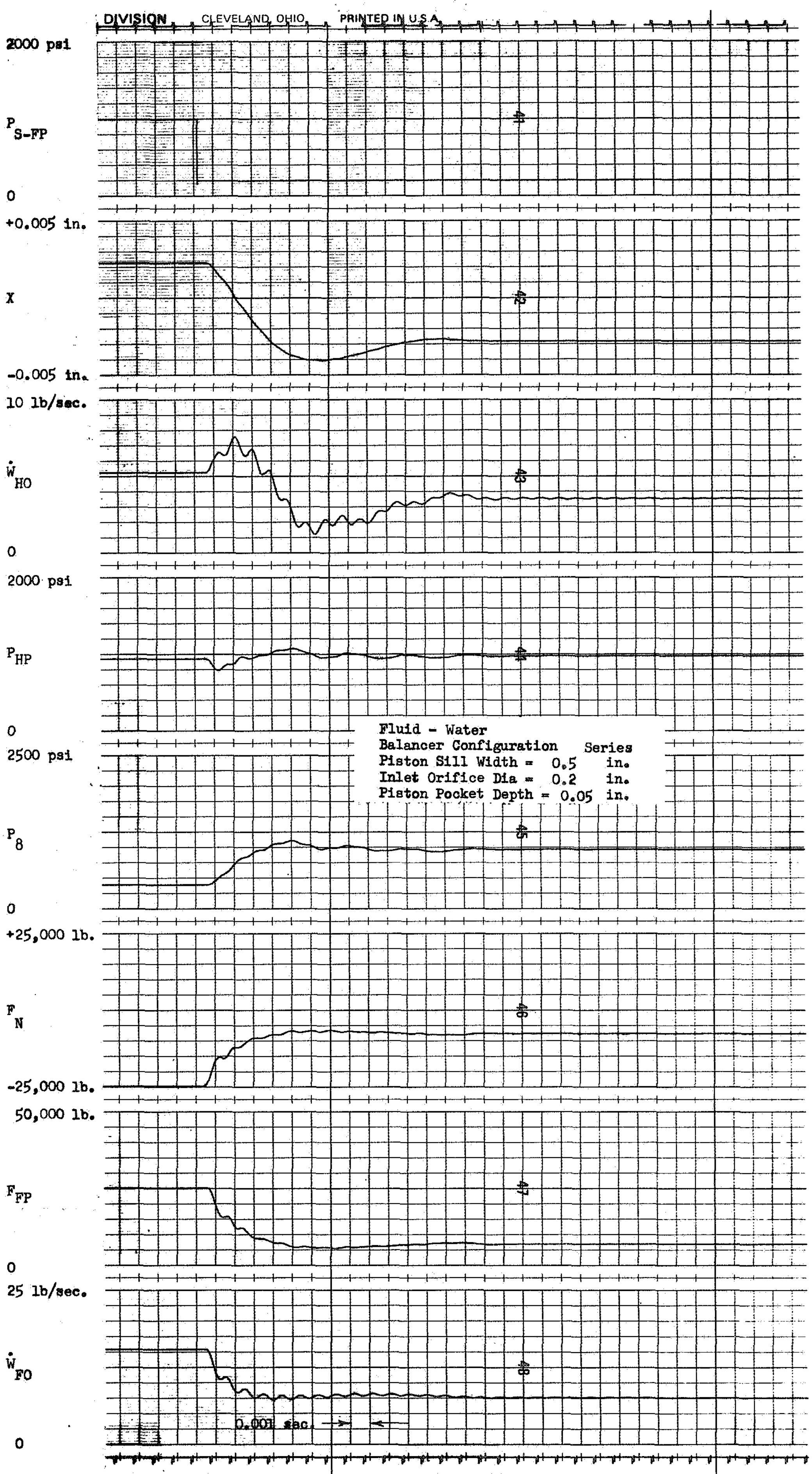


Figure C-60 Step Response - Incompressible, Series Balancer

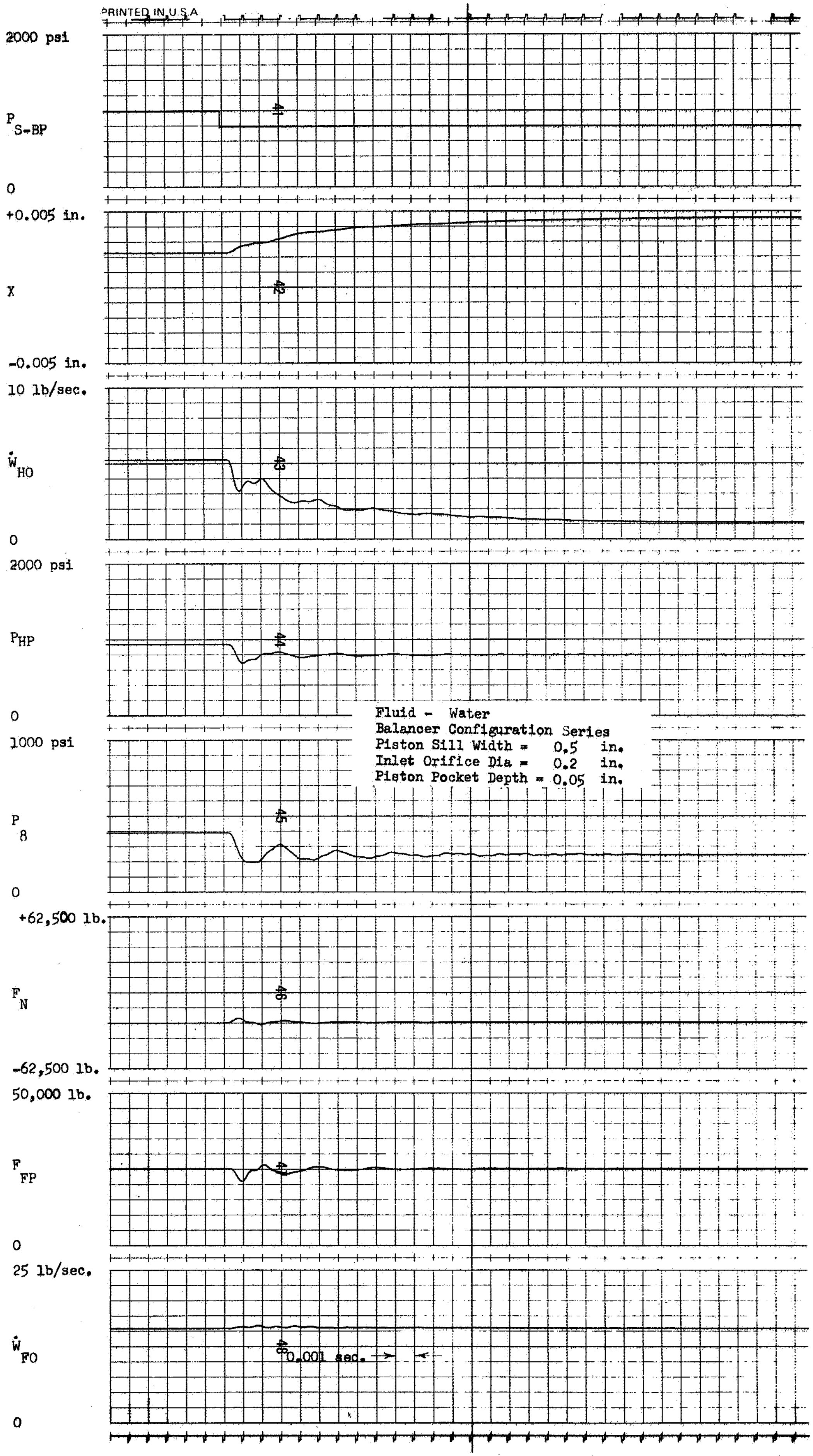


Figure C-61 Step Response - Incompressible, Series Balancer

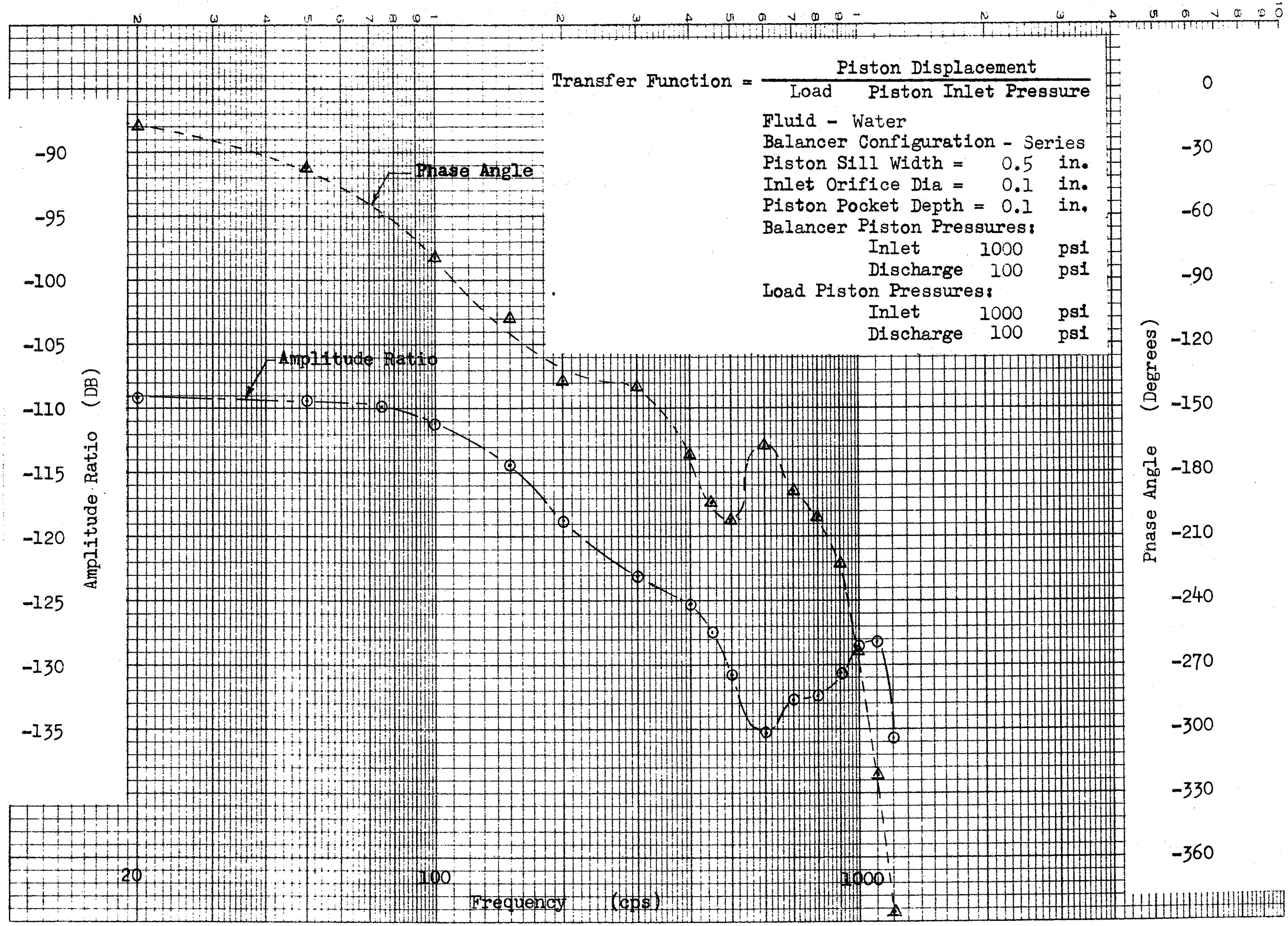


Figure C-62 Frequency Response - Incompressible, Series Balancer

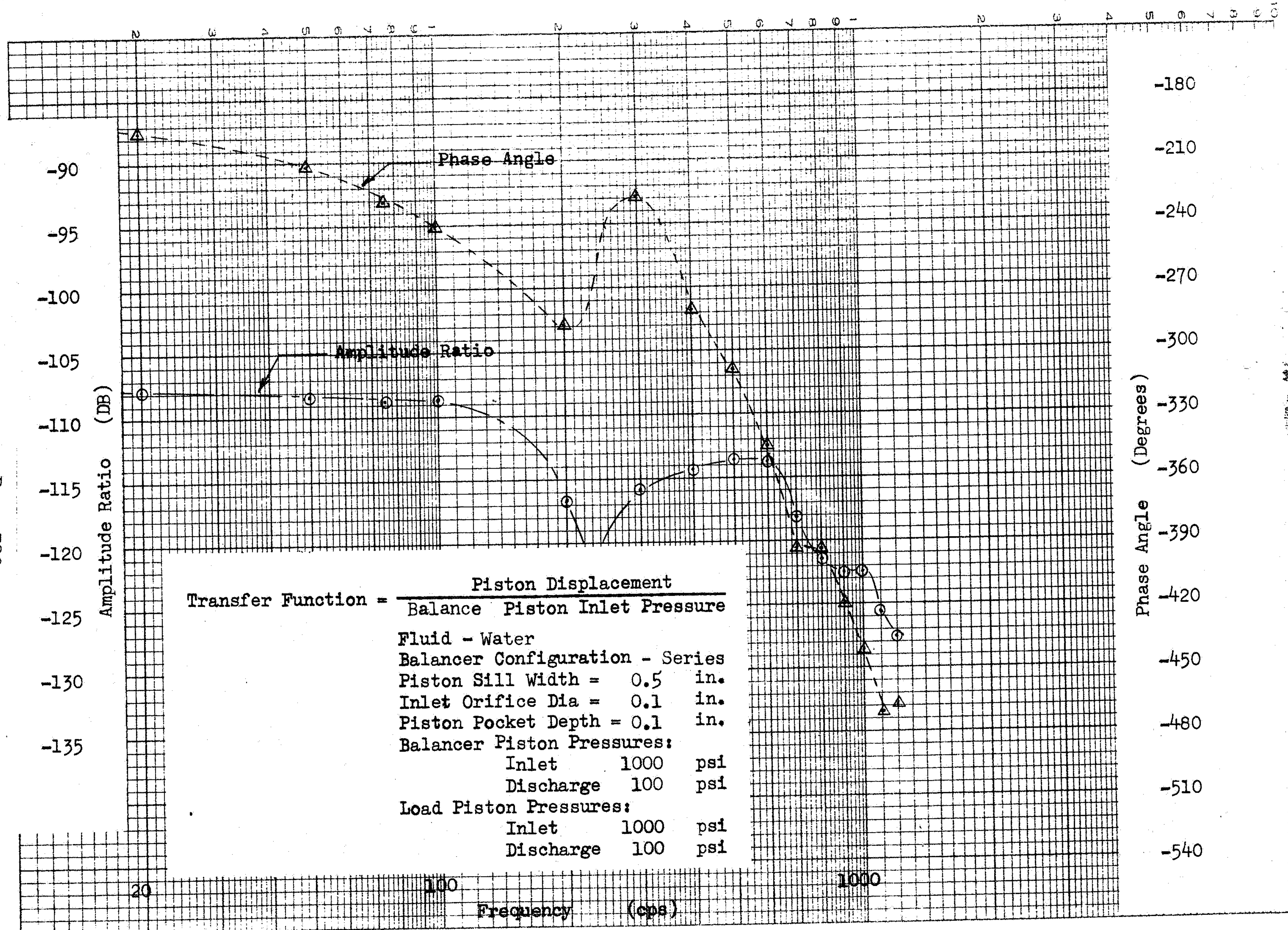


Figure C-63 Frequency Response - Incompressible, Series Balancer

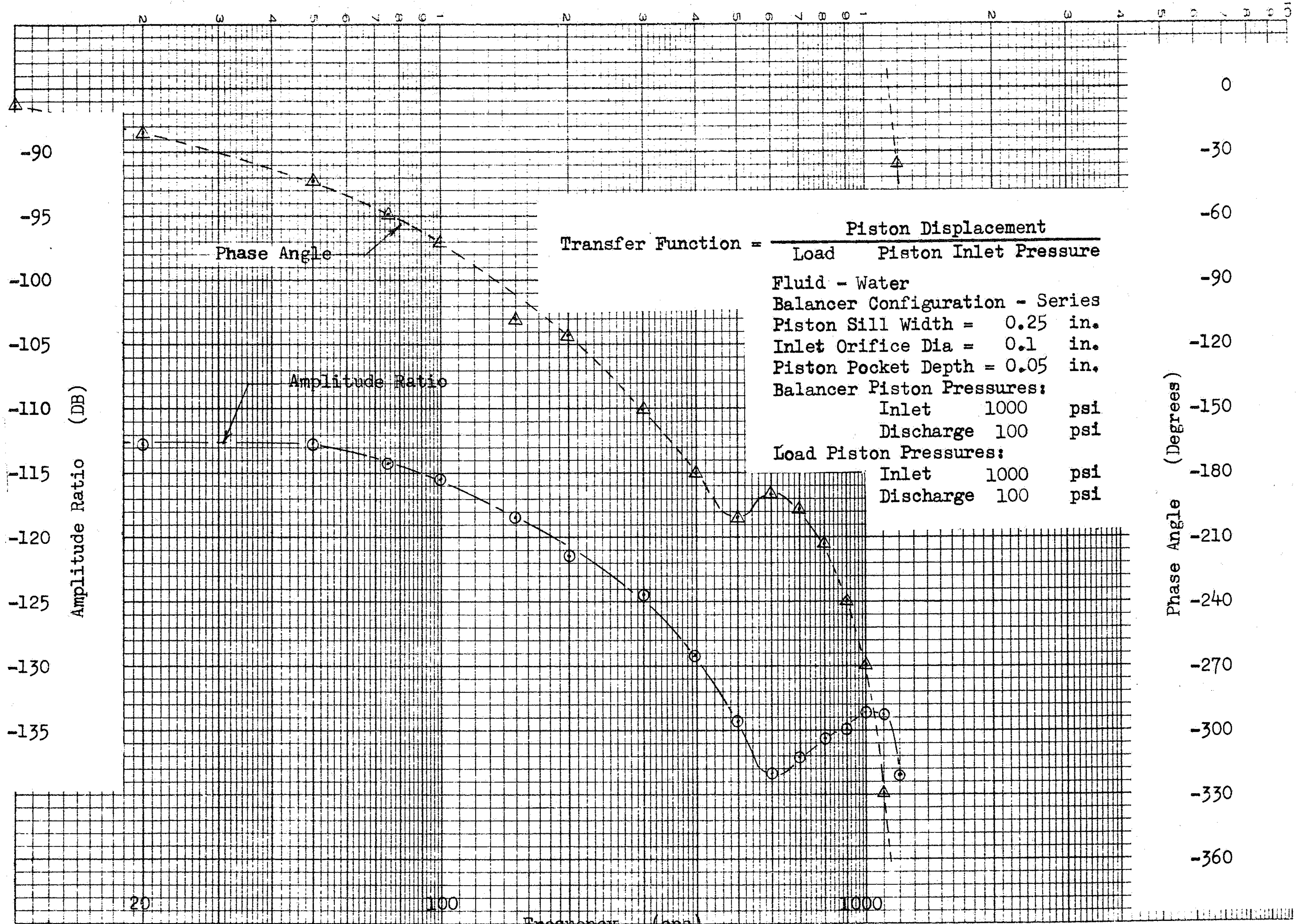


Figure C-64 Frequency Response - Incompressible, Series Balancer

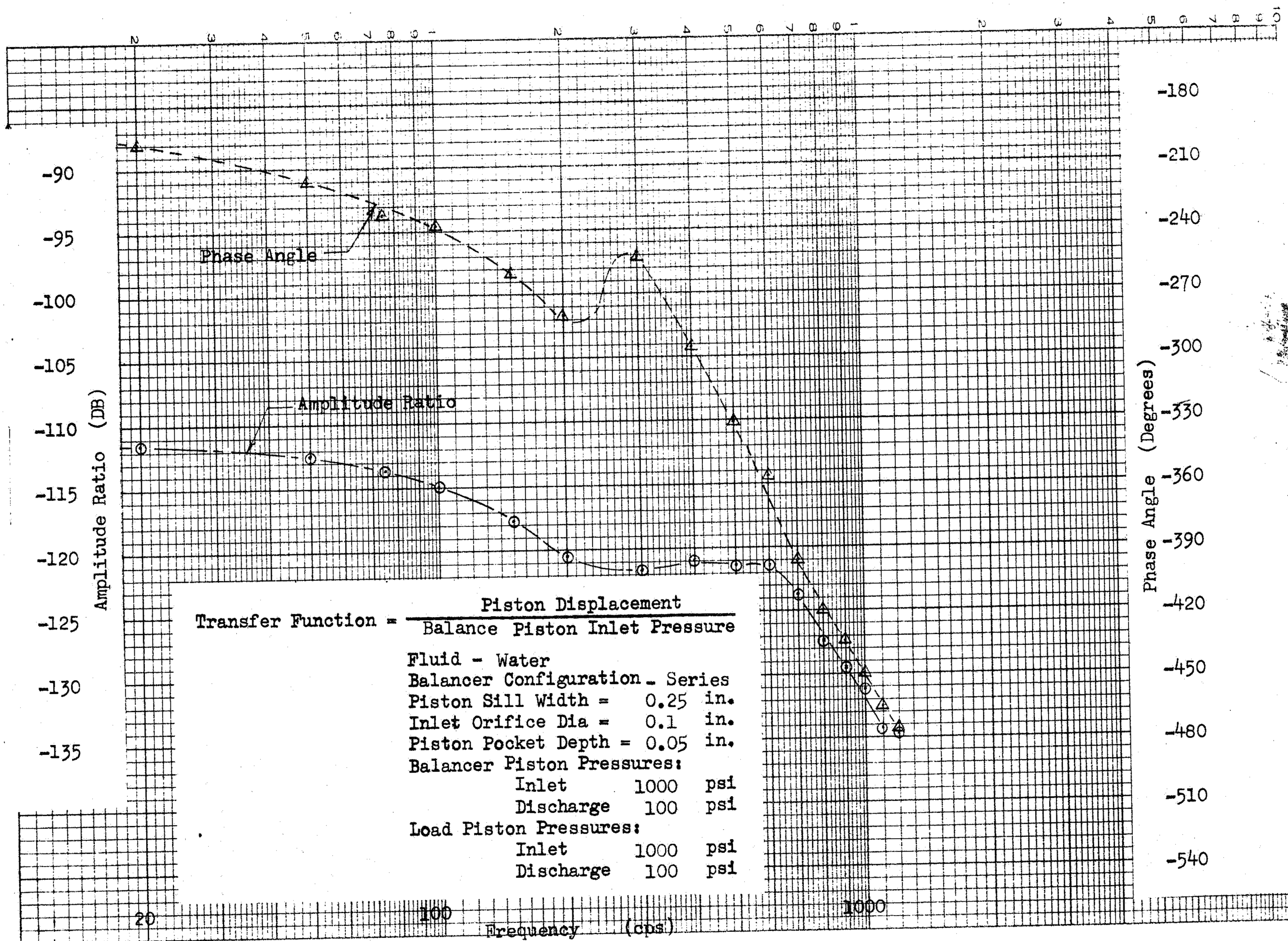


Figure C-65 Frequency Response - Incompressible, Series Balancer

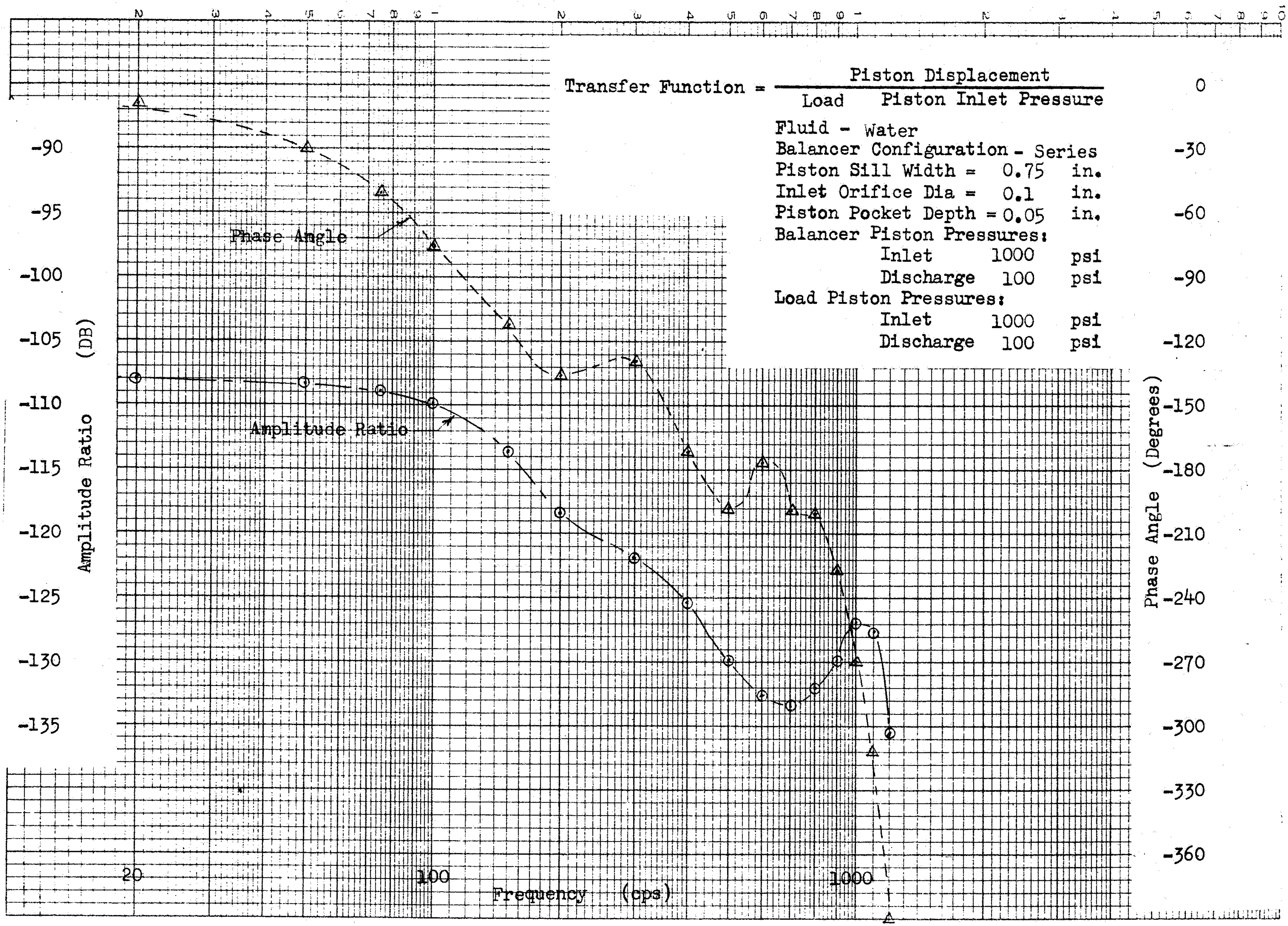


Figure C-66 Frequency Response - Incompressible, Series Balancer

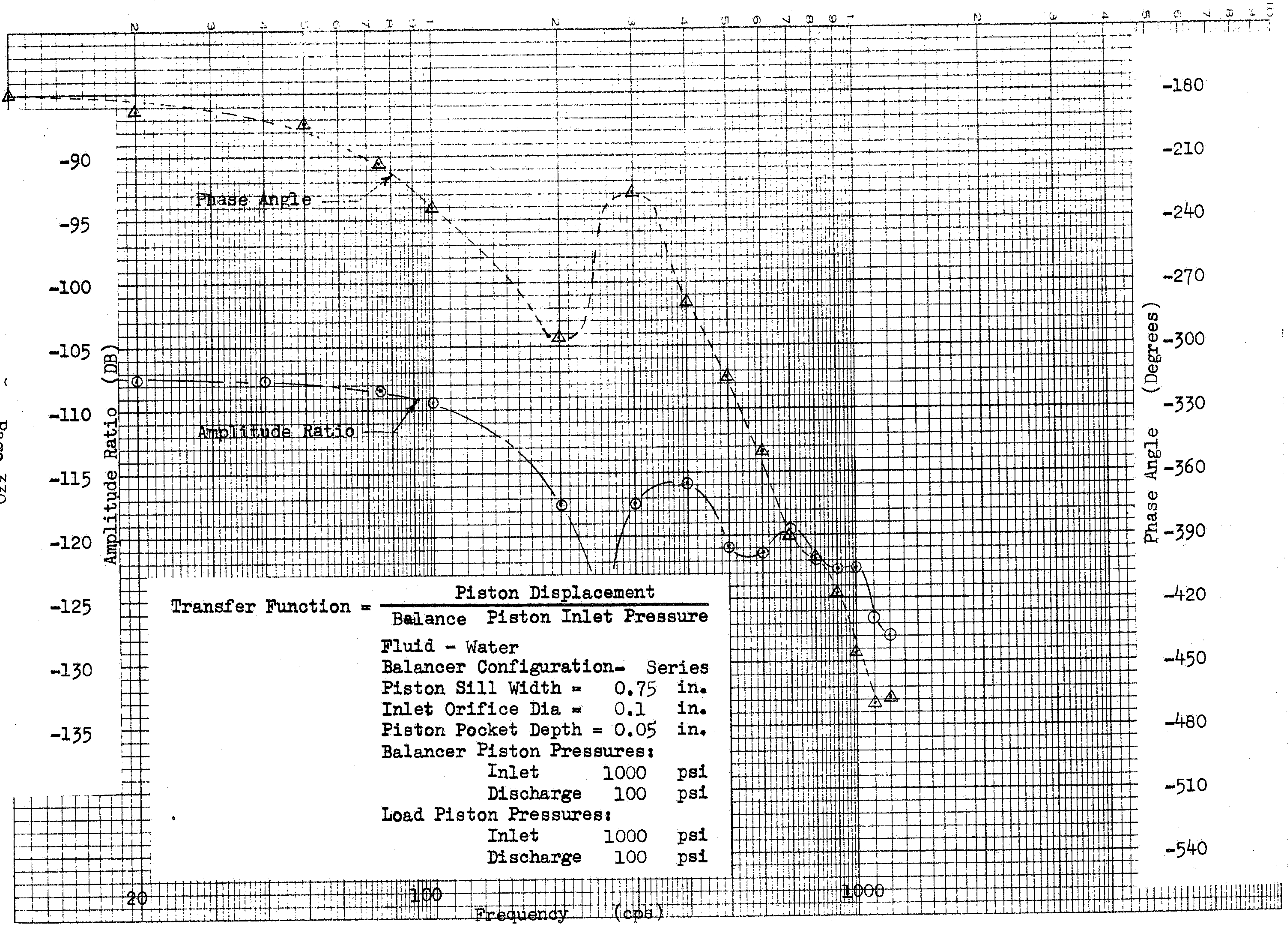


Figure C-67 Frequency Response - Incompressible, Series Balancer

piston displacement to balance piston pressure becomes less damped as the piston sill width increases. However, this is not expected to have any great affect upon stability because it is the damping of the resonance points or poles which define the stability. Although the step response records for the 0.25-in. and 0.75-in. cases are not included, their dynamic behavior is very similar to that obtained with a 0.5-in. sill. The step response also bears out the difference in stiffness where the stiffness is greatest with the narrow sill.

The study of the series incompressible balancer indicates that an increase in the inlet orifice to the balance piston results in a small decrease in relative stability. The system appears quite insensitive to variations in pocket depth and sill width.

3. Parallel Flow Balancer - Compressible Flow

The nominal parameters used in the parallel compressible study are listed on Table C-III. The nominal configuration has a 0.5-in. sill width, a 0.1-in. inlet orifice diameter, and a 0.01-in. pocket depth.

The compressible parallel configuration study included balancer pressure ranges of from 1000 psi to 500 psi, 400 psi to 200 psi, and 200 psi to 100 psi between inlet and discharge. However, most of the study was devoted to the 400 psi to 200 psi range.

The response of only one configuration was obtained in the 1000 psi to 500 psi pressure range. This configuration had an inlet orifice of 0.2-in. instead of the normal value of 0.1-in. The frequency and step responses are shown on Figures No. C-68 through No. C-73. The response to load piston excitation is well-behaved and quite similar to that obtained for the incompressible case. However, Figure No. C-69 shows that the response to balance piston pressure excitation becomes highly resonant. This also is evident from the oscillations of approximately 700 cps present in the step response of Figures No. C-72 and No. C-73. However, the oscillations dampen out and the system is stable.

Frequency response data for the system with a pressure range from 400 psi to 200 psi and nominal parameters is shown on Figures No. C-74 and No. C-75. Again, the response to balance piston pressure excitation shows a very low damped resonance. The phase angle plot passes through approximately 360-degrees, which indicates the presence of two pairs of complex Eigenvalues or poles in the vicinity of 700 cps. The response to a step in load pressure (Figures No. C-76 and No. C-77) shows an overshoot in piston displacement of approximately 100%. A step in balance piston pressure (Figures No. C-78 and No. C-79) produces a very low damped ringing of approximately 700 cps, which corresponds to the resonant peak noted on the frequency response.

TABLE C-III

LIST OF EIGENVALUES OBTAINED FROM THE DIGITAL COMPUTER STUDY

	Real Part	Imaginary Part
1	-91,214	-
2	-27,539	-
3	-32,999	-
4	-16,471	-
5	-18,238	-
6,7	-99.98	±10,528
8,9	-13.8	±8,644
10,11	-1900	±7,718
12,13	-5550	±2,000
14,15	-503	±4,580
16,17	-234	±4,283
18,19	+305	±4,329
20,21	-24	±3,446
22	-3989	-
23	-608	-
24	-21.1	-

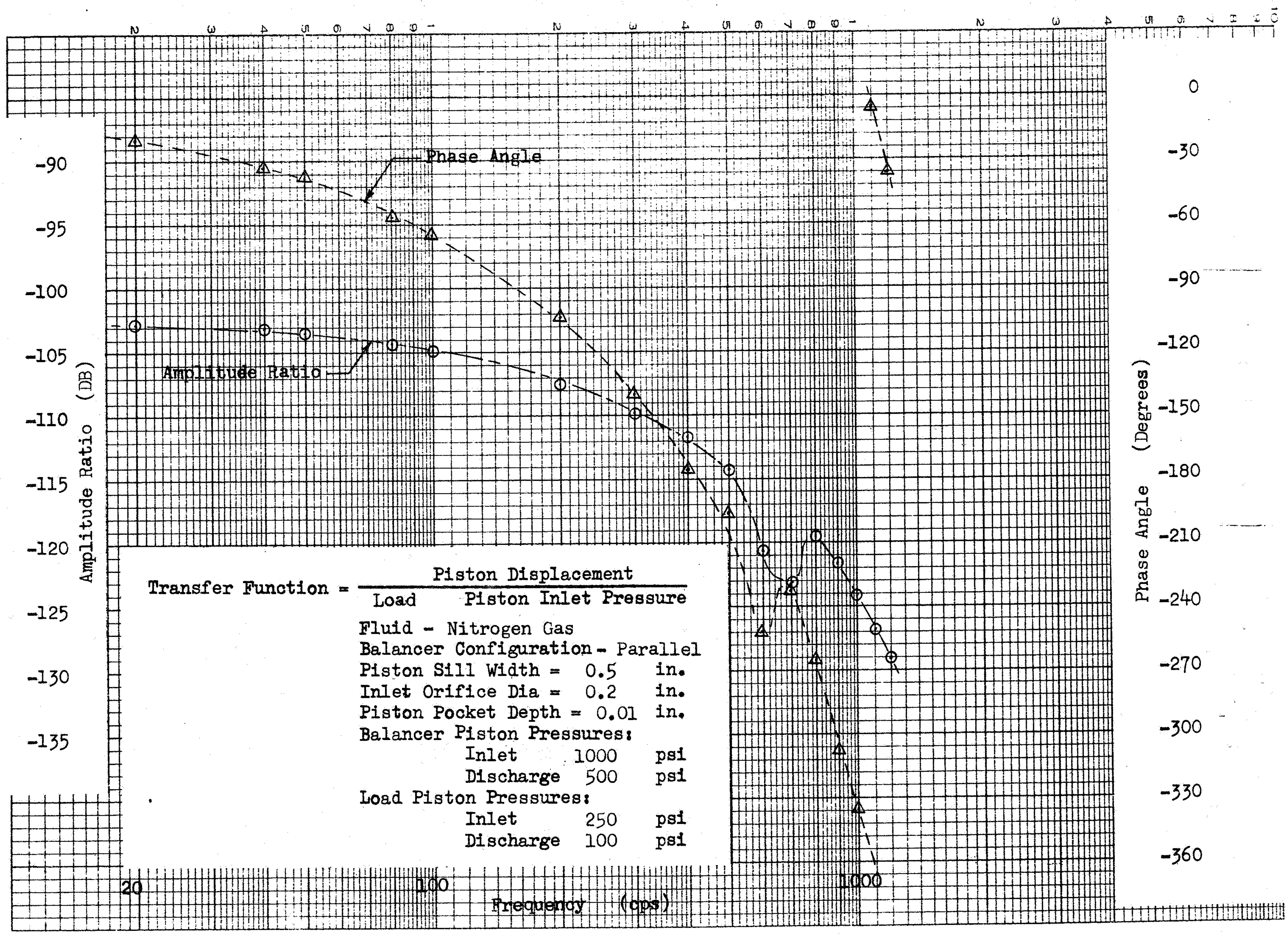


Figure C-68 Frequency Response - Compressible, Parallel Balancer

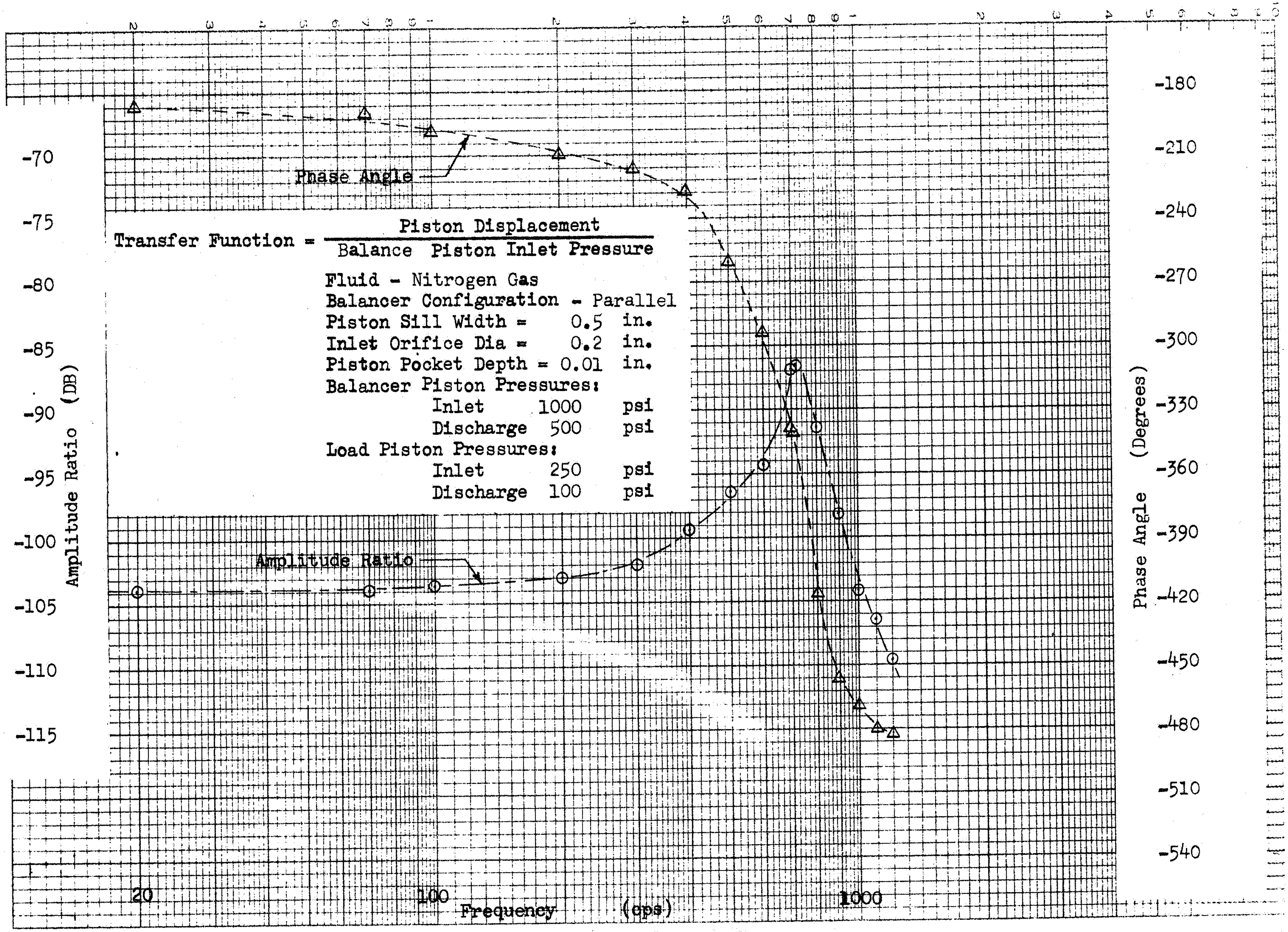


Figure C-69 Frequency Response - Compressible, Parallel Balancer

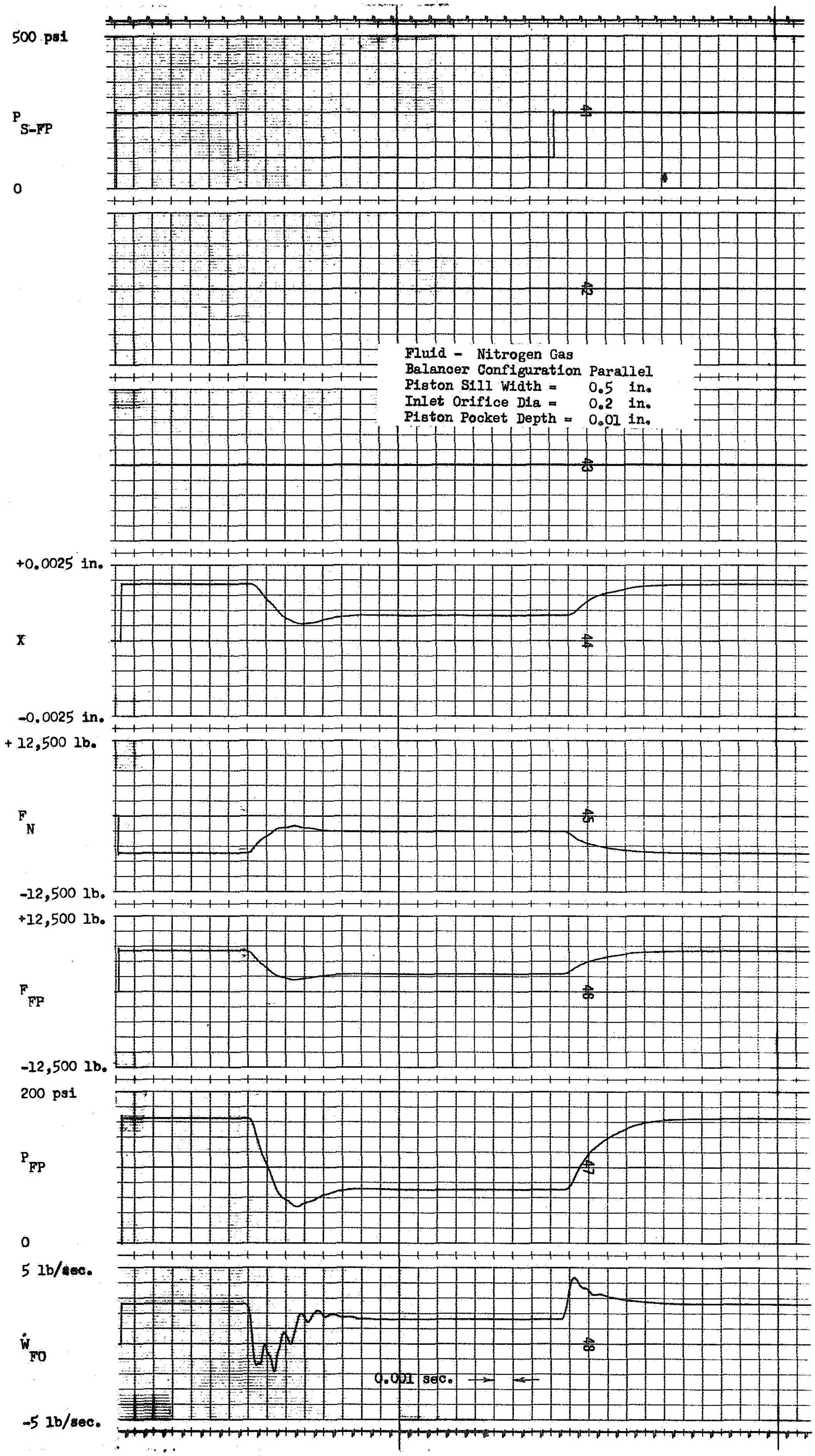


Figure C-70 Step Response - Compressible, Parallel Balancer

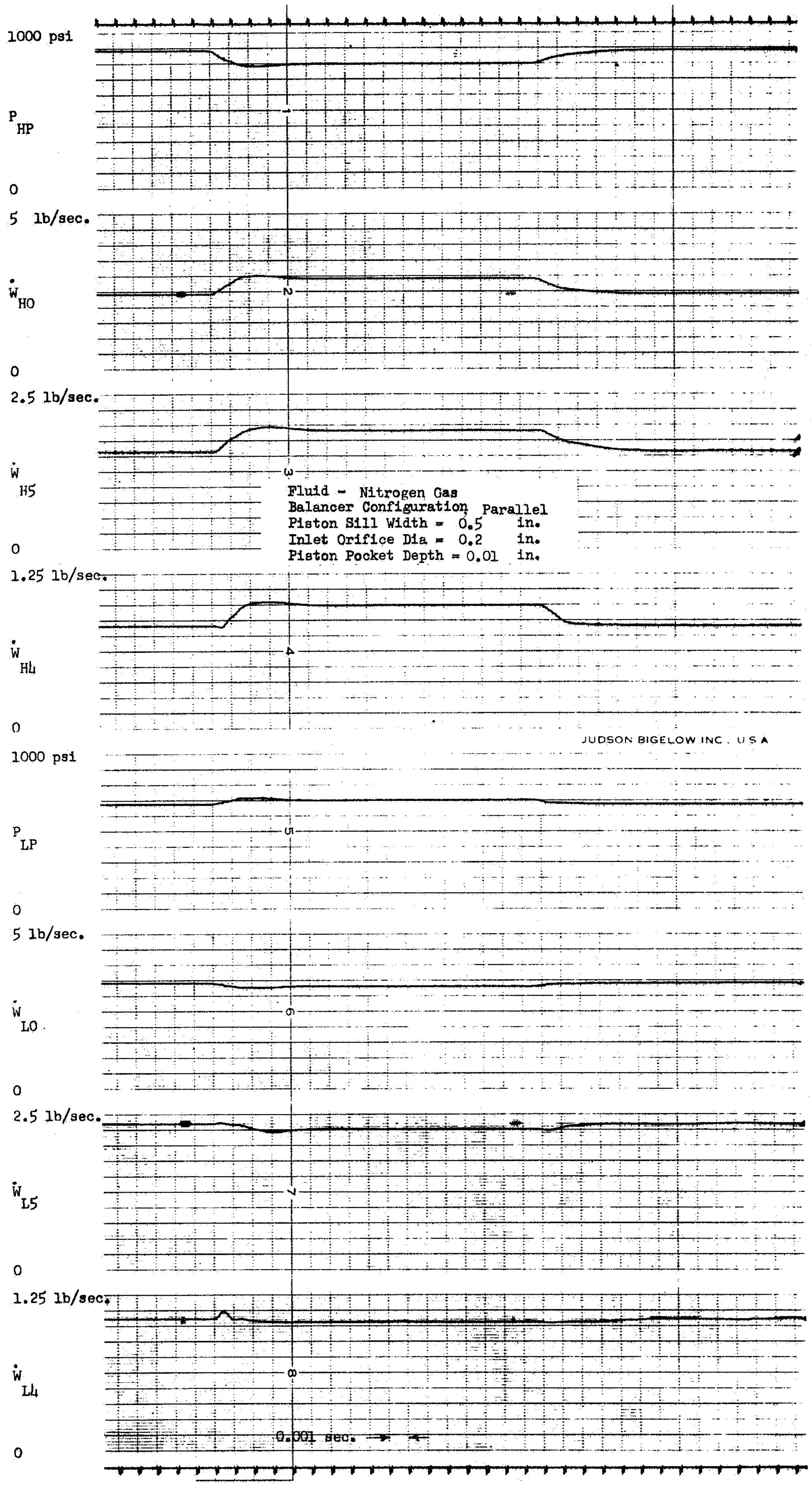


Figure C-71 Step Response - Compressible, Parallel Balancer

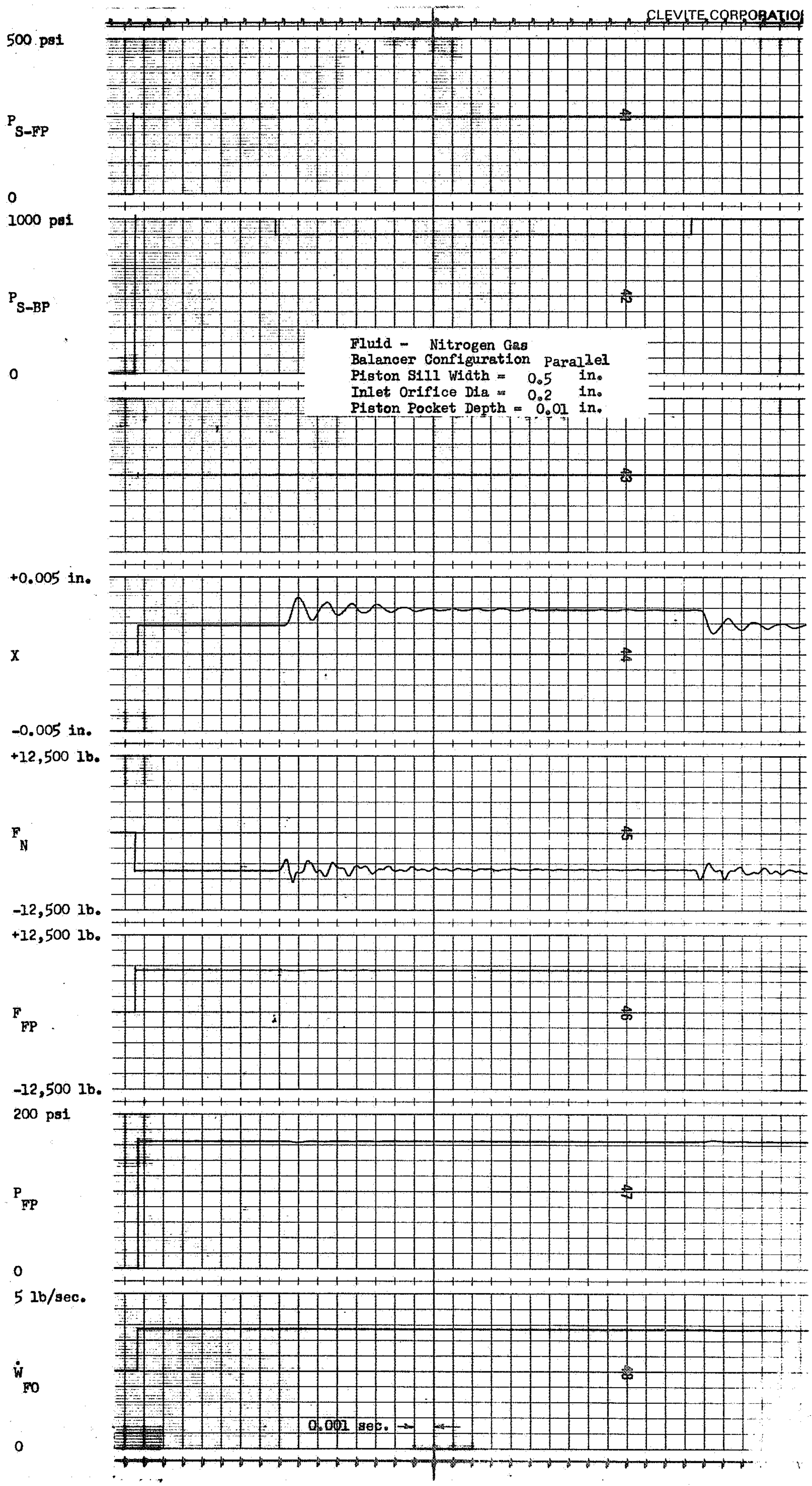


Figure C-72 Step Response - Co[illegible]e, Parallel Balancer

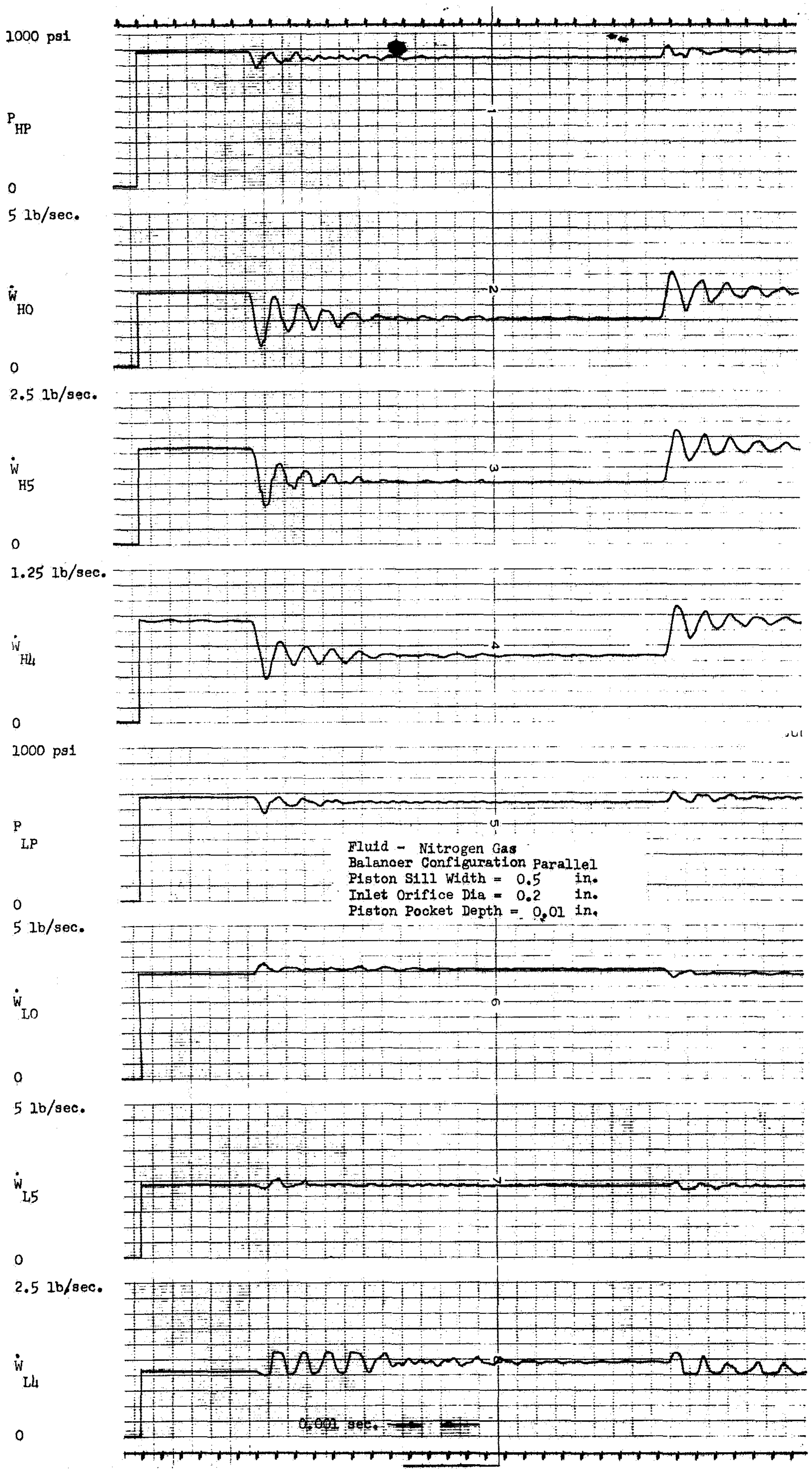


Figure C-73 Step Response - Compressible, Parallel Balancer

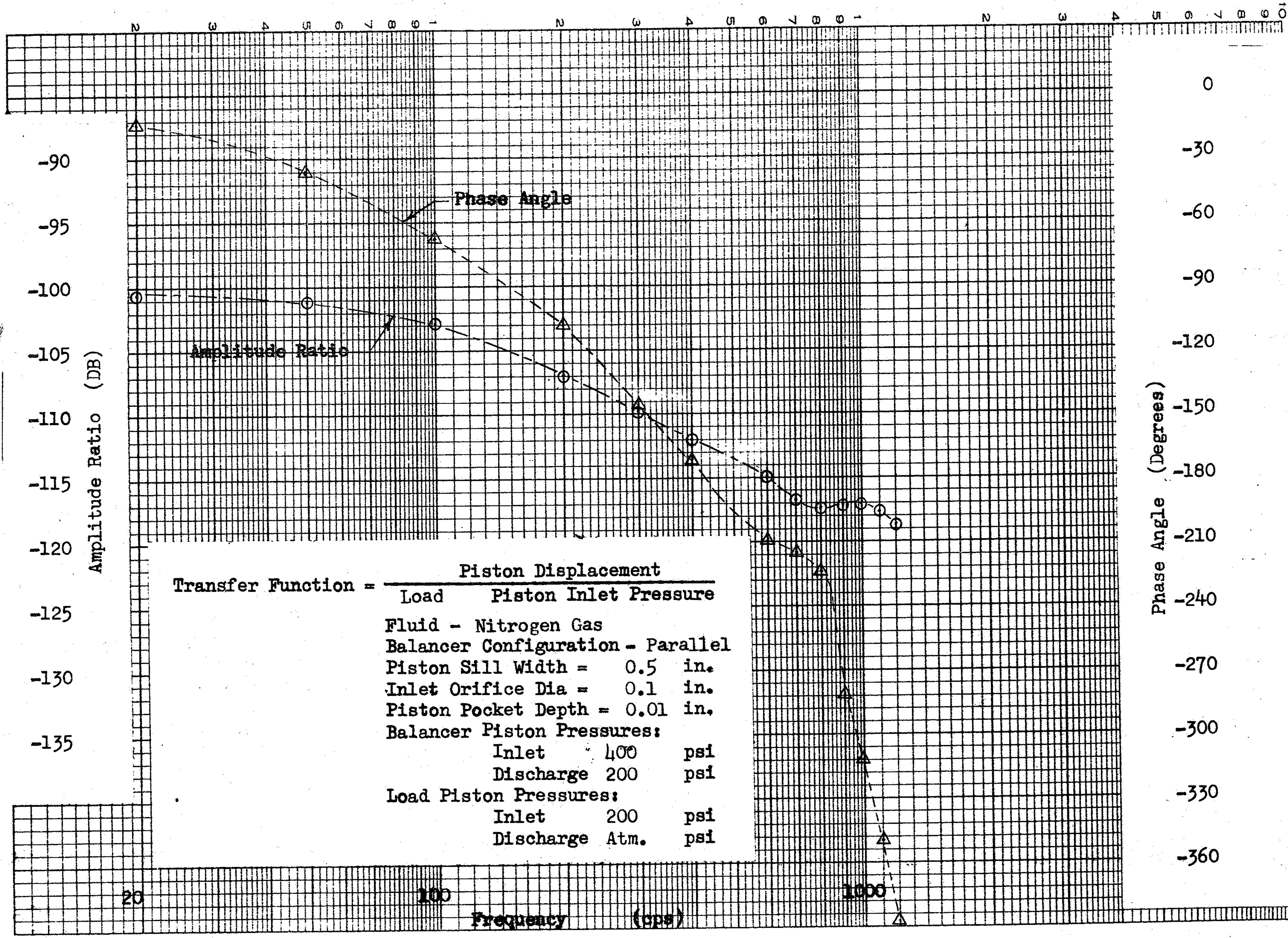


Figure C-74 Frequency Response - Compressible, Parallel Balancer

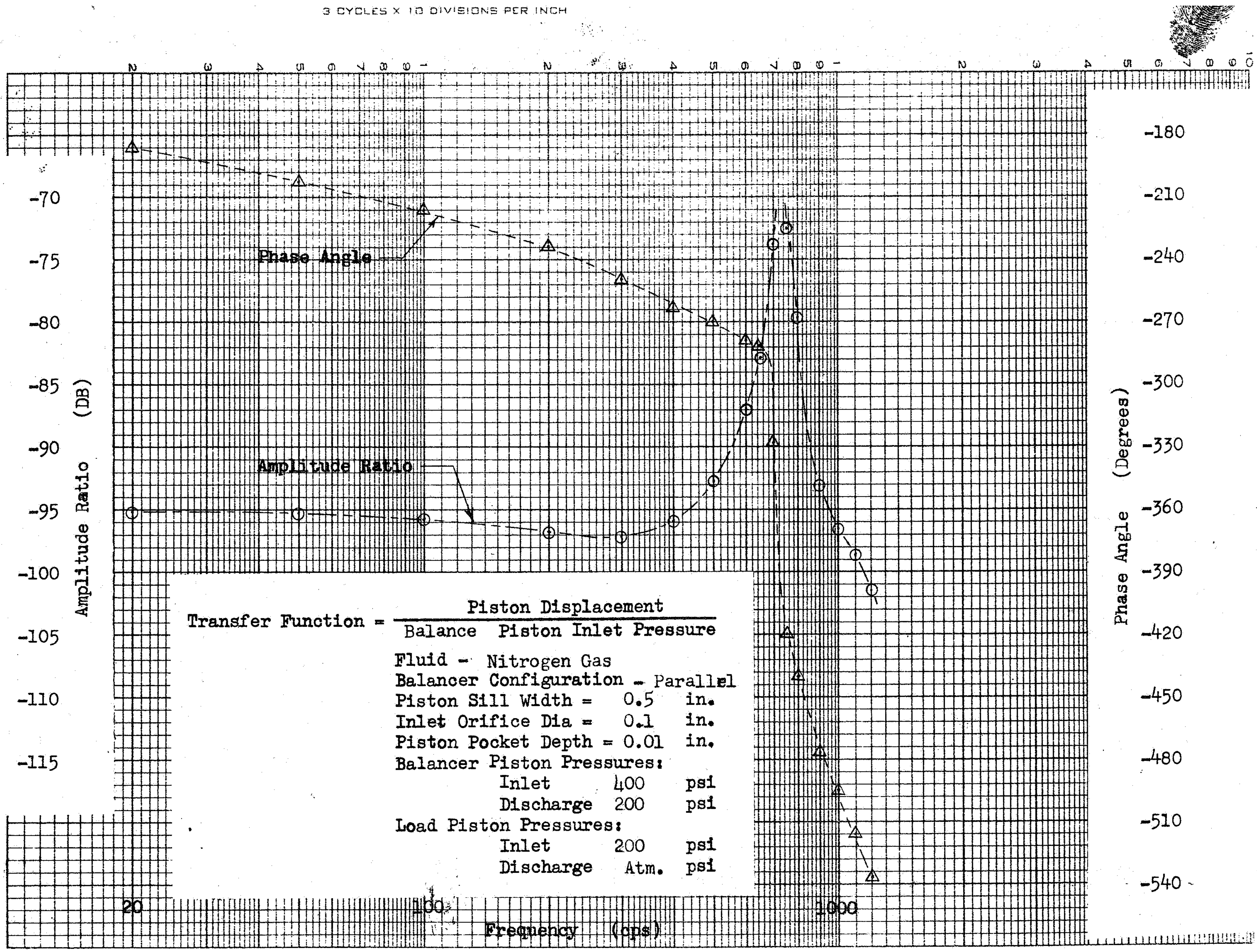


Figure C-75 Frequency Response - Compressible, Parallel Balancer

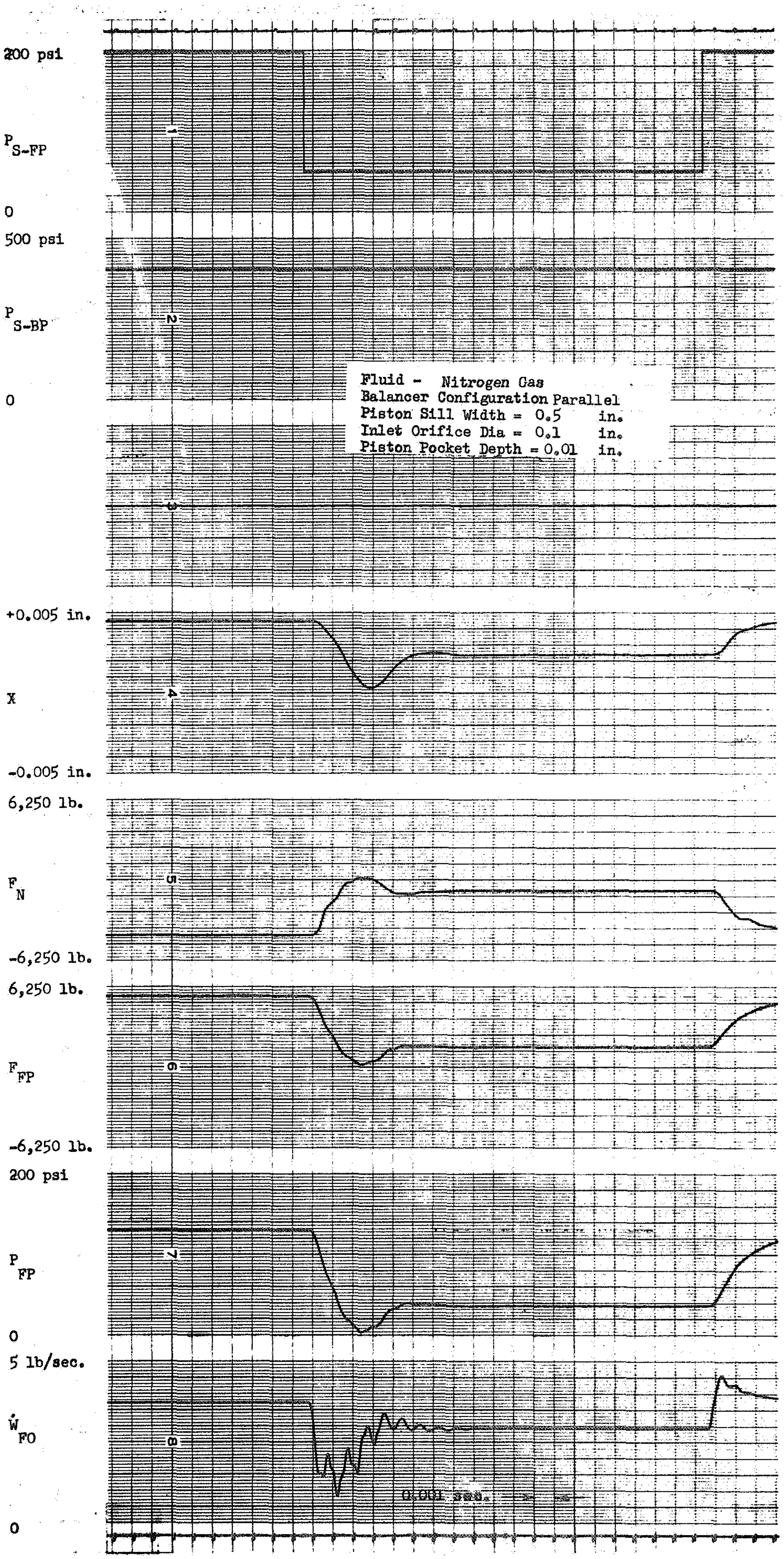


Figure C-76 Step Response - Compressible, Parallel Balancer

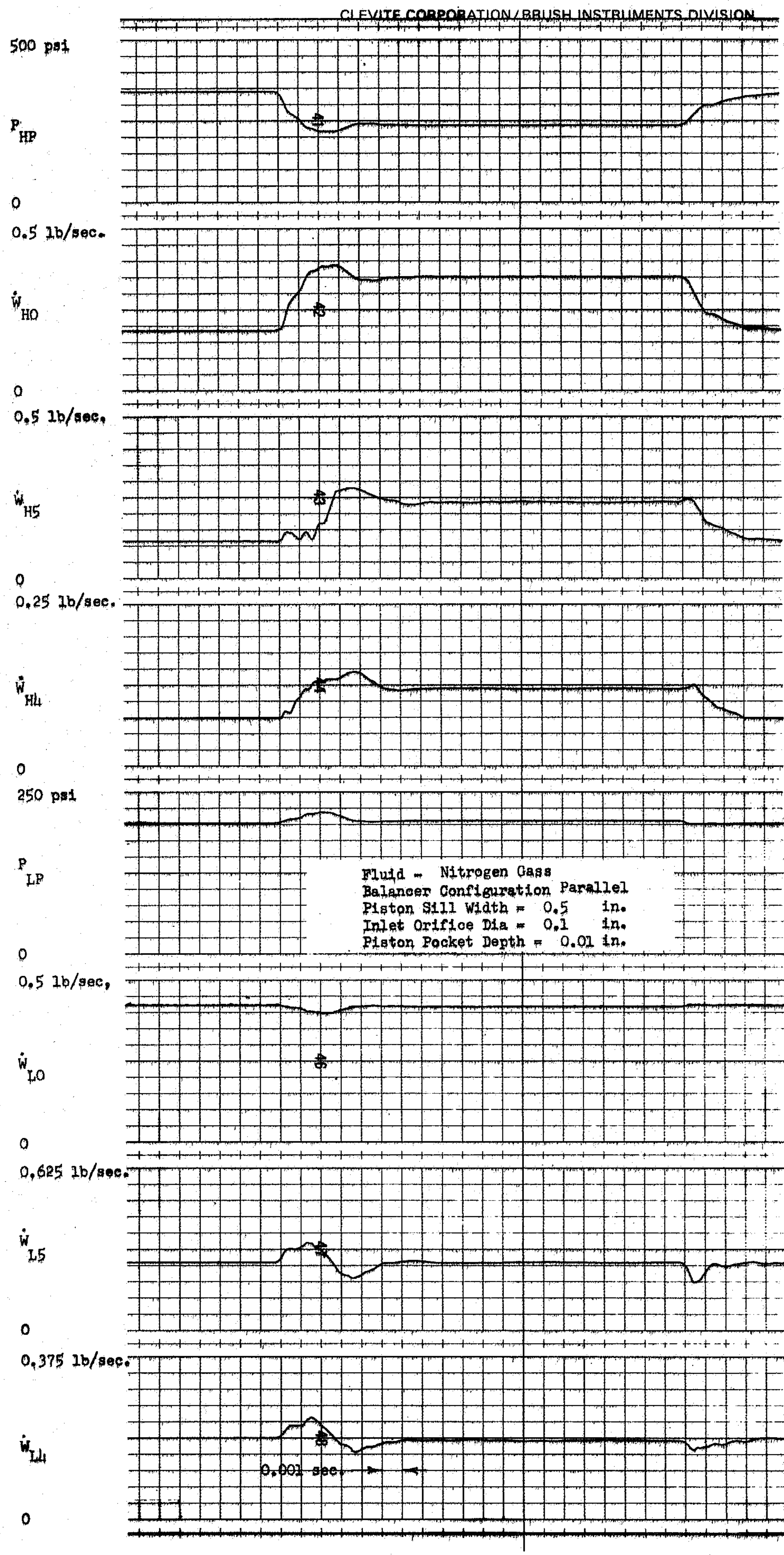


Figure C-77 Step Response - Compressible, Parallel Balancer

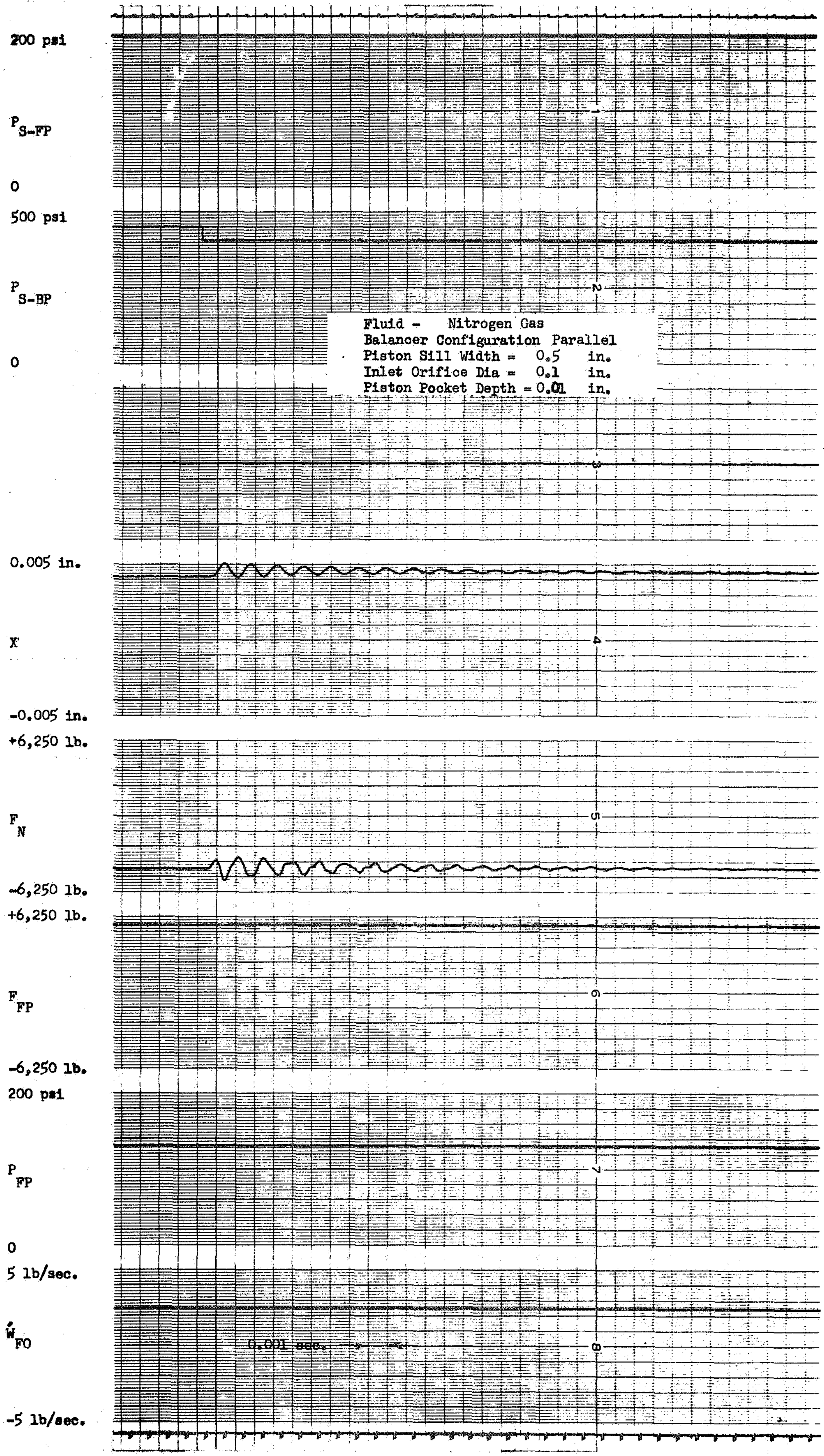


Figure C-78 Step Response - Compressible, Parallel Balancer

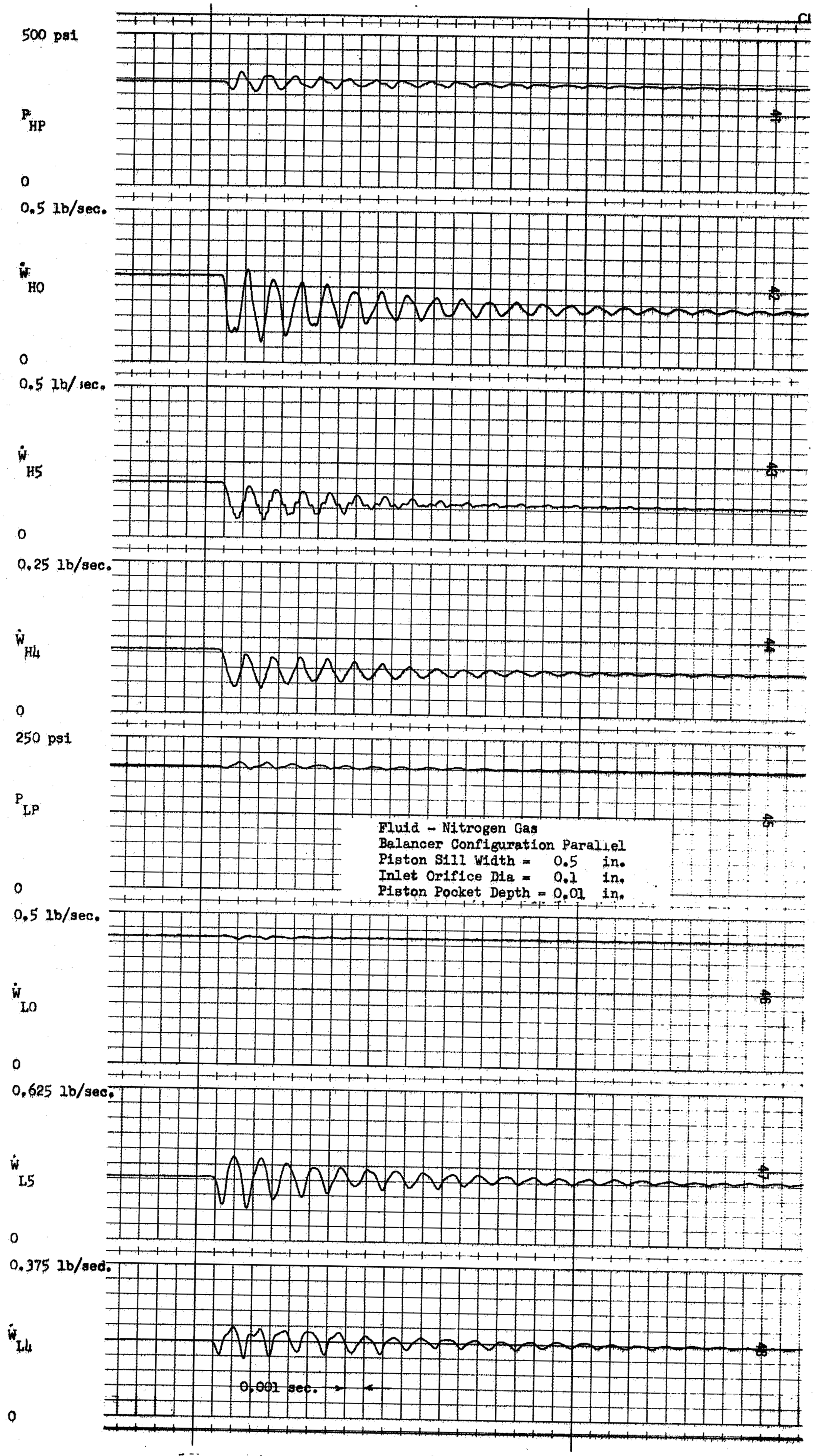


Figure C-79 Step Response - Compressible, Parallel Balancer

Increasing the inlet orifice to 0.2-in. produces the frequency response of Figures No. C-80 and No. C-81. The response to load piston pressure excitation now also shows a low damped resonant peak. Figure No. C-82 is a record of the limit cycle oscillations which occurred while operating with a 0.2-in. orifice. As shown, the limit cycle exists for piston displacements above approximately 0.004-in., but stabilizes as piston displacement is decreased. These records indicate that an increase in inlet orifice diameter is destablizing.

A decrease in pocket depth from 0.01-in. to 0.005-in. produces the frequency response shown on Figures No. C-83 and No. C-84. These plots show slightly greater damping than the nominal configuration. The step response obtained is nearly identical and is not shown here.

The compressible parallel balancer is somewhat sensitive to changes in sill width. Figures No. C-85 and No. C-86 show the system frequency response with a 0.75-in. sill width. The frequency response obtained from load piston pressure excitation now indicates a much lower damped resonance than the nominal case did. However, the response to a step in load piston pressure (Figures No. C-87 and No. C-88) indicates less overshoot in piston displacement. Although not shown, the step response records for the 0.25-in. sill show a greater overshoot than the nominal. Therefore, the frequency response and the step response appear to contradict one another as to the effect of sill width variations. These contradictions may result from the differences in the response to large signals as the step response and to small signals such as the frequency response excitation. For stability considerations, the small signal or frequency response data is more valid. Therefore, the system with the wide sill appears more resonant in nature and less stable.

The study of the system in the 200 psi to 100 psi range showed the system to be unstable. During a brief parameter study, stable conditions were not obtained.

The parameter study of the parallel compressible configuration indicates that the system is sensitive to inlet orifice diameter and sill width, but is quite insensitive to the values of the pocket depth studied. A large orifice diameter resulted in unstable conditions. As the sill width was increased, the system became more underdamped in nature.

4. Series Flow Balancer - Compressible Flow

a. Analog Computer Study

A list of nominal parameters used in the study of the series, compressible flow balancer was given on Table C-II. As with the parallel flow case, a sill width of 0.5-in., an inlet orifice of 0.1-in., and a pocket depth of 0.01-in. were selected as nominal parameters.

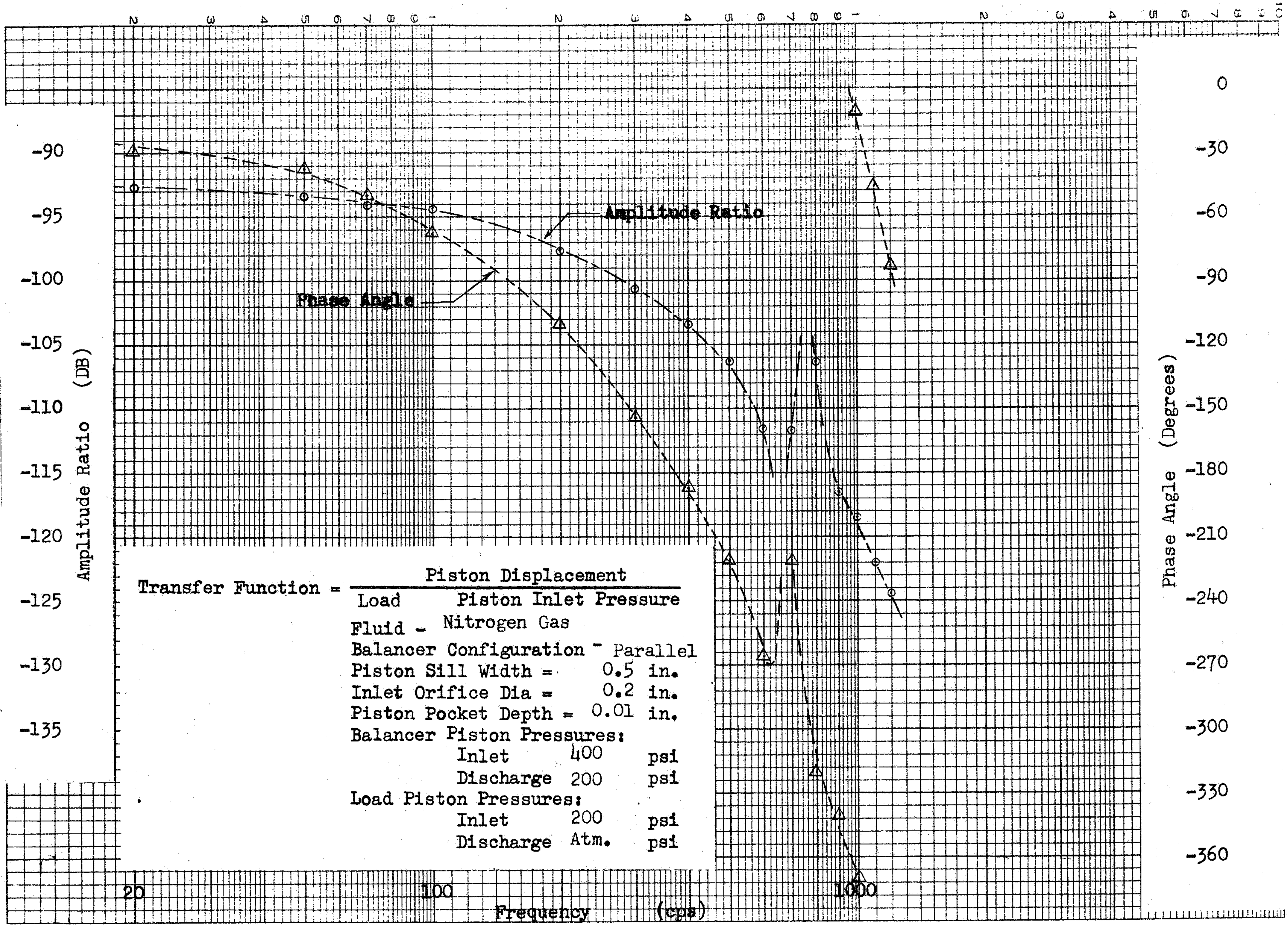


Figure C-80 Frequency Response - Compressible, Parallel Balancer

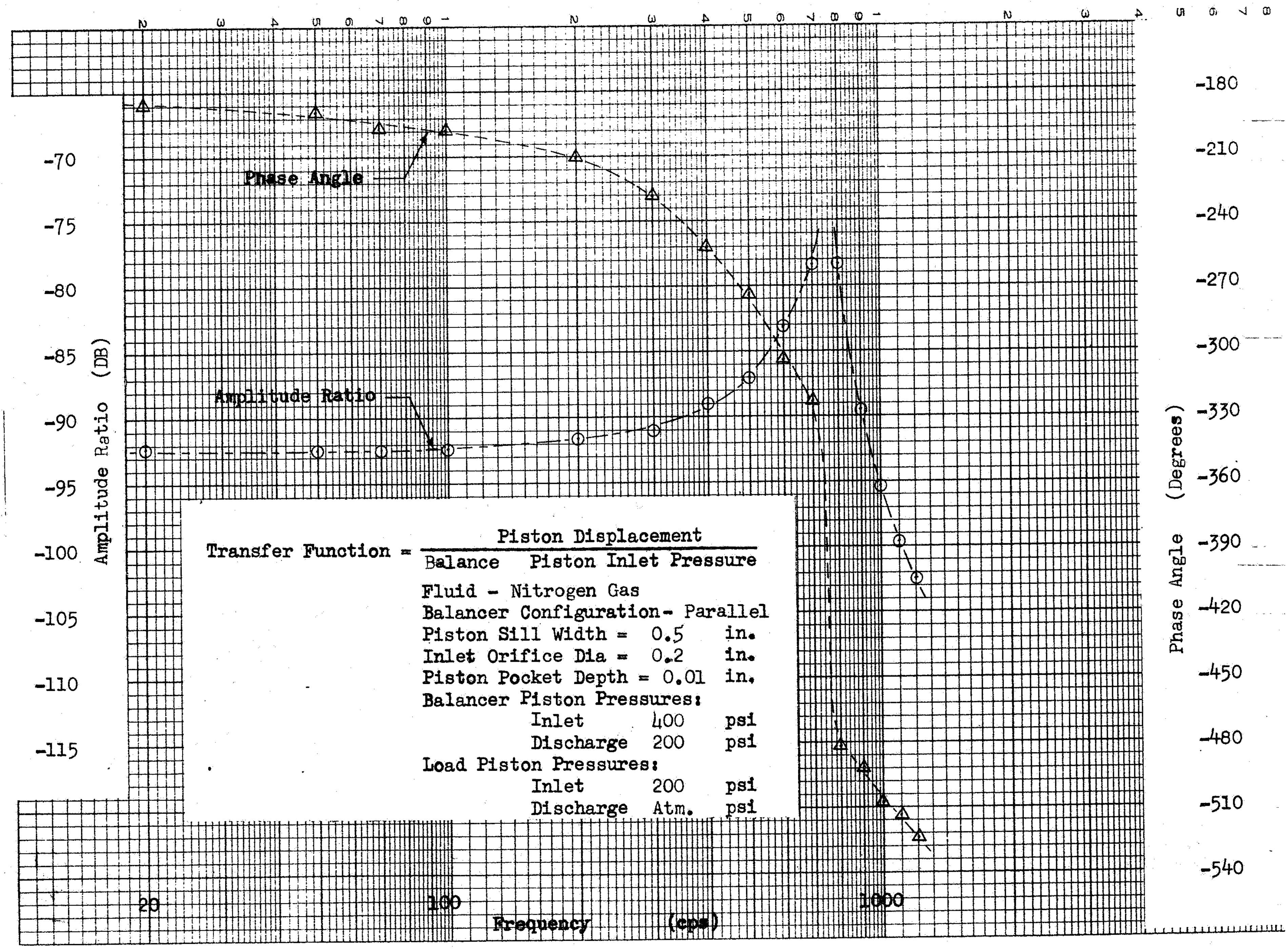


Figure C-81 Frequency Response - Compressible, Parallel Balancer

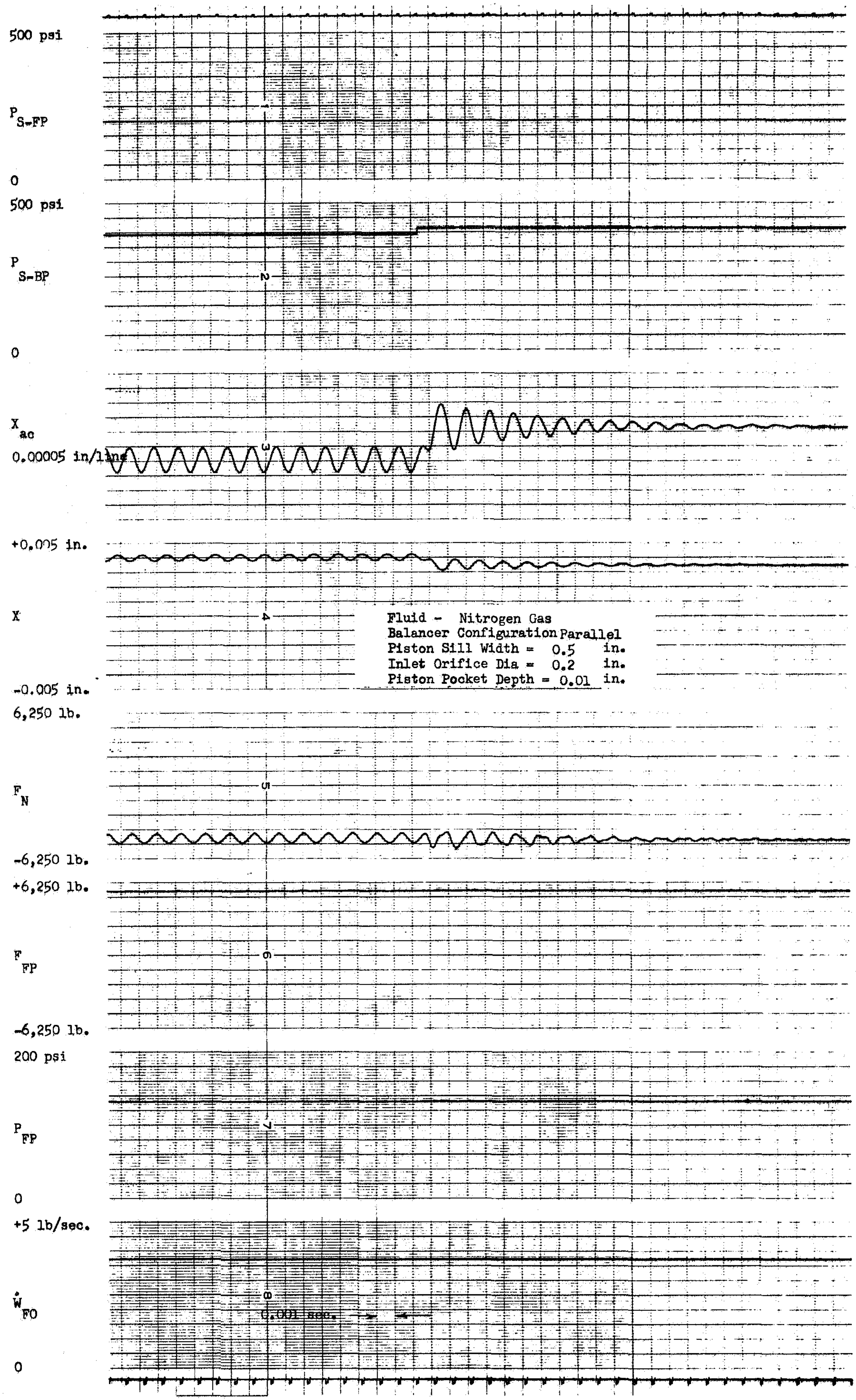


Figure C-82 Step Response - Compressible, Parallel Balancer

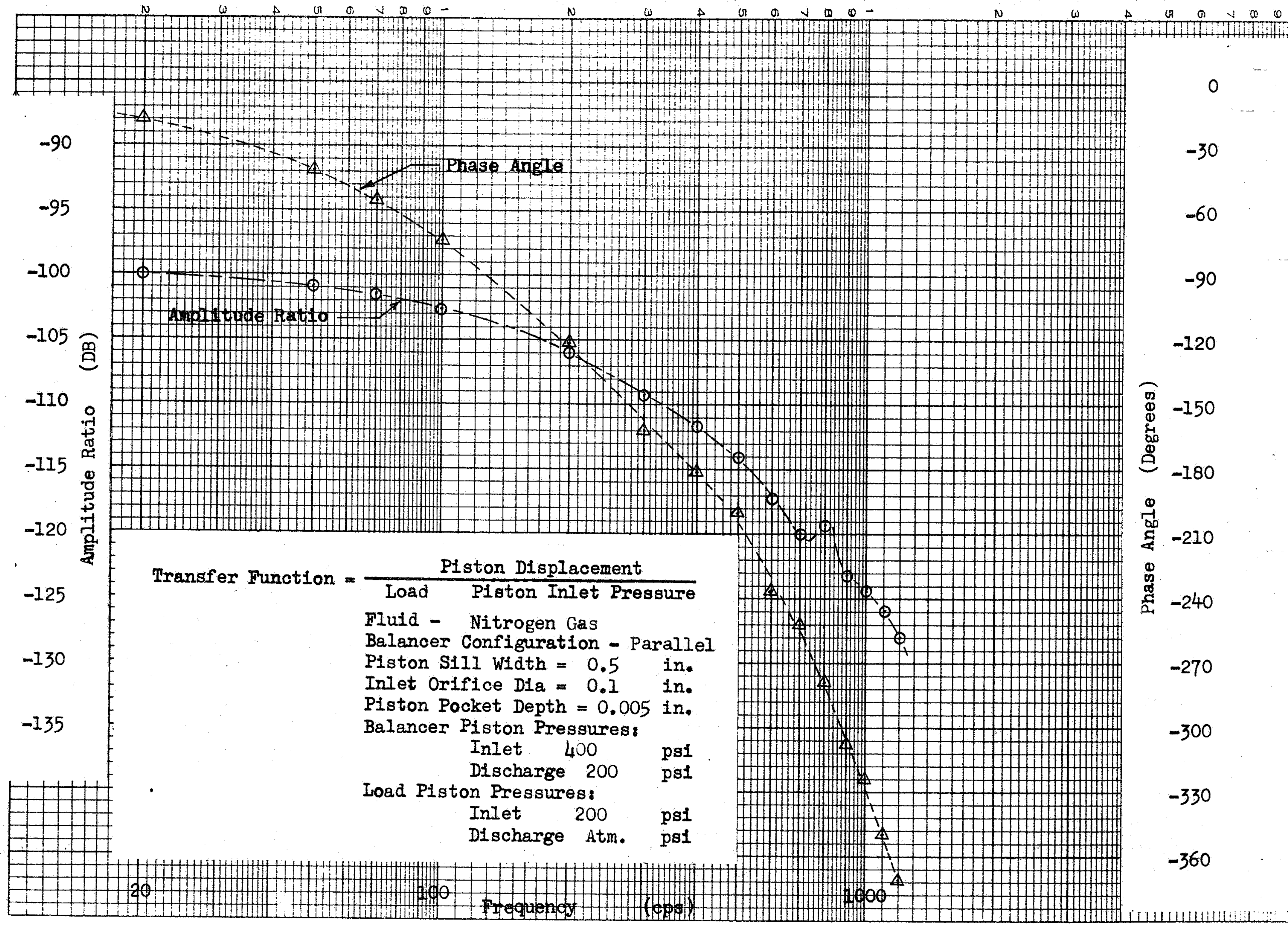


Figure C-83 Frequency Response - Compressible, Parallel Balancer

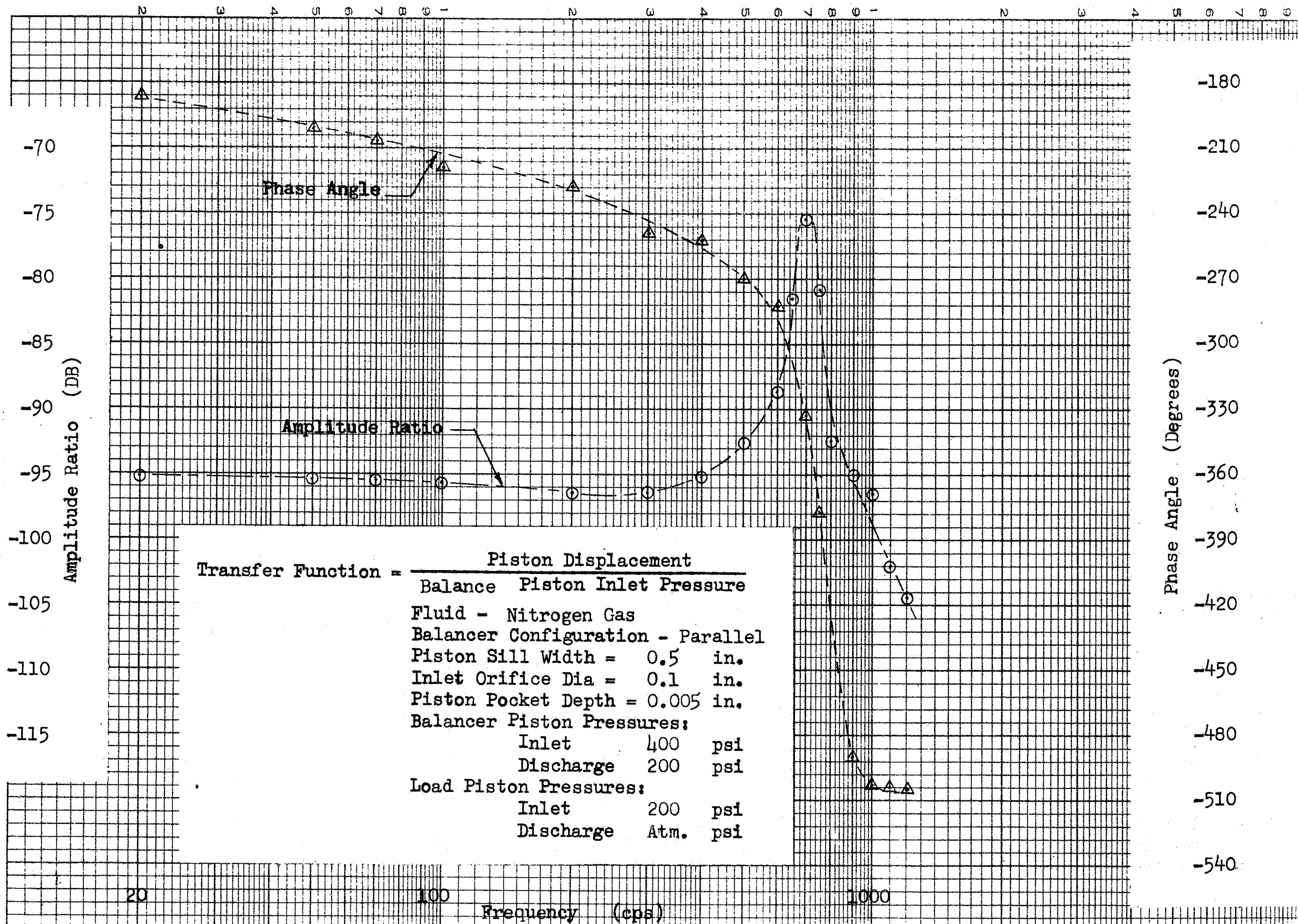


Figure C-84 Frequency Response - Compressible, Parallel Balancer

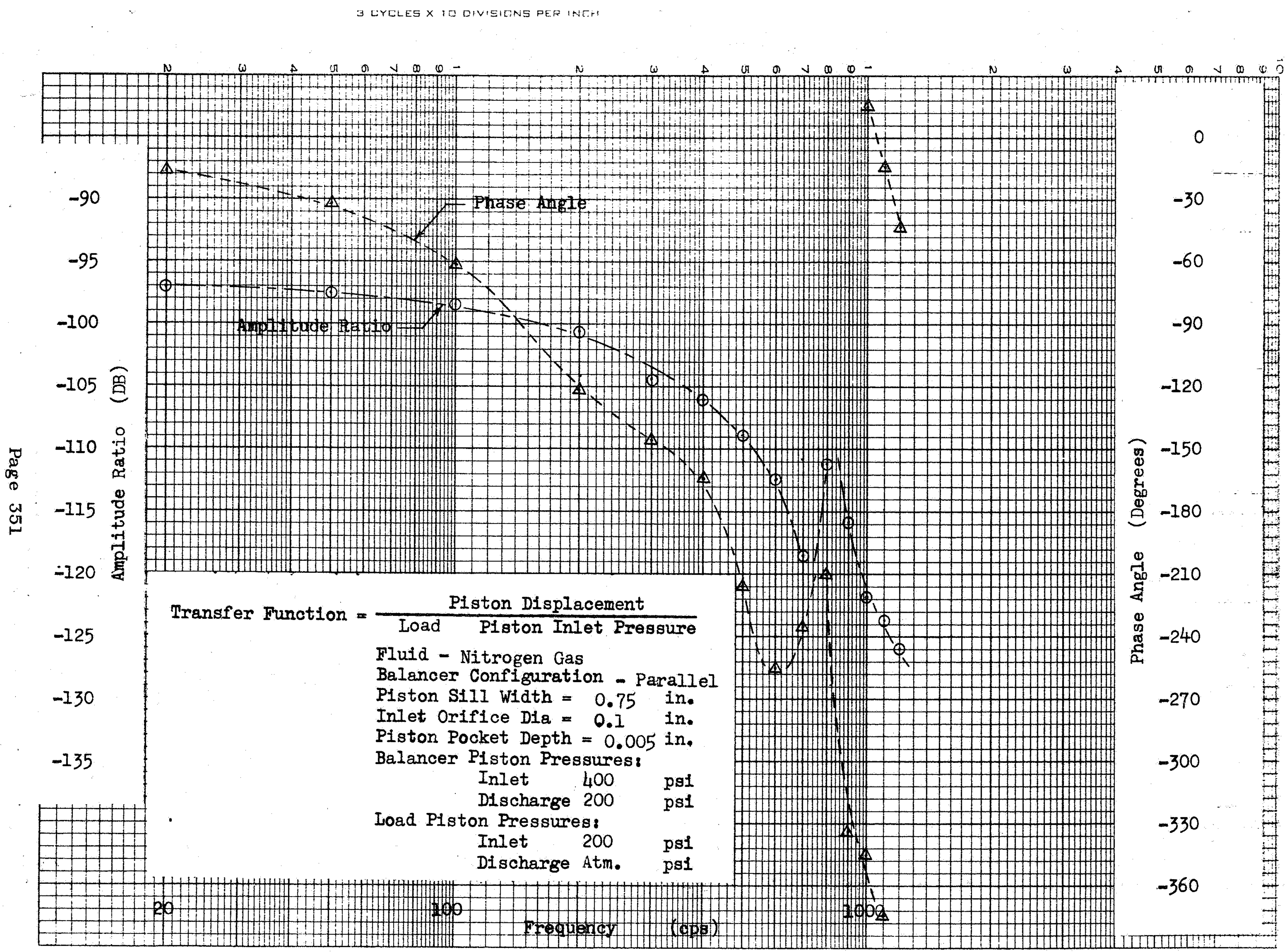


Figure C-85 Frequency Response - Compressible, Parallel Balancer

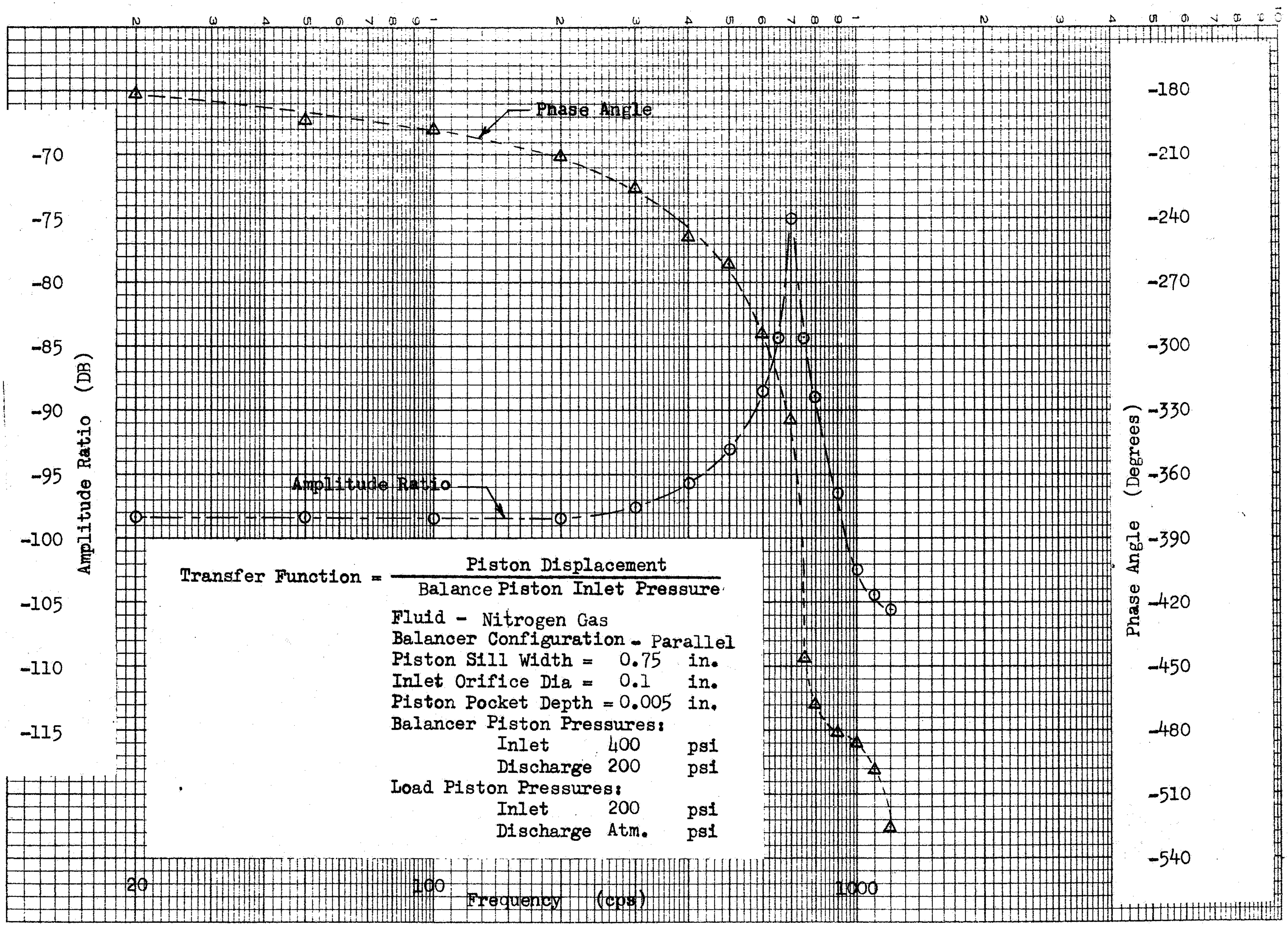


Figure C-86 Frequency Response - Compressible, Parallel Balancer

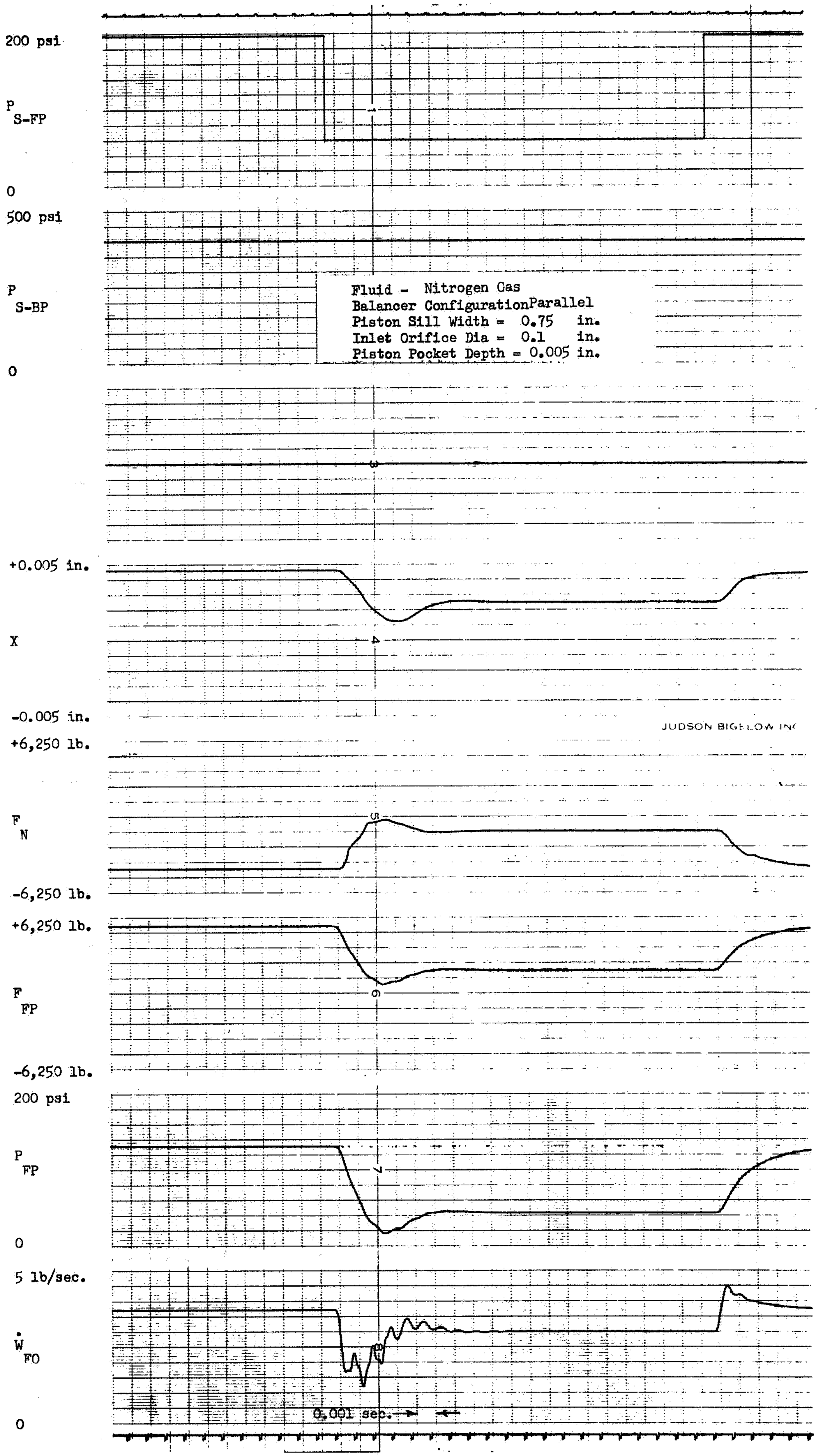


Figure C-87 Step Response - Compressible, Parallel Balancer

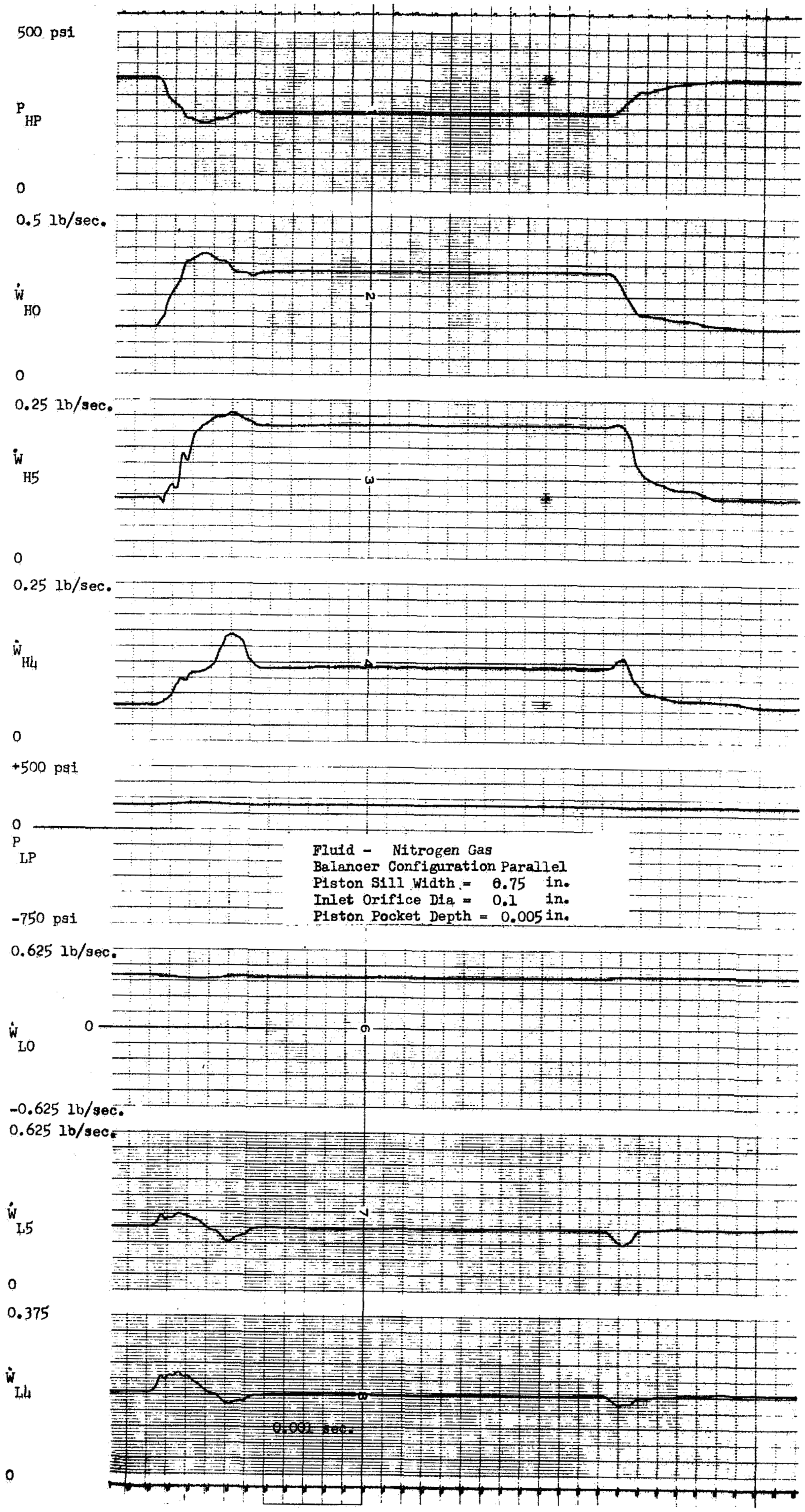


Figure C-88 Step Response - Compressible, Parallel Balancer

For the series compressible case, only the balance piston pressure range of 400 psi to 200 psi was studied. The frequency response for the nominal case is shown on Figures No. C-89 and No. C-90. These plots are similar to those obtained for the corresponding parallel case. The response to steps in the load and balance piston pressures are shown on Figures No. C-91 and No. C-92, respectively. In each case the system appears lightly damped.

Increasing the orifice diameter to 0.2-in. results in an unstable system for piston displacements larger than 0.002-in. The resulting limit cycle oscillations are shown on Figure No. C-93. An inlet orifice of 0.15-in. resulted in limit cycles for values of piston displacement greater than approximately 0.003-in.

An increase in pocket depth from the nominal 0.01-in. to 0.02-in. tended to destabilize the system. The frequency response plots of Figures No. C-94 and No. C-95 show considerably higher resonant peaks than the nominal case did. The step response records of the system with a 0.02-in. pocket depth are shown on Figures No. C-96 and No. C-97. The response to a step in balance piston pressure indicates the system is neutrally stable.

The series, compressible flow balancer also is somewhat sensitive to changes in sill width. The frequency response of the system with a 0.25-in. sill is shown on Figures No. C-98 and No. C-99. The resonances appear to be slightly less damped than for the nominal case. This also is illustrated on Figure No. C-100 by the higher overshoot in piston displacement in response to a step in load piston pressure. However, the response to a step in balance piston pressure (Figure No. C-101) is nearly identical to the nominal case. Increasing the sill width to 0.75-in. also tends to increase the overshoot of piston displacement to a step in load piston pressure (Figure No. C-102). A limit cycle also occurred while operating with the 0.75-in. sill (Figure No. C-103). The limit cycle existed at a piston displacement of approximately 0.0025-in. The system stabilized above and below the value of 0.0025-in. displacement.

The series compressible flow balancer was sensitive to each of the three varied parameters. Increasing the orifice inlet or pocket depth from the nominal resulted in unstable conditions. Deviating in either direction from the nominal sill width appeared to result in less stable operating characteristics.

b. Digital Computer Eigenvalue Evaluation

The use of Aerojet-General Computer Program E32205 entitled "Sensitivities of Large Multiple-Loop Control Systems" for this balancer configuration resulted in a set of Eigenvalues or characteristics roots of the complete system. These roots are sufficient to define system stability and provide a check of the oscillatory behavior associated with this balancer configuration.

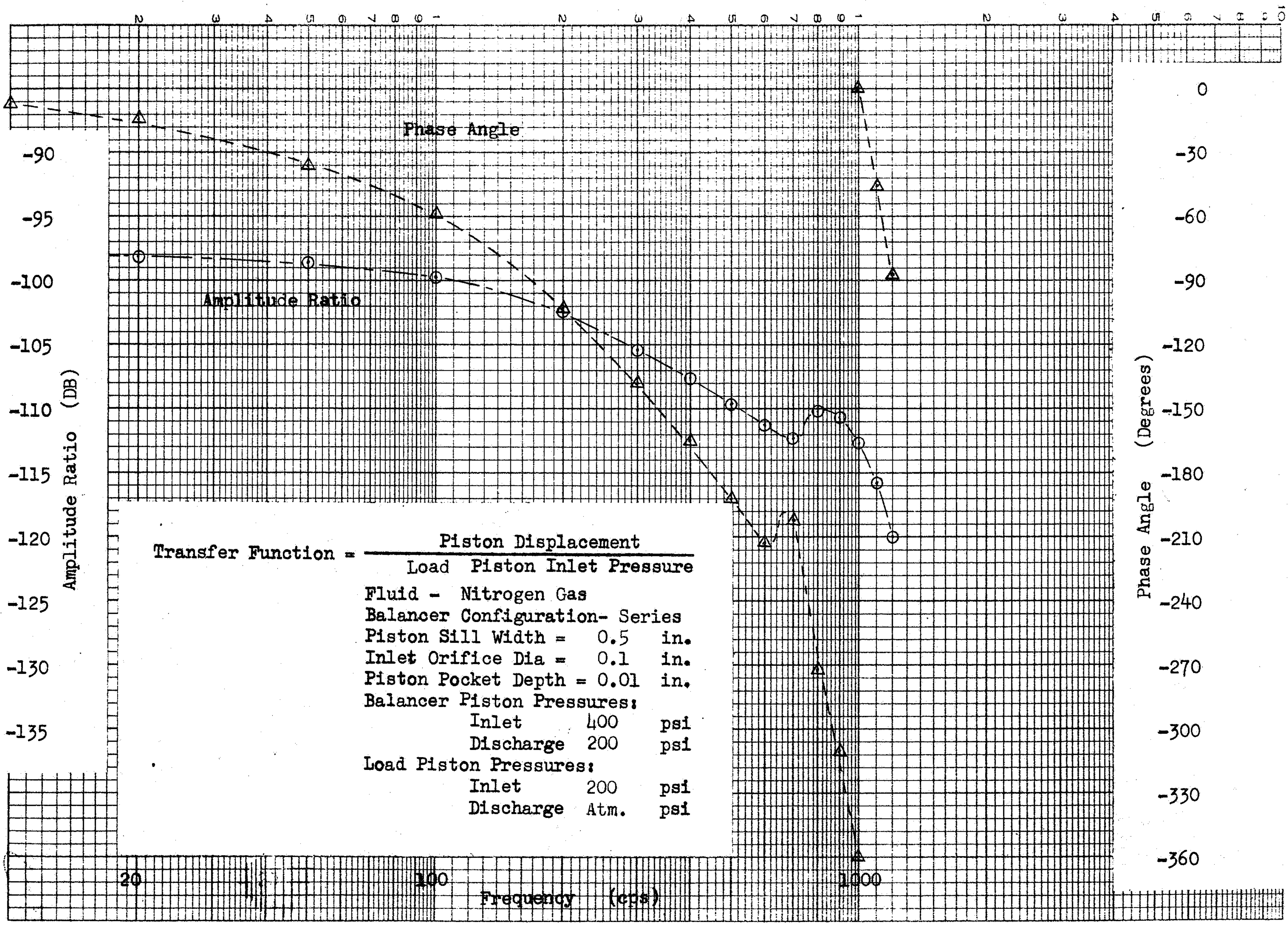


Figure C-89 Frequency Response - Compressible, Series Balancer

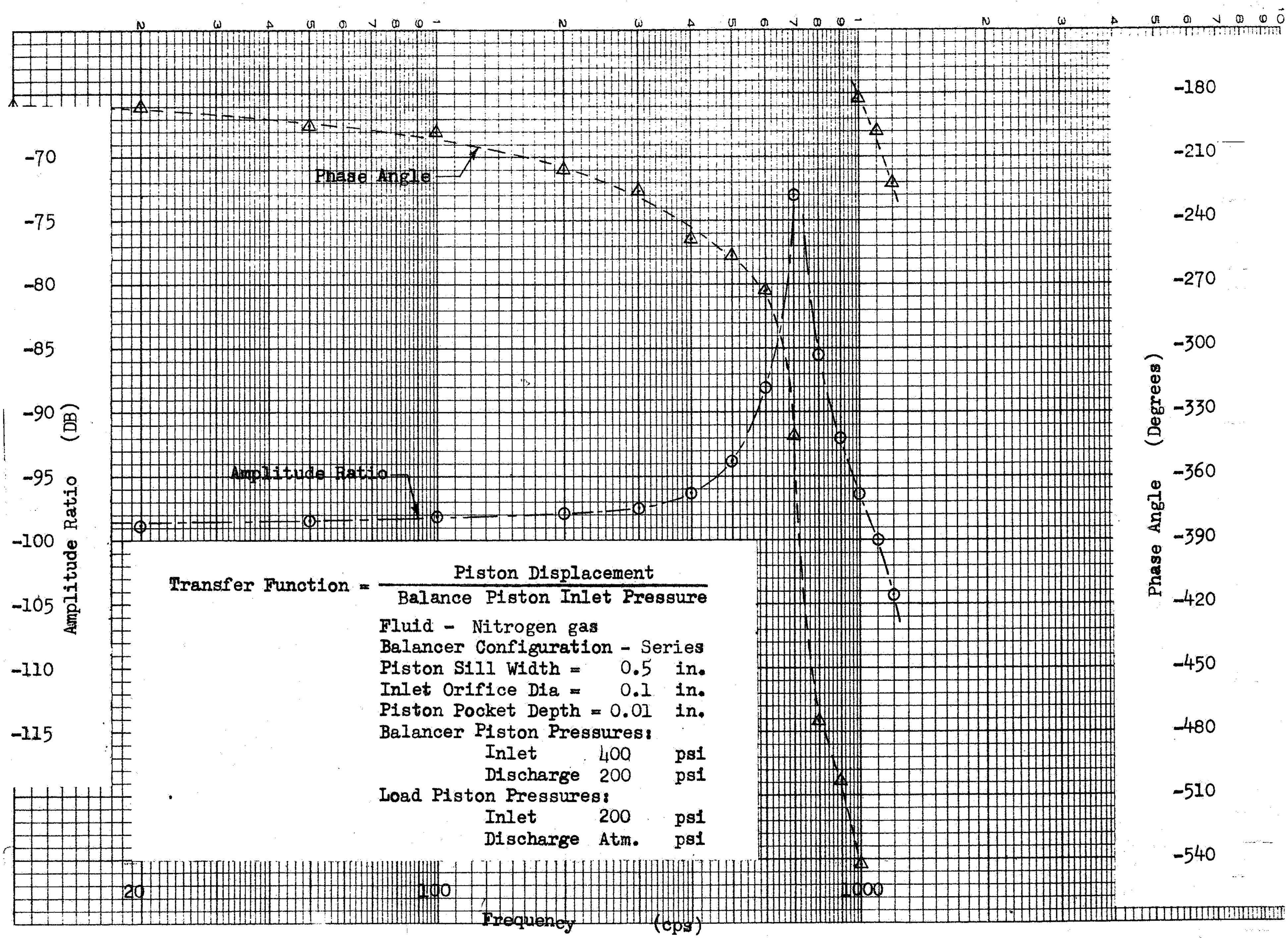


Figure C-90 Frequency Response - Compressible, Series Balancer

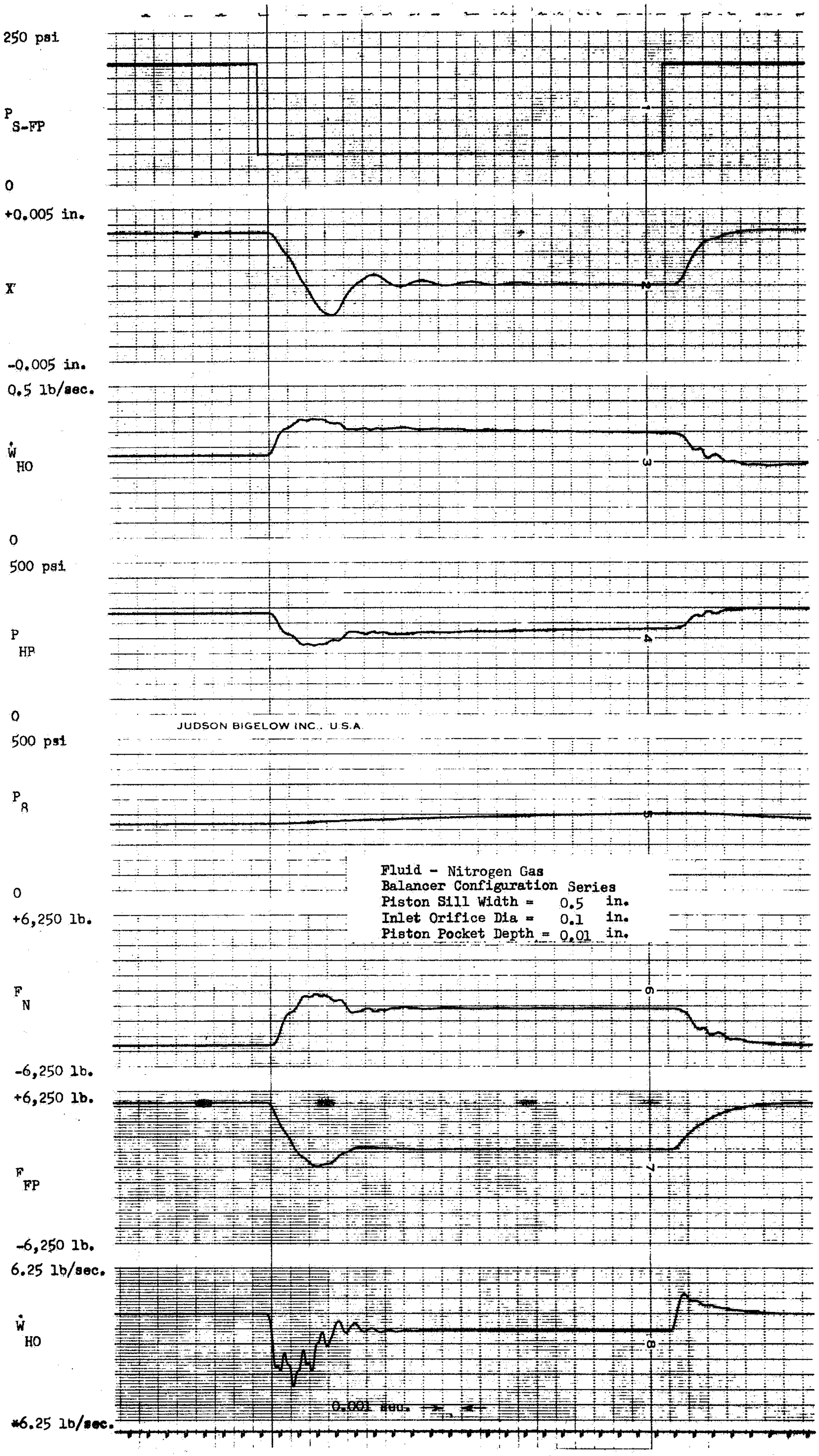


Figure C-91 Step Response - Compressible, Series Balancer

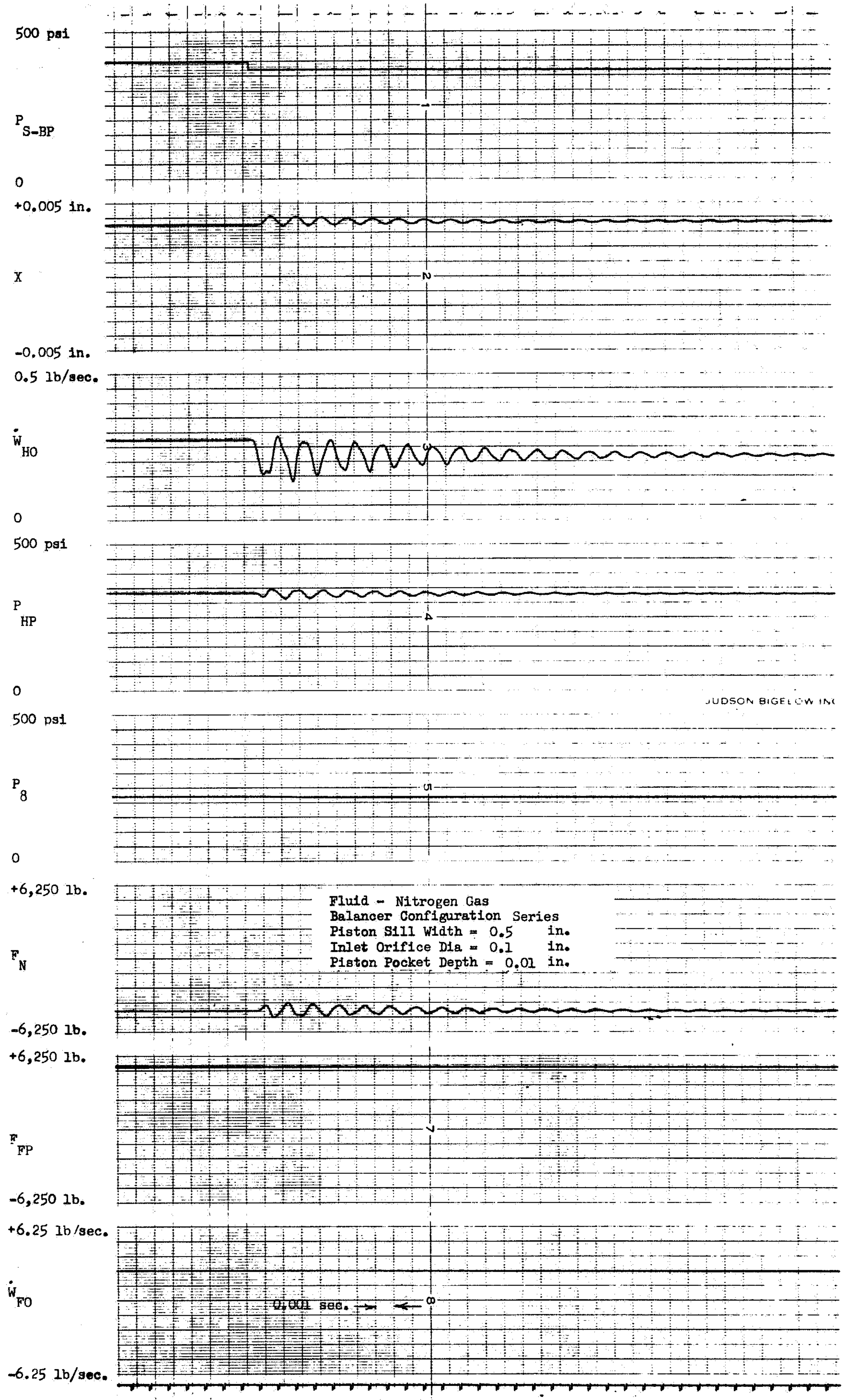


Figure C-92 Step Response - Compressible, Series Balancer

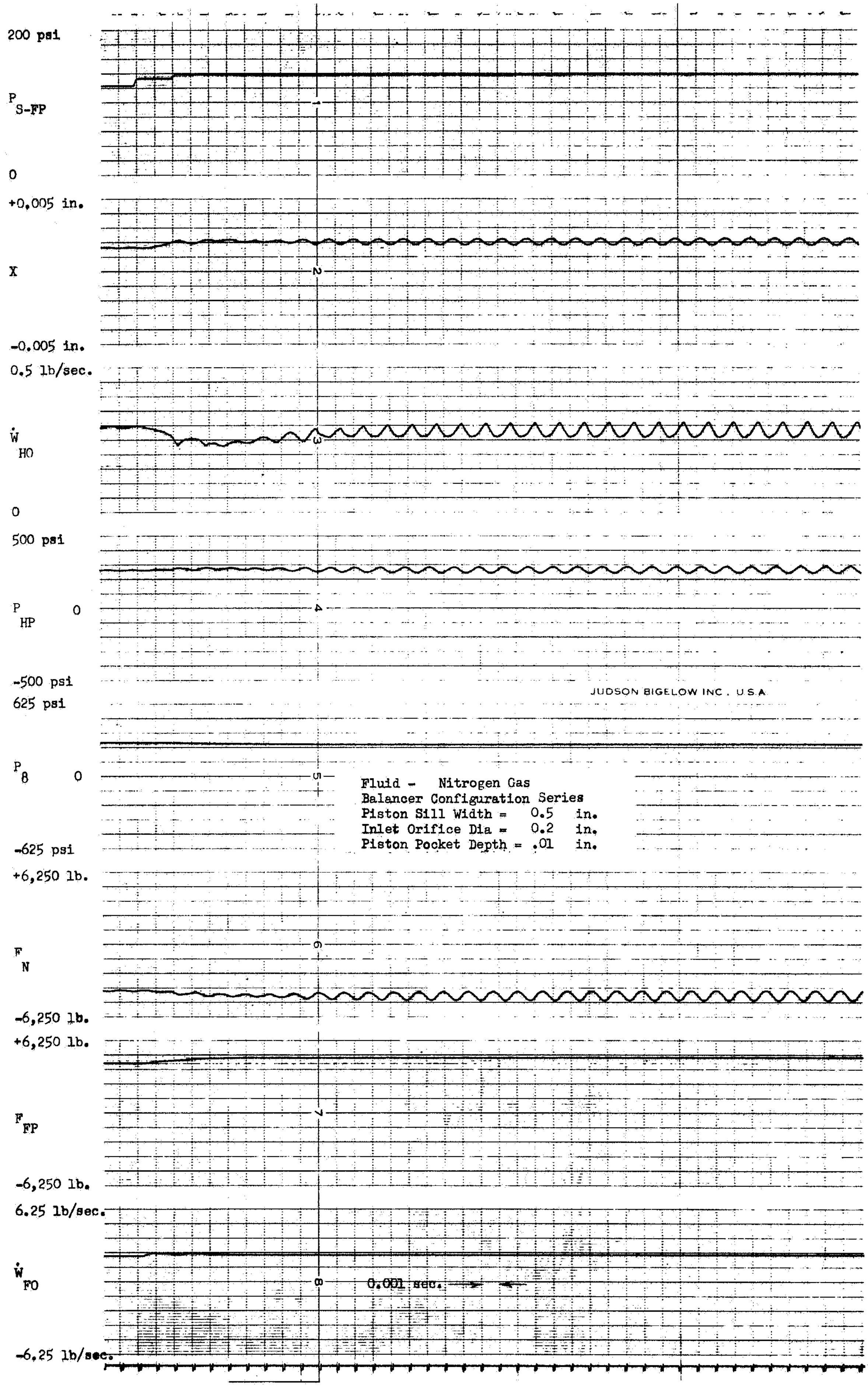


Figure C-93 Step Response - Compressible, Series Balancer

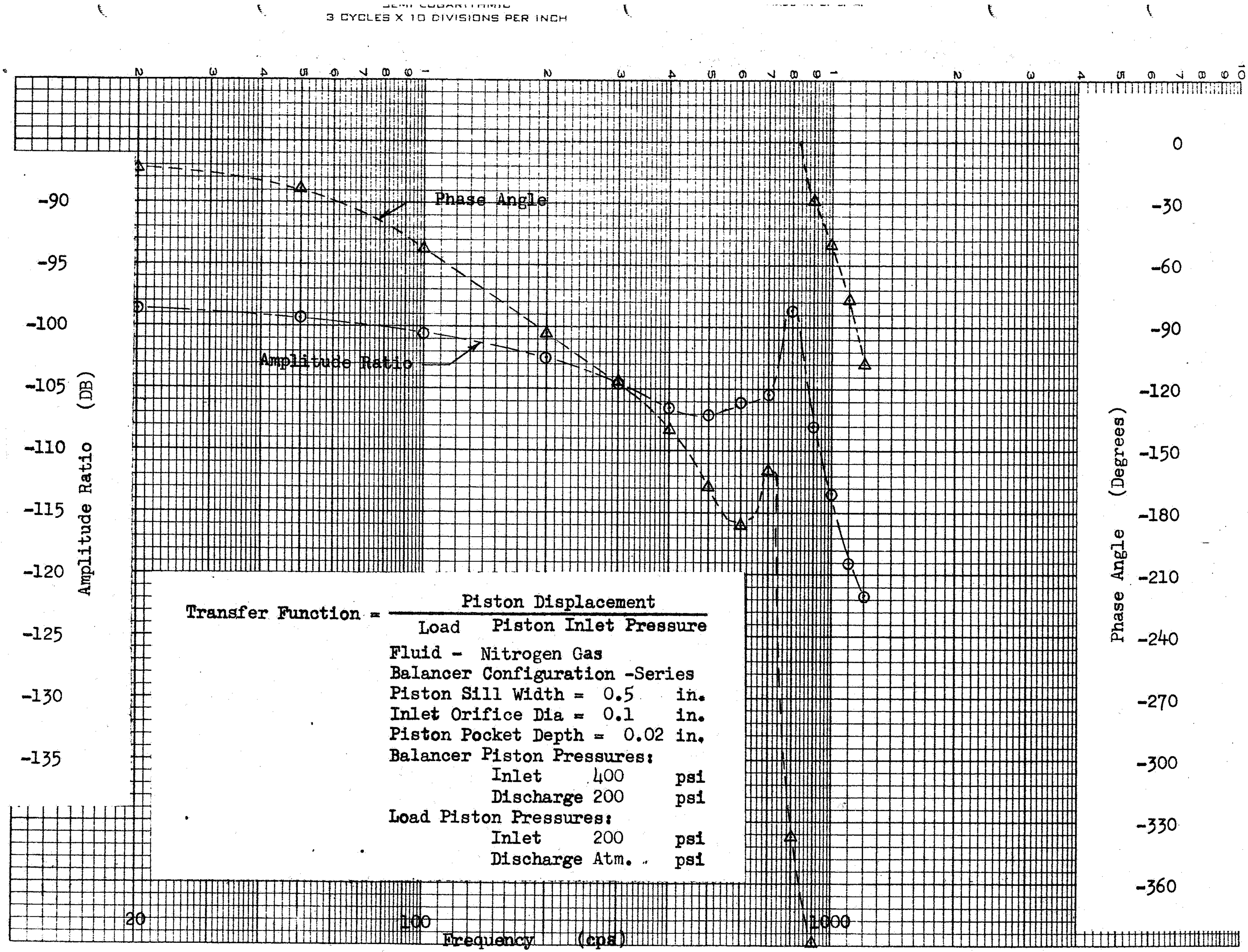


Figure C-94 Frequency Response - Compressible, Series Balancer

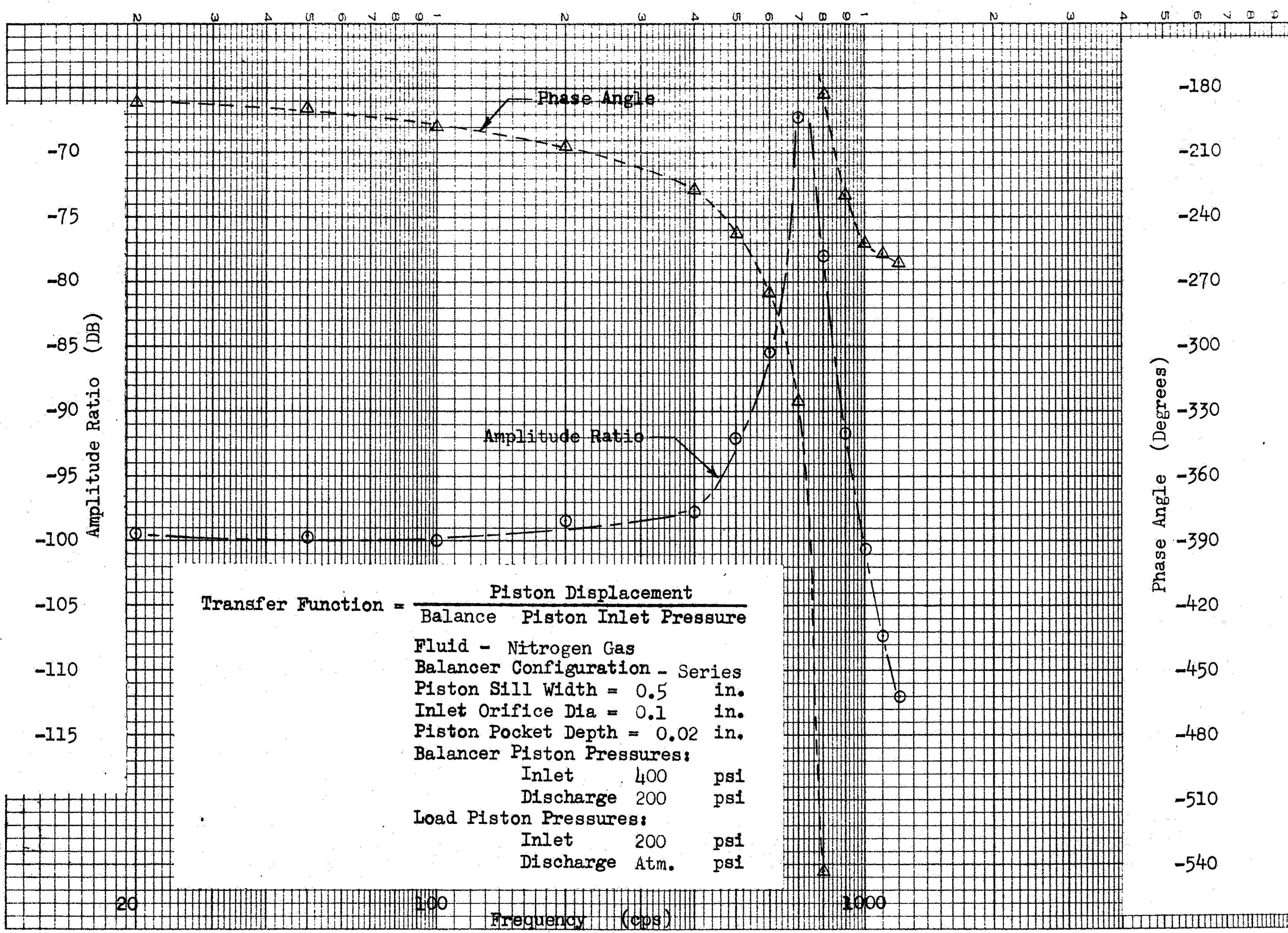


Figure C-95 Frequency Response - Compressible, Series Balancer

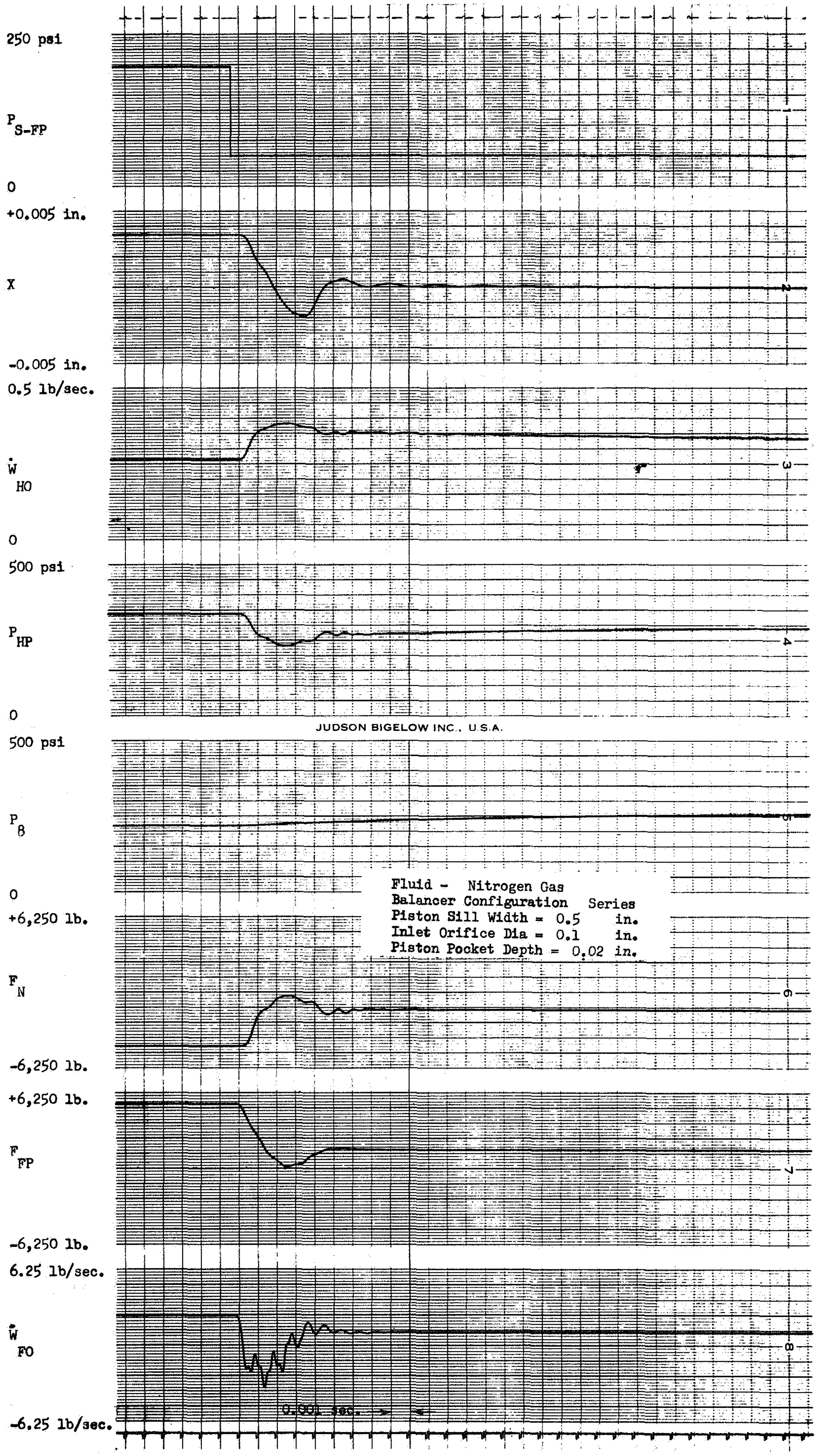


Figure C-96 Step Response - Compressible, Series Balancer

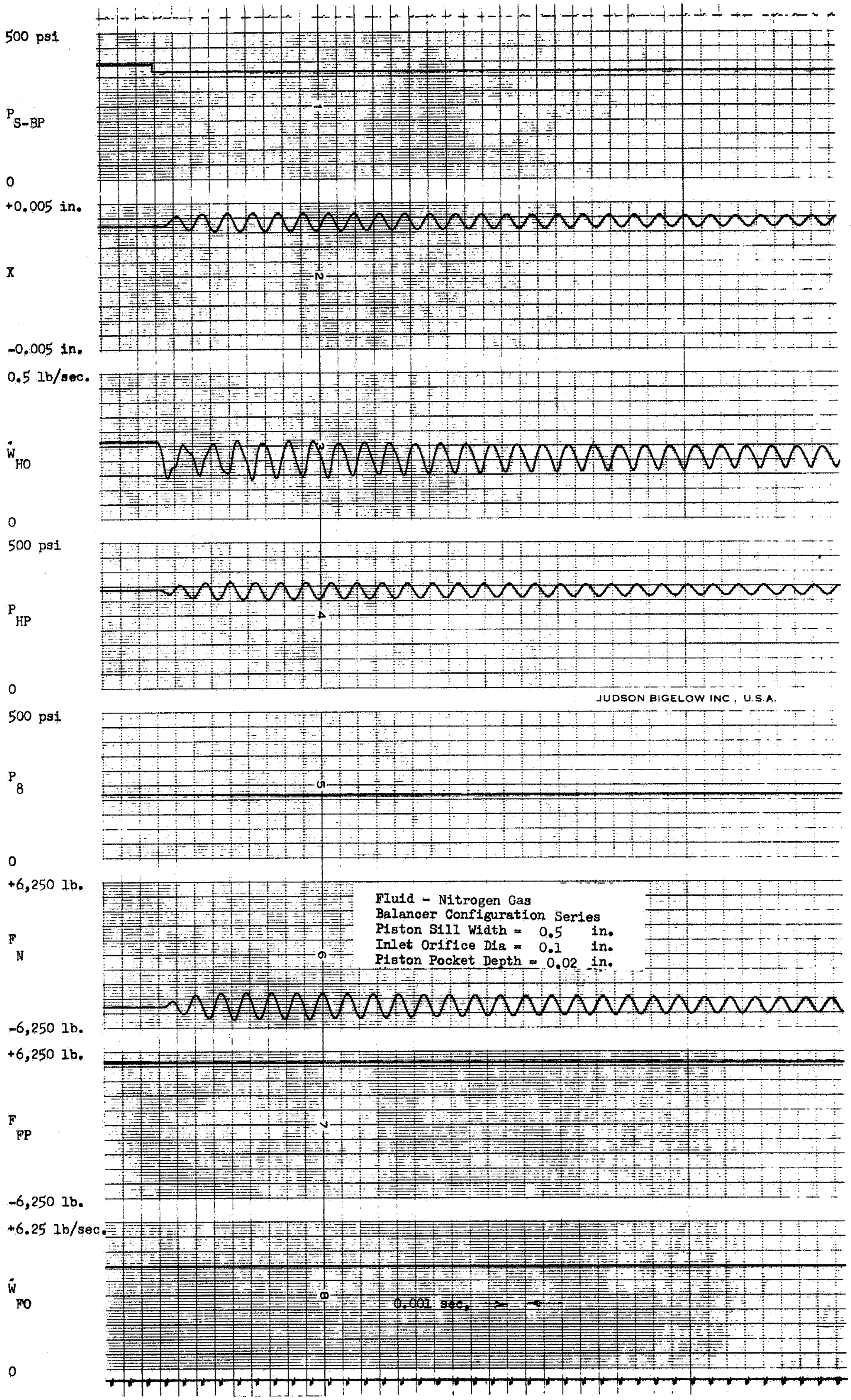


Figure C-97 Step Response - Compressible, Series Balancer

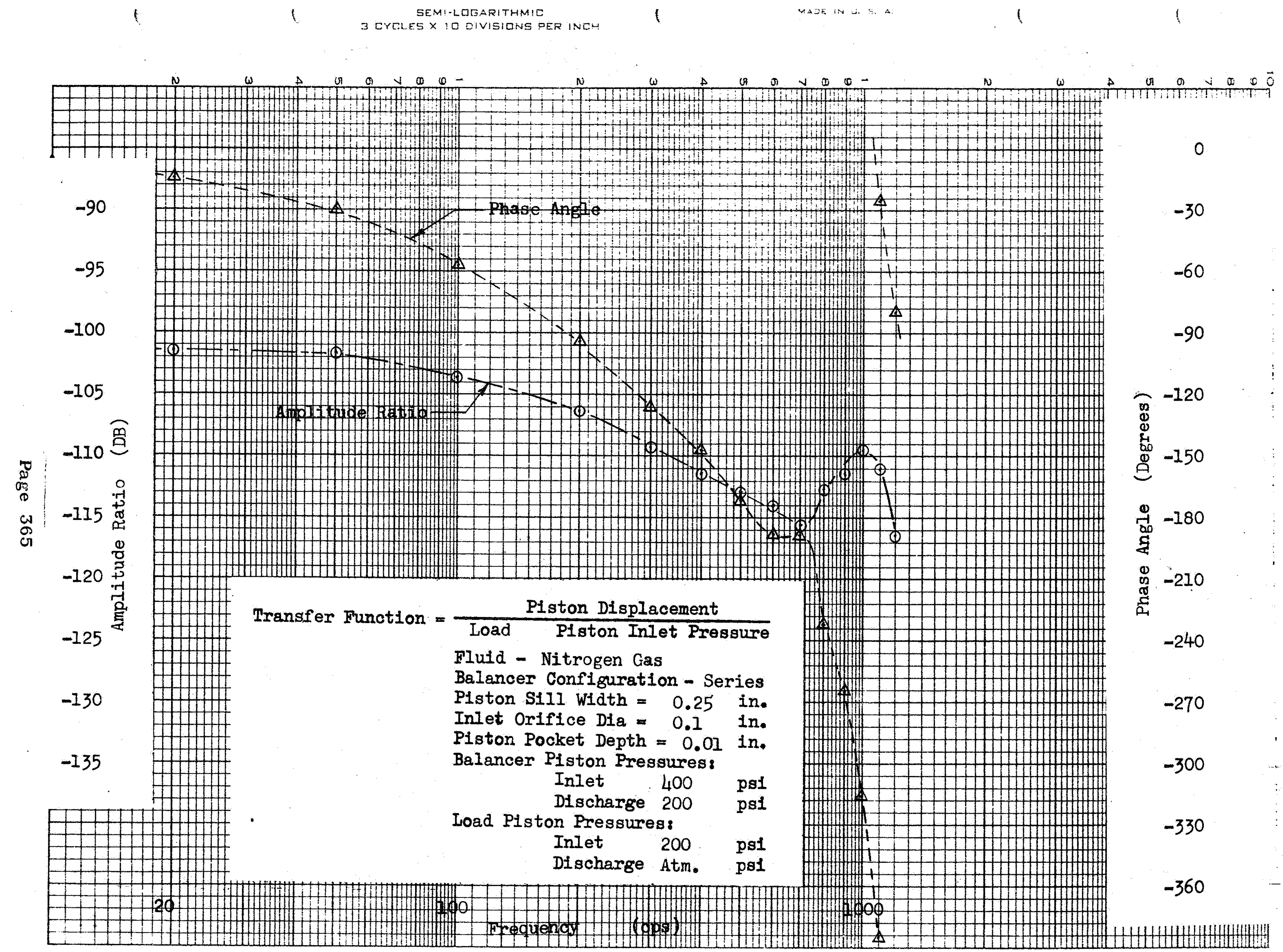


Figure C-98 Frequency Response - Compressible, Series Balancer

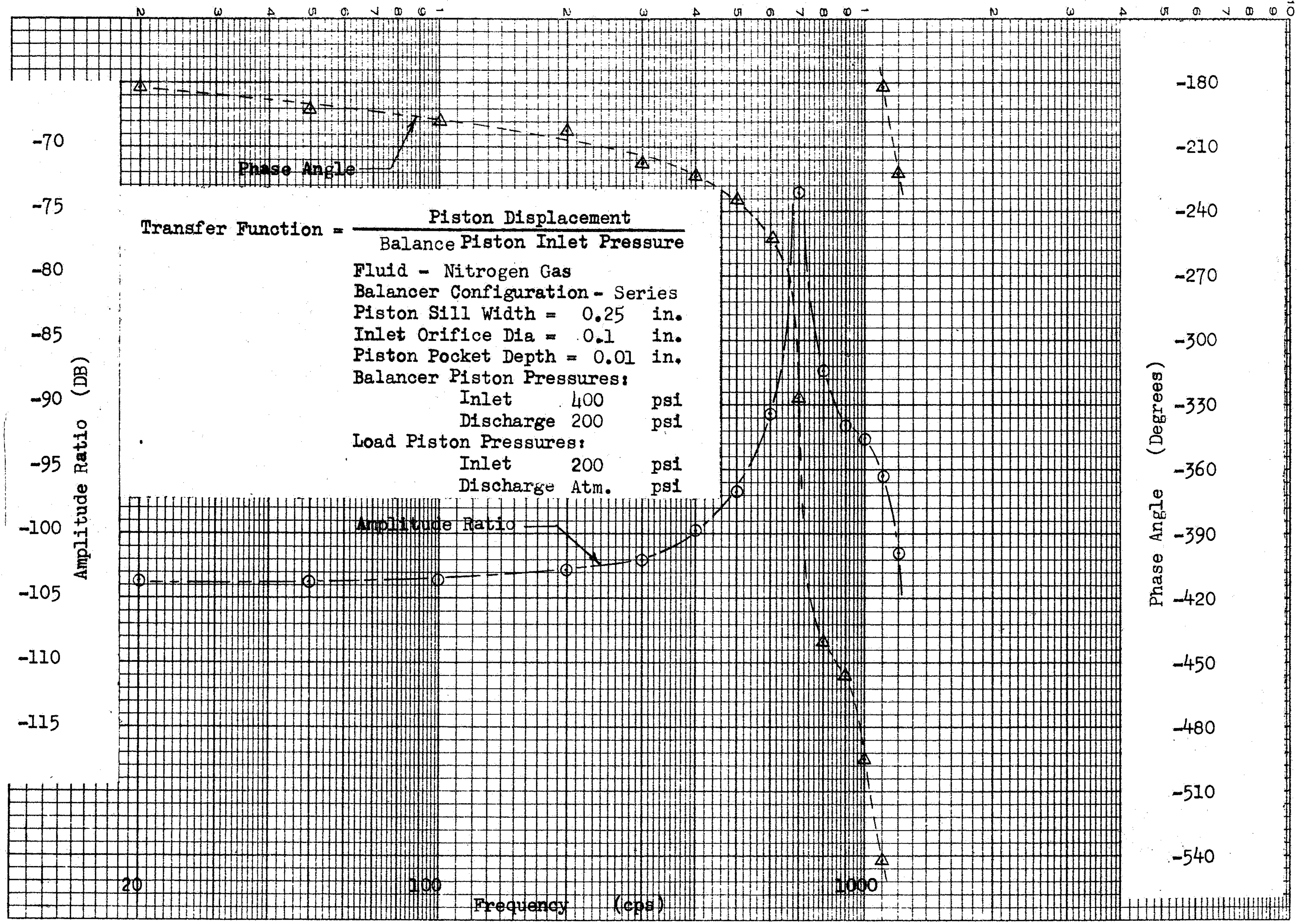


Figure C-99 Frequency Response - Compressible, Series Balancer

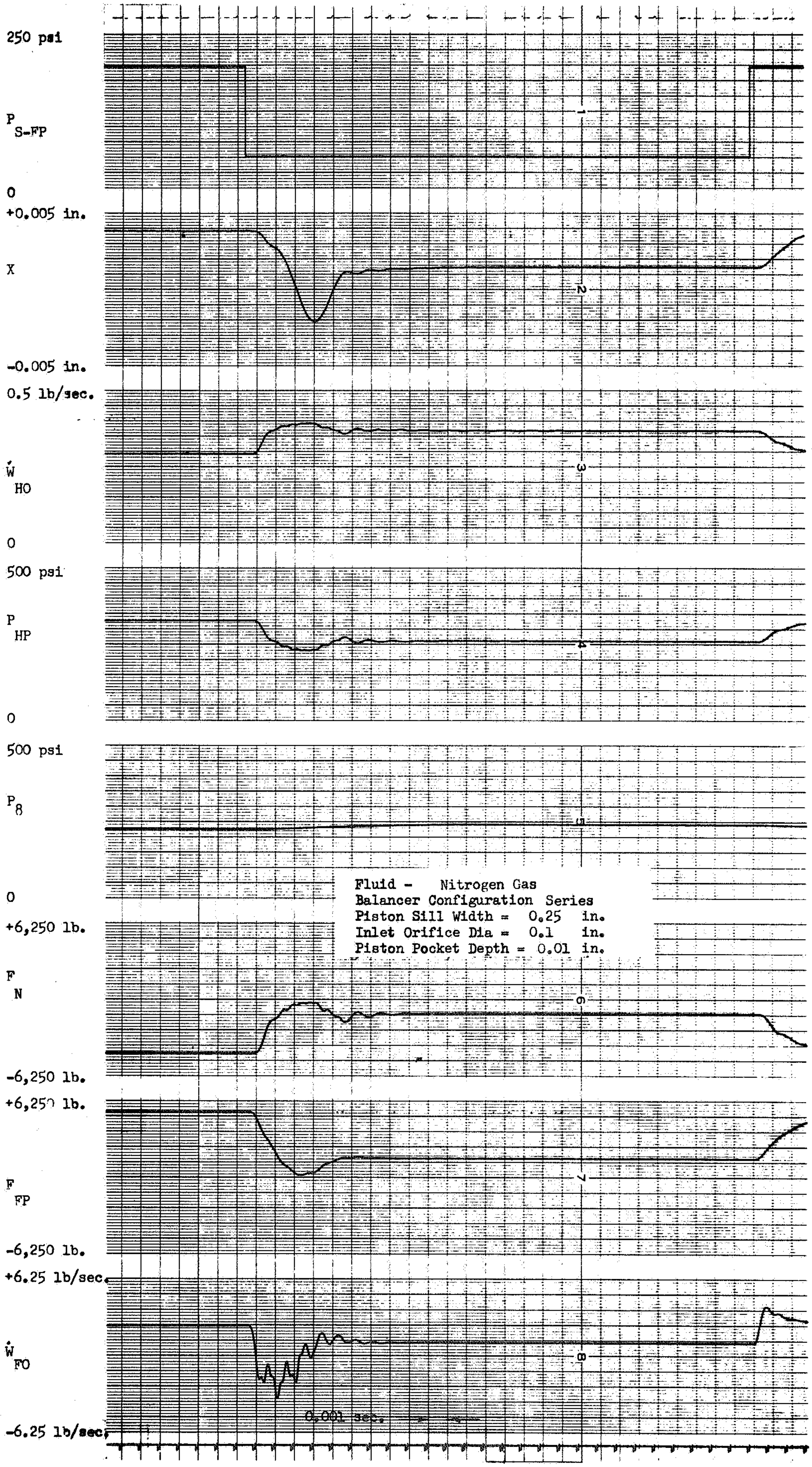


Figure C-100 Step Response - Compressible, Series Balancer

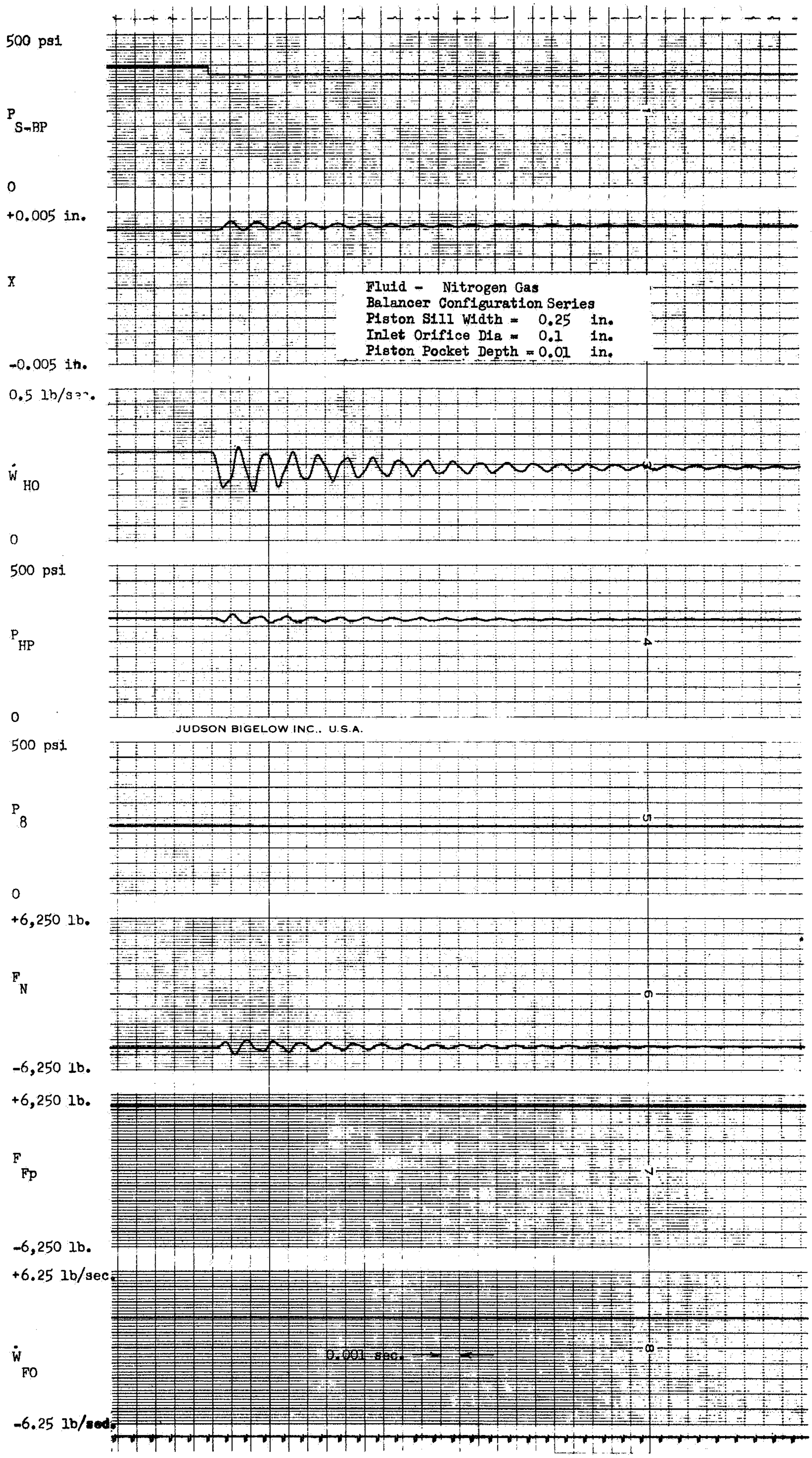


Figure C-101 Step Response - Compressible, Series Balancer

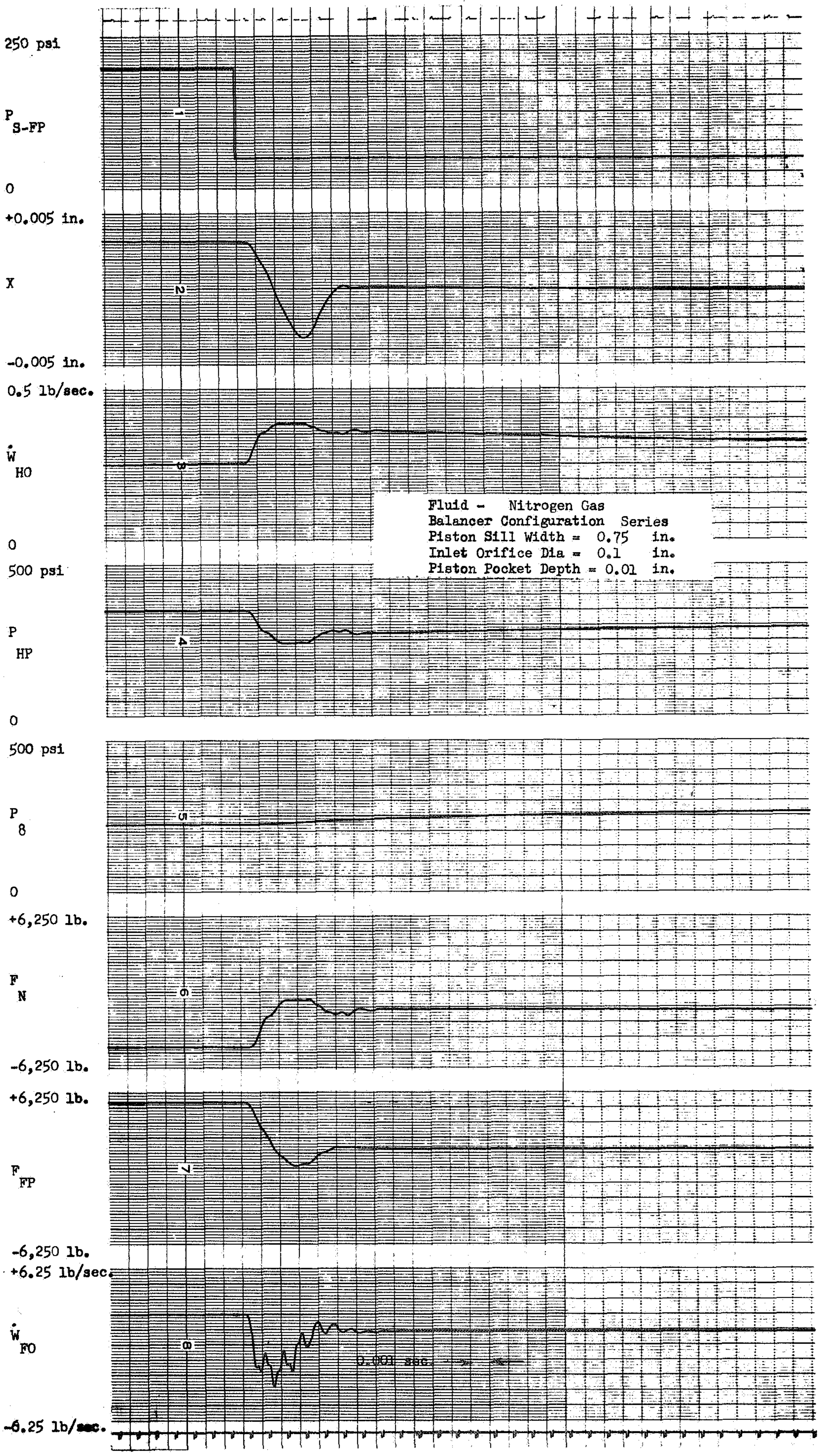


Figure C-102 Step Response - Compressible, Series Balancer

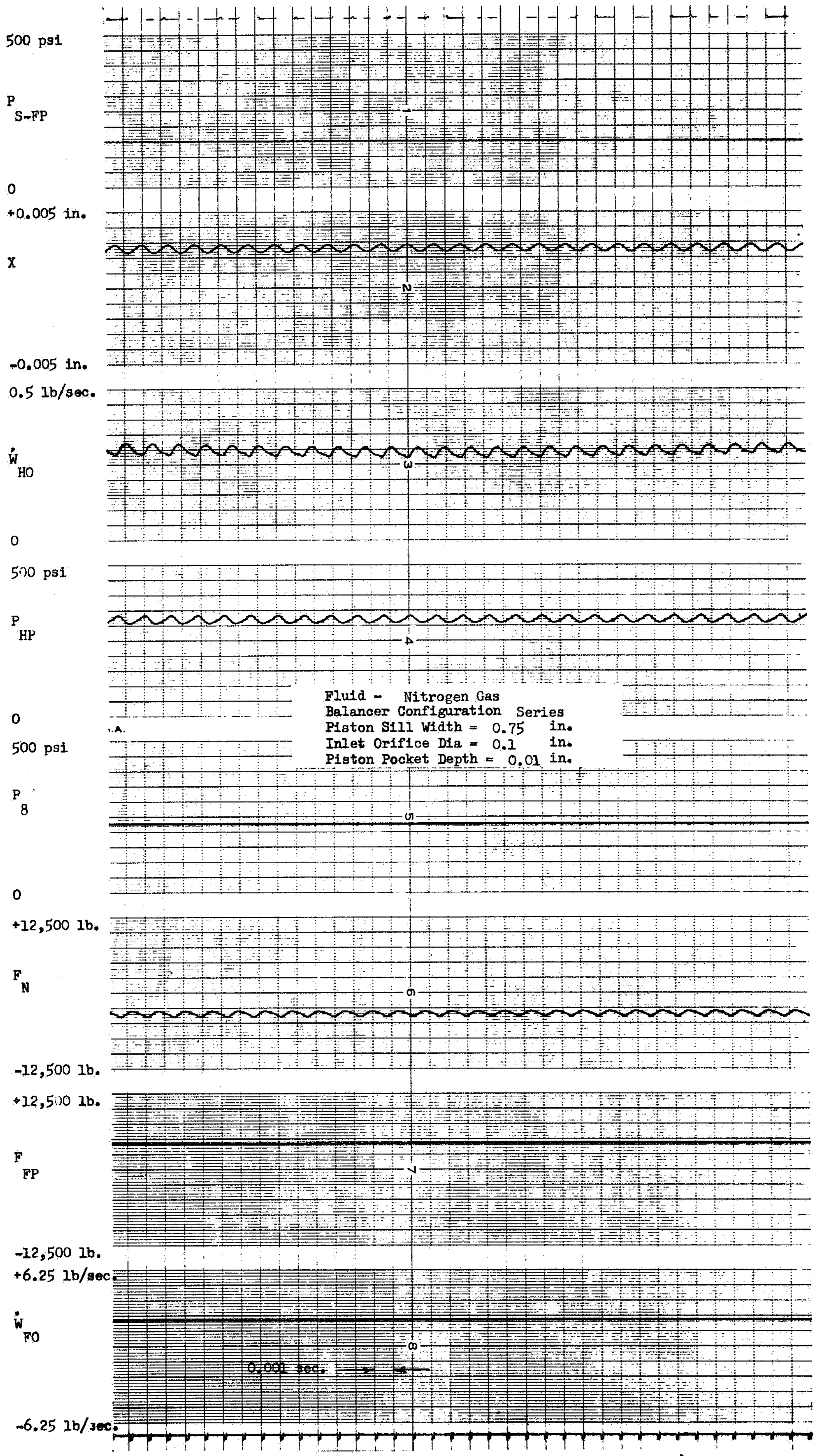


Figure C-103 Step Response - Compressible, Series Balancer

The complete set of equations in state vector form was represented by a 24 x 24 constant coefficient matrix. These coefficients for the linearized equations were evaluated for the nominal physical configuration and operating condition. The resulting Eigenvalues or characteristic roots were given on Table C-III.

Investigation of the 24 roots contained in Table C-III reveals the slightly unstable dominant root pair +48.6 $\pm$ 690. As a result, the system should be extremely oscillatory in the frequency range of 690 cps.

III. CONCLUSIONS AND RECOMMENDATIONS

The major problem in the development of the dynamic model and analog computer simulation of the thrust balancer system was the simulation of the balance piston radial orifices (sill). As simulated, it is not possible to represent very small radial orifice clearances while still being able to adequately simulate the nominal clearances. In any subsequent work, possible refinement of the simulation in this area would be advantageous.

During the parameter study for each of the basic configurations, the effect upon the dynamic response resulting from variations in piston sill width, piston pocket depth, and inlet orifice diameter was determined. From the results of these studies, it was determined that while operating with an incompressible fluid both the parallel and series balancers were very stable and quite insensitive to parameter changes.

The compressible configurations were found to be much less stable and quite sensitive to certain parameters. Variations in inlet orifice diameter had the greatest effect upon the dynamic characteristics for both balancer configuration. Both systems became unstable for large orifice diameters. Increasing piston pocket depth and sill width tended to destabilize the system slightly.

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ATTACHMENT A

(APPENDIX C)

COMPRESSIBLE CONVERSION

It was desired to develop a single dynamic model of the test configuration which would describe the thrust balance system with either incompressible water flow or compressible flow of a perfect gas. The dynamic model with provision for compressible flow was developed from the incompressible flow model by adding the capability of varying the density and bulk modulus of the fluid at each station in the flow circuit as a function of the fluid state at that station. If the fluid behaves as a perfect gas and the process is assumed to be adiabatic, then the fluid properties can be obtained as a function of pressure only.

For a perfect gas

$$P = \gamma RT \qquad \text{Eq. (A1)}$$

or

$$\frac{P}{\gamma T} = \frac{P_s}{\gamma_s T_s}$$

P = pressure (psi)
γ = density (lb/in.^{3})
R = gas constant (in/°R)
T = temperature
s = subscript which indicates conditions at a particular station. Taken as the source in this development.

and

$$\beta = kP \qquad \text{Eq. (A2)}$$

where β = bulk modulus
k = ratio of specific heat

Assuming this process is adiabatic, then

$$\frac{T}{T_s} = \left(\frac{P}{P_s}\right)^{\left(\frac{k-1}{k}\right)} \qquad \text{Eq. (A3)}$$

Combining Equations (A1), (A2), and (A3) yields

$$\gamma = \frac{P_S^{\left(\frac{k-1}{k}\right)}}{R\ T_s}\ P^{\frac{1}{k}} \qquad \text{Eq. (a4)}$$

and

$$\frac{\beta}{\gamma} = \frac{kRT_S}{P_S^{\left(\frac{k-1}{k}\right)}}\ P^{\frac{k-1}{k}} \qquad \text{Eq. (A5)}$$

For nitrogen gas when

$$k = 1.4$$
$$R = 662 \text{ in}/°R$$

then, Equations (A4) and (A5) become

$$\gamma = 1.51 \cdot 10^{-3} \frac{P_S^{\ 0.286}}{T_S} P^{0.714} \qquad \text{Eq. (A6)}$$

and

$$\frac{\beta}{\gamma} = 927 \frac{T_S}{P_S^{\ 0.286}} P^{0.286} \qquad \text{Eq. (A7)}$$

Plots of $P^{0.714}$ and $P^{0.286}$ are shown on Figures C-A1 and No. C-A2, respectively. It is possible to program these functions on the analog computer with function generators. However, if the pressure variation is not too large, an accurate approximation can be made by a linear function. The straight line approximation used for the pressure range of 200 psi to 400 psi is shown on Figures No. C-A1 and No. C-A2. Equation (A6) can then be approximated by:

$$\gamma = K_k + K_\gamma P \qquad \text{Eq. (A8)}$$

where

$$K_k = 1.51 \cdot 10^{-3} \frac{P_S^{\ 0.286}}{T_S} P^{0.714}(0) \qquad \text{Eq. (A9)}$$

$$K_\gamma = 1.51 \cdot 10^{-3} \frac{P_S^{\ 0.286}}{T_S} \frac{\partial P^{0.714}}{\partial P} \qquad \text{Eq. (A10)}$$

Equation (A7) can be approximated by

$$\frac{\beta}{\gamma} = K_c + K_T P \qquad \text{Eq. (A11)}$$

where

$$K_c = 927 \frac{T_S}{P_S^{\ 0.286}} P^{0.286}(0) \qquad \text{Eq. (A12)}$$

$$K_T = 927 \frac{T_S}{P_S^{\ 0.286}} \frac{\partial P^{0.286}}{\partial P} \qquad \text{Eq. (A13)}$$

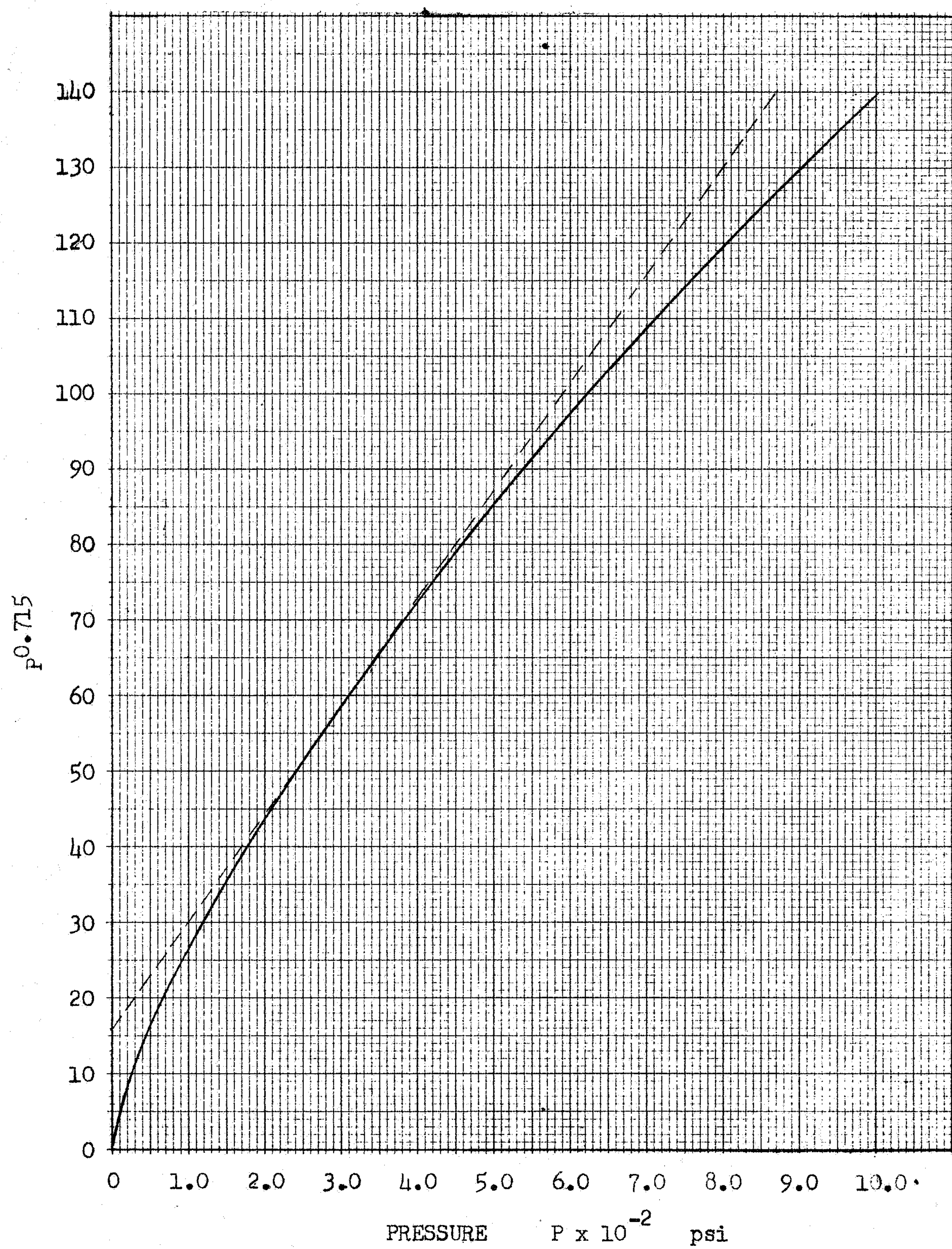

Figure C-A1 Pressure Function $P^{0.715}$

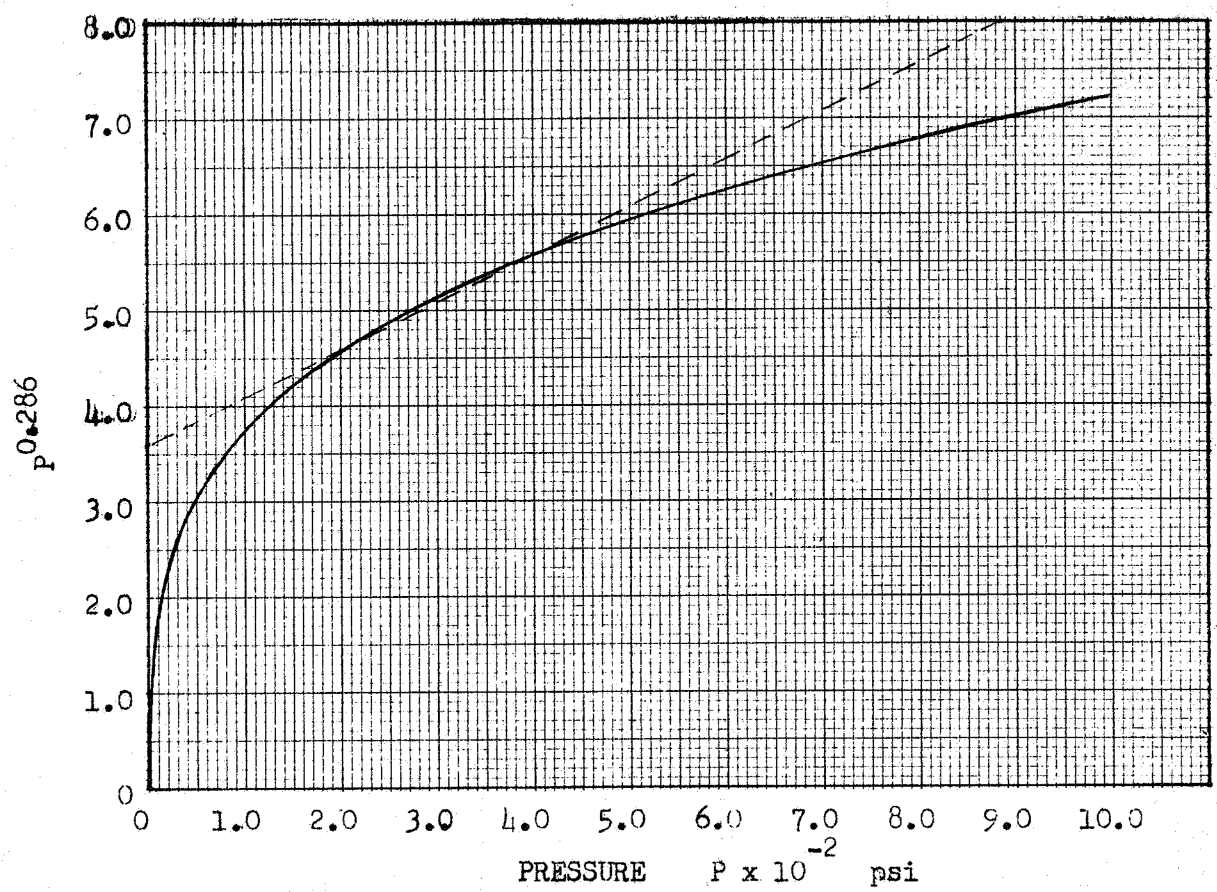

Figure C-A2 **Pressure Function $P^{0.286}$**

The partial derivative terms of Equations (A10) and (A13) indicate the slope of the respective nonlinear curves evaluated at the nominal pressure. The terms, $P^{0.714}(o)$ and $P^{0.286}(o)$, are the value of the linear approximation extended to zero pressure.

In the case of orifice flow where only the inlet and outlet pressures are available, there is a question of what pressure should be used to determine the density. The steady-state pressure drop across the inlet orifices with incompressible flow is obtained from the well-known orifice equation

$$\dot{W} = C_D A \, (2g \, \gamma)^{1/2} \, (P_S - P_o)^{1/2} \qquad \text{Eq. (A14)}$$

where

A = cross-sectional area, $in.^2$
CD = coefficient
g = gravitational constant, in/sec^2
Ps = inlet pressure, psi
Po = outlet pressure, psi
γ = density, $lb/in.^3$

It is desirable to use this equation to describe compressible flow through the orifices instead of the following more complex compressible relationship involving pressure ratios which is given by

$$\dot{W} = C_D \, A \left[\frac{2g}{RT_S}\right]^{1/2} P_S \left\{ \left(\frac{k}{k-1}\right) \left[\left(\frac{P_o}{P_S}\right)^{\frac{2}{k}} - \left(\frac{P_o}{P_S}\right)^{\frac{k+1}{k}} \right] \right\}^{1/2} \qquad \text{Eq. (A15)}$$

Using perfect gas relationship, the density at either the inlet or the outlet of the orifice can be substituted into Equation (A14). Substituting the inlet density given by

$$\gamma = \frac{P_S}{RT_S} \qquad \text{Eq. (A16)}$$

into Equation (A14) yields the following equation

$$\dot{W} = C_D \, A \left[\frac{2g}{RT_S}\right]^{1/2} P_S \left[1 - \frac{P_o}{P_S}\right]^{1/2} \qquad \text{Eq. (A17)}$$

using the density relationship of Equation (A4), the outlet density is given by

$$\gamma = \frac{P_S^{\frac{k-1}{k}}}{RT_S} P_o^{\frac{1}{k}} \qquad \text{Eq. (A18)}$$

Substituting Equation (A18) into Equation (A14) yields

$$\dot{W} = C_D A \left[\frac{2g}{RT_S}\right]^{1/2} P_S \left[\left(\frac{P_o}{P_S}\right)^{\frac{1}{k}} - \left(\frac{P_o}{P_S}\right)^{\frac{k+1}{k}}\right]^{1/2} \qquad \text{Eq. (A19)}$$

Upon comparing Equations (A14), (A17) and (A19), it is noted that they are identical except for the last term contained in the square brackets. A plot of the last term of each of the three equations is shown by the curves on Figure No. C-A3. A comparison of these curves shows that if the density at the output of the orifice is used in the incompressible orifice Equation (A14), the result is a good approximation to the compressible orifice Equation (A15) for pressure ratios above the critical ratio. Because it is intended that the computer model be limited to subsonic flow, the use of Equation (A14) with a variable density adequately describes the inlet orifice flow.

The foregoing arguments also apply to the balance piston radial orifices.

The dynamic model developed is applicable to compressible fluids that are other than a perfect gas if appropriate simplification techniques are applied. These techniques would depend upon the properties of the particular fluid as well as the operating conditions. A method used to evaluate one case for liquid hydrogen was to assume a temperature constant and that the fluid properties varied as a function of pressure only. This technique was applied in the evaluation of a preliminary design for the NERVA turbopump (Contract SNP-1). A model of this type would be an approximation if the operating conditions vary over a wide range because fluid properties normally vary as a function of both pressure and temperature.

It would be necessary to add more thermodynamic equations to determine the fluid properties (including density and bulk modulus) if greater accuracy or a wide range of operating conditions is anticipated. These property functions would be highly complex and would require further refinement of the existing model.

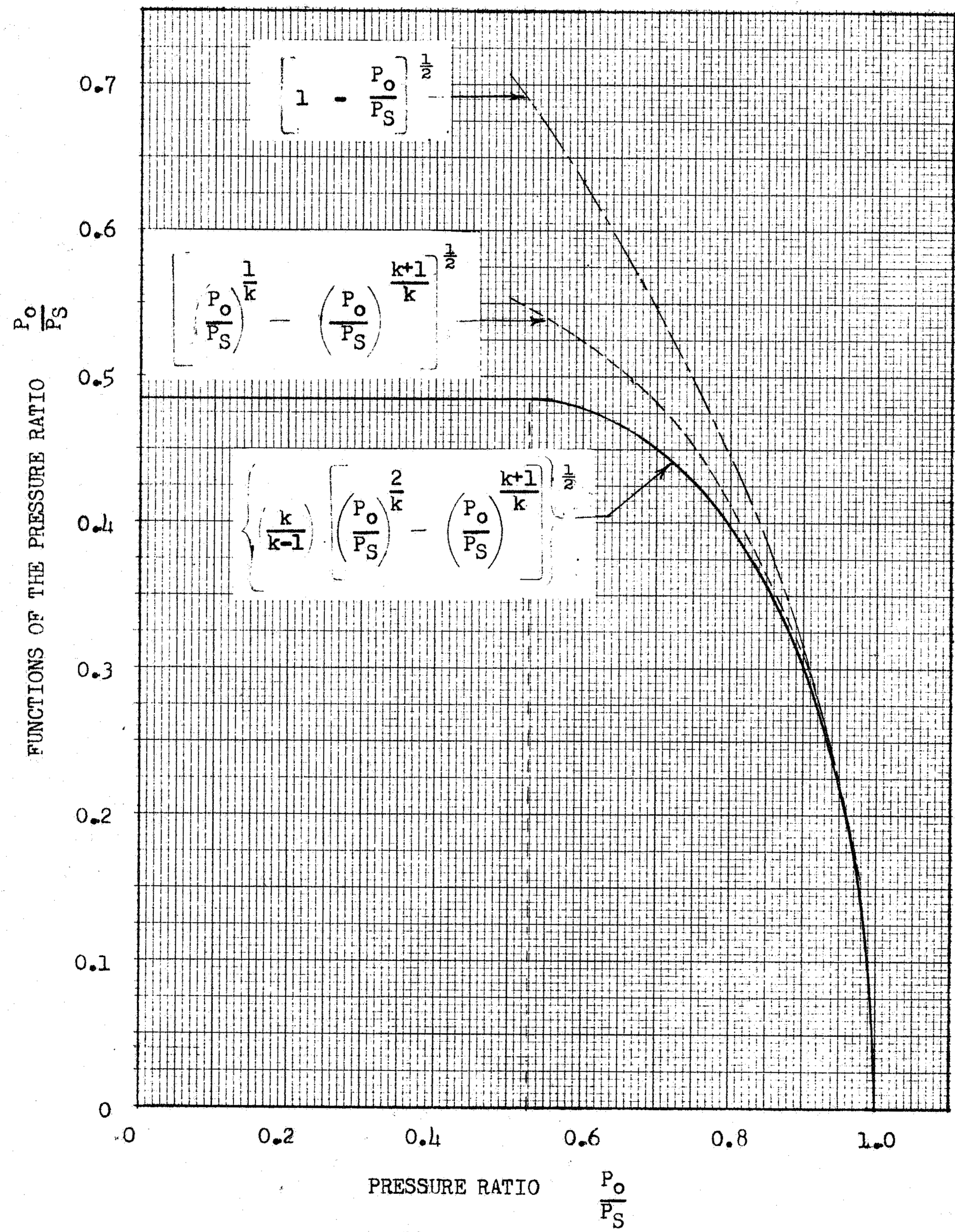

Figure C-A3 **Pressure Ratio Functions**

ATTACHMENT B

(APPENDIX C)

RADIAL FLOW ORIFICES

The radial orifice equations are defined in this attachment. The principal element of the balance piston flow path is the radial orifices formed by the raised piston sills or lands and the housing walls. The piston sills and the housing walls form a variable orifice where the cross-sectional area and, hence, the pressure drop are a function of the gap width between the piston sill and the housing wall.

The total pressure loss through the radial orifice is subdivided into an entrance loss, sill flow loss, and an exit loss. The entrance loss is defined by the following equation.

$$\Delta P_i = P_i - P_1 = \frac{C_A}{8g\,\pi^2\,\gamma_i R_1^2}\left[\frac{1}{h} - \frac{1}{h+D}\right]^2 \dot{w}^2 \qquad \text{Eq. (B1)}$$

where

C_A = entrance coefficient

h = gap width, sil to wall, in.

D = sill height, in.

R_i = sill entrance radius, in.

$\dot{w}$ = weight flow, lb/sec

γ_i = fluid density at the sill entrance, $lb/in.^3$

The entrance loss is a nonlinear function of both the weight flow, $\dot{w}$, and the gap width, h. For the compressible flow case, the density, γ_i, also becomes a variable which is a function of pressure. The pressure drop within the sill gap is described by the following rather complex set of equations.

$$P_1 - P_2 = \Delta P_S - L_S \frac{d\dot{w}}{dt} \qquad \text{Eq. (B2)}$$

$$V_{Avg} = \frac{\dot{w}}{4\pi\,\gamma_s\,h}\left(\frac{R_1 + R_2}{R_1\,R_2}\right) \qquad \text{Eq. (B3)}$$

$$U_{Avg} = \frac{\pi N_{RPM}}{120}(R_1 + R_2) \qquad \text{Eq. (B4)}$$

$$V_{Res} = (V_{Avg}^2 + U_{Avg}^2)^{1/2} \qquad \text{Eq. (B5)}$$

$$R_e = \frac{2\,\gamma\,V_{Res}\,h}{g\mu} \qquad \text{Eq. (B6)}$$

If Re < 2000, it is assumed that laminar flow exists and ΔP_S is given by

$$\Delta P_S = \frac{6\mu \ln (R_2/R_1)}{\gamma \pi h^3} \dot{w} \pm \frac{\gamma_s}{2g} K_r^2 \omega_r^2 (R_2^2 - R_1^2) \qquad \text{Eq. (B7)}$$

The negative sign between the major terms of Equation (B7) accounts for flow outward through the outer sill, and the positive sign accounts for inward flow through the inner wall.

If Re < 2000, it is assumed that turbulent flow exists and ΔP_S is given by the following relationship.*

$$\Delta P_S = \frac{(0.079)\mu^n (\sec \alpha)^{1-n}}{\gamma_S 2^n g^{1-n} (2)^{2-n} (1-n)} \left[\frac{R_2^{1-n} - R_1^{1-n}}{R_1^{1-n} R_2^{1-n}}\right] \frac{\dot{w}^{2-n}}{h^3} \qquad \text{Eq. (B8)}$$

where $\sec \alpha = \frac{V_{Res}}{V_{Avg}}$

N_{rpm} = piston rotational speed, rpm

R_1 = inner sill radius, in.

R_2 = outer sill radius, in.

K_r = rotational constant

ω_r = piston rotational speed, rad/sec

n = Reynolds number exponent

μ = dynamic viscosity, lb-sec/in.^{2}

γ_s = fluid density within the sill, lb/in.^{3}

Equations (B3) through (B8) show the pressure drop through the sill gap to be a complex function of both fluid weight flow, $\dot{w}$, and sill gap width, h. For compressible flow, the density, γ_s, also becomes a variable.

The inertance of the radial orifice, L_s, also is a function of the sill gap width and is given by the following equation.

$$L_s = \frac{1}{J_s h} \qquad \text{Eq. (B9)}$$

where

$$J_s = \frac{\pi g (R_2 + R_1)}{R_2 - R_1} \qquad \text{Eq. (B10)}$$

*Tas, L. N., and Donovan, W. F., "Through-Flow in Concentric and Eccentric Annuli of Fine Clearance With and Without Relative Motion of the Boundaries," Trans. ASME, November 1955

The orifice exit loss is defined by

$$\Delta P_o = P_2 - P_o = \frac{C_B}{8g\ \pi^2\ \gamma_o\ R_o^2} \left[\frac{1}{h}\ \ \frac{1}{h_{oEqv}} \right]^{1/2} W^2 \qquad \text{Eq. (B11)}$$

where C_B = exit coefficient

h_{oEqv} = exit width, in.

R_o = sill exit radius, in.

γ_o = fluid density at the sill exit, lb/in.^{3}

As with both the entrance loss and sill loss, the exit loss is a non-linear function of weight flow and sill gap width. In the compressible flow case, the density also is a variable.

The exact simulation of all the equations describing the flow through the radial orifices on the analog computer would be too complex and would require excessive analog equipment. Therefore, a simplified approach is followed where the three pressure loss terms were evaluated over the expected range of weight flows and sill gaps. The three pressure loss terms are then added to obtain the total orifice pressure drop as a function of weight flow, gap width, and density for compressible flow. The flow through the radial orifice is then described by

$$P_i - P_o = {*P_T} - \frac{1}{J_s\ h}\ \frac{d\dot{w}}{dt} \qquad \text{Eq. (B12)}$$

where

$$\Delta P_T = \Delta P_i + \Delta P_S + \Delta P_o$$

Plots of $\Delta P_T(\dot{w},h)$ for incompressible flow with different sill widths and piston speeds are shown on Figures No. C-B1 through No. C-B8. These pressure drop functions are then simulated on the analog computer. The method of simulation will be described subsequently.

Certain approximations were made in the pressure drop calculations which should be noted. For the balancer configuration and pressures being simulated on the computer, it was determined that the occurrence of laminar flow would be rare; therefore, only the turbulent Equation (B8) is used in the evaluation of the pressure drop through the sill gap. In the calculation of the exit loss, the exit width, h_{oEqv}, is considered infinite because it is much larger than the gap width, h.

Other approximations in the fluid equations involve the density terms. Each of the three pressure drop equations shows that the losses are inversely proportional to density which, in turn, is dependent upon fluid conditions at the point where the equation applies. The three pressure drops are all lumped

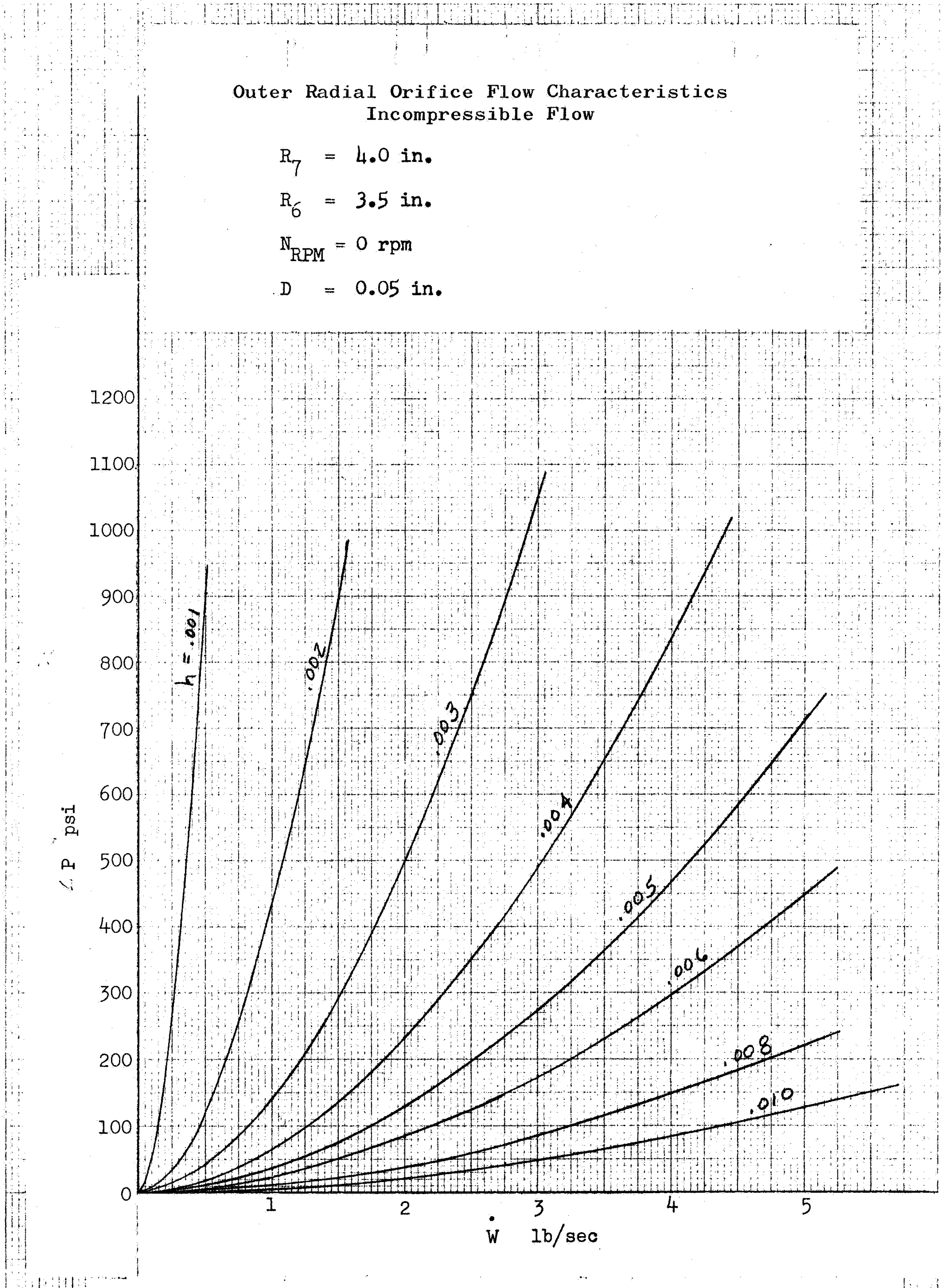

Figure C-B1 Radial Orifice Characteristics - Incompressible Flow

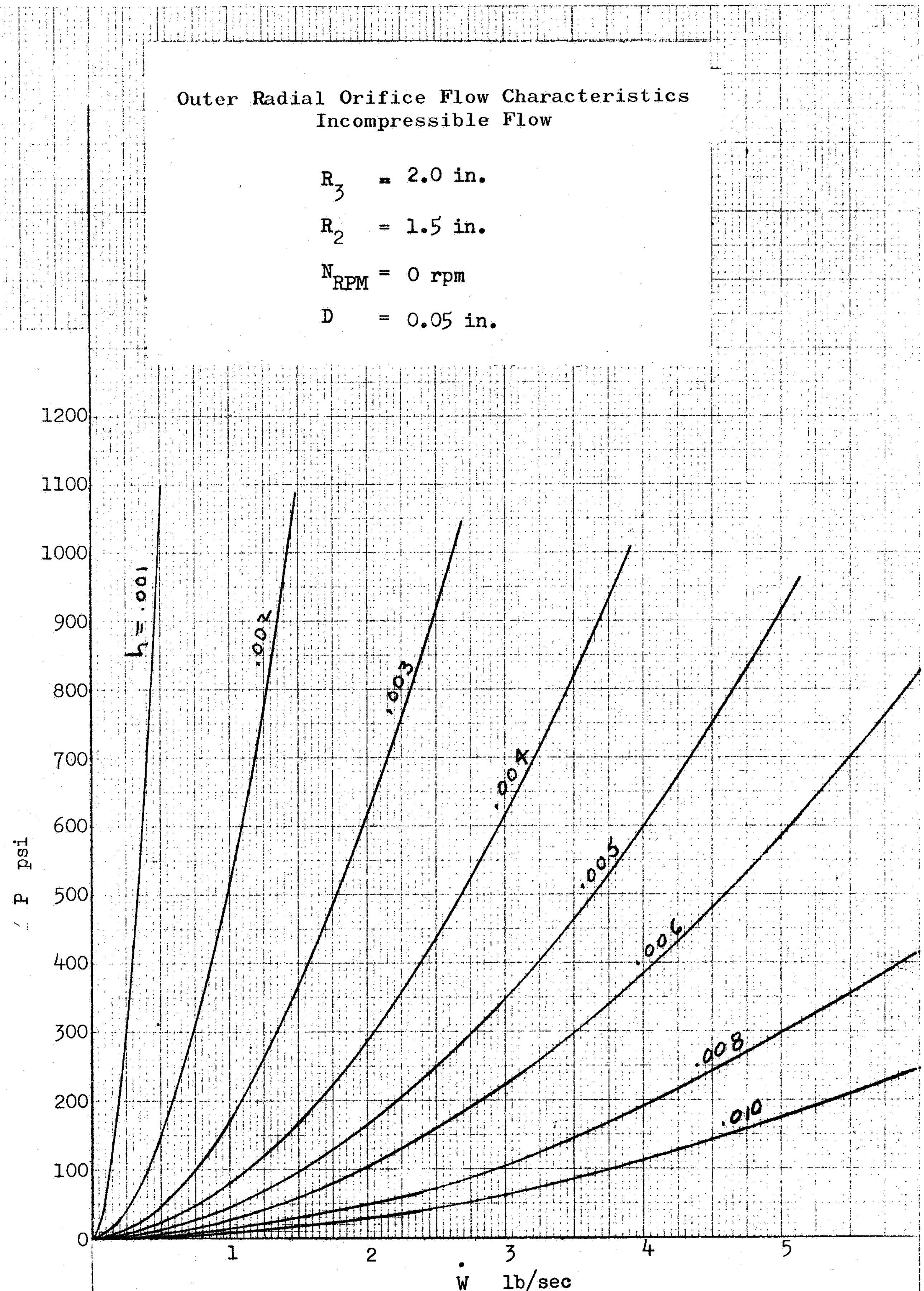

Figure C-B2 Radial Orifice Characteristics - Incompressible Flow

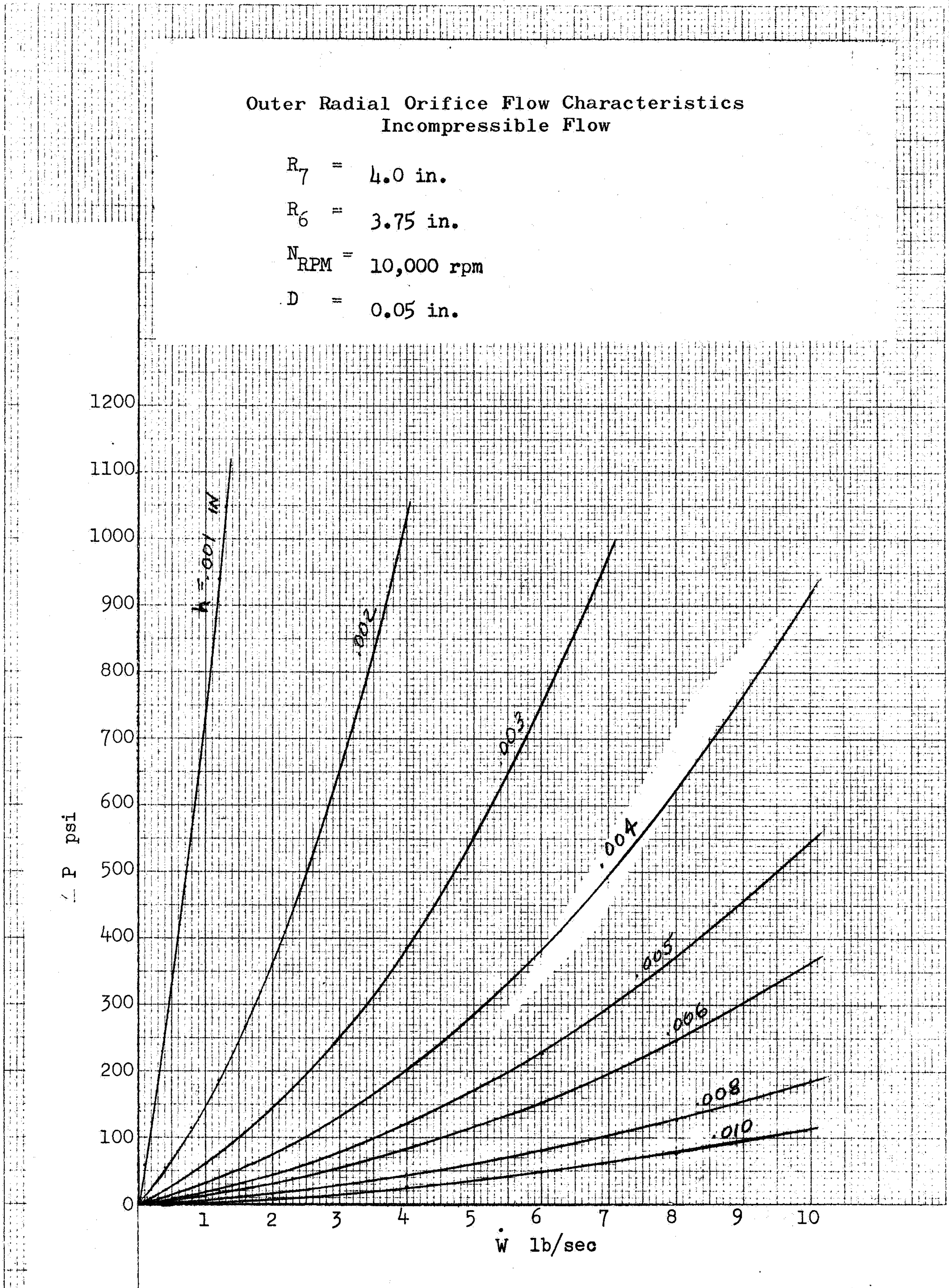

Figure C-B3 Radial Orifice Characteristics - Incompressible Flow

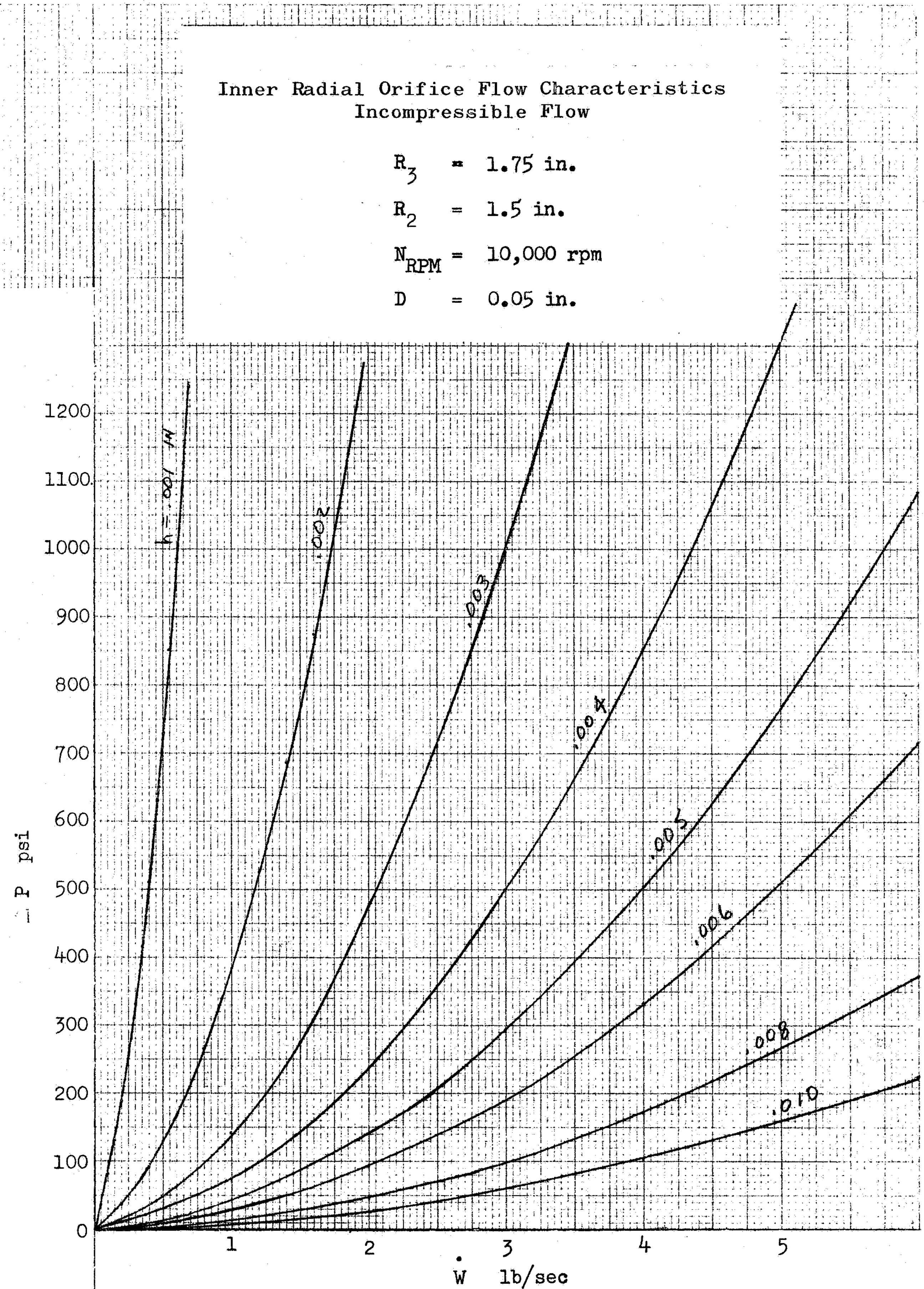

Figure C-B4 Radial Orifice Characteristics - Incompressible Flow

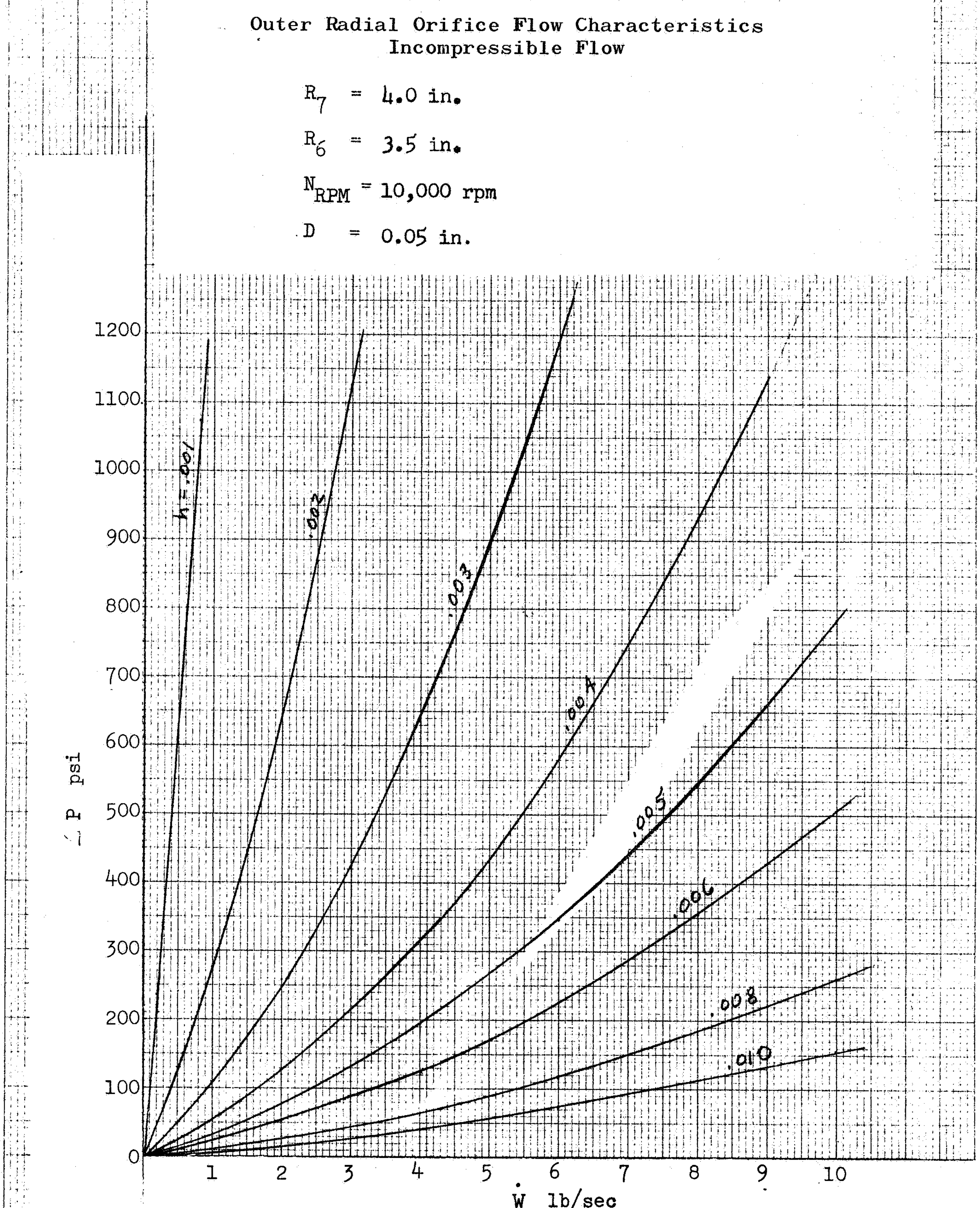

Figure C-B5 Radial Orifice Characteristics - Incompressible Flow

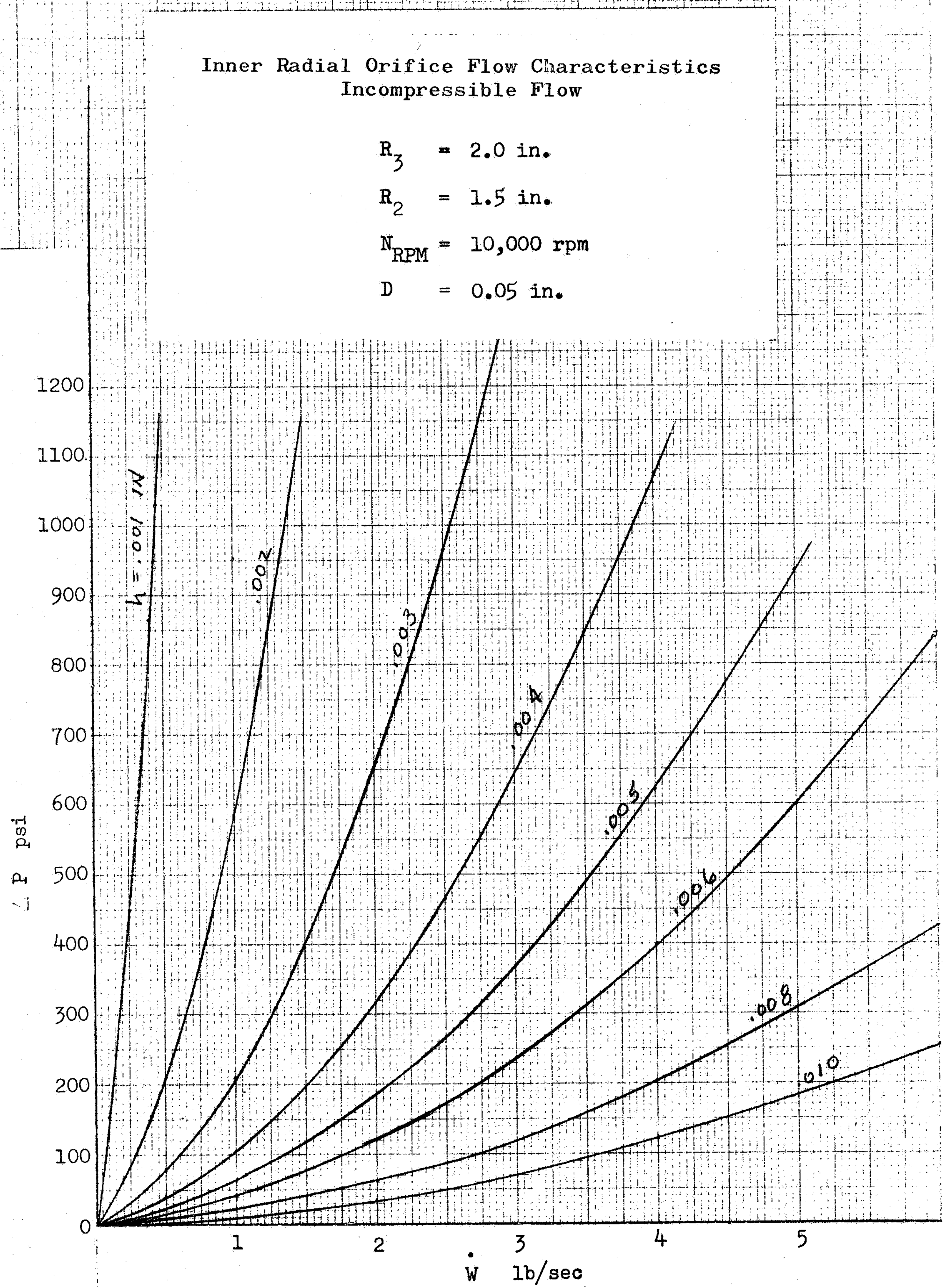

Figure C-B6 Radial Orifice Characteristics - Incompressible Flow

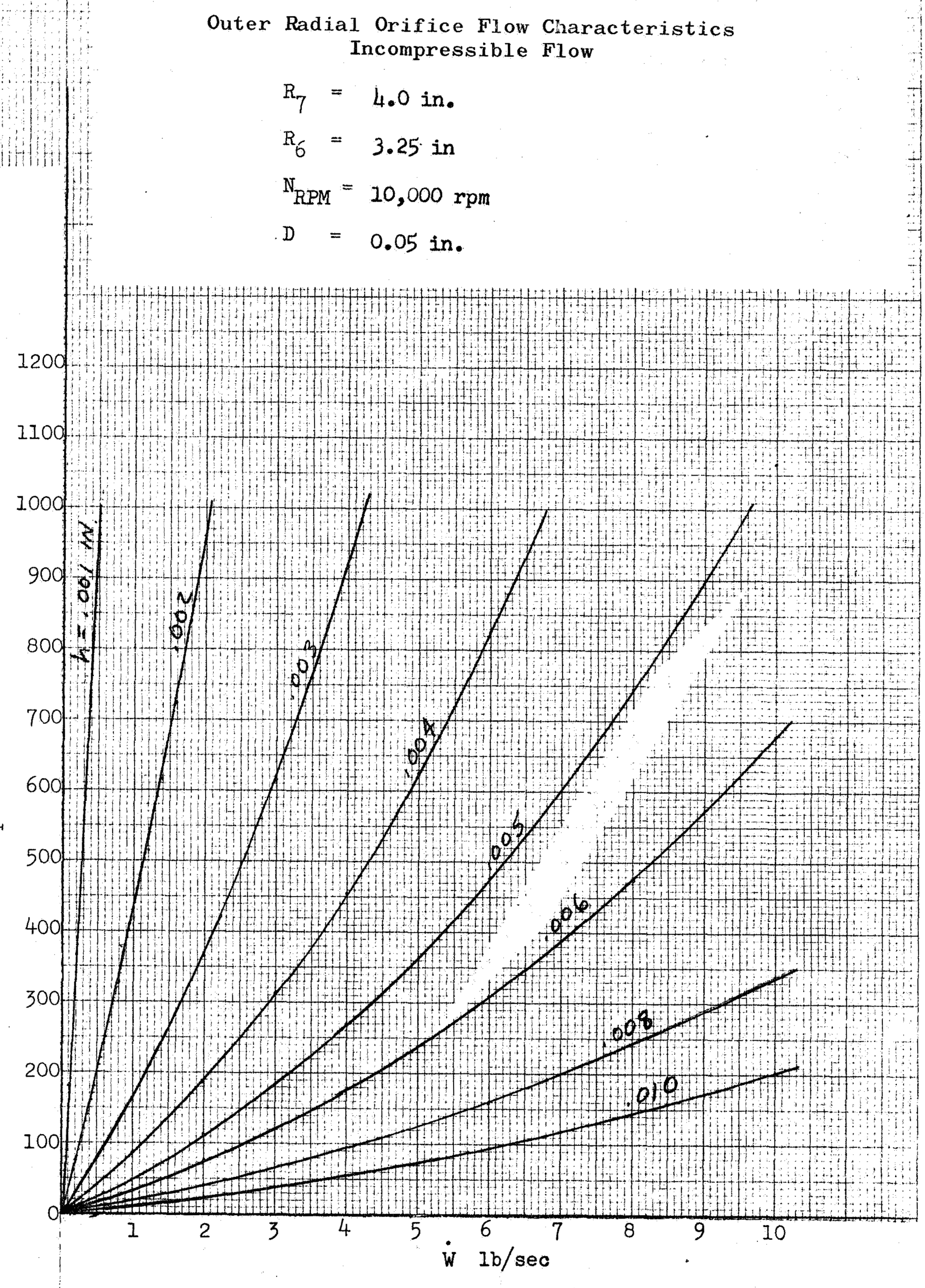

Figure C-B7 Radial Orifice Characteristics - Incompressible Flow

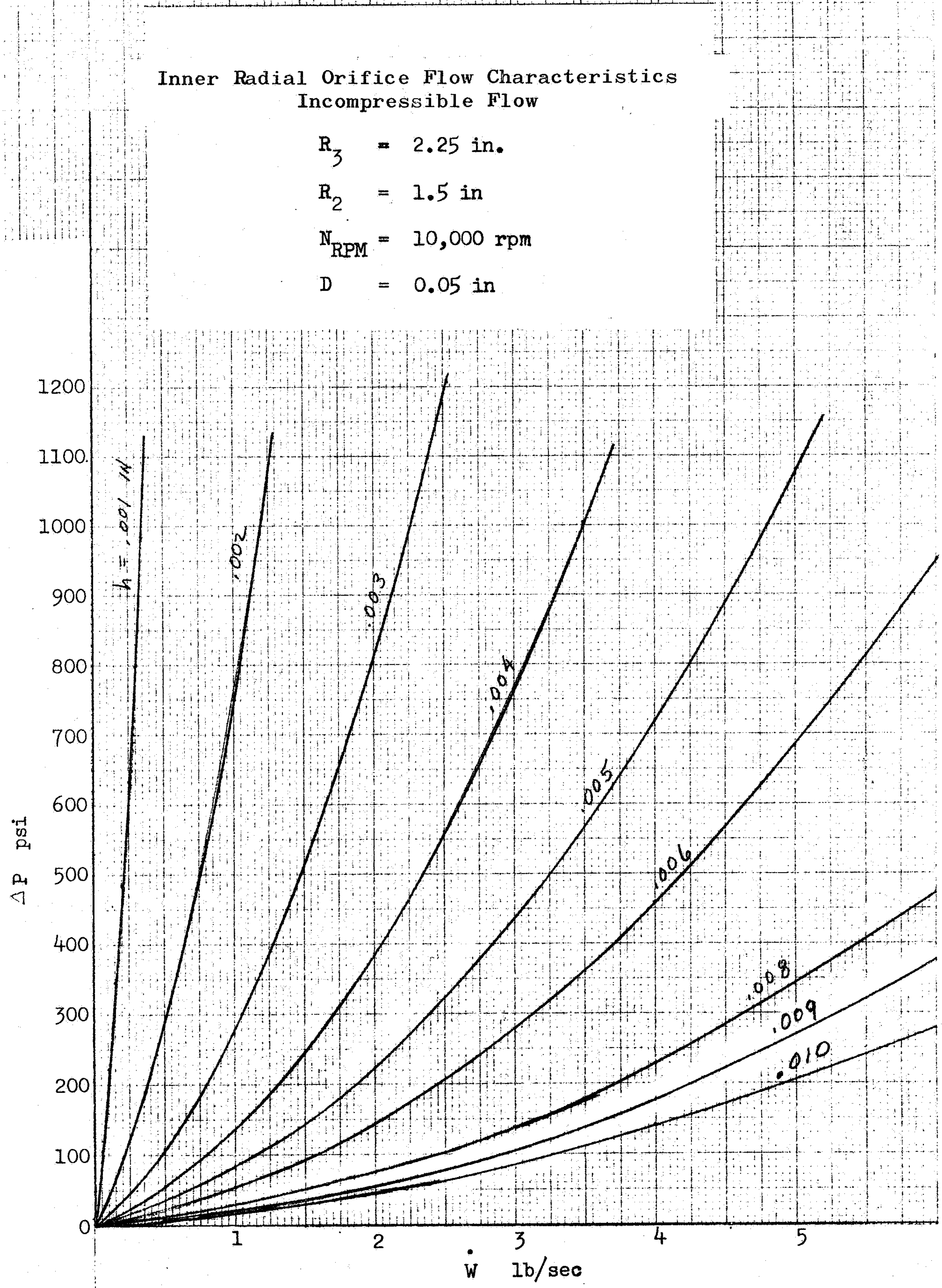

Figure C-B8 Radial Orifice Characteristics - Incompressible Flow

together; therefore, it is impossible to introduce a separate variable density into each loss. As a result, each of the loss components is calculated with a nominal value of density, γ_N, at the point where the equation applies. Plots of the pressure drop function for compressible flow with nominal density are shown on Figures No. C-B9 through No. C-B14. The total pressure drop function is then made a function of density by dividing by a correction term equal to γ/γ_N. The correction term, γ/γ_N, is obtained from the density equations derived in Attachment A where

$$\gamma = K_k - K_\gamma P$$

or

$$\frac{\gamma}{\gamma_N} = \frac{K_k}{\gamma_N} - \frac{K}{\gamma_N} P \qquad \text{Eq. (B13)}$$

The pressure used in the density correction Equation (B13) is an approximation because the pressure varies from point to point through the orifice. An average of the inlet and exit pressures is used in the simulation to obtain the correction term γ/γ_N.

The curves of total pressure loss, as shown on Figures No. C-B1 through No. C-B14, are curve-fit and simulated on the analog computer by two functions which are multiplied together as follows:

$$\Delta P_T = f(\dot{w})\ f(h) \qquad \text{Eq. (B14)}$$

The weight flow function $f(\dot{w})$ is generated in the simulation by a function of the form

$$f(\dot{w}) = K_1\ \dot{w} + K_2\ \dot{w}^2 \qquad \text{Eq. (B15)}$$

while the gap function is represented by a function of the form

$$f(h) = \frac{C_1}{h} + \frac{C_2}{h^2} + \frac{C_3}{h^3} \qquad \text{Eq. (B16)}$$

The polynomial curve-fit technique was selected to facilitate quick changes of sill characteristics, although a function generator could also have been used to fit the curves.

Outer Radial Orifice Flow Characteristics
Incompressible Flow

R_7 = 4.0 in.

R_6 = 3.75 in.

N_{RPM} = 10,000 rpm

D = 0.01 in.

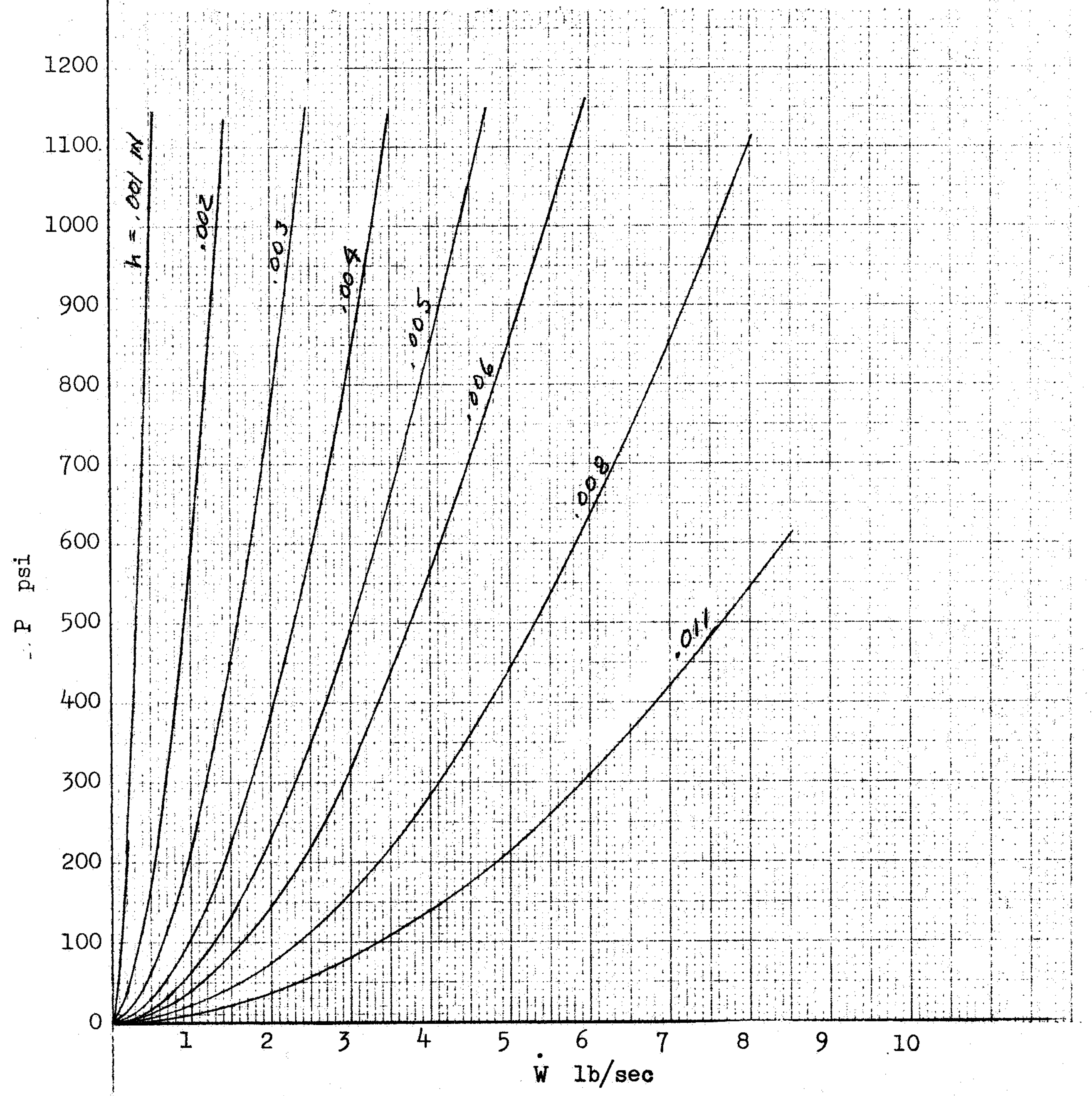

Figure C-B9 Radial Orifice Characteristics - Compressible Flow

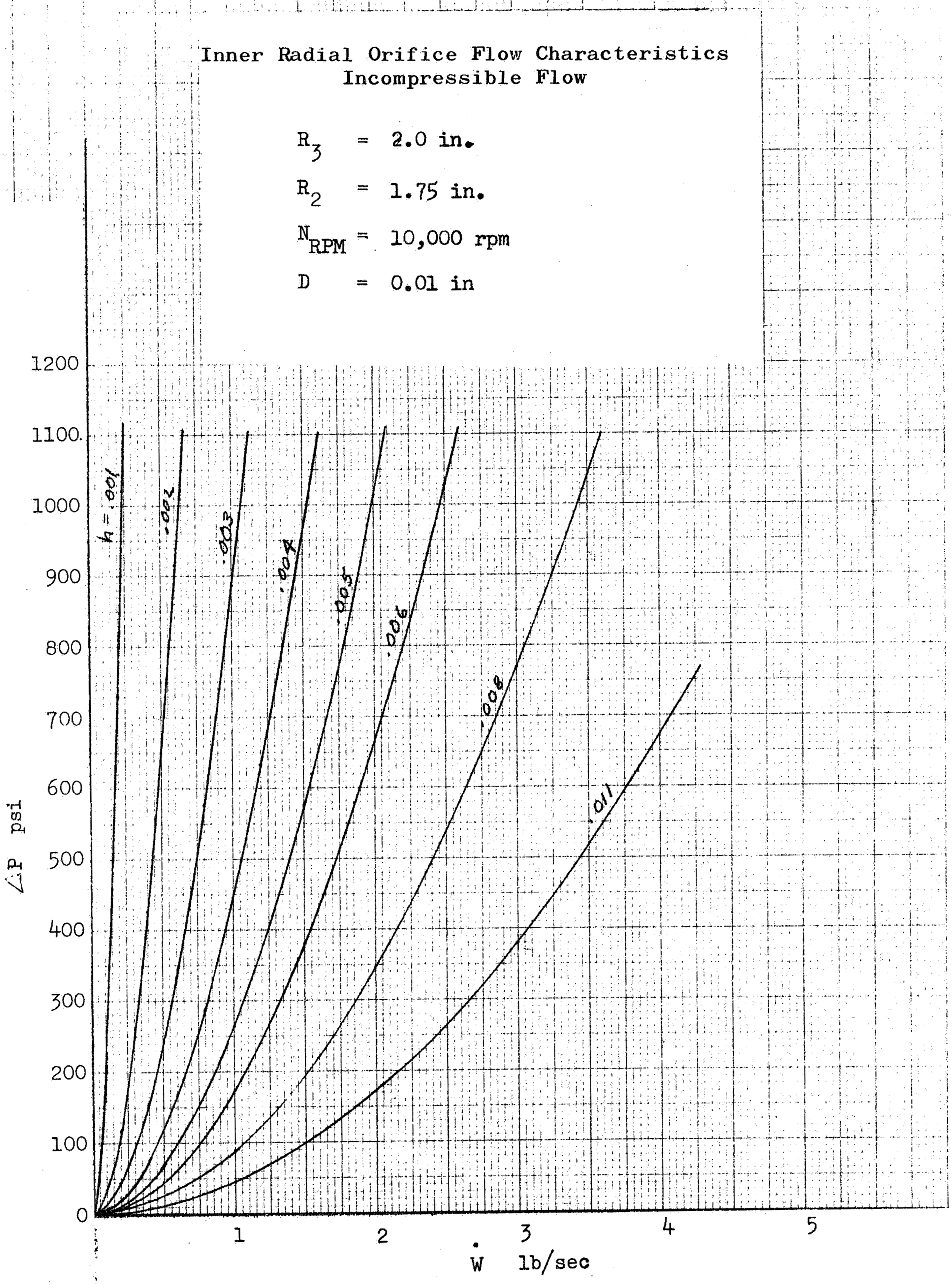

Figure C-B10 Radial Orifice Characteristics - Compressible Flow

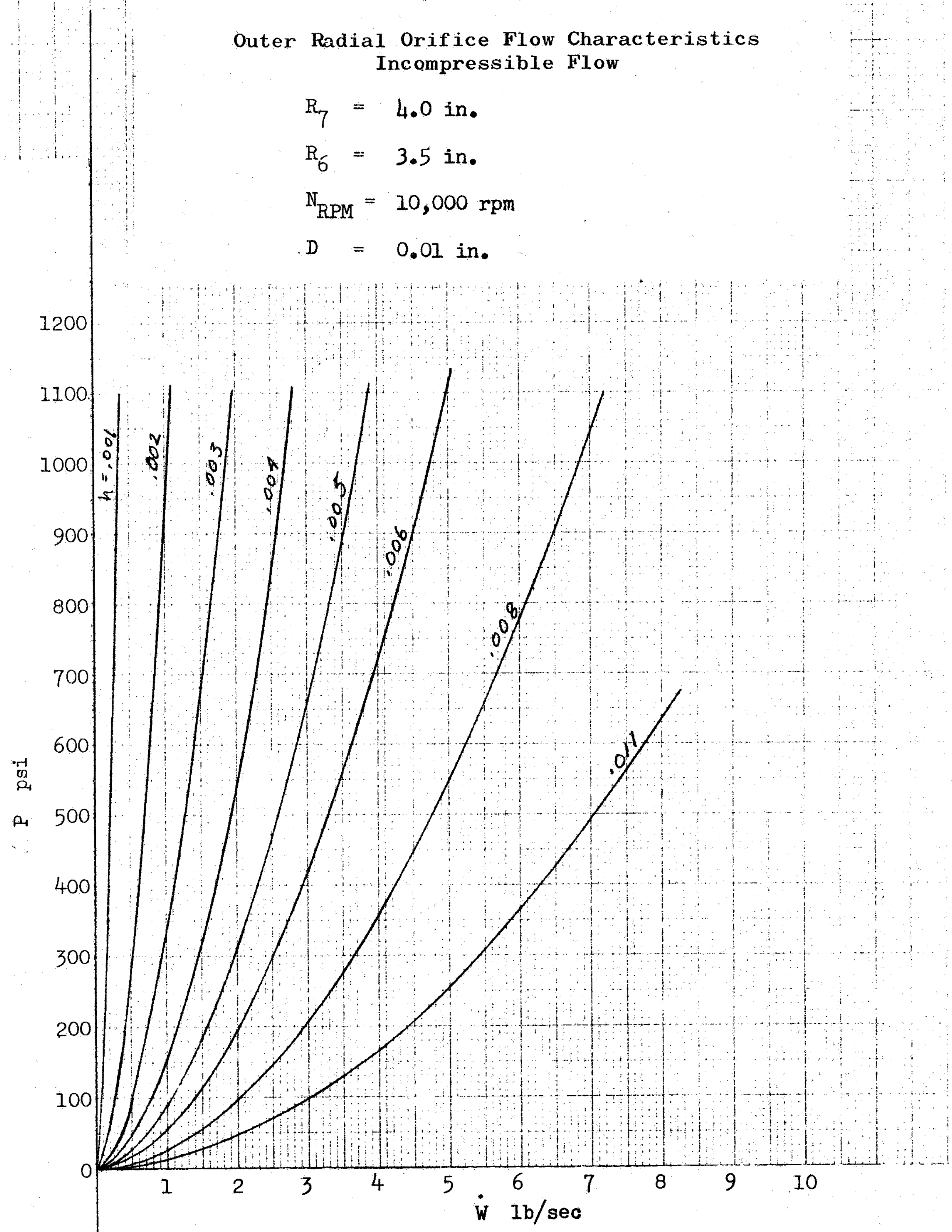

Figure C-B11 Radial Orifice Characteristics - Compressible Flow

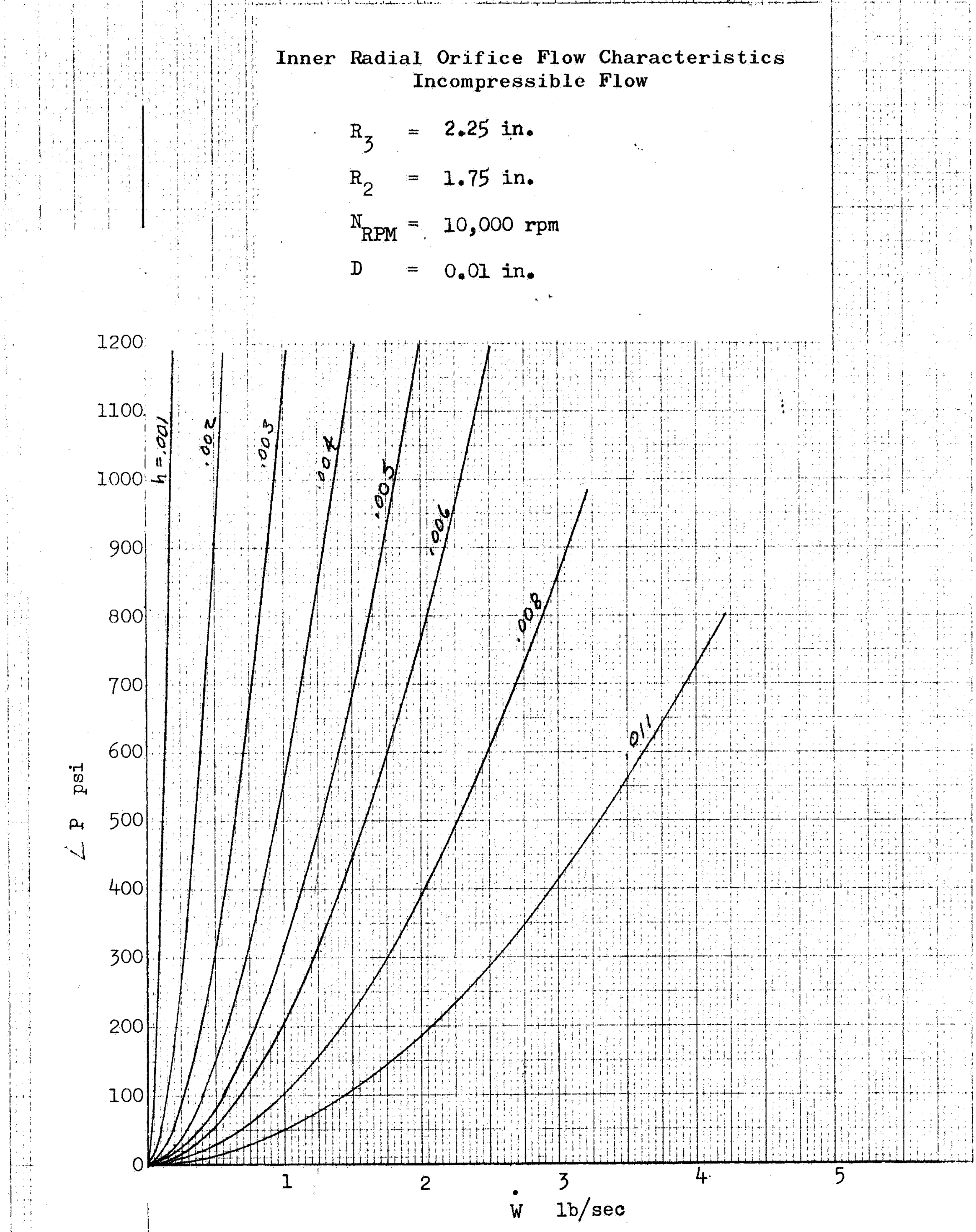

Figure C-B12 Radial Orifice Characteristics - Compressible Flow

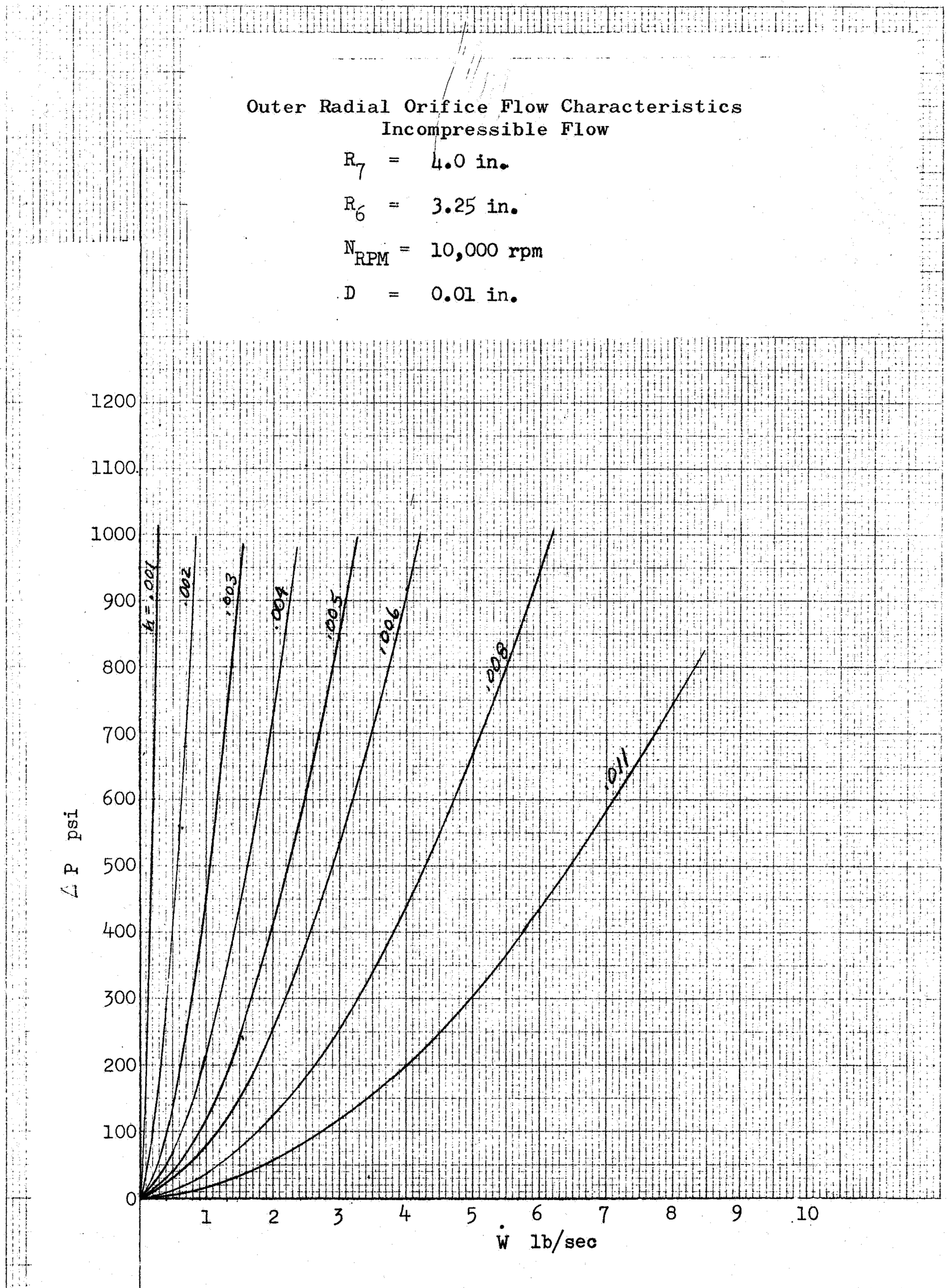

Figure C-B13 Radial Orifice Characteristics - Compressible Flow

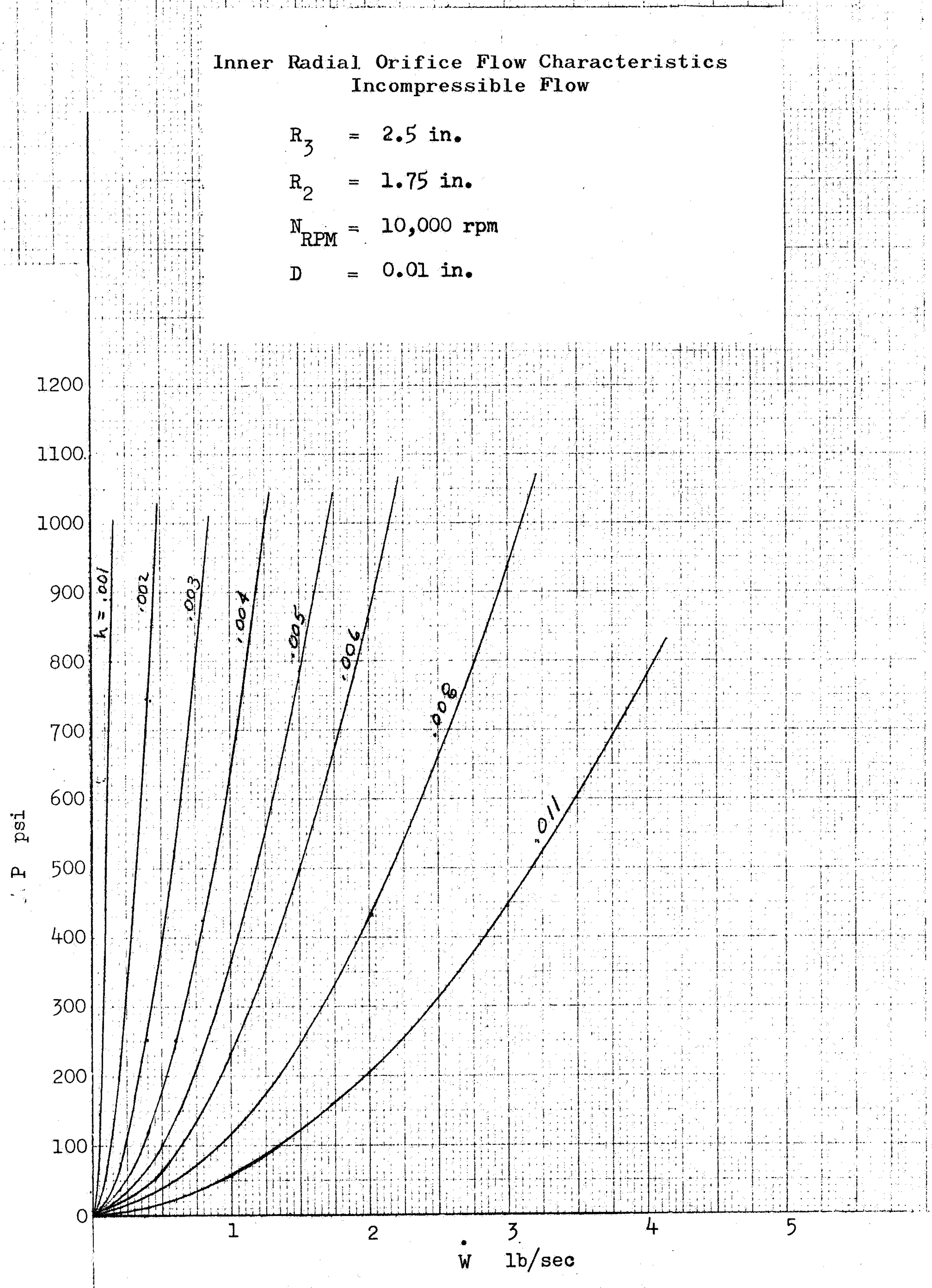

Figure C-B14 Radial Orifice Characteristics - Compressible Flow

ATTACHMENT C

(APPENDIX C)

AXIAL FORCE ON A ROTATING PISTON

The force acting axially upon a piston is obtained by integration of the pressure profile over the total area of the piston. The areas of the balance piston face are made up of the pocket areas and areas associated with the lands or sills.

The force acting upon the piston land is obtained by integration of the pressure profile over the area of the land. A diagram of a land and radial slot is shown on Figure No. C-C1. The pressure gradient within the radial slot formed by the piston land and the housing wall is a function of the total flow within the slot and the rotational speed of the piston. The total flow within the slot is the sum of the through flow (Q) and the squeeze flow (Q_s) caused by the axial motion of the piston land. The squeeze flow is given by:

$$Q_s = v\pi \left(r^2 - R_o^2\right) \qquad \text{Eq. (C1)}$$

where

v = axial velocity of the piston, in./sec

R_o = radius where the squeeze flow is zero, in.

r = radius, in.

Flow outward will be regarded as positive so that the squeeze flow is positive when $r>R_o$ and negative when $r<R_o$. The force on the piston land will be determined for the cases of laminar and turbulent flow through the radial slot. The determination of the force resulting from squeeze film effects with laminar flow conditions will follow the development of Fuller** and Archibald***.

For laminar flow, the pressure gradient within the radial slot is given by

$$-\frac{dP}{dr} = \frac{6\mu Q}{\pi h^3 r} - \frac{\gamma}{g} K_r^2 \omega_r^2 r + \frac{6\mu v \left(r^2 - R_o^2\right)}{h^3 r} \qquad \text{Eq. (C2)}$$

**Fuller, D. P., Theory and Practice of Lubrication for Engineers, Wiley, 1956

***Archibald, F. R., "Load Capacity and Time Relations for Squeeze Films," Trans. ASME, January 1956

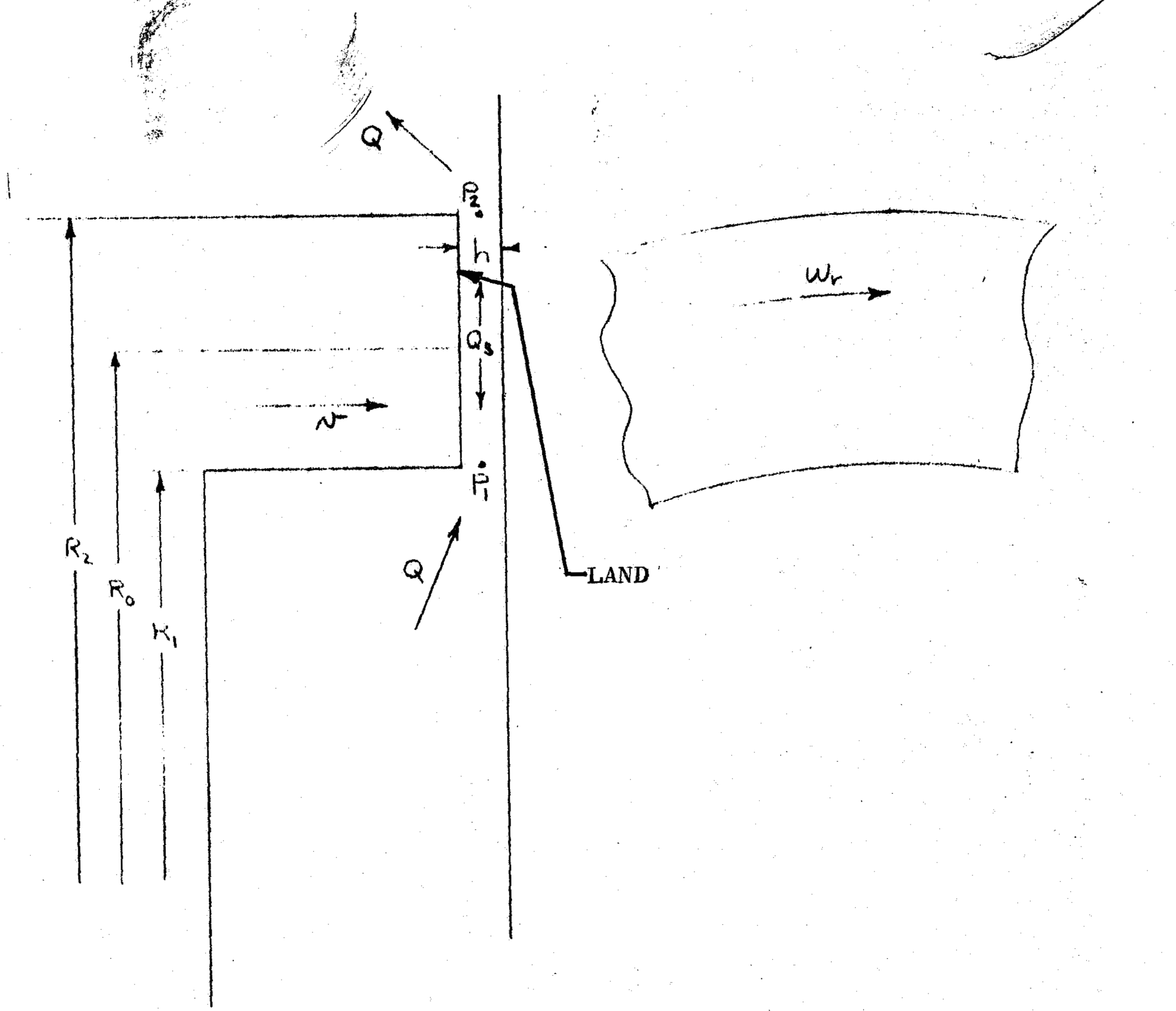

Figure C-C1 DIAGRAM OF PISTON LAND AND RADIAL SLOT

where

μ = absolute viscosity, lb-sec/in.^{2}

Q = flow-through rate, in.^{3}/sec

h = gap width, in.

g = gravitational constant, in./sec^2

γ = weight density, lb/in.^{3}

K_r = rotational constant

ω_r = piston rotational speed, rad/sec

Integrating Equation (C2) from the inside radius R_1 and pressure P_1

$$\int_{P_1}^{P} d\alpha = -\frac{6\mu Q}{\pi h^3}\int_{R_1}^{r}\frac{d\xi}{\xi} + \frac{\gamma}{g}K_r^2\omega_r^2\int_{R_1}^{r}\xi d\xi - \frac{6\mu v}{h^3}\int_{R_1}^{r}\xi - \frac{R_o^2}{\xi}\quad d\xi \qquad \text{Eq. (C3)}$$

the following pressure relationship is obtained:

$$P = P_1 - \frac{6\mu Q}{\pi h^3}\ln\frac{r}{R_1} + \frac{\gamma}{2g}K_r^2\omega_r^2(R^2 - R_1^2) - \frac{6\mu v}{h^3}\left[\frac{(r^2 - R_1^2)}{2} - R_o^2\ln\frac{r}{R_1}\right] \qquad \text{Eq. (C4)}$$

At the outer radius, $r = R_2$ and $P = P_2$, so:

$$Q = \frac{\pi h^3}{6\mu\ln\frac{R_2}{R_1}}\left\{(P_1 - P_2) + \frac{\gamma}{2g}K_r^2\omega_r^2(R_2^2 - R_1^2) - \frac{6\mu v}{h^3}\left[\frac{R_2^2 - R_1^2}{2} - R_o^2\ln\frac{R_2}{R_1}\right]\right\} \qquad \text{Eq. (C5)}$$

However, the flow through (Q) must be independent of the squeeze flow. (At R_o the squeeze flow is zero, so it cannot contribute to through flow.) Therefore, the last term of Equation (C5) must be zero, so that:

$$R_o^2 = \frac{R_2^2 - R_1^2}{2 \ln \frac{R_2}{R_1}} \qquad \text{Eq. (C6)}$$

and

$$Q = \frac{\pi h^3}{6\mu \ln \frac{R_2}{R_1}} \left[(P_1 - P_2) + \frac{\gamma}{2g} K_r^2 \omega_r^2 (R_2^2 - R_1^2) \right] \qquad \text{Eq. (C7)}$$

Substituting Equations (C6) and (C7) into (C4)

$$P = P_1 - \frac{(P_1 - P_2)}{\ln \frac{R_2}{R_1}} \ln \frac{r}{R_1} \qquad \text{Eq. (C8)}$$

$$+ \left[\frac{\gamma}{2g} K_r^2 \omega_r^2 - \frac{3\mu v}{h^3} \right] \left[(r^2 - R_1^2) - \frac{(R_2^2 - R_1^2)}{\ln \frac{R_2}{R_1}} \ln \frac{r}{R_1} \right]$$

The force acting upon the land is then:

$$F = \int_{R_1}^{R_2} P \, 2\pi \, r \, dr \qquad \text{Eq. (C9)}$$

Substituting Equations (C8) into (C9) and integrating:

$$F = \pi\left[\frac{(R_2^2 - R_1^2)}{2\ln\frac{R_2}{R1}} - R_1^2\right] P_1 + \pi\left[R_2^2 - \frac{(R_2^2 - R_1^2)}{2\ln\frac{R_2}{R_1}}\right] P_2 \qquad \text{Eq. (C10)}$$

$$- \frac{\pi\gamma}{4g} K_r^{\ 2}\omega_r^{\ 2}\left[R_2^{\ 4} - R_1^{\ 4} - \frac{(R_2^2 - R_1^2)^2}{\ln\frac{R_2}{R_1}}\right]$$

$$+ \frac{3\pi\mu v}{2h^3}\left[R_2^{\ 4} - R_1^{\ 4} \quad \frac{(R_2^2 - R_1^2)^2}{\ln\frac{R_2}{R_1}}\right]$$

Although the derivation will be omitted, identical relationships for pressure (Equations (C8) and force (Equation (C10)) are obtained for the case of inward flow.

For turbulent flow, the pressure gradient obtained from Tao**** is given by:

$$\frac{-dP}{dr} = \begin{cases} CQ^{2-m}\, r^{m-2} - CV^{2-m}\, \pi^{2-m}\, (R_o^2 - r^2)^{2-m}\, r^{m-2}, & r<R_o \\ C\, Q^{2-m} r^{m-2} + C\, V^{2-m}\, \pi^{2-m}\, (r^2 - R_o^2)^{2-m}\, r^{m-2}, & r>R_o \end{cases} \qquad \text{Eq. (C11)}$$

where

$$C = \frac{(0.079)\ \mu^m\ \gamma^{1-m}\ (\sec\ \alpha)^{1-m}}{g^{1-m}\ 2^m\ (2\pi)^{2-m}\ h^3} \qquad \text{Eq. (C12)}$$

μ = absolute viscosity, lb-sec/in.^{2}

γ = weight density, lb/in.^{3}

****Tao, L. N. and Donovan, W. F., op. cit.

sec α = rotational dependent term

h = gap width, in.

n = Reynolds No. exponent

As for the laminar case, the through-flow and squeeze flow are independent so that the force resulting from each can be calculated separately. However, it is assumed that the through-flow will always be present and of sufficient magnitude to result in the total flow being turbulent.

First, integrating the through-flow term only:

$$- \int_{P_1}^{P} d\alpha = CQ^{2-m} \int_{R_1}^{r} \xi d\xi \qquad \text{Eq. (C13)}$$

$$P - P_1 = - \frac{CQ^{2-m}}{(1-m)} \qquad \text{Eq. (C14)}$$

At $r = R_2$, $P = P_2$ so:

$$Q^{2-m} = \frac{(1-m)}{C} \frac{R_1^{1-m} R_2^{1-m} (P_1 - P_2)}{(R_2^{1-m} - R_1^{1-m})} \qquad \text{Eq. (C15)}$$

Substituting Equation (C15) into Equation (C14) and simplifying

$$P = \frac{(R_2^{1-m} r^{m-1} - 1)}{\left[\left(\frac{R_2}{R_1}\right)^{1-m} - 1\right]} P_1 + \frac{(1 - R_1^{1-m} r^{m-1})}{\left[1 - \left(\frac{R_1}{R_2}\right)^{1-m}\right]} P_2 \qquad \text{Eq. (C16)}$$

The force on the land caused by flow-through is then:

$$F = \int_{R_1}^{R_2} P \, 2\pi \, r \, dr \qquad \text{Eq. (C17)}$$

Substituting Equation (C16) into Equation (C17) and integrating, the force is obtained as a function of the slot boundary pressures:

$$F = \pi \frac{\left[\frac{2\, R_2^{1-m}}{(1+m)} (R_2^{m+1} - R_1^{m+1}) - (R_2^2 - R_1^2)\right]}{\left[\left(\frac{R_2}{R_1}\right)^{1-m} - 1\right]} P_1 \qquad \text{Eq. (C18)}$$

$$+ \pi \frac{\left[(R_2^2 - R_1^2) - \frac{2R_1^{1-m}}{(1+m)} (R_2^{m+1} - R_1^{1+m})\right]}{\left[1 - \left(\frac{R_1}{R_2}\right)^{1-m}\right]} P_2$$

Identical relationships are obtained for the case of inward flow.

The squeeze film effect for turbulent flow is obtained from the second term of Equation (C11).

$$\frac{1}{\beta}\frac{dP}{dr} = \begin{cases} \left(\frac{R_o^2}{r} - r\right)^{2-m}, & r<R_o \\ -\left(r - \frac{R_o^2}{r}\right)^{2-m}, & r>R_o \end{cases} \qquad \text{Eq. (C19)}$$

where

$$\beta' = C\pi^{2-m} V^{2-m} = \frac{(0.079)\ \mu^n\ \gamma^{1-m}\ (\sec\alpha)^{1-m}\ V^{2-m}}{g^{1-m}\ 4\ h^3} \qquad \text{Eq. (C20)}$$

The pressure distribution in the radial slot resulting from squeeze film effects is obtained by integrating Equation (C19).

$$P = \beta' \int_{R_1}^{r} \frac{1}{\beta}\frac{dP}{dg}\ dg \qquad \text{Eq. (C21)}$$

or

$$P = \begin{cases} \beta' \displaystyle\int_{R_1}^{r} \left(\frac{R_o^2}{g} - g \right)^{2-m} d\xi \ , \ r<R_o \\ \\ -\beta' \displaystyle\int_{r}^{R_2} \left(g - \frac{R_o^2}{g} \right)^{2-m} dg \ , \ r>R_o \end{cases} \qquad \text{Eq. (C22)}$$

At $r = R_o$ the two expressions of Equation (C22) must be equal. These expressions for pressure can be integrated numerically or graphically for an assumed value of R_o. The integration is repeated until a value of R_o is found so that the pressure expressions of Equation (C22) are equal. That is:

$$\int_{R_1}^{R_o} \left(\frac{R_o^2}{r} - r \right)^{2-m} dr - \int_{R_o}^{R_2} \left(r - \frac{R_o^2}{r} \right)^{2-m} dr = 0 \qquad \text{Eq. (C23)}$$

Once R_o is determined, the pressure distribution is known and the total squeeze film force can be found from

$$F = \int_{R_1}^{R_2} P \ 2\pi \ r \ dr \qquad \text{Eq. (C24)}$$

or

$$F = 2 \ \pi\beta' \int_{R_1}^{R_2} r \int_{R_1}^{r} \frac{1}{\beta} \frac{dP}{dg} \ dg \ dr \qquad \text{Eq. (C25)}$$

The force upon the piston lands can then be obtained from the radial slot boundary pressures and the piston axial motion. Rewriting Equation (C25) yields

$$F = K_S \frac{V^{2-m}}{h^3} \qquad \text{Eq. (C26)}$$

where

$$K_S = \frac{(0.079)\pi\mu^{\,n}\ \gamma^{1-m}(\sec\alpha)^{1-m}}{2g^{1-m}} \int_{R_1}^{R_2} r \int_{R_1}^{r} \frac{1}{g}\frac{dP}{dg}\, dg\, dr \qquad \text{Eq. (C27)}$$

The double integral of Equation (C27) was evaluated numerically by the computer for the values of radii listed in the following table. A value of 0.25 was used for the Reynolds number exponent.

R_2	R_1	$\int_{R_1}^{R_2} r \int_{R_1}^{r} \frac{1}{\beta}\frac{dP}{d\xi}\, d\xi dr$
4.0	3.75	0.00284
4.0	3.50	0.0371
4.0	3.25	0.1644
1.75	1.50	0.00118
2.00	1.50	0.0173
2.25	1.50	0.0866

The forces upon the pocket areas of the piston are obtained by integrating the following pressure profile over the pocket area.

$$P = P_r + \frac{\gamma}{2g} K_r^2 \omega_r^2 (r^2 - R_r^2) \qquad \text{Eq. (C28)}$$

where

P_r = reference pressure, psi

γ = weight density, $lb/in.^3$

g = gravitational constant, $in./sec^2$

K_r = rotational constant

ω_r = rotational speed, rad/sec

R_r = reference radius, in.

r = radius, in.

The total force upon the pocket area is found by integrating from the inside pocket radius (R_1) to the outside radius (R_2) and is given by:

$$F = \int_{R_1}^{R_2} P \, dr \qquad \text{Eq. (C29)}$$

or

$$F = AP_r + F_\omega \qquad \text{Eq. (C30)}$$

where

$$A = \pi(R_2^2 - R_1^2) \qquad \text{Eq. (C31)}$$

$$F_\omega = \frac{\gamma}{4g} K_r^2 \omega_r^2 (R_2^2 - R_1^2)(R_2^2 + R_1^2 - 2R_r^2) \qquad \text{Eq. (C32)}$$

R_1 = inside pocket radius

R_2 = outside pocket radius

The Equations (C28) through (C32) are used to obtain the forces acting upon both the load and balance pistons.

ATTACHMENT D

(APPENDIX C)

NOMENCLATURE

A	=	cross-sectional area	in.^{2}
B	=	viscous friction coefficient	lb-sec/in.
β'	=	squeeze film constant	
b	=	pipe wall thickness	in.
C	=	fluid capacitances	in.^{2}
C_A	=	entrance loss coefficient	
C_B	=	exit loss coefficient	
C_D	=	orifice coefficient	
C_1, C_2, C_3	=	radial orifice sill gap coefficients	
c	=	acoustic velocity	in./sec
D	=	piston pocket depth	in.
d	=	diameter	in.
E	=	elastic modulus of pipe wall material	psi
F	=	force	lb
F_N	=	net piston force	lb
f	=	friction factor	lb
$f(\alpha)$	=	function of α	
g	=	gravitational constant	in./sec^2
h	=	radial orifice mill gap	in.
h_s	=	nominal radial orifice gap	
J	=	radial orifice inertance coefficient	in./sec^2
K	=	spring constant	
$K_{(\ )}$	=	flow loss coefficient	sec^2/lb-in.^{2}
K_c	=	constant, linearized bulk modulus to density ratio	in.
K_{HSF}	=	squeeze film force constant - high-pressure side	
K_{in}	=	rotational constant, inward flow	
K_k	=	constant, linearized density function	lb/in.^{3}
K_{LSF}	=	squeeze film force constant - low-pressure side	
K_{out}	=	rotational constant, outward force	

K_T	=	constant, linearized bulk-modulus-to-density ratio	$in.^3/lb$
K_γ	=	constant, linearized density function	1/in.
K_1, K_2	=	radial orifice weight flow coefficients	
k	=	ratio of specific heats	
ℓ	=	length of inlet orifice	in.
N_{R1-M}	=	piston rotational speed	rpm
n	=	Reynolds No. exponent	
P	=	pressure	
P_{FC1}	=	load piston return pressure	psi
P_{FC2}	=	load piston vent pressure	psi
P_{FS}	=	load piston inlet pressure	psi
P_{HS}	=	balance piston inlet pressure - high-pressure side	psi
P_{LS}	=	balance piston inlet pressure - low-pressure side	psi
P_s	=	source pressure	psi
Q	=	volume flow rate	$in.^3/sec$
R	=	universal gas constant	in./°R
$R_{(\ )}$	=	radius, constant	in.
$R'_{(\ )}$	=	linearized fluid resistance	$sec/in.^2$
R_{HS}, R_{LS}	=	shaft radii	in.
r	=	radius, variable	in.
T	=	temperature	°R
t	=	time	sec
U_{avg}	=	average tangential fluid velocity	in./sec
V	=	volume	$in.^3$
V_{avg}	=	average radial fluid velocity	in./sec
V_{HO}, V_{LO}	=	cavity volume with piston centered	$in.^2$
v	=	velocity	in./sec
$\dot{W}$	=	weight flow rate	lb/sec
X	=	piston displacement	in.

$d/dt = \circ$	=	derivative	
β	=	fluid bulk modulus	psi
γ	=	weight density	$lb/in.^3$
γ_N	=	nominal weight density	$lb/in.^3$
ΔP	=	pressure difference	psi
μ	=	absolute viscosity	$lb\text{-}sec/in.^2$
ω_r	=	rotational speed	rad/sec

Subscripts

BPL	=	series balance piston labyrinth
F	=	load piston
FO	=	load piston inlet orifice
FP	=	load piston cavity
F_{ω}	=	rotational induced quantity - load piston
F1	=	first load piston labyrinth seal
F2	=	second load piston labyrinth seal
fi	=	load piston inlet lines
fo	=	load piston return lines
H	=	balance piston - high-pressure side
HO	=	balance piston inlet orifice - high-pressure side
HP	=	balance piston pocket - high-pressure side
H_{ω}	=	rotational induced quantity - balance piston - high-pressure side
H1	=	balance piston return cavity - high-pressure side
H2	=	inside radius of inner sill - high-pressure side
H3	=	outside radius of inner sill - high-pressure side
H4	=	inlet to inner sill - high-pressure side
H5	=	inlet to outer sill - high-pressure side
H6	=	inside radius of outer sill - high-pressure side
H7	=	outside radius of outer sill - high-pressure side
H8	=	outer sill outlet - high-pressure side
H58	=	indicates conditions from station H5 to H8
H41	=	indicates conditions from station H4 to H1
hi	=	balance piston inlet lines - high-pressure side
ho	=	balance piston return lines - high-pressure side
L	=	balance piston - low-pressure side
LO	=	balance piston inlet orifice - low-pressure side
LP	=	balance piston pocket - low-pressure side
LS	=	shaft

L_ω	=	rotational induced quantity - balance piston - low-pressure side
L1	=	balance piston return cavity - low-pressure side
L2	=	inside radius of inner sill - low-pressure side
L3	=	outside radius of inner sill - low-pressure side
L4	=	inlet to inner sill - low-pressure side
L5	=	inlet to outer sill - low-pressure side
L6	=	inside radius of outer sill - low-pressure side
L7	=	outside radius of outer sill - low-pressure side
L8	=	outer sill outlet - low-pressure side
L58	=	indicates conditions from station L5 to L8
L41	=	indicates conditions from station L4 to L1
li	=	balance piston inlet lines - low-pressure side
lo	=	balance piston return line - low-pressure side
o	=	balance piston outer return lines
8	=	outer return cavity
S-BP	=	Source pressure, balance piston
S-FP	=	Source pressure, force piston