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PRELIMINARY DEVELOPMENT OF COMPOUND VORTEX AMPLIFIERS FOR HYDRAULIC HIGH-PRESSURE APPLICATION*

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SUMMARY

A compound vortex amplifier has been developed in the field of hydraulic devices at the 700 to 2000 N/cm^2 (1000 to 3000 psi) pressure level. Unlike present vortex control valves where the control pressure must exceed the supply pressure throughout the flow turndown range, the new amplifier demands an input from 0 to 100 N/cm^2 to yield a proportional output from 0 to 620 N/cm^2 at blocked load, with a supply pressure of 965 N/cm^2.

The compound amplifier comprises a pilot stage based on vortex-shear jet modulation, suitably matched to a conventional vortex control valve as the power stage. Complete steady-state test data are presented for the new configuration. Dynamic response will be presented in a future paper.

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INTRODUCTION

Much interest has been shown in hydraulic applications of fluidic amplifiers, both for the control of large flows as reported by Mamzic[1] (1964) with planar amplifiers, by Goldschmied and Kalange[2] (1966) and by Goldschmied[3] (1968) with axisymmetric focussed-jet diverters, and for the control of high pressures as reported by Rivard and Walberer[4] (1965), by Taplin and Datwyler[5] (1965), by Blatter[6] (1966) and others, all with vortex throttling devices.

There is a belief among some workers that fluidic technology will find its most important growth in the hydraulic field where large equipment is to be controlled and where the absence of upstream waterhammer (as achieved by Goldschmied[3]) is absolutely required.

Pneumatic fluidics will largely replace electro-mechanical and pneumo-mechanical control components but it cannot be reasonably expected that it will compete with present solid-state control circuitry over a broad area.

The present paper is concerned with the fluidic control of high hydraulic pressures at the 700 to 2000 N/cm^2 (1000 to 3000 psi) level by means of the hydrodynamic vortex phenomenon.

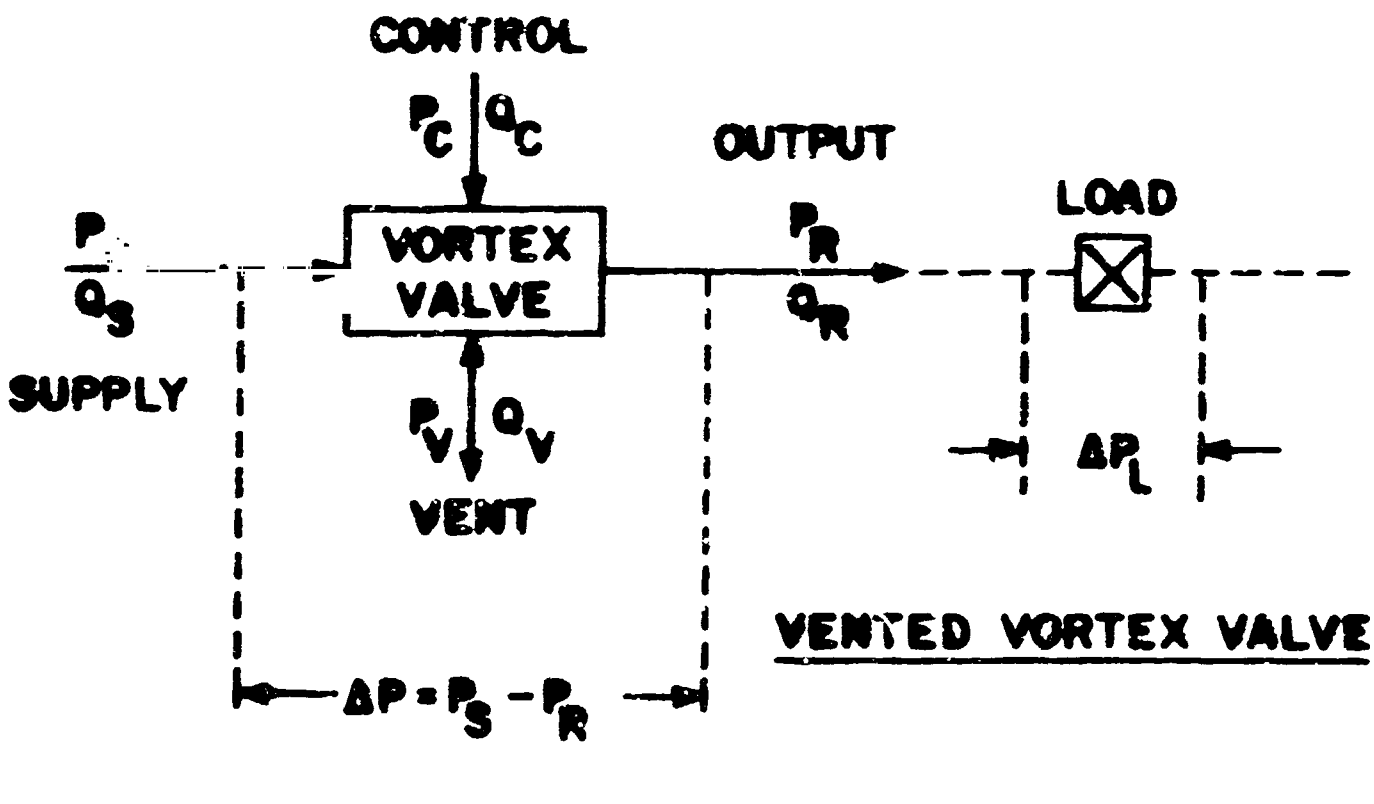
Vortex devices may be classified as control valves if they offer a variable flow resistance in a pipeline, regardless of the control input requirements, or they may be classified as amplifiers if the control input is much smaller than the net output in terms of pressure and flow. Hydraulic vortex devices are described in references 4, 5 and 6 for high-pressure hydraulic application; in all cases the control pressure is higher than the supply pressure throughout the flow turndown range. This fact has been found also in numerous low-pressure model investigations by academic researchers such as Kemper[7] (1965), Lee and Richardson[8,9] (1965) etc.

Having thus established that the present vortex devices are to be classified as control valves (rather than amplifiers) it will be useful to cite modern sources of information on conventional control valve technology. The Aerospace Fluid Components Designer's Handbook[10] (1967) presents an up-to-date compendium on shutoff and control valves from p. 5.2.3 to p. 5.3.7. NASA's contributions to advanced valve technology are summarized in reference 11 (1967).

In general, the control performance of conventional valves is given in terms of a mechanical displacement of the valving element or of a "stroke." For an analogous vortex control valve, the "stroke" is to be interpreted in terms of an input control pressure. Also the term "pressure-drop across the valve" is generally employed; while this is completely defined for the usual inline component, it must be carefully interpreted for the case of the "vented" vortex valve with a supply, a control input, an outlet and a vent or dump.

HYDRAULIC VORTEX CONTROL VALVE

The first phase of the present investigation comprised a steady-state experimental investigation of one of the best vortex throttling devices presented by Blatter[6] (1966) (see Fig. 1) for high-pressure hydraulic application. The vortex device can be made to operate in a vented version (capable of full shutoff of Q_R and Q_S) and also in a closed inline version (capable of 80% turndown of Q_o with full upstream shutoff of Q_s). In both cases the vortex device can be classified as a flow control valve and subjected to the standard criteria of flow capacity, linearity, hysteresis, deadband, valve gain, rangeability and unit sensitivity. The schematic for the vented vortex valve is as follows:

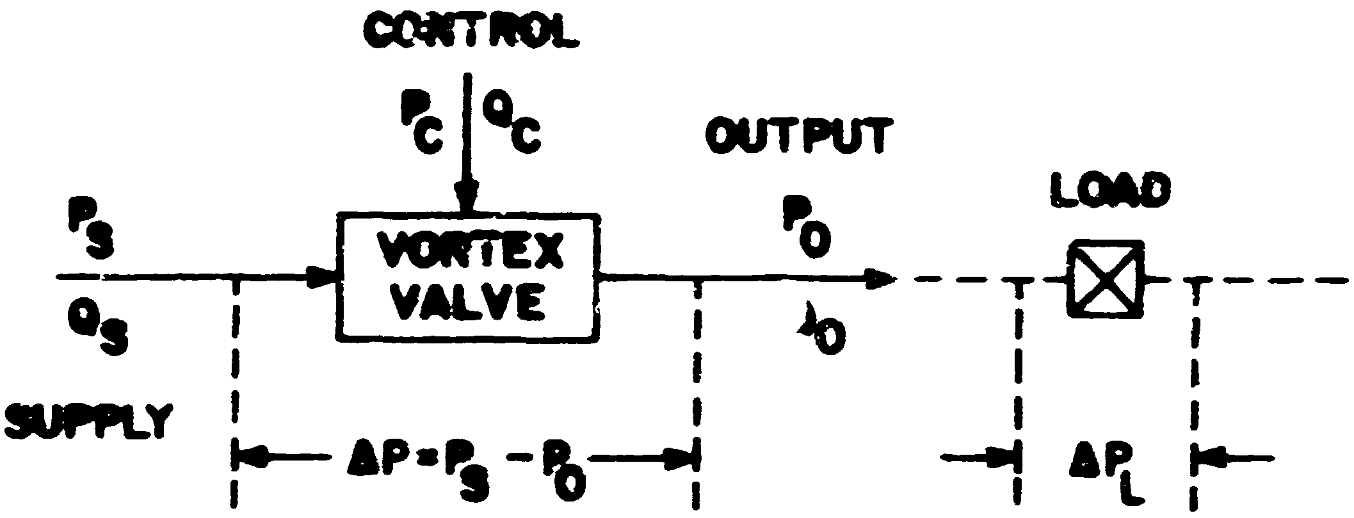


VENTED VORTEX VALVE

NOTE: $Q_R = Q_S + Q_C + Q_V$

The Load is denoted by a resistance coefficient $C_L = \frac{\Delta P_L \cdot D^4}{\rho Q_R^2}$ where ΔP_L is the pressure drop across the load resistance and D is a characteristic valve diameter.

The schematic for the closed inline vortex valve is as follows:



<u>CLOSED VORTEX VALVE</u>

<u>NOTE</u>: $Q_O = Q_S + Q_C$. AT FULL TURNDOWN, $Q_S = 0$ AND $Q_O = Q_C$.

The Load is denoted by a resistance coefficient C_L as above.

The installation of the vortex valve can be such that only the output (P_R, Q_R) is of interest and full shutoff is desired; here the vented version of the vortex valve will be preferred.

In another installation, the vortex valve may be used as a downstream resistance modulator; here only the supply flow Q_s is of interest since it is desired to control and block Q_s for a given P_s. The output $(Q_s + Q_c)$ is dumped and is of no consequence. In this case a modified vented version will be used, with the output receiver eliminated.

Finally the vortex valve can be used as an inline control valve or inline variable throttle, dropping the pressure from P_s to P_o and handling a flow output Q_o to 80% turndown. In a great many applications, this turndown is quite adequate. In all cases, it must be remembered that a control pressure P_c must be supplied above the level of P_s by some 15% to 25%.

The layout of the vortex valve tested is shown in Figure 1; it is a double-outlet test fixture with the right-side end blanked off by a dummy and thus functioning as a single-outlet vented vortex valve with "probe" outlet receiver. The receiver is called thusly because it resembles a total-pressure flow probe with its sharp entrance lip. To expedite the program the vortex fixture was obtained on loan by NASA Marshall Space Flight Center (Bendix Part # B2155533) for the proposed tests.

The components of the test fixture (as shown in Figure 1) are as follows:

1. Test Block
2. Cylindrical Mounting Plug
3. Probe Outlet Receiver
4. Annular Chamber Insert
5. Control Manifold
6. Tangential Control Ports
7. Dummy Plug

For the present series of tests, the vortex valve test fixture was set up with the following geometric proportions, as illustrated in the sketch of Figure 2:

1. Outlet Hole Diameter, D_o = 0.317 cm (0.125")
2. Probe Diameter, D_p = 0.475 cm (0.187")
3. Probe Spacing, L_p = 0.635 cm (0.250")
4. Control Port Diameter, D_c = 0.114 cm (0.045")
5. Number of Control Holes = 4
6. Vortex Chamber Diameter, D_{ch} = 1.27 cm (0.500")
7. Button Diameter, D_B = 1.055 cm (0.415")
8. Vortex Chamber Spacing, L_V = 0.175 cm (0.069")

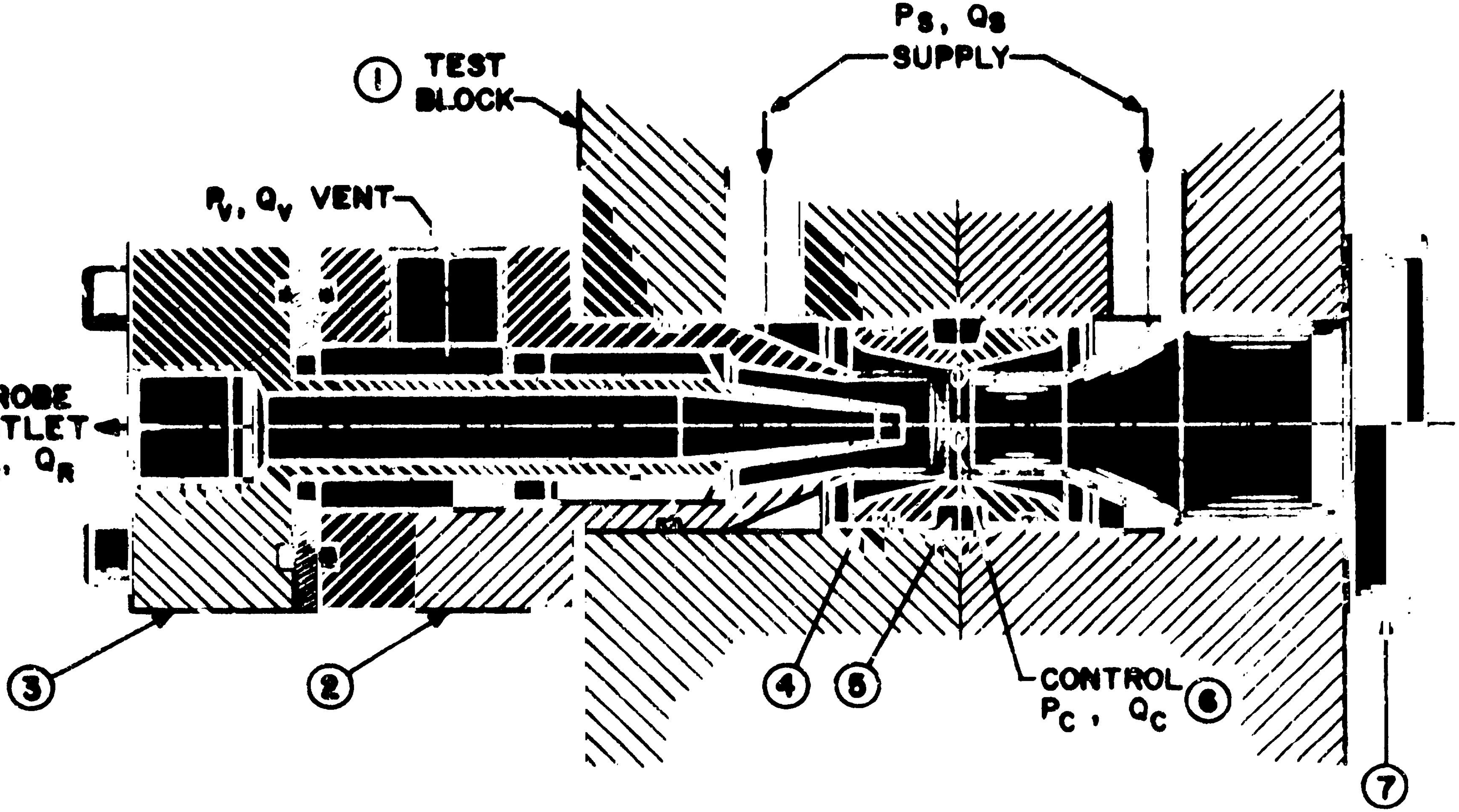


FIG. 1 - LAYOUT OF POWER-STAGE. (SINGLE-OUTLET VORTEX VALVE WITH PROBE PICKOFF)

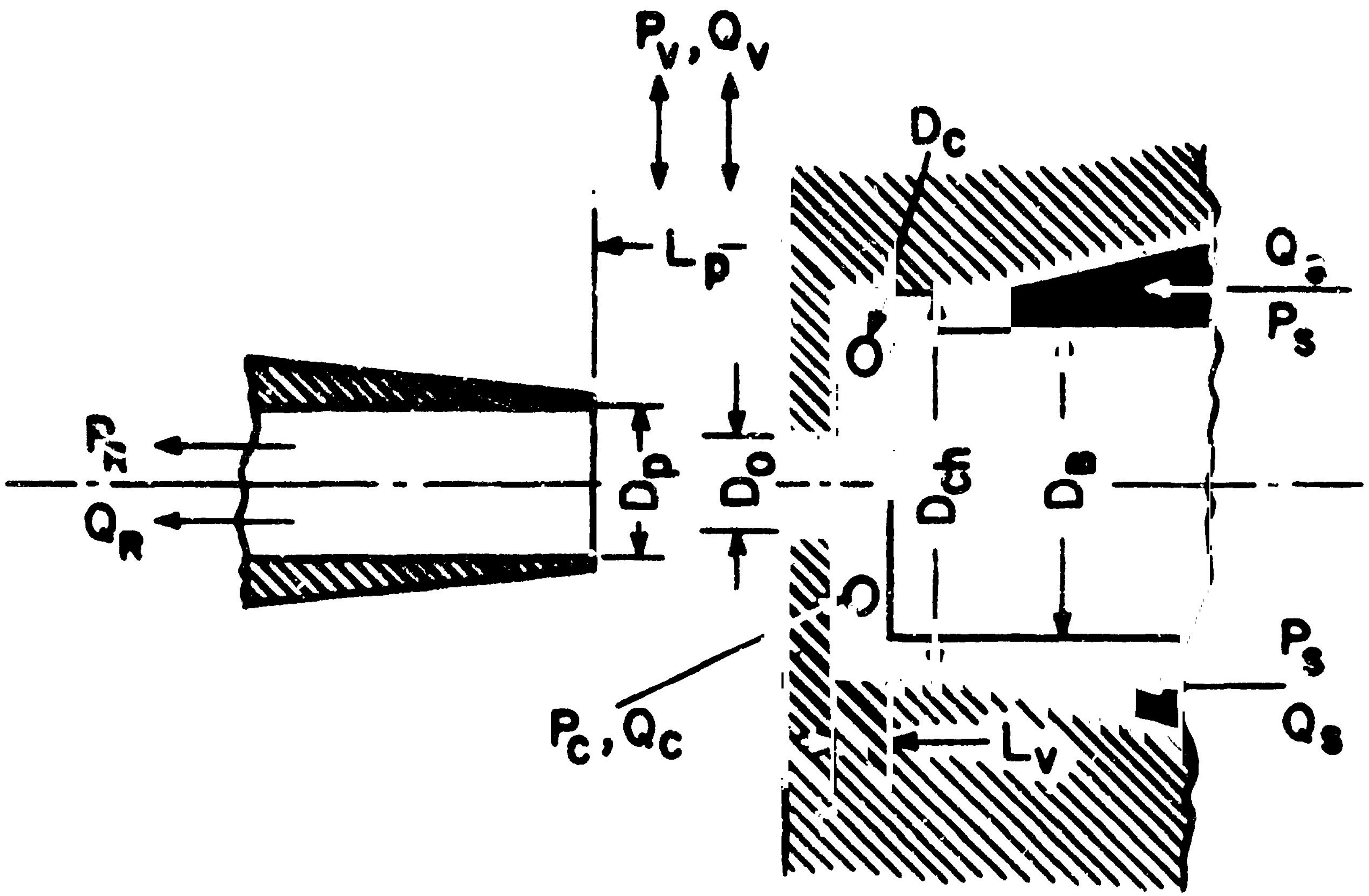


FIG. 2– SCHEMATIC OF VORTEX VALVE.

Blatter[6] presents (Fig. B-4 of ref. 6) the blocked load output pressure P_R, the wide-open-load output flow Q_R and the supply flow Q_s plotted against the control pressure P_c but omits any information on the output performance (P_R vs Q_R) in the operating range between blocked and wide-open loads. Presumably there is the implication that the output curves are all linear. These data, taken at 1590 N/cm^2 (2300 psi) hydraulic supply pressure, are shown in Figure 3. It is seen that the chosen vortex valve design has a control overpressure $[(P_c-P_s)/Ps]$ of 20% for full blockage of the supply flow Q_s and an overpressure of 15% for full turndown of the output flow Q_R. The control pressure range is 25% and 20% respectively.

When the supply flow Q_s is fully blocked, the downstream flow will be only the control flow Q_c which is 20% of the maximum supply flow, for the closed version of the valve; for the vented version, the output flow Q_R will be zero.

The valve was retested at 690 N/cm^2 hydraulic supply pressure to obtain complete and detailed steady-state measurements over the entire operational range at the pressure level specified for the present program.

Figure 4 presents the blocked-load output pressure P_R as a function of the control pressure P_c. An output from 0 to 628 N/cm^2 (0-910 psi) is controlled by an input from 815 to 663 N/cm^2 (1180-960 psi); the gain factor is 6.05 $N/cm^2/N/cm^2$ over the linear portion of the curve which extends only from 150 to 550 N/cm^2 for P_R, or 63% of the total output. The maximum ratio of output pressure P_R over supply pressure P_s is 91%, which is an excellent pressure recovery, making the valve applicable to the operation of piston actuators, torque motors, etc. The deadband of 45 N/cm^2 is also indicated in Figure 4.

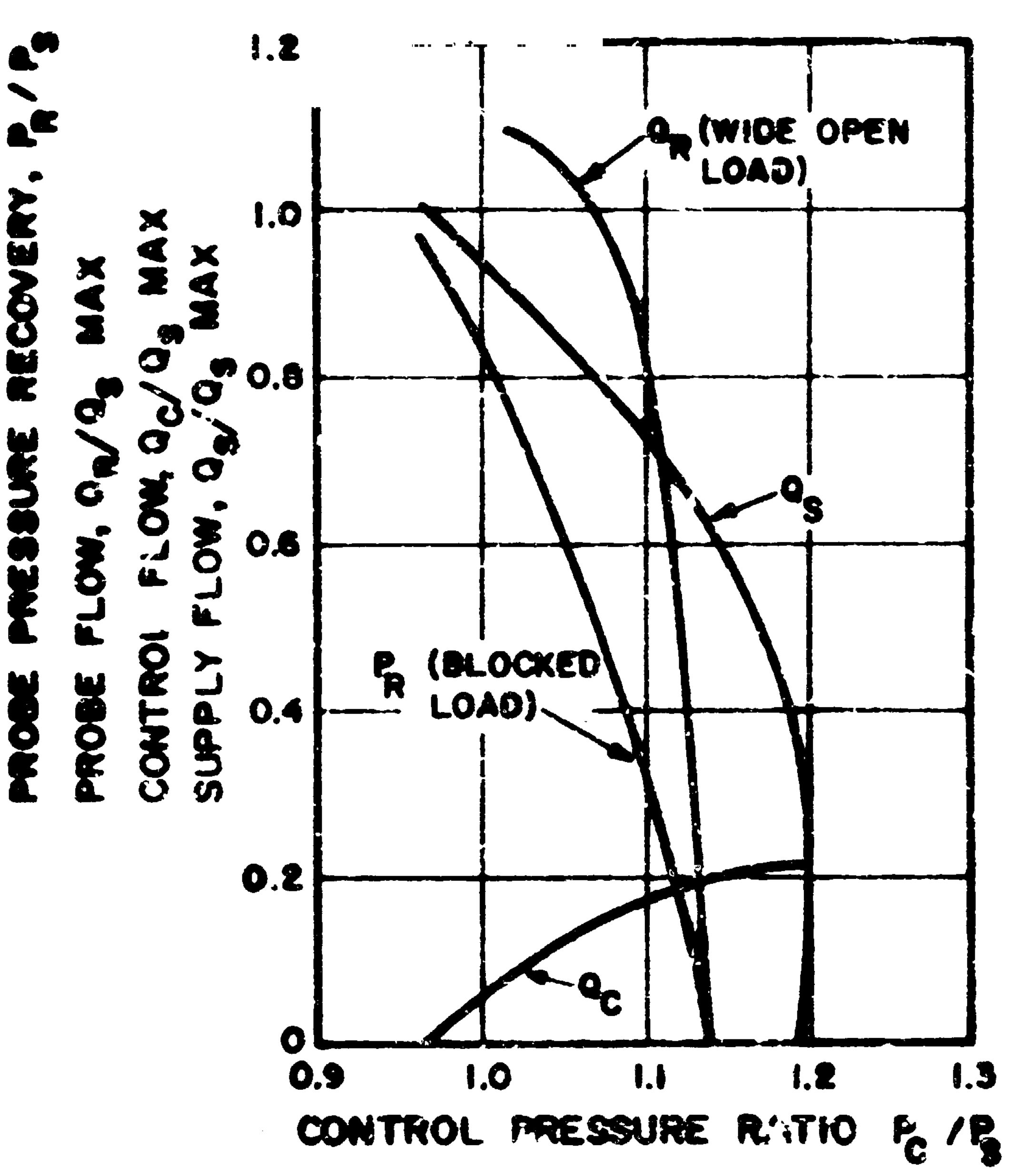


FIG. 3 TYPICAL TEST PERFORMANCE OF POWER-STAGE AT 1590 N/cm^2 SUPPLY PRESSURE.

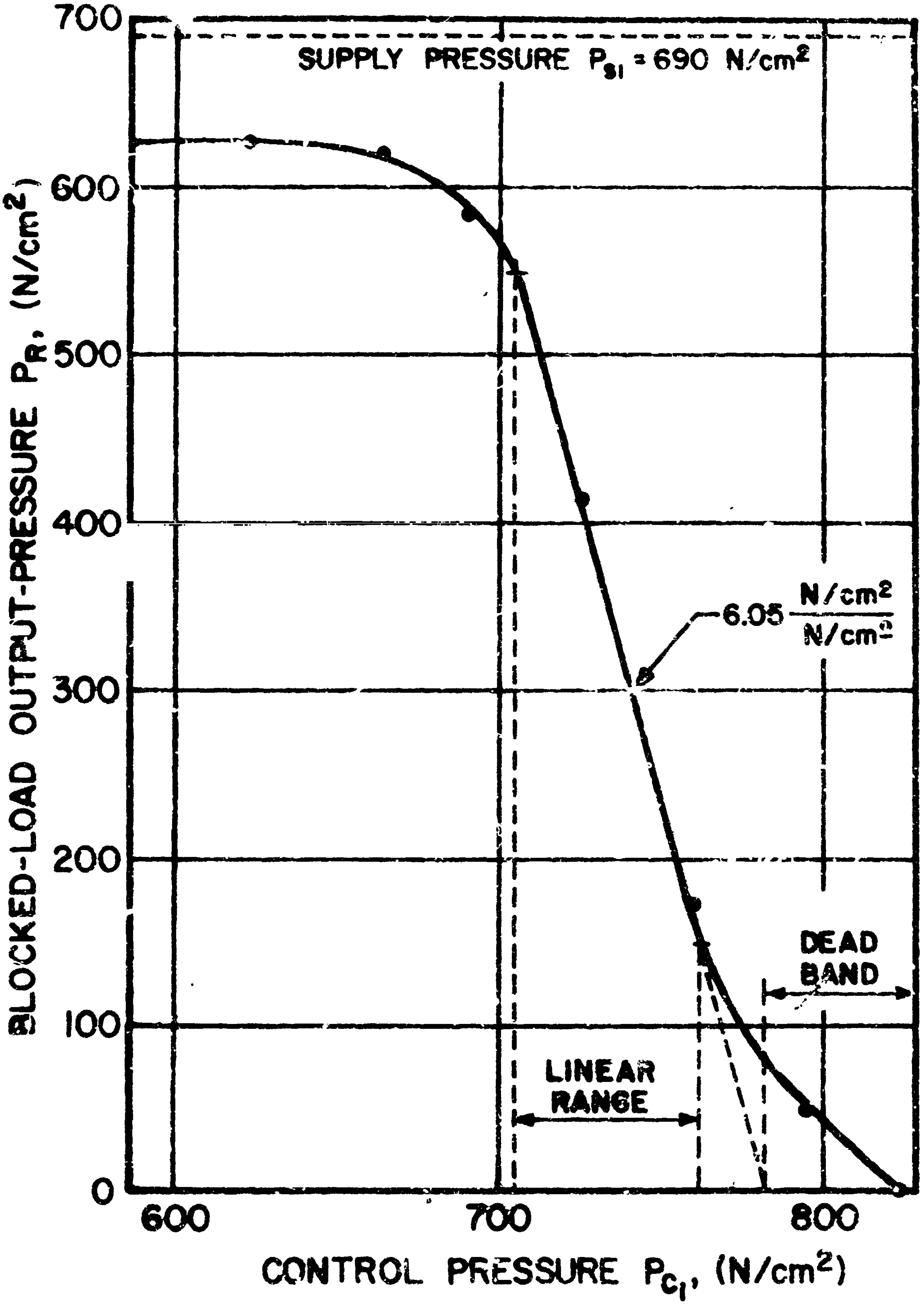


FIG. 4 BLOCKED-LOAD PRESSURE CONTROL-PERFORMANCE OF POWER-STAGE. [$D_R = 0$]

Figure 5 presents the wide-open load performance against control pressure P_c; for the output flow Q_R, a range from 0 to 1040 cm^3/s (0 to 16.5 GPM) is controlled by a pressure P_c from 815 to 663 N/cm^2 (1180 to 960 psi). The output flow Q_R is completely linear from 0 to $Q_R = Q_S$ or 880 cm^3/s; this represents 85% of the total range, and the gain factor is 14.1 $cm^3/s/N/cm^2$. The supply flow Q_S is also shown in Figure 5; it is seen that a higher control pressure P_c = 326 N/cm^2 (1200 psi) is needed to block Q_S fully. The curve for Q_S is nonlinear and shows practically an infinite gain factor from 0 to 300 cm^3/s at a constant control pressure, P_c = 826 N/cm^2.

The control flow Q_c was found to be independent of the output load to a large extent. Figure 6 displays the control flow Q_c as a function of the control pressure P_c and shows the widest spread of test point obtained over the range of output loads. This Q_c vs P_c curve, which represents the input to the vortex valve, gives on the other hand the output loading of the pilot stage of a compound amplifier; it is therefore most important for the present development because this paper is concerned with the possible matching of a pilot stage to the vortex valve so as to achieve overall input/output amplification.

The characteristics of the Q_c vs P_c curve are quite unusual; Q_c remains at a very low level, less than 20 cm^3/s until P_c reaches approximately 550 N/cm^2 and then it increases rapidly up to 190 cm^3/s when P_c reaches 800 N/cm^2, leveling off thereafter. The curve can be approximated by a parabolic equation as follows:

$$(Q_c - 25) = K(P_c - 560)^2$$

as shown in Figure 6, where $K = 0.30 \times 10^{-2}$.

While Fig. 3 (as given in ref. 6) presents only the output at blocked-load and at wide-open-load (with the implicit assumption of linearity in the intermediate operational area), Figure 7 presents a complete output map P_R vs Q_R of the vortex valve at various constant values of P_c such as 620, 663, 690, 725, 760 and 795 N/cm^2 while the supply pressure was maintained at 690 N/cm^2 (1000 psi). This map shows that straight lines cannot be drawn between corresponding points on the

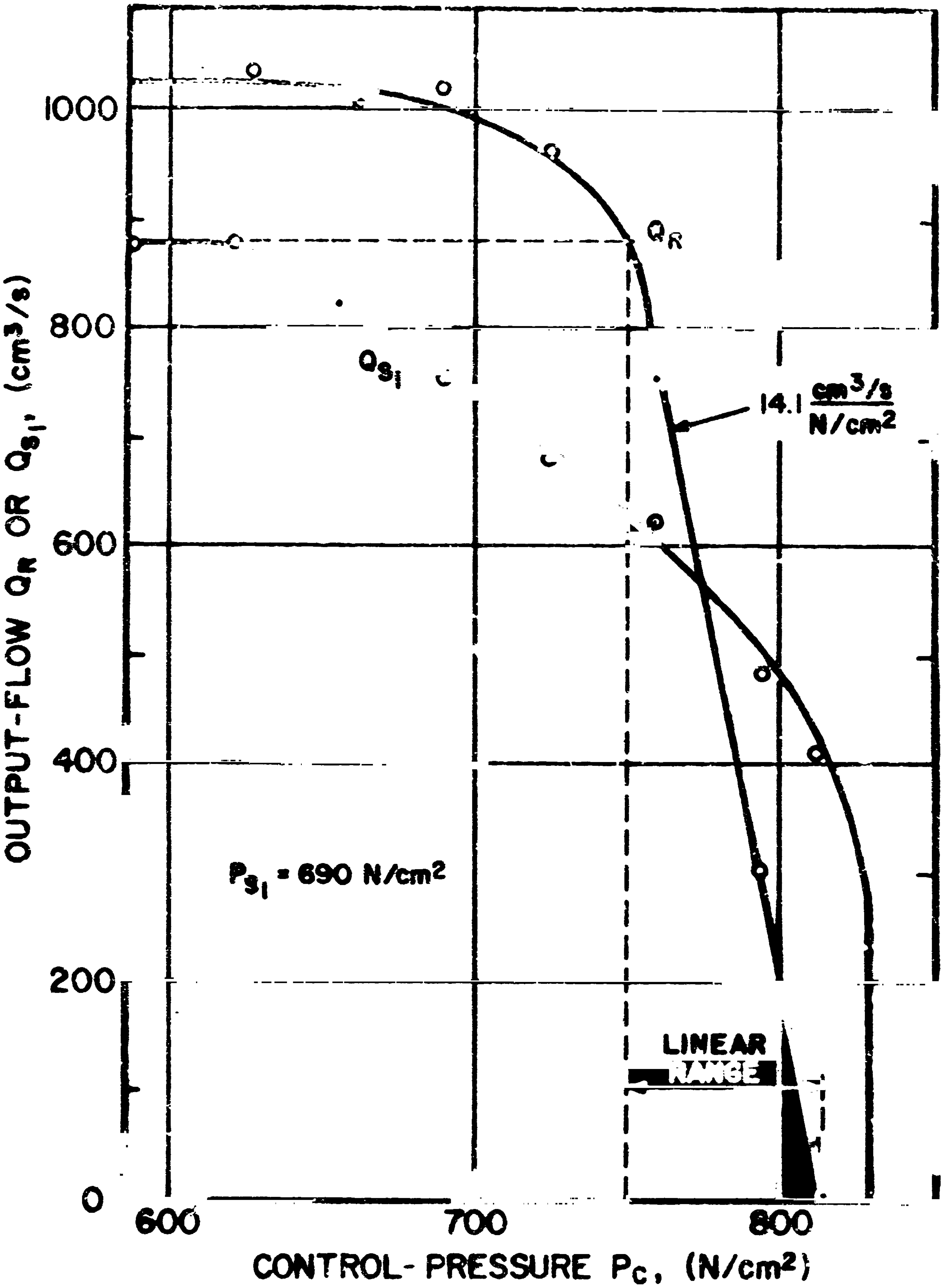


FIG. 5 - WIDE-OPEN-LOAD FLOW CONTROL-PERFORMANCE OF POWER-STAGE.

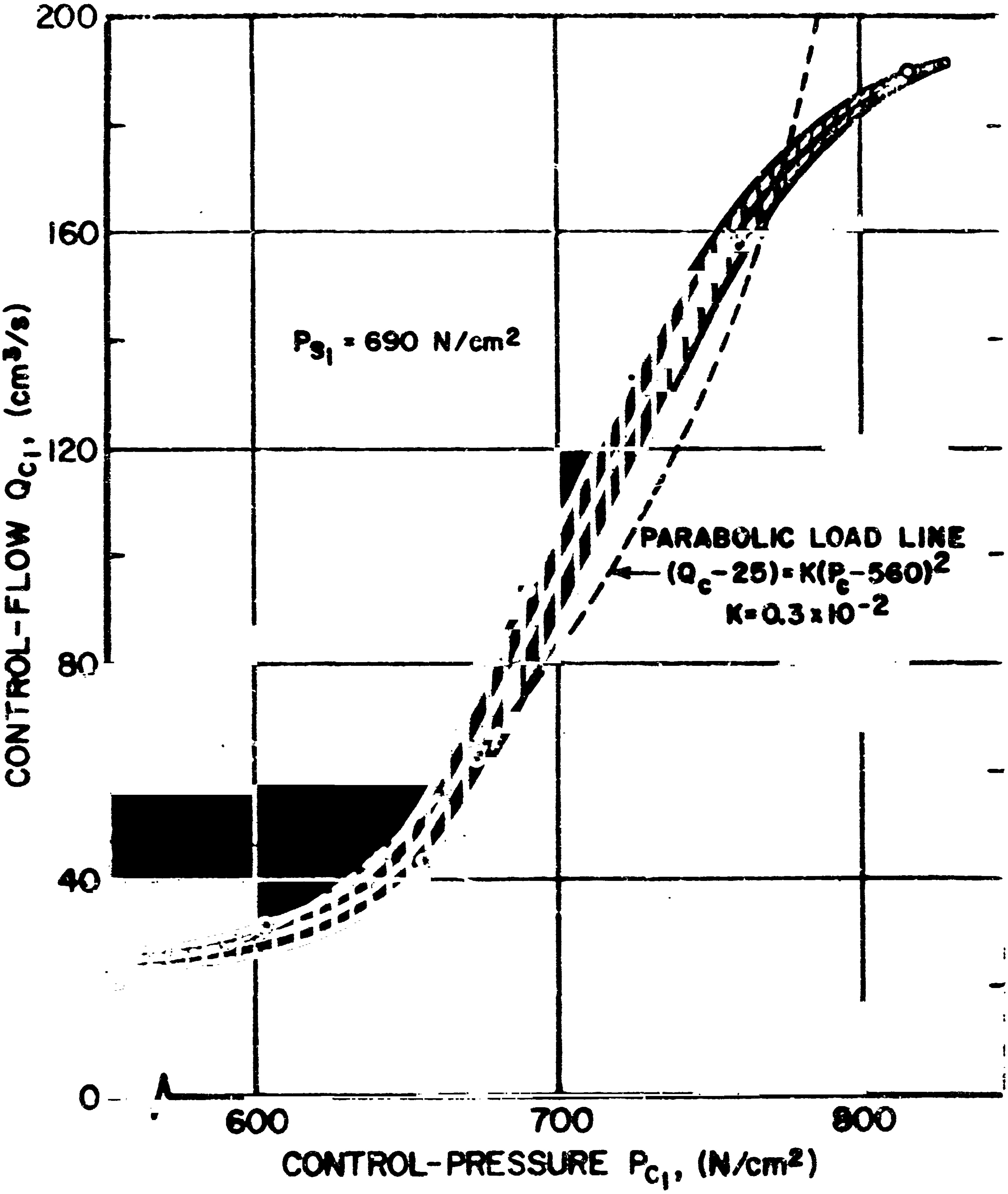


FIG. 6 - CONTROL-PRESSURE vs. CONTROL-FLOW OF POWER-STAGE FOR ALL OUTPUT LOADS.

blocked-load (Q_R=0) line and the wide-open load line, such as A-A' and B-B' and still achieve a reasonable representation of reality. To the contrary there is a very strong nonlinear behavior; this requires that the downstream load line be superposed on the operating map of Figure 7 and the intersection point determined graphically. For instance, if the downstream load line should be a typical parabolic one as indicated dashed in Figure 7, at the intersection point C there will be no change in P_R and Q_R for control pressure changes from P_c = 620 to P_c = 725; the valve will be completely insensitive in that control interval! The vortex control valve, as given by Blatter,[6] is thus fully described both geometrically and experimentally in regard to steady-state performance at 690 N/cm^2 (1000 psi) hydraulic supply pressure. It only remains to observe that the output was subject to periodic pressure fluctuations of some ± 50 N/cm^2 in the intermediate control range, which made it difficult at times to read pressure gauges accurately and which would not be readily tolerated in actual hydraulic control systems.

COMPOUND VORTEX AMPLIFIER

The goals of the present investigation relate to the development of a practical hydraulic vortex device with pressure amplification for application to hydraulic servovalves without mechanical moving parts (such as sleeves, spools or poppets) and impervious to fluid contamination and lack of fluid lubricating qualities. This would imply that any working fluid may be employed in a hydraulic control system as against a specially developed oil which is carefully manufactured and maintained.

From the control viewpoint the important parameter is the overall output/input ratio which is defined as the gain (of pressure, flow or fluid power). Here no consideration is taken of the fluid power expended from a steady-state supply source to operate this control device; power efficiency is secondary in the satisfactory operation of a control loop.

As a first approach to the problem it was conceived to use the present vortex control valve (as given by Blatter[6] and as tested and presented above) as a power stage of a compound amplifier and to develop

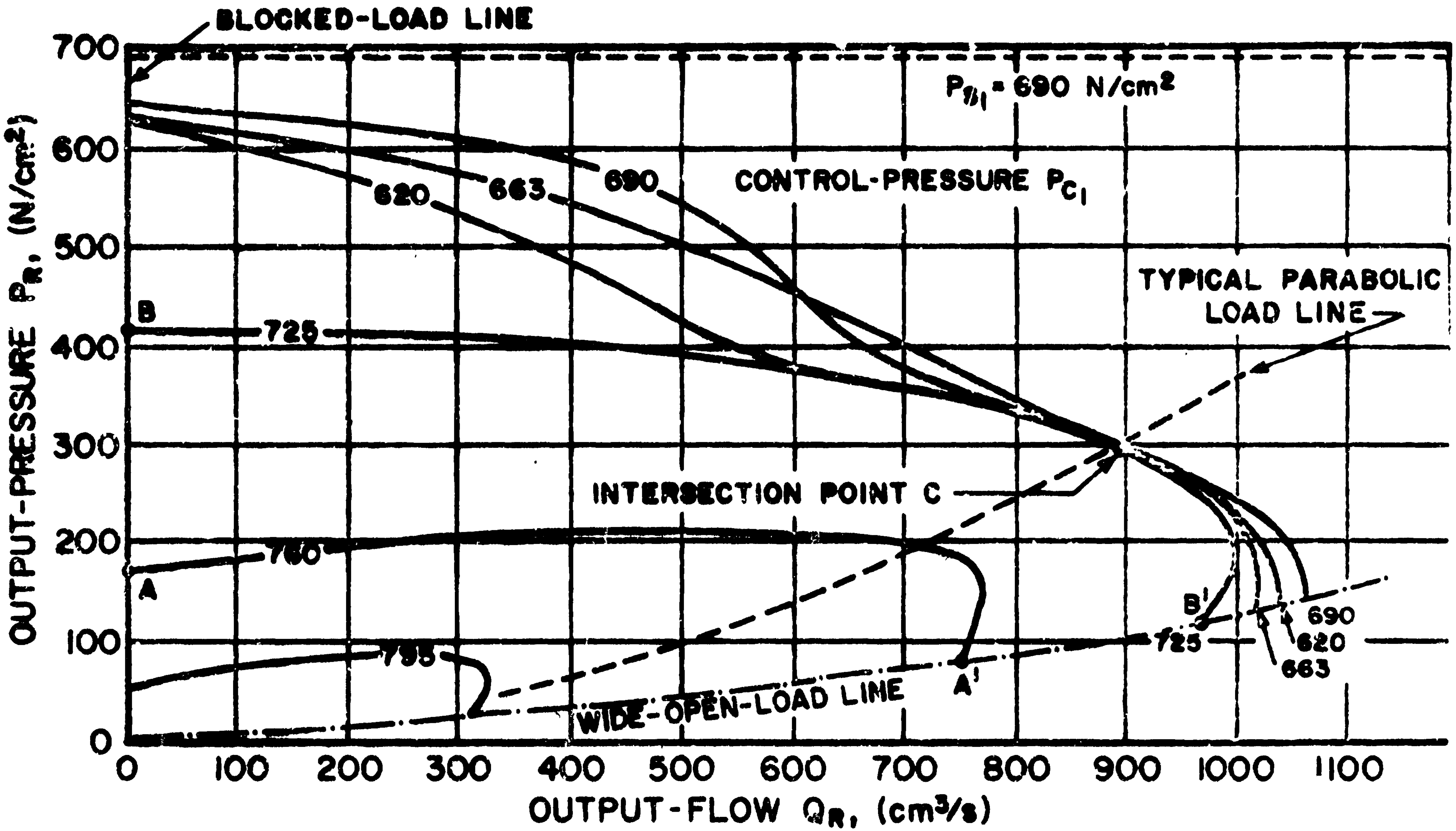


FIG. 7- OUTPUT MAP OF POWER-STAGE AT CONSTANT CONTROL-PRESSURES

a suitably matched pilot stage for it; the feasibility and the preliminary development of such a compound vortex amplifier is the objective of the present investigation.

After the above investigation of the power-stage, the pilot-stage requirements have become apparent; the function of the pilot-stage is to provide a moderate modulation of a high-pressure flow source by means of a weak control input in the vicinity of zero pressure. At full control (i.e. zero output) the pilot-stage must deliver at least 189 cm^3/s (3 GPM) at about 825 N/cm^2; at zero control (i.e. full output) the pilot stage must deliver less than 30 cm^3/s (0.5 GPM) at about 620 N/cm^2.

The control input curve of the power-stage (Q_c vs P_c as shown in Figure 6) becomes the load curve for the pilot stage; it can be approximated by the parabolic load line (as shown dashed in Figure 6)

$$(Q_c - 25) = 0.003(P_c - 560)^2$$

Furthermore this high pressure modulation must be achieved by the lowest possible input pressure range.

Several amplifier configurations may possibly be used for the pilot-stage; the impact-modulator (jet-against-jet) and the confined-jet devices were considered and rejected because of poor flow recovery. A brief theoretical analysis indicated the vortex-shear modulator as the best candidate for the pilot-stage application. This type of modulator has been disclosed and discussed by B. A. Otsap[12] (1964) for low-pressure pneumatic application (approximately 50 N/cm^2) in regard only to blocked-load output pressures. No pneumatic flow data have been supplied by the author nor any information on high-pressure (700-2000 N/cm^2) hydraulic operation.

A small stainless-steel vortex-shear modulator was designed, built and tested at hydraulic supply pressures over 700 N/cm^2 (1000 psi) to evaluate its performance for the present application. Figure 8 presents the results obtained, after some experimentation with the control-port diameter, at 860 N/cm^2 (1250 psi) hydraulic supply pressure; the output pressure P_o is plotted against the output flow Q_o for constant values of

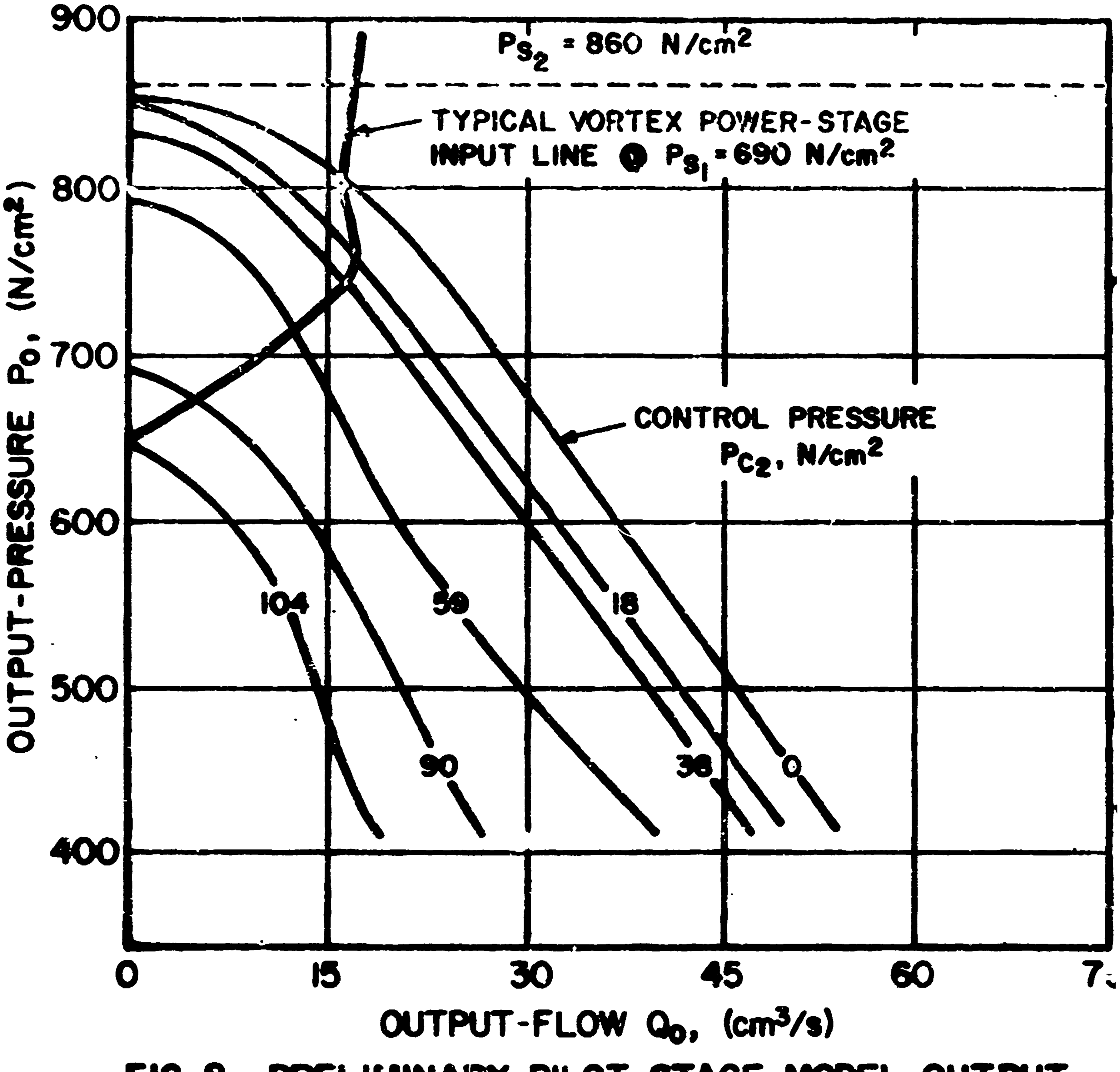


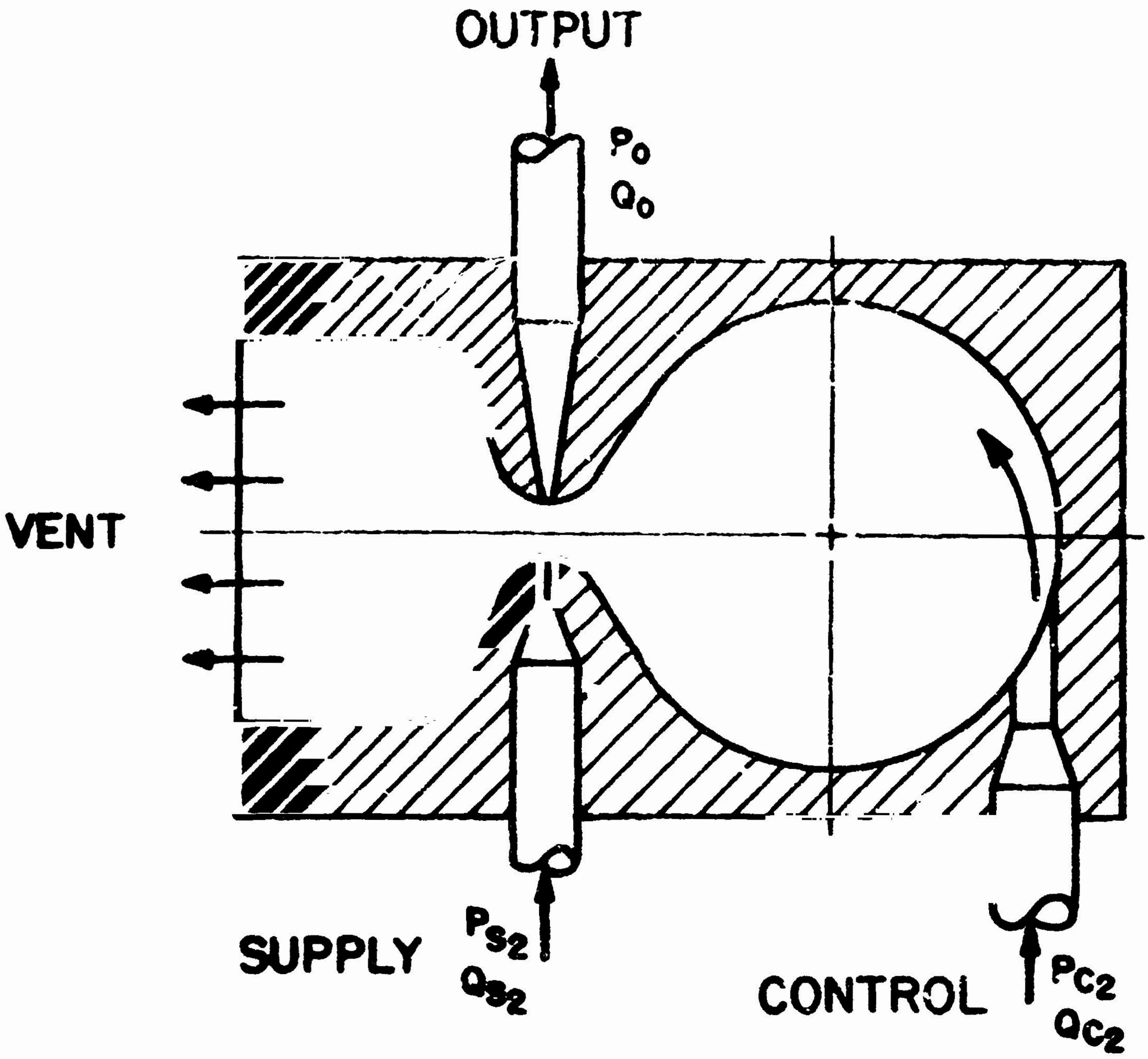
FIG. 8 - PRELIMINARY PILOT-STAGE MODEL OUTPUT PERFORMANCE.

the control pressure P_c, i.e. 0, 18, 38, 59, 90 and 104 N/cm^2. It is seen that an input increment from 0 to 104 N/cm^2 reduces the blocked-load pressure output from 850 to 650 N/cm^2. The load line shown in Figure 8 has been scaled down arbitrarily from Figure 6 for best fit to the model vortex-shear performance; it is seen that two parameters are available for matching the pilot-stage to the given power-stage, i.e. the size of the vortex-shear modulator and its supply pressure.

The size of the vortex-shear modulator was suitably increased and the final geometry of the pilot-stage is given in Figure 9 with all critical dimensions. Its performance is given in Figure 10 at constant input pressure of 0.48, 69, 86, 103 and 121 N/cm^2 and at 965 N/cm^2 (1400 psi) hydraulic supply pressure. It was found necessary, from tests of the compound vortex amplifier to use a higher supply pressure to the pilot-stage in order to obtain stable operation. The load curve shown in Figure 10 is the input curve P_{c_1} vs Q_{c_1} from Figure 6; the intersection points A and B represent the extremes of zero overall output P_R and full overall output P_R respectively. Figure 10 thus yields the graphical demonstration of a satisfactory match between pilot-stage and power-stage.

A schematic of the compound vortex amplifier is given in Figure 11 with the flow and pressure nomenclature; it is to be noticed that the output P_o, Q_o of the pilot-stage is the same as the input P_{c_1}, Q_{c_1} to the power stage.

After the individual tests of the pilot-stage and of the power-stage, the components were assembled on the bench and tested together at hydraulic supply pressures $P_{s_1} = 690$ N/cm^2 (1000 psi) (power-stage) and $P_{s_2} = 965$ N/cm^2 (1400 psi) (pilot-stage).



CAVITY DEPTH:	1.28 cm (0.504")
THROAT:	0.800 cm (0.314")
SUPPLY ORIFICE:	0.218 cm (0.086") DIA
RECEIVER ORIFICE:	0.282 cm (0.111") DIA
CONTROL ORIFICE:	0.635 cm (0.250") DIA

FIG. 9 - PILOT-STAGE LAYOUT. (VORTEX-SHEAR MODULATOR)

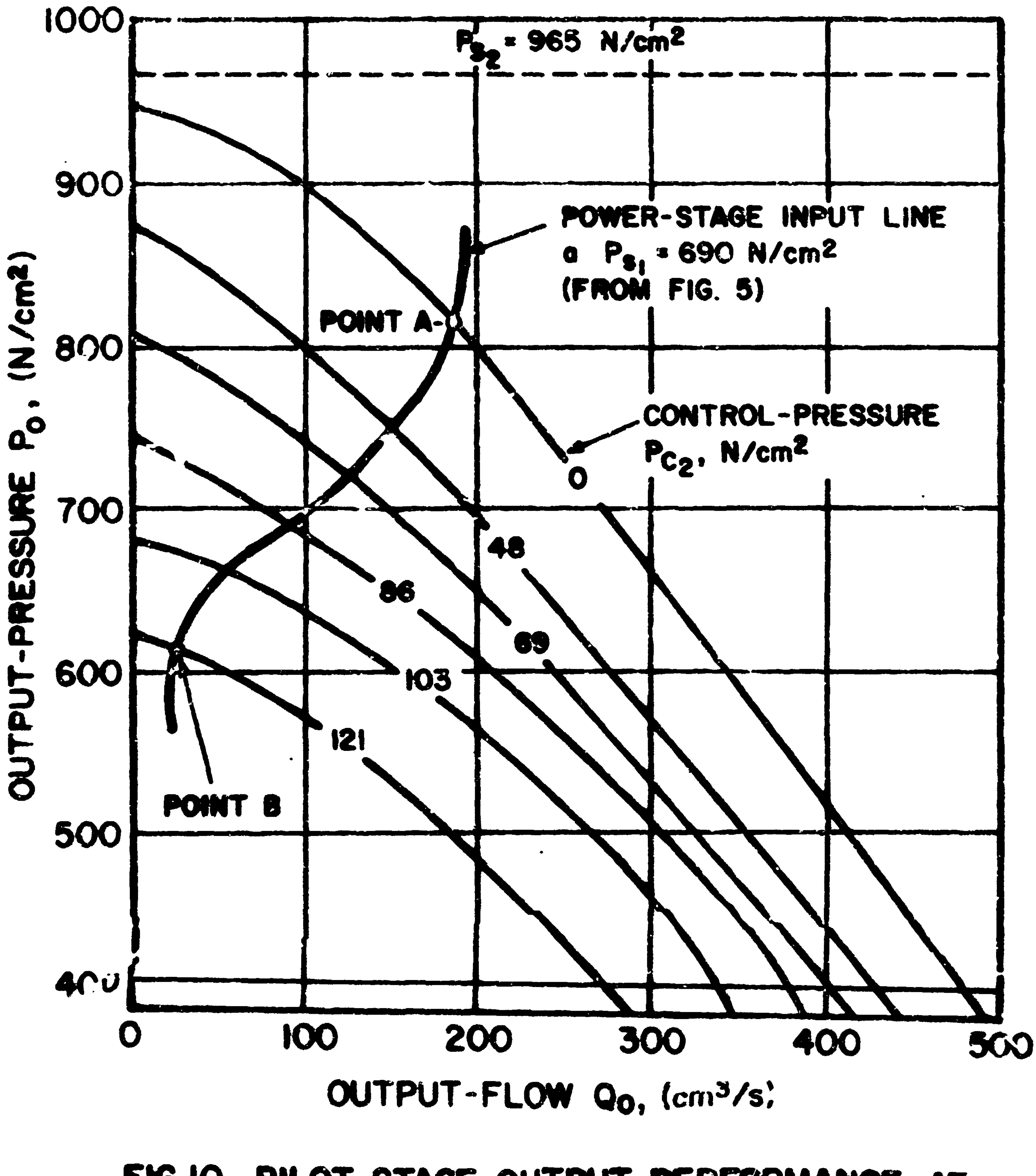


FIG. 10 - PILOT-STAGE OUTPUT PERFORMANCE AT CONSTANT CONTROL PRESSURES.

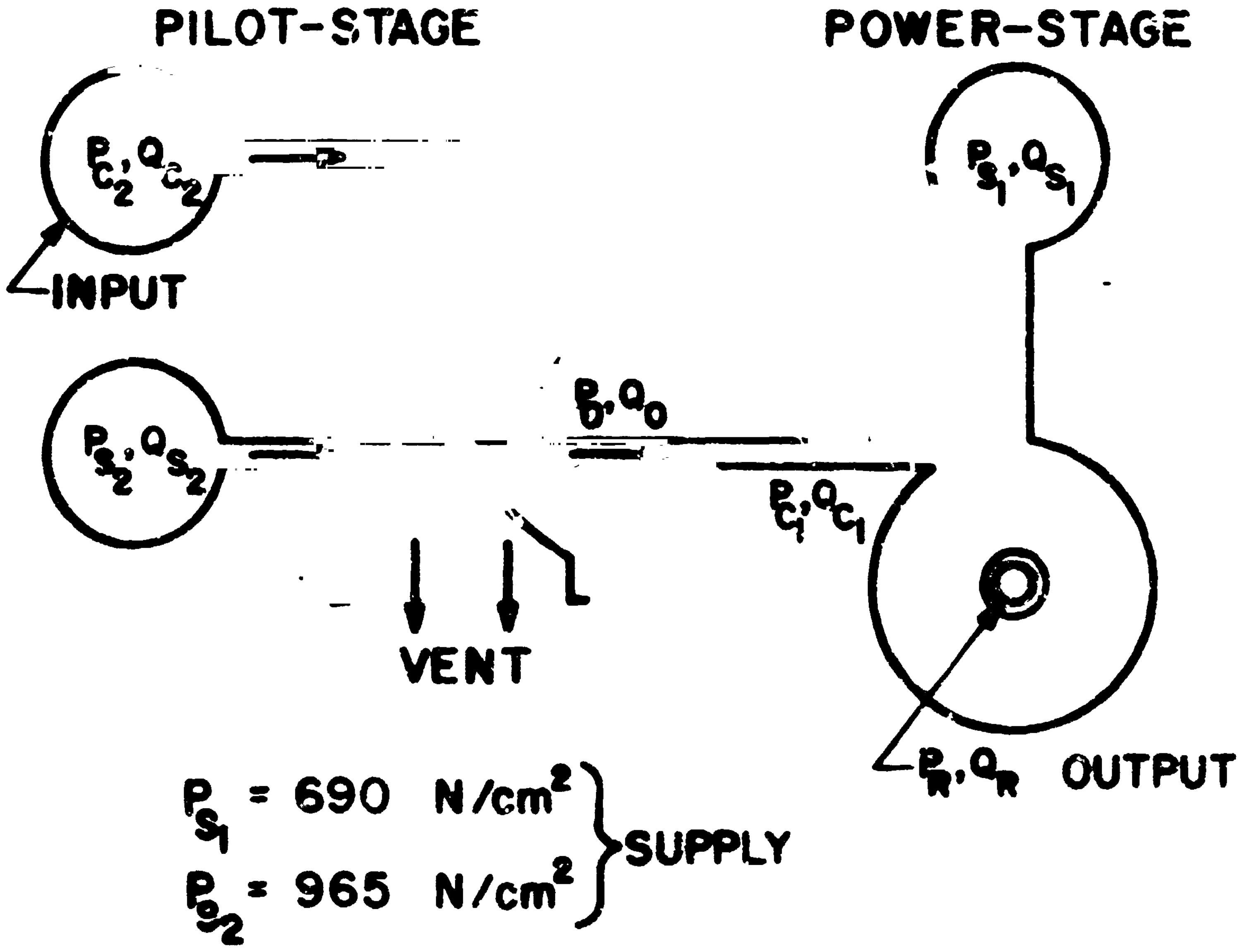


FIG. 11 LAYOUT OF COMPOUND VORTEX AMPLIFIER.

Figure 12 presents the performance of the compound vortex valve at wide-open load; the gain factor has been doubled as against Figure 5, from 14.1 to 28.4 ($cm^3/s/N/cm^2$), but the linear range has decreased, now being limited from 50 to 700 cm^3/s. Also there is a deadband of 5 N/cm^2 for the control pressure P_{c_2}. The main feature is, of course, that the control pressure range is from 0 to 75 N/cm^2 as against 663 to 815 of Figure 5.

Figure 13 presents the performance of the compound vortex valve at blocked-load; the gain factor has been increased to 7.4 $N/cm^2/N/cm^2$ and the linear range has been increased, now extending from 75 to 600 N/cm^2 or 85% of the total output. Also the deadband has been greatly reduced, from 45 (Figure 4) to 10 N/cm^2. The control pressure range is somewhat larger than at wide-open load, from 0 to 105 N/cm^2.

In addition to the blocked-load and the wide-open load performance, it is quite important to establish the output at intermediate load, i.e. to determine the operational range of the compound vortex amplifier.

Figure 14 presents the output pressure P_R against the control pressure P_{c_2}, for several constant-load lines, from blocked to wide-open. The amplifier can operate anywhere in the dotted area; the control boundary, shown by a dashed line, represents the onset of saturation when a control increment produces no corresponding output increment.

This boundary, separating the control area from the saturation area, is sensitive to the load since it is only 38 N/cm^2 at zero load (extrapolated) and increases to 110 N/cm^2 at full (blocked) load. It would be much more desirable if the control was independent of the load.

Constant output pressure P_R can be maintained against changing load with very small control pressure increments. For instance, P_R = 300 N/cm^2 can be maintained from blocked-load to the maximum allowable with a control pressure increment from 51 to 74 N/cm^2 or only 23 N/cm^2.

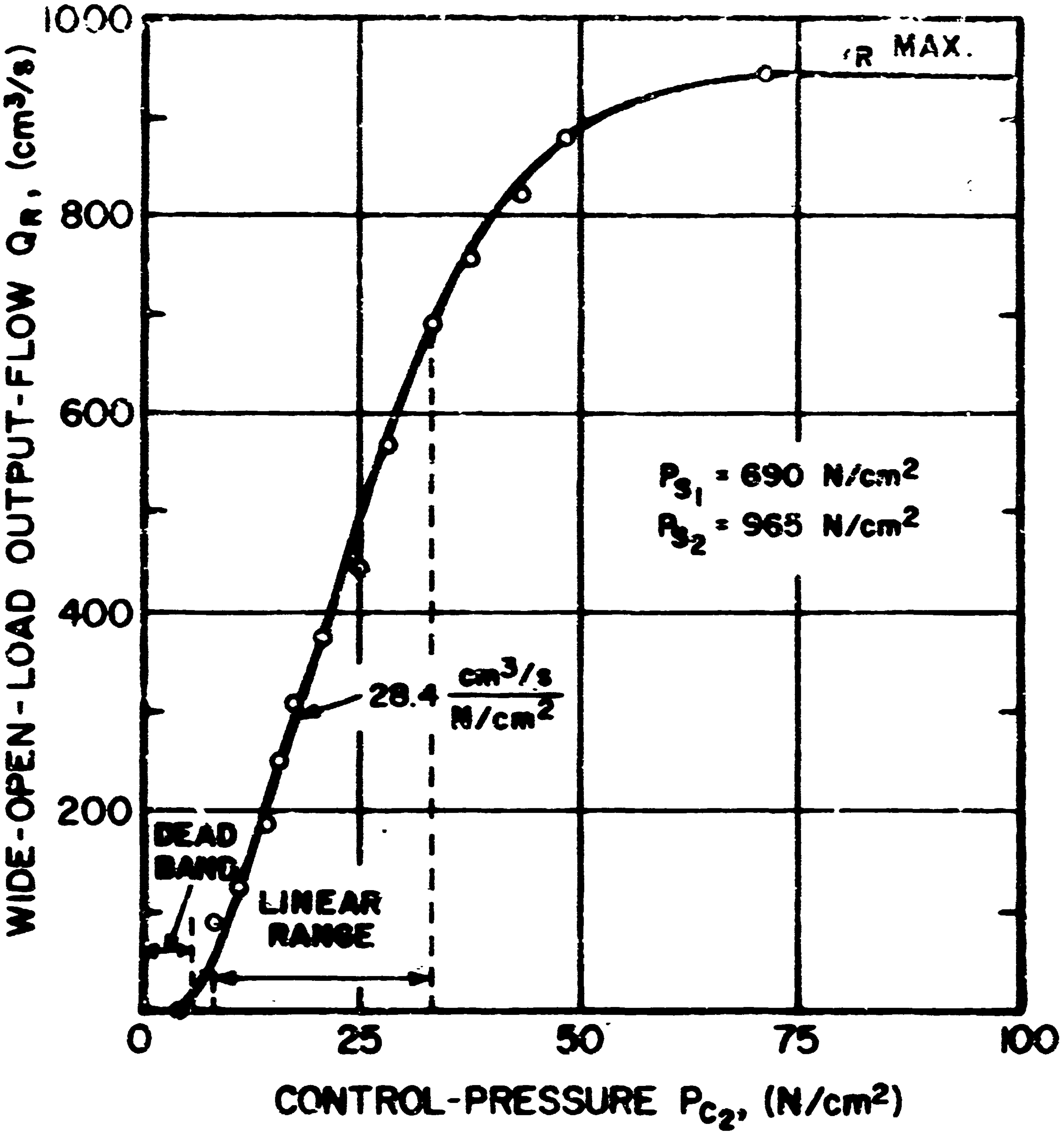


FIG. 12 - WIDE-OPEN-LOAD FLOW CONTROL-PERFORMANCE OF COMPOUND VORTEX AMPLIFIER.

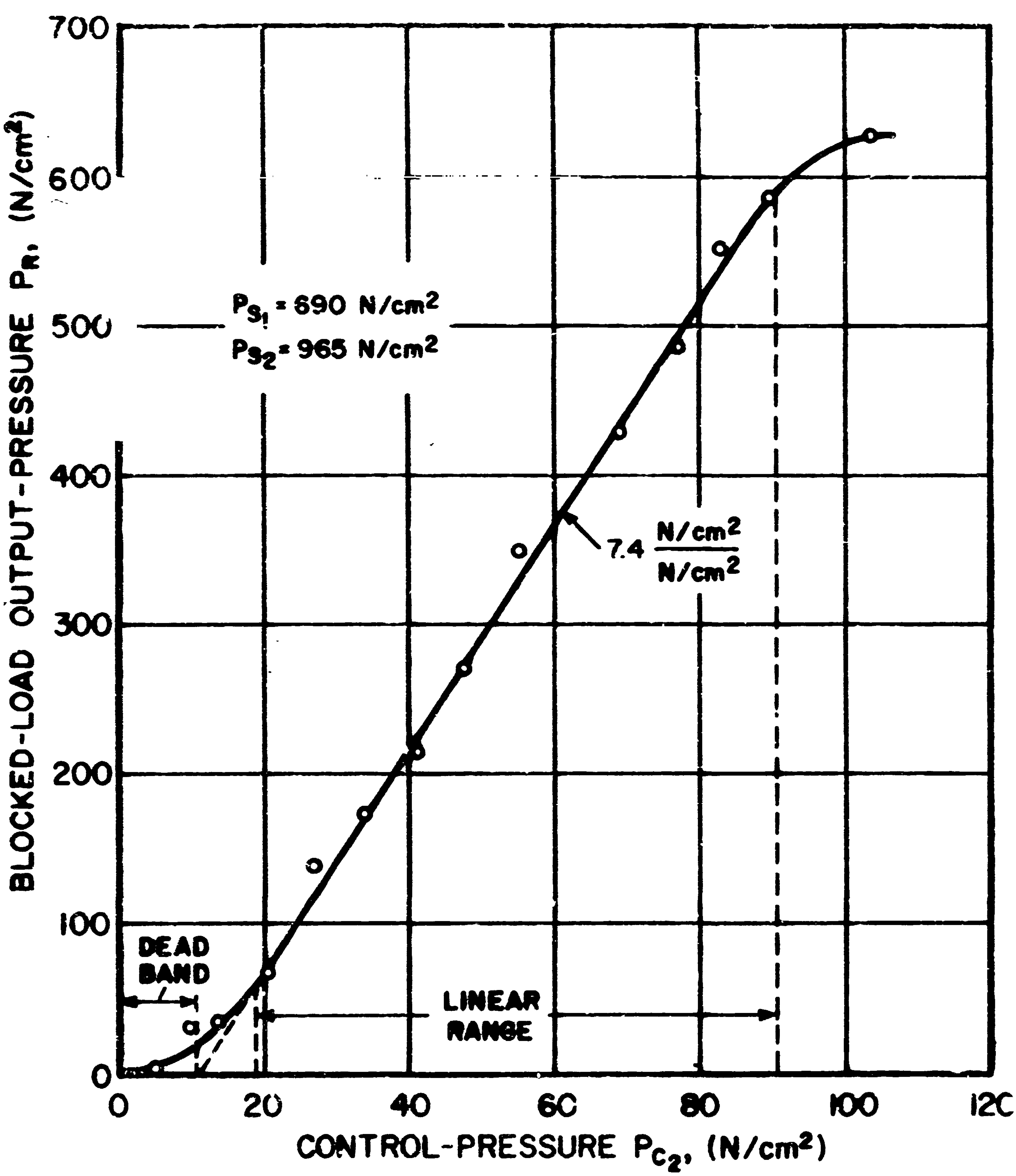


FIG. 13- BLOCKED-LOAD PRESSURE CONTROL-PERFORMANCE OF COMPOUND VORTEX AMPLIFIER.

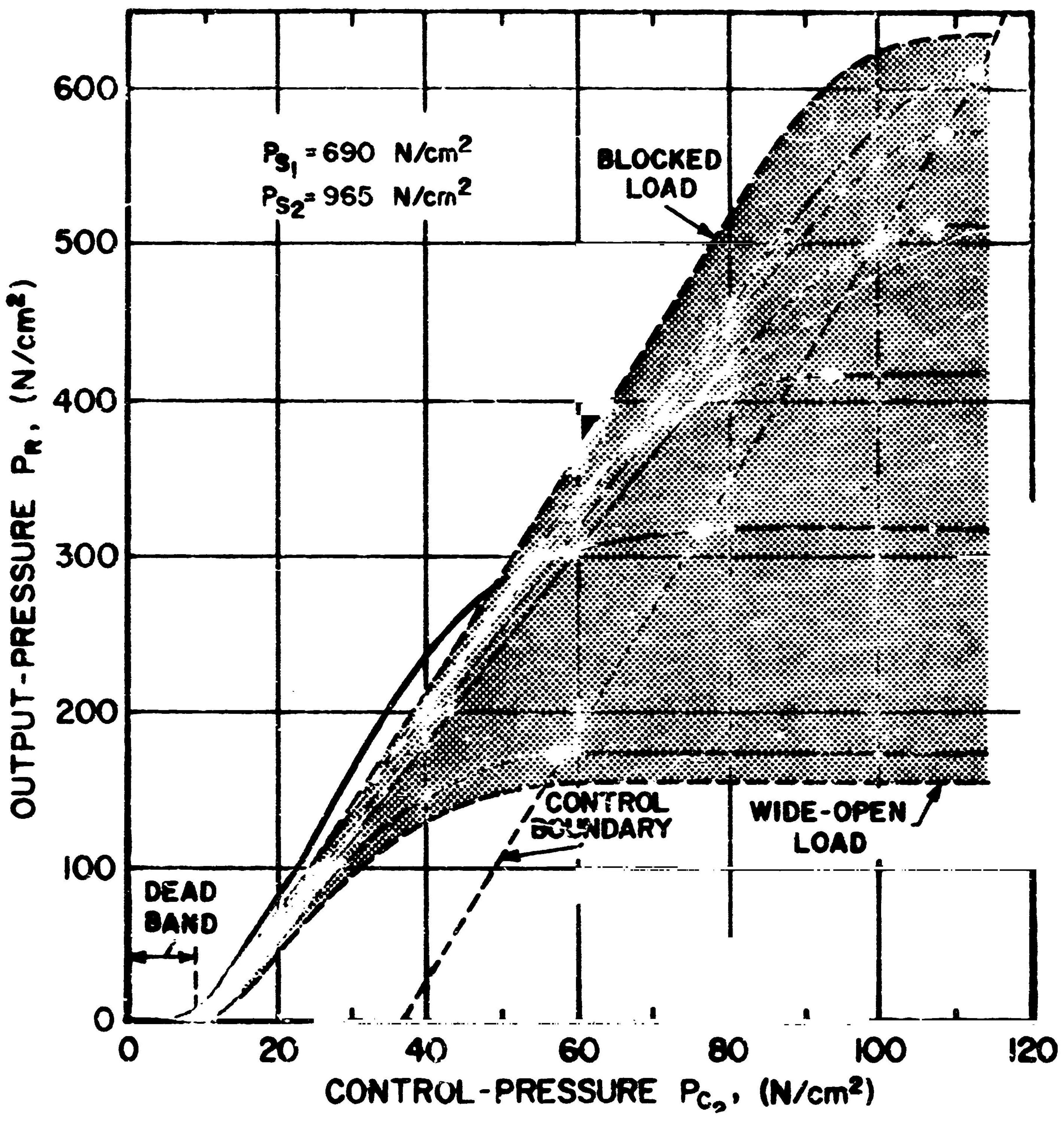


FIG. 14 - CONSTANT-LOAD PRESSURE CONTROL-PERFORMANCE OF COMPOUND VORTEX AMPLIFIER.

Similarly Figure 15 presents the output flow Q_R plotted against the control pressure P_{c_2} for several intermediate loads between blocked and wide-open. The operational range of the compound vortex amplifier is shown dotted.

Constant flow Q_R can be maintained against changing load by small control pressure increments; for instance a flow of 600 cm^3/s can be maintained from wide-open load to the maximum allowable load with a control pressure increment from 29 N/cm^2 to 70 N/cm^2 or only 41 N/cm^2.

Finally the complete output map P_R vs Q_R is shown in Figure 16, both with lines of constant control pressure P_{c_2} = 100, 80, 60, 50, 40, 30 and 20 N/cm^2 and with lines of constant load, from blocked to wide-open. This output map is to be compared with that of Figure 7 for the vortex valve alone. It is seen that the compound vortex amplifier has a usable output performance and that it can be matched to any load line in a stable manner as a function of control pressure.

To conclude the comparison between the compound vortex amplifier and the power-stage (vortex valve described by Blatter[6]), Figure 17 shows the blocked-load pressure output P_R plotted against the control pressure P_{c_2} and Figure 18 shows the wide-open load flow output Q_R plottdd against the control pressure P_{c_2}. The compound vortex amplifier has the characteristics of a usable control component while the vortex valve (power-stage) would find very limited application.

CONCLUSIONS

The present approach has been successful in achieving a hydraulic vortex amplifier with both pressure gain and flow gain from input to output and with acceptable linearity and deadband. A higher gain is desirable and research is continuing to this effect.

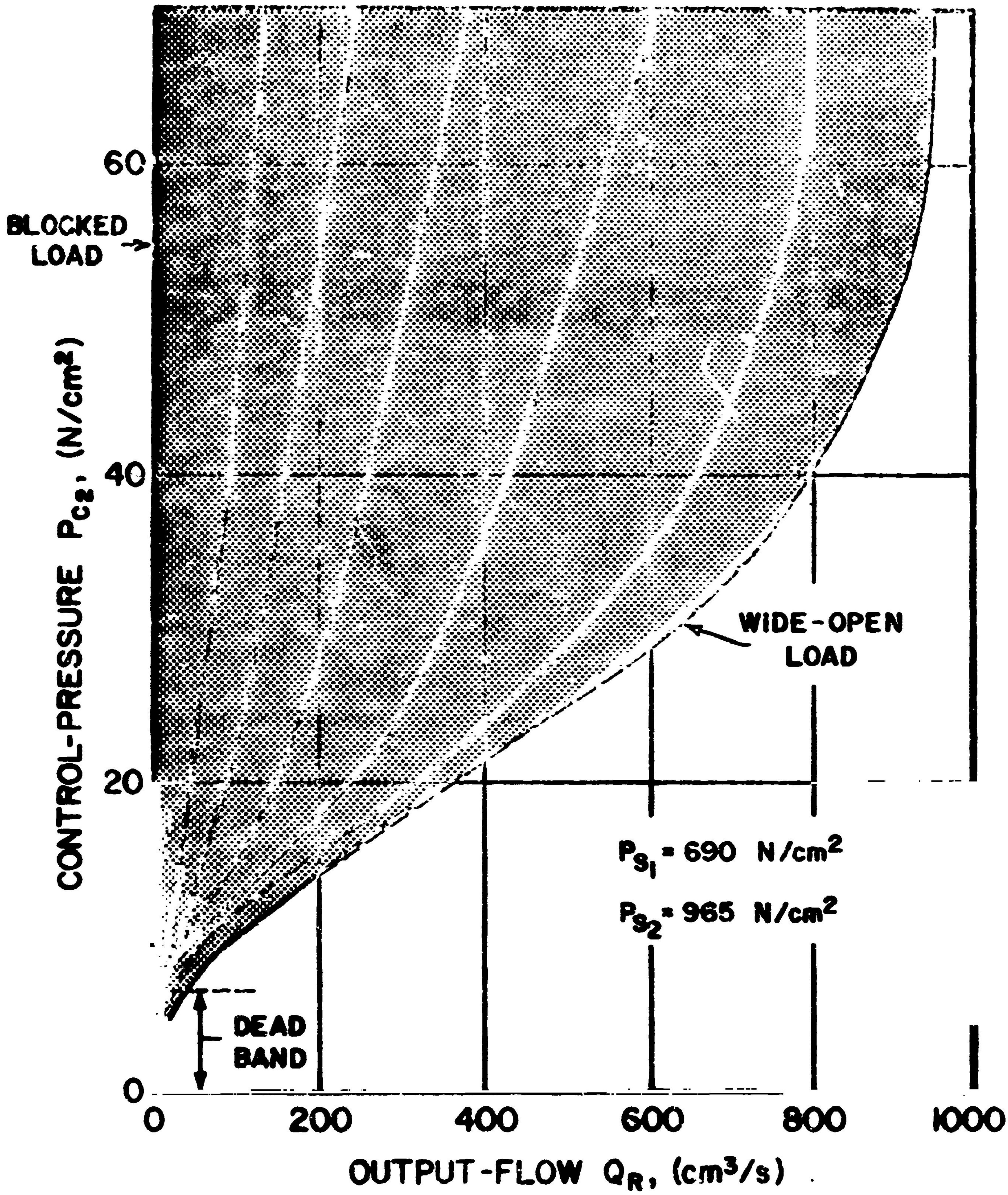


FIG. 15 - CONSTANT-LOAD FLOW CONTROL-PERFORMANCE OF COMPOUND VORTEX AMPLIFIER.

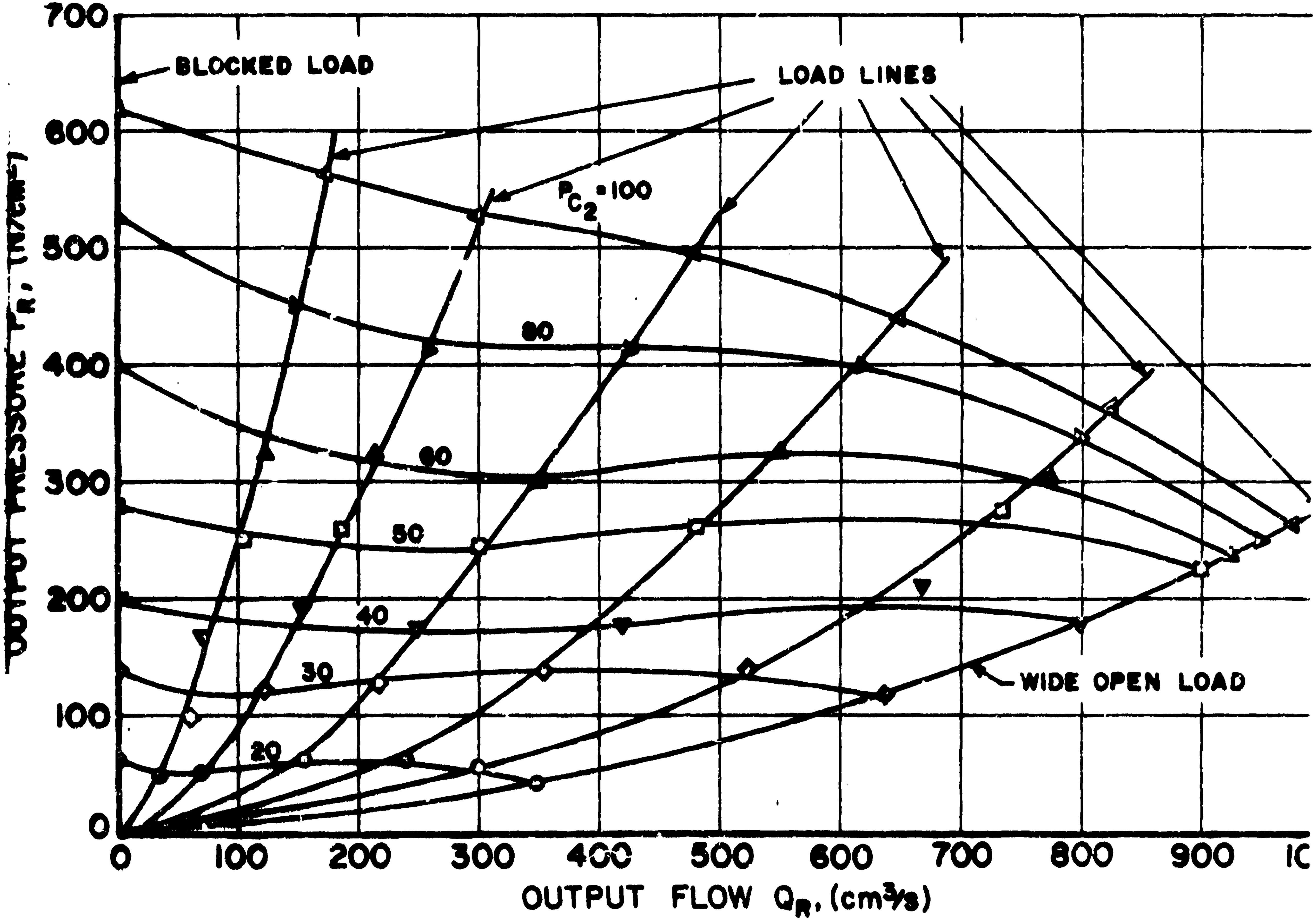


FIG. 16- OUTPUT MAP OF COMPOUND VORTEX AMPLIFIER.

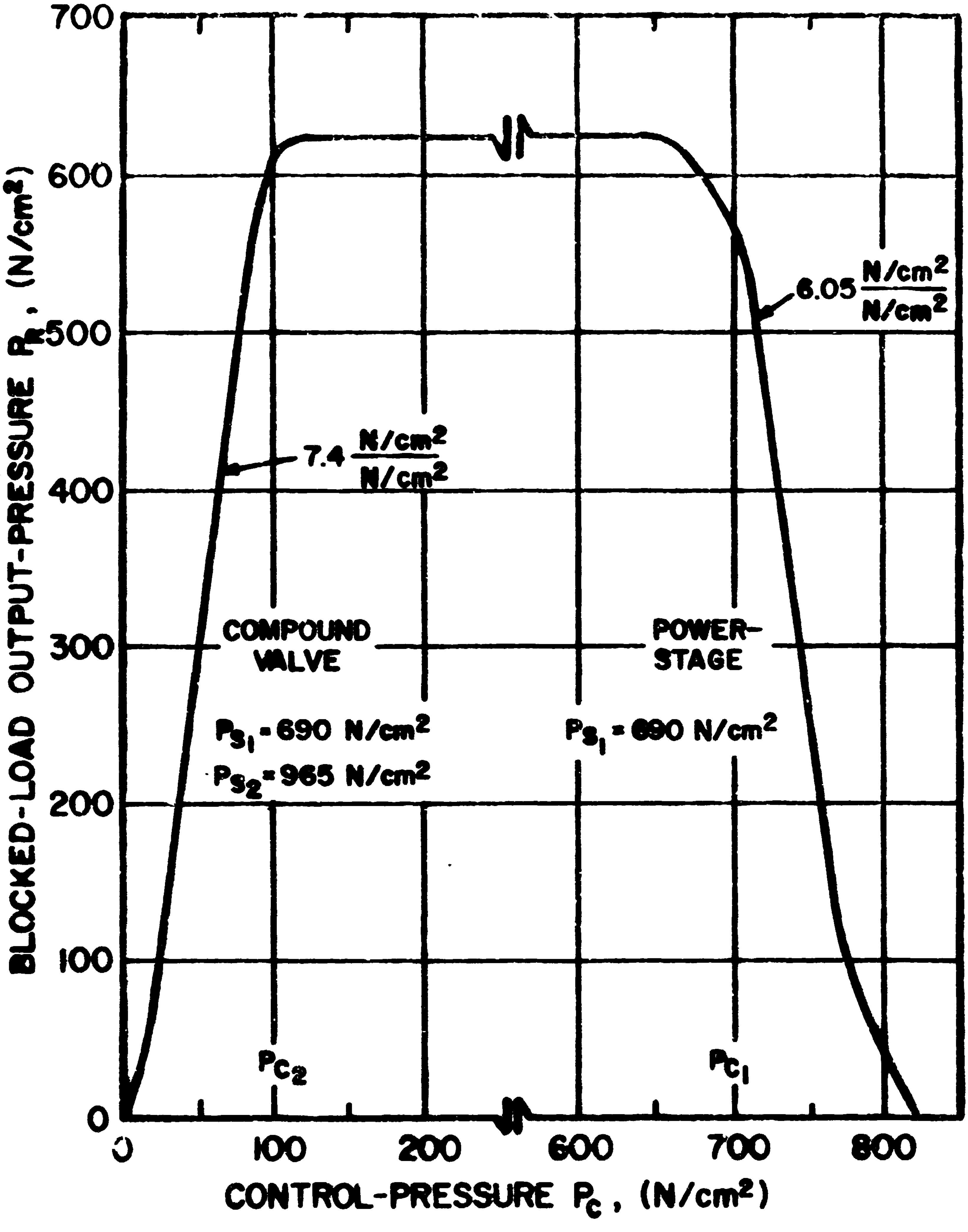


FIG. 17 - BLOCKED-LOAD COMPARATIVE PRESSURE CONTROL-PERFORMANCE OF COMPOUND AMPLIFIER AND OF POWER-STAGE.

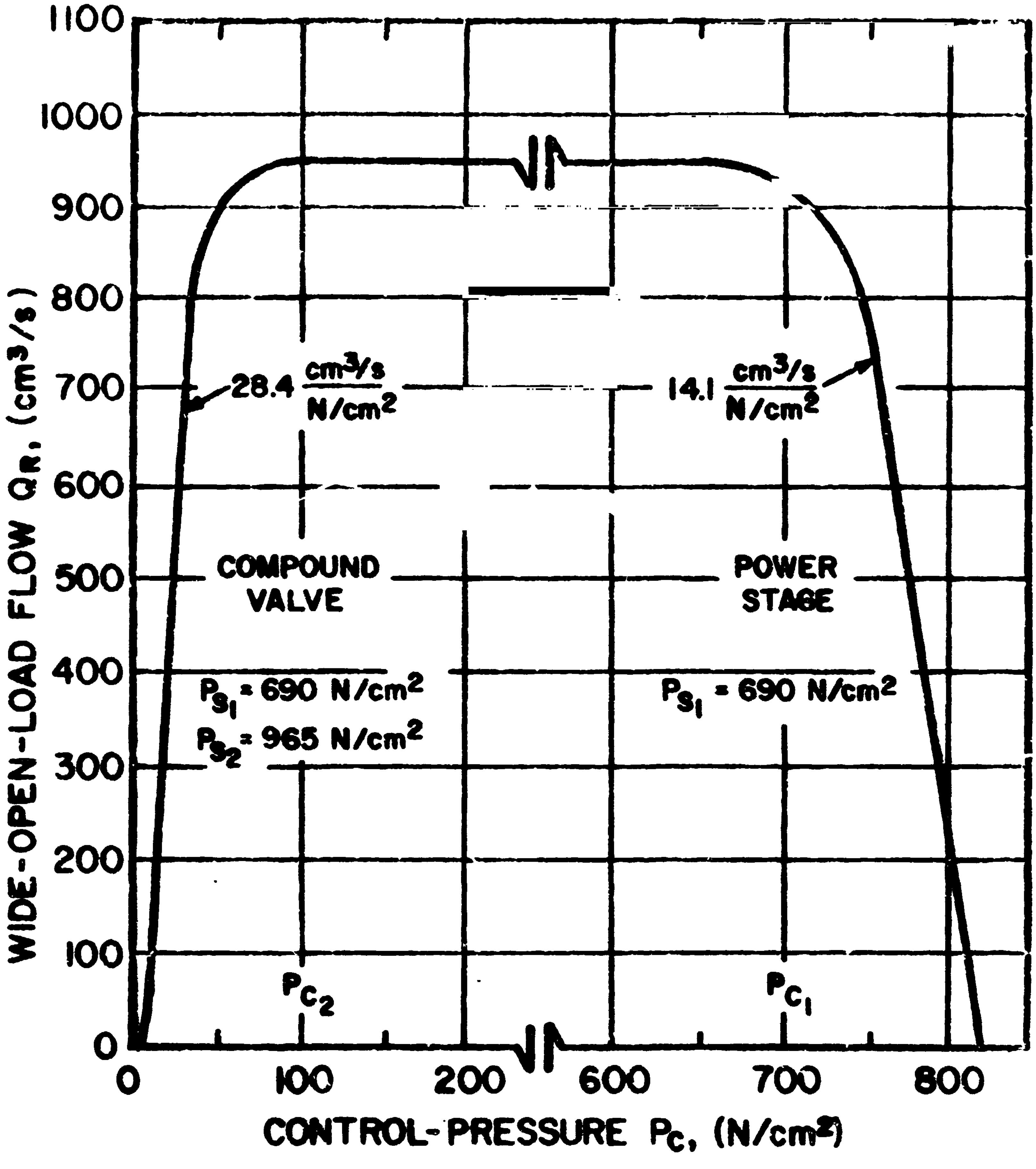


FIG. 18- WIDE-OPEN-LOAD COMPARATIVE FLOW CONTROL-PERFORMANCE OF COMPOUND AMPLIFIER AND OF POWER-STAGE.

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