A STUDY ON THE DYNAMIC CHARACTERISTICS OF A B-1 QUICK SERVICE VALVE

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ABSTRACT

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This thesis presents the investigation of dynamic behaviour of a B-1 Quick Service Valve both analytically and experimentally. A mathematical model of discharging of the Q.S.V., when connected to constant volume in which compressed air is exhausting at a known rate of reduction pressure characteristics, was developed. With this model, the pressure-time characteristics of constant volume which is connected with or without the Q.S.V., can be predicted by using computer simulation programs. It is adequately represented in the thesis that the experimental results are in good agreement with the results which are computed in simulation programs.

The investigation of this system and computer simulation programs developed here are quite useful for examining parameters which affect the performance of the Q.S.V. After having established the relation between the parameters, tuning procedures of timing orifices are presented.

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NOMENCLATURE

a	$(D - d)/2$; mm
A, A_1, A_2	Equivalent effective orifice area or geometrical sectional area; mm^2 - cm^2
A	$\frac{V_b \alpha}{K \cdot R \sqrt{T_b}}$
ΔA	$A_1 - A_2$; mm^2
A_d	Upperside diaphragm chamber
A_e	Effective diaphragm area; mm^2
A_{ed}	Lowerside of effective diaphragm area; mm^2
A_{eu}	Upperside of effective diaphragm area; mm^2
A_{d1}	Sectional area of upper end of piston; mm^2
A_{d2}	Sectional area of lower end of piston cylinder; mm^2
A_{d3}	$(A_{d2} - A_{d4})$; mm^2
A_{d4}	Sectional area of passage provided in the lower end of piston; mm^2
A_1, A_2	Total effective diaphragm area on which P_1 and P_2 are acting, respectively; mm^2
A_D	Effective orifice area of orifice D; mm^2 - cm^2
A_{26}	Effective orifice area of control orifice A_{26}; mm^2 - cm^2
A_{27B}	Combined equivalent orifice area of check valve C_{27} and orifice B in series; mm^2 - cm^2
A_{47E}/A_{47EA}	Combined effective orifice area of check valve C_{47} and orifice E in series, or check valve C_{47}, orifice E and orifice A, all in series; mm^2 - cm^2

B_d	Lowerside of diaphragm chamber
C_d	Discharge coefficient of orifice
C_i	$A_i(2g/RT)^{\frac{1}{2}}$, $i = 1, 2, \ldots n$
C_{27}	Check valve 27
C_{47}	Check valve 47
d	Diameter of the rigid center; mm
D	Diameter of the outer diaphragm rim; mm
D_p	Diaphragm and piston assembly
D_s	Diaphragm stiffness; g/mm
F_{f1}	Static friction acting along the piston; g
F_{s2}, F_{s4}	Spring forces of check valves C_{27} and C_{47} respectively; g
g	Acceleration due to gravity; 980.665 cm/sec^2
K	$\left[\frac{\gamma g}{R}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\right]^{\frac{1}{2}}$
ℓ	Length of corrugation's generator; mm
m	Mass of gas in a volume; Kg sec^2/cm
$\dot{m}_B$	Air flow rate through the resistance A_{27B}; Kg sec/cm
$\dot{m}_D$	Air flow rate through orifice D; Kg sec/cm
$\dot{m}_E$	Air flow rate through control orifice A_{26}; Kg sec/cm
$\dot{m}_{26}$	Air flow rate through the resistance A_{47E}/A_{47EA}; Kg sec/cm
n	Polytropic exponent
ΔP	$P_1 - P_2$ or pressure difference across a air resistance; g/mm^2-Kg/cm^2
ΔP_u	Limiting pressure differential required by the diaphragm and piston to switch upwards; g/mm^2, and
ΔP_d	corresponding pressure differential for switching downwards, g/mm^2
P, P_1, P_2	Absolute pressure; Kg/cm^{2}a
P_a	Ambient pressure; 1.033 Kg/cm^2 - 10.33 g/mm^2
P_d	Downstream pressure; Kg/cm^{2}a

P_f	Final pressure; Kg/cm^2a
P_{ff}	Steady-State final pressure; Kg/cm^2a
P_o, $P(0)$	Initial pressure; Kg/cm^2a
P_u	Upstream pressure; Kg/cm^2a
R	Gas constant; 2927.6 Kg cm/^oK Kg
t	Time; sec.
T	Process temperature; ^oK
T_a	Room or ambient temperature; ^oC
T_b	Brake pipe pressure temperature; ^oK
T_f	Final temperature; ^oK
T_o, $T(0)$	Initial temperature; ^oK
T_u	Upper stream temperature; ^oK
V_b	Brake pipe volume; cm^3
V, V_1, V_2	Volume size; cm^3 - litre
W_d	Lumped weight of diaphragm assembly; g
α	$\frac{K R \sqrt{T_b} A}{V_b}$
α	$\frac{1}{2}\{\left(\frac{A_2}{A_1}\right)^2 + 1 - \beta\}$
β	$\frac{\Delta P}{P_a}$
γ	Ratio of specific heats; 1.402 for air
ρ	Air density; Kg sec^2/cm^4
ρ_a	Ambient mass density of air; Kg sec^2/cm^4
τ	Dimensionless time

CHAPTER 1

INTRODUCTION

1.1 FUNDAMENTALS OF AIR BRAKE OPERATION OF A FREIGHT TRAIN

A schematic illustration of the air brake system of a typical train operating in the continent of North America is shown in Figure 1.1.[1] This brake system is a combination of various devices, which have been designed to meet present-day train handling requirements for freight and passenger trains. The equipment can be employed for either type of service without altering the piping on the devices.

Very briefly, and referring to Figure 1.1, the system consists of a locomotive control unit situated at the head-end of the train, and a car control unit located at each and every single car. The locomotive control unit in turn consists of the compressor which supplies air at a suitable pressure as the working medium of the entire brake system, a brake valve assembly incorporating the control lever, and the brake cylinders which are responsible for actuating the brake rigging and shoes at the locomotive only. The car control unit, similarly, consists of the ABD control valve, with its combined emergency and auxiliary reservoir, as well as the brake cylinders which actuate the brake rigging and shoes of that particular car only. The locomotive control unit, and the car control units are connected together in a chain-like manner by the brake pipe which therefore runs the full length of the car.

The main controlling signal is initiated at the locomotive, and is transmitted to the cars by the brake pipe. The control valve at

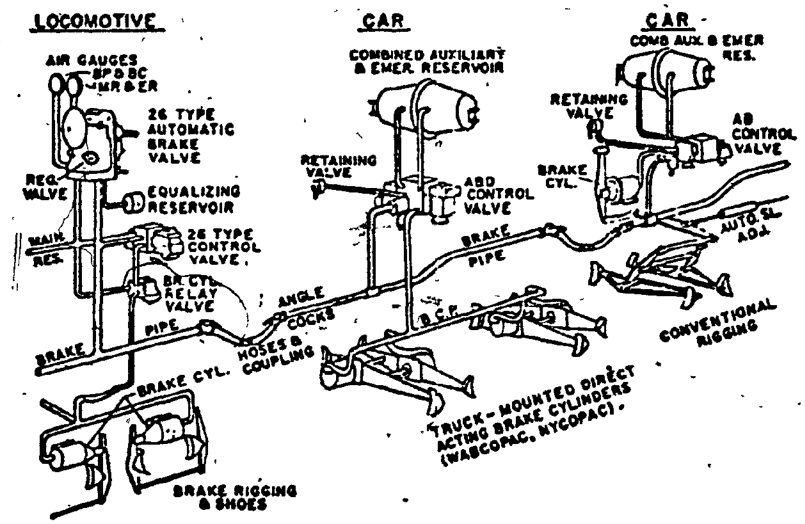

Figure 1.1 Schematic illustration of train air brake system

each car then senses the signal from the brake pipe and responds accordingly.

The air brake system operates on a pressure reduction basis. This means that when the brakes are not applied, the system is fully charged to the selected operating pressure. Subsequent reduction in the brake pipe pressure gives rise to a brake application.

The amount of pressure reduction and the rate at which it occurs are determined by the position of the locomotive brake valve handle. The brake pipe pressure is reduced at either of two rates, namely:

1.- Service rate of reduction, or

2.- Emergency rate of reduction.

This thesis is only concerned with the air brake system when it operates at a service rate of reduction of brake pipe pressure. This is obtained by placing the locomotive brake valve handle in the "Service" application zone.

For a more detailed description of the train air brake system see reference (2).

For better understanding of air brake system phenomena, typical brake pipe pressure reductions and brake cylinder pressure build-up rates at each car for full service application are shown in Figure 1.2.[3] This figure shows the brake cylinder pressure and brake pipe pressure at the 1st, 50th and 100th cars of the train, which has 101 cars of 50 ft length each. It is observed that the brake cylinder

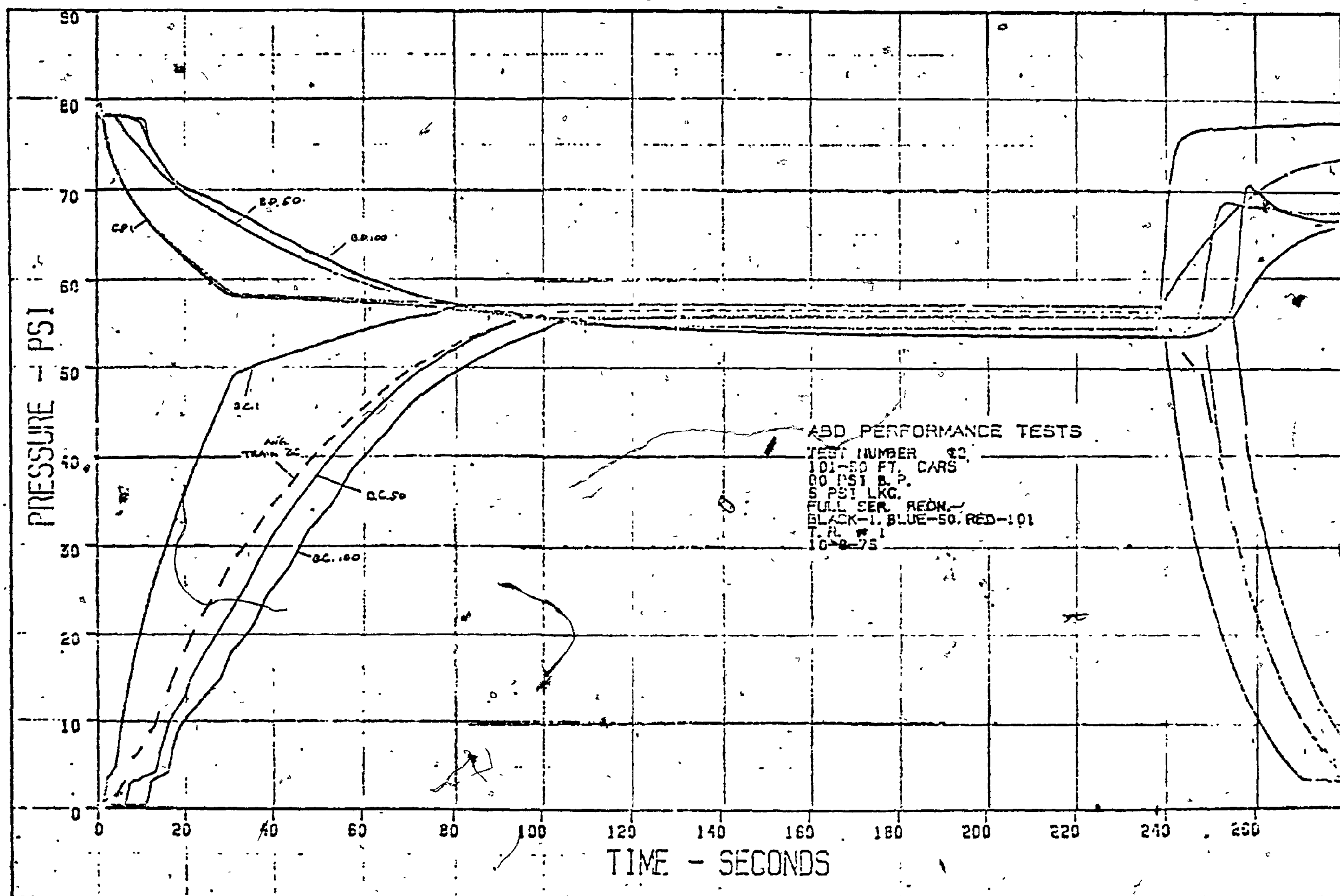

Figure 1.2 Typical brake pipe and brake cylinder pressure characteristics

pressure on the 100th car does not start to build up until approximately 12 seconds after full service application is made at the locomotive, while the head-end car is already braking at a substantial rate. Also, the brake on the last car is fully applied at about 105 seconds later. Similar delays can be observed for 50th car. These delays are due to time required for the pressure reduction signal to be transmitted down the brake pipe, which is over 5000 ft in this case. The delays are even more pronounced considering the present tendency to use more cars (say 100) of greater length (100 ft).

Figure 1.2 means that the 100th car, up to approximately 12 seconds after the brake application, is running close to the initial train speed prior to braking. Therefore, the difference in relative speed of each car and the slacking in the train increase as the braking progresses. This may result in damaged equipment. In any case, the train takes a longer time, and therefore a long stopping distance than it would if all the cars were able to respond simultaneously.

The shortening of stopping distances can be done mainly by shortening the propagation time and the time required to exhaust the compressed air from the brake pipe to achieve the desired pressure reduction. Another approach of course is to review the design of the control valve of each car to achieve quicker response. This thesis is concerned with the first approach, namely, by employing a relay valve commonly known as the B-1 Quick Service Valve (hereafter referred to simply as the Q.S.V.), manufactured and supplied by the Westinghouse Air Brake Company.

The Q.S.V. functions to respond and propagate brake pipe pressure reduction through a train to provide faster propagation time for service application by a quicker local venting of brake pipe pressure. Briefly, this valve behaves like an oscillator when it senses a pressure reduction in the brake pipe. It reduces the brake pipe pressure by a further 1 psi to 1¼ psi for each cycle of oscillation. Thus, the Q.S.V. also acts as a booster relay to ensure that the downstream of the brake pipe receives a stronger pressure reduction signal.

1.2 REVIEW OF PREVIOUS INVESTIGATION

The author has not located any scientific work done to investigate the behaviour of Q.S.V. analytically or for that matter, anything related to a fluid oscillator of a similar type. Most of the publications available on this subject related to test data released by the manufacturer or experience revealed by the users.

In 1971, JNR[4] (Japanese National Railways), presented probably one of the most extensive and organized experimental studies of a Quick Action Valve, which performs similar functions as the Q.S.V., covering detailed investigations of each structural components. Most of the experimental treatments were carried out on cases where the brake pipe takes possibly a similar form to that in the actual cars. The structure of this Quick Action Valve schematically is shown in Figure 1.3.

A typical discussion on the Q.S.V., a paper by C. Wright[5], will be examined closely. An example is shown in Figure 1.4 to illustrate the advantage of employing the Q.S.V. at each car of a

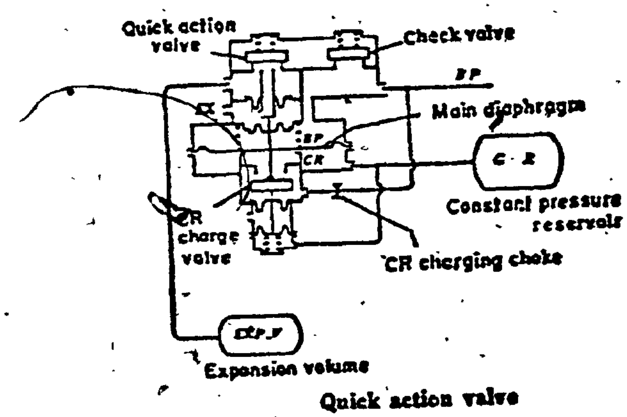

Figure 1.3 Schematic illustration of Quick Action Valve

freight train. These curves are brake cylinder pressure characteristics of train rack tests comparing the operation with and without the Q.S.V. From this figure, the brake cylinder pressure build-up time is quicker with the Q.S.V. than without (76 sec. as against 145 sec. to build up to 50 psig brake cylinder pressure). This means that a 47% reduction in time is obtainable with the Q.S.V.

Figure 1.5 from the same reference shows typical brake cylinder pressure difference between the head and rear-end cars at any instant of time for full service application. The solid line represents the brake cylinder pressure difference characteristics with the Q.S.V., and the dotted line represents the similar characteristic without it. The peak of the pressure difference between the head and rear-end cars on the train is approximately 25 psig at 45 sec. with the Q.S.V., whereas a similar peak difference value occurs slightly later but lingers on for a much longer period in the case when the Q.S.V. is not being employed.

This figure shows that there is a significant reduction in transmission time required for full service to be effected at the last car, i.e. when the difference returns to zero value. The transmission time is therefore approximately 75 sec. with the Q.S.V. as compared to 140 sec. without it. The result is therefore a decrease in the tendency for slack action which may otherwise promote shock.

In order to understand the dynamic behaviour of the entire Q.S.V. and its interaction with the brake pipe, it is essential to have an analytical understanding of the functioning of each structural component, and especially the effect of some of the geometrical parameters.

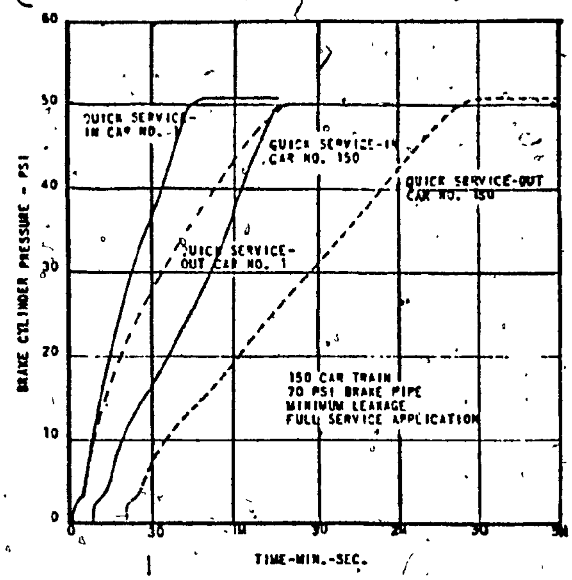

Figure 1.4 Brake cylinder pressure response with Q.S.V. and without.

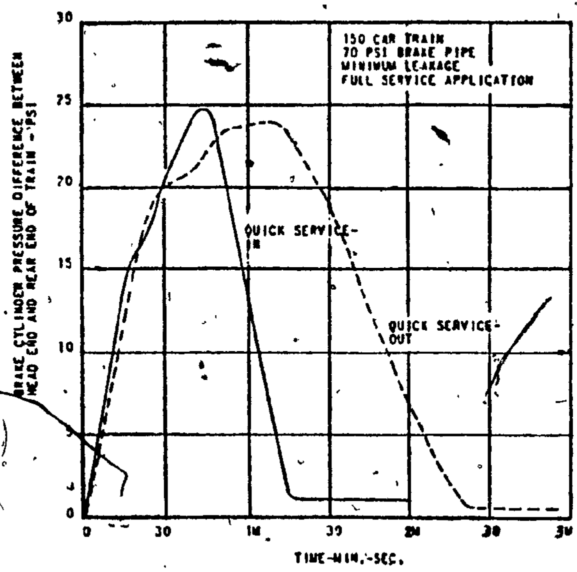

Figure 1.5 Brake cylinder pressure difference between head and rear end of train with Q.S.V. and without.

Thus, this thesis begins by looking at the mechanical and pneumatic parts of the Q.S.V. analytically, which will be discussed in detail in Chapter 2. Consequently, the whole analysis will be carried out as a fluid control system, from which the dynamic equations describing the behaviour of Q.S.V. are obtained. The solution of the dynamic equations are obtained by the digital computer using numerical techniques. The solution gives the pressure fluctuations in the brake pipe and the operating chamber volume of Q.S.V., some other pressure - time characteristics and the frequency of oscillation. The various parameters, namely, the timing orifices, brake pipe volume, and rate of reduction of brake pipe pressure, which affect the performance of Q.S.V. are considered and studied. Lastly, a design procedure is proposed, which attempts to lay down some criteria of "tuning" a Q.S.V. in order to meet performance and safety requirements.

CHAPTER 2

THEORETICAL ANALYSIS

2.1 INTRODUCTION

The objective of this Chapter is to investigate the performance of a typical Q.S.V. on a theoretical basis. It is therefore necessary to establish a dynamic model which will be exploited to simulate the system response to various rates of reduction of brake pipe pressure. The model will also be utilized to investigate how different parameters affect the performance. A detailed description of the Q.S.V. and its operating principle are discussed in Section 2.2. In Section 2.3, an investigation of switching condition of diaphragm is presented. The system equations describing the behaviour of the Q.S.V. are developed in Section 2.4. In Section 2.5, a detailed procedure of evaluation of size of resistance to air flow and the combined orifice area are discussed.

2.2 OPERATING PRINCIPLES OF THE Q.S.V.

The photographs of the Q.S.V. with its components are shown in Figures 2.1 and 2.2. Figure 2.3[6] shows a schematic diagram of this valve. It consists of an operating chamber of fixed volume V_2, a diaphragm and piston assembly D_p which opens and closes two check valves C_{27} and C_{47}, and several orifices A, B, C, D and E, whose principal function is to control the timing of the operation of this

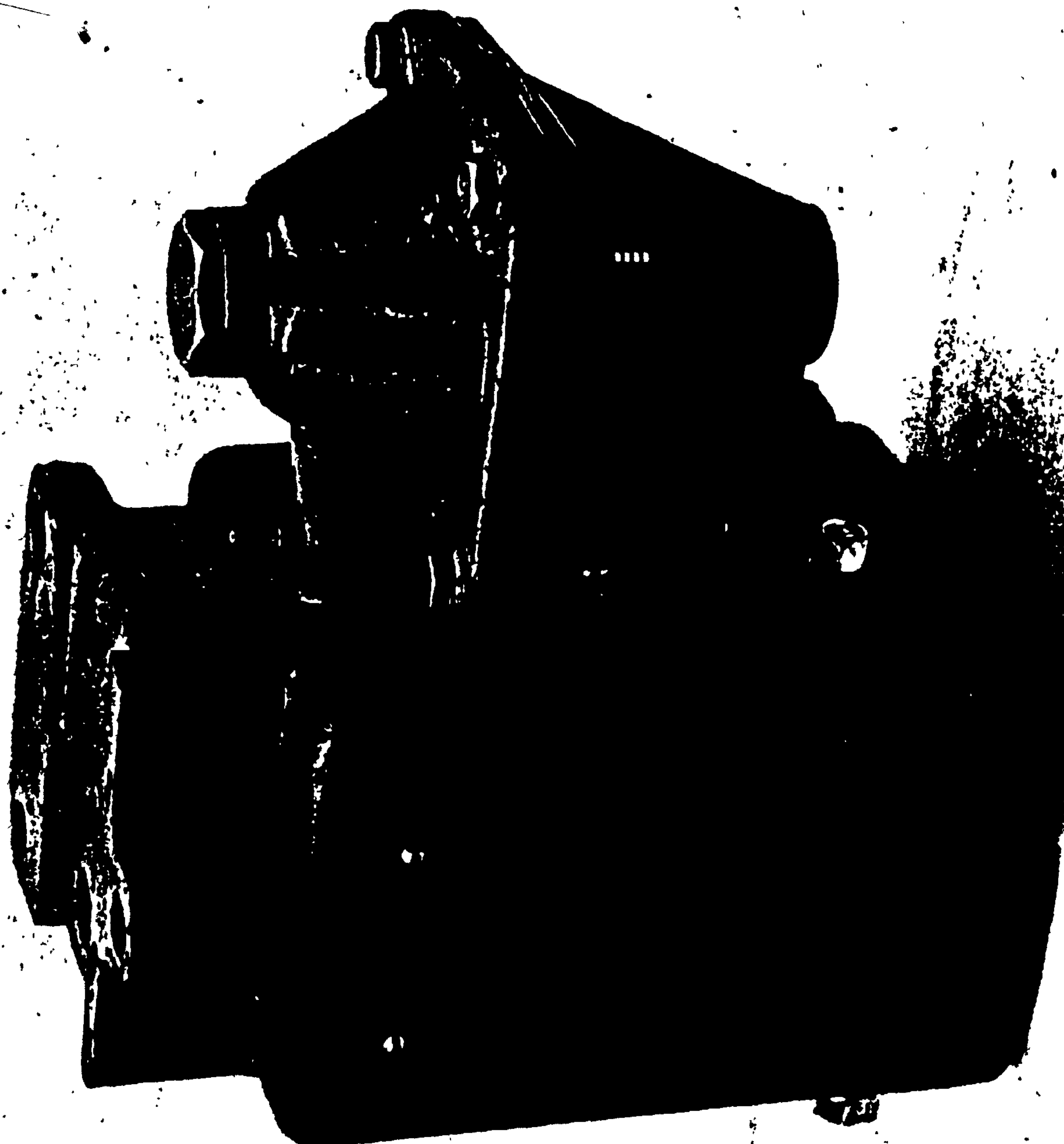

Figure 2.1 A Pictorial View of the B-1 Quick Service Valve

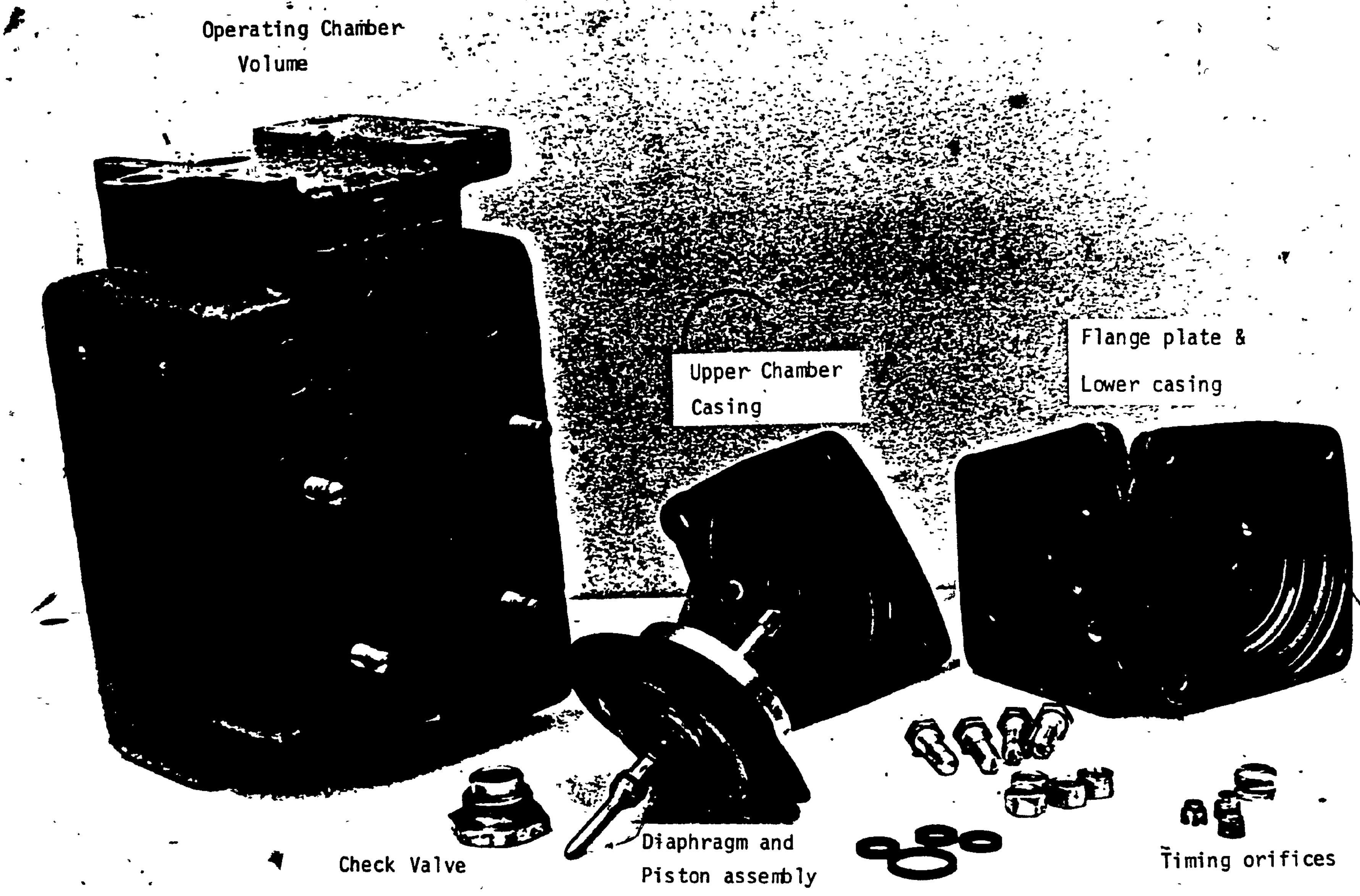

Figure 2.2 A Pictorial View of the [illegible]-1 Quick Service Valve and its components

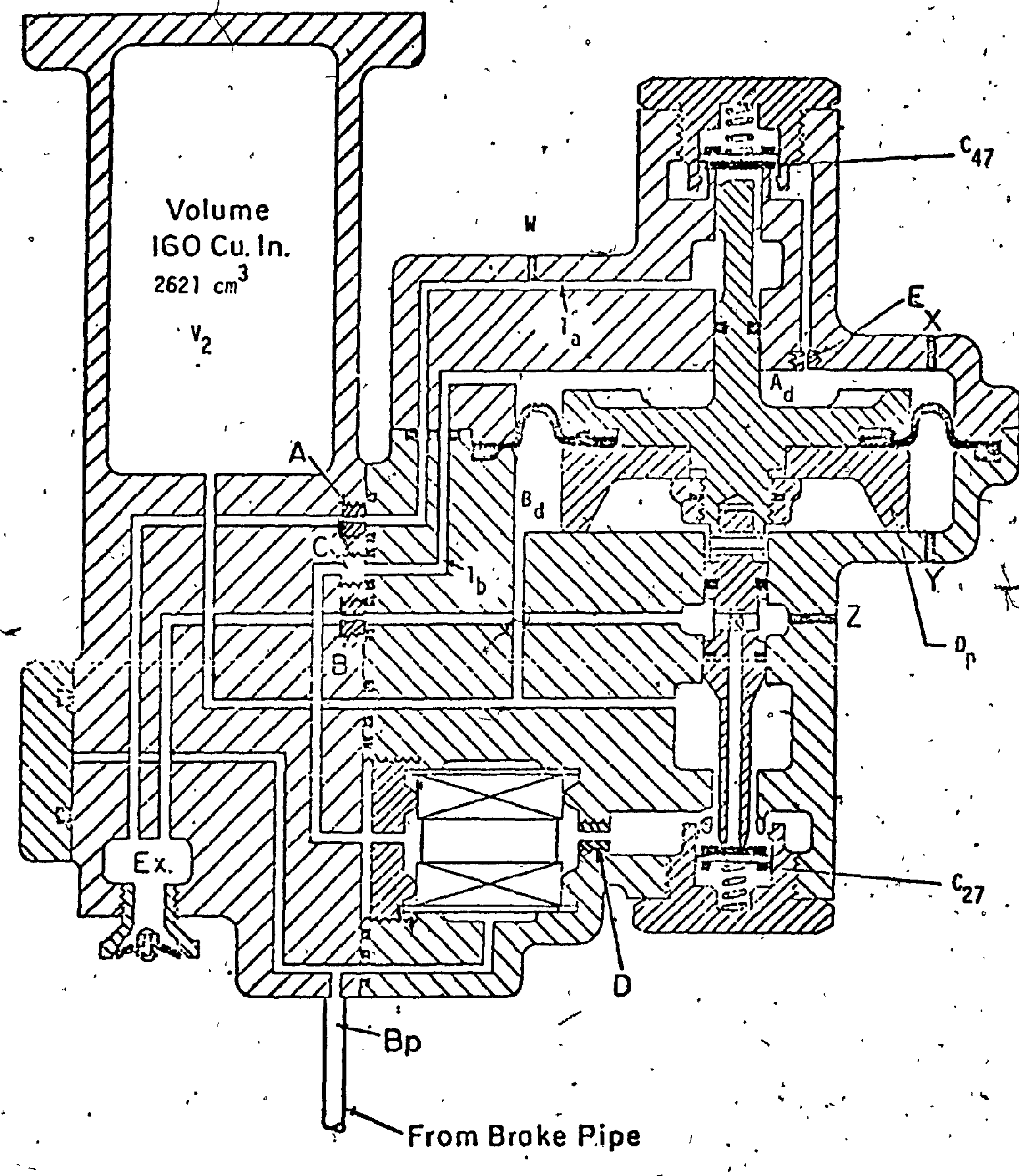

Figure 2.3 Diagrammatic drawing of B-1 Quick Service Valve (courtesy WABCO Ltd., Westinghouse Air Brake Division)

valve. The Q.S.V. is designed for use on cars of different length by varying the size of these orifices. The different schedules are reproduced in Table 2.1[6] with some editorial changes. Figure 2.4 shows the manner in which the principal components of the Q.S.V. are connected to one another as well as the relation of the valve to the brake pipe. In Figure 2.4, check valves C_{27} and C_{47} are represented simply as cam-actuated spring-return 2-way valves, with the diaphragm and piston assembly D_p furnishing the actuation under suitable pressure conditions in the diaphragm chambers A_d and B_d, respectively. Flow paths in this diagram connecting the various components are assumed to have negligible resistance to air flow. Consequently, the lower chamber B_d is in direct communication with operating chamber V_2, with a common pressure level at all times. This pressure is denoted by the symbol P_2. Similarly, in the absence of the orifice C in the flow path 1_b, the pressure P_1 in the upper diaphragm chamber A_d will be assumed to be the same as the brake pipe pressure at all times.

Under normal train running conditions during which the Q.S.V. is inactive, the operating chamber volume V_2 pressure is at the same pressure as the brake pipe. Under the combined effect of pressure difference in the two chambers, spring forces in check valves C_{27} and C_{47}, as well as static friction on the piston stem, the diaphragm takes up the lower position, thus closing check valves C_{27} and C_{47}.

If the brake pipe pressure should at any time start reducing its level at above a certain rate, either because of a controlled brake application, or because of excessive leakages in the brake system, the

TABLE 2.1

ORIFICE SCHEDULE FOR B-1 QUICK SERVICE VALVES

		VALVE PORTION				PIPE BRACKET					
		Orifice E		Orifice D		Orifice A		Orifice B		Orifice C	
Set	Car Length	Size	Dia. In.	Size	Dia. In.	Size	Dia. In.	Size	Dia. In.	Size	Dia. In.
1	Under 75 ft.* (Present)	#50 Drill Pc. 91149	.0700	1/64 Drill Pc. 522497	.0156	#46 Drill Pc. 551320	.0810	#55 Drill Pc. 517998	.0520	-	-
2	Under 75 ft.* (Proposed)	#50 Drill Pc. 91149	.0700	#76 Drill Pc. 578253	.0200	#46 Drill Pc. 551320	.0810	#52 Drill Pc. 578209	.0635	#24 Drill Pc. 578826	.1520
3	75 ft.or Longer* (Present)	#50 Drill Pc. 91149	.0700	1/64 Drill Pc. 522497	.0156	-	-	#62 Drill Pc. 94033	.0380	-	-
4	75 ft.or Longer* (Proposed)	#50 Drill Pc. 91149	.0700	#76 Drill Pc. 578253	.0200	-	-	#54 Drill Pc. 578254	.0550	-	-

* Measured along the pipe between end hose couplings.

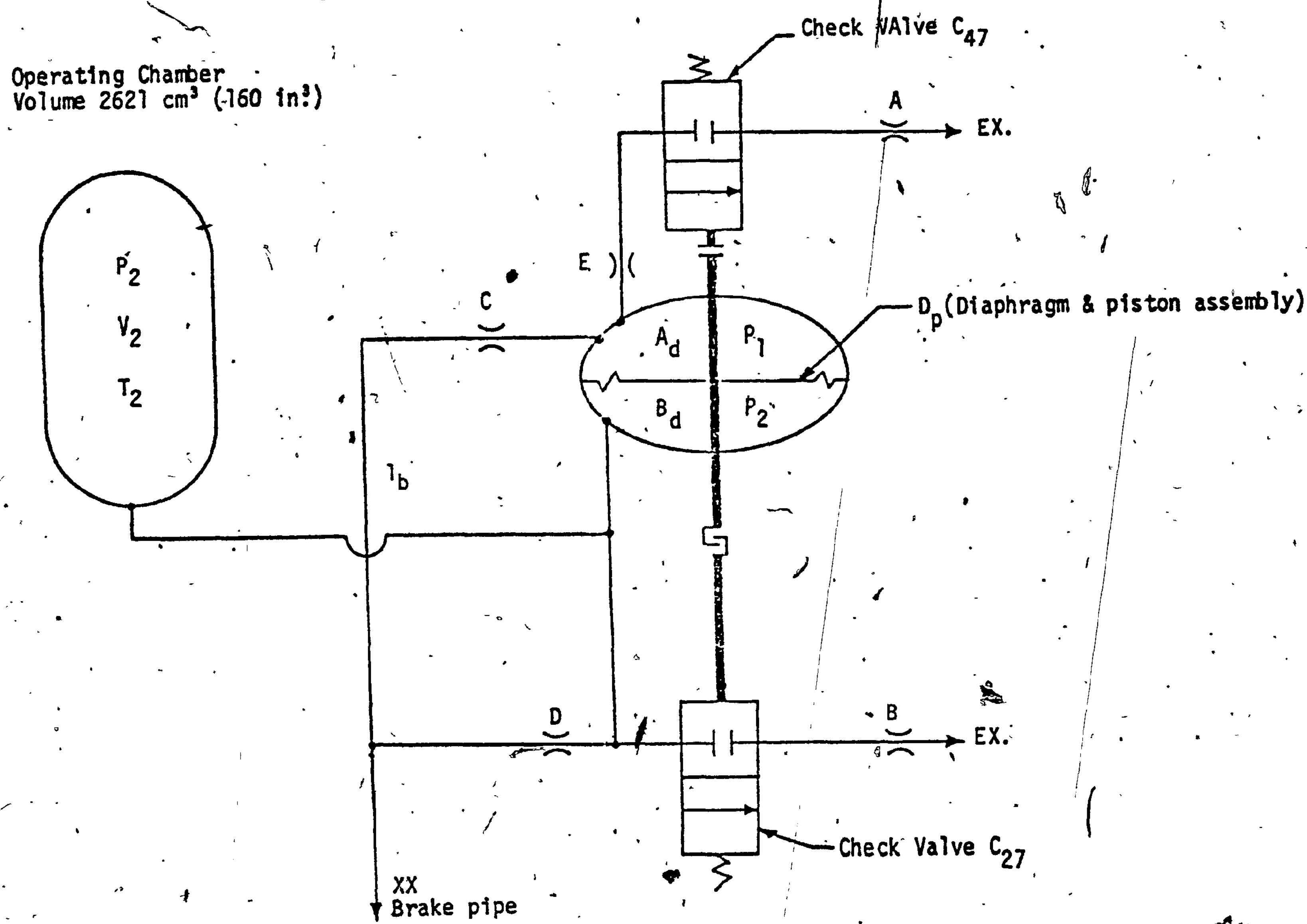

Figure 2.4 Schematic representation of B-1 Quick Service Valve

Q.S.V. will discharge as shown in Figure 2.5. Here the brake pipe is represented simply as a fixed volume V_1, and the control orifice through which the brake pipe air is vented is replaced by an orifice A_{26} as shown in this figure. The pressure P_1 in upper diaphragm chamber A_d, decreases at the same rate as the brake pipe, while pressure P_2 (in operating chamber volume V_2 and lower diaphragm chamber B_d) will discharge to the brake pipe via orifice D at a slower rate. It becomes apparent that there may come a point in time at which the pressure difference across the diaphragm is sufficient to lift the diaphragm upwards. Until this happens, the Q.S.V. is said to operate in a first mode, designated Mode 1, during which the diaphragm remains in its lowermost position.

In Mode 2 of the operation in which the diaphragm assumes an uppermost position, the Q.S.V. discharges itself as shown in Figure 2.6. The brake pipe air, as well as the air contained in the upper diaphragm A_d, now vents to the atmosphere through two main routes:

1. Through the control orifice in the brake pipe which brought along the reduction of the brake pipe pressure in the first place, and

2. Through the fluid-path l_b and l_a along which one finds three fluid resistances in series, namely, orifice E, check valve C_{47} and orifice A. For purpose of analysis, it is possible to replace this group of resistances by a single, equivalent resistance (to be designated as A_{47EA}).

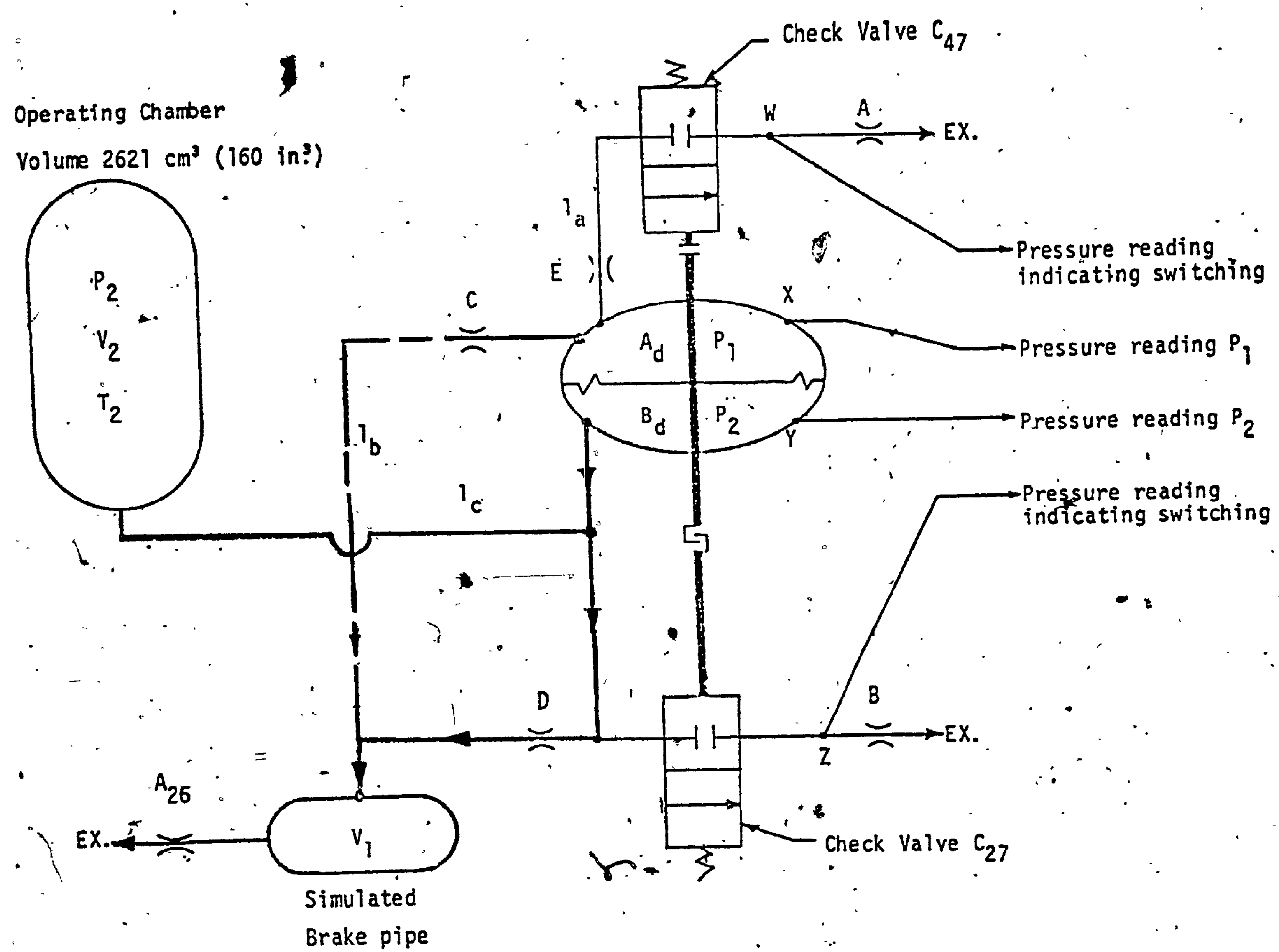

Figure 2.5 B-1 Quick Service Valve operating in Mode 1

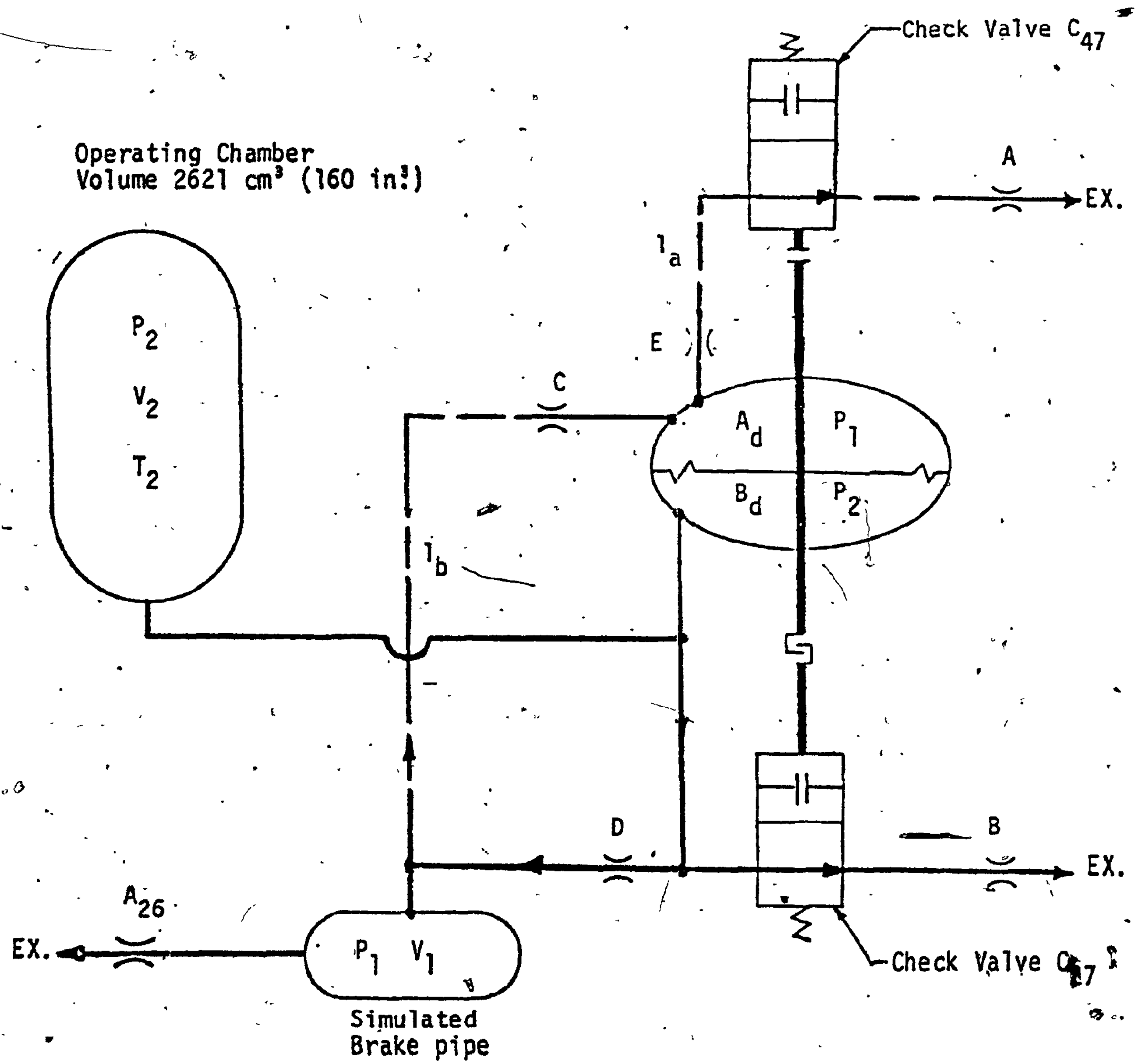

Figure 2.6 B-1 Quick Service Valve operating in Mode 2

There is a third path, i.e., via orifice D, through which a relatively small amount of air flows from the combined volume V_2 and B_d into the brake pipe. This quantity of air flow is relatively small.

Consequently, the combined volume of V_2 and B_d is considered to discharge into the atmosphere through the fluid resistance group consisting of check valve C_{27} in series with orifice B (This group may be replaced by a single, equivalent resistance, to be designated A_{27B}), and into the brake pipe.

It follows from the description of Mode 2 operation of this Q.S.V., that it is the magnitudes of the fluid resistances A_{47EA} and A_{27B} that determine the time required to build up a pressure differential sufficient to cause the diaphragm to take up its lowermost position again. Hence, the Q.S.V. oscillates between the two positions when the brake pipe pressure is reduced at a suitable rate. Notice that orifice C is omitted in this thesis in conformity with the majority of the schedules used in Table 2.1.

As a summary, Figure 2.7 illustrates diagramatically how the brake pipe pressure P_1 and pressure P_2 in the operating chamber volume V_2 varies with respect to time as the Q.S.V. discharges itself. Until the time T_1, the process corresponds to Mode 1 operation, i.e., in this stage, the pressure difference required to move the diaphragm assembly D_p upwardly is being developed due to the different rates of reduction of pressure between the operating chamber volume V_2 and brake pipe volume V_1. Subsequently, at time T_1, a sufficient pressure differential

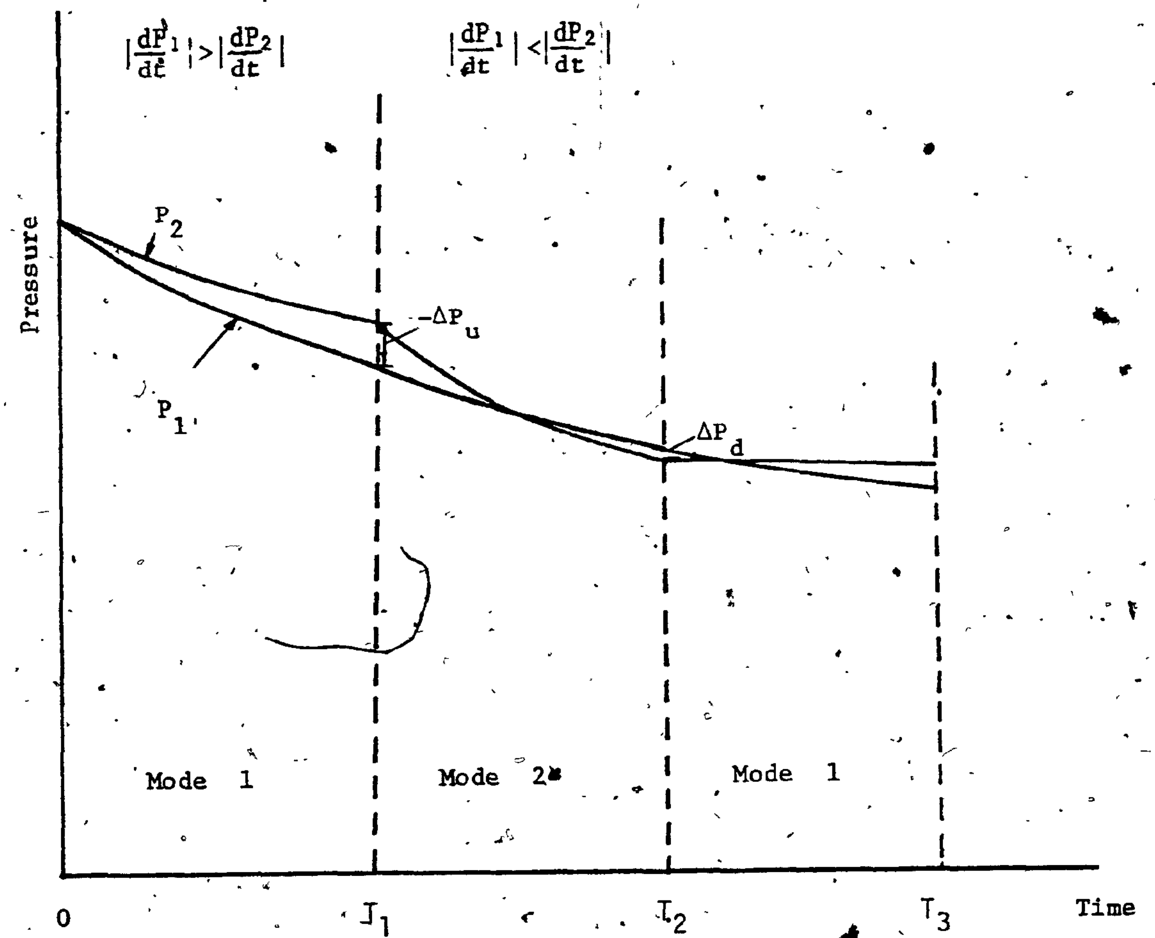

Figure 2.7 Pressure variation with P_1 and P_2 during brake application

across the diaphragm causes the diaphragm assembly to take up its uppermost position, opening the check valves C_{27} and C_{47}. After this, the process corresponds to Mode 2 operation. The pressure in operating chamber volume V_2 is gradually reduced to below that in the brake pipe volume rate. At time T_2, a sufficient pressure differential causes the diaphragm assembly to take down its lowermost position again. Hence, the pressure differential between P_1 and P_2 changes from negative to positive alternately.

For the purpose of analyzing the behaviour of Q.S.V., let us reconsider the two modes of operation of Q.S.V., as described previously. For convenience, Figure 2.5 which depicts Mode 1 operation, is simplified to Figure 2.8, showing two volumes V_2 and V_1 connected by the orifice D with V_1 discharging into the atmosphere through the control orifice A_{26}. In this diagram and for computational purposes, V_2 also includes the volume of the lower diaphragm chamber B_d, and V_1 also includes the upper diaphragm chamber A_d. The following symbols are used:

A_D	effective orifice area of orifice D; cm^2
A_{26}	effective orifice area of control orifice A_{26}; cm^2
$\dot{m}_D$	air flow rate through orifice D; Kg sec/cm
$\dot{m}_{26}$	air flow rate through orifice A_{26}; Kg sec/cm

Similarly, Figure 2.6 which depicts the Mode 2 operation, is simplified to Figure 2.9. For Mode 2 operation, the following symbols are also used:

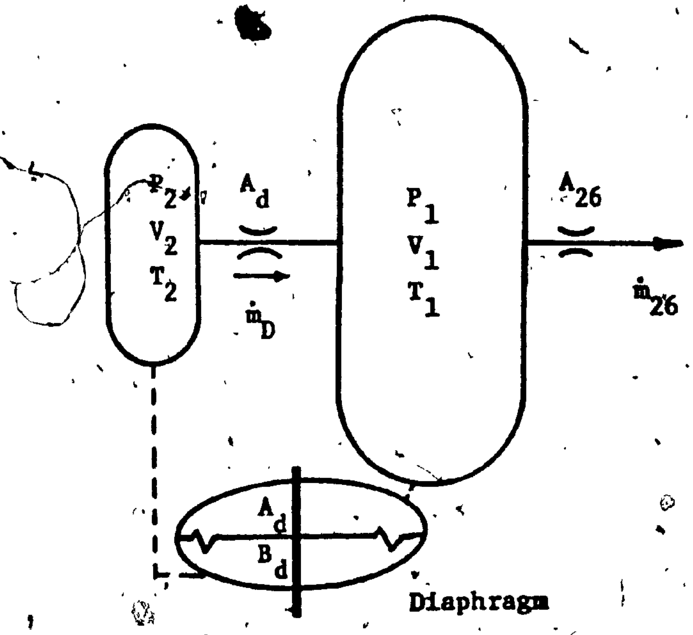

Figure 2.8 Pneumatic diagram for Mode 1 operation

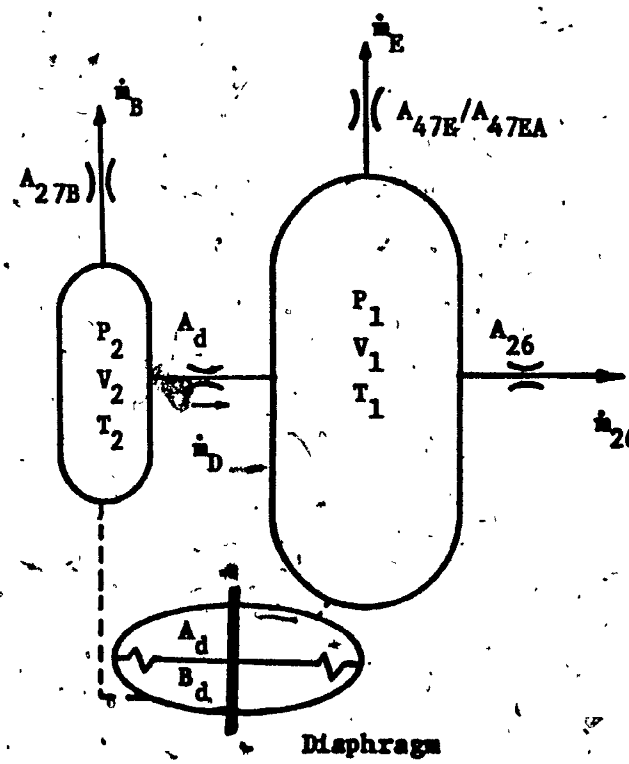

Figure 2.9 Pneumatic diagram for Mode 2 operation

A_{27B} combined effective area of check valve C_{27} and orifice B in series; cm^2

A_{47E}/A_{47EA} combined effective area of check valve C_{47} and orifice E in series; or combined effective area of check valve C_{47} and orifices E and A, all in series; cm^2

$\dot{m}_B$ air flow rate through the resistance A_{27B}; kg sec/cm

$\dot{m}_E$ air flow rate through the resistance A_{47E}/A_{47EA}; kg sec/cm.

2.3 EVALUATION OF THE CONDITION OF SWITCHING OF DIAPHRAGM

2.3.1 Introduction

As discussed in Section 2.2, the Q.S.V. operates principally in one of two principal modes depending on the position of the diaphragm. In order to establish the conditions under which the diaphragm switches from the lowermost to uppermost position and vice versa, it is necessary to examine the forces acting on the diaphragm analytically. These forces are contributed by the spring forces of the check valves, the diaphragm stiffness and the static friction acting along the side of the piston. These forces must be overcome before any switching motion can occur. The pressure forces acting on both sides of the diaphragm eventually overcome these forces and cause the switching motion to occur.

When the Q.S.V. is fully charged, the diaphragm assembly normally takes up the lowermost position. It requires an upward force balance of a sufficient magnitude to switch the diaphragm assembly to its uppermost position. Similarly, subsequent switching back requires a downward force balance.

Based on assumption (f) in Appendix 1 (i.e., the diaphragm assembly is to switch instantaneously from one position to the other once the appropriate switching condition is satisfied) only the static force balances on the diaphragm are considered in its limiting positions.

The diaphragm and piston assembly employed in the Q.S.V. is shown in Figure 2.10 with major geometrical dimensions. This figure is similar to that of the schematic shown in Figure 2.3, with the operating chamber volume being omitted. Steady-state performance of the diaphragm is obtained by a force balance. Figure 2.11(a) and Figure 2.11(b) show the pressure distribution acting on the diaphragm assembly when the diaphragm is in its lowermost and uppermost positions. Similarly, the total forces acting on the diaphram assembly (namely, pressure forces, spring forces, etc.) are shown in the free-body diaphragm of Figure 2.12(a) and Figure 2.12(b). In these figures, the following symbols are used:

F_{s2}, F_{s4} spring forces of check valves C_{27} and C_{47}, respectively; g

A_1, A_2 total effective diaphragm area on which P_1, P_2 are acting, respectively; mm^2

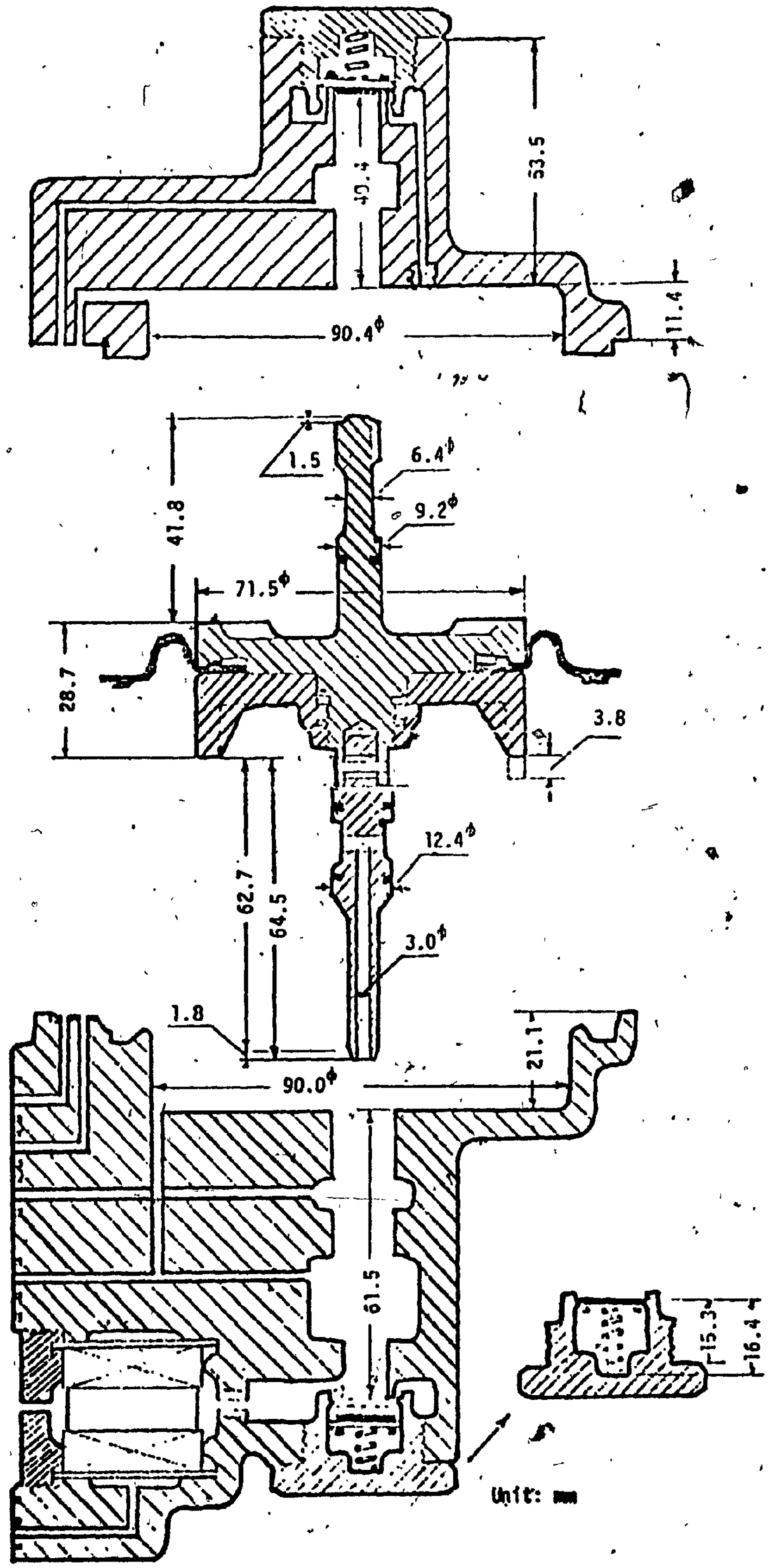

Figure 2.10 Geometrical dimension of Q.S.V.'s component

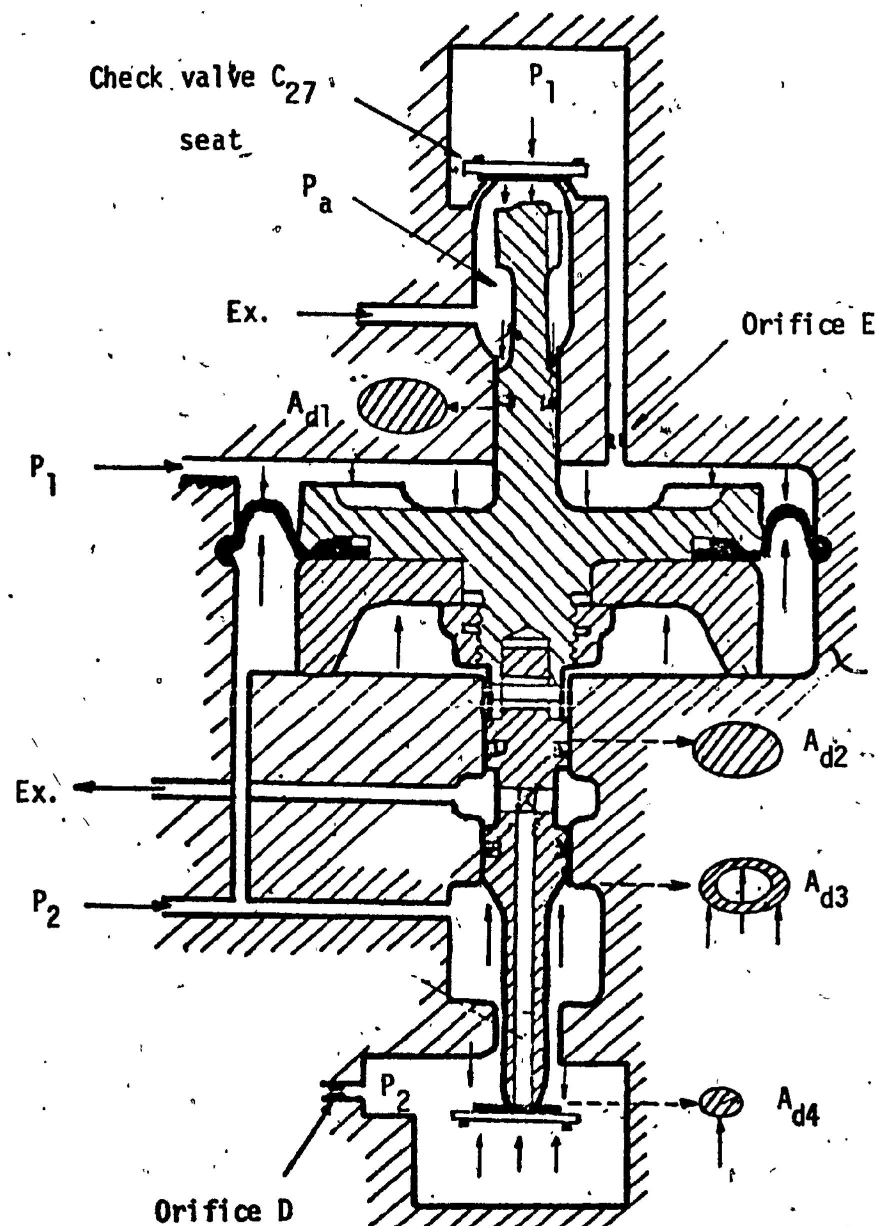

Figure 2.11(a) The pressure distribution on the diaphragm assembly which is in its lowermost position.

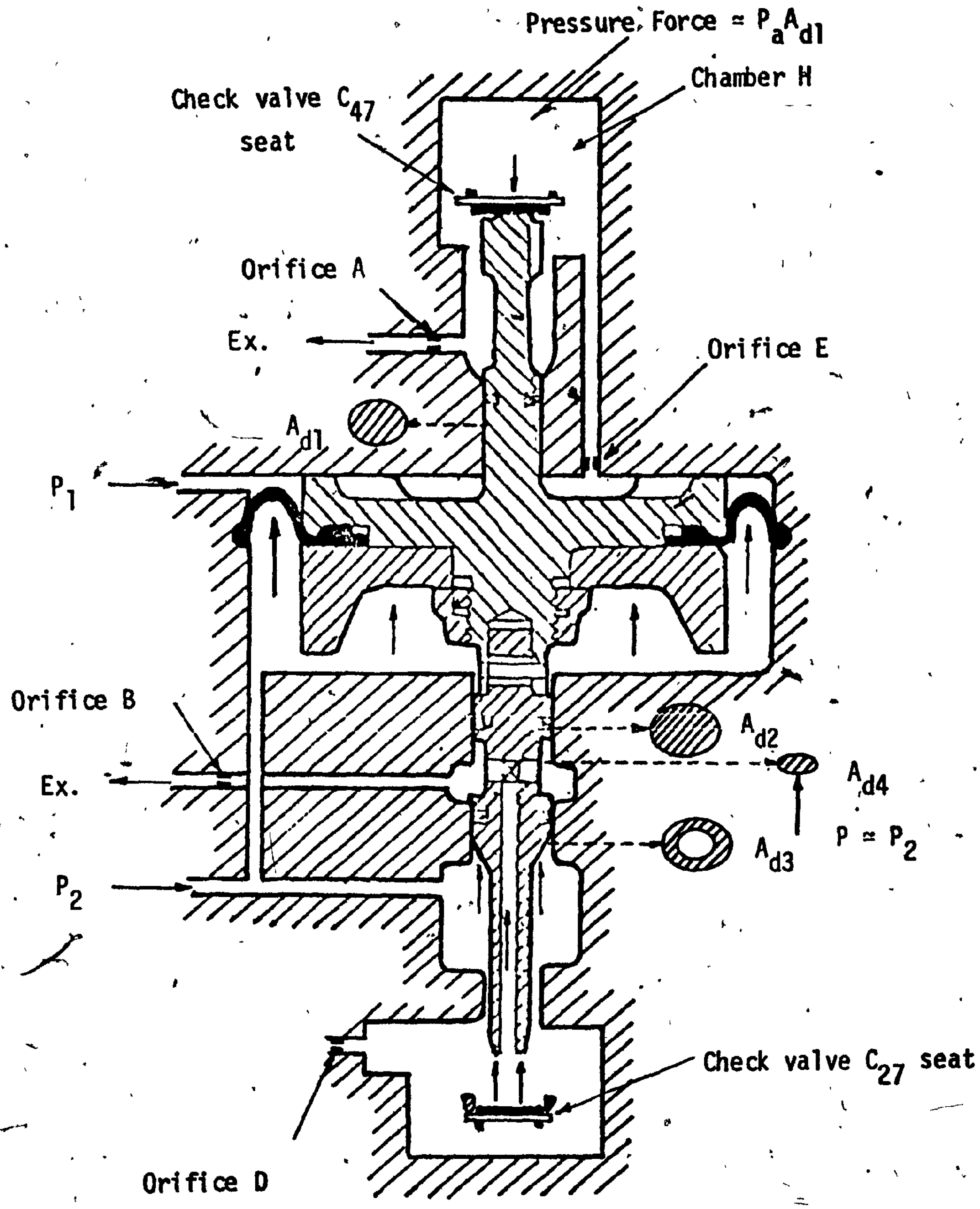

Figure 2.11(b) The pressure distribution on the diaphragm assembly which is in its uppermost position.

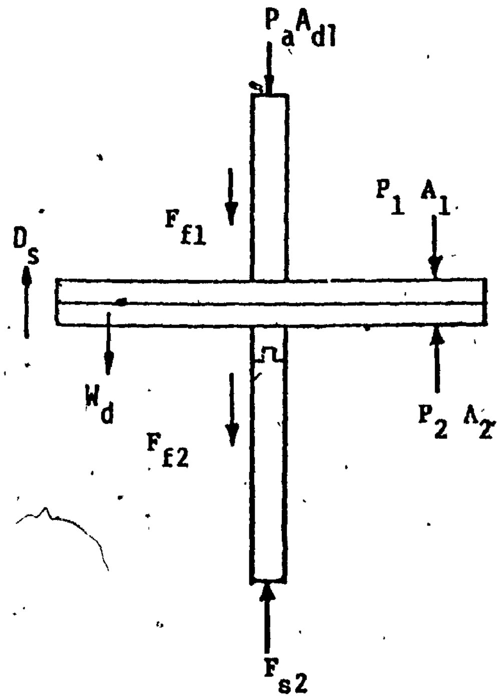

Figure 2.12(a) Free-body diagram for Mode 1 operation (diaphragm is in its lowermost position)

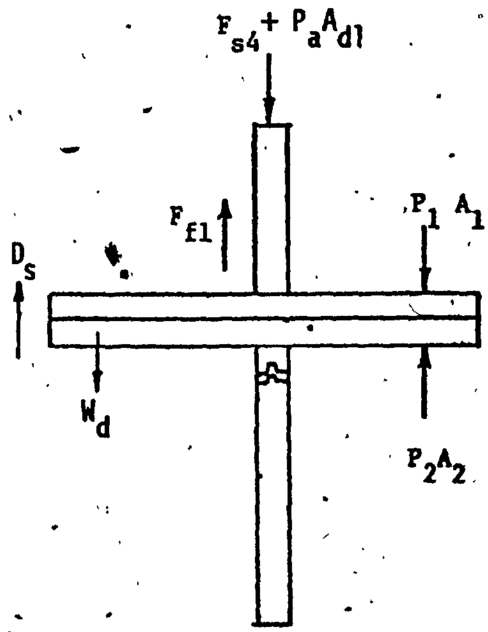

Figure 2.12(b) Free-body diagram for Mode 2 operation (diapragm is in its uppermost position)

A_{d1}	sectional area of upper end of piston; mm^2
A_{d2}	sectional area of lower end of piston cylinder; mm^2
A_{d3}	$(A_{d2} - A_{d4})$; mm^2
A_{d4}	sectional area of passage provided in the lower end of piston; mm^2
D_s	diaphragm stiffness; g/mm
P_1, P_2	pressure acting on diaphragm; g/mm^2a (absolute)
F_{f1}	static friction acting along the piston; g
P_a	ambient pressure; 10.33 g/mm^2
W_d	lumped weight of diaphragm assembly; g.

The cross-sectional areas A_{d1}, A_{d2}, A_{d3} and A_{d4}, spring forces F_{s2} and F_{s4}, diaphragm stiffness D_s and static friction F_{f1} were determined experimentally. Their values are tabulated in Appendix 2.

The effective area A_e of a diaphragm used in typical industrial control may be evaluated by using the following expression[7], with symbols as defined in Figure 2.13:

$$A_e = \frac{1}{3} \cdot \frac{\pi}{4} (D^2 + Dd + d^2) \qquad (2.3.1)$$

where D = diameter of the outer diaphragm rim; mm^2

d = diameter of the rigid center; mm^2

Since in the upper chamber D = 90.4 mm^2, and d = 71.5 mm^2, Equation (2.3.1) yields

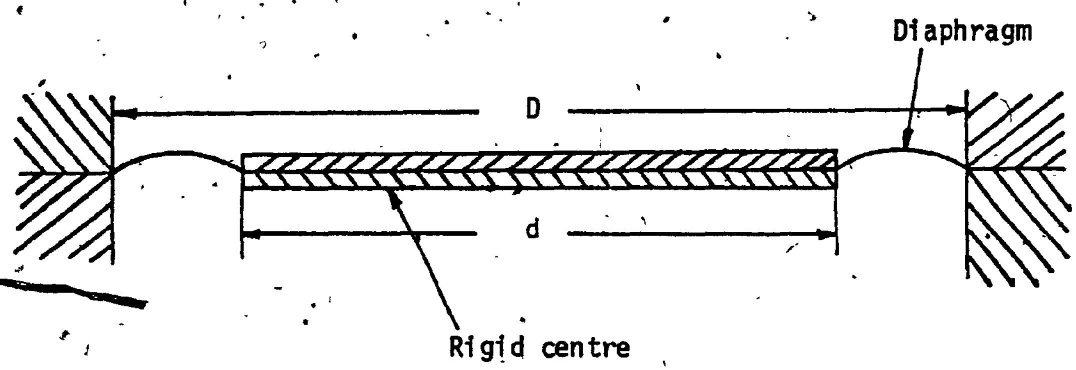

Figure 2.13 Schematic diagram of diaphragm

$$A_{eu} = 5170 \text{ mm}^2 \ (8.01 \text{ in}^2)$$

Similarly in the lower chamber D = 90.0 mm^2, and d = 71.5 mm^2. Equation (2.3.1) gives

$$A_{ed} = 5143 \text{ mm}^2 \ (7.97 \text{ in}^2)$$

According to Ref. (7), the effective diaphragm area is assumed constant if the following condition is satisfied, i.e.,

$$\ell/a \geq \pi/2 \qquad (2.3.2)$$

where ℓ = length of corrugation's generator; mm

$a = (D - d)/2$; mm.

Since in the present case, ℓ = 19.8 mm and a = 9.5 mm, the condition (2.3.2) is satisfied. Therefore the diaphragm areas A_{eu} and A_{ed} are assumed constant.

The following symbols are also employed in the evaluation of the switching conditions of the diaphragm assembly.

$$\Delta P = P_1 - P_2; \ g/mm^2 \qquad (2.3.3)$$

$$\Delta A = A_1 - A_2; \ mm^2 \qquad (2.3.4)$$

ΔP_u = the limiting pressure differential required by the diaphragm and piston to switch upwards; g/mm^2, and

ΔP_d = the corresponding pressure differential for switching downwards; g/mm^2.

The force balance equations are obtained as follows.

2.3.2 Force Balance Required to Move the Diaphragm Assembly Upwards from the Lowermost Position.

Referring to Figure 2.11(a), the effective diaphragm area employed in the Q.S.V. on which the pressure P_1 acts, is:

$$A_1 = (A_{eu} - A_{d1}) = 5104 \text{ mm}^2$$

Thus the pressure force acting on the upperside of the diaphragm assembly is:

$$\text{Pressure Force} = P_1A_1 + P_aA_{d1}$$

Similarly the effective diaphragm area for the lowerside on which the pressure P_2 acts, is:

$$A_2 = (A_{ed} - A_{d2}) + A_{d3} + A_{d4} = 5143 \text{ mm}^2$$

Thus, the pressure force acting on the lowerside of the diaphragm assembly is:

$$\text{Pressure Force} = P_2A_2$$

Referring to Figure 2.12(a), the switching condition is:

$$P_2A_2 + D_S + F_{S2} \geq P_1A_1 + P_aA_{d1} + F_{f1} + W_d \qquad (2.3.5)$$

Substituting Equations (2.3.3) and (2.3.4) into Equation (2.3.5) and after arranging the equation, yields

$$\Delta P_u \leq \frac{D_S + F_{S2} - F_{f1} - W_d - P_aA_{d1}}{A_2} - \frac{\Delta A}{A_2} P_1 \qquad (2.3.6)$$

where the symbols are as defined in Section 2.3.1.

The magnitude of the R.H.S. of Equation (2.3.6) is always observed to be negative. Hence, its absolute value becomes:

$$|\Delta P_u| \geq \frac{-D_s - F_{s2} + F_{f1} + W_d + P_a A_{d1}}{A_2} + \frac{\Delta A}{A_2} P_1 \qquad (2.3.7)$$

2.3.3 Force Balance Required to Move the Diaphragm Assembly Downward from the Uppermost Position.

Referring to Figure 2.11(b), in this case, the pressure P_1 is exhausted to atmosphere through the orifice E and check valve C_{47}, and then orifice A. Consequently, the pressure in chamber H is no longer at atmospheric pressure. However, the pressure in chamber H may be assumed to be very close to atmospheric pressure due to the presence of orifice E and especially when the orifice A is not present. Similarly, the pressure in the passage provided in the lower end of the piston may be assumed to be P_2 because of the presence of orifice B (see curve Z of Figure 4.3 in Section 4.3.1).

Thus, the effective area of the diaphragm assembly on which the pressure P_1 acts, is

$$A_1 = A_{eu} - A_{d1} = 5104 \text{ mm}^2$$

The pressure force acting on the upper side of the diaphragm assembly is

$$\text{Pressure Force} = P_1 A_1 + P_a A_{d1}$$

Similarly, the effective diaphragm area on which pressure P_2 acts, is

$$A_2 = (A_{ed} - A_{d2}) + A_{d3} + A_{d4} = 5143 \text{ mm}^2$$

Thus, the pressure force due to P_2 is:

$$\text{Pressure Force} = P_2\{(A_{ed} - A_{d2}) + A_{d3} + A_{d4}\}$$

Referring to Figure 2.12(b), the required switching condition is:

$$P_1A_1 + F_{s4} + W_d + P_aA_{d1} \geq P_2A_2 + D_s + F_{f1} \qquad (2.3.8)$$

where the symbols are as defined in Section 2.3.1. Substituting Equations (2.3.3) and (2.3.4) into Equation (2.3.8) and after rearranging Equation (2.3.8), yields

$$\Delta P_d \geq \frac{D_s + F_{f1} - F_{s4} - W_d - P_aA_{d1}}{A_2} - \frac{\Delta A}{A_2} P_1 \qquad (2.3.9)$$

It is seen that the switching conditions characteristic equations, Equations (2.3.7) and (2.3.9) are linear functions of the instantaneous value of the brake pipe pressure P_1.

2.4 SYSTEM EQUATIONS

As outlined in Section 2.2, the entire model consists of two main portions, one of which is the modelling of the pneumatic discharge of the system during Mode 1 operation, the other, the modelling of the pneumatic discharge during Mode 2 operation. The system equations describing the pressure-time characteristics are derived in this Section.

2.4.1 Mode 1 Operation

Referring to the Mode 1 operation as illustrated in Figure 2.8, the pressure difference due to the variation of mass flow rate in and out between the two volumes V_1 and V_2 (as a matter of fact, the pressure difference between the two volumes is the same as that of across the diaphragm), and making a mass flow rate balance in and out of each volume, we have:

$$\frac{dm_1}{dt} = \dot{m}_D - \dot{m}_{26} \qquad (2.4.1)$$

for the volume V_1. Similarly,

$$\frac{dm_2}{dt} = - \dot{m}_D \qquad (2.4.2)$$

for the volume V_2.

It is shown in Equation (A1.9) of Appendix 1 that the variation of pressure in a discharging volume is given by

$$\frac{dP}{dt} = \frac{nRT(0)}{V} \left(\frac{P}{P(0)}\right)^{\frac{n-1}{n}} \cdot \frac{dm}{dt} \qquad (A1.9)$$

Applying Equations (2.4.1) and (2.4.2) into Equation (A1.9), we have the following equations to describe the Mode 1 operation:

$$\frac{dP_1}{dt} = \frac{nRT(0)}{V_1} \left(\frac{P_1}{P_1(0)}\right)^{\frac{n-1}{n}} (\dot{m}_D - \dot{m}_{26}) \qquad (2.4.3)$$

for the volume V_1. Similarly,

$$\frac{dP_2}{dt} = \frac{-nRT(0)}{V_2} \left(\frac{P_2}{P_2(0)}\right)^{\frac{n-1}{n}} (\dot{m}_D) \qquad (2.4.4)$$

for the volume V_2. It is shown in Appendix 1 that the mass flow rate equations are given by

$$\frac{dm}{dt} = \frac{C_d A P_u}{\sqrt{RT_u}} \sqrt{\frac{2\gamma g}{(\gamma-1)} \left[\left(\frac{P_d}{P_u}\right)^{2/\gamma} - \left(\frac{P_d}{P_u}\right)^{(\gamma+1)/\gamma}\right]} \quad \text{(A1.10)}$$

for subsonic flow, and

$$\frac{dm}{dt} = \frac{C_d A P_u}{\sqrt{RT_u}} \sqrt{\gamma g \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad \text{(A1.11)}$$

for critical flow condition.

2.4.2 Mode 2 Operation

Referring to Figure 2.9, the mass flow rate balance is obtained in the same manner as in Section 2.4.1:

$$\frac{dm_1}{dt} = \dot{m}_D - \dot{m}_{26} - \dot{m}_E \quad (2.4.5)$$

for the volume V_1,

and

$$\frac{dm_2}{dt} = - \dot{m}_D - \dot{m}_B \quad (2.4.6)$$

for the volume V_2,

where $\dot{m}_B$ = mass flow rate through the resistance A_{27B}; kg sec/cm, and

$\dot{m}_E$ = mass flow rate through the resistance A_{47EA} or resistance A_{47E}; kg sec/cm.

Substituting Equations (2.4.5) and (2.4.6) into Equation (A1.9), we have

$$\frac{dP_1}{dt} = \frac{nRT(0)}{V_1} \left(\frac{P_1}{P_1(0)}\right)^{\frac{n-1}{n}} (\dot{m}_D - \dot{m}_{26} - \dot{m}_E) \quad (2.4.7)$$

for the volume V_1.

Similarly,

$$\frac{dP_2}{dt} = \frac{nRT(0)}{V_2} \left(\frac{P_2}{P_2(0)}\right)^{\frac{n-1}{n}} (\dot{m}_D - \dot{m}_B). \qquad (2.4.8)$$

for the volume V_2.

2.5 EVALUATION OF SIZE OF RESISTANCE TO AIR FLOW

2.5.1 Discharging Method

For the sake of simplicity, a number of air resistances are treated as equivalent orifices. The experimental technique utilized in evaluating equivalent orifice sizes consists of discharging a known volume of air through the air resistance in question and observing the time interval required for the pressure in the volume to drop from its initial pressure, P_o, to a final pressure, P_f. The air temperature inside the reservoir decreases, due to expansion of air, while a discharging process takes place. However, after the discharging process, the compressed air temperature in the reservoir may return to ambient temperature due to the transfer of heat through the reservoir. The steady-state pressure P_{ff} attained at this state is utilized in Equation (2.5.1)[8]:

$$A = 198\, V \frac{1}{t} \log_{10} \frac{P_o + 1.03}{P_{ff} + 1.03} \sqrt{\frac{1}{T_a + 273}} \;(\text{mm}^2) \qquad (2.5.1)$$

where A = Equivalent effective orifice area; mm^2

V = Known tank volume; in litres

P_o = Initial pressure; 5.0 Kg/cm^{2}g

P_{ff} = Steady-state final pressure; approximately 1.0 Kg/cm^{2}g

T_a = Room or ambient temperature; in degrees Celsius (°C)

This expression may be obtained by eliminating α from Equation (A7.3) and Equation (A7.4) in Appendix 7 and by substituting numerical values for the constants. It should be noted that since expression (2.5.1) applies only to sonic discharge conditions, the experiment has to be so arranged that sonic flow takes place throughout the entire pressure range right down to P_o.

Equation (2.5.1) has been examined experimentally with known geometrical area square-edge orifice in order to verify the accuracy of the result calculated. The result is outlined in Appendix 3.

2.5.2. Consideration of Air Resistances in Series

For the purpose of simplicity, a system of pneumatic resistances connected in series may be assumed to be equivalent to a single orifice. The detailed derivation of this is outlined in Appendix 4.

For example, consider a situation in which two pneumatic resistances are in series. This is shown schematically in Figure 2.14. It is shown in Equation (A4.6) of Appendix 4 that the combined equivalent orifice is given by

$$A_t = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2 \frac{1}{(1 + x_2)}}} \qquad (2.5.2)$$

where x_2 is as defined by Equation (A4.11) in Appendix 4.

Now equation (2.5.2) may be simplified as follows if it is assured that $x_2 \ll 1$,

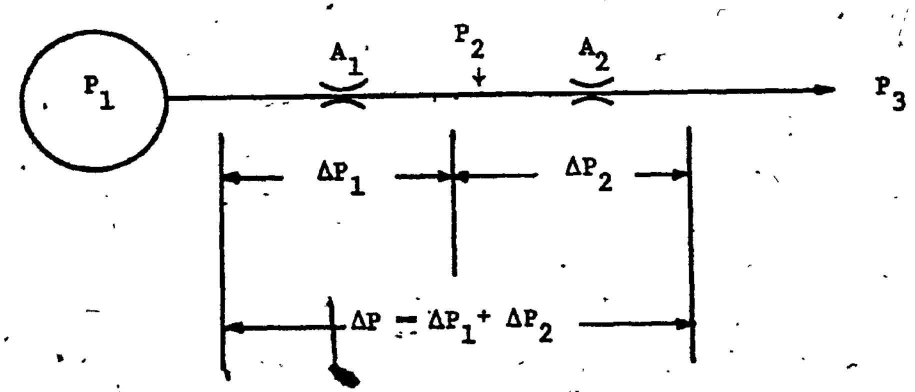

Figure 2.14 Schematic illustration of orifices in series

i.e.
$$A_t' = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}} \tag{2.5.3}$$

This is a much simpler expression to use for calculating the equivalent orifice area of two resistances in series, if somewhat less accurate when compared with Equation (2.5.2). The degree of accuracy is estimated by studying the ratio

$$\frac{A_t'}{A_t} = \frac{\sqrt{1 + \left(\frac{A_2}{A_1}\right)^2 /(1 + x_2)}}{\sqrt{1 + \left(\frac{A_2}{A_1}\right)^2}} \tag{2.5.4}$$

The relation of this ratio $\frac{A_t'}{A_t}$ to the pressure drop (measured in multiples of atmospheric pressure, i.e. $\frac{\Delta P}{P_a}$) is shown in Figure 2.15, with the component area ratio $\frac{A_2}{A_1}$ as a parameter. It is seen that for values of pressure drop of 5 atmospheres, the discrepancy between A_t' and A_t is less than 20% as long as the area ratio is outside the following range:

$$0.9 < \frac{A_2}{A_1} < 3.5$$

When Equation (2.5.3) is used for two orifices connected in series, as long as the individual effective orifice area ratio is outside $0.9 < A_2/A_1 < 3.5$, the combined equivalent orifice area can be assumed for the series in terms of the individual effective orifice area.

For three and four orifices connected in series, the combined equivalent effective orifice can be similarly determined starting from Equation (2.5.2):

$$A_{t3} = \frac{A'_t\ A_3}{\sqrt{A'^2_t + A_3^2}} = \frac{A_1\ A_2\ A_3}{\sqrt{(A_1A_2)^2 + (A_2A_3)^2 + (A_1A_3)^2}} \qquad (2.5.5)$$

for three orifices connected in series.

Similarly

$$A_{t4} = \frac{A_{t3}\ A_4}{\sqrt{A_{t3}^2 + A_4^2}}$$

$$= \frac{A_1\ A_2\ A_3\ A_4}{\sqrt{(A_1A_2A_3)^2 + (A_2A_3A_4)^2 + (A_1A_3A_4)^2 + (A_1A_2A_4)^2}} \qquad (2.5.6)$$

for four orifices connected in series.

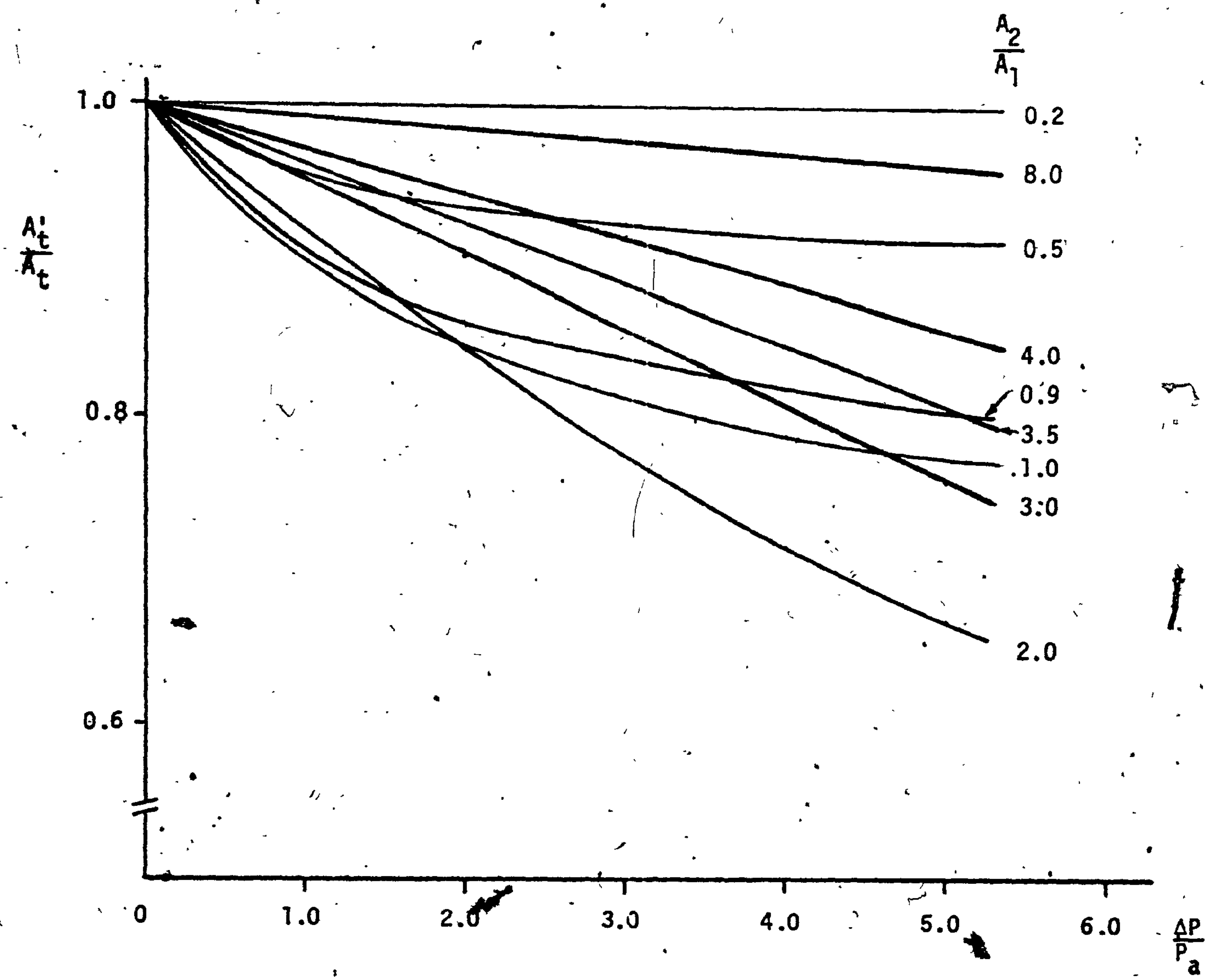

Figure 2.15 Relation of ratio A'_t/A_t to the pressure drop $\Delta P/P_a$

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 GENERAL

An experimental investigation and verification of the Q.S.V. assembly was carried out to verify the validity of the theoretical relationships derived in Chapter 2. It was decided to utilize a reservoir V_1 to simulate the volume of air in the brake pipe corresponding to the length of three or four typical cars of 50 or 75 feet long. Although a reservoir does not behave exactly like a brake pipe which is generally 1¼" in internal diameter, it is believed that the results obtained from this investigation will serve to provide adequate modelling of the dynamic characteristics of this valve.

Tests have been carried out on the Q.S.V. for a number of different timing orifices, reservoir sizes and at different rates of reduction of pressure in the reservoir.

3.2 EXPERIMENTAL SET-UP

The experimental arrangement is shown in Figure 3.1 and a schematic arrangement is shown in Figure 3.2. Compressed air is adjusted to a desired pressure by a pressure regulator and is supplied to the reservoir, V_1, through the control valve 1. A control valve 3, also manually operated, is used to remotely control the another valve 2,

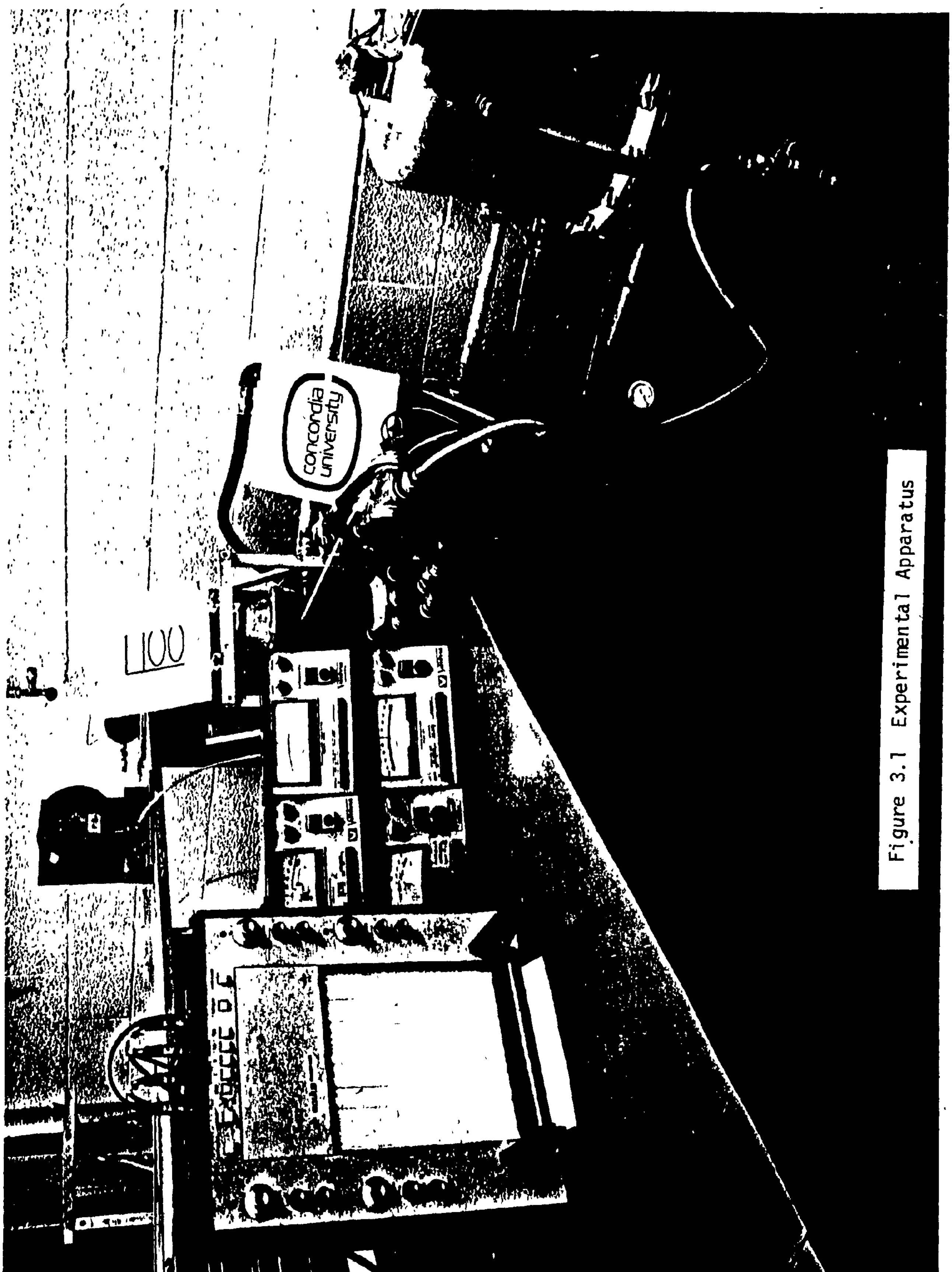

Figure 3.1 Experimental Apparatus

EXPERIMENTAL SET-UP

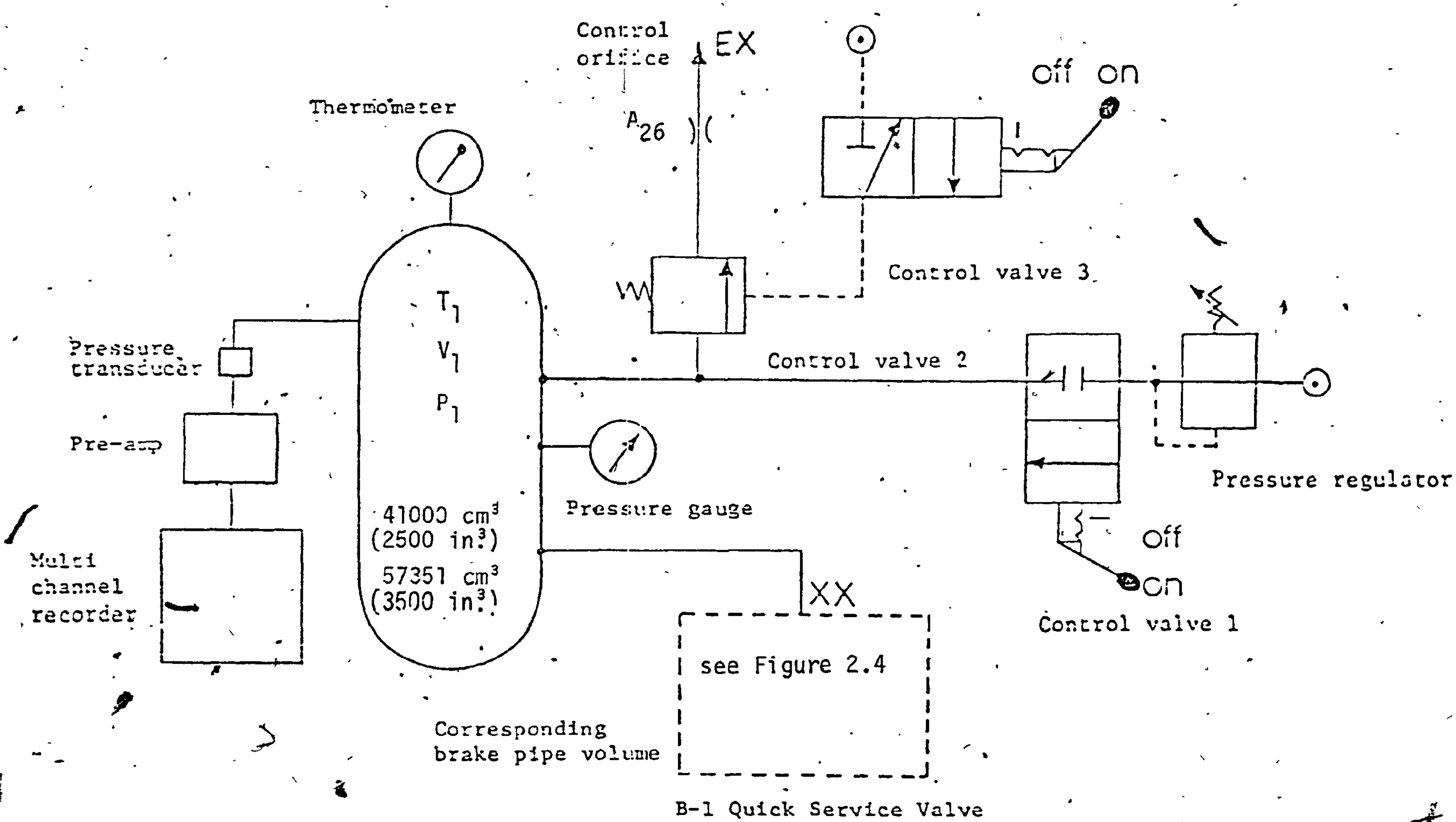

Figure 3.2 Laboratory set-up for testing the B-1 Quick Service Valve

the function of which is to vent the compressed air in the reservoir V_1, through a control orifice A_{26} to the atmosphere. Proper choice of the size of this orifice will then provide different rates of pressure reduction. The temperature of compressed air is inside the reservoir V_1 and is measured by using a Copper-Constantin thermocouple with a digital readout. In order to measure a pressure inside the Q.S.V., pressure transducers are inserted at the following locations, as shown in Figure 2.3 and Figure 2.5.

Point X	To provide pressure reading P_1 in the upper diaphragm chamber A_d.
Point Y	To provide pressure reading P_2 in the lower diaphragm chamber B_d.
Point Z	To provide a pressure reading which is either equal to P_2 when the check valve C_{27} is open (indicating that the diaphragm and piston are at the uppermost position), or equal to atmospheric pressure when the valve is cut-off (indicating that the diaphragm and piston are at the lowermost position). This pressure reading provides fairly accurate switching times of the valve and therefore, conveniently replaces a displacement reading of the piston.
Point W -	To provide a pressure reading when the check valve C_{47} is cut-off, indicating that the diaphragm assembly is at its lowermost position.

A second experimental set-up is also used for the evaluation of the equivalent orifice area of air resistance, namely check valves C_{27} and C_{47} in fully opened conditions together with the orifices A, B or E in series A_{47E} or A_{47EA} and A_{27B}. For this, the set-up is the same as that shown in Figure 3.2 but without the Q.S.V. and with the control orifice replaced by the orifice of resistances in question.

The following equipment was used: a Validyne pressure transducer DP15TL (Multiple Range Differential Pressure Transducer) together with a Validyne transducer indicator CD12 as well as a Gould Brush 440. A four channel strip recorder was used to monitor the pressure at various locations of the Q.S.V. as shown in Figure 2.3. A liquid type pressure gauge was used to provide steady-state pressure measurements. The digital thermometer used in the experiments was an Omega Type 2809 Digital Thermometer.

3.3 EXPERIMENTAL PROCEDURE

For testing the dynamic performance of the Q.S.V., the following steps are taken (refer to Figure 3.2):

(a) The control valve 3 is manually shifted to the OFF position.

(b) The pressure regulator is set to the desired pressure.

(c) Control valve 1 is manually shifted to the ON position to allow air to charge up the reservoir as well as the Q.S.V. through the connection XX.

(d) On fully charging the system, the control valve 1 is manually shifted back to the OFF position.

(e) The control valve 3 is manually shifted to the ON position, which in turn opens the control valve 2 to allow the system to discharge through the control orifice A_{26}. The various pressure readings are recorded at locations as described in the previous Section.

To evaluate the size of equivalent orifices, the following steps are followed:

(a) Control orifice A_{26}, replaced by the air resistance, is to be evaluated.

(b) The Q.S.V. is to be removed from the set-up.

(c) The control valve 3 is manually shifted to the OFF position.

(d) The regulator is set to the desired pressure, approximately 5.0 kg/cm^2 g (71.6 psig)

(e) The control valve 1 is manually shifted to the ON position to allow air to charge up the reservoir V_1.

(f) On fully charging the system, the control valve 1 is manually shifted back to the OFF position.

(g) The control valve 3 is manually shifted to the ON position, which in turn, opens the control valve 2 to allow the system to discharge through the unknown air resistance.

CHAPTER 4

DYNAMIC BEHAVIOUR OF THE Q.S.V.

4.1 INTRODUCTION

By making use of the theoretical and experimental techniques developed in the previous Chapter, this Chapter attempts to show the various aspects of the behaviour of the Q.S.V. under different combinations of working conditions and other parameters.

Some experimental data based on the present design of the Q.S.V. are first given. These data are then compared with an analytical model developed in Chapter 2. Having established the validity of the mathematical model, the latter is utilized to help demonstrate how some working conditions and physical parameters affect the behaviour of this valve.

This Chapter is organized as follows. A summary is given in Section 4.2.1, listing the results of experimental determination of such characteristics as the coefficient of discharge of orifices and an evaluation of the polytropic constant which is suitable for subsequent simulation of the system behavibur. In Section 4.2.2, the lumped equivalent orifice sizes of resistances in series that are found inside the Q.S.V. are discussed. This is followed by a discussion of the switching characteristics of the Q.S.V. in Section 4.2.3. By this time, there is sufficient quantitative information to carry out a numerical simulation of the analytical model.

Section 4.3 presents the basic behaviour of the Q.S.V., principally the decay of the system pressure P_1 under a combination of conditions, and the oscillatory behaviour of the valve. Experimental results will be compared against the results of simulation.

The following section, 4.4, is then devoted to investigating the affect of some important parameters on the behaviour of the valve. These results of the investigation are presented according to the two principal modes of operation.

A conclusion is given in Section 4.5.

4.2 DETERMINATION OF CONSTANTS

4.2.1 Experimental Determination of Discharge Coefficient

The following is a summary of experiments and results, with an indication of the analytical technique involved wherever appropriate.

Coefficients of Discharge and Effective Orifice Area.

Using expression (2.5.1) and the experimental procedure described in Section 3.3, the following parameters have been determined.

1. Area of Check valve C_{27} = 4.143 mm^2 (dia. = 0.09 in.)
2. Area of Check valve C_{47} = 9.009 mm^2 (dia. = 0.13 in.)
3. Discharge coefficient of orifice D

$C_d \doteq 0.63$ 1/64 Drill (dia. = 0.0156 in.) (Table 2.1) (when the pressure difference between the up and down streams approximately 1.5 psi)

$C_d \doteq 0.76$ #76 Drill (dia. = 0.02 in.) (Table 2.1) (when the pressure difference between the up and down streams is approximately 1.5 psi)

Polytropic Exponent "n"

The technique described in Reference (13) and the result thereof as summarized by expression(A1.12), Appendix 1, is employed to determine the suitable polytropic exponent that can be used to describe the extent of heat transfer during a discharging process of the type as described above, and notably in the experimental set-up of Chapter 3. This value of "n" has been found to be approximately 1.03, suggesting a-near-isothermal process when the "brake pipe volume" V_1, discharges slowly to atmosphere.

4.2.2. Combined Equivalent Effective Orifice Area A_{27B}, A_{47E}/A_{47EA}

Table 4.1 shows the combined equivalent effective orifice area, namely, A_{27B} and A_{47E}/A_{47EA}, which were obtained experimentally and theoretically by using expression (2.5.1) and the experimental procedure described in Section 3.3, and Equation (2.5.3) and Equation (2.5.5) respectively. The equivalent effective orifice area of check valves C_{27} and C_{47} as obtained in Section 4.2.1 were substituted into Equation (2.5.3) and Equation (2.5.5) to evaluate the combined equivalent effective orifice area theoretically. The results obtained theoretically and experimentally are in good agreement each other.

Experimental Results Equation (2.5.1)	Theoretical Results Equations (2.5.3), (2.5.5) and (2.5.6)
<u>Set 1</u> (Table 2.1)	<u>Set 1</u>
A_{27B} = 1.084 mm^2 (dia.=0.0463 in.)	A_{27B} = 1.034 mm^2 (dia.=0.0452 in.)
<u>Set 2</u> (Table 2.1)	<u>Set 2</u>
A_{27B} = 1.553 mm^2 (dia.=0.0554 in.)	A_{27B} = 1.409 mm^2 (dia.=0.0527 in.)
<u>Set 3</u> (Table 2.1)	<u>Set 3</u>
A_{27B} = 0.6 mm^2 (dia.=0.0342 in.)	A_{27B} = 0.576 mm^2 (dia.=0.0337 in.)
<u>Set 4</u> (Table 2.1)	<u>Set 4</u>
A_{27B} = 1.203 mm^2 (dia.=0.0487 in.)	A_{27B} = 1.139 mm^2 (dia.=0.0474 in.)
<u>Set 1</u>	<u>Set 1</u>
A_{47EA} = 1.505 mm^2 (dia.=0.0563 in.)	A_{47EA} = 1.674 mm^2 (dia.=0.0575 in.)
<u>Set 2</u>	<u>Set 2</u>
A_{47EA} = 1.583 mm^2 (dia.=0.0559 in.)	*A_{47EAC} = 1.739 mm^2 (dia.=0.0586 in.)
<u>Set 3</u>	<u>Set 3</u>
A_{47E} = 1.986 mm^2 (dia.=0.0626 in.)	A_{47E} = 1.869 mm^2 (dia.=0.0607 in.)
<u>Set 4</u>	<u>Set 4</u>
A_{47E} = 1.986 mm^2 (dia.=0.0626 in.)	A_{47E} = 1.869 mm^2 (dia.=0.0607 in.)

*. A_{47EAC} = Combined equivalent orifice area of check valve C_{47}, orifice A, orifice C and orifice E, all in series.

TABLE 4.1

4.2.3 Switching Conditions

Figure 4.1 shows how the pressure differential across the diaphragm, i.e., $\Delta P = P_1 - P_2$ varies as the "brake pipe pressure" P_1 decreases with time. In fact, ΔP undergoes a series of fluctuations between positive and negative values, with peaks indicating instances in which the Q.S.V. switches downwards from its uppermost position, and the valleys indicating those instances in which the reverse switching takes place. The peaks are labelled as a_1, a_2 and a_3 (downward switching) and the valleys as b_0, b_1 and b_2 (upward switching).

One may draw the following qualitative conclusions:

1. If a curve be drawn, joining the peaks at a_1, a_2 and a_3, of Figure 4.1, one obtains the downward switching condition of the Q.S.V. as shown in the ΔP_d characteristic in Figure 4.2.
2. Similarly, the curve joining the valleys b_0, b_1, b_2 and b_3 shows the upward switching condition (ΔP_u, Figure 4.2).

It is seen from these results that ΔP_u is always negative, i.e., pressure P_2 at the lower chamber B_d is greater and varies slightly from -0.4 g/mm^2 (-0.5 psi) to -0.14 g/mm^2 (-0.2 psi) over a system pressure range up to 49.2 g/mm^2 (70 psig). On the other hand, ΔP_d is always positive in value, increasing more or less linearly from 0.6 g/mm^2 (0.8 psi) when P_1 is around 15.5 g/mm^2 (22 psig) to below 0.8 g/mm^2 (1.1 psi) at 49.2 g/mm^2 (70 psig). Numerically, these may be represented by the following empirical relations:

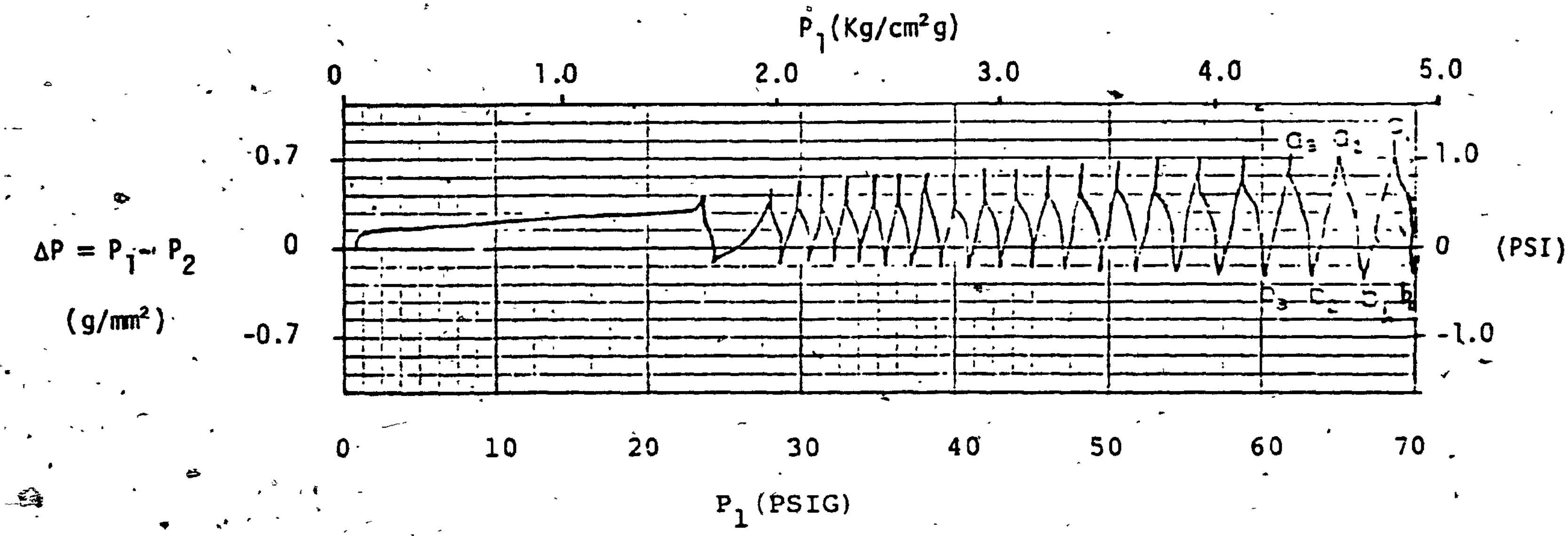

Figure 4.1 Relation between ΔP and P_1 during discharging

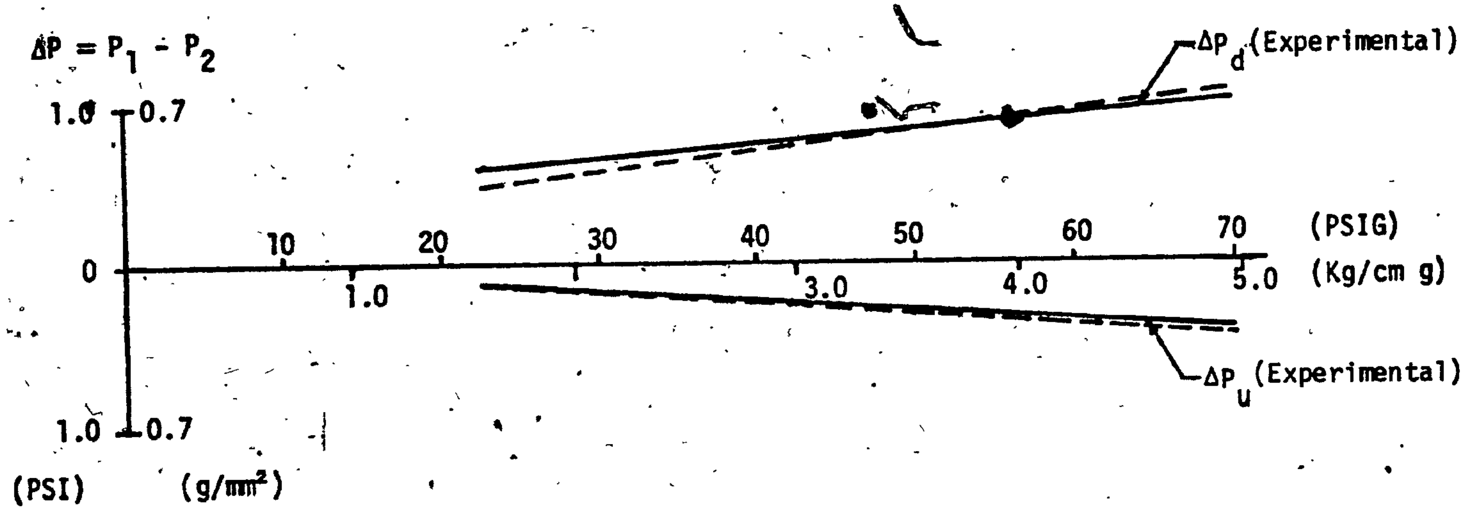

Figure 4-2 Switching condition of B-1 Quick Service Valve, $\Delta P \sim P_1$

$$\Delta P_u = - 0.00625 \; P_1; \; g/mm^2$$

$$\Delta P_d = + 0.00625 \; P_1 + 0.28; \; g/mm^2$$

The curves ΔP_d and ΔP_u, in solid line, are obtained experimentally. Corresponding to these, the theoretical results as developed in Section 2.3 for switching conditions, are shown in Figure 4.2 in dotted lines. The results obtained theoretically and experimentally agree very well..

4.3 EXPERIMENTAL AND THEORETICAL RESULTS

4.3.1 The Q.S.V. Dynamic Characteristics

Typical pressure versus time characteristics of the Q.S.V. and the switching behaviour under service application, are shown in Figures 4.3 and 4.4. The pressure readings are taken from points X, Y, Z and W as described in Section 3.2 (Figure 2.5), with the curves correspondly labelled: X (for P_1), Y (for P_2), Z (pressure between check valve C_{27} and orifice B) and W (pressure between check valve C_{47} and orifice A). For this set of experiments, the equipment was first charged to 70 psig and a triggering pressure reduction rate of 4 psi/sec (initial value, without Q.S.V.) was employed.

It is observed from curves Z and W of Figure 4.3 that the Q.S.V. is triggered into an oscillating mode, which lasts for approximately 40 seconds, at an oscillating frequency of approximately 0.85 cycle/second. At the end of this oscillatory period, the "brake pipe pressure" P_1 is at around 10 psig, with the Q.S.V. ceasing to oscillate any further,

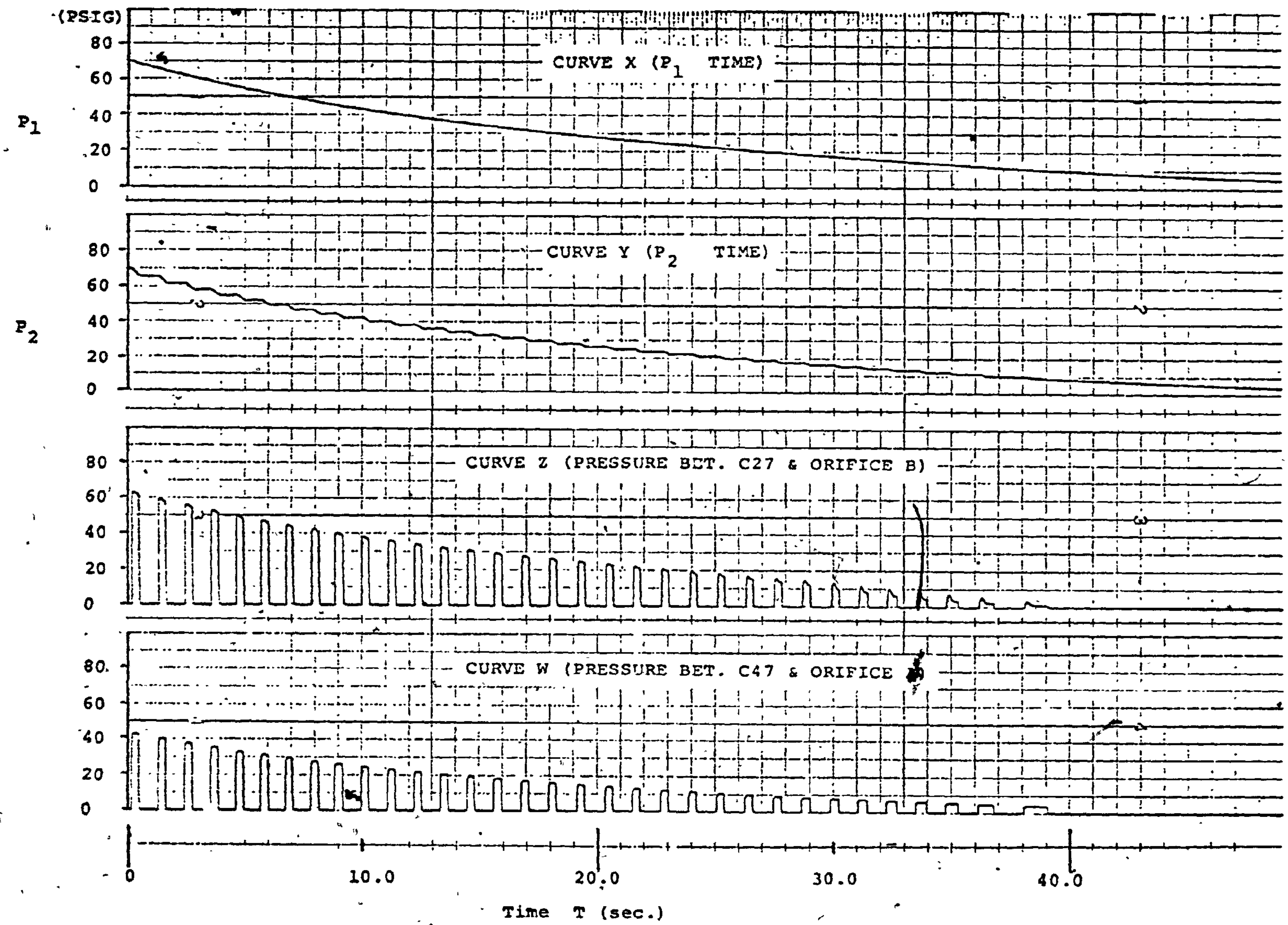

Figure 4.3 Typical experimental dynamic behaviour of B-1 Quick Service Valve

maintaining an "open" state to continuously exhaust the system.

Curves Z and W of Figure 4.3 carry the same information as the curves of Figure 4.4 except that the timing scale is expanded.

Referring to curve Z of Figure 4.4, the rapid increase in the air pressure between check valve C_{27} and orifice B indicates that check valve C_{27} opens and closes instantaneously. A similar situation exists between check valve C_{47} and orifice A, as observed from curve W, of the same figure. It is also important to note that both check valves open and close at essentially the same time. These observations justify assumption (f) in Appendix 1, namely that the check valves are assumed to be opened or closed instantaneously, especially when the pressures P_1 and P_2 are large.

As indicated in Table 2.1, Section 2.2, there are four different sets of orifices presently employed or proposed for use in the railway industry. In order to show the behaviour of the Q.S.V. employing the different sets of orifices with differing "brake pipe volume" V_1, and at different pressure reduction rates (i.e. different sizes of orifice A_{26}, see Chapter 3 for experimental set-up), the pressure P_1 in each case has been plotted against non-dimensionalized time $\tau = (KR\sqrt{T_u}) \times (A_{26}/V_1)t$, [9] with the quantity $(KR\sqrt{T_u})$ arbitrarily set to unity for the present purpose. The results are shown in Figure 4.5. Also shown is the corresponding discharge curve P_1 with the Q.S.V. "cut-off" in order to help observe the effectiveness of employing the Q.S.V.

Referring to Figure 4.5, it is evident that Set 3 helps to exhaust

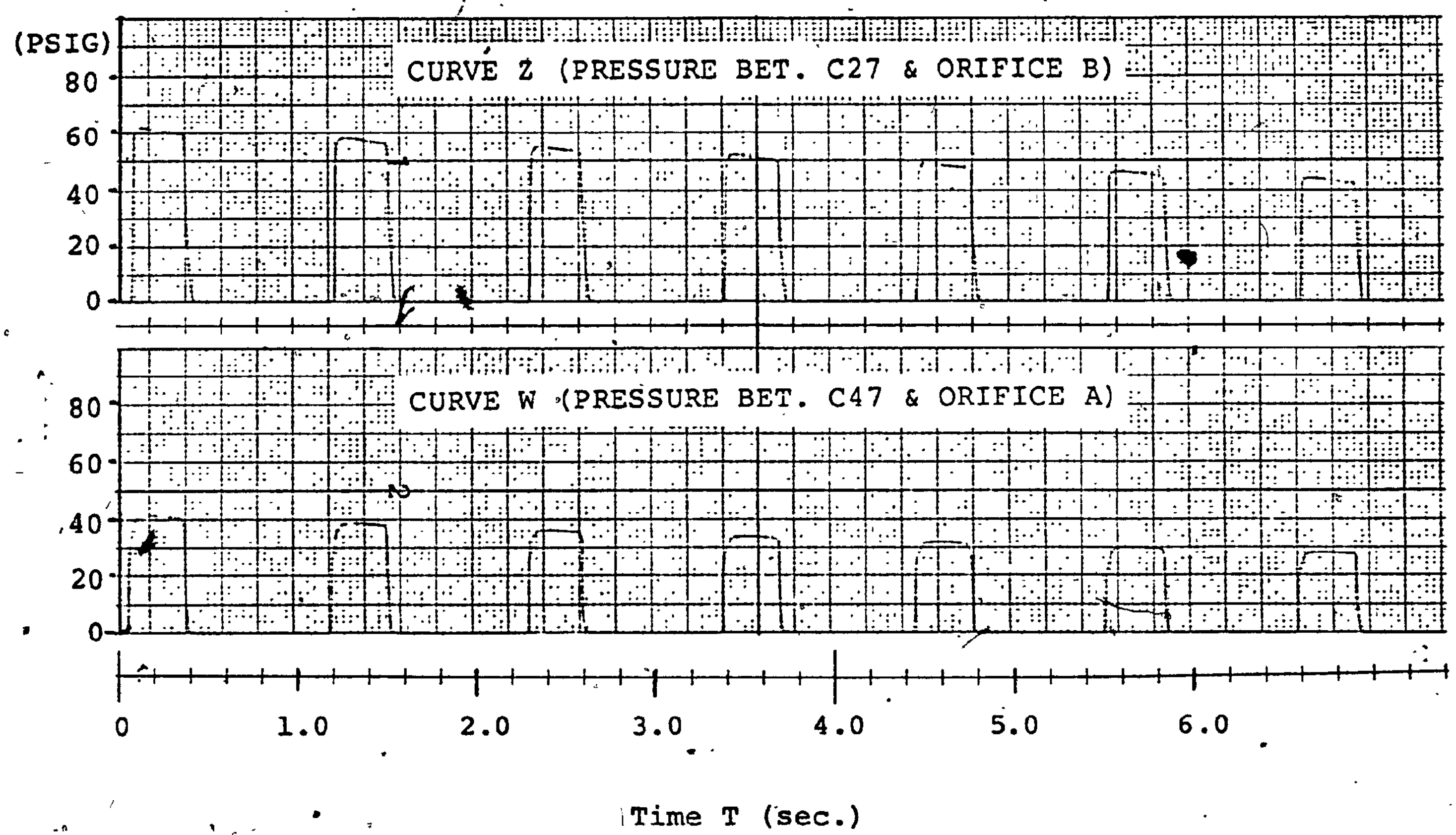

Figure 4.4 Switching relation between C_{27} and C_{47} during discharging

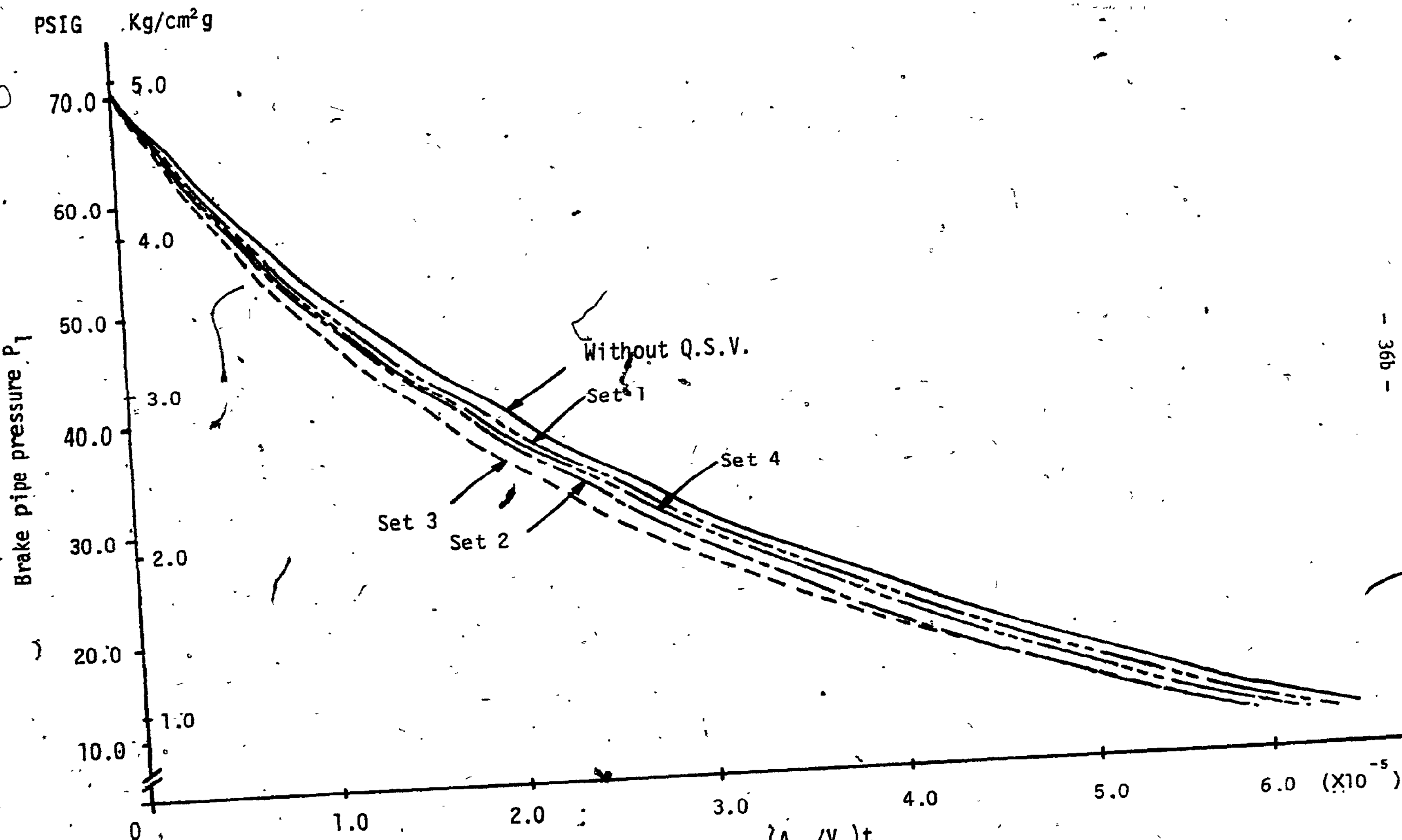

Figure 4.5 Pressure P_1 vs. time curves for different setting timing orifice

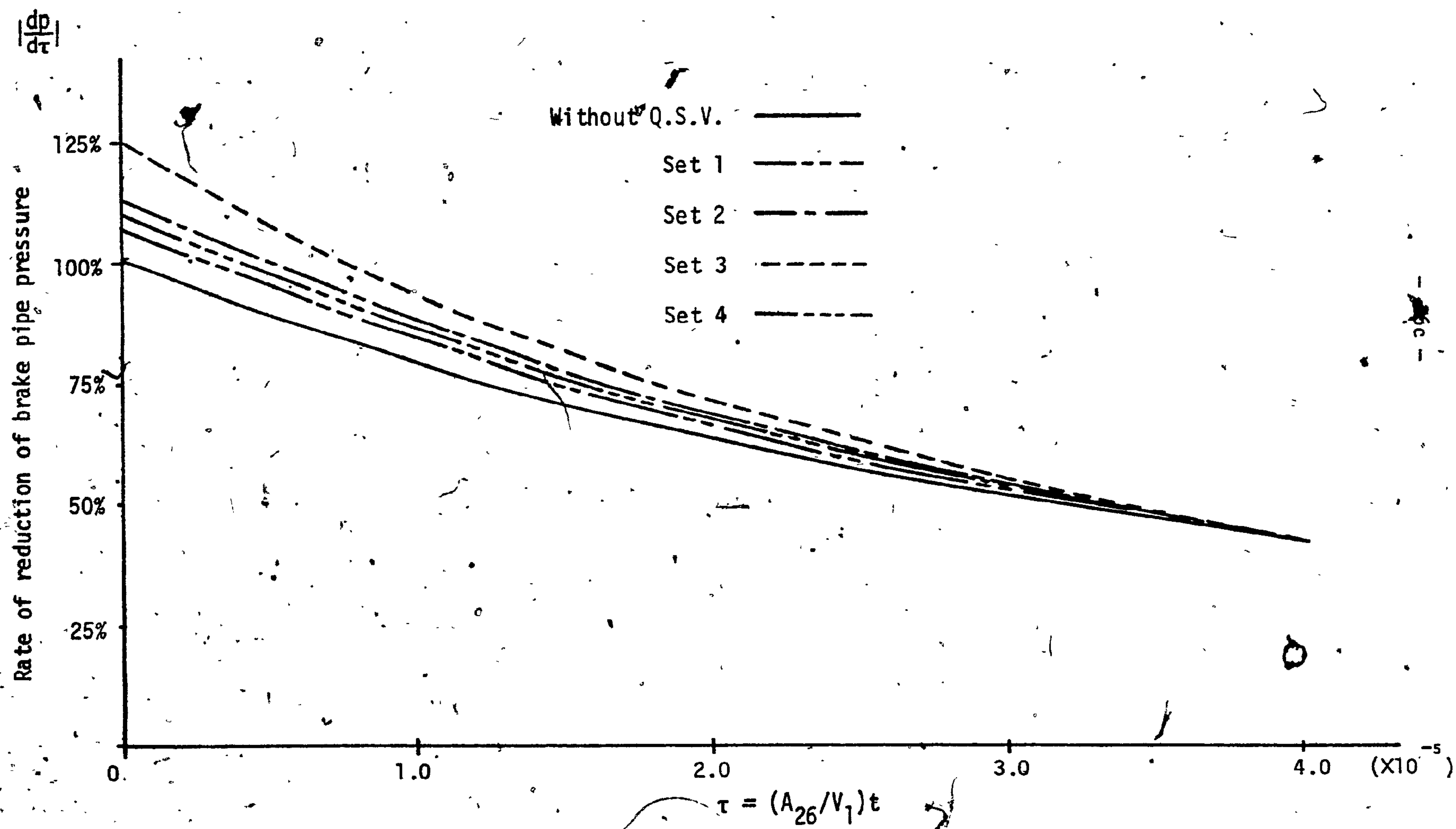

Figure 4.6 Relation between the rate of reduction of brake pipe pressure vs. normalized parameters τ with different setting timing orifice

the brake pipe pressure P_1 to the greatest extent. There is an extra reduction of 3.6 psi at time $(A_{26}/V_1)t = 3.0$; $cm^{-1}sec$, if one compares the curve for Set 3 against that with the Q.S.V. cut-off. By applying the technique of graphical differentiation on the curves shown in Figure 4.5, the corresponding instantaneous rate of reduction of pressure $|\frac{dP_1}{d\tau}|$ is shown in Figure 4.6 in all five cases. It is observed that the Q.S.V. increases the rate of reduction in each case (all four curves seen to be above the curve for the case without Q.S.V.), with Set 3 showing the greatest amount of increase throughout the range of the experiment.

4.3.2 <u>Results of Computation Vs. Empirical Data</u>

Digital computation is carried out on the CDC 6000 computer at Concordia University, Montreal, simulating the dynamic transients of the system under conditions as shown in the experimental set-up in Figure [illegible]2.

The simulation programs are based on the analysis derived in Chapter 2. The principal differential equations are Equations (2.4.3) and (2.4.4) for Mode 1 operation and Equations (2.4.7) and (2.4.8) for Mode 2 operation and the switching condition of the Q.S.V., Equations (2.3.7) and (2.3.9). The set of simultaneous differential equations are solved by using the Runge-Kutta routine. This method is outlined in Appendix 5. The computer program consists of switching from Equations (2.4.3) and (2.4.4) to Equations (2.4.7) and (2.4.9) and vice versa, dictated by the prevailing switching conditions

ΔP_u or ΔP_d. It is also necessary to monitor continuously if each orifice is undergoing subsonic flow (Equation (A1.10)) or choked flow (Equation (A1.11)), the flow chart in Appendix 6 briefly outlines the computational procedure, demonstrating how the program switching is being carried out.

The results that are of particular interest at this point are:

1. How the system pressure P_1 decays with time.
2. The frequency and period of oscillation of the valve.
3. How the variations of different geometrical and system parameters may influence the computation results of the simulation program developed.

For ease of comparison, Figure 4.5 which illustrates the Q.S.V. response measured with different combinations of orifices employed, is simplified to Figures 4.7 (a), (b), (c) and (d) where curves (a) and (b), in solid lines, are the measured response of the "brake pipe pressure" P_1 without the Q.S.V. and that with the Q.S.V. respectively. Corresponding to these, the computed responses are shown in dotted lines; namely, response P_1 without the Q.S.V., (c), and that with the Q.S.V., (d).

It can be readily observed that in all four cases, curves (a) and (c), without the Q.S.V., agree with one another well throughout the entire period during which the system discharges its air through the control orifice A_{26} (see Figure 3.2). However, with the Q.S.V., the

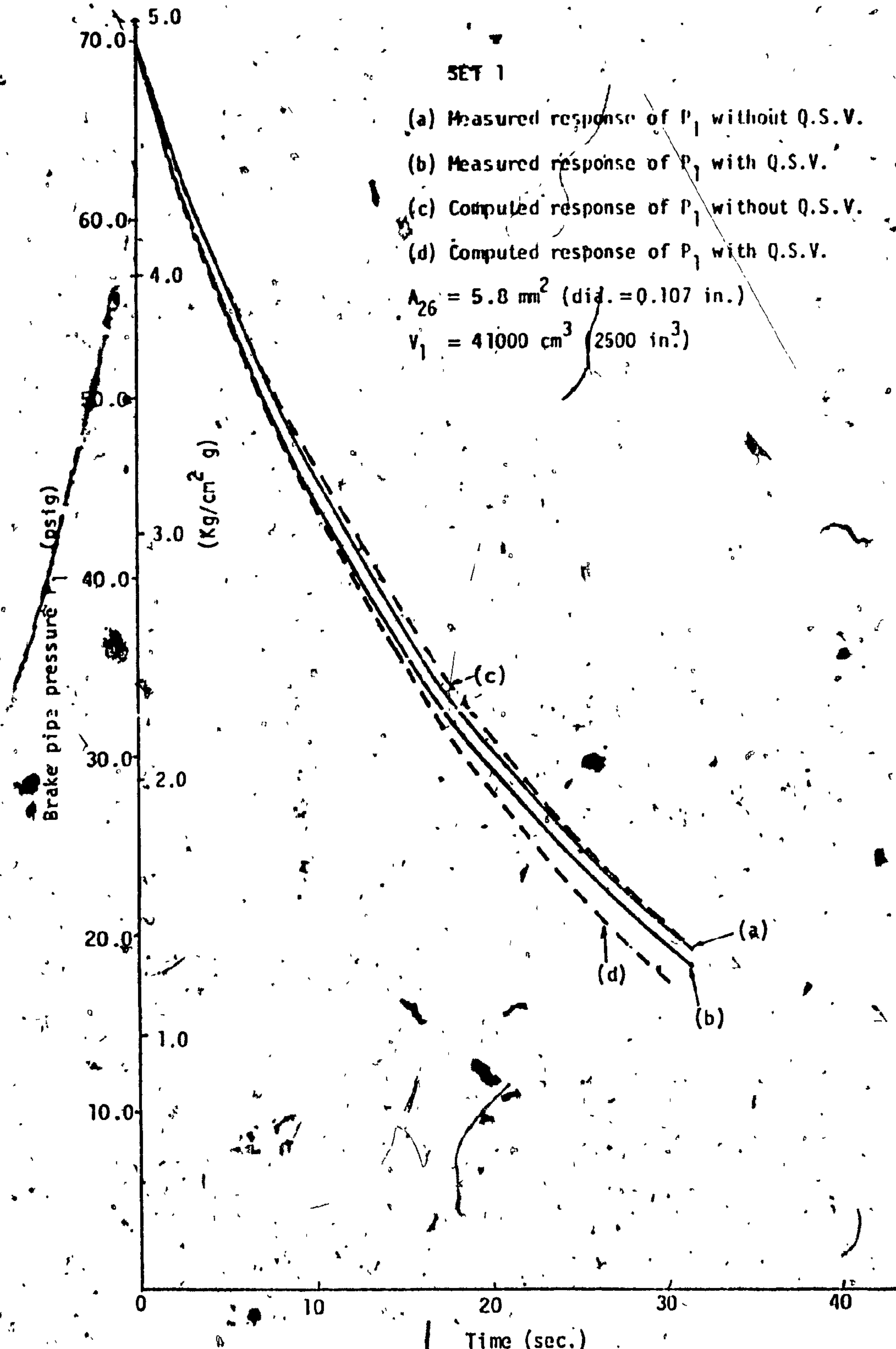

Figure 4.7(a) Experimental results vs. theoretical model for brake pipe pressure P_1

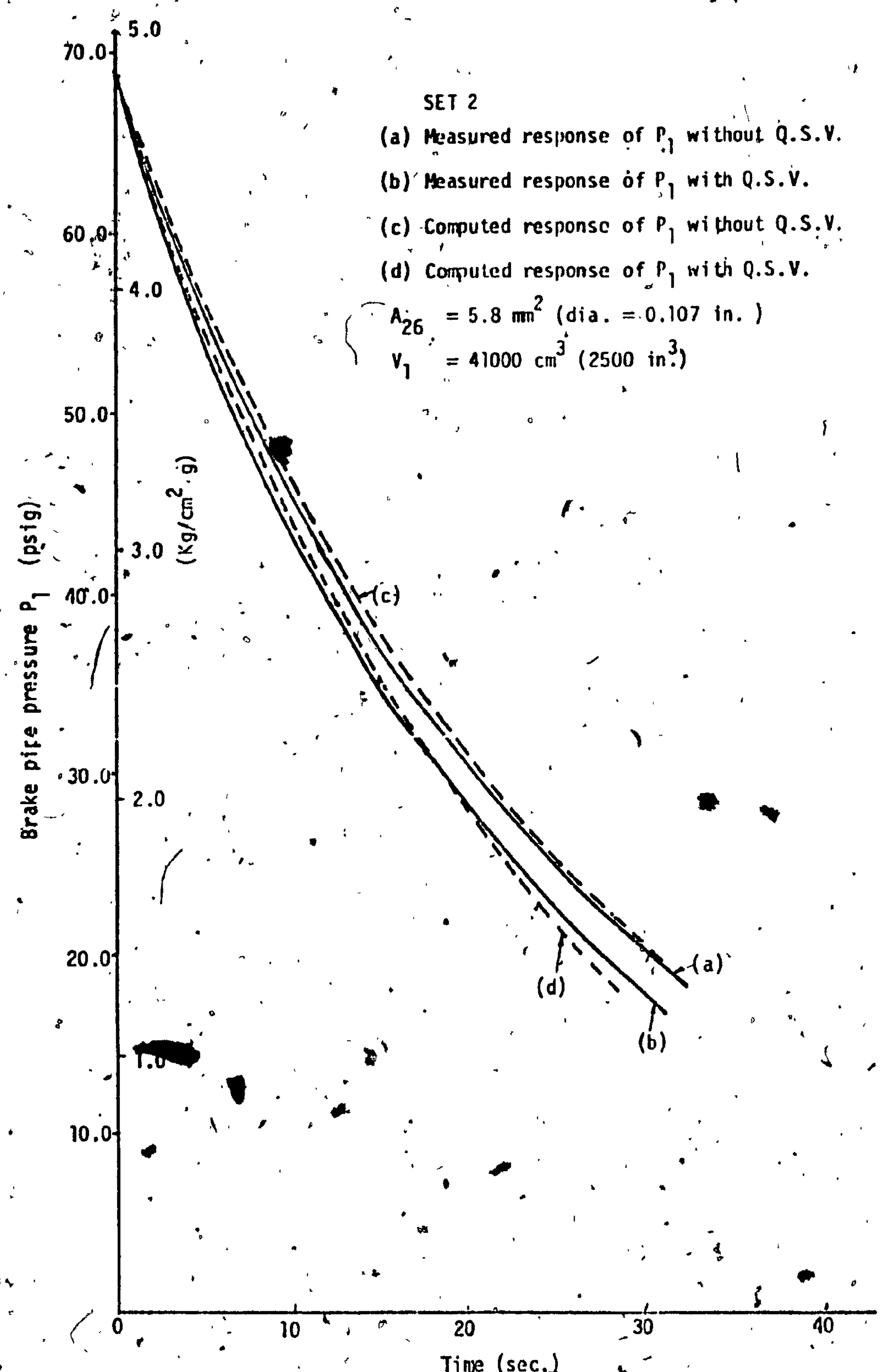

Figure 4.7 (b) Experimental results vs. theoretical model for brake pipe pressure P_1

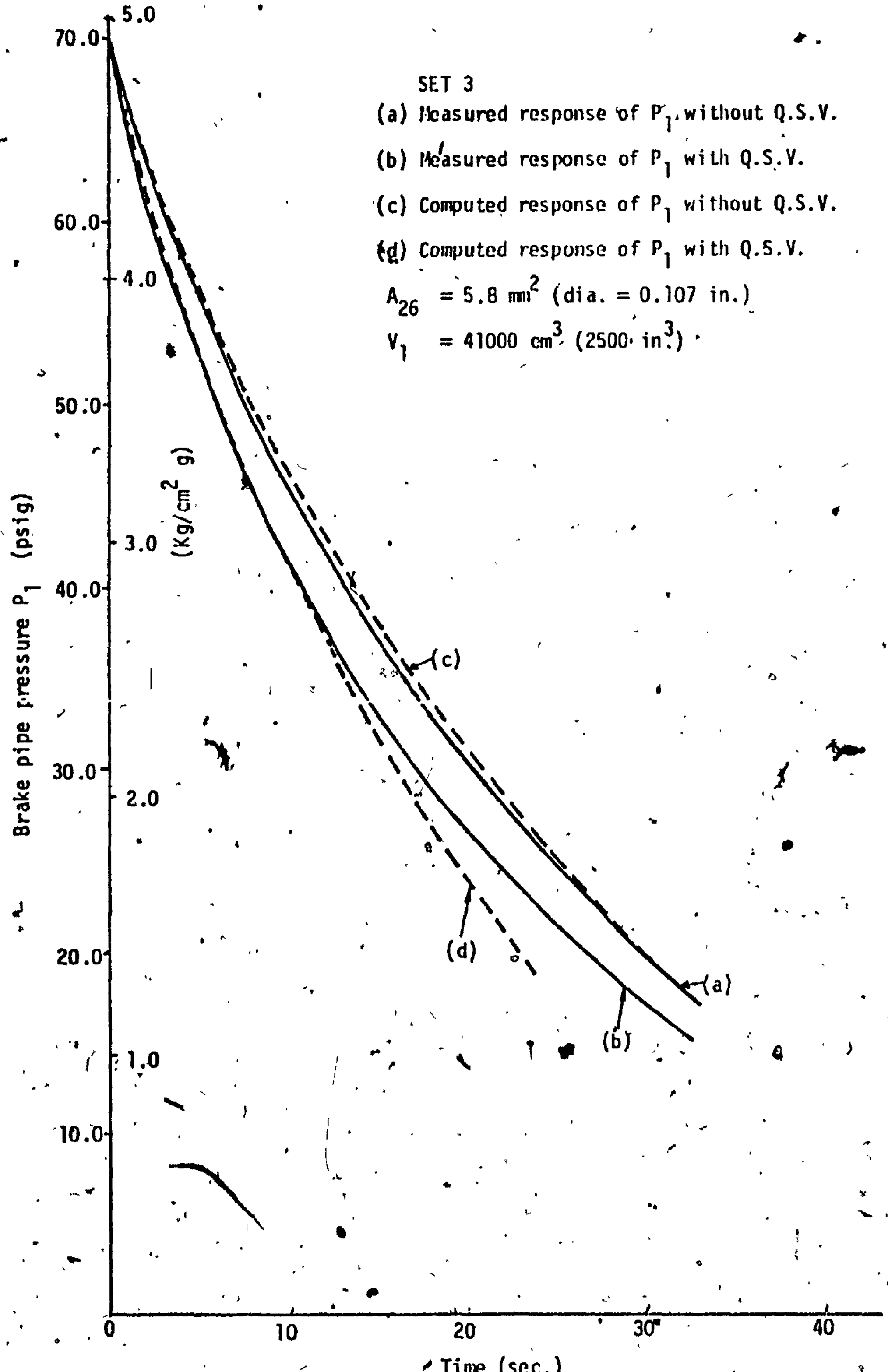

Figure 4.7(c) Experimental results vs. theoretical model for brake pipe pressure P_1

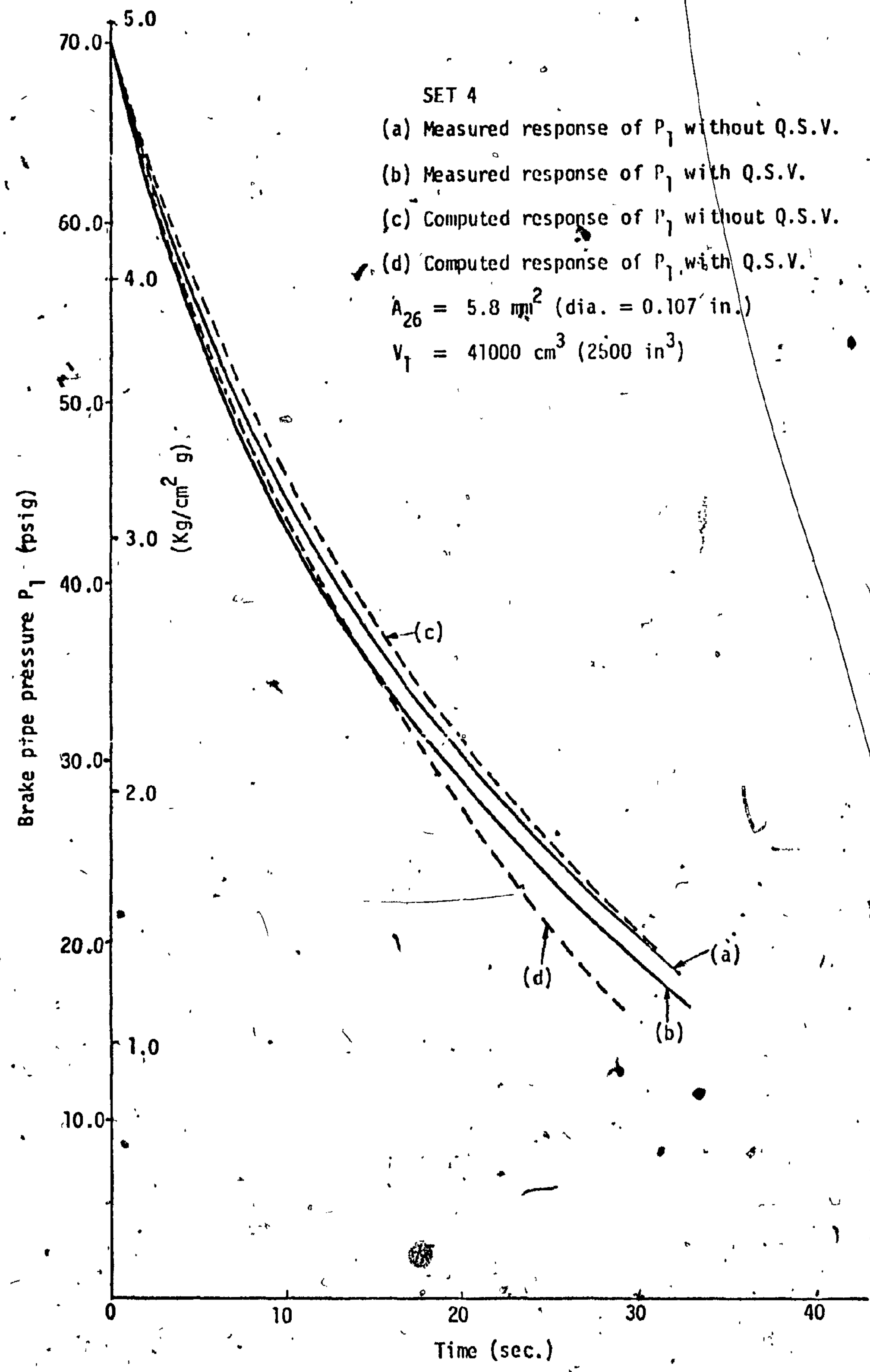

Figure 4.7(d) — Experimental results vs. theoretical model for brake pipe pressure P_1

curves (b) and (d) demonstrate good agreement during the period covering the initial 20 seconds or so, after which the system pressure P_1 drops below 30 psig, which is outside the range of interest in actual practice.

Another parameter of interest is the frequency and period of oscillation of the Q.S.V. in operation. Figure 4.8 shows the actual empirical sequence of oscillation in curve (a), as compared to that provided by the mathematical model (b). The frequency and period in each case are summarized in Table 4.2.

It is seen that in Sets 2 and 4, the simulated results agree with the measured quantities fairly well. However, the period of Set 3 according to the theoretical model is approximately twice as compared with empirical data. On the other hand, the theoretical model of Set 1 predicts continual oscillatory behaviour as compared to the abrupt stop of the actual system after 10 seconds.

A few words of comment are presented here. Firstly, the theoretical model is shown to be adequate within the normal working range of pressure P_1 for which the Q.S.V. is created in the first place, i.e., to assist service application. Secondly, this simplistic model has neglected the effect of such parameters as inertia of moving parts, continual spring forces, frictional forces and backlashes, which tend to exert more influence on the behaviour at the lower end of the pressure scale.

Figures 4.9 (a), (b), (c) and (d) show the switching behaviour of

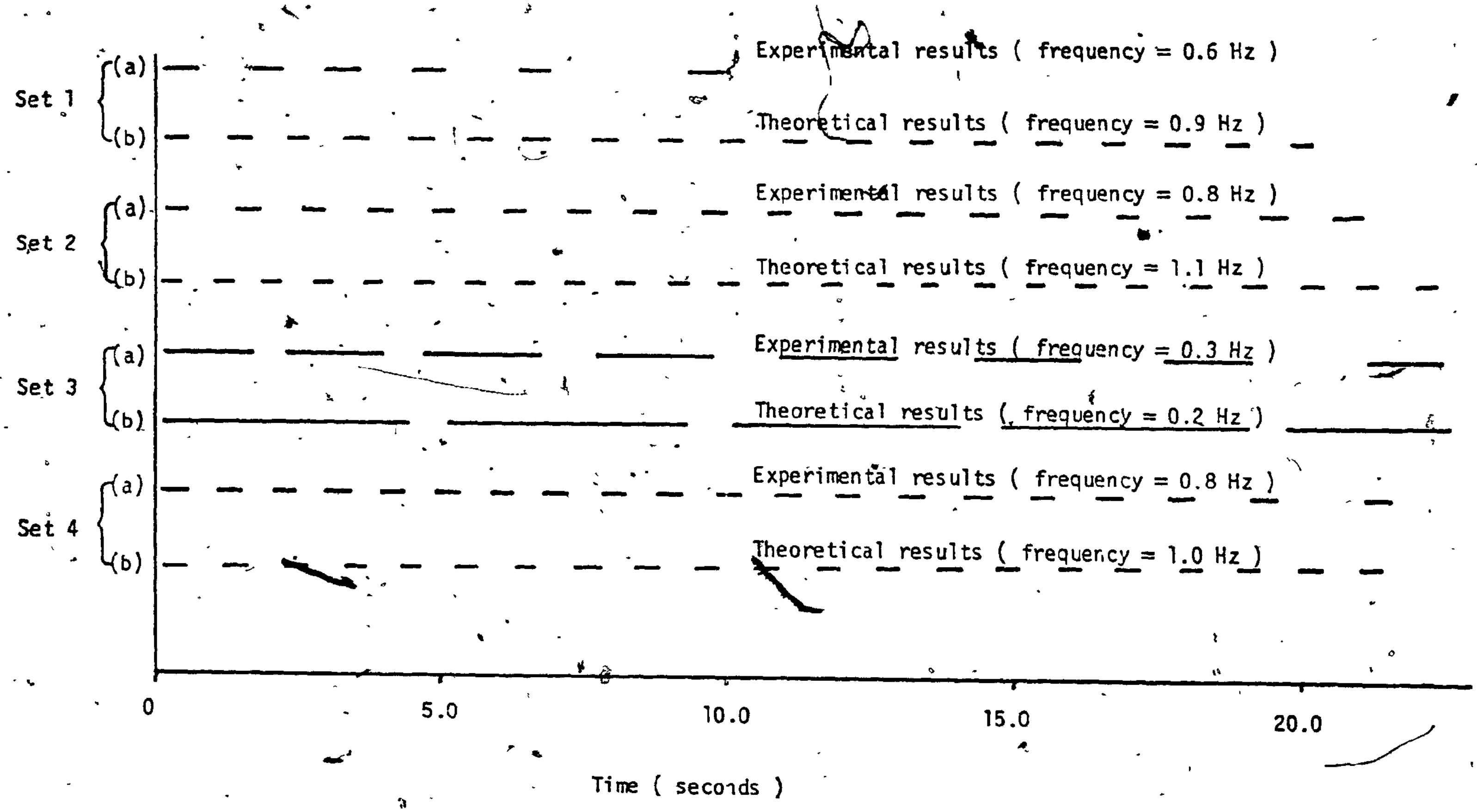

Figure 4.8 Empirical and Theoretical sequence of oscillation of the Q.S.V.

(A dash refer to duration of Mode 2, and a flash refer to duration of Mode 1)

Set No.	EXPERIMENTAL		THEORETICAL	
	Number of Oscillation	Cycle/Sec.	Number of Oscillation (up to 25 psig)	Cycle/Sec.
SET 1	6	0.566	21	0.933
SET 2	31	0.798	26	1.12
SET 3	8	0.342	4	0.21
SET 4	21	0.75	22	0.993

TABLE 4.2

Oscillation of the B-1 Quick Service Valve
with Different Size of Timing Orifices.

the Q.S.V. under different orifice settings employed. The pressure readings are taken from point Z as described in Section 3.2. Referring to Figures 4.9 (a) and (c), it is seen that the Q.S.V. stops oscillating after 10, 21 seconds respectively and takes up a position which partially opens the check valve C_{27} and, no doubt, also check valve C_{47}.

It is also observed that the check valves of the Q.S.V. with Set 1 are not closed completely during the operation (see Figure 4.9(a)). Similarly, the check valves with Set 3 are not closed completely 5 seconds later in operation. Consequently, some degree of leakage takes place, which influences the time required to develop sufficient pressure differential across the diaphragm. The results of computation on the other hand, predict continual oscillatory behaviour; this is equivalent to dumping more air than it should from the brake pipe.

An experimental note is mentioned here. In the process of carrying on the same dynamic test over a great number of times, it has been observed that the actual pattern of oscillation seldom repeats itself exactly. This phenomenon is to be expected of any dynamic system involving rubber mould diaphragms, backlashes and sliding friction. In other words, curves (a) and (b) in Figures 4.7, curve (a) in Figure 4.8 and also curve (a), (b), (c) and (d) in Figure 4.9 can be only be taken as being representative.

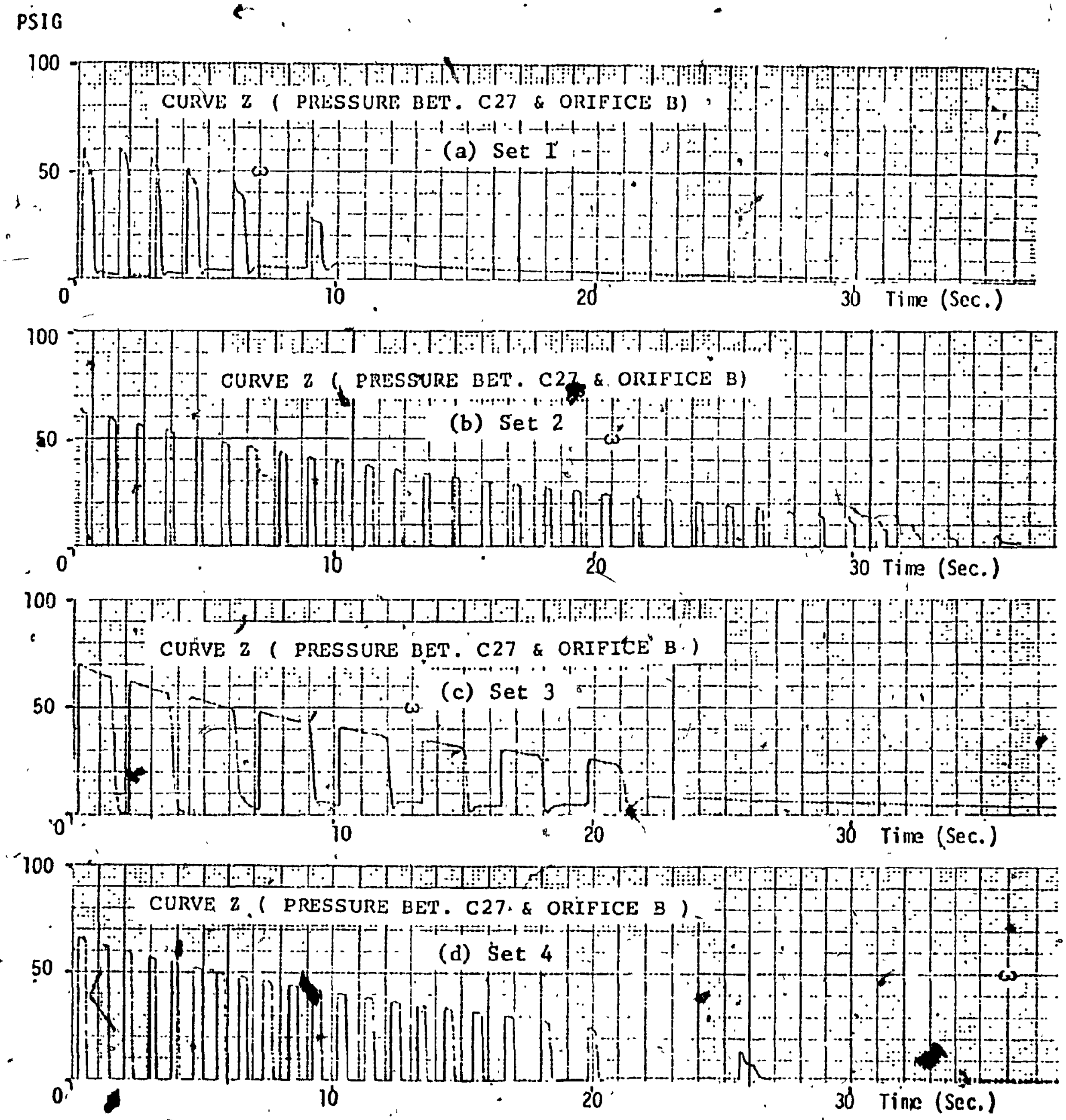

Figure 4.9 Characteristic of curve z under different setting timing orifices

4.4 EFFECTS OF PARAMETERS ON THE BEHAVIOUR OF THE Q.S.V.

4.4.1 Introduction

Since the analytical model and the corresponding digital simulation programs have been shown above to give an adequate description of the behaviour of the actual system, they will be utilized in this Section to study the affects of some important parameters on the dynamics of the Q.S.V.

The major parameters affecting the dynamic behaviour of the Q.S.V. may be considered as follows:

1. The ratio of brake pipe volume to operating chamber volume; V_1/V_2. This is equivalent to investigating the effect of the length of the car and/or the number of cars assigned to one Q.S.V.
2. Rate of reduction of brake pipe pressure.
3. Timing orifices, i.e., orifices D, A_{27B} and A_{47E}/A_{47EA} (see Section 2.2).

In this Section, emphasis is placed on the ability of the Q.S.V. to switch from one mode of operation to the other (or vice versa), and also on the time taken before the switching occurs. For this reason, Section 4.4.2 is devoted to the Mode 1 operation and to how the parameters affect the duration of this mode at the first cycle of oscillation. Similarly, Section 4.4.3 emphasizes the duration of the Mode 2 operation of the first cycle of oscillation. The reason for this approach is that the oscillations tend to take place with a fairly uniform period (frequency) as shown in Figure 4.8. This period (on the two positions of the time duration that make up the period) seems to play a fairly decisive role in the rate of pressure reduction which the Q.S.V. brings about. Furthermore, this information will be shown in the next Chapter to be extremely useful in deciding the proper "tuning" of the Q.S.V. to meet practical requirements.

The discussions in the subsequent Sections will be based on the data presented in the following figures. Figure 4.10 shows the time required by the Q.S.V. to develop sufficient pressure differential across the diaphragm to switch from Mode 1 to Mode 2 operation for different sizes of orifice D, different car lengths and different rates of reduction of brake pipe pressure. The rates of reduction of brake pipe pressure included on these graphs are 100% (Figure 4.10(a)), 75% (Figure 4.10(b)) and 50% (Figure 4.10(c)) of full service application, and the car lengths are 60, 80 and 100 feet long. (Note: 100% service rate is defined as equivalent to a drop of brake pipe pressure from 70 psig to 50 psig in 1.4 seconds, see Ref. 1.)

One immediate conclusion that can be drawn from studying Figure 4.10(a), (b) and (c) is that, except in the case of large sizes of orifice D, the time interval shown may be considered to be fairly independent of the car length, especially from 60 ft. length upwards. Consequently, the data in Figure 4.10 has been utilized, together with further data for slower pressure reduction rates, to give Figure 4.11, which shows the relation between the duration of

Mode 1 operation and size of orifice D, with the rate of reduction of brake pipe pressure P_1 as the parameter. The very small reduction rates are actually due to leakages in the brake system which are conventionally expressed in psi per minute.

Figure 4.12 shows the effect of volume ratios on the time required for the Q.S.V. to return to Mode 1 operation from the first Mode 2 cycle.

Figure 4.13 illustrates diagramatically the relation between the brake pipe pressure and operating chamber pressure reduction under different volume ratios V_1/V_2. i.e., different car lengths, which influence the time required to return to Mode 1 operation.

Figure 4.14 shows the effect of the rate of reduction of brake pipe pressure against the time required to switch from Mode 2 to Mode 1 operation.

Figure 4.15 illustrates diagramatically the effect of the rate of reduction of brake pipe pressure under Mode 2 operation.

Figure 4.16(a),(b) and (c) show the time required by the Q.S.V. to return to Mode 1 operation, after its first Mode 2 operation for different sizes of the timing orifices, namely, A_{27B} and A_{47E}/A_{47EA}, for different car lengths and different rates of reduction of brake pipe pressure. The rate of reduction of brake pipe pressure is examined at 100%, 75%, 50%, 25% and 10% or less of full service rate and the car length is examined with lengths of 60, 80 and 100 feet long.

Figure 4.17 shows the minimum magnitude of combined equivalent orifice A_{27B} required to return to the Mode 1 operation under different rates of reduction of brake pipe pressure. Figure 4.10 illustrates diagramatically the effect of combined equivalent orifice A_{27B} and A_{47E}/A_{47EA} under Mode 2 operation.

4.4.2 Parameters Affecting Mode 1 Operation

- Effect of Volume Ratio (V_1/V_2)

Referring to Figure 4.10 (a), (b) and (c), a variation of brake pipe volume introduces a variation of time required to develop the sufficient pressure difference across the diaphragm. It is found that by keeping all the parameters at a constant value when the orifice D size is small enough, in this case approximately 2.07 mm^2, an increase of brake pipe volume ratio does not affect the time required to develop the sufficient pressure difference across the diaphragm. However, it is observed that when the orifice D size is large enough, for this case approximately greater than 15.0, 12.0 and 8.0 mm^2 at 100%, 75% and 50% of full service application respectively, a reduction of brake pipe volume ratio increases the time required to develop the sufficient pressure differential across the diaphragm.

- Effect of Rate of Reduction of Brake Pipe Pressure

The effect of rate of reduction of brake pipe pressure may be seen from Figure 4.11. It is found that, for a constant value of the orifice D, the time required to develop the sufficient pressure differential across the diaphragm increases as the rate of reduction is

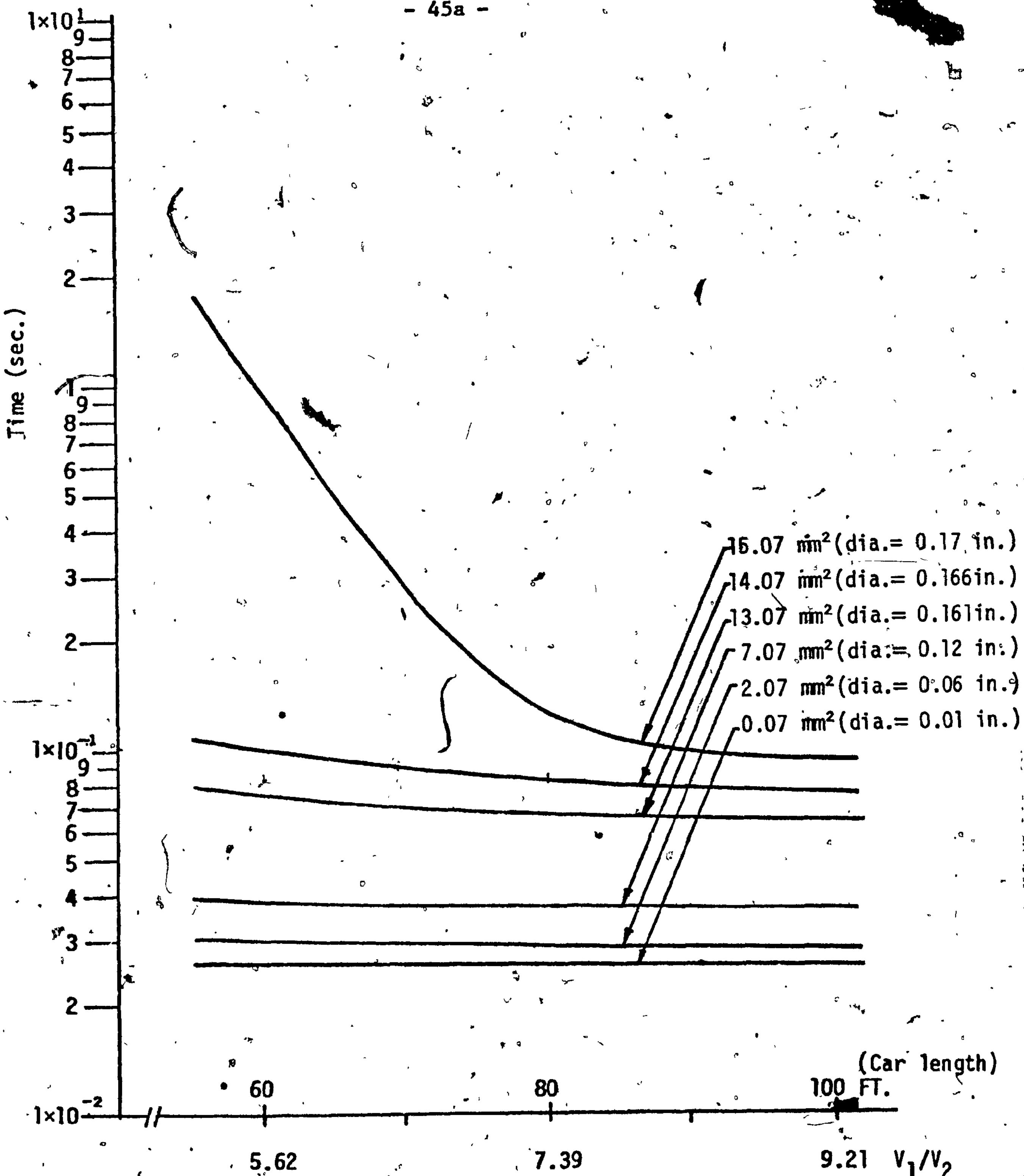

Figure 4.10(a) Effect of timing orifice D and the Volume Ratio under 100% of Full Service Application

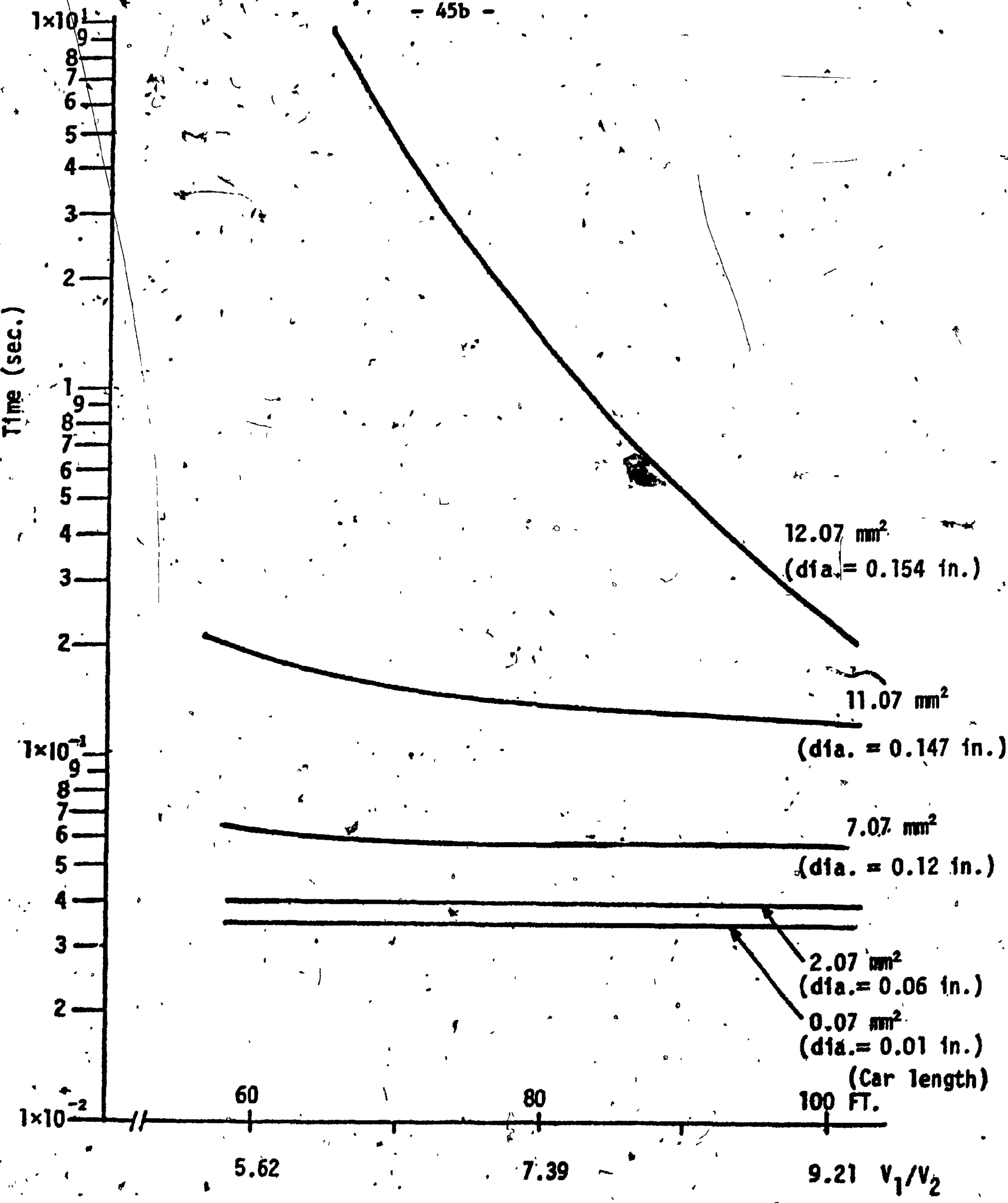

Figure 4.10(b) Effect of timing orifice D and the Volume Ratio under 75% of Full Service Application

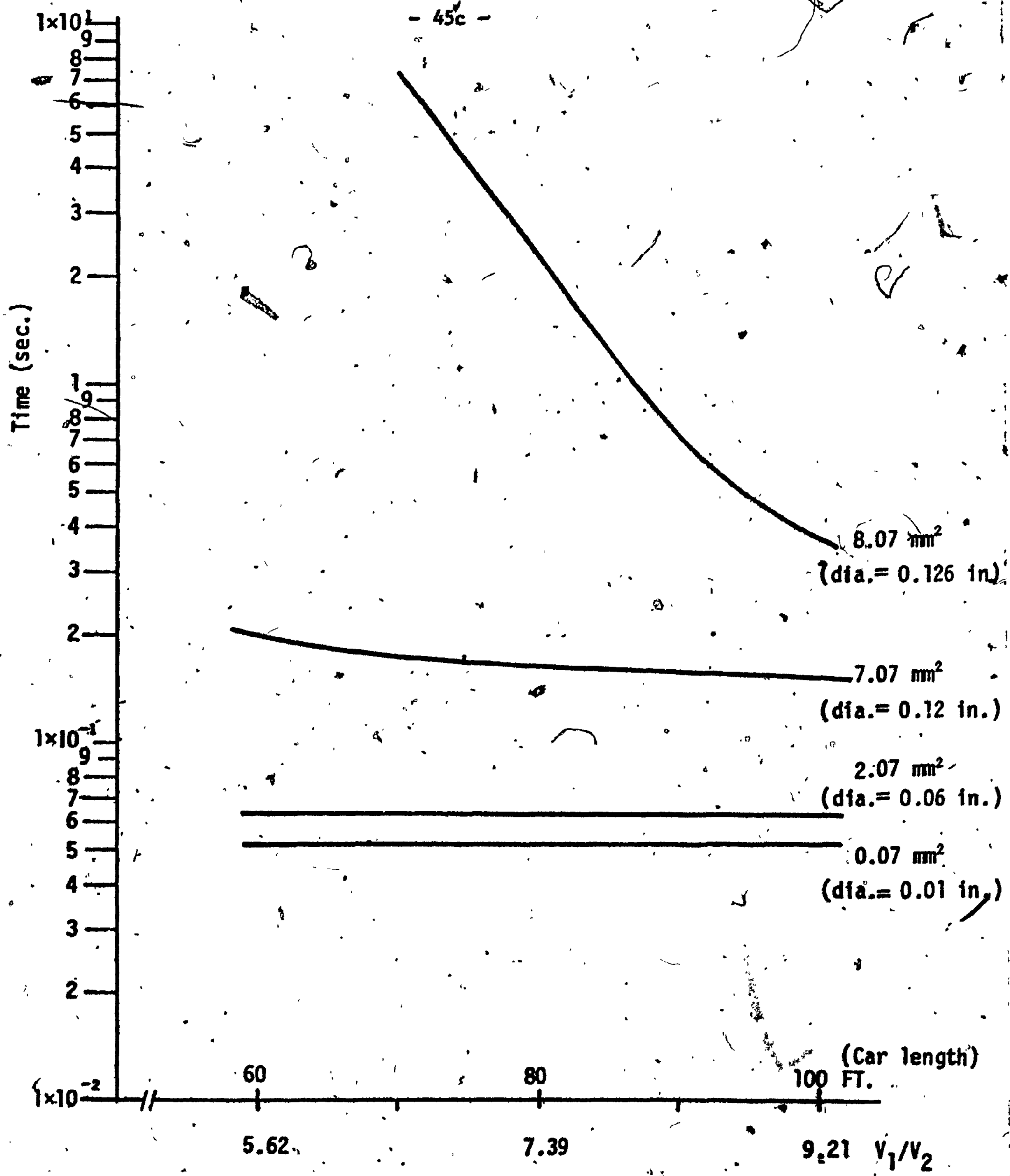

Figure 4.10(c) Effect of timing orifice D and the Volume Ratio under 50% of Full Service Application

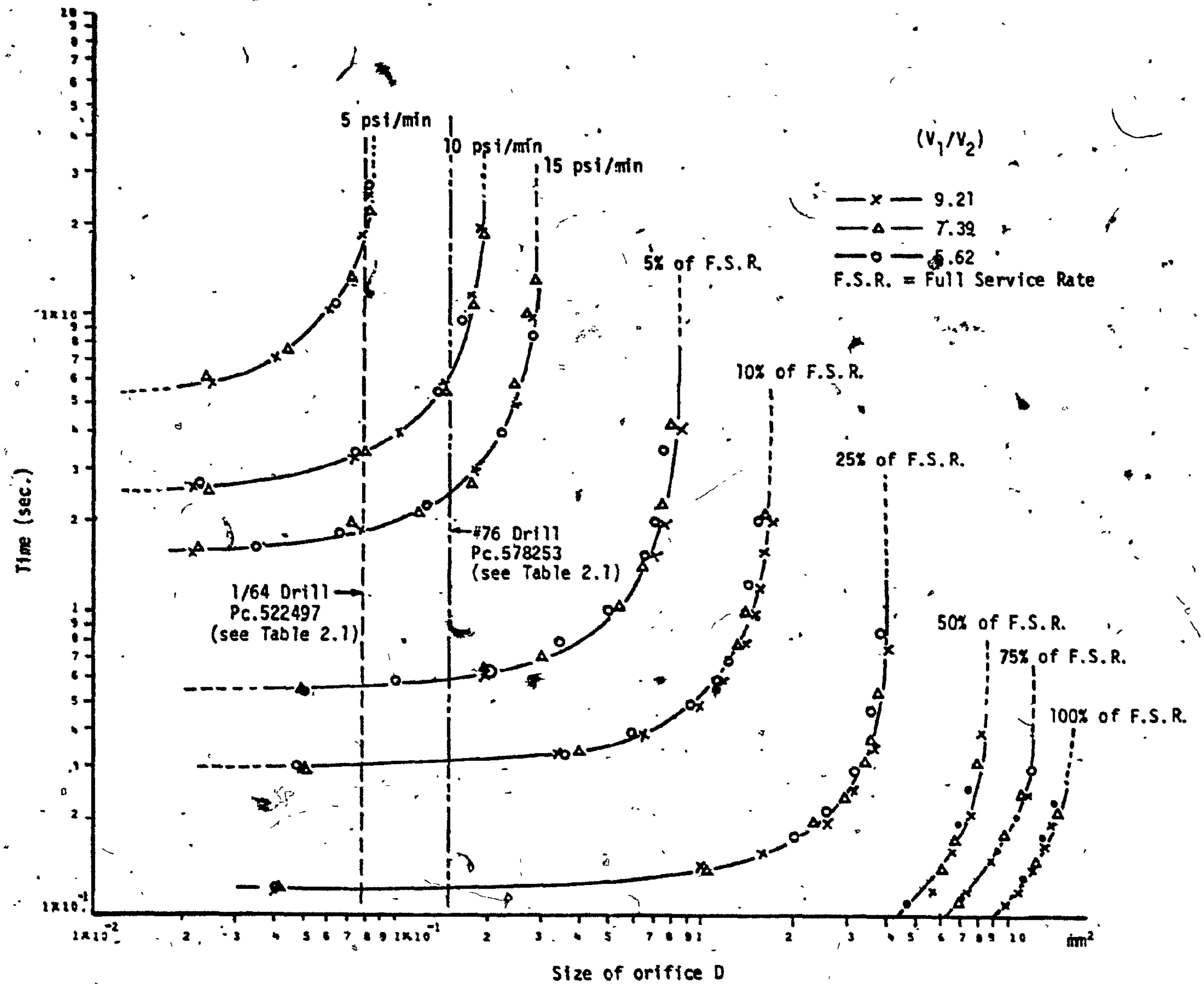

Figure 4.11 Relation between the rate of reduction of P_1, size of orifice D and time required to switch the Mode 1 to Mode 2 operation.

decreased. For instance, it is approximately 0.12, 0.31 and 0.6 seconds at 25%, 10% and 5% of full service rate respectively, when the orifice D is #76 (see Table 2.1). The reason for this is that as discussed previously in Section 2.2, a decrease in the rate of reduction of brake pipe pressure causes a slower decrease of the difference of pressure between the brake pipe and operating chamber volume. Thus it takes a longer time to develop the sufficient pressure differential across the diaphragm.

- <u>Effect of Timing Orifice D</u>

As an example of this discussion, Figure 4.11 is closely examined. An increase in size of orifice D increases the time required to develop the pressure differential across the diaphragm to switch it upwards. This phenomenon can be explained by the fact that the rate of reduction of operating chamber pressure is increased due to an increase in size of orifice D. This slows down the building up of the difference of pressure between the operating chamber volume and brake pipe required to switch the diaphragm assembly upwards. As an example, from Figure 4.11, it takes approximately 0.3, 0.4 and 0.8 seconds with orifice D size of 0.05 mm^2 (dia. = 0.01 in.), 0.65 mm^2 (dia. = 0.033 in.) and 1.4 mm^2 (dia. = 0.053 in.) respectively, when the rate of reduction is 10% of full service application.

It is also found that if the magnitude of orifice D is greater than a certain value, depending on the rate of reduction of brake pipe pressure, the time required to switch the diaphragm assembly from lowermost to uppermost position, i.e., from Mode 1 to Mode 2 operation, approaches infinity. For instance, the limiting size of orifice D is 16.0, 13.0, 8.0, 4.0, 1.6 and 0.86 mm^2 at the rate of reduction of brake pipe pressure of 100%, 75%, 50%, 25%, 10% and 5%. This may result in the diaphragm remaining in its lowermost position permanently.

4.4.3 Parameters Affecting the Mode 2 Operation

- Effect of Volume Ratio (V_1/V_2)

The effect of volume ratio V_1/V_2 on the time required to switch the diaphragm assembly from Mode 2 operation to Mode 1 operation with 100%, 50%, and 10% of full service application rates are best shown in Figure 4.12. It is found that by keeping all the parameters at a constant value, the time required to switch back the diaphragm assembly shows a tendency to decrease with an increase in brake pipe volume ratio. This phenomenon can be explained by the fact that, referring to Figure 4.13, an increase in brake pipe volume reduces the rate of reduction of brake pipe pressure. Thus, an increase in brake pipe volume introduces more time required to switch from Mode 2 back to Mode 1 operation.

- Effect of Rate of Reduction of Brake Pipe Pressure

It is found that a decrease in the rate of reduction of brake pipe pressure decreases the time required to switch the diaphragm assembly back from uppermost to lowermost position. This phenomenon is more clearly illustrated in Figure 4.14 which has been reproduced from

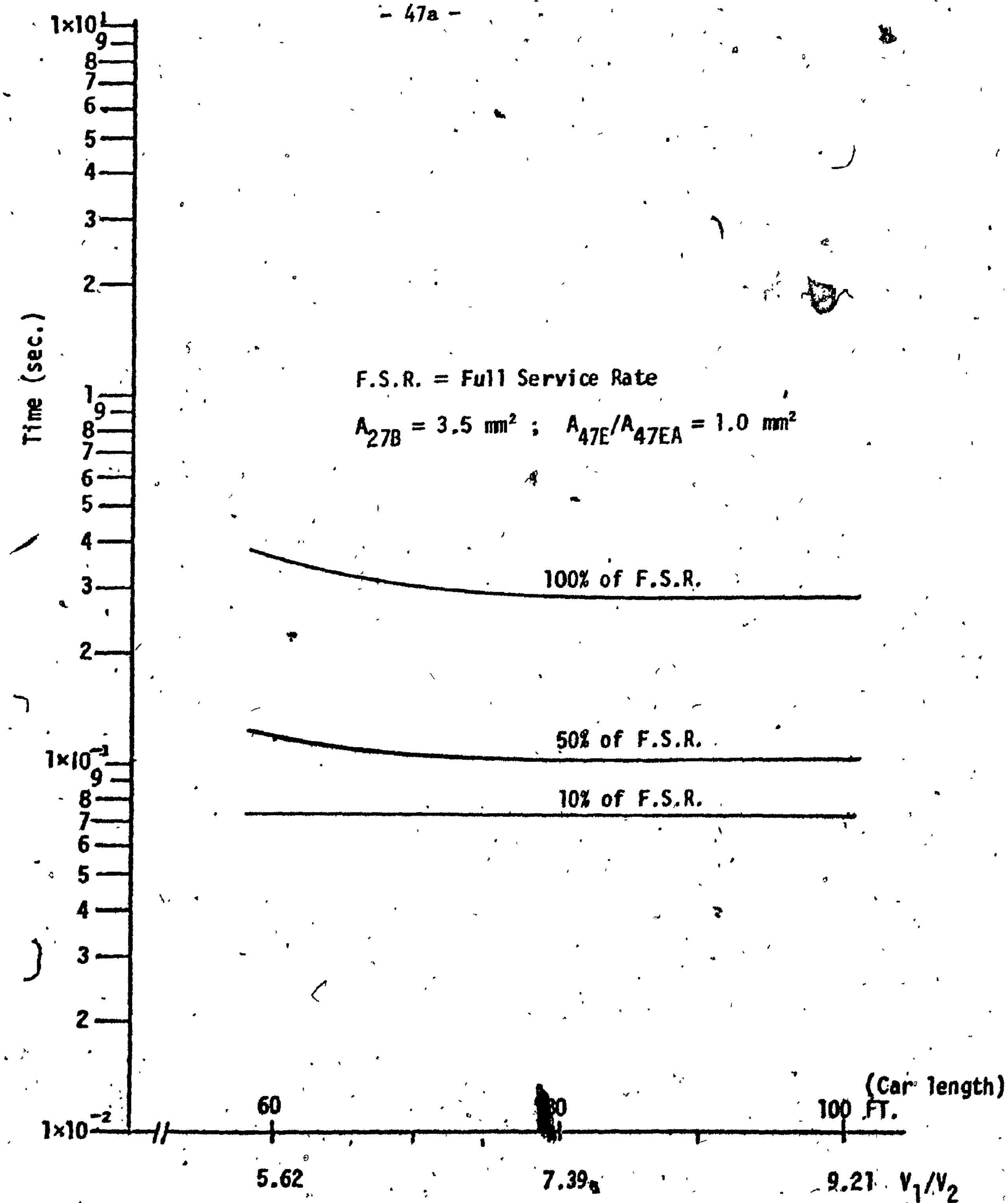

Figure 4.12 Effect of volume ratio vs. time required to terminate Mode 2 operation

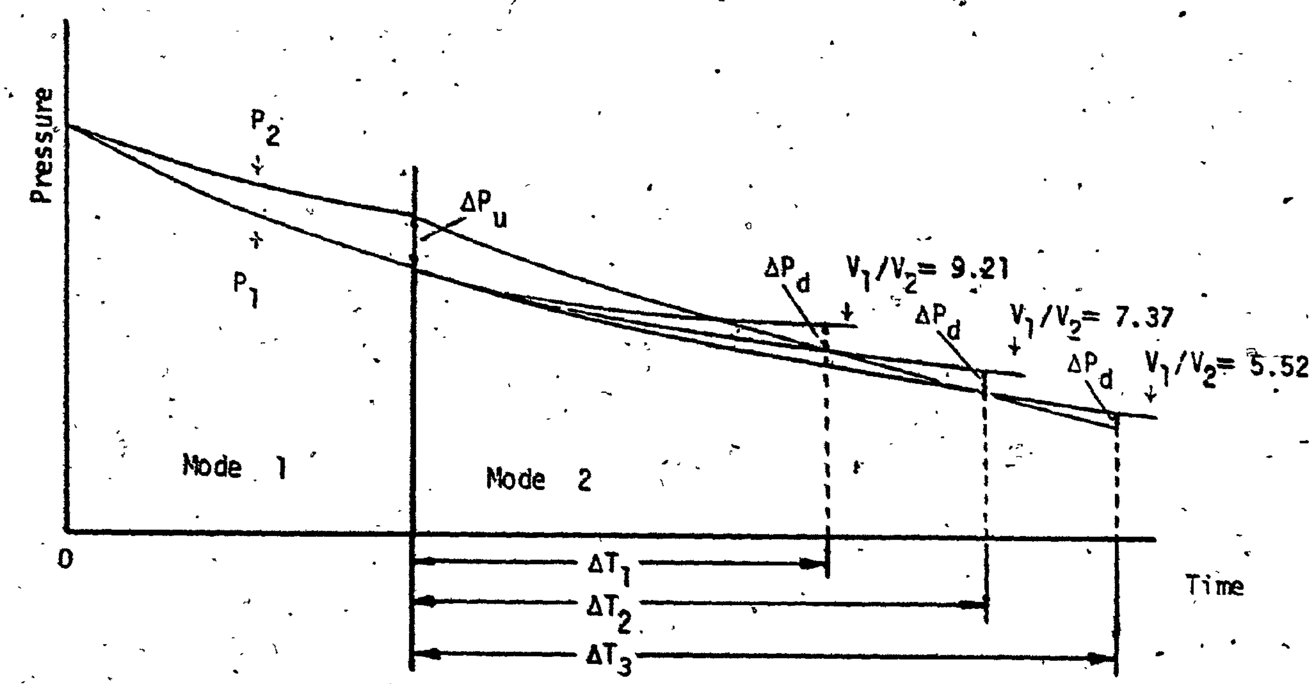

Figure 4:13 Effect of brake pipe volume vs. time rquired to switch the operation from Mode 2 to Mode 1.

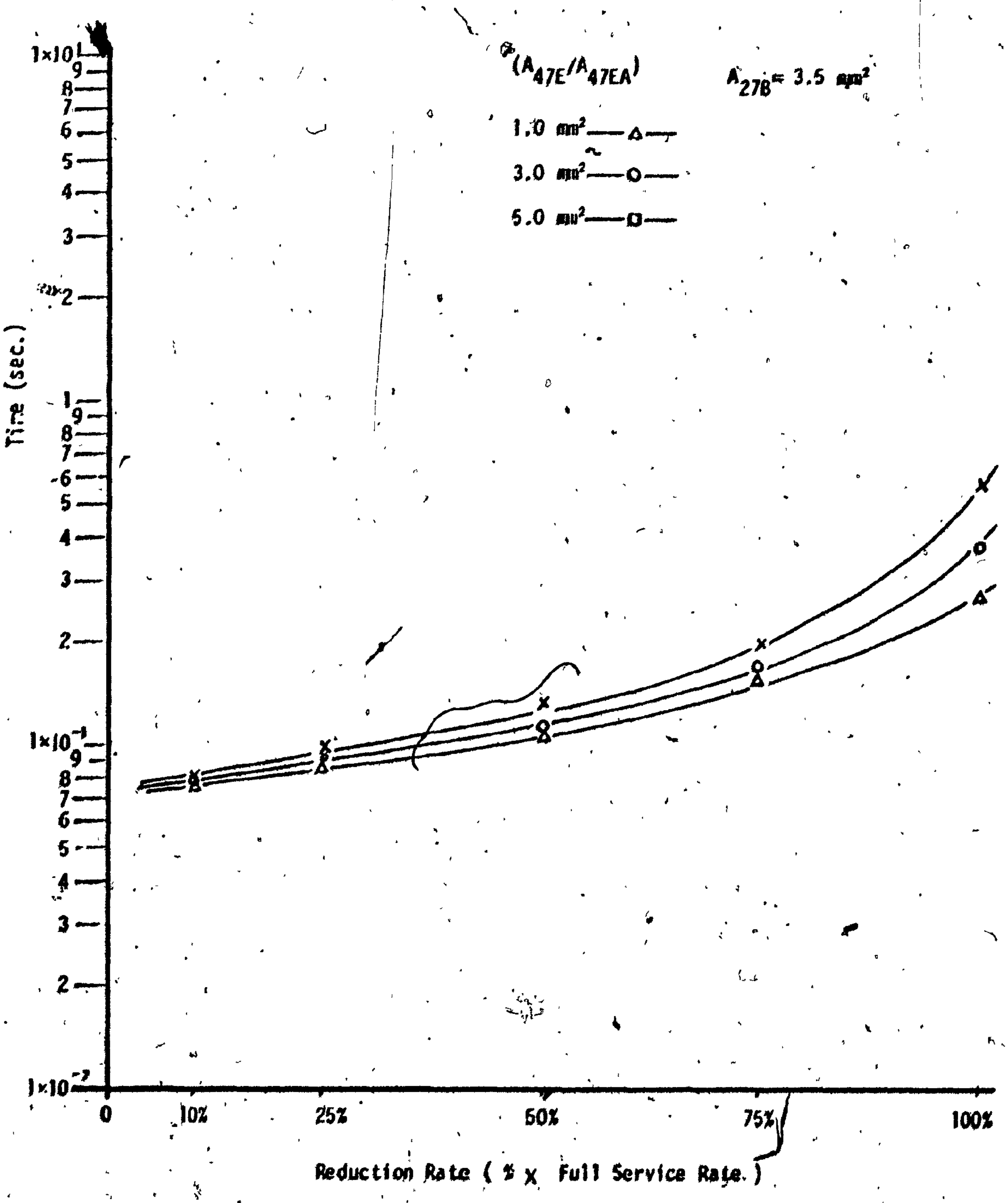

Figure 4.14 Effect of rate of reduction vs. time required to switch from Mode 2 to Mode 1 operation

Figure 4.16(a), for $A_{27B} = 3.5\ mm^2$ and $A_{47E}/A_{47EA} = 5.0,\ 3.0,\ 1.0\ mm^2$.

This phenomenon can also be explained as follows: Since the rate of reduction of the operating chamber pressure may be assumed at a constant value, the time required to switch the diaphragm assembly back to lowermost position is decreased because the decrease in the rate of reduction of brake pipe pressure causes an increase in the difference of rate of reduction of pressure between the brake pipe and the operating chamber volume (refer to Figure 4.15).

- Effect of Equivalent Orifices A_{27B} and A_{47E}/A_{47EA}

As an example of this discussion, Figure 4.16(a) may be examined closely. If the magnitude of A_{27B} is smaller than a certain value, the time required to switch back to Mode 1 operation approaches infinity, i.e., the diaphragm is maintained in its uppermost position. The limiting values of A_{27B} against the different rates of reduction of brake pipe pressure are more clearly illustrated in Figure 4.17. These values vary only very slightly with the value of A_{47E}/A_{47EA}. The diaphragm assembly will never be switched from Mode 2 to Mode 1 operation when the values of A_{27B} fall into the shaded area on the curve under different rates of reduction of brake pipe pressure. This phenomenon can be explained as follows: Referring to Figure 4.18, it is obvious that if the rate of reduction of the operating chamber pressure, which depends on the magnitude of equivalent orifice A_{27B}, is too great compared to that of the brake pipe pressure, it will never be possible for P_1 to exceed P_2, and therefore the condition of downward switching will

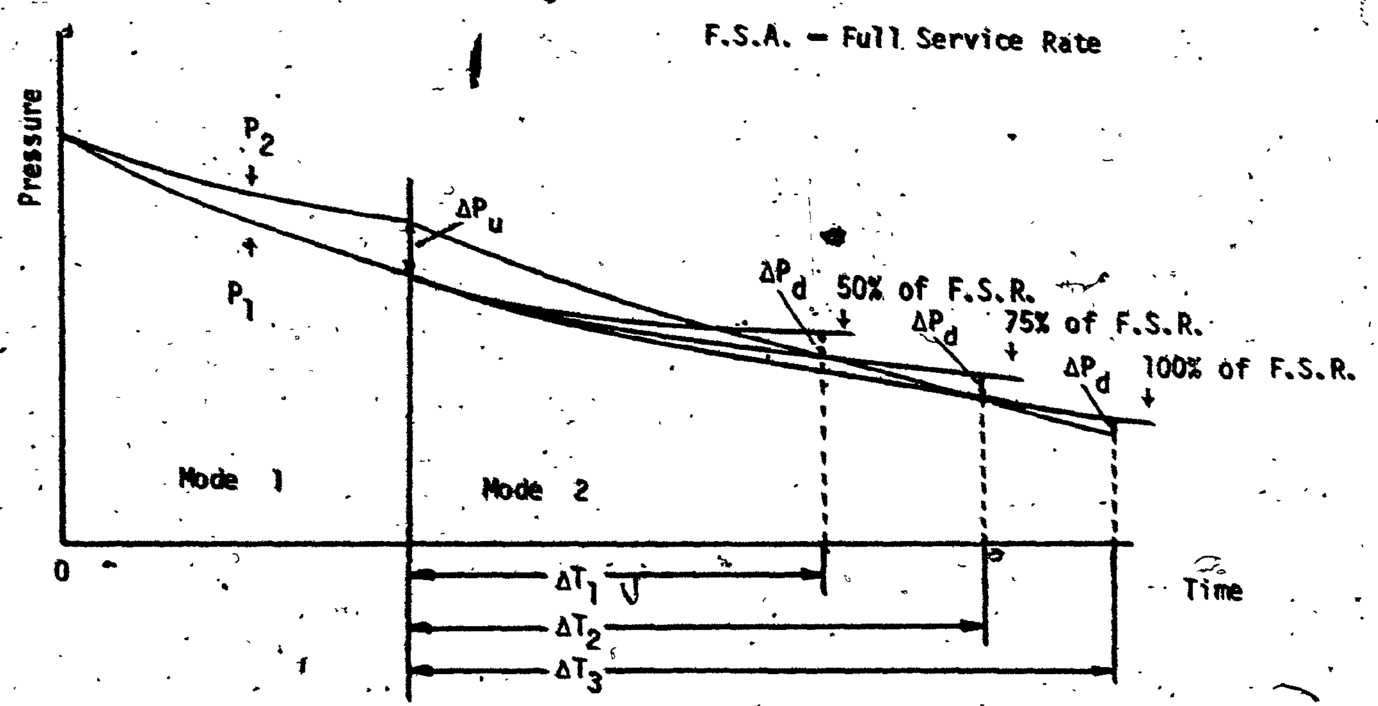

Figure [illegible]15 Effect of Rate of Reduction of Brake Pipe Pressure

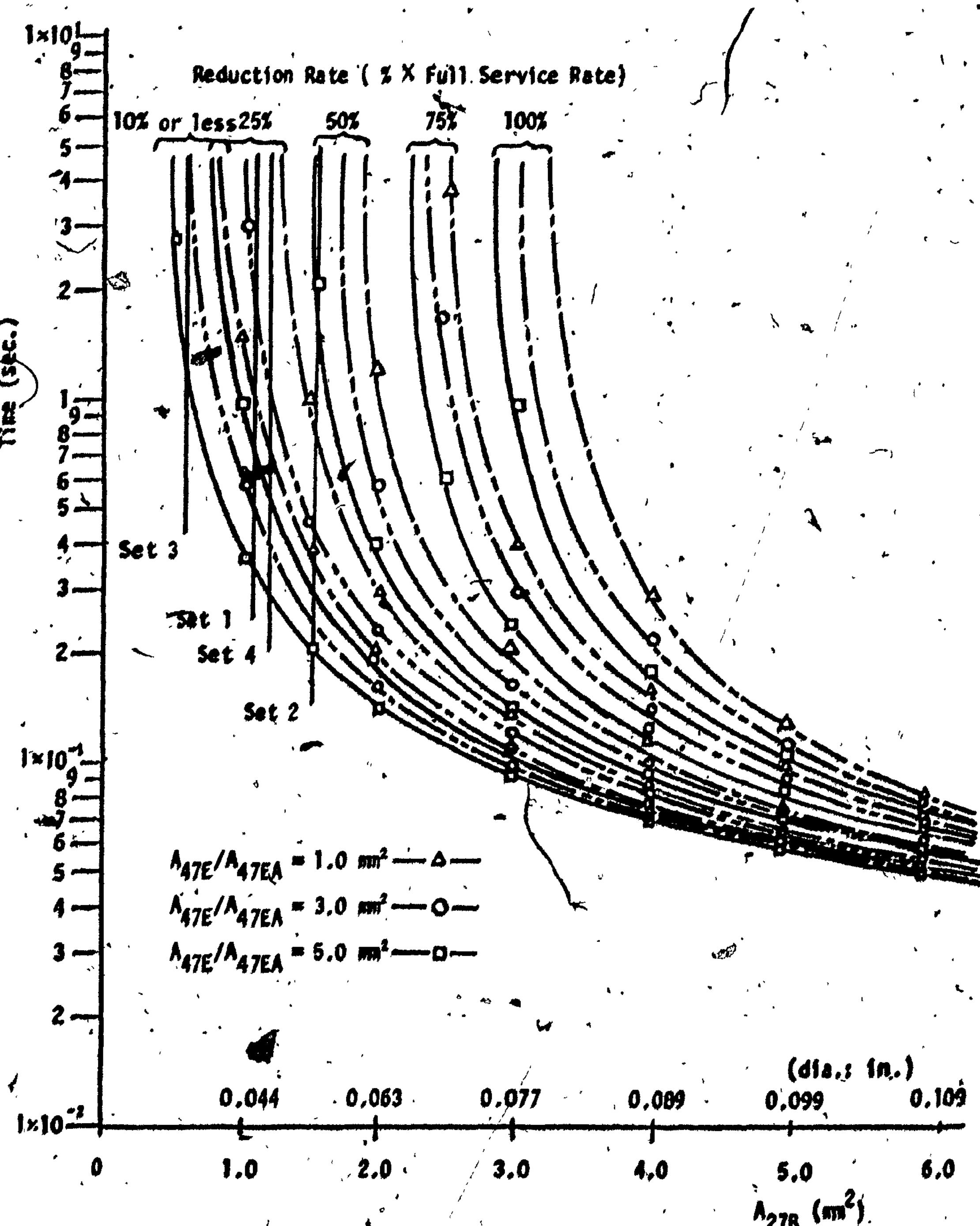

Figure 4.16(a) Time required to terminate Mode 2 operation as a function of A_{27B}, A_{47E}/A_{47EA} and rate of reduction of brake pipe pressure (for $V_1/V_2 = 9:21$)

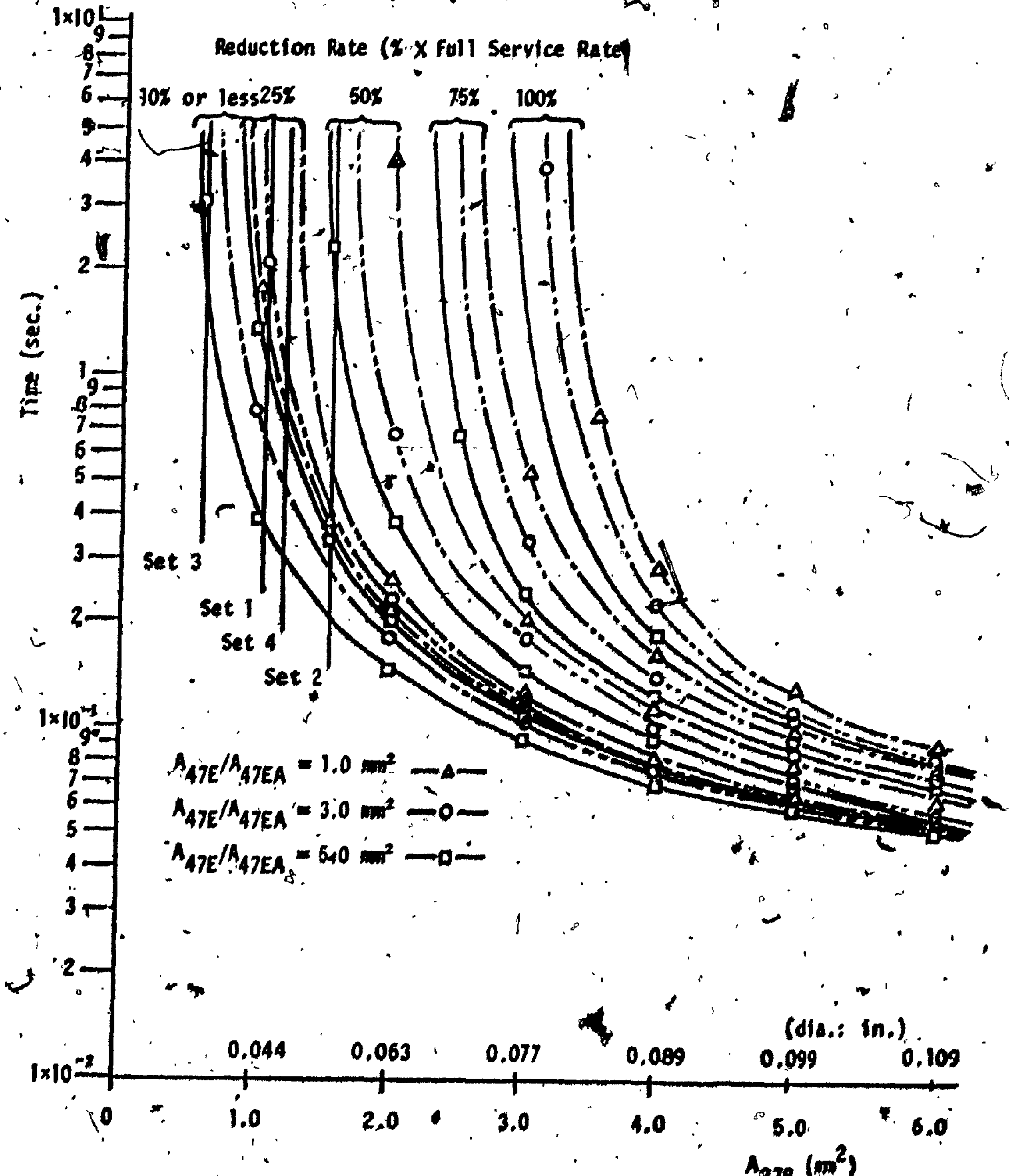

Figure 4.16(b) Time required to terminate Mode 2 operation as a function of A_{27B}, A_{47E}/A_{47EA} and rate of reduction of brake pipe pressure (for $V_1/V_2 = 7.37$)

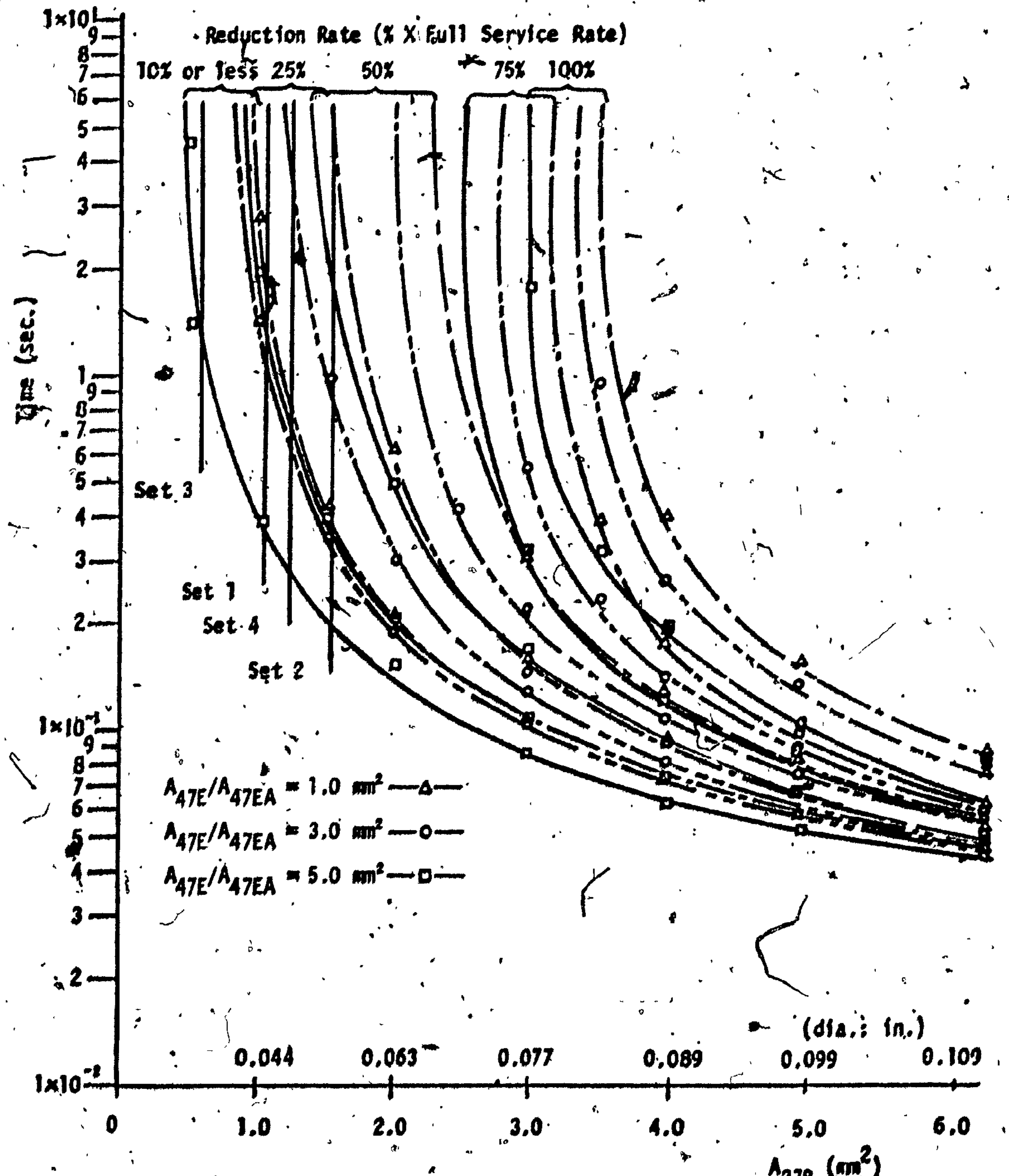

Figure 4.16(c) Time required to terminate Mode 2 operation as a function of A_{27B}, A_{47E}/A_{47EA} and rate of reduction of brake pipe pressure (for $V_1/V_2 = 5.52$)

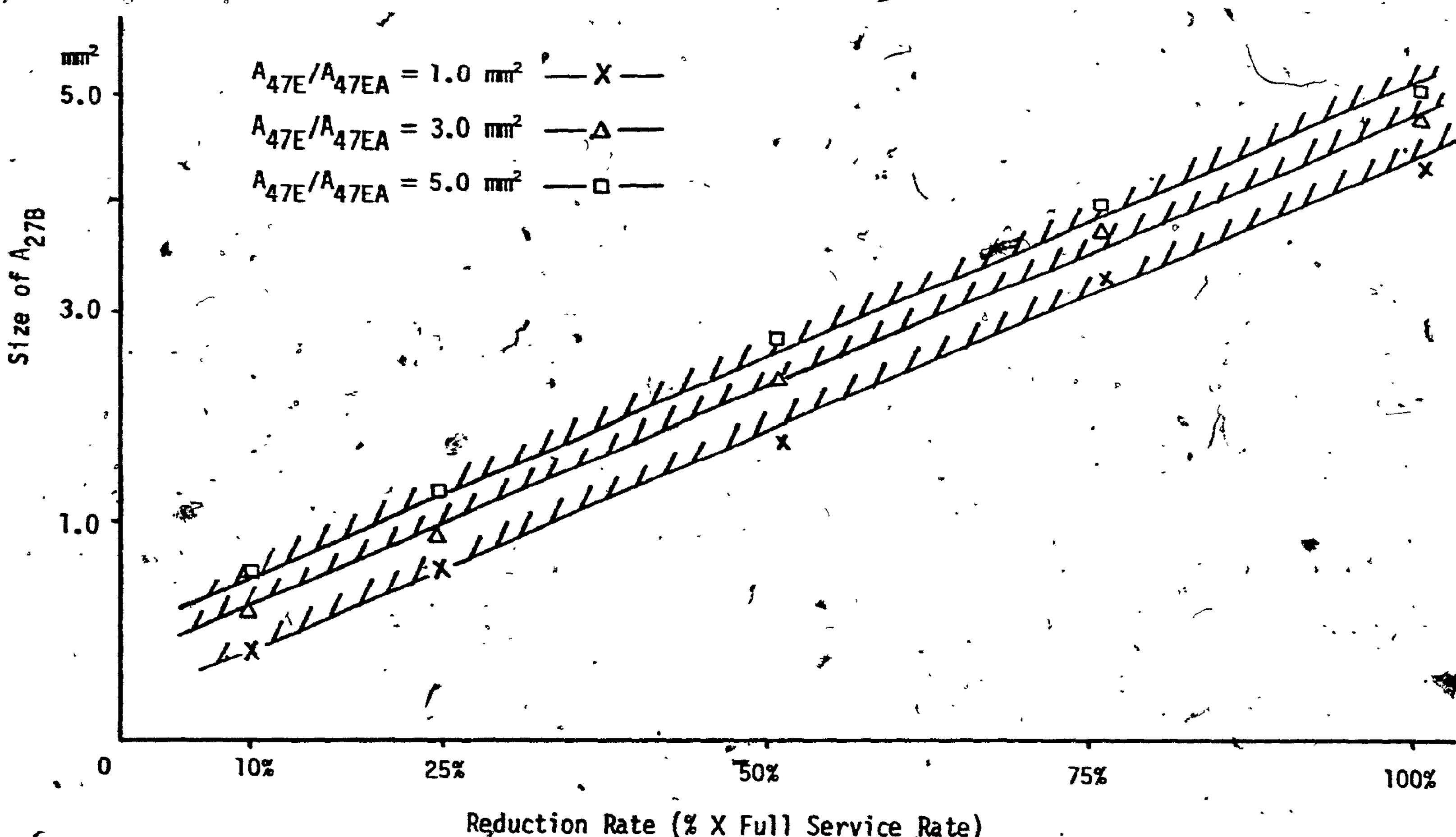

Figure 4.17 The limiting values of A_{27B} size at different rate of reduction of brake pipe pressure

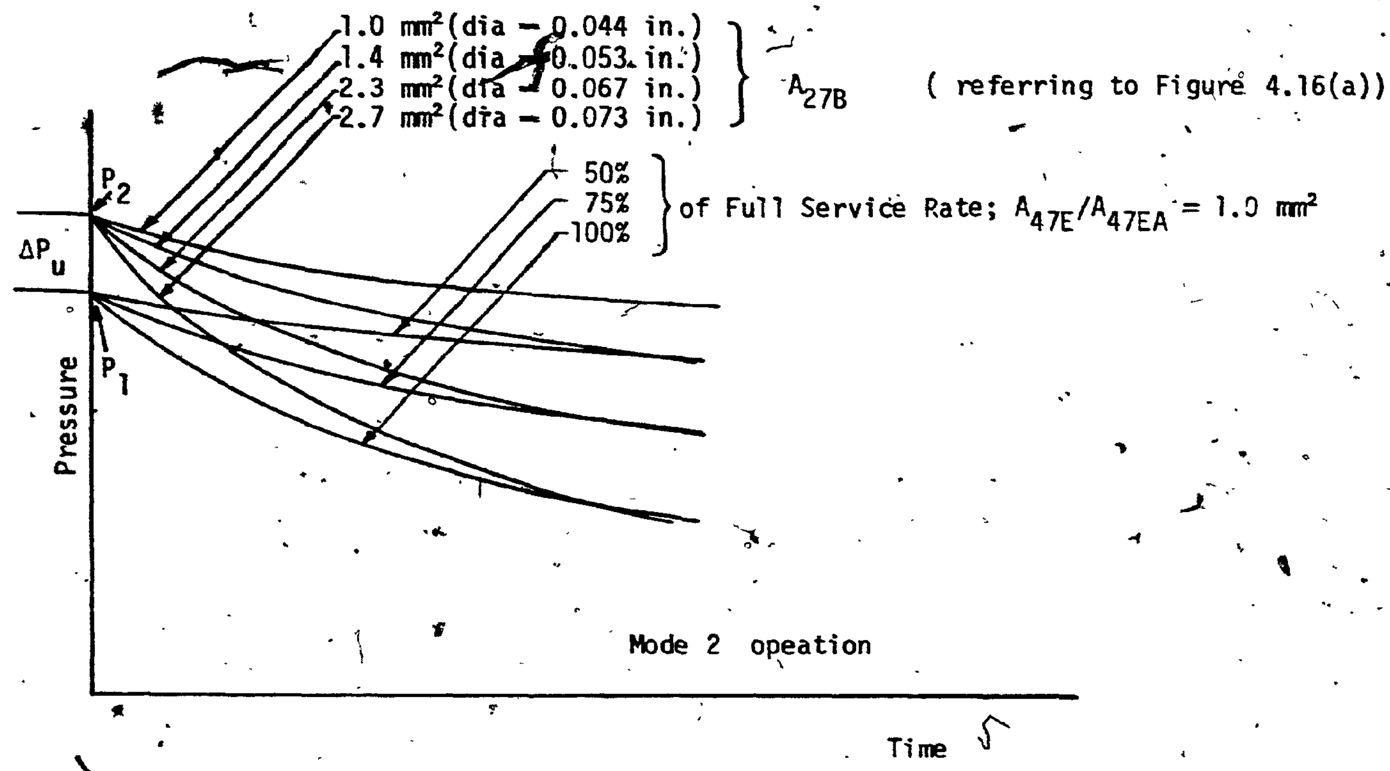

Figure 4.18 Effect of Equivalent Orifices A_{27B} and A_{47E}/A_{47EA} against the time interval of Mode 2 operation

never be satisfied.

From Figure 4.16 (a), it is found that the time required to switch the diaphragm assembly is mainly governed by the magnitude of A_{27B} rather than that of A_{47E}/A_{47EA}. As an example, if the desired time to switch the diaphragm is approximately 1.0 sec., under 100% of full service rate, the choice of magnitude of A_{27B} and A_{47E}/A_{47EA} for this is that $3.0 \sim 3.4$ mm^2 (dia. = 0.077 ∿ 0.082 in.) for A_{27B}, against $1.0 \sim 5.0$ mm^2 (dia. = 0.044 ∿ 0.099 in.) for A_{47EA}. This means that a variation of A_{27B} is 10% against 400% for A_{47E}/A_{47EA}.

4.5 CONCLUSION

In this chapter, some experimental data were first obtained to be included in the analytical model of the Q.S.V. which was developed in Chapter 2, as well as to test the validity of the assumptions made in the analysis. For instance, air resistances are treated as equivalent orifices, the effective area of which are obtained experimentally by using expression (2.5.1) and the experimental procedure described in Section 3.3. This procedure was verified against some known orifices. Subsequently, it was utilized to determine the equivalent orifice for check valves and orifices in series, with the series of pneumatic resistance also assumed to be equivalent to a single orifice. The experimental results are then found to be in good agreement with theoretical calculations based on Equation (2.5.3), (2.5.5) and (2.5.6). These experimental and theoretical results have been tabulated in Table 4.1 for easy comparison.

In Section 4.2.3, the theoretical switching conditions developed in Chapter 2 by considering force balances have been compared with the experimental data. The results are in good agreement with each other.

In order to examine the dynamic behaviour of the Q.S.V., pressure readings have been taken according to the experimental procedure described in Section 3.2. From this set of experiments, it has been revealed that the check valves situated at the two extremities of the piston assembly open and close essentially instantaneously and simultaneously. These observation confirm that assumption (f) in Appendix 1 is varid one.

Based on the numerical values of the necessary parameters which has been obtained experimentally and verified theoretically, the system equations which describe the dynamic behaviour of the Q.S.V. are then solved by using the CDC 6000 digital computer. It has been observed that the theoretical model predicts very well the actual Q.S.V. performance under service application for a range of pressure P_1 down to 30 psig; that is for the normal operating pressure range of the Q.S.V.

The theoretical model has then been utilized extensively to study the effects which some important parameters have on the performance of Q.S.V. by considering its two principal modes of operation. The results are summarized as follows.

For Mode 1 operation:

(1) For small sizes of the orifice D the time duration of this mode may be considered to be faily independent of the car length or volume ratio V_1/V_2 (refer to Figure 4.10)

(2) Increase in rate of reduction of brake pipe pressure decreases the duration of Mode 1 operation if the size of orifice D remains the same. (refer to Figure 4.11)

(3) Increase in size of orifice D increases the duration of Mode 1 operation. In fact, for each rate of reduction of brake pipe pressure, there is a limiting size of orifice D, above which the duration becomes infinite. In other wards, the Q.S.V. will not switch to Mode 2 operation at all.

It has also been observed that, from Figure 4.11, the Q.S.V. which employed as orifice D according to the present schedules as given in Table 2.1 will be placed into operation for a reduction rate, or leakage rate of under 5 psi/min. On the other hand, according to the proposed schedule, the Q.S.V. will not react to 5 psi/min. but to 8 psi/min. or more.

For Mode 2, more parameters dominate the operation. These include car length, (or volume ratio V_1/V_2), reduction rate of brake pipe pressure and combined equivalent orifices A_{27B} and A_{47E}/A_{47EA}.

(1) Increase in volume ratio slightly decreases the duration of Mode 2 operation. (refer to Figure 4.12)

(2) Increase in reduction rate of brake pipe pressure increases the duration of Mode 2 operation. (refer to Figure 4.14)

(3) The duration of Mode 2 operation is related to the size of A_{27B} in the form of a family of rectangular hyperbolic curves, with the rate reduction of brake pipe pressure. (including leakage), and the size of A_{47EA} as parameters. (refer to Figure 4.16(a), (b), and (c))

(4) There is a lower limit on the value of A_{27B}, for switching to be possible from Mode 2 to Mode 1 operation at each rates of reduction of brake pipe pressure. (refer to Figure 4.17)

Furthermore by studying Figure 4.16, it is found that according to the value of A_{27B} as given in the proposed schedule (Set 2 and 4 as listed in Table 2.1) the Q.S.V. can react to lower rates of reduction of brake pipe pressure as against the present schecules (Set 1 and 3) and do so with a shorter duration of Mode 2 operation.

CHAPTER 5

TUNING PROCEDURE OF THE QUICK SERVICE VALVE

5.1 INTRODUCTION

The dynamic behaviour of the Q.S.V. depends on a number of variables such as rate of reduction of brake pipe pressure, volume ratio between the brake pipe and operating chamber in the Q.S.V. and tuning the timing orifices. This Chapter is, however, only concerned with the tuning of timing orifices when the Q.S.V. is operating under service application rate. This Chapter is, therefore, devoted to determining the proper size of timing orifices in order to obtain a desirable performance of the Q.S.V.

Before proceeding with the formulation of the problem, the two conditions for satisfactory operation of the Q.S.V. should be understood, and they are listed as follows:

1. The Q.S.V. must not respond to brake system leakage rate.
2. The Q.S.V. must not create an "emergency" rate during "service" application.

These requirements can be met by a proper selection of the sizes of the timing orifices. In order to determine the timing orifices of the Q.S.V. with desirable performance, the following information is required:

(i) Brake system leakage rate during train operation;

(ii) Length of car, in other words, the volume ratio as discussed in Chapter 4;

(iii) Magnitude of the rate of reduction of brake pipe pressure corresponding to the full service rate (70 to 50 psig in 1.4 seconds, see Ref. 1);

(iv) Time required to develop a sufficient pressure differential across the diaphragm to switch the latter from one position to the other, and vice versa.

This information may be used in the following manner:

- From the information concerning the brake pipe system leakage rate and the length of the car, it is possible to determine the size of orifice D.

- With knowledge of the rate of reduction of brake pipe pressures and the length of the car, magnitude of combined equivalent orifice A_{47E}/A_{47EA} can be obtained to provide service operation without creating an emergency rate.

- After the magnitude for A_{47E}/A_{47EA} has been established, it is possible to determine the magnitude of A_{27B} depending on the time specified to switch the operation from Mode 2 to Mode 1, and the rate of reduction of brake pipe pressure.

It is not intended, however, to cover all possible cases, but to show only the basic principles of the tuning procedure by way of an example. As an example, it is assumed that the following information is available.

(i) Brake system leakage is assumed at 5 psi/min. in the worst case.

(ii) Car length is assumed to be 100 feet long.

(iii) Rate of reduction of brake pipe pressure is assumed to be 100% of full service rate (an initial reduction of 70 to 50 psig in 1.4 seconds).

(iv) Time required to switch the operation from Mode 2 to Mode 1 is assumed to be approximately 0.5 seconds.

This Chapter is organized as follows. Section 5.2 discusses the determination of size of orifice D; the magnitude of combined equivalent orifices A_{47E}/A_{47EA} and A_{27B} are determined in Section 5.3 and Section 5.4 presents the flow chart of the tuning procedure as a summary.

5.2 DETERMINATION OF SIZE OF ORIFICE D

In order to determine the size of orifice D, the following conditions and values assumed in the example are:

1. The Q.S.V. must not respond to brake system leakage rate.
2. Brake system leakage is assumed at 5 psi/min. in the worst case.
3. Car length is assumed to be 100 feet.

Figure 5.1 shows the maximum and minimum sizes of orifice D for satisfactory operation under Mode 1 operation. The shaded area at each curve corresponding to the size of orifice D, indicates that the Q.S.V. does not operate satisfactorily. It provides the limiting value

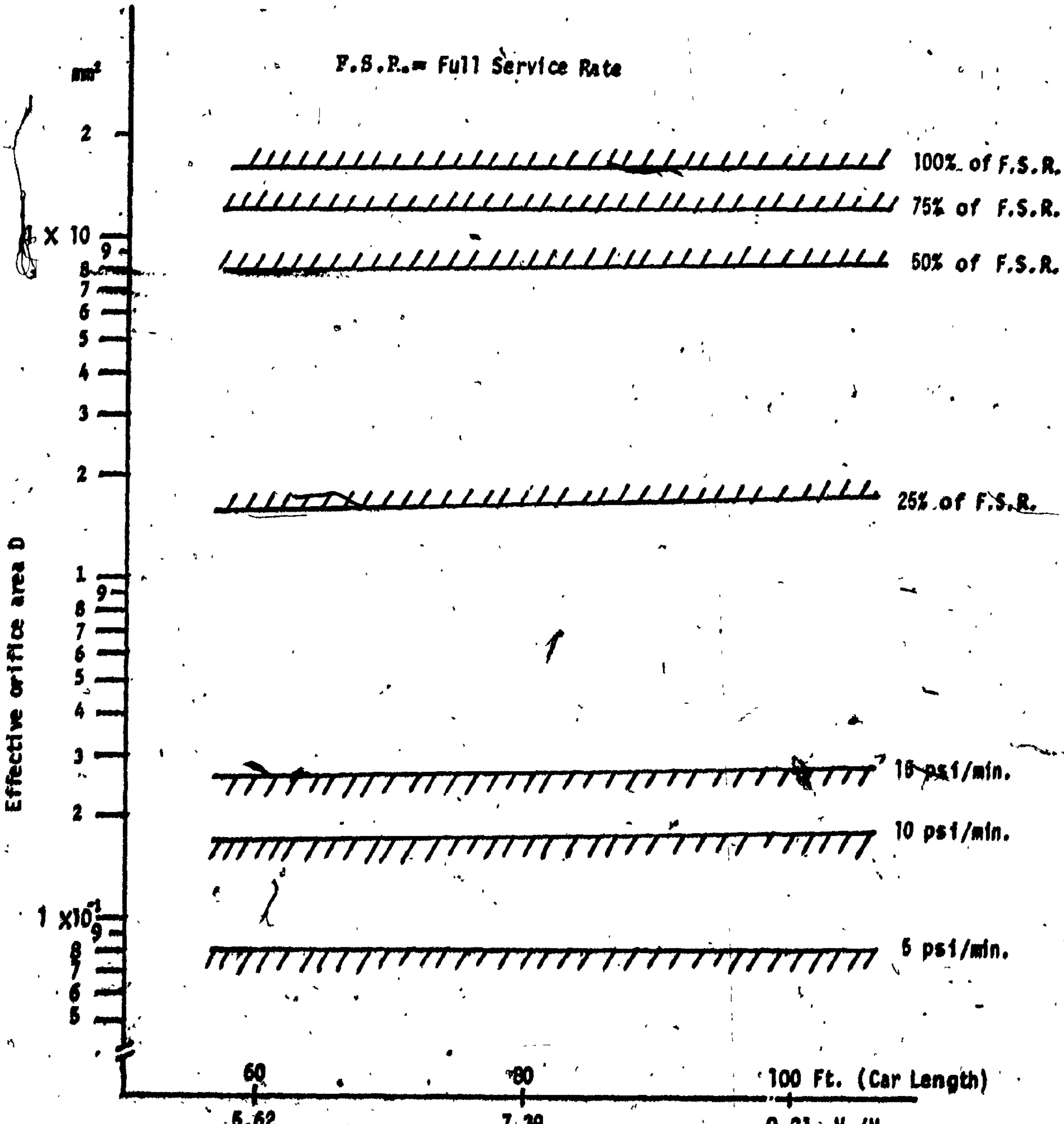

Figure 5.1 Limitation of size of orifice D

of the orifice size D for different car lengths and at different rates of brake pipe pressure reductions, above which the Q.S.V. will take an infinite period of time to switch from Mode 1 to Mode 2 operation. The curves in Figure 5.1 are obtained with reference to Figure 4.11, by taking vertical asypmtotes to the family of curves (size D vs. time). One notes two families of curves in Figure 5.1. The upper family corresponds to rates of service application. If a Q.S.V. is to react to a certain maximum rate, say 50% of full service application, the orifice D must not be larger than the values shown by the line for 50% of full service application. It should lie below it, otherwise, according to Figure 4.11, the Q.S.V. will remain in its Mode 1 condition indefinitely. Thus this family of curves sets the upper limit to the choice of orifice D.

On the other hand, the lower family of curves in Figure 5.1 corresponds to leakages in the brake system. If a train is not to react to a system leakage rate greater than, say, 5 psi/min., then orifice D must not take on a value which is smaller than those indicated by the 5 psi/min. line in Figure 5.1. This family of curves therefore sets the lower limit for the orifice D. Consequently, the size of orifice D, for the present example, should be between approximately 0.08 mm^2 (dia. = 0.013 in.) and less than approximately 1.6 mm^2 (dia. = 0.06 in.). From a sensitivity point of view, it is desirable that the size of orifice D be as close as possible to the lower value. Such an orifice D gives a quicker response of the Q.S.V. operation. In this case, let us take the size of orifice D to be approximately 0.1 mm^2 (dia. = 0.014 in.)

to avoid drilling too small a hole. From Figure 4.11, the time required to switch the operation from Mode 1 to Mode 2 at the very first cycle, can be found to be less then 0.1 second.

5.3 DETERMINATION OF COMBINED EQUIVALENT ORIFICES A_{47E}/A_{47EA} and A_{27B}

The combined equivalent orifices A_{47E}/A_{47EA} and A_{27B} determine the time required to switch the operation from Mode 2 to Mode 1, as demonstrated in Figure 4.16 of Chapter 4. In order to determine the magnitude of A_{47E}/A_{47EA} and A_{27B}, the following conditions and specifications in the example must be considered:

(i) The Q.S.V. must not create an "emergency" rate during "service" application.

(ii) The car length is assumed as 100 feet long.

(iii) Rate of reduction of brake pipe pressure is assumed at 100% of full service rate (70 to 50 psig in 1.4 seconds, see Ref. 1).

(iv) The time required to switch the operation from Mode 2 to Mode 1 is assumed to be approximately 0.5 second.

Figure 5.2 shows the limiting magnitude of combined equivalent orifice A_{47E}/A_{47EA}. The construction of this curve is explained in Appendix 7. The shaded area at each curve corresponds to the magnitude of A_{47E}/A_{47EA} which will create an emergency situation when the train is reacting to the service rate indicated by that curve. In the present case, A_{47E}/A_{47EA} is found to be slightly less than 3.8 mm² (dia.= 0.87 in.) as indicated by the point X in Figure 5.2. In the present case, let us take the values of A_{47E}/A_{47EA} to be 3.5 mm². The size of orifice A and orifice E can be chosen arbitrarily, as long as the

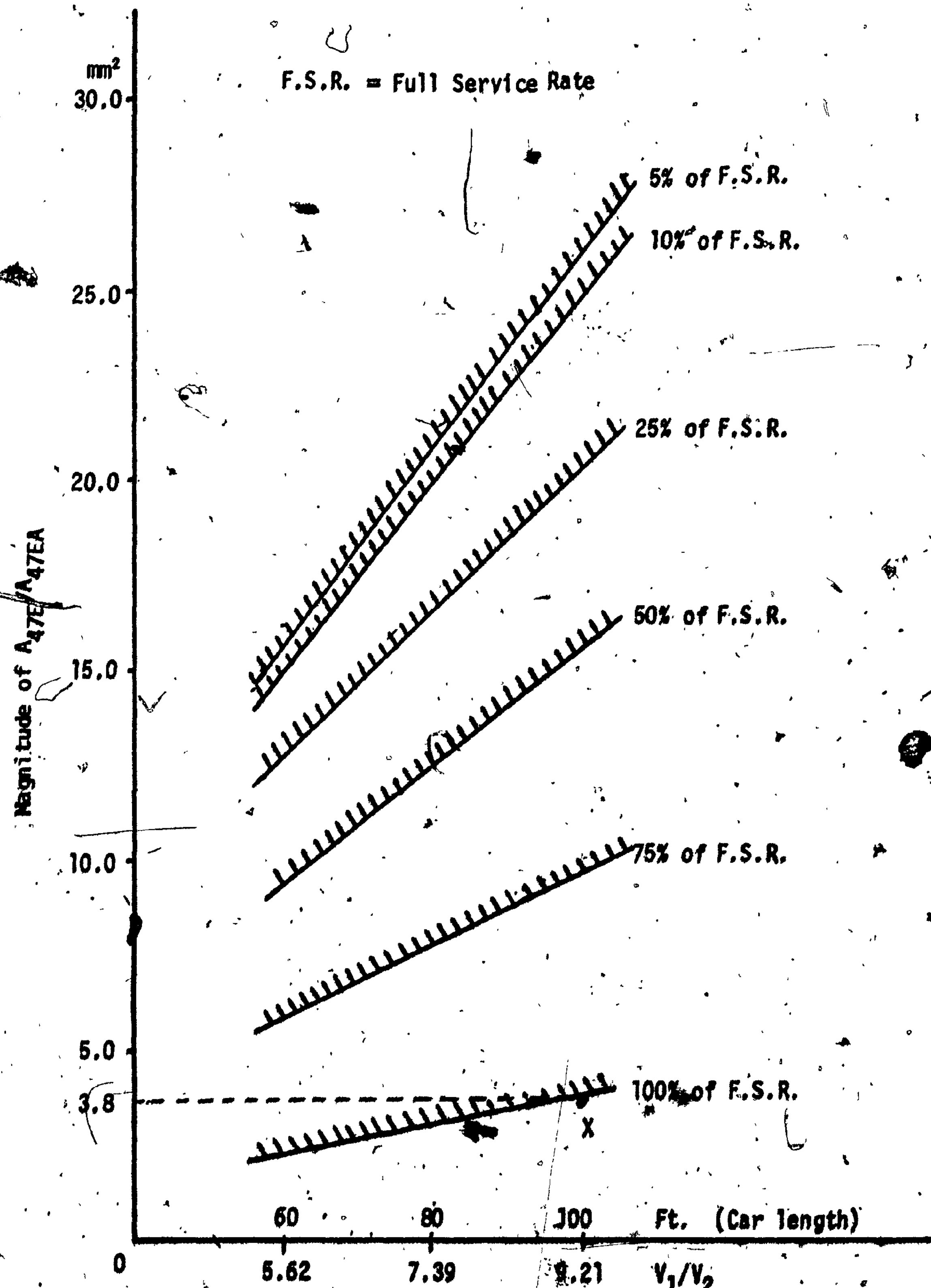

Figure 5.2 The limitation of Combined equivalent orifice A_{47E}/A_{47EA} Equation (A7.7)

combined equivalent orifice A_{47E}/A_{47EA} is 3.5 mm² in area. These values of A and E can be found from Figure 5.3(a) which is based on Eqn. (2.5.5). For this case, orifice E = 4.6 mm² and orifice A = 7.0 mm², is one possible set of solutions as indicated by point Y in Figure 5.3(a). In absence of orifice A, Figure 5.3(b) is utilized to determine the orifice E. Figure 5.3(b) is based on Eqn. (2.5.3). For this case, orifice E = 3.9 mm² approximately.

To help determine the size of A_{27B}, one can make use of the series of curves in Figure 4.16 in the previous Chapter. For the present case, Figure 4.16(a) has been reproduced as Figure 5.4 for a car length of 100 feet. It shows the relation between A_{27B} and the time required to return to Mode 1 operation, having service rates and the size of A_{47E}/A_{47EA} as parameters. It should be noted here that the size of orifice D does not appreciably affect these curves, which depict the Q.S.V. performing in the Mode 2 operation. The magnitude of A_{27B} is determined as follows. The intersection Z between the horizontal line for time=0.5 second and the interpolated curve for A_{47E}/A_{47EA} = 3.5 mm² at 100% of full service application rate gives the magnitude of A_{27B} as approximately 3.4 mm² (dia. = 0.081 in.). The orifice B which is in series with the check valve C_{27}, can be obtained from Figure 5.5, which is based on Eqn. (2.5.3) and a check valve area of 4.143 mm². The size of orifice B has been found to be 6.0 mm², as indicated by the point Q in the figure.

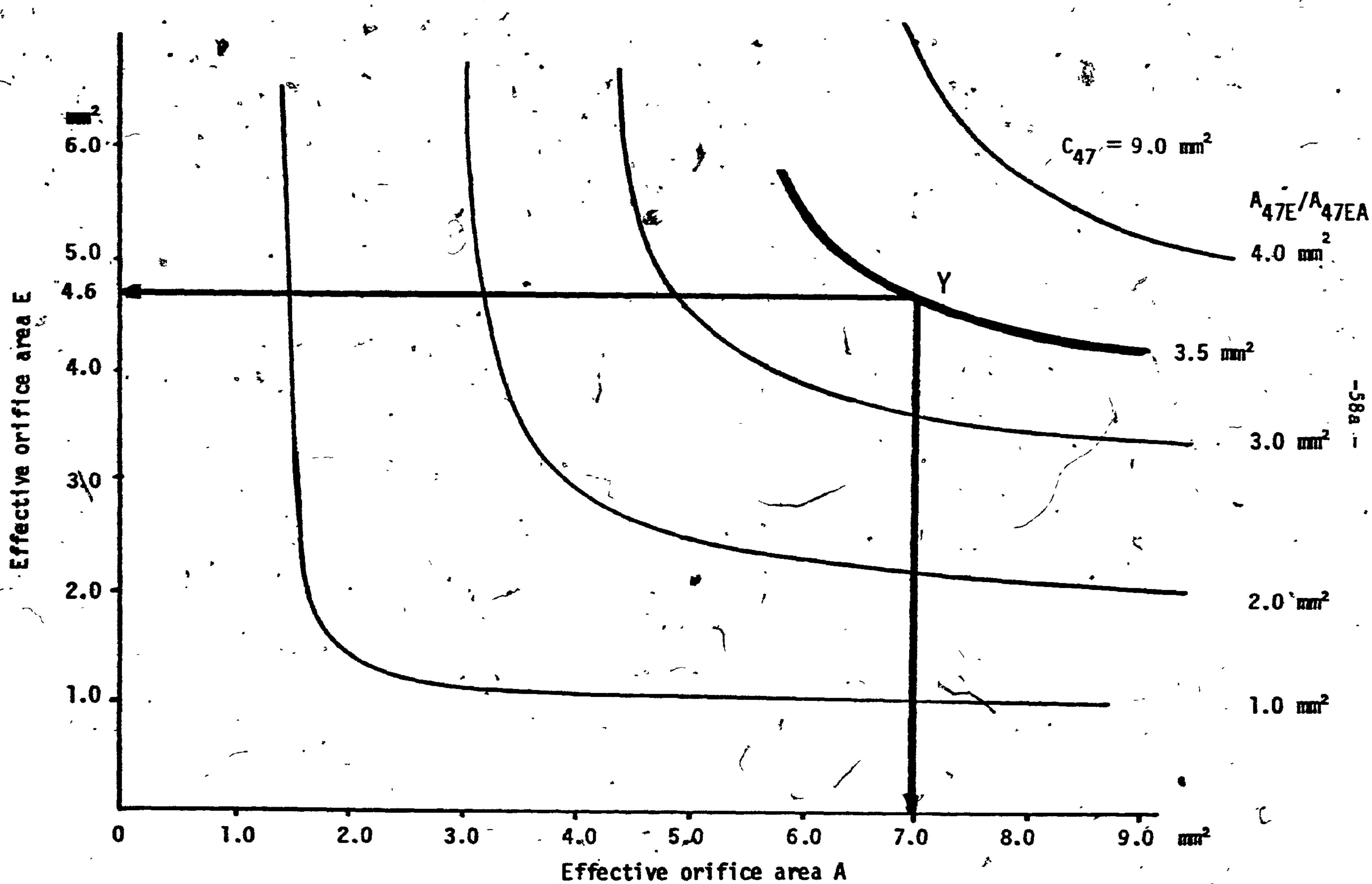

Figure 5.3(a) Relation of orifice E and orifice A against the parameter A_{47E}/A_{47EA} : Equation (2.5.5)

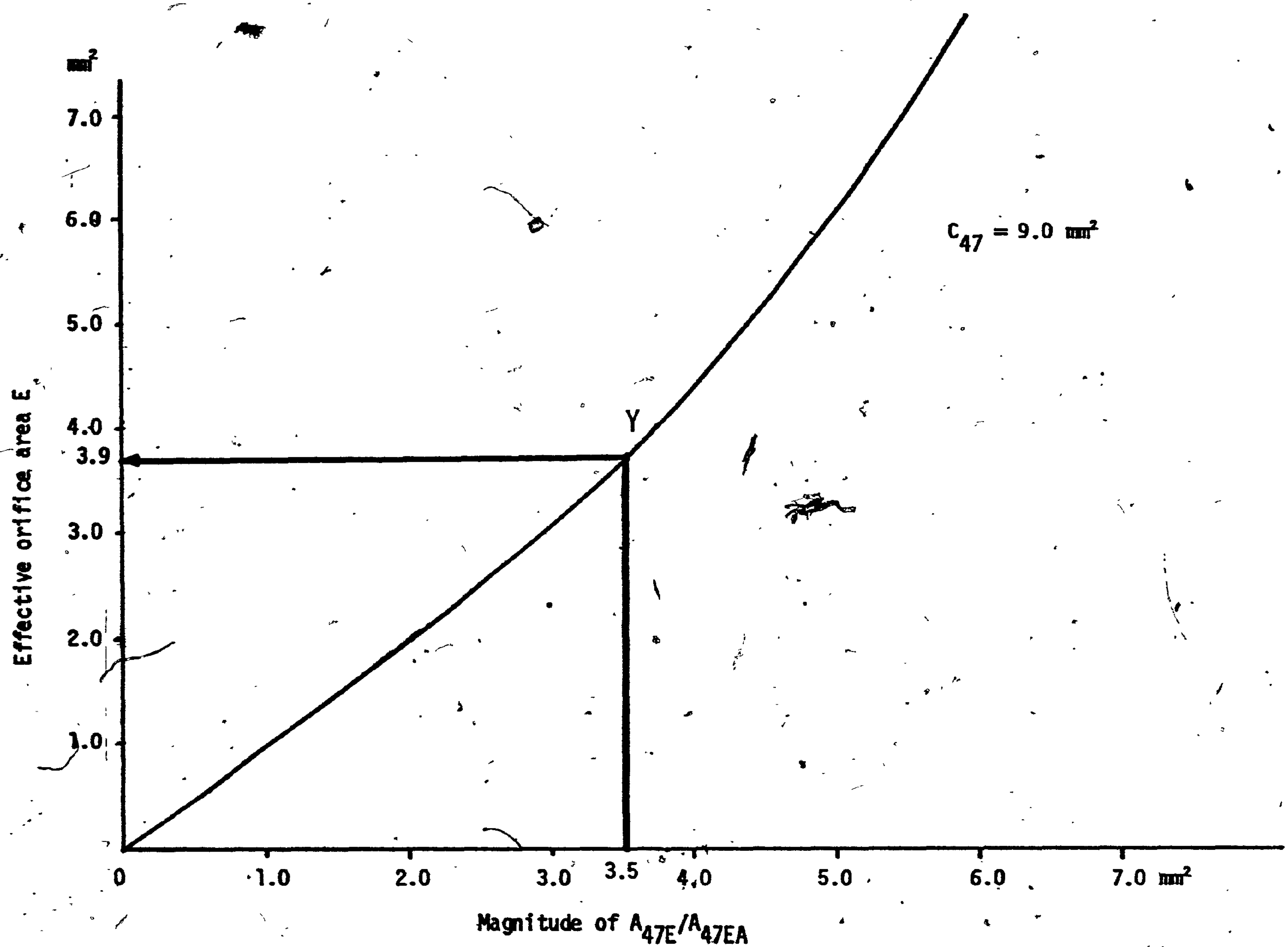

Figure 5.3(b) Relation between the orifice E and magnitude of A_{47E}/A_{47EA}; Equation(2.5.3)

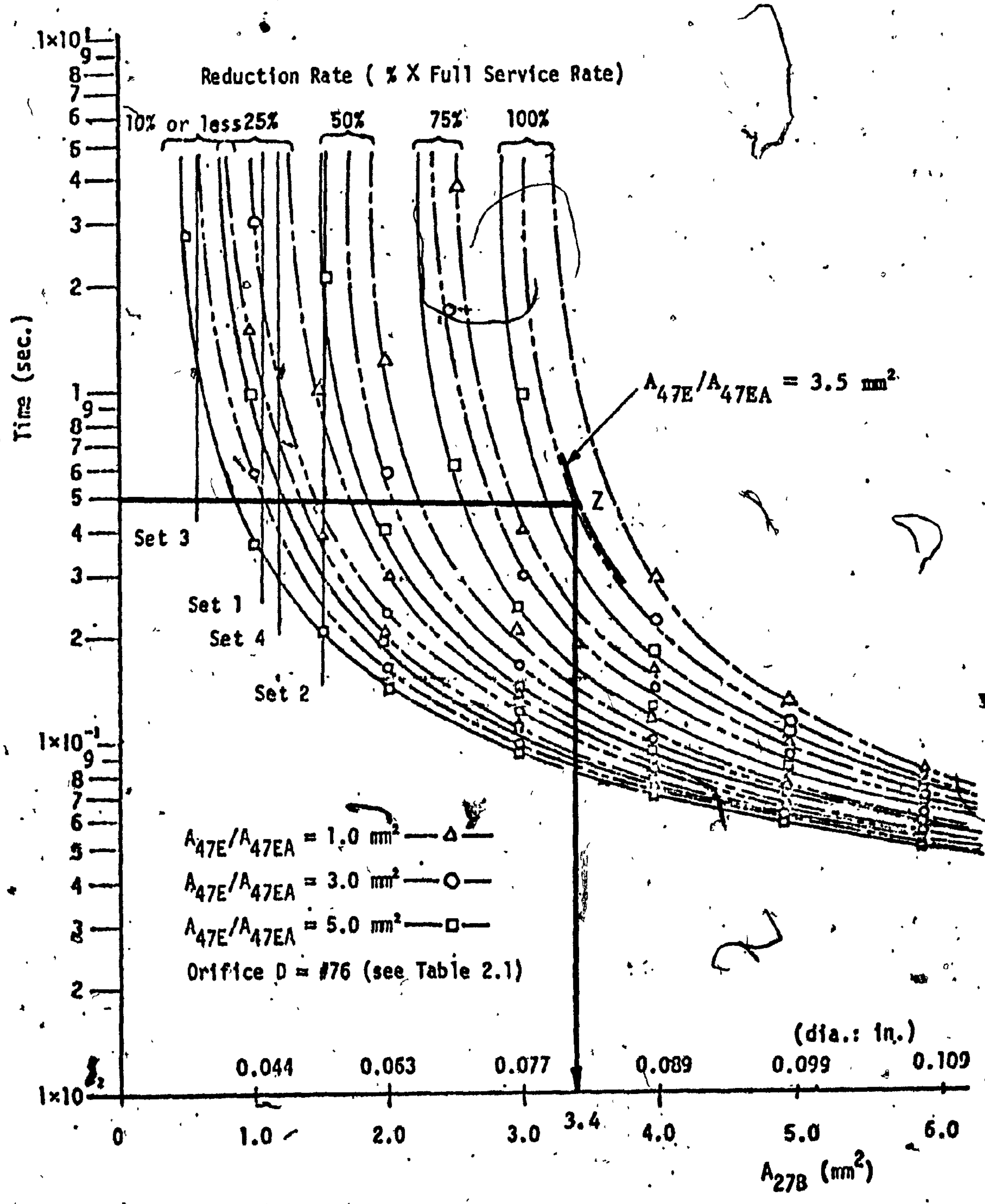

Figure 5.4. Relation between A_{27B} and the time required to return to Mode 1 operation

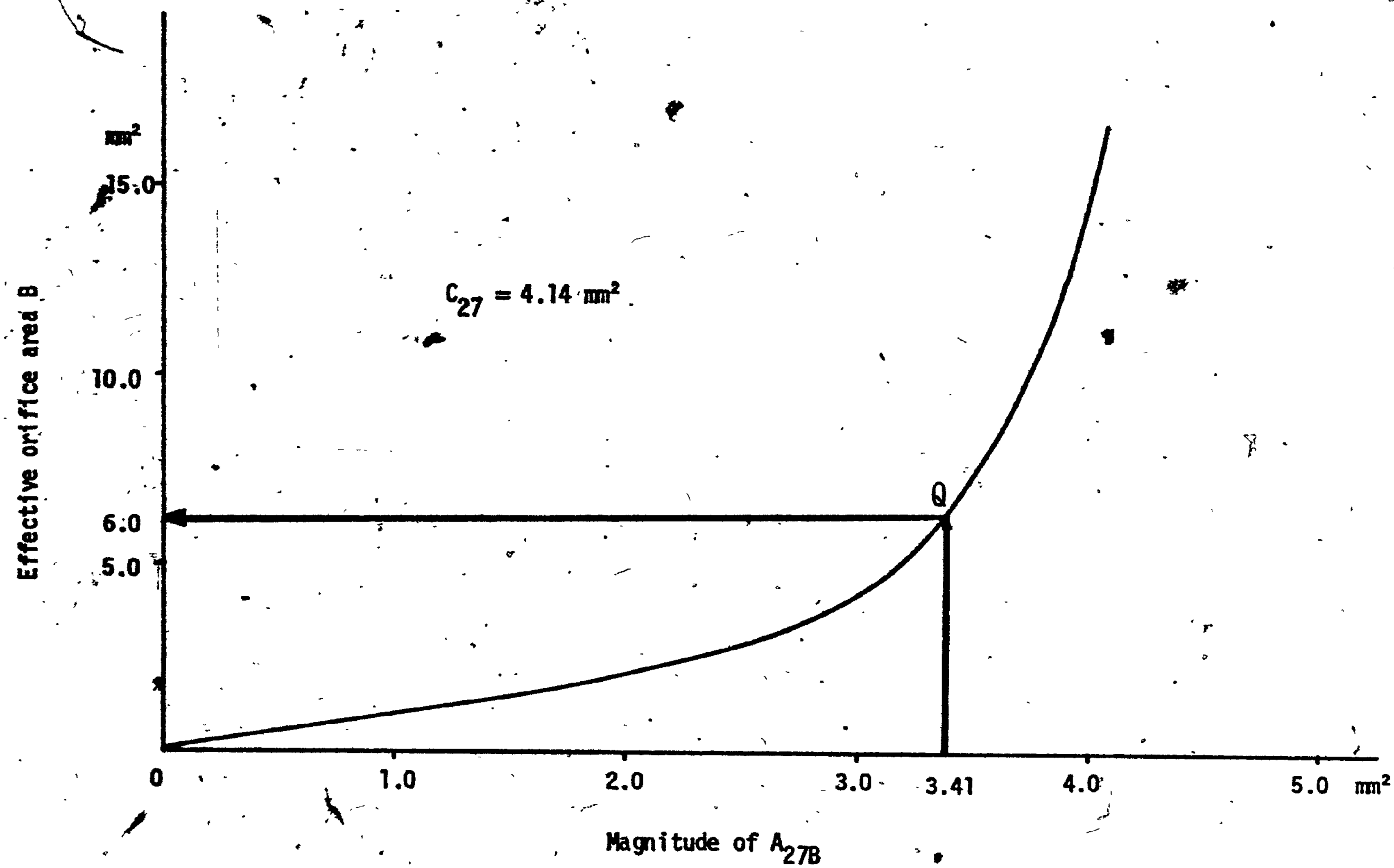

Figure 5.5 Relation between the orifice B and magnitude A_{27B}; Equation (2.5.3)

5.4 VALIDATION OF TUNING PROCEDURE AND CHECK FOR EMERGENCY RATE

For the present example, the results of applying the tuning procedure are summarized in Table 5.1. These results have been utilized in the simulation program developed in Chapter 2 to test for the validity of the tuning procedure. The simulation program is outlined in Appendix 8. The simulation results are summarized as Figures 5.6, 5.7 and 5.8, which show the sequence of oscillation simulated,(as in Figure 4.8 with time), the brake pipe pressure P_1 also as a function of time, as well as the instantaneous rate of reduction of brake pipe pressure dP_1/dt as a function of the brake pipe pressure P_1. It is observed from Figure 5.6 that the time duration t_a is 0.04 second approximately at the very first cycle to switch the Q.S.V. into Mode 2 operation, and that t_b is 0.5 second approximately, as the duration of Mode 2 operation.

From Figure 5.8, it is observed that the pressure reduction rate of the train in question is above the limiting curve for emergency rate. Therefore, according to the principle discussed in Appendix 7, Section A7.3, the Q.S.V. does not create any emergency situation. Summarizing, the tuned set of orifices proposed by the tuning procedure outlined above, are satisfactory.

5.5 CONCLUSION

By the example utilized in the foregoing section, it is obvious that the tuning procedure for the timing orifices are satisfactory. The tuning procedure is outlined in the following flow chart as summary.

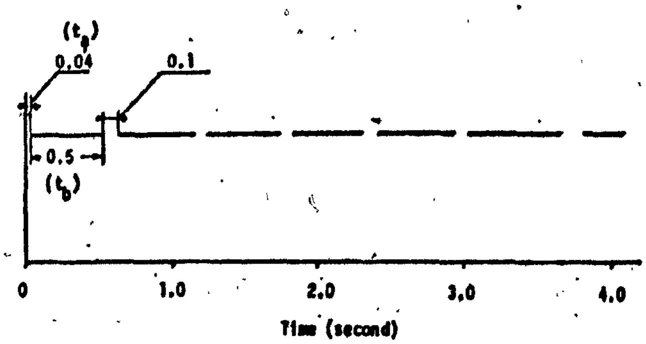

Figure 5.6 Simulated result of sequence of oscillation of the Quick Service Valve

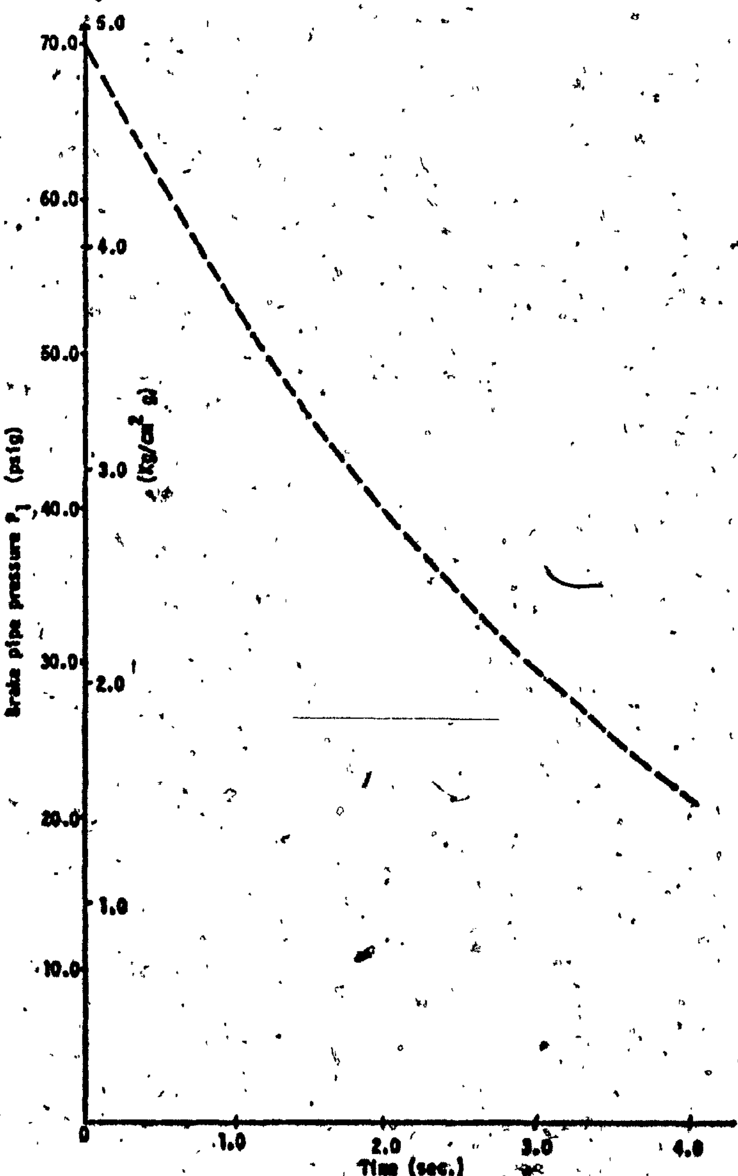

Figure 5.7 Simulated result for Brake pipe pressure P_1

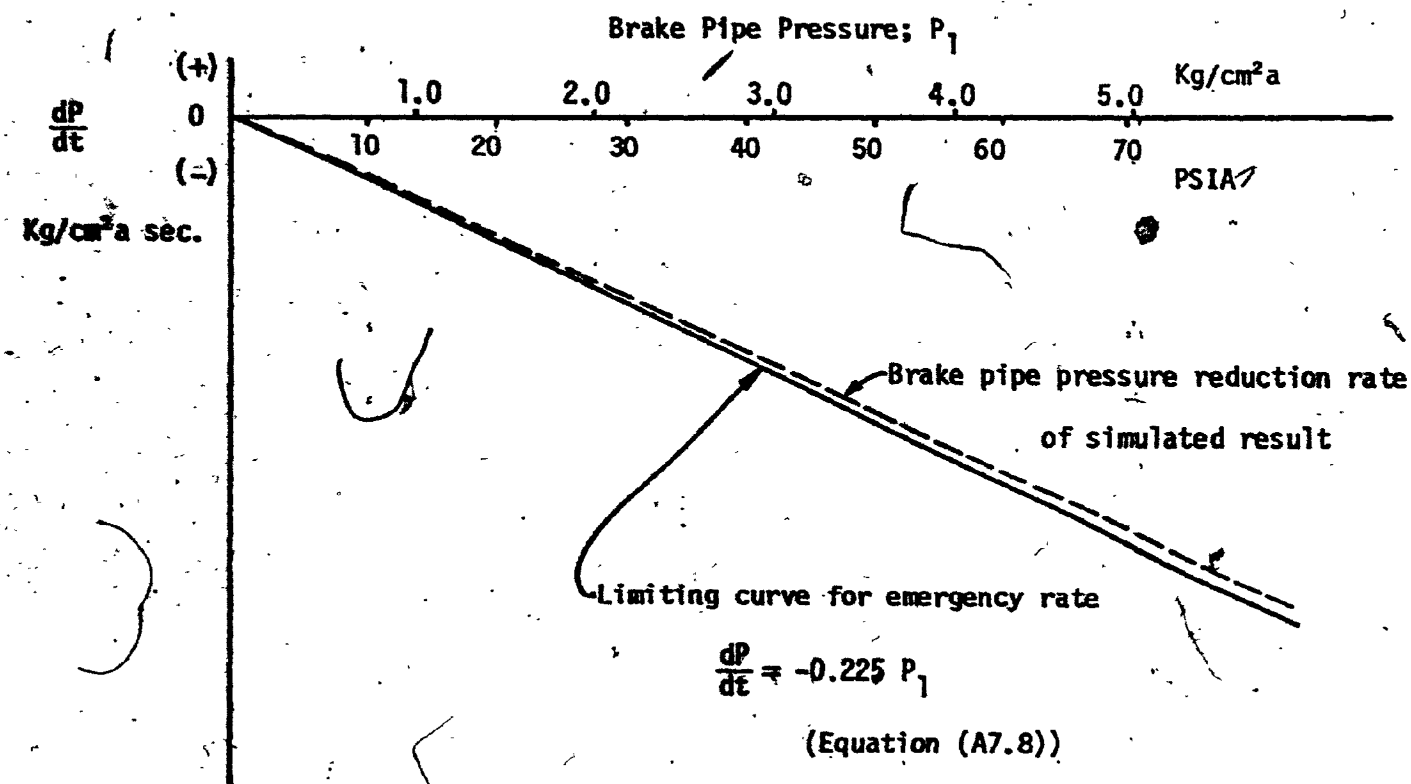

Figure 5.8 Brake pipe pressure reduction rate of simulated result as compared with emergecy rate.

Obtaining information required:

1. Brake system leakage rate during train operation.
2. Car length.
3. Rate of reduction of brake pipe pressure corresponding to the full service rate(1).
4. Desired time required to switch the operation from Mode 2 to Mode 1.

↓

Determination of orifice D:

1. Use Figure 5.1.
2. From the infromation concerning (1) & (2) above, determine the size of orifice D as close as possible to the brake system leakage referance curve.
3. Use Figure 4.11.
4. By using the value of D obtained above, the time required to switch the operation from Mode 1 to Mode 2 can be found.

↓

Determination of magnitude of A_{47E}/A_{47EA}:

1. Use Figure 5.2.
2. From the condition concerning (2) & (3) above, obtain a limiting maximum of magnitude of A_{47E}/A_{47EA}.
3. Use Figure 5.3(a) or (b) to determine size of orifices A and E.

↓

Determination of magnitude of A_{27B}:

1. Use Figure 5.4.
2. From the specification of the example concerning (4) and by using the value of A_{47E}/A_{47EA} obtained above, the intersection of horizontal line for time and the curve of A_{47E}/A_{47EA} at the required reduction rate gives the magnitude of A_{27B}.
3. Use Figure 5.5 to determine orifice B.

SPECIFICATIONS	
Brake pipe system leakage	5 psi/min.
Rate of reduction of brake pipe pressure corresponding to full service application.	100%
Car length	100 feet
Duration between Mode 2 and Mode 1 operation	0.5 sec.

PROPOSED ORIFICE SCHEDULE		
ORIFICE		SIZE (mm^2)
D		0.1
A_{47E}/A_{47EA}		3.5
A_{47E}	E	3.9
or	E	4.6
A_{47EA}	A	7.0
A_{27B}		3.4
B		6.0

TABLE 5.1

DATA SHEET FOR TUNING Q.S.V.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 CONCLUSION

This thesis is primarily concerned with assessing the dynamic performance of the B1 Quick Service Valve. To facilitate this study, a simulated load in a form of a closed volume has been used throughout instead of the actual brake pipe, or a section of it. This has been found necessary to provide the basis of a first attempt to investigate the component performance. Moreover, the behaviour of a long brake pipe subject to venting at different locations along its length is not yet well-established and constitutes a separate topic of research which is currently carried out at the Fluid Control Centre of this University. Subject to the information available, from the brake pipe research work, the results and conclusions presented in this thesis may well have to be adjusted before being applied to the 'real' situation on the freight train.

The first conclusion to be drawn is that the Q.S.V. (Quick Service Valve) is a useful piece of equipment for reducing the brake pipe pressure at a faster rate. This by itself is a known and established fact, although the author has demonstrated quantitatively the actual amount of increase in the reduction rate for each particular set of parameters built into the Q.S.V. Moreover, the effects of different combinations of the parameters (namely, the length of car, the rate of brake pipe pressure reduction that would take place in the absence of a Q.S.V, the sizes of the timing orifices), have been analysed and documented in this thesis. Furthermore, in order to put the results of the analysis into the proper perspective, one chapter has been devoted to developing a procedure for selecting the timing orifices to achieve best performance compatible with reasonable safety and reliability. The analysis and design has been made possible by the development of a mathematical model which describes the dynamic behaviour of the Q.S.V. This model has been tested against experimental tests. There is good agreement between theory and actual performance, validating the usefulness of the model as well as justifying the various assumptions and simplifications that have been considered necessary in developing the model.

Briefly speaking, the time duration of the Q.S.V. operating in Mode 1 depends principally on the rate of reduction of brake pipe pressure and the size of orifice D. Similarly, the time duration for Mode 2 operation depends on the size of orifice A, and E taken together as a group, and that of orifice B, as well as the rate of pressure reduction and the length of the car in question. Strictly speaking, the size of D also has some small effect on the Mode 2 operation. However, the dichotomy utilized in this thesis simplifies matters a great deal without appreciable loss of accuracy.

The Q.S.V. actively exhausts air from the brakepipe during its Mode 2 operation. Consequently, the effectiveness of the valve in its role to remove air from the system depends on the time duration of its Mode 2 operation as well as the size of orifices A and E and check valve C47. However no specific attempt has been made in this thesis to define a criterion to measure effectiveness in this sense. Rather, as borne out in Chapter 5, it is recognised that there is a limit to the quantity of air that can be removed from the system, beyond which the problem of safety and reliability takes over. In other words, the increased rate of pressure reduction in the brake pipe cannot exceed the so-called emergency rate, which in turn is a constraint imposed by the ABD control valve on each car. Hence, a Q.S.V. may be pushed to be as effective as possible as long as it is safe to do so. Any higher rate of pressure reduction that may be achieved, (and no doubt can be easily achieved) has no practical valve at this point of time.

6.2 SUGGESTION FOR FURTHER WORK

There are several areas of work which warrant further research.

Firstly, an alternative design of a quick service valve should be looked at, which does not behave like an oscillator as the B1 Quick Service Valve. This requires a sensitive monitoring of the instantaneous rate of change of the brake pipe pressure to open or close a vent valve. The principle of a bleeding orifice similar to orifice D in the B-1 Quick Service Valve, can be utilized to advantage.

A closer examination of the behaviour of the diaphragm and piston assembly will throw light on ways and means of shaping the switching condition curves, and the effect on the performance of the Q.S.V. as a whole. The inertial effect of the piston assembly on switching especially at lower pressure valves should be investigated.

The subject of air flow through air resistances in series requires both analytical and experimental study, in order to come up with practical and simple expressions for a single equivalent resistance, suitable for a range of flow conditions.

The analysis and experimentation of this thesis should be extended to investigation of the behaviour of quick service valves operating with real loads, namely in adjacent sections of a brake pipe, and not on closed volumes. As a start, one has to investigate the flow and pressure wave phenomena that exist inside a pipe with venting orifices at one end and at different locations along its length. Having achieved this, one can then procede to study the interaction between adjacent Quick Service Valves.

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APPENDIX 1

DISCHARGING PROCESS OF CONSTANT VOLUME

In order to obtain the fundamental gas equations describing the behaviour of the compressed air discharging from a constant volume, the following assumptions are made:

(a) Orifices are assumed as ideal square-edged orifices;

(b) Air is treated as a perfect gas;

(c) Air flow through the orifice is assumed to be an adiabatic process;

(d) Air inside a reservoir is assumed as a polytropic process;

(e) Discharge coefficient of square-edged orifice is assumed not to vary with the upstream and downstream conditions;

(f) Check valves, namely, C_{27} and C_{47}, are assumed to be opened or closed instantaneously.

A1.1 Pneumatic Variables in a Reservoir

Based on the assumptions, the fundamental equation describing the gas state can be expressed as follows:

$$\frac{P}{\rho^n} = \frac{P_a}{\rho_a^n} = \text{Constant} \tag{A1.1}$$

where P = Absolute pressure; kg/cm^2a

P_a = Ambient pressure; 1.033 kg/cm^2a

ρ = Mass density of air; $kg\ sec^2/cm^4$

ρ_a = Ambient mass density of air; $kg\ sec^2/cm^4$.

The polytropic exponent "n" is to be determined experimentally.

Differentiating Equation (A1.1), one obtains

$$d\rho = \frac{\rho}{nP}\,dP \tag{A1.2}$$

Since the mass of air inside the reservoir can be expressed as:

$$m = \rho V \tag{A1.3}$$

where m = Mass of air; $kg\ sec^2/cm$

V = Volume of reservoir, a constant; cm^3.

Differentiating Equation (A1.3) with respect to time, one obtains

$$\frac{dm}{dt} = V\,\frac{d\rho}{dt} \tag{A1.4}$$

Substituting Equation (A1.2) into Equation (A1.4), the right hand side of Equation (A1.4) becomes:

$$\frac{dm}{dt} = \frac{V\rho}{nP}\,\frac{dP}{dt} \tag{A1.5}$$

From the ideal gas relationships, we have

$$\rho = \frac{P}{RT} \tag{A1.6}$$

where R is the gas constant.

Substituting Equation (A1.6) into Equation (A1.5), the resulting relationship of pressure change to mass flow rate change is:

$$\frac{dP}{dt} = \frac{nRT}{V}\frac{dm}{dt} \qquad \text{(A1.7)}$$

The temperature change in the reservoir in this study, is considered by assuming a process that relates temperature to pressure. Based on the assumption of polytropic process, the resulting relationships of temperature change to pressure change is:

$$T = T(0)\left(\frac{P}{P(0)}\right)^{\frac{(n-1)}{n}} \qquad \text{(A1.8)}$$

where $T(0)$ = Initial temperature; °K

$P(0)$ = Initial pressure; kg/cm^2a

T = Process temperature; °K

P = Pressure variation after increment time; kg/cm^2a.

Substituting Equation (A1.8) into Equation (A1.7), we have

$$\frac{dP}{dt} = \frac{nRT(0)}{V}\left(\frac{P}{P(0)}\right)^{\frac{(n-1)}{n}}\frac{dm}{dt} \qquad \text{(A1.9)}$$

The mass flow rate of compressed air involves temperature, pressure and density changes as well. Based on the assumption (c), most standard texts on thermodynamics give an analysis of the mass flow rate of gas through an orifice as:

$$\frac{dm}{dt} = \frac{C_d A P_u}{\sqrt{RT_u}}\sqrt{\frac{2\gamma g}{(\gamma-1)}\left[\left(\frac{P_d}{P_u}\right)^{2/\gamma} - \left(\frac{P_d}{P_u}\right)^{(\gamma+1)/\gamma}\right]} \qquad \text{(A1.10)}$$

for subsonic flow, and

$$\frac{dm}{dt} = \frac{C_d A P_u}{\sqrt{RT_u}}\sqrt{\gamma g\left(\frac{2}{(\gamma+1)}\right)^{(\gamma+1)/(\gamma-1)}} \qquad \text{(A1.11)}$$

for critical flow,

where C_d = Discharge coefficient of orifice

A = Geometrical orifice area; cm^2

γ = Rate of specific heats; 1.402 for air

g = Gravity; 980.665 cm/sec^2

P_u = Upstream pressure; kg/cm^2 a

P_d = Downstream pressure; kg/cm^2 a

T_u = Upstream air temperature; ^oK

Critical flow takes place when the pressure ratio P_d/P_u is less than 0.528. The derivation of Equations (A1.10) and (A1.11) are well demonstrated as in References (9), (10) and (11).

A1.2 Coefficient of Discharge of Orifice

Based on assumption (e), discharge coefficient C_d has to be considered in order to calculate the mass flow rate through the entire pressure ratio. Because C_d itself varies with mass flow rate, the effect can be considerable, particularly in Equation (A1.10). According to the data published by Grace and Lapple [12], the value of discharge coefficient for square-edge orifices, 0.82, can be considered accurate within ± 2%, while choked flow takes place. Also, the extensive consideration of Anderson [9] gives that square-edge orifices are very erratic at small pressure drops across the orifice and have a somewhat unpredictable variation of discharge coefficient with respect to the pressure ratio. However, in this study, the discharge coefficient for square-edge orifices is employed as 0.82 for the entire pressure ratio except orifice D since the pressure differential across the orifice D is usually very small, namely, approximately 1 psi; therefore, the discharge coefficient of this has to be determined experimentally. Similarly, the lumped equivalent resistances A_{47E}/A_{47EA} and A_{27B} are determined experimentally.

A1.3 Evaluation of Polytropic Constant

Based on assumption (d), the polytropic constant has to be determined. According to Reference (13), if a reservoir is discharged through an orifice and the pressure and temperature variations are monitored, then the polytropic constant may be obtained by the following relationship:

$$n = \frac{\ln \frac{P_0}{P_f}}{\ln \frac{P_0 T_f}{P_f T_0}} \qquad \text{(A1.12)}$$

where P_0 = Initial pressure; kg/cm^2a

P_f = Final pressure; kg/cm^2a

T_0 = Initial temperature; ^oK

T_f = Final temperature; ^oK

It should be noted that the exponent of polytropic presented is based on a particular experimental set-up. The rate of heat transfer of the air, for discharging and charging processes, is also undoubtedly a function of the environmental temperature, and also depends on the physical properties of the material and the geometrical configuration of the reservoir.

APPENDIX 2

DIAPHRAGM ASSEMBLY CONSTANT

$A_{d1} = 66.5\ mm^2$ $A_{d2} = 120.8\ mm^2$

$A_{d3} = 113.7\ mm^2$ $A_{d4} = 7.07\ mm^2$

$W_d = 260\ g$

$F_{f1} = 545.5\ g$

When the diaphragm is in its uppermost position.

$F_{s4} = 366.9\ g$

$D_s = 1000\ g$

When the diaphragm is in its lowermost position.

$F_{s2} = 305.8\ g$

$D_s = 1318.2\ g$

APPENDIX 3

VERIFICATION OF ACCURACY OF DISCHARGING METHOD

The square-edge orifice used in the experimental set-up is as follows:

Sectional Area = 2.483 mm^2

Discharge coefficient assumed for this is; (C_d = 0.82)[9]

Effective area = C_d x sectional area

= 2.036 mm^2

Effective area of this orifice obtained by Equation (2.5.1) is:

= 2.061 mm^2

Thus

$$C_d = \frac{2.061}{2.48} \doteq 0.83$$

Equation (2.5.1) is good enough to evaluate the equivalent orifice of the unknown device.

APPENDIX 4

DETERMINATION OF COMBINED EFFECTIVE AREA OF AIR RESISTANCES IN SERIES

For this purpose, the following expression for air flow is used, as suggested by Sanville[14]:

$$\frac{dm}{dt} = A\sqrt{2gP_d(P_u - P_d)} \qquad (A4.1)$$

where P_u = Up stream pressure of orifice; $Kg/cm^2 a$

P_d = Down stream pressure of orifice; $Kg/cm^2 a$

A = Effective orifice area; cm^2

g = Acceleration due to gravity; 980.665 cm/sec^2

R = Gas constant; 2927.6 Kg cm/^oK Kg

T_u = Up stream air temperature; ^oK

Consider a system of pneumatic restrictions connected in series. The series of pneumatic restrictions may be assumed to be equivalent to a single restriction[15], [16]. For theoretical analysis of air restrictions in series the work published by Ando[15] has been found very useful. This derivation is included in this Appendix.

In steady-state, the mass flow through the orifices must be equal. Refering to Figure A4.1, the mass flow rate may be expressed as follows:

$$\dot{m} = C_1\sqrt{P_2 \Delta P_1} = C_2\sqrt{P_3 \Delta P_2} \qquad (A4.2)$$

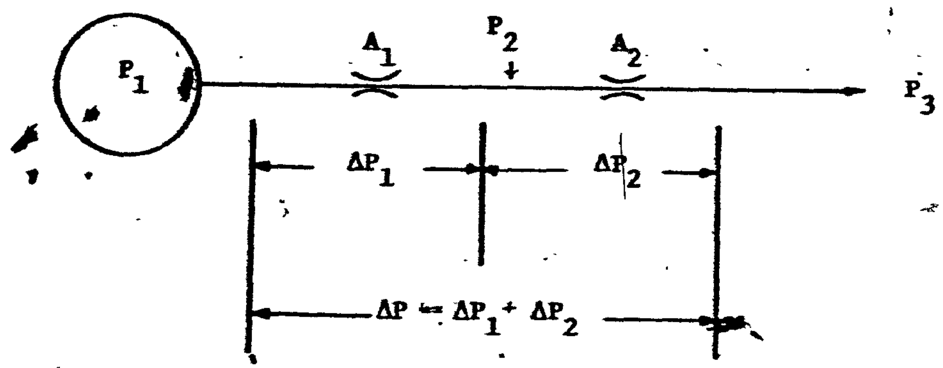


Figure A4.1 Schematic illustration of orifices in series where $\Delta P_1 = P_1 - P_2$

$\Delta P_2 = P_2 - P_3$

$C_i = A_i(2g/RT)^{\frac{1}{2}}, \ i = 1,2$

A_i = Effective orifice area, $i = 1,2$

Temperature change is assumed to be negligible. Pressure P_2 is expressed as:

$$P_2 = P_3 + \Delta P_2 = (1 + x_2)\ P_3 \qquad \text{(A4.3)}$$

where $x_2 = \Delta P_2/P_3$

Total pressure drop across the two orifices is:

$$\Delta P = \Delta P_1 + \Delta P_2 \qquad \text{(A4.4)}$$

The mass flow rate through the system of restrictions may be expressed in terms of the total pressure drop given in Equation (A4.2), i.e.,

$$\dot{m} = C_t\sqrt{P_3\Delta P} \qquad \text{(A4.5)}$$

where $C_t = A_t(2g/RT)^{\frac{1}{2}}$

A_t = equivalent orifice area.

From Equation (A4.2) to Equation (A4.5), we have

$$\dot{m} = C_t\sqrt{P_3\Delta P} = C_t\sqrt{P_3(\Delta P_1 + \Delta P_2)}$$

$$(\dot{m})^2 = C_t^2\ (P_3\Delta P_1 + P_3\Delta P_2)$$

$$\left(\frac{\dot{m}}{C_t}\right)^2 = \frac{\dot{m}^2}{C_1^2}\ \frac{1}{1 + x_2} + \frac{\dot{m}^2}{C_2^2}$$

or
$$\frac{1}{A_t^2} = \frac{1}{A_1^2}\,\frac{1}{(1 + x_2)} + \frac{1}{A_2^2}$$

i.e.
$$A_t = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2\,\frac{1}{1 + x_2}}} \qquad \text{(A4.6)}$$

The value of x_2 may be evaluated for the following special case.

In this study, let us assume that the mass flow through the combined orifice, which is assumed as a single orifice, is choked flow condition and that $P_3 = P_a$, i.e., ambient pressure.

From Equation (A4.2), we have

$$\dot{m} = C_1\sqrt{x_1}\,P_2 = C_2\sqrt{x_2}\,P_a \qquad \text{(A4.7)}$$

where
$$x_1 = \Delta P_1/P_2$$
$$x_2 = \Delta P_2/P_a$$

Thus, Equation (A4.7) becomes

$$x_1 = x_2\left(\frac{A_2}{A_1}\right)^2 \left(\frac{P_a}{P_2}\right)^2 \qquad \text{(A4.8)}$$

From Equation (A4.4), we have

$$\Delta P = \Delta P_1 + \Delta P_2 = x_1 P_2 + x_2 P_a = x_2\left(\frac{A_2}{A_1}\right)^2 \left(\frac{P_a}{P_2}\right)^2 P_2 + x_2 P_a$$

From Equation (A4.3), thus

$$\Delta P = x_2\left(\frac{A_2}{A_1}\right)^2 \frac{P_a^2}{(1 + x_2)P_a} + x_2 P_a \qquad \text{(A4.9)}$$

or
$$\Delta P/P_a = \left(\frac{A_2}{A_1}\right)^2 \frac{x_2}{1 + x_2} + x_2 \qquad \text{(A4.10)}$$

Solving Equation (A4.10) for x_2, we have the following quadratic equation

$$x_2^2 + \left[\left(\frac{A_2}{A_1}\right)^2 + 1 - \frac{\Delta P}{P_a}\right] x_2 - \frac{\Delta P}{P_a} = 0$$

i.e.

$$x_2 = -\alpha + \sqrt{\alpha^2 + \beta} \qquad \text{(A4.10)}$$

where

$$\alpha = \tfrac{1}{2}\left\{\left(\frac{A_2}{A_1}\right)^2 + 1 - \beta\right\}$$

$$\beta = \frac{\Delta P}{P_a}$$

This equation shows that x_2 may be determined from the effective orifice area ratio of the resistances in series and the overall pressure drop ΔP.

It should be noted that the arrangement of terms in each of the equations is such that A_t depends on the order in which the restrictions are installed.

APPENDIX 5

4TH ORDER RUNGE-KUTTA INTEGRATING ROUTINE

The general form of a system of m ordinary differential equations may be represented as follows:

$$\frac{dP_i}{dt} = f_i(t, P_1, P_2 \dots P_m) \quad i = 1, 2, 3, 4 \dots m.$$

Specifically, as applied to the theoretical model on the Q.S.V., where only two pressure variables are monitored, the equations are:

$$\frac{dP_1}{dt} = f_1(t, P_1, P_2)$$

$$\frac{dP_2}{dt} = f_2(t, P_1, P_2)$$

The 4th order Runge-Kutta method of integrating these two equations is as follows:

Let h be the time-increment between successive integrations (the step of integration). After the nth step, evaluate the following parameters, four for each equation:

$$K_1 = hf_1(t, P_{n1}, P_{n2})$$

$$L_1 = hf_2(t, P_{n1}, P_{n2})$$

$$K_2 = hf_1(t_n + h/2, P_{n1} + K_1/2, P_{n2} + L_1/2)$$

$$L_2 = hf_2(t_n + h/2, P_{n1} + K_1/2, P_{n2} + L_1/2)$$

$$K_3 = hf_1(t_n + h/2,\ P_{n1} + K_2/2,\ P_{n2} + L_2/2)$$

$$L_3 = hf_2(t_n + h/2,\ P_{n1} + K_2/2,\ P_{n2} + L_2/2)$$

$$K_4 = hf_1(t_n + h/2,\ P_{n1} + K_3/2,\ P_{n2} + L_3/2)$$

$$L_4 = hf_2(t_n + h/2,\ P_{n1} + K_3/2,\ P_{n2} + L_3/2)$$

Based on these parameters, the next values of P_1 and P_2 are computed:

$$P_{n1+1} = P_{n1} + (K_1 + 2K_2 + 2K_3 + K_4)/6$$

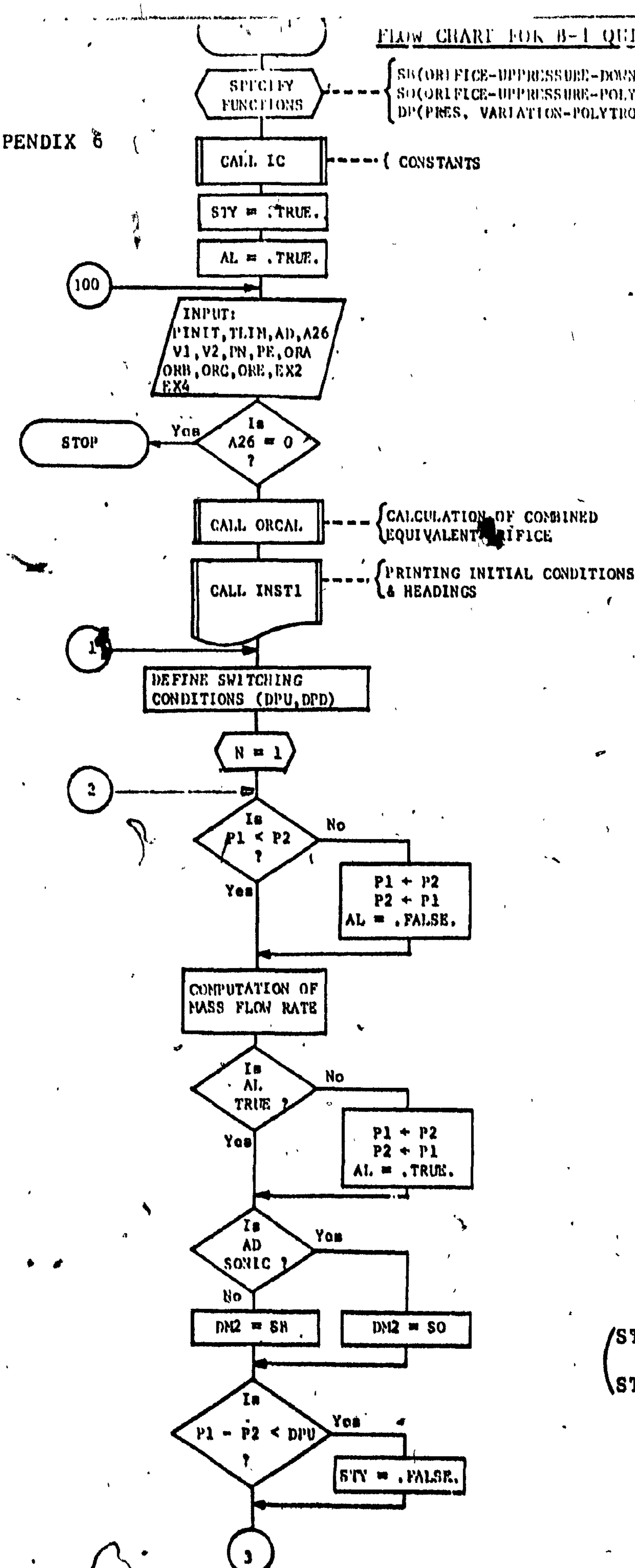
$$P_{n2+1} = P_{n2} + (L_1 + 2L_2 + 2L_3 + L_4)/6$$

$$t_{n+1} = t_n + h$$

These procedures are repeated to cover the required period of time that is of interest. In general, as the integration step size h is reduced, the accuracy of computation tends to increase at the expense of increased computation time.

The Runge-Kutta methods for numerical integration are quite popular since they are self-starting, i.e., only the initial conditions have to be specified. They are therefore used not only for complete integration, but also for providing starting values for other methods.

APPENDIX 6

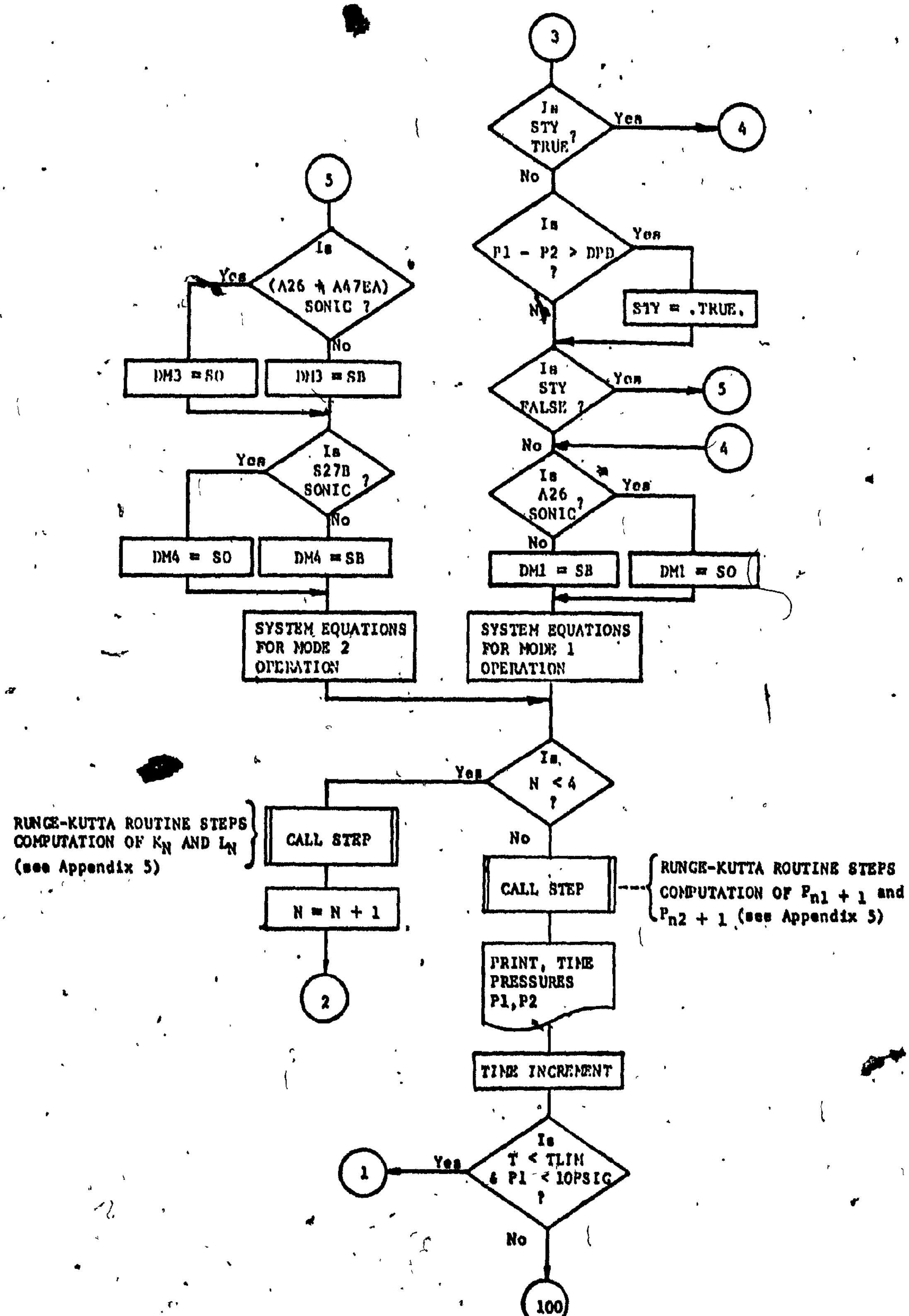


LOCAL VARIABLES

PINIT:	Initial pressure
TLIM:	Time limit
AD:	Effective area of orifice D, and
A26:	Effective area of control orifice A26
V1:	Brake pipe volume, and
V2:	Operating chamber volume
PN:	Polytropic exponent regarding brake pipe pressure process, and
PE:	Polytropic exponent regarding operating chamber pressure process
ORA:	Effective area of orifice A, and
ORB:	Effective area of orifice B, and
ORC:	Effective area of orifice C, and
ORE:	Effective area of orifice E, and
EX2:	Effective area of Check valve C_{27}, and
EX4:	Effective area of check valve C_{47}
DPU:	ΔP_u (see Section 2.3)
DPD:	ΔP_d (see Section 2.3)
SO:	Mass flow rate under sonic condition
SB:	Mass flow rate under subsonic condition
DM1:	Mass flow rate through A26, and
DM2:	Mass flow rate through AD, and
DM3:	Mass flow rate through A26 and A47EA, and
DM4:	Mass flow rate through A27B
P1:	Brake pipe pressure
P2:	Operating chamber pressure

STY = .TRUE. → MODE 1

STY = .FALSE. → MODE 2


3
Is STY TRUE ?
Yes
4
No
Is P1 - P2 > DPD ?
Yes
STY = .TRUE.
No
Is STY FALSE ?
Yes
5
No
4
Is A26 SONIC ?
Yes
No
DM1 = SB
DM1 = SO
SYSTEM EQUATIONS FOR MODE 1 OPERATION
5
Is (A26 + A47EA) SONIC ?
Yes
No
DM3 = SO
DM3 = SB
Is S27B SONIC ?
Yes
No
DM4 = SO
DM4 = SB
SYSTEM EQUATIONS FOR MODE 2 OPERATION
Is N < 4 ?
Yes
No
RUNGE-KUTTA ROUTINE STEPS COMPUTATION OF K_N AND L_N (see Appendix 5)
CALL STEP
N = N + 1
2
CALL STEP
RUNGE-KUTTA ROUTINE STEPS COMPUTATION OF $P_{n1} + 1$ and $P_{n2} + 1$ (see Appendix 5)
PRINT, TIME PRESSURES P1, P2
TIME INCREMENT
Is T < TLIM & P1 < 10PSIG ?
Yes
1
No
100

APPENDIX 7

A7.1 Rate of Pressure Reduction and Equivalent Venting Orifice

A set of typical brake pipe pressure vs. time curves are shown in Figure 1.2. These curves may be approximated by an empirical function [9], assuming that the drop in pressure is due to discharge through a single orifice into the atmosphere:

$$P = P_o e^{-\alpha t} \qquad \text{(A7.1)}$$

where P = instantaneous brake pipe pressure; $Kg/cm^2 a$

P_o = initial brake pipe pressure; $Kg/cm^2 a$

t = time, second

and α is given analytically by Ref. (9):

$$\alpha = \frac{K R \sqrt{T_b} A}{V_b} \qquad \text{(A7.2)}$$

where V_b = brake pipe volume; cm^3

A = effective area of the venting orifice; cm^2

T_b = air temperature in the brake pipe; ^oK

R = gas constant; 2927 $Kg\ cm/^oK\ Kg$

and K is given by Ref. (9):

$$K = \left[\frac{\gamma g}{R} \left(\frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}} \right]^{\frac{1}{2}}$$

where γ = ratio of specific heat of air ; 1.402

g = acceleration due to gravity; 980.665 cm/sec^2.

Equation (A7.2) can be rewritten as follows to give the value of A:

$$A = \frac{V_b \alpha}{K R \sqrt{T_b}} \tag{A7.3}$$

Taking the logarithm of both sides of Equation (A7.1) and solving for α:

$$\ln P = \ln P_o - \alpha t$$

$$\alpha = \frac{1}{t} \ln \frac{P_o}{P} \tag{A7.4}$$

Thus Equation (A7.4) enables the determination of the value α experimentally.

Differentiating Equation (A7.1) with respect to time:

$$\frac{dP}{dt} = - P_o \alpha e^{-\alpha t} \tag{A7.5}$$

From Equations (A7.1) and (A7.5), the rate of reduction of brake pipe pressure can be expressed in terms of the brake pipe pressure:

$$\frac{dP}{dt} = - \alpha P \tag{A7.6}$$

According to Ref. (1), brake pipe pressure reduction rates are classified as follows:

1. A brake pipe pressure drop of 70 to 50 psig in more than 1.4 seconds is considered to be calling for a service rate.
2. A brake pipe pressure drop of 70 to 50 psig in less than 1.2 seconds is considered to be calling for an emergency rate.

Corresponding to the full service rate, the value of α may be obtained empirically by substituting the pressure and time values in (1) above in this Section into the R.H.S. of Equation (A7.4). Thus, for full service rate (100% F.S.R.):

$$\alpha = \frac{1}{1.4} \ln \frac{(70 + 14.7)}{(50 + 14.7)} = 0.192 \text{ sec}^{-1}$$

Similarly, for emergency rate, using the parameters given in (2) above, $\alpha = 0.225 \text{ sec}^{-1}$. Hence values of α, as well as those for application rates less than 100% F.S.R. and some system leakage rates, are tabulated in the first column of Table A7.1.

Based on Equation (A7.3), one obtains an equivalent orifice, the area of which depends on the value of α, brake pipe volume, etc. as given in the equation. The values of the area A corresponding to each rate of brake pipe pressure reduction and train lengths, have been converted on this basis and are also tabulated in Table A7.1.

A7.2 Limiting Size of A_{47E}/A_{47EA} Without Creating Emergency Rate

During a normal service application, an inadvertant emergency rate may be created due to an excessively large venting area in the brake pipe. This can only happen when the Q.S.V. is in its Mode 2 operation.

Referring to Figure 2.9, and assuming no system leakage, the sum of the control orifice A_{26} and the equivalent orifice A_{47E}/A_{47EA} utilized as the Q.S.V., should therefore not exceed the limiting orifice size for emergency rate as derived in Section A7.1 and listed in Table A7.1. Thus, for a given service application rate imposed on

		α sec^{-1}	Brake Pipe Volume (cm^3)		
			24131.9	19305.5	14479.2
			100 feet	80 feet	60 feet
			Venting Orifice A (mm^2)		
Service Application Rates (without Q.S.V.)	100% of F.S.R.	0.192	23.27	18.62	13.96
	75% of F.S.R.	0.144	17.45	13.76	10.47
	50% of F.S.R.	0.096	11.64	9.31	6.98
	25% of F.S.R.	0.048	5.82	4.65	3.49
	10% of F.S.R.	0.019	2.33	1.86	1.40
	5% of F.S.R.	0.010	1.16	0.93	0.70
System Leakage Rates	5 psi/min (leakage)	0.001	0.12	0.10	0.07
	10 psi/min (leakage)	0.002	0.25	0.20	0.15
	15 psi/min (leakage)	0.003	0.39	0.31	0.24
Emergency Application		0.225	27.15	21.72	16.29

$K = 0.396$, $R = 2927$ Kg cm/^oK Kg, $T_b = 295$ ^oK

Note: F.S.R. = Full Service Rates.

TABLE A7.1

the brake pipe in the absence of the Q.S.V., the maximum limiting size of A_{47E}/A_{47EA} that can be fitted in a Q.S.V. without the danger of creating an emergency situation, can be evaluated as follows:

A_{47E}/A_{47EA} + orifice size A_{26} for the given service rate (without Q.S.V.)

≤ venting orifice size A for emergency rate

or

limiting size of A_{47E}/A_{47EA} = venting orifice size A for emergency rate

- orifice size A_{26} for the given service rate (without Q.S.V.) (A7.7)

Take for example the case of a brake pipe designed to operate at 100% F.S.R. According to Table A7.1, the venting orifice A for this rate of reduction without Q.S.V. is 23.27 mm^2 for a train of 100 feet length. The value of A for emergency rate is 27.15 mm^2 for this length of train (also given in Table A7.1). Consequently, at this rate of service application, the maximum size of A_{47E}/A_{47EA} is, according to Equation (A 7.7), (27.15 - 23.27) ≑ 3.9 mm^2.

Employing this reasoning, it is possible to construct a design chart such as the one shown in Figure 5.2 to give the limiting values of A_{47E}/A_{47EA} that can be fitted in a Q.S.V. without placing the train into emergency.

A7.3 Method of Determining Possible Occurrence of Emergency

Given a magnitude of A_{47E}/A_{47EA}, it may be required to test whether the Q.S.V. would create an emergency rate or not during service application.

Considering Equation (A7.6), the rate of reduction of pressure can be expressed in terms of brake pipe pressure P and the parameter α. For the emergency rate, using the value of α which has been computed in Section A7.1, Equation (A7.6) becomes:

$$\frac{dP}{dt} = -0.225 P \qquad \text{(A7.8)}$$

with the corresponding curve as plotted in Figure A7.1.

Note that Figure A7.1 is divided into two zones. If the pressure reduction of a brake pipe operates totally within the zone above the curve, no emergency response is expected. On the other hand, if the pressure reduction at any time goes into the zone beneath the curve, emergency will take place. Hence Figure A7.1 may be conveniently utilized to test whether a given Q.S.V. may send the train into emergency or not by first obtaining the P ∿ t response under a suitable load. From this response, a dP/dt ∿ P characteristic may be obtained by numerical techniques and by eliminating the variable t. This characteristic can be superimposed on the reference curve of Figure A7.1, and a conclusion can be drawn immediately as to whether emergency can occur or not.

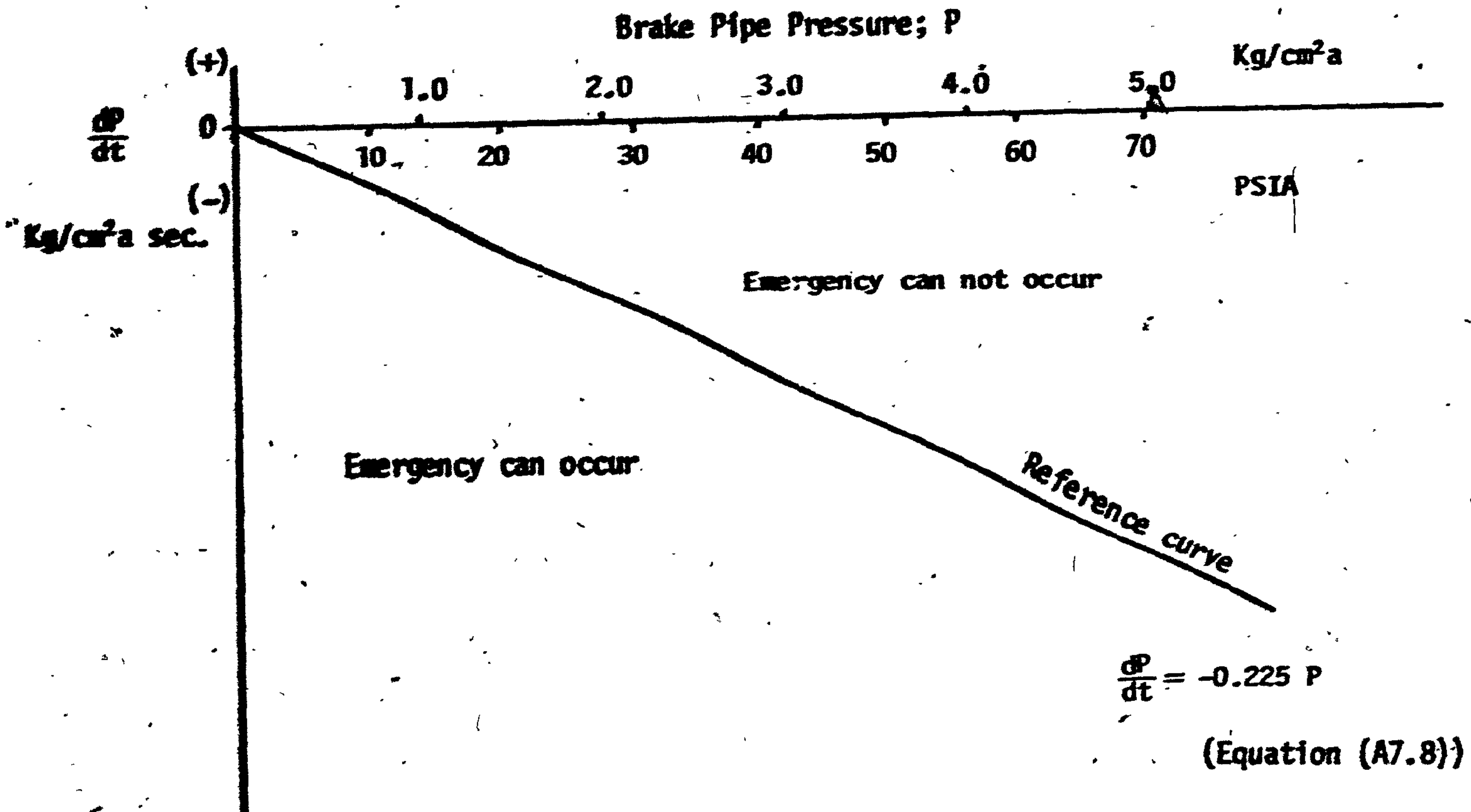


Figure A7.1 Reference curve of emergency rate

SIMULATION PROGRAM FOR B-1 QUICK SERVICE VALVE

```
C
C     NOMENCLATURE  OF STATEMENT FUNCTION
C
C     SB(ORIFICE-UPPRESSURE-DOWNPRESSURE-POLYEXPONENT)
C
C     SO(ORIFICE-UPPRESSURE-POLYEXPONENT)
C
C     DP(PRESSURE -POLYEXPONENT-VOLUME SIZE)
C
C
C     IN ABSENCE OF ORIFICE, SUBSTITUTE VALUE OF ZERO CORRESPONDING TO
C     THE INPUT OF ORIFICE SPECIFIED
C
C
      PROGRAM B1QSV(INPUT,OUTPUT)
      DOUBLE H,T
      LOGICAL GRAPH1,METRIC
      LOGICAL AL,STY
      COMMON/BLK1/V1,V2,TLIM,AD,A26,ORA,ORB,ORC,ORE,A47EA,A27B,EX2,EX4,P
     +N,PE,COM
      COMMON/BLK2/TA,R,PA,CONV,GM2,GP10G,AA,AAA,PART1,CRIP,GMM1,T
      COMMON PINIT,METRIC,CCV,PO0
      EXTERNAL IC,INST1,STEP,VSTEP,ORCAL,CEOA
C
      DIA(W)= SQRT(4.E0*W/3.1415926E0)/2.54E0
      TEMP(A,B)=TA*(A/PO)**((B-1.0)/B)
      SB(A,B,C,D)=A*B*SQRT(((C/B)**GM2-(C/B)**GP10G)/TEMP(B,D))
      SO(A,B,C)=A*B*SQRT(((GMM1/2.0)*AA**AAA)/TEMP(B,C))
      DP(A,B,V)=B*R*TEMP(A,B)*PART1/V
C
C     INITIAL CONDITIONS
C
      READ*, PINIT,TLIM
      READ*,GRAPH1,METRIC
      PRINT 15
   15.FORMAT(*1*)
      H=2.D-02
      LT=1.D0/(2.D0*H)
      L10=10*LT
C
      CALL IC
      AL=.TRUE.
      READ*,AD,A26,V1,V2,PN,PE
      IF(AD.EQ.0.0) STOP
 1000 CONTINUE
      READ*,ORA,ORB,ORC,ORE,EX2,EX4
      IF(ORA.EQ.0.0) STOP
      STY=.TRUE.
      CALL ORCAL
      CALL INST1
C
      PRINT 30
   30 FORMAT(* *,130(*-*))
```

```
      PRINT 80
   80 FORMAT(*0*,T10,*TIME*,T34,10(*-*),*P2*,10(*-*),T63,10(*-*),*P1*,10
     +(*-*))
      PRINT 85
   85 FORMAT(* *,T10,*(SEC)*,T20,*STATUS*,T33,*KGSCG*,T42,*PSIG*,T51,*DP
     +DT*,T62,*KGSCG*,T71,*PSIG*,T80,*DPDT*)
      P0=PINIT+PA
      PP1=PP2=P0
      PNL=P0*0.6
      T=0.D0
      I=L=0
C
C     CALCULATION
C
   10 CONTINUE
      P1=PP1
      P2=PP2
      P1KG=P1-PA
      P2KG=P2-PA
      P1PG=P1*CCV-14.7
      P2PG=P2*CCV-14.7
      DPD=0.6/70.0*P1PG+0.4
      DPU=-0.45/70.0*P1PG
      DO 5 N=1,4
      IF(P1-P2) 25,25,20
   20 CONTINUE
      CA=P1
      P1=P2
      P2=CA
      AL=.FALSE.
   25 CONTINUE
      SB1=SB(A26,P1,PA,PN)
      SB2=SB(AD,P2,P1,PE)
      SO1=SO(A26,P1,PN)
      SO2=SO(AD,P2,PE)
      SB3=SB(A47EA+A26,P1,PA,PN)
      SO3=SO(A47EA+A26,P1,PN)
      SB4=SB(A27B,P2,PA,PE)
      SO4=SO(A27B,P2,PE)
      DP1=DP(P1,PN,V1)
      DP2=DP(P2,PE,V2)
      IF(AL) GO TO 50
      CA=P1
      P1=P2
      P2=CA
      AL=.TRUE.
   50 CONTINUE
      DM2=SB2
      IF((P1/P2).LE.CRIP) DM2=SO2
      IF(P1.GT.P2) DM2=-DM2
      IF((P1PG-P2PG).LE.DPU) STY=.FALSE.
      IF(STY) GO TO 45
      IF((P1PG-P2PG).GE.DPD) STY=.TRUE.
```

```
      IF(.NOT.STY) GO TO 35
C
C     MODE 1
C
   45 CONTINUE
      IS=5HMODE1
      DM1=SO1
      IF((PA/P1).GE.CRIP) DM1=SB1
C
C     SYSTEM EQUATIONS
      F1=DP1*(DM2-DM1)
      F2=DP2*(-DM2)
      GO TO 60
   35 CONTINUE
C
C     MODE 2
C
      IS=5HMODE2
      DM3=SO3
      IF((PA/P1).GE.CRIP)  DM3=SB3
      DM4=SO4
      IF ((PA/P2).GE.CRIP) DM4=SB4
C
C     SYSTEM EQUATIONS
C
      F1=DP1*(DM2-DM3)
      F2=DP2*(-DM2-DM4)
   60 CONTINUE
      IF(N.EQ.1) S1=F1
      IF(N.EQ.1) S2=F2
C
C     RUNGE-KUTTA METHODS
C
      CALL STEP(P1,P2,PP1,PP2,F1,F2,N,H)
C
    5 CONTINUE
      IF(MOD(I,L10).EQ.0) PRINT  70
   70 FORMAT(*0*)
      PRINT 100,I,T,IS,P2KG,P2PG,S2,P1KG,P1PG,S1
  100 FORMAT(* *,1X,I4,2X,F7.3,5X,A8,2(2F9.3,F11.6))
   75 CONTINUE
      T=T+H
      I=I+1
      IF(T.LE.TLIM.AND.P1PG.GE.20.0) GO TO 10
      GO TO 1000
      END
```

```
      SUBROUTINE ORCAL
      COMMON/BLK1/V1,V2,TLIM,AD,A26,ORA,ORB,ORC,ORE,A47EA,A27B,EX2,EX4,P
     +N,PE
      SORA=ORA*ORA
      SORB=ORB*ORB
      SORC=ORC*ORC
      SORE=ORE*ORE
      SEX2=EX2*EX2
      SEX4=EX4*EX4
      A27B=SQRT(SEX2*SORB/(SEX2+SORB))
      IF(ORB.EQ.O.)A27B=EX2
      IF(ORC.EQ.O.AND.ORA.EQ.O) A47EA=SQRT(SORE*SEX4/(SORE+SEX4))
      IF(ORC.EQ.O.AND.ORA.NE.O) A47EA=ORE*EX4*ORA/SQRT(SORE*SEX4+SEX4 *S
     +ORA+SORE*SORA)
      IF(ORC.NE.O.AND.ORA.NE.O) A47EA=ORE*EX4*ORA*ORC/SQRT(SORE*SEX4 *SO
     1RA+SEX4*SORA*SORC+SORE*SORA*SORC+SORE*SEX4*SORC)
      IF(ORE.EQ.O.)A47EA=EX4
      RETURN
      END


      SUBROUTINE IC
      DOUBLE T
      LOGICAL METRIC
      COMMON/BLK2/TA,R,PA,CONV,GM2,GP1OG,AA,AAA,PART1,CRIP,GMM1,T
      COMMON PINIT,METRIC,CCV,POO
      T=0.DO
      CCV=14.230385E0
      CONV=1./CCV
      POO=PINIT
      IF(METRIC)POO=PINIT*CCV
      IF(.NOT.METRIC) PINIT=PINIT*CONV
      G=980.665E0
      R=2927.6E0
      TA=295.E0
      PA=1.0333E0
      GAMMA=1.402E0
      GMM1=GAMMA-1.E0
      GMP1=GAMMA+1.E0
      GM2=2.E0/GAMMA
      GOGM1=GAMMA/GMM1
      GP1OG=GMP1/GAMMA
      AA=2.E0/GMP1
      AAA=GMP1/GMM1
      COT=2.E0*GOGM1*G
      CRIP= (2.E0/GMP1)**GOGM1
      PART1= SQRT(COT/R)
      RETURN
      END
```

```
      SUBROUTINE    INST1
      LOGICAL METRIC
      COMMON/BLK1/V1,V2,TLIM,AD,A26,ORA,ORB,ORC,ORE,A47EA,A27B,EX2,EX4,P
     +N,PE,COM
      COMMON PINIT,METRIC,CCV,P00
      EXTERNAL DATE
      DIA(W)= SQRT(4.E0*W/3.1415926E0)/2.54E0
      CONVE=0.06102
      EV1=V1*CONVE
      EV2=V2*CONVE
      VR=V1/V2
      ER=A26/AD
      D26=DIA(A26)
      DD=DIA(AD)
      DA=DIA(ORA)
      DB=DIA(ORB)
      DC=DIA(ORC)
      DE=DIA(ORE)
      D27B=DIA(A27B)
      D47EA=DIA(A47EA)
      DEX2=DIA(EX2)
      DEX4=DIA(EX4)
      CALL DATE(TODAY)
      CALL SECOND(TYME)
      CALL TIME(CLOCK)
      PRINT 2
      PRINT 1 ,TODAY,CLOCK,TYME
    1 FORMAT(*0TODAY=*, A10, * CLOCK=*, A10, * THE ELAPSED CPU TIME IS*,
     +G14.5,*(SEC)*)
      PRINT 2
    2 FORMAT(130(*-*),/)
      PRINT  3,PN,PE
    3 FORMAT(*0*,T7,*POLYTROPIC INDEX1=*,F8.5,*   POLYTROPIC INDEX2=*,F8
     +.5)
      PRINT 4,V1,EV1,V2,EV2
    4 FORMAT(*0*,T7,*VOLUME1=*,F8.2,*CC *,F8.0,*CU.IN.            VOLUME2=*,
     1F8.2,*CC*,F10.0,*CU.IN.*)
      PRINT 5,TLIM,COM
    5 FORMAT(*0*,T7,*TIME LIMIT=*,F5.1,* SEC*,T35,A15)
      PRINT   6,VR,ER
    6 FORMAT( *0*,T7,*VOLUME RATIO=*,F8.5,*   ORIFICE RATIO=*,F10.3)
      PRINT 7,AD,DD
    7 FORMAT(*0*,T7,*ORAD =*,2PF10.7,* SQ.MM      DIA=*,0PF10.7,* IN.*)
      PRINT 8,A26,D26
    8 FORMAT(*0*,T7,*ORA26=*,2PF10.7,* SQ.MM      DIA=*,0PF10.7,* IN.*)
      PRINT 9,ORA,ORB,ORC,ORE
    9 FORMAT(*0*,T7,*ORA=*,2PF10.6,*   ORB=*,F10.6,*    ORC=*,F10.6,*
     +ORE=*,F10.6,* - - - SQ.MM*)
      PRINT 10,DA,DB,DC,DE
   10 FORMAT(*0*,T7,*ORA=*,  F10.6,*   ORB=*,F10.6,*    ORC=*,F10.6,*
     +ORE=*,F10.6,* - - - IN.*)
```

```
      PRINT 11 ,A27B,A47EA
   11 FORMAT(*O*,T7, *TOTAL EQUIVALENT EFFECTIVE ORIFICE AREA A27B=*,2PF
     +8.6,*     A47EA=*,F8.6,* - - - SQ.MM*)
      PRINT 12,D27B,D47EA
   12 FORMAT(*O*,T7,*TOTAL EQUIVALENT EFFECTIVE ORIFICE AREA   D27B=*, F
     +8.6,*     D47EA=*,F8.6,* - - - IN.*)
      PRINT  13,EX2,EX4
   13 FORMAT(*O*,T7, *EX. VALVE 27=*,2PF8.6,*    EX.VALVE 47=*,F8.6,* -
     +- - SQ.MM*)
      PRINT 15,DEX2,DEX4
   15 FORMAT(*O*,T7, *EX. VALVE 27=*,  F8.6,*    EX.VALVE 47=*,F8.6,* -
     +- - IN.*)
      PRINT 14,PINIT,POO
   14 FORMAT(*O*,T7,*INITIAL PRESSURE=*,F5.2,*(KG/CM.G)    *,F5.2,*PSIG*)
      PRINT 2
      RETURN
      END
```

```
      SUBROUTINE    STEP(P1,P2,PP1,PP2,F1,F2,I,H)
      DIMENSION FK(5),FL(5)
      FL(I)=F1*H
      FK(I)=F2*H
      IF(I-3)10,20,30
   20 P1=PP1+FL(I)
      P2=PP2+FK(I)
      RETURN
   10 P1=PP1+FL(I)/2.E0
      P2=PP2+FK(I)/2.E0
      RETURN
   30 CONTINUE
      PP1=PP1+ (FL(1)+2.E0*FL(2)+2.E0*FL(3)+FL(4))/6.E0
      PP2=PP2+(FK(1)+2.E0*FK(2)+2.E0*FK(3)+FK(4))/6.E0
      RETURN
      END
```

OTODAY= 76/10/07, CLOCK= 18.27.28, THE ELAPSED CPU TIME IS 18.602 (SEC)

POLYTROPIC INDEX1= 1.00000 POLYTROPIC INDEX2= 1.00000
VOLUME1=24131.90CC 1473.CU.IN. VOLUME2= 2621.00CC 160.CU.IN.
TIME LIMIT= 10.0 SEC.
VOLUME RATIO= 9.20713 ORIFICE RATIO= 232.719
ORAD = .1000000 SQ.MM DIA= .0140402 IN.
ORA26=23.2718770 SQ.MM DIA= .2143873 IN.
ORA= 7.000000 ORB= 6.000000 ORC= 0.000000 ORE= 4.600000 - - - SQ.MM
ORA= .117536 ORB= .108817 ORC= 0.000000 ORE= .095280 - - - IN.
TOTAL EQUIVALENT EFFECTIVE ORIFICE AREA A27B=3.409224 A47EA=3.535795 - - - SQ.MM
TOTAL EQUIVALENT EFFECTIVE ORIFICE AREA D27B= .082026 D47EA= .083534 - - - IN.
EX. VALUE 27=4.143000 EX.VALUE 47=9.009000 - - - SQ.MM
EX. VALUE 27= .090423 EX.VALUE 47= .133340 - - - IN.
INITIAL PRESSURE= 4.92(KG/CM.G) 70.00PSIG

	TIME (SEC)	STATUS	P2 KGSCG	P2 PSIG	P2 DPDT	P1 KGSCG	P1 PSIG	P1 DPDT
0	0.000	MODE1	4.919	70.004	0.000000	4.919	70.004	-1.144432
1	.020	MODE1	4.919	70.003	-.005768	4.896	69.679	-1.139415
2	.040	MODE2	4.919	70.001	-1.551404	4.873	69.356	-1.307333
3	.060	MODE2	4.888	69.561	-1.543194	4.847	68.984	-1.301606
4	.080	MODE2	4.857	69.123	-1.534728	4.821	68.615	-1.295905
5	.100	MODE2	4.826	68.687	-1.526281	4.796	68.247	-1.290233
6	.120	MODE2	4.796	68.254	-1.517847	4.770	67.880	-1.284509
7	.140	MODE2	4.766	67.823	-1.509417	4.744	67.516	-1.278974
8	.160	MODE2	4.736	67.395	-1.500976	4.719	67.152	-1.273390
9	.180	MODE2	4.706	66.969	-1.492502	4.693	66.791	-1.267839
10	.200	MODE2	4.676	66.545	-1.483944	4.668	66.431	-1.262326
11	.220	MODE2	4.646	66.124	-1.475167	4.643	66.072	-1.256867
12	.240	MODE2	4.617	65.706	-1.464489	4.618	65.715	-1.251514
13	.260	MODE2	4.588	65.290	-1.456370	4.593	65.360	-1.245224
14	.280	MODE2	4.559	64.877	-1.448990	4.568	65.006	-1.238892
15	.300	MODE2	4.530	64.465	-1.441853	4.543	64.655	-1.232568
16	.320	MODE2	4.501	64.056	-1.434065	4.519	64.305	-1.226263
17	.340	MODE2	4.472	63.649	-1.427984	4.494	63.957	-1.219981
18	.360	MODE2	4.444	63.243	-1.421191	4.470	63.610	-1.213733
19	.380	MODE2	4.416	62.840	-1.414473	4.446	63.266	-1.207491
20	.400	MODE2	4.387	62.438	-1.407820	4.421	62.923	-1.201204
21	.420	MODE2	4.359	62.038	-1.401228	4.397	62.582	-1.195104
22	.440	MODE2	4.331	61.640	-1.394691	4.374	62.243	-1.188950
23	.460	MODE2	4.303	61.244	-1.388206	4.350	61.905	-1.182823
24	.480	MODE2	4.276	60.850	-1.381770	4.326	61.569	-1.176722
25	.500	MODE2	4.248	60.458	-1.375382	4.303	61.235	-1.170648
26	.520	MODE2	4.221	60.067	-1.369039	4.279	60.903	-1.164601
27	.540	MODE2	4.193	59.679	-1.362740	4.256	60.573	-1.158581
28	.560	MODE1	4.166	59.292	.009257	4.233	60.244	-1.000699
29	.580	MODE1	4.166	59.294	.007737	4.213	59.959	-1.000567
30	.600	MODE1	4.167	59.296	.005836	4.193	59.674	-1.000387
31	.620	MODE1	4.167	59.297	.002082	4.173	59.309	-1.000083
32	.640	MODE1	4.167	59.297	-.004149	4.153	59.105	-[illegible]96725
33	.660	MODE2	4.147	59.295	-1.354963	4.133	58.822	-1.[illegible]43548
34	.680	MODE2	4.139	58.911	-1.347517	4.110	58.497	-1.138562
35	.700	MODE2	4.113	58.528	-1.340084	4.088	58.174	-1.133580
36	.720	MODE2	4.0[illegible]	58.148	-1.332650	4.065	57.852	-1.128633
37	.740	MODE2	4.059	57.770	-1.325230	4.043	57.532	-1.123493
38	.760	MODE2	4.033	57.394	-1.317782	4.020	57.212	-1.118791
39	.780	MODE2	4.007	57.020	-1.310283	3.998	56.895	-1.113920
40	.800	MODE2	3.980	56.648	-1.302461	3.976	56.570	-1.109089

41	.820	MODE2	3.954	56.278	-1.294590	3.953	56.263	-1.104331
42	.840	MODE2	3.929	55.911	-1.285666	3.931	55.950	-1.099166
43	.860	MODE2	3.903	55.546	-1.279005	3.909	55.638	-1.093592
44	.880	MODE2	3.878	55.183	-1.272643	3.888	55.327	-1.088017
45	.900	MODE2	3.852	54.822	-1.266438	3.866	55.018	-1.082457
46	.920	MODE2	3.827	54.462	-1.260340	3.844	54.711	-1.076915
47	.940	MODE2	3.802	54.104	-1.254326	3.823	54.405	-1.071393
48	.960	MODE2	3.777	53.748	-1.248381	3.802	54.101	-1.065894
49	.980	MODE2	3.752	53.394	-1.242497	3.780	53.799	-1.060418
50	1.000	MODE2	3.727	53.041	-1.236669	3.759	53.498	-1.054964
51	1.020	MODE2	3.703	52.690	-1.230890	3.738	53.198	-1.049534
52	1.040	MODE2	3.678	52.340	-1.225159	3.717	52.900	-1.044127
53	1.060	MODE2	3.653	51.992	-1.219472	3.696	52.604	-1.038744
54	1.080	MODE2	3.629	51.646	-1.213828	3.676	52.309	-1.033384
55	1.100	MODE2	3.605	51.301	-1.208224	3.655	52.016	-1.028048
56	1.120	MODE2	3.581	50.958	-1.202660	3.634	51.724	-1.022735
57	1.140	MODE2	3.557	50.617	-1.197133	3.614	51.434	-1.017445
58	1.160	MODE1	3.533	50.277	.008282	3.594	51.145	-.878797
59	1.180	MODE1	3.533	50.279	.006976	3.576	50.895	-.878684
60	1.200	MODE1	3.533	50.281	.005364	3.559	50.645	-.878533
61	1.220	MODE1	3.533	50.282	.002903	3.541	50.395	-.878291
62	1.240	MODE1	3.533	50.282	-.003289	3.523	50.145	-.875756
63	1.260	MODE2	3.533	50.281	-1.189676	3.506	49.896	-1.004756
64	1.280	MODE2	3.509	49.943	-1.183124	3.486	49.611	-1.000359
65	1.300	MODE2	3.486	49.607	-1.176580	3.466	49.327	-.995983
66	1.320	MODE2	3.462	49.273	-1.170038	3.446	49.044	-.991631
67	1.340	MODE2	3.439	48.941	-1.163486	3.426	48.762	-.987302
68	1.360	MODE2	3.416	48.611	-1.156902	3.407	48.482	-.983000
69	1.380	MODE2	3.393	48.283	-1.150242	3.387	48.2[illegible]3	-.978729
70	1.400	MODE2	3.370	47.956	-1.143469	3.367	47.9[illegible]5	-.974503
71	1.420	MODE2	3.347	47.632	-1.135098	3.348	47.648	-.970234
72	1.440	MODE2	3.324	47.310	-1.129005	3.329	47.373	-.965336
73	1.460	MODE2	3.302	46.989	-1.123324	3.309	47.098	-.960423
74	1.480	MODE2	3.279	46.670	-1.117811	3.290	46.826	-.955510
75	1.500	MODE2	3.257	46.353	-1.112406	3.271	46.555	-.950629
76	1.520	MODE2	3.235	46.037	-1.107080	3.252	46.285	-.945758
77	1.540	MODE2	3.213	45.723	-1.101820	3.233	46.016	-.940905
78	1.560	MODE2	3.191	45.410	-1.096617	3.215	45.749	-.936073
79	1.580	MODE2	3.169	45.099	-1.091464	3.196	45.483	-.931260
80	1.600	MODE2	3.147	44.789	-1.086356	3.177	45.219	-.926469
81	1.620	MODE2	3.125	44.480	-1.081292	3.159	44.956	-.921697
82	1.640	MODE2	3.104	44.173	-1.076267	3.140	44.694	-.916947
83	1.660	MODE2	3.082	43.868	-1.071280	3.122	44.434	-.912217
84	1.680	MODE2	3.061	43.563	-1.066330	3.104	44.175	-.907508
85	1.700	MODE2	3.040	43.261	-1.061414	3.086	43.918	-.902819
86	1.720	MODE2	3.019	42.959	-1.056532	3.068	43.661	-.898151
87	1.740	MODE2	2.997	42.659	-1.051684	3.050	43.406	-.893504
88	1.760	MODE1	2.976	42.361	.007415	3.033	43.153	-.771745
89	1.780	MODE1	2.977	42.362	.006294	3.017	42.933	-.771650
90	1.800	MODE1	2.977	42.364	.004926	3.001	42.713	-.771523
91	1.820	MODE1	2.977	42.365	.002989	2.986	42.494	-.771328
92	1.840	MODE1	2.977	42.365	-.002512	2.970	42.274	-.769504
93	1.860	MODE2	2.977	42.364	-1.044534	2.955	42.036	-.882830
94	1.880	MODE2	2.956	42.068	-1.038766	2.937	41.805	-.878968
95	1.900	MODE2	2.935	41.773	-1.033002	2.920	41.556	-.875125
96	1.920	MODE2	2.915	41.480	-1.027233	2.902	41.307	-.871304
97	1.940	MODE2	2.894	41.188	-1.021443	2.885	41.060	-.867504
98	1.960	MODE2	2.874	40.899	-1.015605	2.868	40.813	-.863730
99	1.980	MODE2	2.853	40.610	-1.009640	2.851	40.568	-.859990
100	2.000	MODE2	2.833	40.324	-1.002836	2.833	40.324	-.854361
101	2.020	MODE2	2.813	40.039	-.994642	2.814	40.081	-.852127
102	2.040	MODE2	2.793	39.757	-.991555	2.799	39.839	-.847798
103	2.040	MODE2	2.774	39.475	-.984655	2.782	39.598	-.843472
104	2.080	MODE2	2.754	39.195	-.981843	2.766	39.359	-.839153
105	2.100	MODE2	2.734	38.916	-.977148	2.749	39.120	-.834861

106	2.120	MODE2	2.715	38.639	-.972494	2.732	38.883	-.830579
107	2.140	MODE2	2.696	38.363	-.967893	2.716	38.640	-.826315
108	2.160	MODE2	2.676	38.008	-.963337	2.699	38.413	-.822068
109	2.180	MODE2	2.657	37.814	-.958823	2.683	38.180	-.817840
110	2.200	MODE2	2.638	37.542	-.954347	2.666	37.947	-.813629
111	2.220	MODE2	2.619	37.271	-.949908	2.650	37.717	-.809436
112	2.240	MODE2	2.600	37.001	-.945502	2.634	37.487	-.805262
113	2.260	MODE2	2.581	36.733	-.941129	2.618	37.258	-.801106
114	2.280	MODE2	2.562	36.466	-.936787	2.602	37.031	-.796969
115	2.300	MODE2	2.544	36.200	-.932475	2.586	36.804	-.792849
116	2.320	MODE2	2.525	35.935	-.928192	2.570	36.579	-.788748
117	2.340	MODE2	2.506	35.671	-.923938	2.554	36.356	-.784665
118	2.360	MODE1	2.488	35.409	.006643	2.539	36.133	-.677738
119	2.380	MODE1	2.488	35.411	.005681	2.525	35.940	-.677657
120	2.400	MODE1	2.488	35.412	.004520	2.512	35.747	-.677551
121	2.420	MODE1	2.488	35.413	.002934	2.498	35.554	-.677393
122	2.440	MODE1	2.488	35.413	-.001780	2.485	35.362	-.676184
123	2.460	MODE2	2.488	35.413	-.917073	2.471	35.169	-.775736
124	2.480	MODE2	2.470	35.152	-.911992	2.456	34.949	-.772344
125	2.500	MODE2	2.452	34.894	-.906910	2.440	34.730	-.768970
126	2.520	MODE2	2.434	34.636	-.901814	2.425	34.511	-.765615
127	2.540	MODE2	2.416	34.380	-.896684	2.410	34.294	-.762282
128	2.560	MODE2	2.398	34.126	-.891471	2.394	34.078	-.758975
129	2.580	MODE2	2.380	33.873	-.885968	2.379	33.862	-.755718
130	2.600	MODE2	2.362	33.622	-.879831	2.364	33.647	-.752196
131	2.620	MODE2	2.345	33.372	-.875266	2.349	33.434	-.748383
132	2.640	MODE2	2.327	33.123	-.870910	2.334	33.221	-.744568
133	2.660	MODE2	2.310	32.876	-.866662	2.319	33.010	-.740763
134	2.680	MODE2	2.293	32.630	-.862488	2.305	32.800	-.736970
135	2.700	MODE2	2.275	32.385	-.858372	2.290	32.591	-.733193
136	2.720	MODE2	2.258	32.141	-.854303	2.275	32.382	-.729428
137	2.740	MODE2	2.241	31.899	-.850277	2.261	32.175	-.725681
138	2.760	MODE2	2.224	31.657	-.846287	2.246	31.969	-.721949
139	2.780	MODE2	2.207	31.417	-.842333	2.232	31.764	-.718233
140	2.800	MODE2	2.191	31.170	-.838411	2.218	31.561	-.714533
141	2.820	MODE2	2.174	30.940	-.834519	2.203	31.358	-.710849
142	2.840	MODE2	2.157	30.703	-.830656	2.189	31.186	-.707181
143	2.860	MODE2	2.141	30.467	-.826821	2.175	30.955	-.703529
144	2.880	MODE2	2.124	30.232	-.823013	2.161	30.755	-.699894
145	2.900	MODE2	2.108	29.999	-.819231	2.147	30.557	-.696274
146	2.920	MODE2	2.091	29.766	-.815474	2.133	30.359	-.692670
147	2.940	MODE2	2.075	29.534	-.811741	2.119	30.162	-.689083
148	2.960	MODE1	2.059	29.304	.005957	2.106	29.967	-.595181
149	2.980	MODE1	2.059	29.306	.005132	2.094	29.797	-.595113
150	3.000	MODE1	2.059	29.307	.004148	2.082	29.628	-.595034
151	3.020	MODE1	2.059	29.308	.002844	2.070	29.459	-.594095
152	3.040	MODE1	2.059	29.308	-.001003	2.058	29.290	-.594230
153	3.060	MODE1	2.059	29.308	-.003157	2.046	29.121	-.591716
154	3.080	MODE2	2.059	29.307	-.806293	2.034	28.953	-.670936
155	3.100	MODE2	2.043	29.078	-.801887	2.021	28.760	-.675951
156	3.120	MODE2	2.027	28.850	-.797494	2.007	28.568	-.672990
157	3.140	MODE2	2.011	28.624	-.793113	1.994	28.377	-.670043
158	3.160	MODE2	1.995	28.399	-.788740	1.980	28.187	-.667111
159	3.180	MODE2	1.980	28.175	-.784372	1.967	27.997	-.664194
160	3.200	MODE2	1.964	27.952	-.780003	1.954	27.808	-.661292
161	3.220	MODE2	1.948	27.731	-.775624	1.941	27.621	-.658407
162	3.240	MODE2	1.933	27.511	-.771218	1.928	27.434	-.655540
163	3.260	MODE2	1.918	27.292	-.766746	1.914	27.248	-.652695
164	3.280	MODE2	1.902	27.074	-.762062	1.901	27.063	-.649880
165	3.300	MODE2	1.887	26.858	-.756703	1.888	26.878	-.646907
166	3.320	MODE2	1.872	26.643	-.752751	1.876	26.694	-.643630
167	3.340	MODE2	1.857	26.430	-.748996	1.863	26.511	-.640350
168	3.360	MODE2	1.842	26.217	-.745338	1.850	26.329	-.637078
169	3.380	MODE2	1.827	26.005	-.741744	1.837	26.149	-.633817
170	3.400	MODE2	1.812	25.795	-.738202	1.825	25.969	-.630568

171	3.420	MODE2	1.798	25.585	-.734701	1.812	25.790	-.627332
172	3.440	MODE2	1.783	25.377	-.731236	1.799	25.612	-.624109
173	3.460	MODE2	1.768	25.169	-.727804	1.787	25.434	-.620899
174	3.480	MODE2	1.754	24.962	-.724402	1.775	25.258	-.617704
175	3.500	MODE2	1.739	24.757	-.721030	1.762	25.083	-.614522
176	3.520	MODE2	1.725	24.552	-.717680	1.750	24.908	-.611354
177	3.540	MODE2	1.711	24.348	-.714357	1.738	24.735	-.608200
178	3.560	MODE2	1.696	24.145	-.711058	1.726	24.562	-.605059
179	3.580	MODE2	1.682	23.943	-.7[illegible]783	1.714	24.390	-.601933
180	3.600	MODE2	1.668	23.742	-.704529	1.702	24.220	-.598820
181	3.620	MODE2	1.654	23.542	-.701298	1.690	24.050	-.595721
182	3.640	MODE2	1.640	23.343	-.698080	1.678	23.880	-.592635
183	3.660	MODE2	1.626	23.145	-.694898	1.666	23.713	-.589564
184	3.680	MODE2	1.612	22.948	-.691729	1.654	23.545	-.586506
185	3.700	MODE1	1.598	22.751	.005344	1.643	23.378	-.506582
186	3.720	MODE1	1.599	22.753	.00[illegible]604	1.632	23.234	-.506530
187	3.740	MODE1	1.599	22.754	.003914	1.622	23.090	-.506463
188	3.760	MODE1	1.599	22.755	.002951	1.612	22.946	-.506371
189	3.780	MODE1	1.599	22.756	.001452	1.602	22.802	-.506217
190	3.800	MODE1	1.599	22.755	-.002105	1.592	22.658	-.504511
191	3.820	MODE2	1.599	22.755	-.685853	1.582	22.515	-.578839
192	3.840	MODE2	1.585	22.560	-.682084	1.570	22.350	-.576305
193	3.860	MODE2	1.571	22.366	-.678321	1.559	22.187	-.573783
194	3.880	MODE2	1.558	22.174	-.674563	1.547	22.024	-.571274
195	3.900	MODE2	1.544	21.982	-.670803	1.536	21.861	-.568779
196	3.920	MODE2	1.531	21.792	-.667034	1.525	21.700	-.566297
197	3.940	MODE2	1.518	21.603	-.663239	1.513	21.539	-.563832
198	3.960	MODE2	1.505	21.414	-.659383	1.502	21.379	-.561386
199	3.980	MODE2	1.491	21.227	-.655310	1.491	21.220	-.558977
200	4.000	MODE2	1.478	21.042	-.650775	1.480	21.061	-.556370
201	4.020	MODE2	1.465	20.857	-.647400	1.469	20.903	-.553549
202	4.040	MODE2	1.452	20.673	-.644178	1.458	20.746	-.550727
203	4.060	MODE2	1.440	20.490	-.641037	1.447	20.589	-.547913
204	4.080	MODE2	1.427	20.308	-.637949	1.436	20.434	-.545107
205	4.100	MODE2	1.414	20.127	-.634905	1.425	20.279	-.542313
206	4.120	MODE2	1.401	19.947	-.631895	1.414	20.125	-.539529
207	4.140	MODE2	1.389	19.767	-.628917	1.403	19.972	-.536757