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A PERFORMANCE ANALYSIS OF THE ARMY EXTERNAL CARDIAC COMPRESSOR (Stroke-Limited Model)

by
Sterling J. Haidt
Kenneth E. Woodward

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U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20438

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ABSTRACT

Cardiac arrest, with the associated loss of oxygenated blood circulating to the brain, swiftly results in death. Utilizing new methods of cardiopulmonary resuscitation, the heart may be restarted, circulation resumed, and the life of the individual saved. One method of cardiac resuscitation recently proposed consists in rhythmically depressing the chest, thereby squeezing the heart and forcing the blood to circulate. This method is called external cardiac compression.

A simple, rugged external cardiac compressor has been developed by the Harry Diamond Laboratories in cooperation with the Walter Reed Army Institute of Research using a fluid amplifier for its power and logic. The machine is stroke-limited and cycles on the completion of a stroke, without pause. The pulse may also be synchronized with an EKG signal. The device has only two control variables, stroke (½ to 2½ in.) and depending on stroke, a frequency of 50 to 140 cpm. The ratio of systolic to total period is 0.7. The operational characteristics reported were obtained in tests of the compressor using a spring, whose spring constant was 33 1/3 lb/in., as a physical model of the sternum.

1. INTRODUCTION

Cardiac arrest, with the associated loss of oxygenated blood circulating to the brain, swiftly results in death. Utilizing new methods of cardiopulmonary resuscitation, the heart may be restarted, circulation resumed, and the life of the individual saved.

Cardiopulmonary resuscitation requires the delivery of well-oxygenated blood to the vital organs of the body and especially to the brain. The brain, deprived of a supply of oxygenated blood for 4 to 6 minutes, will suffer irreparable damage. Therefore, time is very limited.

The resuscitation effort usually consists in the maintenance of blood circulation by artificial means and the oxygenation of the circulating blood. Oxygenation can normally be accomplished by the methods of artificial respiration (ref 1). Circulation of the blood can be maintained artificially by the rhythmic squeezing of the heart in a manner simulating the normal pumping action of the heart. The squeezing may be accomplished either internally, through an incision in the chest wall, or externally. The

external method consists in alternately depressing and releasing the sternum of the individual thereby compressing the heart between the sternum and the spine. As Kouwenhoven (ref 2) puts it, "...the heart is limited anteriorly by the sternum and posteriorly by the vertebral bodies. Its lateral movement is restricted by the pericardium. Pressure on the sternum compresses the heart between it and the spine, forcing out blood. Relaxation of the pressure allows the heart to fill." The depression of the chest may be done either mechanically (ref 3, 4, 5, 6, 7, 8, 9, 10) or manually (ref 1, 11, 12, 13). Several companies are currently manufacturing machines which compress the chest by external means.

The Harry Diamond Laboratories in cooperation with the Walter Reed Army Institute of Research is presently engaged in the development of an external cardiac compressor (ECC) using a fluid amplifier for power and control. The purpose of this development is to build a chest compressor capable of living in military environments while providing support for the soldier in need. This report attempts to describe the considerations necessary for the design of an effective ECC, evaluates an engineering prototype, and describes the design changes resulting from the study.

2. BACKGROUND

Until the introduction of external cardiac compression by Kouwenhoven in 1960, the primary treatment for cardiac arrest was thoracotomy, followed by the manual squeezing of the intact heart. Because of the inherent dangers of chest incision, thoracotomy was usually attempted with reluctance, and as a consequence much valuable time was lost. When internal cardiac massage has been attempted in the past, it almost always has been performed by a physician. With the introduction of an external method of manual cardiac compression, a means for cardiac resuscitation is made available to persons other than physicians. This technique of manual external cardiac compression can be easily taught to nonmedical personnel.

Manual chest compression has certain disadvantages. First, with only one rescuer present, it is exceedingly difficult and fatiguing (ref 14) to perform cardiac compression and artificial respiration either simultaneously or serially for long periods. Both are necessary for successful cardiopulmonary resuscitation. Secondly, since many individuals are involved in rescue work, there are inherent variations in how the resuscitation is performed, and standardization of the procedure with precision

is difficult. The use of a mechanical ECC eliminates the above difficulties. The ECC allows the rescuer to concentrate, without interruption, on artificial respiration. Further, the characteristics of ECC operation can be predetermined and fixed.

The primary objective of any ECC unit is to provide the chest compression necessary for adequate perfusion of the blood throughout the body. In addition, it should be simple to operate, reliable, portable, rugged, and inexpensive both to purchase and maintain.

The major disadvantage of a mechanical ECC may be the time lost in securing and fitting it to the patient. This disadvantage may be overcome by placing the ECC near the area of a probable cardiac arrest and having it ready for immediate operation. Further, to minimize lost time, the ECC must necessarily be portable. It should be small enough to fit in an ambulance and light enough to be handled by one man. Since time is very limited, the controls of the ECC should be minimal, simple to operate, and conveniently located.

3. FUNCTIONAL REQUIREMENTS

Cardiac output flow is the main parameter determining the effectiveness of the ECC. This flow is determined by the heart rate and the stroke volume delivered by the heart. Stroke volume in turn, depends on the size of the heart, the extent of diastolic filling and systolic emptying (ref 15). Other factors affecting cardiac output, such as myocardial strength of contraction are not of immediate concern in the application of an ECC device to a patient. Functionally the ECC device must recognize the significance of heart rate and stroke volume in circulatory perfusion. The heart rate is determined by the number of chest compressions per minute. The amount of systolic emptying and diastolic filling (per cycle) depends largely on the shape of the chest-deflection-versus-time curve for each cycle of chest compression. Systolic emptying depends on the actual amount of depression of the sternum as well as the rate of sternum compression, because of the elastic character of the chest and tissues surrounding the heart. In any event, the limit of chest depression should correspond to the maximal safe squeezing of the heart and rib cage. The force required to compress the chest of the individual, of course, depends on the elastic properties of the chest of the individual. Finally diastolic filling may relate to the length of time the heart is left uncompressed, although the exact functional relationship has not been determined.

At the present time, the optimal shape of a single cycle of ECC ram excursion is unknown. Investigators have used ratios of systolic period to total period which vary from 0.33 to 0.7 (ref 5, 6, 7, 8). A compression frequency of 120 cpm has been suggested by one investigator. Most investigators, however, seem to agree on compression rates of 40 to 60 cpm as optimal for the "average" individual. In addition, the depression of the sternum of the "average" individual is suggested as 3 to 5 cm (1 to 2 in.).

Since all individuals cannot be treated as average, the ECC must be designed with a degree of functional flexibility, for use on individuals whose heart size, chest size, chest stiffness, and heart rate may differ considerably. Heart and chest size vary with the age, sex, and habits of the individual (ref 15). The "spring constant" of the chest is a simplified measure of the elasticity of the sternum-ribs assemblage. No data could be found in the literature to indicate the linearity of the sternum's elasticity. In this development, linearity was assumed, and the chest's spring constant was calculated by dividing force by displacement. The range in chest spring constants seemed to vary from 37 to 75 lb/in. (ref 5). In addition, heart rate varies with age and sex. For example, the heart rate of a child is considerably higher than that of an adult.

Since one of the reasons for developing an ECC is to make cardiac resuscitation techniques available to personnel who are not physicians, e.g., ambulance personnel or nurses, it is imperative that the ECC be simple to operate. The ECC should also be highly reliable and utilize a convenient power source (such as compressed air tanks carried in ambulances), and be inexpensive to purchase and maintain.

4. THE ARMY EXTERNAL CARDIAC COMPRESSOR

The prototype Army External Cardiac Compressor, illustrated in figures 1 and 2, consists of a piston driven by the gases flowing from a bistable fluid amplifier. The piston serves to compress the sternum and is driven down by the pressure of the emerging jet. The stroke of the piston is limited by triggers which control switching flows to the fluid amplifier. At the end of the down stroke, a trigger struck by the piston assembly allows a flow of gas to switch the amplifier to exhaust. The amplifier starts entraining gas from the cylinder, thereby sucking the cylinder upward. In addition, the stored forces in the compressed sternum act to push the piston up. At the end of the upstroke, another valve is opened to atmosphere by the piston assembly striking it, and sufficient control flow is developed to

switch the amplifier back to its initial state. In the above manner, one cycle of operation is executed. In addition, the upper valve may be triggered by an electropneumatic solenoid controlled by an external EKG signal thereby synchronizing operation of the piston to the cardiac cycle. The length of stroke is controlled by the length of adjustable rod connected to the piston. The ratio (which shall be called R) of systolic duration (downstroke period) to the total period is determined by a combination of the input pressure and the resistance of the pulse rate control valve. Because the resistance of the pulse rate control valve is variable, the frequency of compressions is made variable.

The entire piston-cylinder-arm arrangement is able to slide up and down on the vertical post attached to the base plate in order to accommodate various chest sizes. The stroke may be varied continuously from approximately ½ to 2 ½ in.

4.1 Performance Characteristics

To evaluate the performance of the prototype ECC, the following testing procedure was devised:

A spring with a constant of 33 1/3 lb/in. was selected to simulate the elasticity of the sternum. This selection was based on the output capabilities of an existing commercial ECC unit already in clinical use. Although the spring constant seems a bit low, it did provide a convenient standard against which the ECC could be tested. Certain output parameters of the ECC were deemed physiologically important. These parameters were: the stroke or ram excursion, stroke frequency, the total period, systolic period of ram travel down, and the excursion-time character of a single stroke cycle. In addition, the ratio of systolic period to total period was calculated.

The values of the above parameters were controlled by adjusting the input pressure to the amplifier, the frequency control, and the excursion control. Since the stroke and the spring constant were known, it was also possible to calculate the force applied to the spring.

"Isofrequency" plots of the ratio (R) of downstroke time to total period versus input pressure were obtained for strokes of 1, 1 ½, 2, and 2 ½ in. The experimental procedure consisted in (1) setting the stroke at a given value, (2) increasing the pressure until the given stroke was attained, (3) adjusting the frequency control for the proper frequency, and (4) measuring the systolic period (t_d). The frequency and t_d were obtained from

an oscilloscope trace of the pressure above the piston. The pressure was raised by increments of 5 psig, and the frequency control, adjusted each time to produce the same frequency for each increment of pressure change. Figures 3A, 3B, 3C, and 3D describe the performance characteristics of the unit at the beginning of this evaluation.

Figure 3A with a stroke of 1 in. affords a typical example of the characteristics obtained. All curves show comparatively high values of R (ratio of downstroke time to total period) which at low pressures decrease asymptotically with the increasing pressure. The downstroke time t_d was found to be essentially a function of input pressure and was independent of the frequency control setting (fig. 4). There always existed a certain minimum pressure required to achieve the required downstroke, since the pressure forces had to be at least equal to the maximum spring force to complete the downward excursion. By increasing the pressure, the downstroke time became increasingly shorter, asymptotically approaching a lower limit. As downstroke time decreased, R decreased simultaneously. In contrast, the upstroke time of the ram was controlled predominantly by the frequency control. At its least-resistance setting, the control allowed the shortest upstroke time.

It should be noted that the values of R deemed to be physiologically acceptable (R = 0.33 minimum) existed for the least pressure required to cause the ECC to operate. Further increases in pressure not only caused the value of R to decrease below 0.33, but power was unnecessarily consumed. Consequently for any selected excursion, the best operating point occurred for pressures just high enough to cause the ram to move up and down. A typical picture of cylinder pressure (the magnitude of which is proportional to the displacement of the spring) versus time appears in figure 5A for 60 cpm and 1 ½ in. stroke. The pressures during both upstroke and downstroke vary exponentially with time.

Table I shows the power consumption for the unmodified ECC and for subsequent modified versions at a 2 in. excursion and 60 cpm.

4.2 Early Medical Evaluation

The first animal test demonstrated a severe shortcoming in control of the device. During the early phase of the experiment, perfusion was not adequate, and the operator logically

Table I. Comparative Power Requirements

Frequency (cpm)	Stroke (in.)	Pressure (psig)	Flow (Scfm)	Power (ft-lb/sec)
Unmodified ECC with Cylinder Seals				
60	2	38	3.12	284
Ummodified ECC without Cylinder Seals				
60	2	39	3.15	295
Modified ECC* with Cylinder Seals				
60	2	30	2.04	147
Modified ECC* without Cylinder Seals				
60	2	33	2.20	174

*Breathing valve added in cylinder receiver of amplifier and amplifier power nozzle reduced to 0.063 in. depth from 0.093 in. depth.

increased input pressure to increase the ECC's rate. Unwittingly, however, the operator only caused the ratio of R to decrease from values near 0.4 to 0.2 (fig. 3C). A ratio of 0.2 would seem physiologically undesirable considering the ratios used by other investigators; consistent with this, this first experiment resulted in poor perfusion of the animal. The other chief criticism of the ECC by the medical personnel on the basis of this test was that the ram retarded the free expansion of the chest since the ram upstroke was dependent upon the rate of cylinder gas entrainment by the fluid amplifier. Design changes were consequently initiated.

4.3 Modifications to the ECC

It was decided that an increase in the R ratio characteristics of the ECC was desirable. One possible way to increase the ratio was to decrease the upstroke time. It was thought that this could be decreased by decreasing the frictional force acting on the piston. This seemed to be a simple first step. To reduce this retarding force, the plastic seals between the piston and the cylinder were removed. Figure 6A,

6B, 6C, and 6D show the characteristics which were obtained after the decrease in friction. In general, the ratios of R are higher, however, the removal of the seals necessitated an increase in the pressure and flow to drive the unit, because of the incurred leakage past the piston. Consequently the efficiency was lowered, as shown in table I, although not significantly.

Subsequently experiments were performed to determine the forces retarding the piston during the upstroke. It was found that the major retarding force on the piston during its upward travel was due to air trapped in the cylinder which was forced to escape back through the interaction region of the fluid amplifier to atmosphere. The frictional force between cylinder and piston (without the seals) amounted to less than 5 lb when gas trapping was eliminated. By allowing the air within the cylinder to escape directly to the atmosphere immediately after completion of the downstroke, the upstroke time of the ECC would become dependent mainly on the recoil of the sternum. From the physiological viewpoint there would exist no unnecessary force retarding the expansion of the chest of the individual. The desired modification was achieved using a "breathing valve" or pneumatic diode now being used in the Army Emergency Respirator (ref 16). Essentially, the valve opens a vent or bleed to the atmosphere during the upstroke and closes it during the downstroke.

4.4 Effect of Modifications

The insertion of the breathing valve had significant effects on the performance of the ECC. With the exit of the cylinder air to atmosphere during the upstroke, the upstroke time decreased significantly. In addition, the upstroke time was dependent primarily on the recoil forces of the spring (the sternum) and independent of the input pressure and frequency control. Since the output resistor comprising the frequency control was now an ineffective control of upstroke time, it was eliminated. Control of frequency could be achieved by increasing or decreasing input power. Therefore, the number of controls was reduced from three to two.

Because of the decrease in upstroke time, the oscillation frequency increased greatly. In addition, the ratio of the systolic to total period increased to the mid to upper range of values considered physiologically acceptable by investigators in the field, and for any selected excursion, remained essentially constant regardless of input pressure to

the amplifier. Figure 5 shows the pulse shapes obtained before and after the "breathing valve" modification for the same input pressure and stroke. It can be seen that the frequency increased from 60 cpm to 92 cpm and the ratio R increased from .39 to .62. In addition, the upstroke portion of the pulse is linear in character.

With the removal of the frequency control, only two input control variables remained: stroke and input pressure. Therefore, for any combination of stroke and input pressure, the frequency and the ratio R were fixed for a given spring constant. Figure 7 shows the ECC's characteristics obtained with the breathing valve added. The characteristics shown are condensed by plotting "isostroke" curves for frequency versus input pressure since R is essentially a constant. After adding this valve, however, it was found that the frequencies were excessively high especially for the shorter strokes (fig. 7, 1 in, and 1 ½ in. strokes). In an effort to reduce the frequencies for the shorter strokes, the area of the inlet nozzle of the fluid amplifier was decreased by 33 percent (i.e., the aspect ratio was reduced to 2:1 from 3:1). Figure 8 shows the resulting frequencies for the various strokes after the reduction was made. Since the frequencies were still on the high side, it was felt that the efficiency of the ECC could be increased by replacing the upper seal (between the piston and cylinder) earlier removed. Figure 9 shows the corresponding and acceptable characteristics with the seal replaced. Table I also shows the new and much improved power requirements. In addition, figure 10 shows the pressure-flow characteristics for the amplifiers with 2:1 and 3:1 aspect ratios. The reduction in flow caused by the lesser aspect ratio helped boost efficiency considerably, since work output remained essentially constant.

4.5 Later Medical Evaluations

Subsequent to the incorporation of the valve in the cylinder and after the amplifier's aspect ratio was reduced to 2:1 from 3:1, several animal tests were performed using the device. These dogs were large, and it was found that their chests exhibited spring constants considerably in excess of 33 lb/in., the constant of the model used in the development. Consequently the amplifier was saturated and performance was not acceptable. As a result of these tests it was decided to return to the amplifier with a 3:1 aspect ratio. By using the larger aspect ratio, the amplifier could be made to work in its design range.

5. DISCUSSION

As a result of the study, important and desirable functional changes were introduced in the ECC. The ratios of systolic to total period have been significantly increased (from .4 or less to approximately .75). A paper by Birch (ref 8) suggests that a lower cycling rate with a high ratio of R (.7) will provide the best perfusion. The breathing valve should also allow the chest to expand under minimal resistance and in so doing aid venous filling.

In addition, with the removal of the frequency control, the ECC now has only two controls, stroke and input power. Once the stroke has been set (or it could be preset and fixed), the input power is the only parameter which may be varied by the ECC operator. By varying input power, the frequency of operation can be controlled, while the ratio R remains relatively constant and fixed at a value deemed physiologically desirable. The only moving parts of the ECC (excluding the piston) are the downstroke and upstroke triggers and the breathing valve. With this minimum of three moving parts and the number of controls now limited to stroke and frequency, operation of the ECC should be reliable and simple.

The question arose during the development of this ECC as to the advantages (or disadvantages) of a time-cycled machine over a stroke-cycled machine. Since the present machine is stroke-cycled, the cycle begins again immediately at the termination of upstroke. Therefore, there is no pause at any time in the cycle; however, with a time-cycled machine, the downward excursion is initiated by an internal timer which initiates the cycle after a set time interval. The machine waits this given interval whether the chest is fully expanded or not. Therefore, with a time-cycled machine there exists the definite possibility of a pause.

Figure 5C shows the type of pulse that would be obtained with a time-cycled ECC. Essentially, the cycle would consist of turning ram pressure on for 0.5 sec and then turning it off for 0.5 sec. As shown (fig. 5C), this timing ratio would allow for a 0.26-sec pause after the upstroke cycle is completed for a cycling rate of 60 cpm and stroke of 1 ½ in.

Some investigators feel that a pause is necessary for complete venous refilling. For the high ratios of 0.7, (ref 8) however, the pause would be very short. It is known that at least one commercially available ECC operates in a time-cycled

manner. It remains to be seen whether the present stroke-cycled ECC has any advantages (or disadvantages) over the time-cycled units. It is presumed that future medical experiments will clarify this point.

The power requirements for the final ECC are higher than most models. This should be expected due to the power losses through the fluid amplifier. Whether the higher power requirements will place a severe limit on the ECC remains to be seen. It is hoped that its reliability, ruggedness, simplicity, and inexpensiveness will offset its power inefficiencies.

6. SUMMARY

An ECC has been developed which uses a fluid amplifier for its power and logic. The machine is stroke-limited and cycles upon completion of a stroke, without pause. The device may also have its pulses synchronized with an EKG signal through the use of an appropriate cardiac programmer. The device has only two controls: stroke and frequency. The pulse characteristics as defined by the ratio of systolic to total period are physiologically acceptable according to the literature. These pulse characteristics were obtained using a spring having a spring constant of 33 1/3 lb/in. as a physical model of the sternum. It yet remains for medical evaluations to establish the effectiveness of this device in resuscitation.

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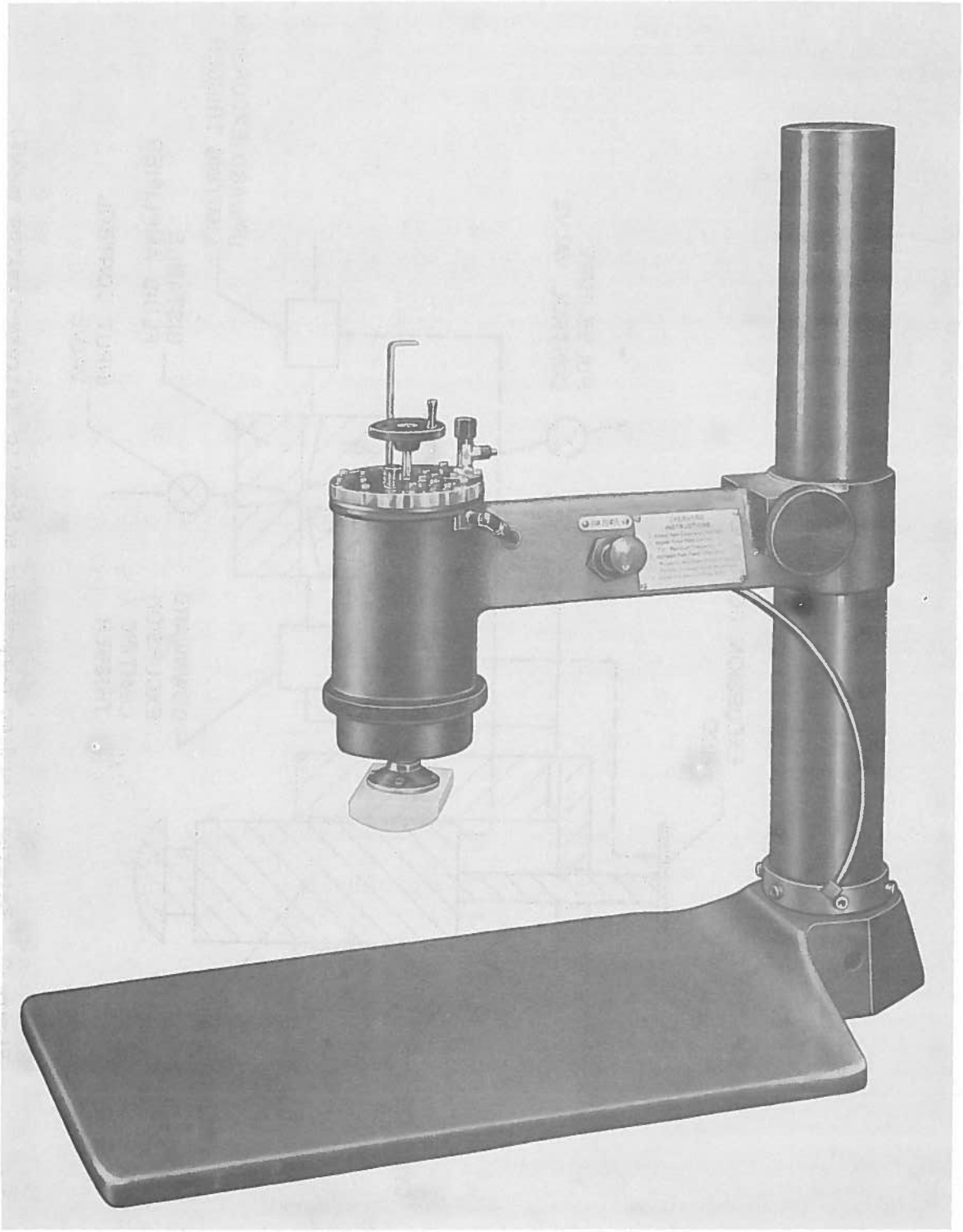

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Fig. I External Cardiac Compressor (Stroke-Limited Model)

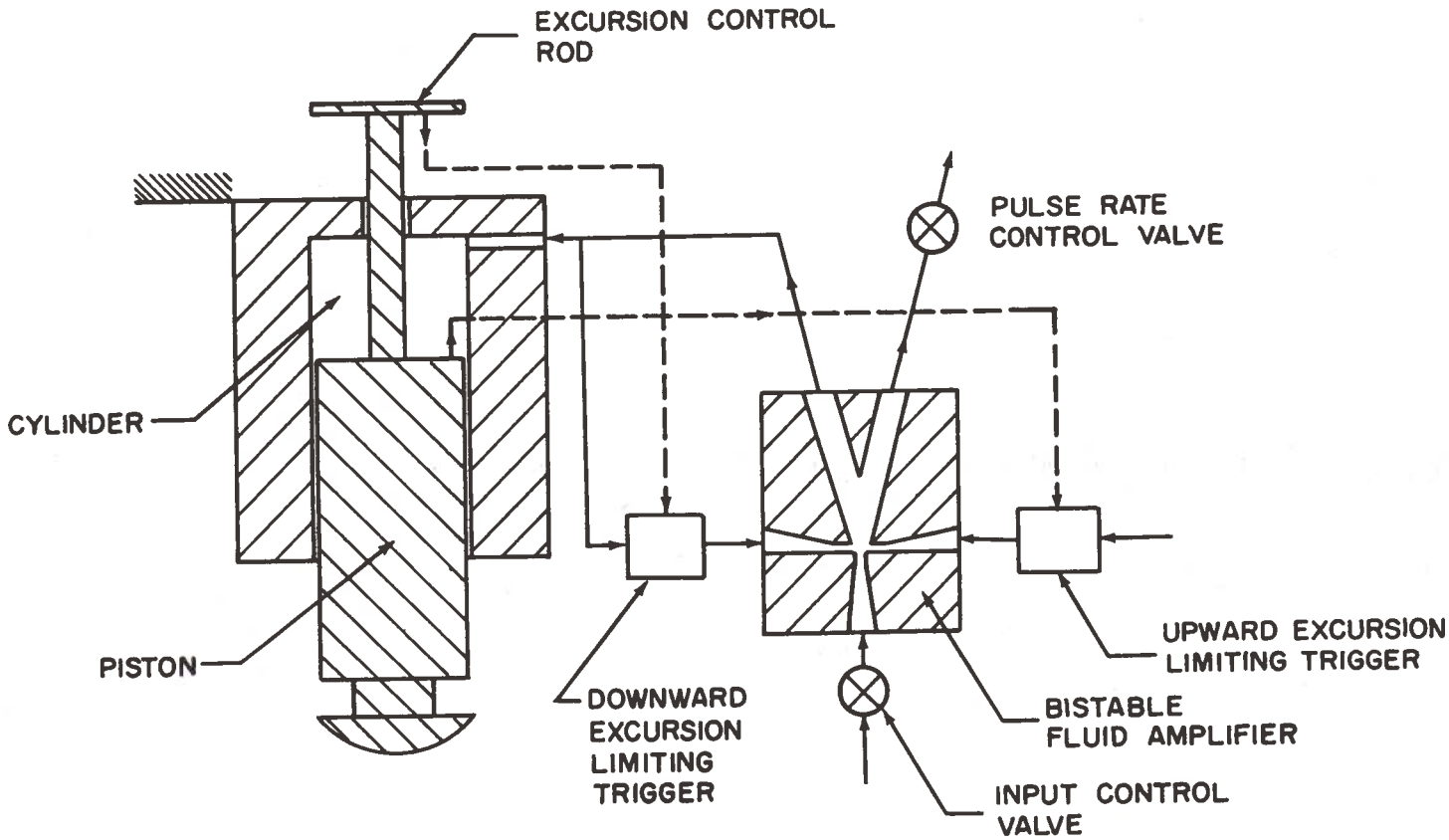

Figure 2. External cardiac compressor schematic (stroke-limited model).

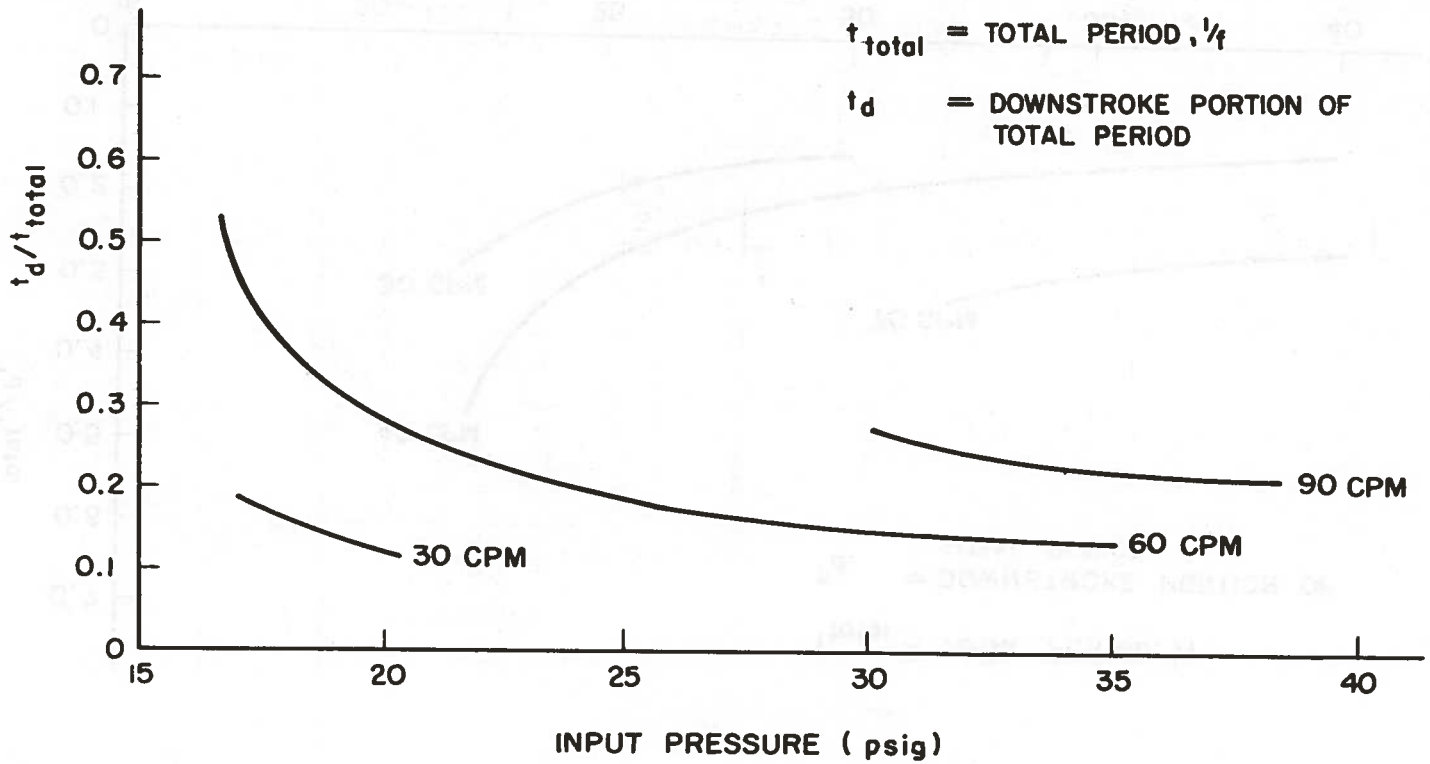

Figure 3A. Operating characteristics, 1 in. stroke, unmodified ECC with seals.

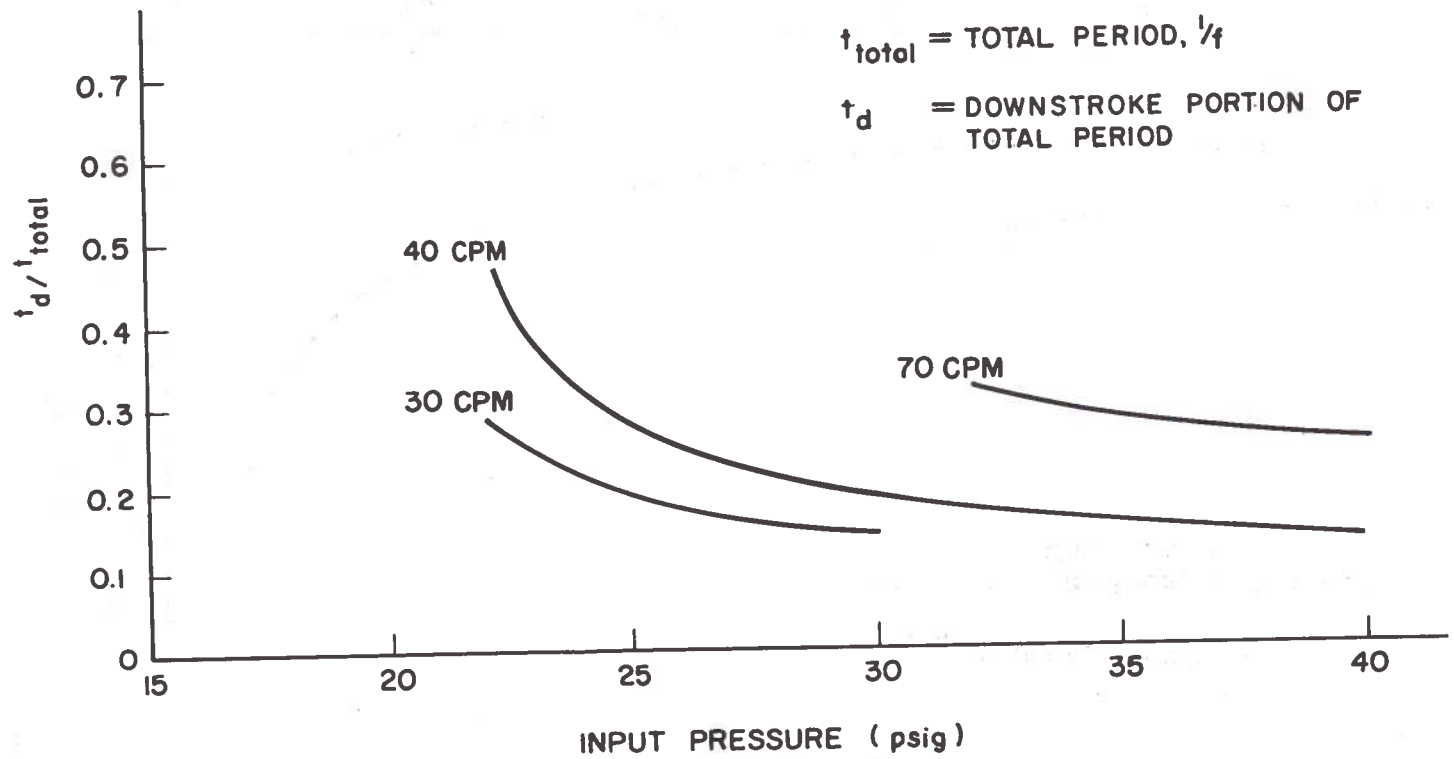

Figure 3B. Operating characteristics, 1 1/2 in. stroke, unmodified ECC with seals.

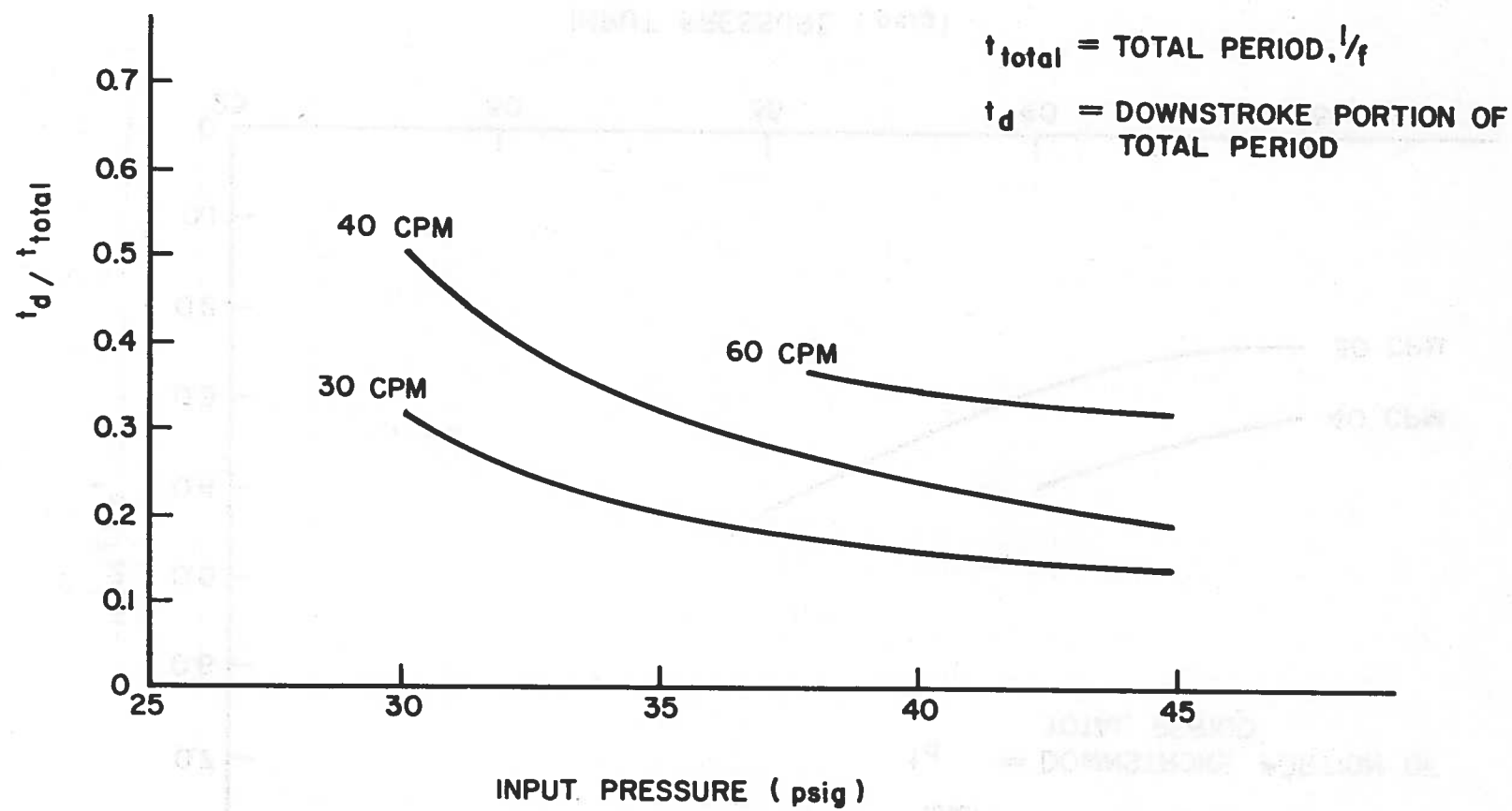

Figure 3C. Operating characteristics 2 in. stroke, unmodified ECC with seals.

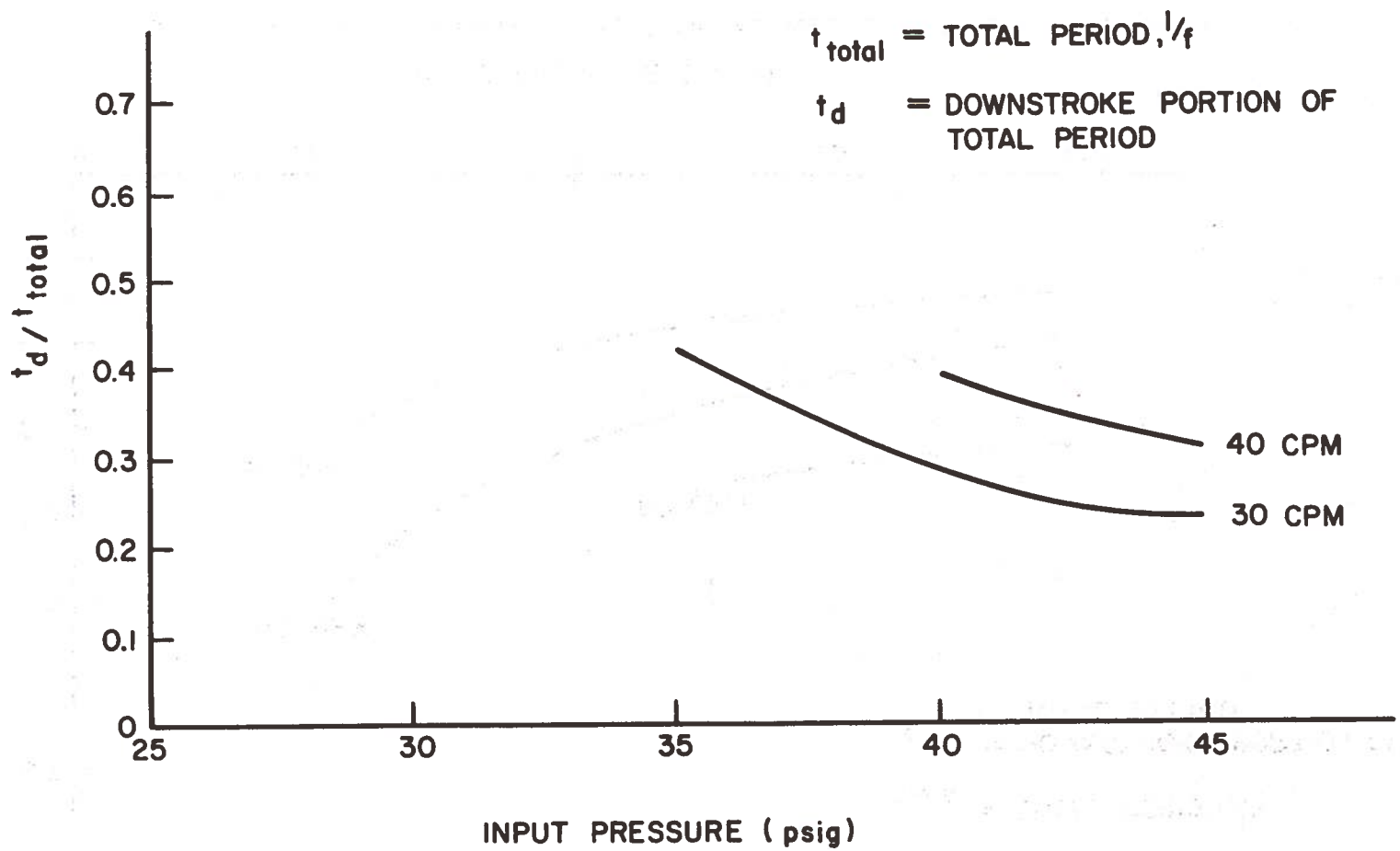

Figure 3D. Operating characteristics, 2 1/2 in. stroke, unmodified ECC with seals.

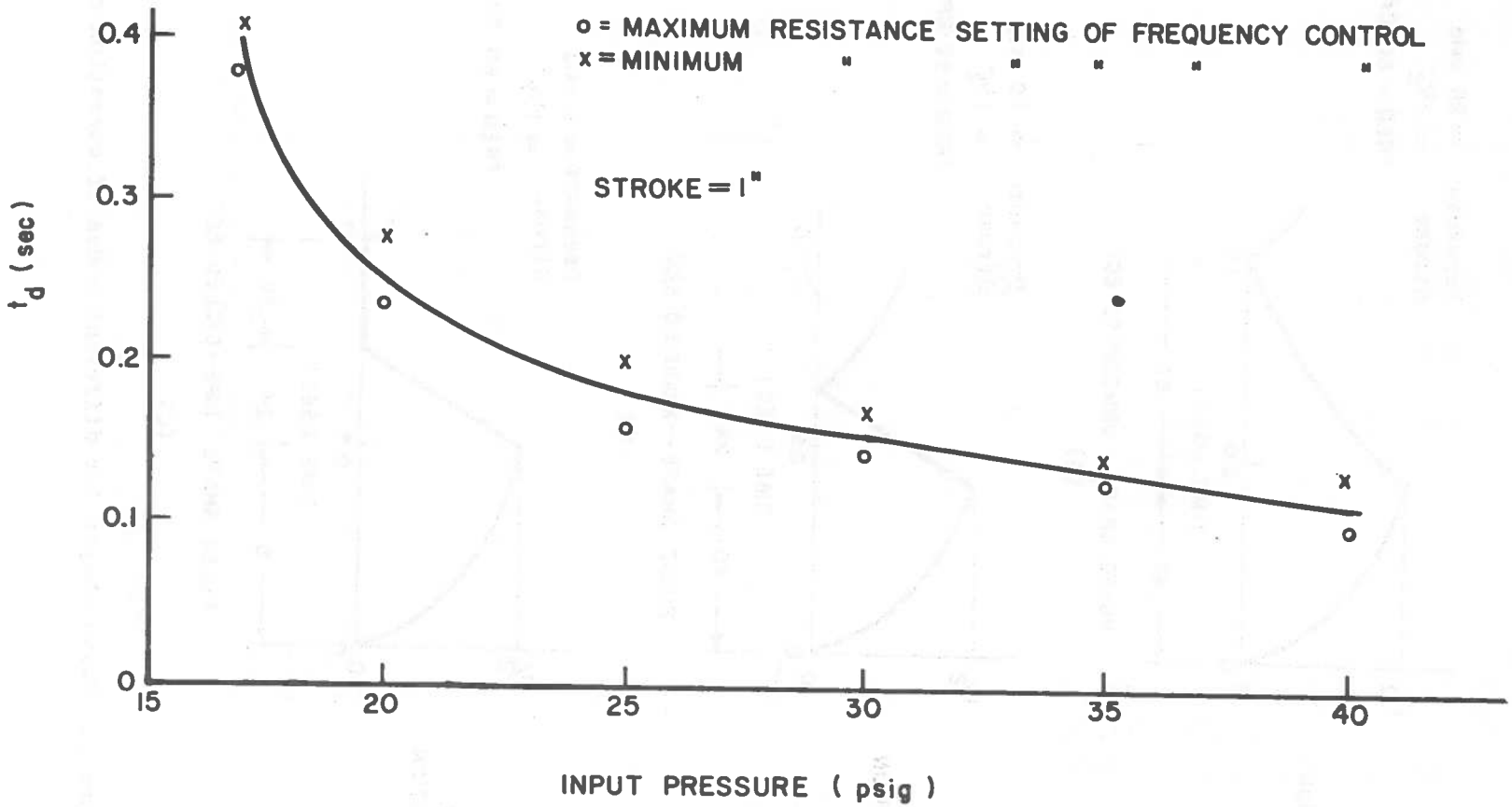

Figure 4. Downstroke time—pressure characteristics.

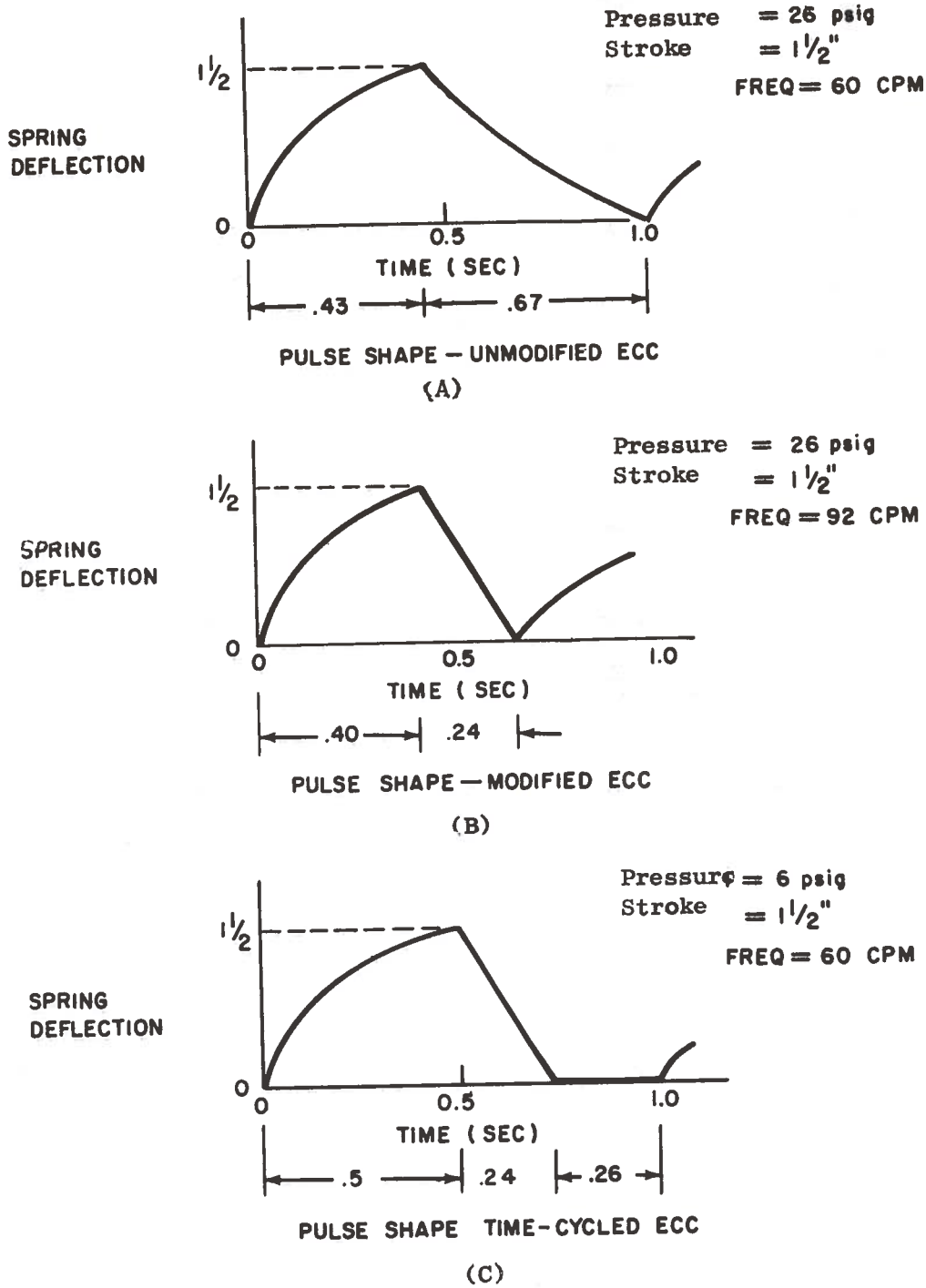

Figure 5. Pulse shapes for different modes of operation of ECC.

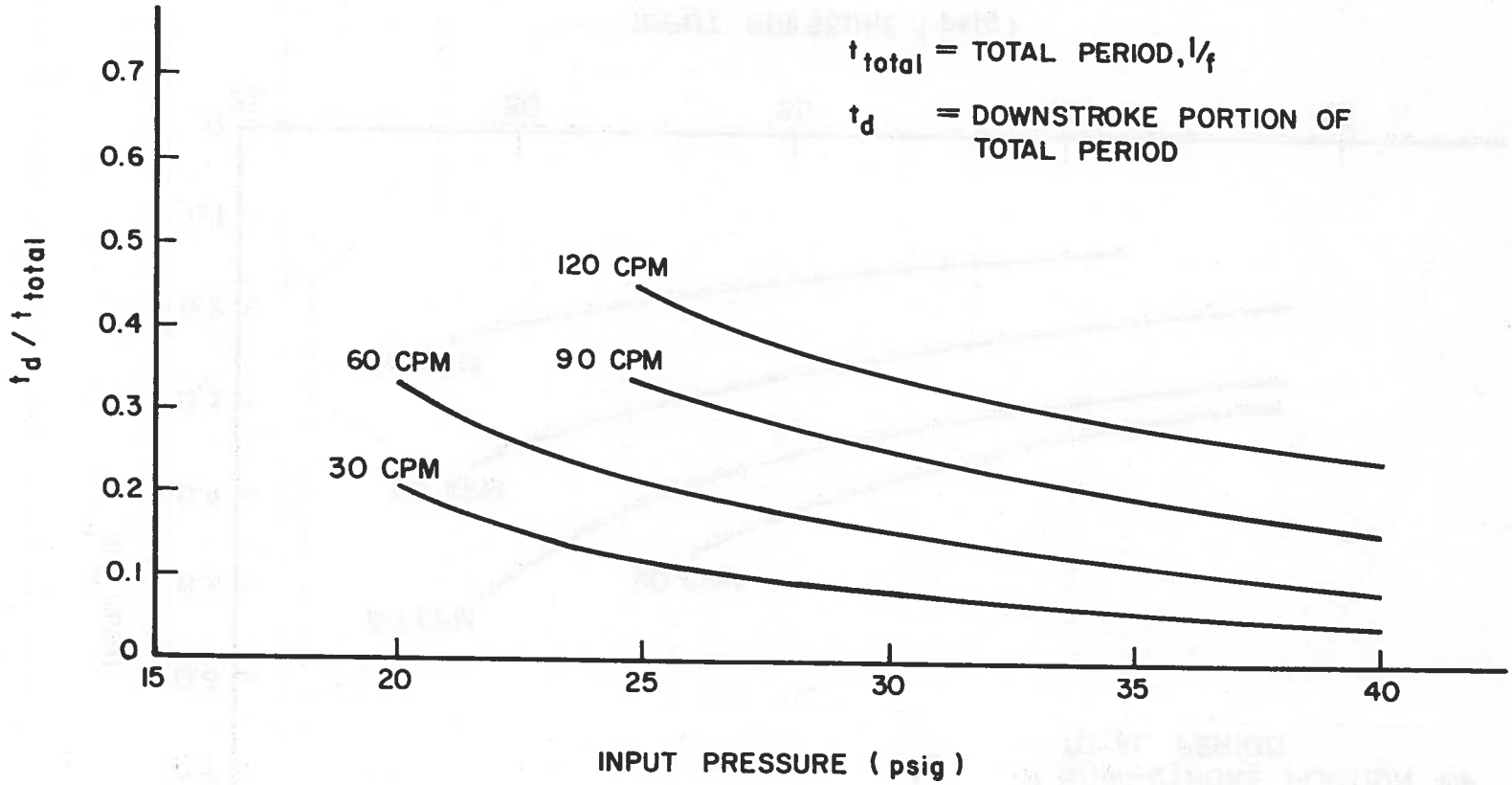

Figure 6A. Operating characteristics, 1 in. stroke, unmodified ECC without seals.

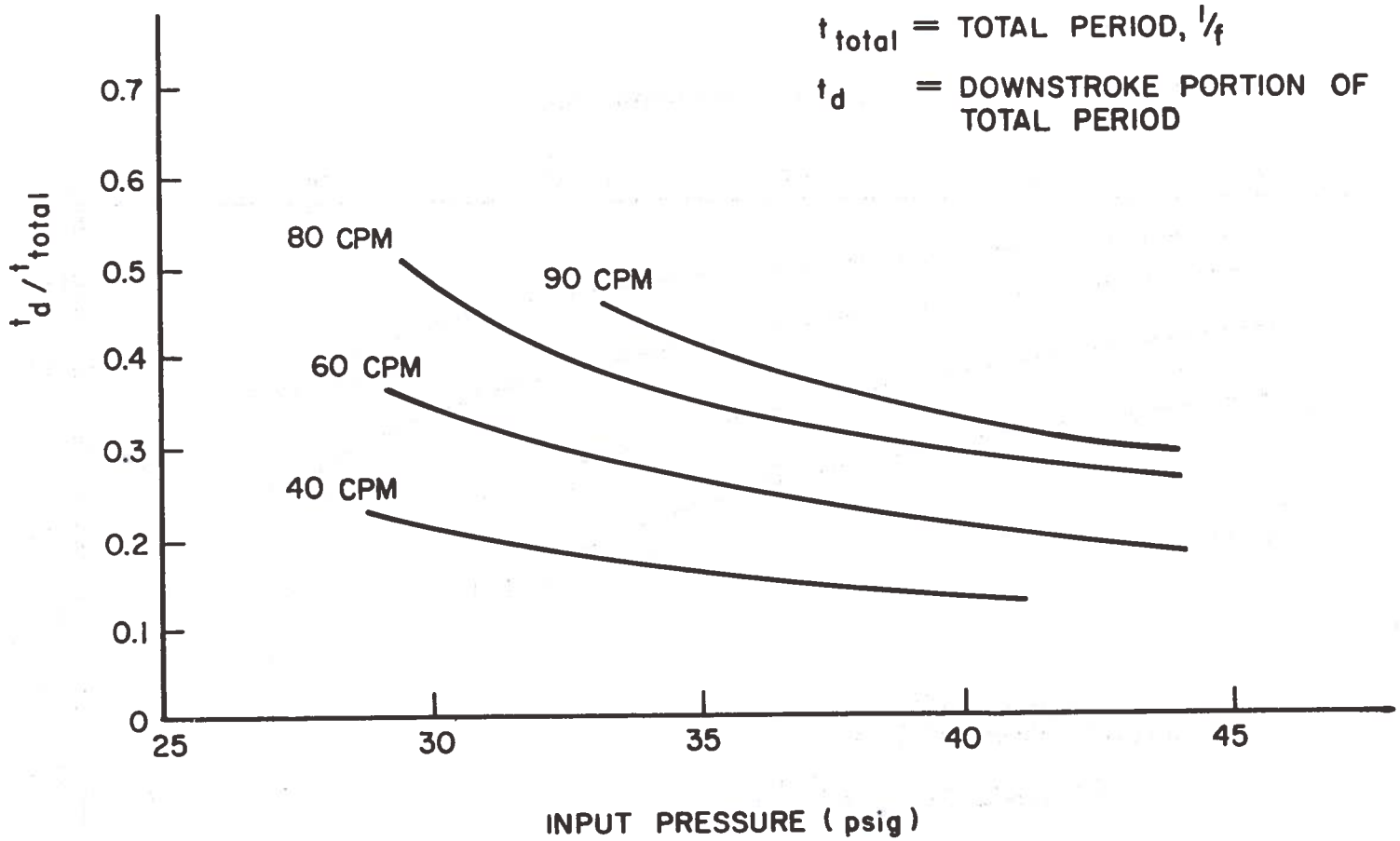

Figure 6B. Operating characteristics, 1 1/2 in. stroke, unmodified ECC without seals.

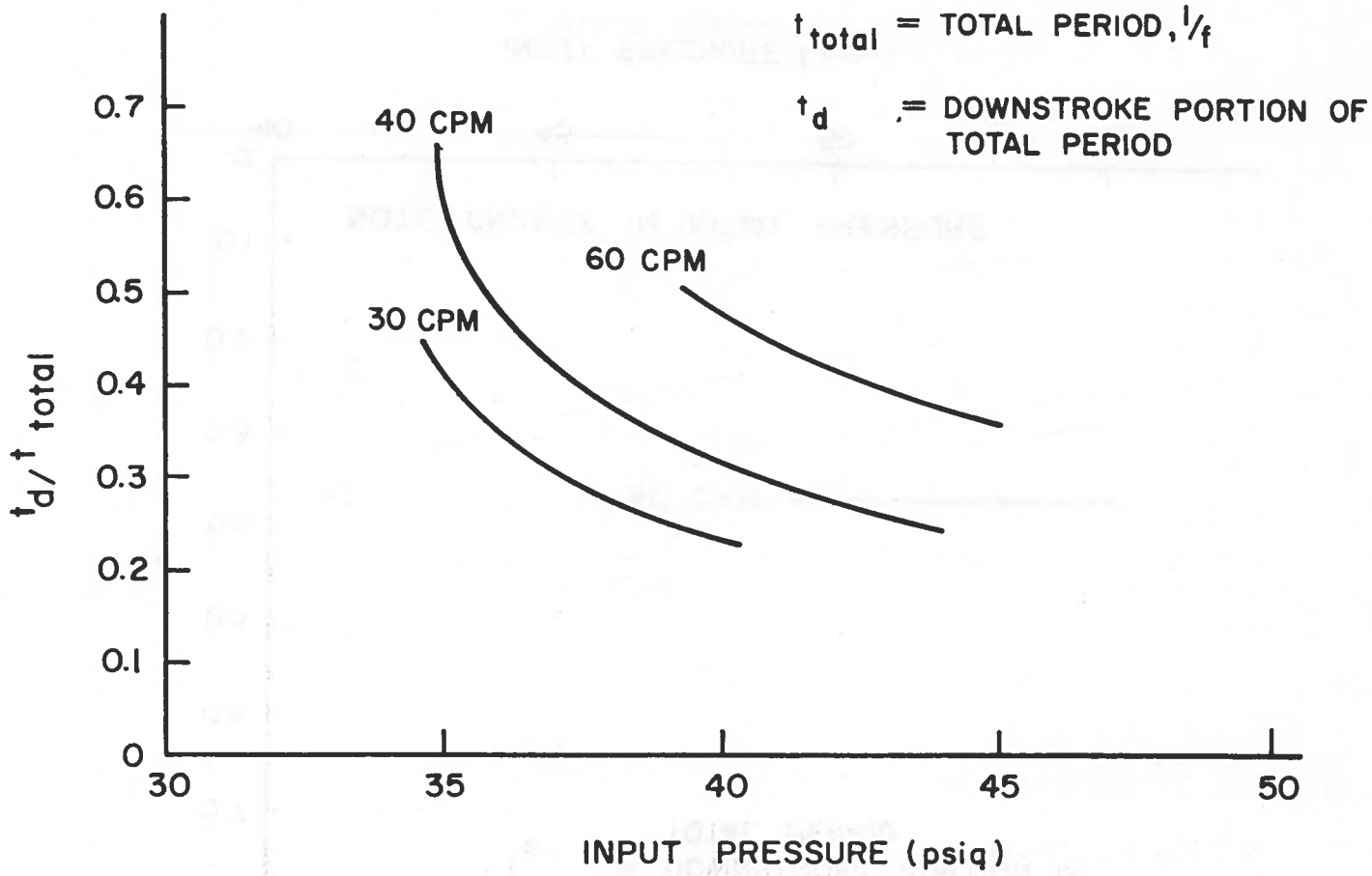

Figure 6C. Operating characteristics, 2 in. stroke, unmodified ECC without seals.

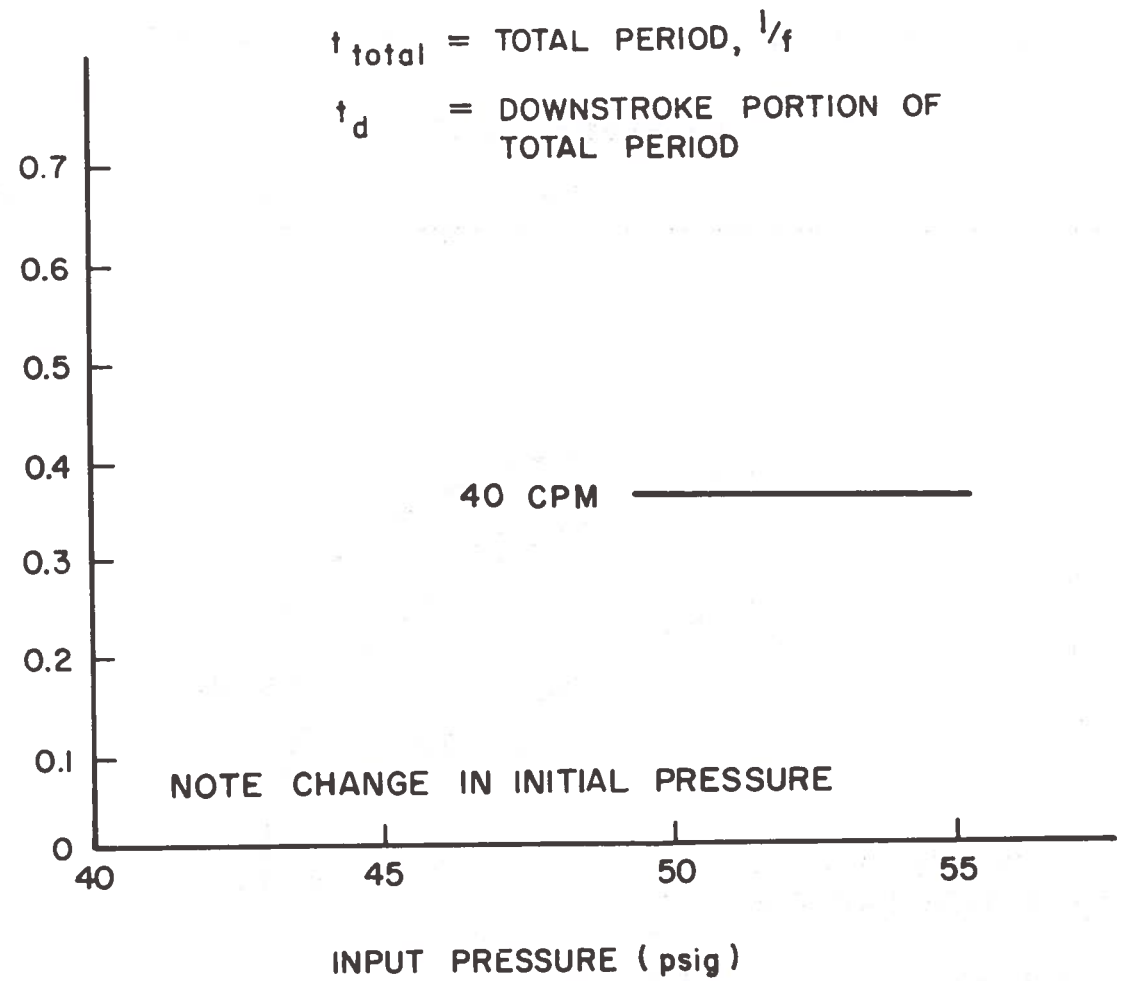

Figure 6D. Operating characteristics, 2 1/2 in. stroke, unmodified ECC without seals.

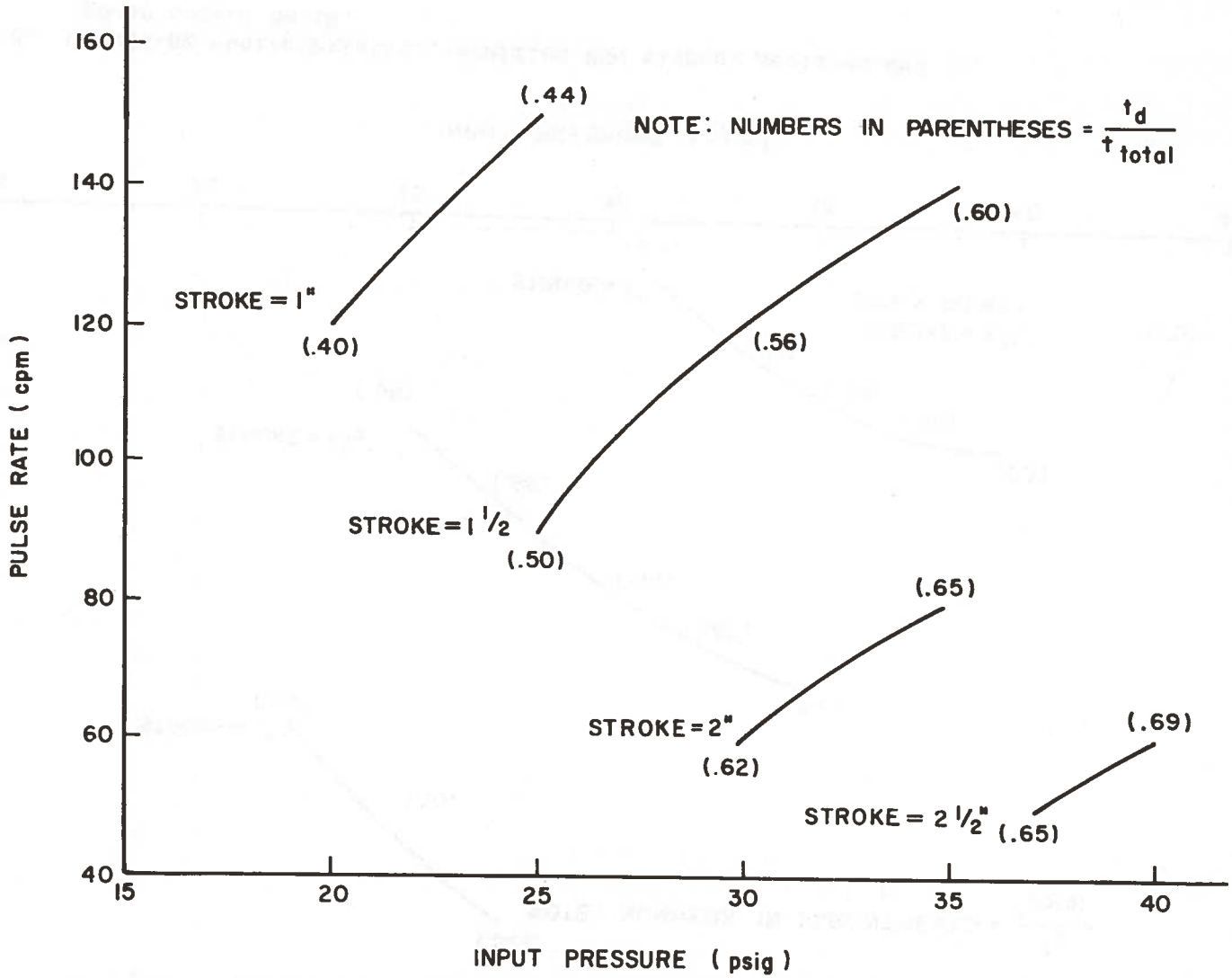

Figure 7. Operating characteristics, modified ECC without seals—0.093 in. power nozzle depth.

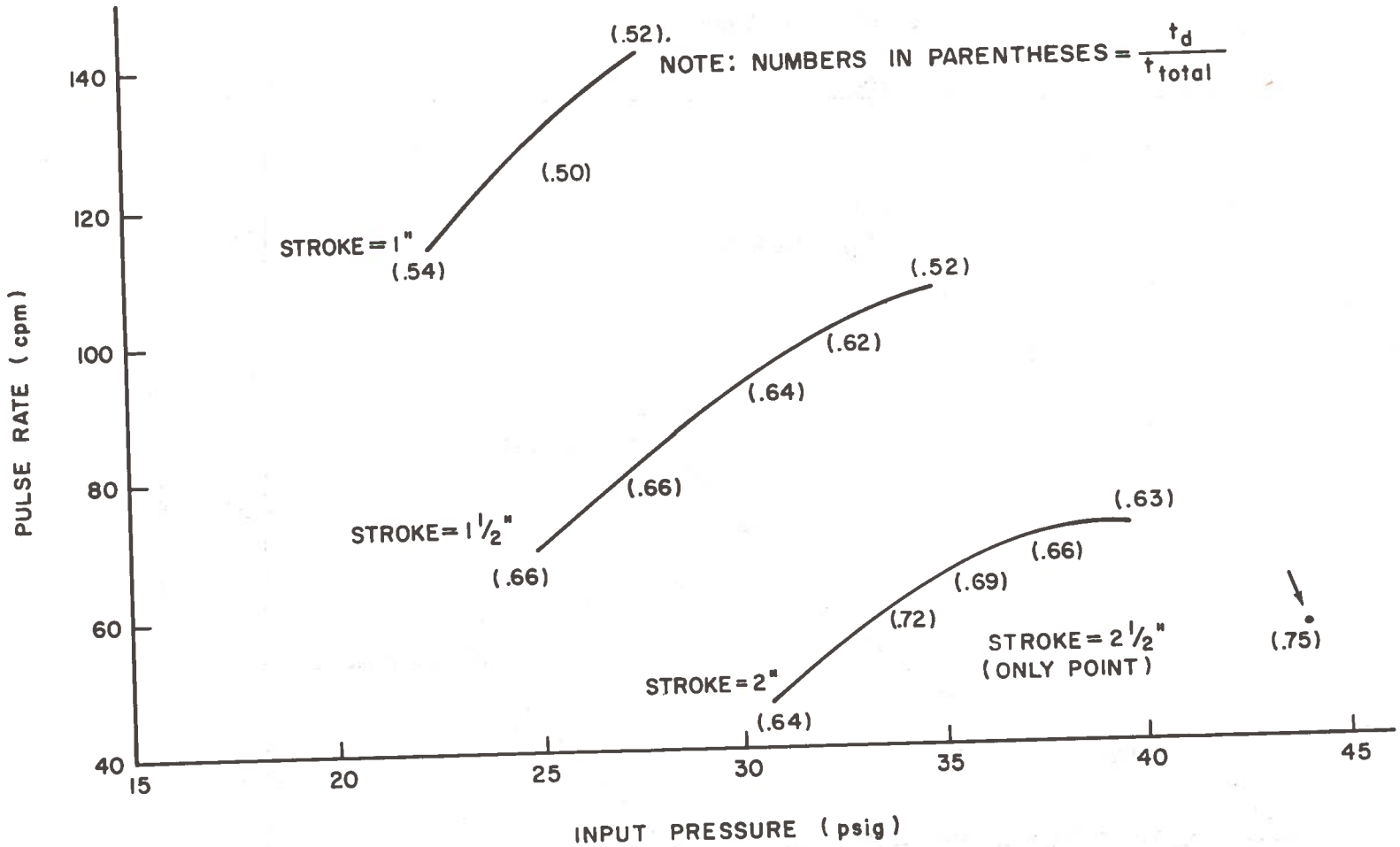

Figure 8. Operating characteristics, modified ECC without seals—0.063 in. power nozzle depth.

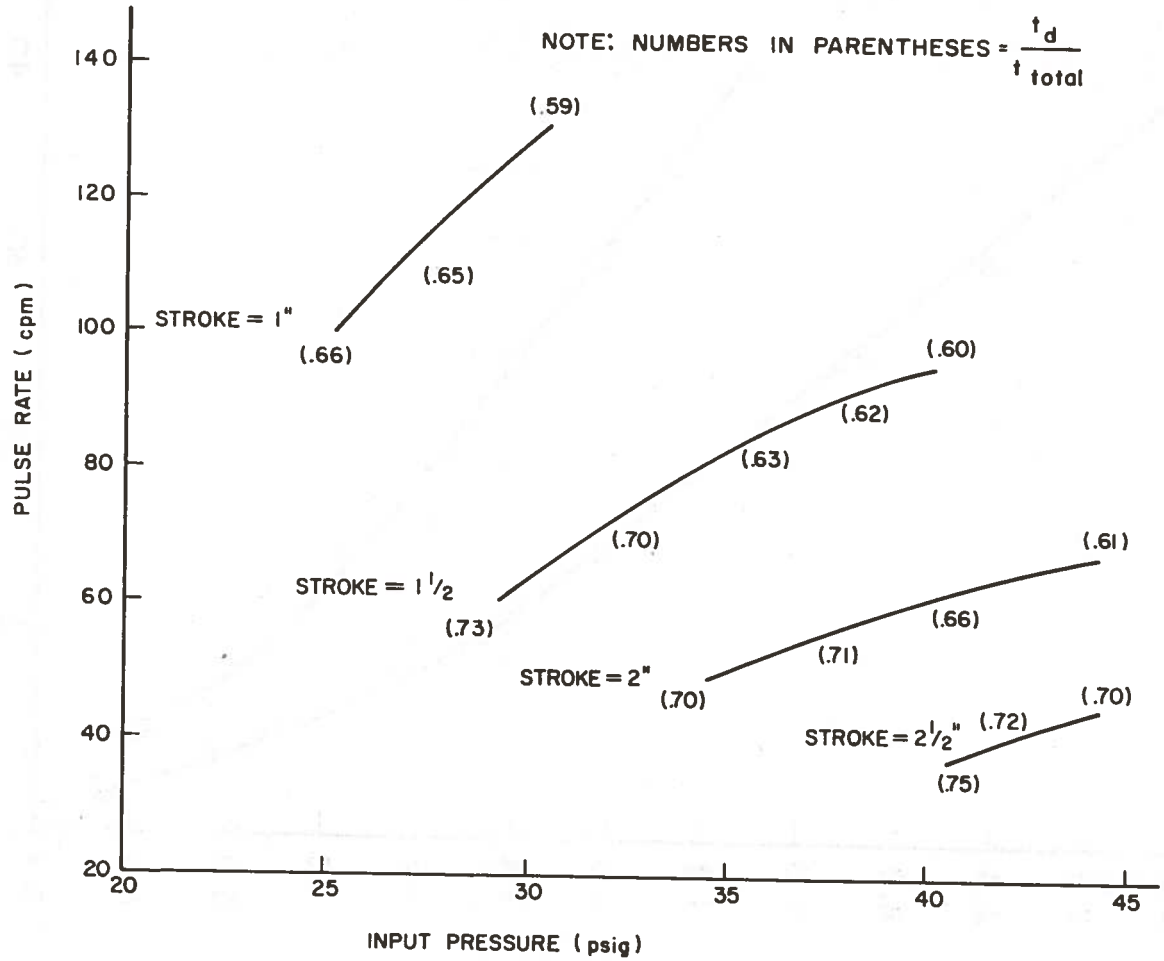

Figure 9. Operating characteristics, modified ECC with 0.063 in. power nozzle depth.

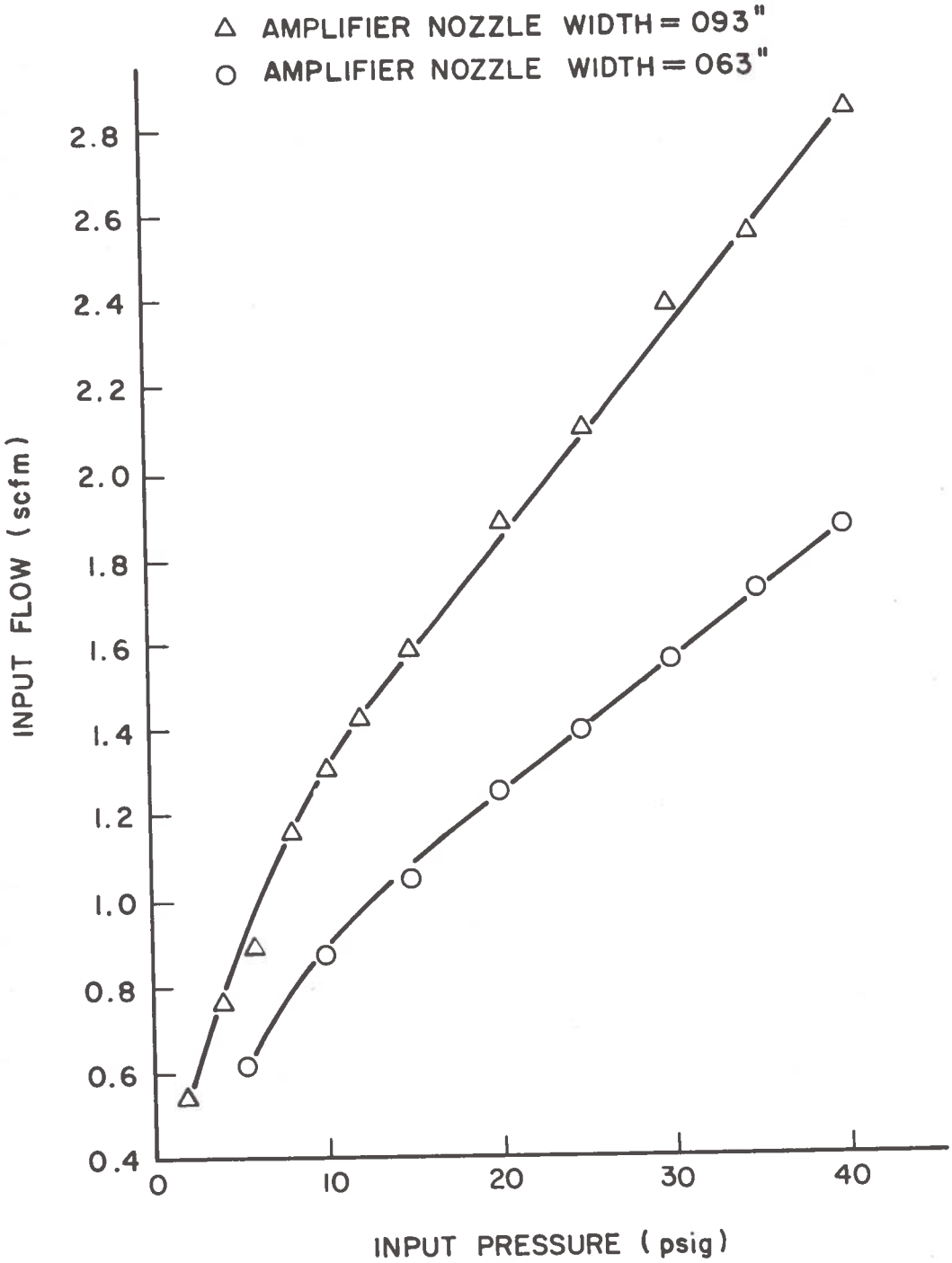

Figure 10. Pressure-flow characteristics of fluid amplifier.

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Cardiac arrest, with the associated loss of oxygenated blood circulating to the brain, swiftly results in death. Utilizing new methods of cardiopulmonary resuscitation, the heart may be restarted, circulation resumed, and the life of the individual saved. One method of cardiac resuscitation recently proposed consists in rhythmically depressing the chest, thereby squeezing the heart and forcing the blood to circulate. This method is called external cardiac compression.

A simple, rugged external cardiac compressor has been developed by the Harry Diamond Laboratories in cooperation with the Walter Reed Army Institute of Research using a fluid amplifier for its power and logic. The machine is stroke-limited and cycles on the completion of a stroke, without pause. The pulse may also be synchronized with an EKG signal. The device has only two control variables, stroke (1/2 to 2 1/2 in.) and depending on stroke, a frequency of 50 to 140 cpm. The ratio of systolic to total period is 0.7. The operational characteristics reported were obtained in tests of the compressor using a spring, whose spring constant was 33 1/3 lb/in, as a physical model of the sternum.

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