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EXHAUST-SYSTEM LEAK TEST:
QUANTITATIVE PROCEDURE

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16. Abstract

A quantitative, periodic motor vehicle safety-inspection test for determining the leakage rate of engine exhaust from an automotive exhaust system was investigated. Two technical approaches were evaluated, and the better one was selected for development of necessary special equipment and test procedures. The results of the measurement are expressed as the diameter of a single round hole, equivalent in leakage rate to the sum of all leaks in the exhaust system being tested. This method is capable of measuring leaks equivalent in size down to about a 1/16-inch hole; discrimination between leaks of 1/8-to 1/2-inch diameter is reliable and easily achieved. Total time to conduct a test and evaluate results is estimated to be from 2 to 5 minutes. In addition, the test imposes a reproducible pressure stress on each system tested; this provides reasonable assurance that the system will remain structurally intact until the next inspection period without developing catastrophic leakage. A field test kit has been developed which can accommodate engine displacements to 460 cubic inches. Flow calibration data are given. A detailed test procedure complete with leak-size determination graphs and a calculation nomograph is presented in an appendix.

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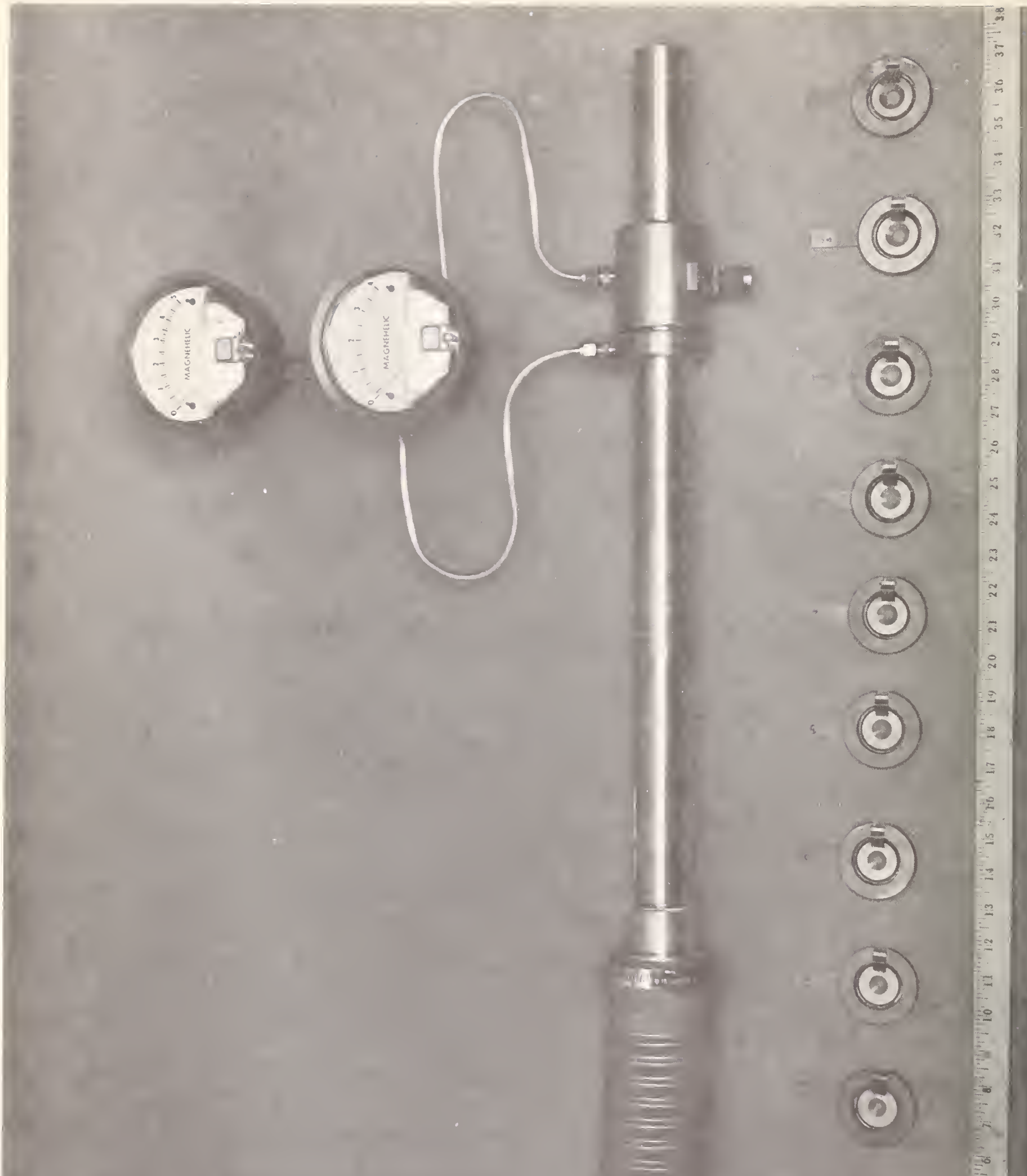
PREFACE

The work described in this report constituted one major task of a two-year project carried out by the Measurements and Instrumentation Division of the Transportation Systems Center (TSC) and sponsored by the Research Institute, National Highway Traffic Safety Administration (NHTSA), Department of Transportation, Washington, D. C. The Project Plan Agreements (PPA's) covering this work were (FY1971) PPA HS01, Engine Exhaust Monitor; and (FY1972) PPA HS201, Vehicle Contamination by Exhaust. The resources (funding) for these PPA's were $250,000 and $100,000, respectively. The Task Manager at NHTSA was Manuel J. Lourenco; Task Managers at TSC were (FY1971) Dr. A.E. Barrington and Earl C. Klaubert; and (FY1972) Earl C. Klaubert.

Two other major tasks were included in the above-cited PPA's. The first was an evaluation of the degree of self-contamination of vehicles in like-new condition by their own engine exhaust (see Mathews, S.M., "Measurement of Vehicle Contamination by Exhaust Gases," Report No. DOT-TSC-NHTSA-71-7). The second was a feasibility study of a potentially low-cost large-volume instrument for measuring vehicle self-contamination by exhaust (see Klaubert, E.C. and J.C. Sturm, "Evaluation of Length-of-Stain Gas Indicator Tubes for Measuring Carbon Monoxide in Air," Report No. DOT-TSC-NHTSA-71-8).

Valuable contributions to the work described in this present report were made by A.L. Lavery, who initially suggested the use of two orifice sizes to create different backpressures and also to measure tailpipe flow rates; and by A.J. Broderick, who performed early analytical studies of the concept and offered constructive consultation on numerous aspects during the development program.

The engineering model of the exhaust-system leak-test device which resulted from the work described herein is shown in the frontispiece.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1. INTRODUCTION

1.1 BACKGROUND

Accidental self-contamination of the passenger compartment of a motor vehicle by exhaust gases (principally, carbon monoxide, CO) is known to have resulted in serious injury or death in occasional cases. While firm data are scarce, such self-contamination has been suspected in a significant number of additional instances. To evaluate the scope of this possible problem, the Transportation Systems Center (TSC) initiated a program under the sponsorship of the National Highway Traffic Safety Administration (NHTSA) to develop a test to measure the integrity of vehicle passenger compartments against this contamination; such test should be suitable for widespread use in State-regulated periodic motor-vehicle inspections (PMVI). No valid, practicable test could be found for use on stationary vehicles. Only moving-vehicle, on-the-road techniques (or perhaps, the use of wind tunnels) could produce representative passenger-compartment pressurization (or depressurization) and exterior eddy currents. Also, leaks of known sizes in specified locations would have to be introduced into the exhaust system of the vehicle under test. Such a procedure would be very expensive and time-consuming, and was not justified by the limited known incidence of significantly hazardous cases. An alternative approach was required.

Vehicle self-contamination by exhaust could be expected to occur via two major routes: (a) gases discharged from leaks in the exhaust system could enter the passenger compartment through body openings and defects along the entire length of the vehicle; and (b) exhaust discharged from the tailpipe might be caught up in aerodynamic eddies around the rear of the vehicle and then enter through openings there. With respect to the latter route, related research at TSC[1] has shown that self-contamination of cars in new condition generally is negligible. (American manufacturers voluntarily test and, if necessary, modify all new designs to ensure this performance.) If visual inspection of the vehicle rear showed this area to be physically in as-new condition, no serious self-contamination hazard should exist from this source. Therefore, self-contamination reasonably could be expected only from gases escaping from leaks in the exhaust system and entering through defects in the passenger compartment. If there were no leaks in the exhaust system, the presence of such body defects (which are impractical and expensive to detect and quantize) would be of no concern. On the other hand, if the exhaust system were to leak, and if an inexpensive test therefore existed or could be found, it would be cheaper, easier, and more reliable to find such leaks (or at least establish their existence) and repair them than try to determine if and to what extent they result in contamination of the passenger compartment.

Many states include in their PMVI some sort or degree of exhaust-system inspection, and vehicles may be rejected if their exhaust systems leak "excessively." The problem is that all such exhaust-systems inspection procedures impose unknown and unreproducible stresses (i.e., pressures) on the systems tested, and the criteria for evaluation of test effects are very subjective and non-quantitative.

Therefore, a need does exist for a quantitative, reproducible exhaust system leak test.

1.2 OBJECTIVE

The objective herein was to develop a quantitative, automotive-exhaust-system leak test which would be suitable for large-scale application in State-regulated (safety) PMVI. There were two basic requirements: (a) provide objective criteria for quantitative evaluation of the leakage from exhaust systems, and (b) apply a known pressure stress, within specified minimums and maximums, to each system tested to insure that it possesses sufficient structural integrity to survive in reasonably sound condition until the next inspection period. In addition, the test: first, should be quick and easy to perform; second, require minimal operator training and competence; and third, sell at a price acceptable to franchised automotive service stations.

1.3 TECHNICAL APPROACH

Two approaches to a quantitative exhaust-system leak test were considered in some detail: (a) pressurization of the system from the tailpipe exit by an external source of compressed air, to within specified pressure limits, with measurement of the steady-state volumetric leakage rate; and (b) engine pressurization of the system by exhaust, to within specified pressure limits, with some method of determining the mass rate of exhaust lost from system leaks. Both techniques were evaluated analytically and empirically, and the engine-pressurized method was selected for final development.

1.4 SUMMARY OF RESULTS

The results of this investigation are summarized immediately below; subsequent sections of this report describe in greater detail the physical characteristics of the two approaches, the evaluation procedures, and the results.

1.4.1 External-Source Exhaust-System Leak Test

The external-source technique was found to have several severe shortcomings: (a) It required delivery of compressed air at a regulated low pressure (three pounds per square inch gage, psig, i.e., above ambient barometric pressure) at flow rates which might tax the capacity of compressors at smaller service stations. While most stations could be expected to provide compressed air, this would restrict the areas in the station grounds where testing could be performed and would require the use of a cumbersome air hose. (b) The quantitative accuracy of the test would be affected by variations in temperature between different exhaust systems and by temperature changes in a given system. (c) Many engines might stop with both the intake and exhaust valves of one cylinder partially open in an overlap position, which would allow very large flow rates to escape through the carburetor. After a brief experimental evaluation, this technique was rejected from further consideration.

1.4.2 Engine-pressurized Exhaust-System Leak Test

A technique has been developed which provides reproducible, quantitative assessment of the total leakage rate from an automotive exhaust system. The results of the measurement are expressed as the diameter of a single round hole equivalent in leakage rate to the sum of all leaks from the exhaust system being tested. This method is capable of measuring leaks equivalent to a 1/16-inch diameter hole; the detection of, and discrimination between, leaks of 1/8-inch and larger in increments of 1/8-inch are very reliable and easily achieved. Total time to conduct an exhaust-system leak test and evaluate the results, for an experienced operator, is estimated to be from 2 to 5 minutes, depending on the number of repetitive measurements made to verify results.

In addition, the test imposes a reproducible pressure stress, within specified maximums and minimums, on each system tested; this tends to insure that the system still possesses adequate strength to survive until the next inspection without developing catastrophic leakage (barring impact with or from exterior objects).

An invention disclosure[2] for the above concept has been filed with the TSC Patent Counsel.

A possibly improved version of the present, generally used, leak test also was conceived but not tested. A relief valve would be used to generate a known back-pressure stress on the exhaust system, and a silencer would attenuate the sound of gas leaving the valve. This method still is unquantitative and subjective, and has not been evaluated.

2. EXTERNAL-SOURCE EXHAUST-SYSTEM LEAK TEST

2.1 CONCEPT

The open end of the exhaust tailpipe would be sealed, either internally or externally, with a plug or fitting which provided for passage of air into the exhaust system. A source of compressed air and a pressure regulator would deliver perhaps 15 standard cubic feet per minute (SCFM), i.e., at 70°F, 1 atmosphere absolute pressure of air at a regulated pressure of 3.0 + 0.1 psig (or other pressure and tolerance as prescribed). A variable-area flowmeter, or rotameter, would measure volumetric flow rate of air into the exhaust system, and a pressure gage would indicate the pressure developed inside the system. If system leaks were small enough to permit the full supply pressure of 3 psig to be developed, the flow rate required to maintain this pressure would be a measure of the combined effect of system leaks. If the leaks were large enough to prevent system pressure from rising to 3 psig at the maximum flow rate (and this maximum flow rate would have to be specified and accurately controlled), then the steady-state pressure which was developed at maximum flow would be a measure of system leakage.

2.2 EVALUATION

While virtually every franchised automotive service station can be expected to have compressed air available, many stations would not have compressors capable of supplying 15 SCFM continuously; however since such air normally is stored at pressures of from 50 to 100 psig, blowdown through the regulator probably could supply sufficient quantity for a test.

A serious disadvantage, for a quantitative test, is the sensitivity of the technique to exhaust-system temperature. The mass flow rate of a gas through an orifice (the leaks in the system) is inversely proportional to the square root of the absolute temperature of the gas, all other factors being constant. If the vehicle had just been driven into the inspection station, its exhaust system would be quite hot near the front (engine) end; the actual temperature would depend on the specific vehicle, its speed near the station, climatic conditions, time after engine shutoff, position of the leak along the length of the system, etc. The temperature of the air as it approached any leaks in the system would be affected by many of these same factors. If the system had any leaks, the steady-state leakage rate measured thus could be affected significantly, and the reading would increase as the exhaust system cooled. Readings taken outdoors in winter on a system allowed to cool thoroughly would be substantially higher than readings made on the same system when hot. In general, such results could lead to quite inharmonious dispute between car owner and inspector.

Another problem may arise, especially with larger V-8 engines designed for high performance. There is a reasonable probability that the engine will stop with both the inlet and exhaust valves for some cylinder partially open in the overlap region at the end of the exhaust stroke. In such a case, the pressurizing air would have almost unrestricted passage through the exhaust system, into the cylinder, and thence, through the intake manifold and carburetor to the open air. Some "jogging" of the starter motor might serve to correct this condition, but it would add to the time required for the test and there would be room for argument that the condition would always occur in certain engines.

A system based on the above concept was assembled to evaluate the idea. A small portable compressor and storage tank served as the base, and the required valves, regulators, and rotameters of two different ranges were mounted on an attached panel (see Fig 2-1). The system was tested briefly on a vehicle used for development and evaluation of these concepts (a 1968 Chevelle four-door sedan with 230-cubic inch displacement (cid) 6-cylinder engine). This vehicle had been equipped with a completely new exhaust system, all joints and seams of which had been sealed with an exhaust-system sealing compound. Holes of known sizes then were drilled into the exhaust system; when desired, these holes could be sealed with high-temperature-resistant pads supported by stainless-steel hose clamps.

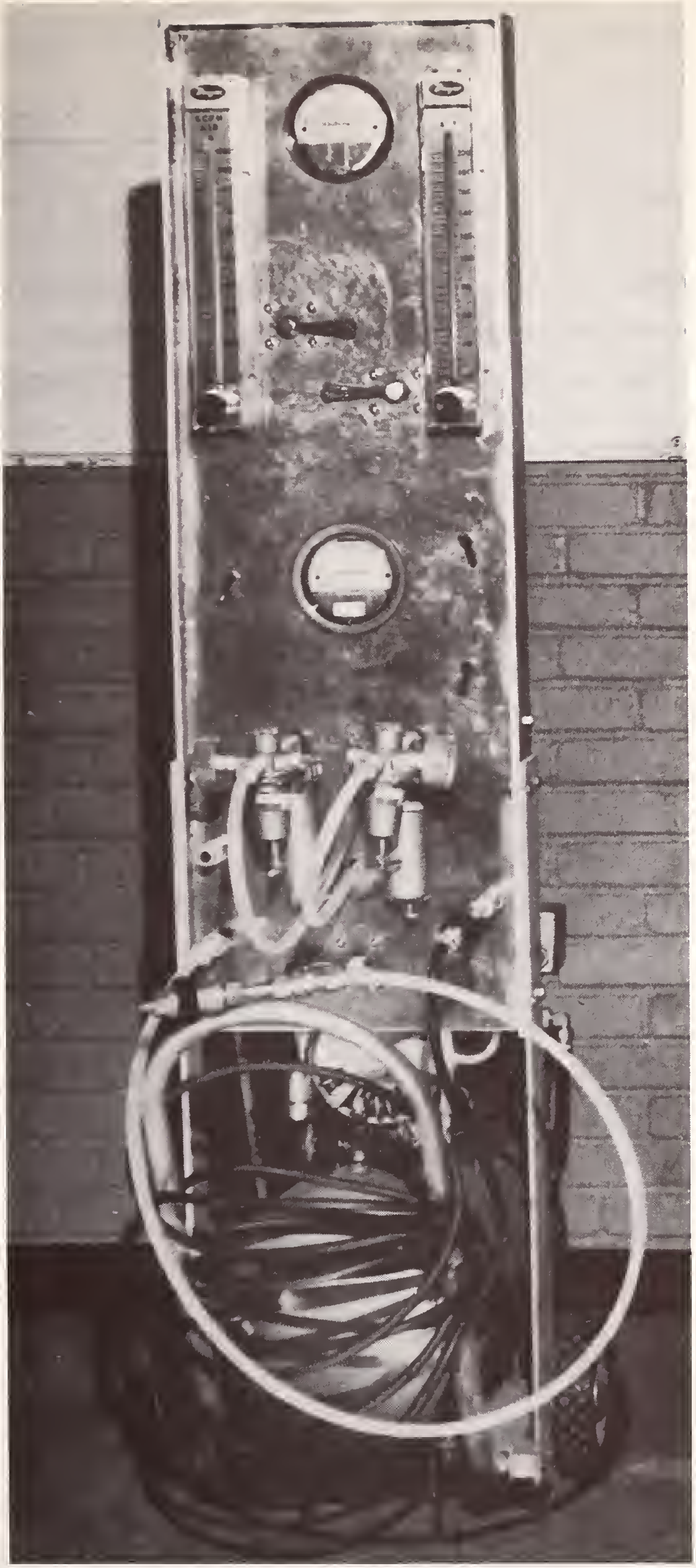


Figure 2-1. External-Source Exhaust-System Leak-Test Prototype Assembly

When attempts were made to pressurize the supposedly sealed system, the maximum 17 SCFM flow rate of the test device was insufficient to develop a pressure of 3 psig. Air was found to be leaking out of the heat-riser section of the exhaust manifold; other leakage paths, if present, were not identified. Independent leakage tests on the same exhaust system by the technique to be described in section 3 below verified that there indeed was some leakage from this exhaust system, probably from the heat riser, but that it was equivalent to that of a hole of approximately 3/32-inch diameter. The air-flow rate and resultant backpressure observed in the test with this external-source method would suggest a leak equivalent to a hole of 3/8-inch diameter or larger; this size is at least 16 times the area detected with the other method which, at that time, had justified considerable confidence in its performance.

Since the competitive approach to be described in section 3 was performing so well and was relatively free of difficulties, and in view of the potential problems described earlier in this section, development of the external-source leak test was terminated at this point with the concurrence of the sponsor.

3. ENGINE-PRESSURIZED EXHAUST-SYSTEM LEAK TEST

3.1 CONCEPT

The engine-pressurized technique is based on the fact that the mass-flow rate of a gas through an orifice (in this case, the leak) increases as the pressure drop across the orifice increases. If a constant mass-flow rate of a gas at constant temperature is delivered to a leaky exhaust system and the pressure in the system is made to increase, e. g., by a variable restriction attached to the tailpipe, the flow rate of exhaust from the leak will increase and that from the tailpipe will decrease proportionately. The engine of the vehicle under test is operated at idle speed as a constant-mass-flow pump. A device attached to the tailpipe exit provides two different degrees of restriction to exhaust flow, and thus, generates two pressure levels within the system. This device also can indicate the relative flow rates of exhaust from the tailpipe at the two pressure levels produced. The lesser restriction develops a very low backpressure (typically 0.02 to 0.3 psig); at this low pressure, relatively little gas escapes from leak(s) in the system, and tailpipe flow is a reasonably good indication of total mass-flow rate from the engine. The greater restriction is designed to produce a backpressure of from 3 to 5 psig in an exhaust system which has no leaks; however, a single hole of 1/2-inch diameter will reduce this backpressure to between 0.9 and 0.04 psig (depending on engine-flow rate), in which case more exhaust escapes from the leak than from the tailpipe restriction. Relationships can be developed between tailpipe flow/backpressure parameters and size of exhaust system leak which will permit the expression of total system leakage as the size of a single hole allowing equivalent leakage.

Early in the development of this technique, the intent was to measure the two mass-flow rates and take the difference; it was recognized that, for small leaks, this would mean taking the relatively small difference between two large and not too precisely determined quantities. As the work progressed with the orifice meter selected as described below, the concept evolved and simplified, and an important effect of the final configuration was recognized. Later in this section it will be shown that the sizes of orifices required to develop backpressures of 3 to 5 psig for automotive engines at idle are in the range of from 0.2 to 0.4 inch (inside diameter (id)). The flow resistance of these small holes is markedly higher than the resistances of normal mufflers and of exhaust pipes with typical diameters of 1.5 to 2.25 inches. It was desired to detect exhaust-system leaks down to sizes equivalent at least to 1/8-inch diameter and as large as 1/2-inch. The effect of the small metering orifices is to "magnify" the loss from small exhaust leaks by comparing it with the flow at equivalent pressures through these 0.2- to 0.4-inch holes, which are of comparable size to, and are even smaller than some of, the leak sizes to be evaluated. It is this "magnifying" effect which has given this test technique the outstanding sensitivity and size discrimination which will be evident in later sections of this report.

3.2 SYSTEM COMPONENTS

The flowmeter used to measure tailpipe-exhaust flow is the heart of this technique, and as such, received careful consideration as to type selected. The substance being measured is a compressible gas which will be measured at two different pressures in any given test, and at different temperatures at least for different vehicles; therefore, a mass-dependent, rather than a volume- or velocity-dependent, device was desired. The gas may be hot and may be contaminated with particulates (soot), and oil and gasoline vapors; it will contain high concentrations of water vapor and may carry entrained water droplets. Therefore, the flowmeter selected must not be subject to sticking as a result of such contamination, and must be resistant to corrosion, elevated temperatures (at least to 175°C), and hydrocarbon and water vapors or liquids. The meter must have wide dynamic range, and yet, be sensitive to relatively small changes in flow. It must be rugged, reasonably insensitive to operating attitude, accurate (or, at least, reproducible), and modest in price when mass-produced.

The types of flowmeters normally used to measure mass flow of gases include positive displacement or "wet test," variable-area or rotameter, venturi, and orifice meters. The first of these meters could be ruled out immediately on the bases of contamination, ruggedness, attitude sensitivity, size, and cost. Rotameters are subject to sticking, difficult to clean, attitude-sensitive, and in large sizes expensive. Venturi meters are expensive, long relative to diameter, not amenable to interchange of venturi element for change in capacity, and not notably superior to orifice meters when efficient pressure-drop recovery is unessential (as in this application). Consequently, the orifice flowmeter, with interchangeable orifices to increase the range of measurable flow rates, seemed to be clearly indicated as the optimum type of instrument for this use.

The next most important component of the system is the pressure-measuring equipment. Reasonably accurate measurement of pressure differential is required over two ranges: 0 to 0.4 psid (psi differential) and 0 to 5 psid. Fortunately, as the technique evolved to final form, the precision and accuracy tolerances demanded could be substantially relaxed. For an operational system, the most economical approach was to use two pressure gages in parallel; one gage spanned the 0-to 0.4-psid range but could be overpressured to at least 5 psid without injury, and the other gage had a 0-to 5-psid range. However, during development and calibration of the system, when the maximum feasible degree of rangeability, resolution, and accuracy was desired, a Baratron Type 77 electronic pressure gage (MKS Instruments, Inc., Burlington, MA) was used for all pressure measurements. To provide permanent records of test and calibration measurements, the Baratron was connected to a 10-inch strip-chart recorder.

The remaining components were quite elementary in nature. A reinforced silicone rubber/fiberglass fabric hose 3 inches in diameter x 4 feet in length was used to connect the orifice flowmeter to the exhaust system (or to the flow-calibration system). A quick-acting coupling which can accommodate a wide range of exhaust tail-pipe diameters and shapes (not all are round) will be practically mandatory for an operational unit; however, it was not essential during development, and effort was not diverted to devise such a coupling. A simple fitting using compressed silicone rubber sheet for sealing served adequately.

3.3 DESIGN ASSUMPTIONS

To make the engine-pressurized technique as simple and rapid to use as possible, it was desired to eliminate any measurement of, or correction for, gas temperature. As mentioned in section 2.2 above, gas temperature is an important parameter in the orifice flow relationship; pressure drop varies directly and linearly with absolute temperature of the gas. Although gas temperatures for various cars and/or climatic conditions were expected to differ substantially, it was assumed that there would be little change in temperature during the conduct of a single exhaust-system leak test.

The other major assumption on which this technique was based was that total-exhaust mass-flow rate from the engine would be constant during the test, independent of exhaust backpressure. If this were not true, there would be no way to tell, from only tail-pipe measurements as was desired, how much gas was being lost from system leaks.

To validate this test method, it was important to investigate the accuracy of these assumptions. The results of these studies are given below.

A third assumption also is implicit in this procedure; viz., the effective molecular weight of the exhaust gas does not vary within a given test. Increasing the backpressure on an engine does indeed impose an added load on the engine (which has to do more pumping work), and conceivably, some minor changes in gas species present in the exhaust could be detected. However, consideration of the molecular weights and concentrations of exhaust gas species and of small changes therein indicated that the effect of such variations on the average molecular weight of the mixture should be quite negligible. No experimental verification of this premise was attempted.

3.3.1 Engine-Exhaust Temperature versus Backpressure

The development model of the orifice flowmeter was equipped with a thermistor probe to measure exhaust gas temperature, both to verify the constant temperature assumption and to provide data for orifice flow calculations. Exhaust tailpipe temperature vs. backpressure was measured in detail on only one car, the 1968 Chevelle mentioned in section 2.2 above. If any discernible effect was expected, it was that exhaust temperature would increase slightly as backpressure was raised from 0 to 5 psig; calculations of adiabatic compression predicted an increase of ca 2°C. However, the surprising result of increasing backpressure was a pronounced drop in temperature. The fully warmed-up exhaust system and flowmeter had been indicating a zero-backpressure gas temperature of about 135°C; in slightly over 1 minute after backpressure was raised to 4.7 psig, gas temperature stabilized at 50°C. Note that gas temperature was measured upstream of the orifice which produced the backpressure, not after expansion to ambient pressure. The effect was very repeatable and was linear with pressure within the above limits.

To confirm, in a rough manner, that no drastic change in combustion phenomena was responsible for this unexpected temperature change, a thermocouple was fastened to the exterior of the exhaust pipe just downstream from the flange attaching it to the engine-exhaust manifold. Another cycle of measurements was made while both tailpipe gas and upstream exhaust-pipe external surface temperatures were monitored. As tailpipe gas temperature fell linearly from 135° to 50°C, upstream pipe-surface temperature climbed linearly from 269° to 293°C; evidently, there was no significant change in combustion phenomena. Thus, the approximate temperature drop of the exhaust (upstream temperature was pipe wall, not actual gas) while passing from manifold to tailpipe increased from 134° to 243°C as backpressure was raised from 0 to 4.7 psig. The only apparent explanation for the lower gas temperatures is increased heat transfer to the exhaust-system walls, and then, to the air under the car.

Approximate heat-transfer calculations were made to estimate total heat-loss rate, heat loss by radiation and convection, and overall heat-transfer coefficients, for minimum and maximum pressure conditions. The results showed unusually high overall coefficients for gas-to-gas heat exchangers, in spite of this less-than-optimum location of exhaust system close to automobile floor. Because of the higher pressure, the gas was compressed to a higher density which resulted in an approximately 38 percent longer residence time in the system; but the amount of heat lost by the gas increased by about 78 percent. No fully satisfactory explanation for this phenomenon could be found; but there was no doubt that the effect indeed occurred and was repeatable.

Although explanation of this phenomenon would have been desirable, it was not essential to the program; knowledge of it, to permit corrective action, was sufficient. The remedy for this effect was to arrange to insert the smaller orifice rapidly and to read the peak pressure drop developed across this smaller orifice as quickly as possible, before the exhaust system had time to cool enough to affect seriously the reading. With this provision, the assumption of essentially constant gas temperature during a single test was considered to be justified.

3.3.2 Constant Engine-Exhaust Flow versus Backpressure

Changes in mass flow through the engine, as exhaust backpressure was varied, were monitored by measuring the flow rate of air into the carburetor with a rotameter which produced a pressure drop of only 3 inches of water or less essentially independent of air-flow rate. Engine speed was monitored by an electronic counter which counted all breaker-point openings for 10 seconds. It was found that, for a fully warmed engine operating at steady-state conditions, individual 10-second counts routinely would differ by ± 5 to 7 percent but the average of 10 such consecutive counts, when compared with the average of another 10 consecutive counts taken immediately following the first, usually would agree within ±1 count in 500 and often within a fraction of a count. Thus it was established that steady-state engine speed averaged over a period of 100 to 120 seconds was highly reproducible; this is the quantity referred to when the term "engine speed" is used below. It should be noted that, while engine speed during one 10-second period might differ by perhaps 10 percent from that observed during the following 10-second period, air flow indicated by the rotameter during the two periods generally showed no detectable change.

The 1968 Chevelle mentioned in section 2.2 above was used for the first evaluation of engine mass throughput vs. backpressure. This 230 cid, 6-cylinder engine had accumulated an indicated 22,000 miles at the time of the test. As exhaust backpressure was increased from 0 to about 5 psig at constant throttle setting, engine idle speed decreased by 10 to 15 percent in repeated tests but air inflow to the carburetor dropped by only 0.5 to 0.7 percent. To provide additional data, a 1971 Toyota Corolla with a 1600-cubic-centimeter (96.9 cubic inches) 4-cylinder engine which had been driven about 7500 miles was tested similarly. From 0 to 5 psig backpressure, this engine also lost 15 percent in speed while air inflow diminished by 3.6 percent. While this smaller engine's air-flow variation was considerably greater than that observed for the Chevelle, the absolute magnitude of the change was considered unlikely to have a serious effect upon the validity of the test. Program requirements precluded studying a number of vehicles with engines of different sizes, ages, and carburetion. However, it was felt that the assumption of essentially constant mass flow during a given test had been sufficiently verified.

3.4 ENGINEERING-MODEL FLOWMETER DESIGN

As discussed in section 3.2 above, an orifice-type mass flowmeter was selected for this application. Orifice flowmeters are subdivided into several classes, depending primarily on the longitudinal location of the upstream and downstream pressure taps or ports relative to the orifice position. For this application, a choice had to be made between only two of these classes: radius taps or flange taps. The Chemical Engineers' Handbook[3] defines these tap locations as follows:

a. Radius Taps. Static holes located 1-pipe-diameter upstream and 1/2-pipe-diameter downstream from the upstream surface of the orifice plate.

b. Flange Taps. Static holes located 1-inch upstream and 1-inch downstream from the respective surfaces of the orifice plate.

In regard to the relative merits of the above tap locations, the same reference[3] states: "Radius taps are theoretically the best: the downstream pressure tap is located at about the mean position of the vena contracta (the point of lowest pressure, which moves up- or downstream somewhat as orifice size or flow rate is changed); the upstream tap is sufficiently far upstream to be unaffected by the distortion of the flow in the immediate vicinity of the orifice. Flange taps offer the sometimes great advantage that the pressure taps can be built into the plate carrying the orifice. Thus the entire apparatus can be quickly inserted in a pipeline at any convenient flanged joint without the necessity for drilling holes in the pipe. By merely replacing standard flanges with special orifice flanges suitable pressure taps are made available." Apparently because of this convenience (for appropriate locations), the American Society of Mechanical Engineers (ASME) has developed extensive tables of operating parameters for flange-tapped fluid flowmeters.[4]

If calculations of actual mass flow were to be made routinely in this test procedure, flange taps probably would have been the better choice since tables of parameters are available. However, this method generally will not be used to determine mass flows explicitly. Radius taps produce greater observed pressure differentials than flange taps for the same flow conditions, and therefore, yield greater test sensitivity. No existing flanged joint is available at which merely to substitute tapped flanges; a complete meter must be provided for this specific purpose.

Although orifices made to proper specifications are supposed to exhibit predictable performance, this was not always realized in earlier experiments with the prototype exhaust flowmeter; orifices that were apparently identical except in hole size demonstrated variations in flow coefficient which were quite dissimilar but individually repeatable. Orifices are known to be quite sensitive to variations in configuration on the upstream face; the upstream features required to provide a practicable quick-change capability necessarily departed significantly from the rigid constraints demanded for use of tabulated data. For the latter several reasons, it was considered essential to perform actual flow calibration of the engineering-model orifices; therefore, it seemed best to use radius taps rather than flange taps to obtain the maximum sensitivity.

For best accuracy (± 0.5percent), ASME data[4] indicate the ratio of orifice diameter D_2 to pipe D_1 must be maintained between $0.15 \leq D_2/D_1 \leq 0.75$. Based on the range of orifice sizes to be used (0.157 to 0.880 inch, as discussed below), nominal 1-1/4-inch Schedule 40 pipe (1.66-inch outside diameter (od) x 1.40-inch inside diameter (id)) was selected for the flowmeter body. Carbon steel was undesirable because of potential rusting; brass pipe was selected over stainless steel for ease and economy of fabrication, at least for the engineering-model flowmeter (other materials of construction may be more economical for mass production). For the three smallest orifice sizes, the D_2/D_1 ratio with this size pipe is less than ASME indicates[4] is optimum. However, the sensitivity of this technique to small leaks is greatest for these small orifice sizes, and the possible decrease in accuracy caused by this condition was considered not serious.

It was desired to maintain the pressure drop across the smaller orifice of each pair between 3 and 5 psi for leak-free exhaust systems, since most typical passenger cars develop a maximum exhaust backpressure of about 5 psig at top speed and full throttle. Hence, an exhaust system in acceptable condition presumably could be required to withstand 5 psig without failure;

rupture of the system at pressures not exceeding this level could be defined (in any legislation that would inaugurate legally this test) as prima facie evidence of an unacceptable condition. Since the sensitivity of the leak test increases as the maximum pressure increases, it was desired to utilize the upper portion of this 5-psig range for the test. Furthermore, the stress imposed by this relatively high pressure (compared to normal-driving exhaust pressures) will help to weed out exhaust systems which are in marginal mechanical condition.

ASME specifications[4] for best accuracy require that the pressure drop across the orifice, Δp, with respect to the upstream static pressure, p_1, be constrained to the ratio $\Delta p/p_1 \leq 0.2$. At low Δp's, p_1 quite accurately equals Δp plus ambient barometric pressure p_A. However, as Δp increases toward 5 psig, the high-velocity flow in the flowmeter body downstream of the orifice lowers the pressure at the downstream tap slightly below p_A; hence in the vicinity of $\Delta p = 5$ psig, p_1 is somewhat less than $\Delta p + p_A$. The ratio $\Delta p/p_1$ at $\Delta p = 5$ psig therefore may surpass $5/19.7 = 0.254$, which exceeds the ASME recommendation cited above. As will be shown below, this condition will be realized only with exhaust systems in almost totally leak-free condition and only then at the maximum flow (or engine size) end of the range of a given orifice pair. A leak of only 1/8-inch diameter, equivalent to the condensate drain hole provided in many mufflers, will bring Δp within ASME limits for all but the largest engine sizes. The wide discrimination between leak sizes larger than 1/8-inch diameter indicates that such rigorous accuracy (±0.5 percent) is not essential to the purposes of this test procedure.

Both orifice meter references[3,4] require the use of flow-straightening vanes or tube bundles upstream of the orifice to stop any swirling motion of the fluid flow. Such swirling can be produced by flow around bends in the gas piping, such as are found in typical exhaust systems and may be introduced in the flexible hose used to connect the flowmeter to the exhaust system tailpipe. Accordingly, a bundle of 1/4-inch od x 0.180-inch id tubes 2.75-inch long was installed in the upstream end of the flowmeter.

The capability for rapid interchange of different-size orifice assemblies was provided by a breechblock-type joint between upstream and downstream (relative to the orifice) flowmeter body parts. For this engineering model, a quarter-turn interrupted-thread joint was the most feasible design; for a mass-produced device, numerous more economical quick-acting joint configurations are available.

Section 3.3.1 above discusses the need for rapid insertion of the smaller orifice of a test pair to circumvent possible cooling effects. An earlier prototype flowmeter which used separate orifice plates did not offer this capability. That design was modified to provide hinged orifice-pair assemblies. The smaller orifice is pivoted on the downstream face of the larger orifice plate and can lie down out of the flow stream of the larger orifice. When a small-orifice reading is desired, a plunger is pressed which swings the smaller orifice up to close off the larger orifice and allow gas to flow only through the smaller orifice. When the plunger is released, gas pressure against the smaller orifice pushes that orifice away from the fixed larger-orifice plate and the smaller orifice drops into its recess in the flowmeter downstream body section. This hinged-pair assembly offers the added advantage that an operator cannot easily mismatch (accidentally or deliberately) separate small and large orifices in incorrect combinations to produce erroneous test pressure-ratios.

The resultant engineering model of the exhaust system leak test flowmeter is shown in detail in figures 3-1 through 3-4. Note that, in these figures, the insulation which normally would surround the flowmeter body to protect the operator from the hot meter and also to minimize heat loss from the flowmeter, has been omitted.

Figure 3-1 shows an exploded view of the orifice flowmeter assembly without the pressure gages or flexible hose for coupling to an automobile tailpipe. Two dual-orifice assemblies are shown from a downstream point of view to illustrate the large-orifice low-pressure and small-orifice high-pressure conditions, from left

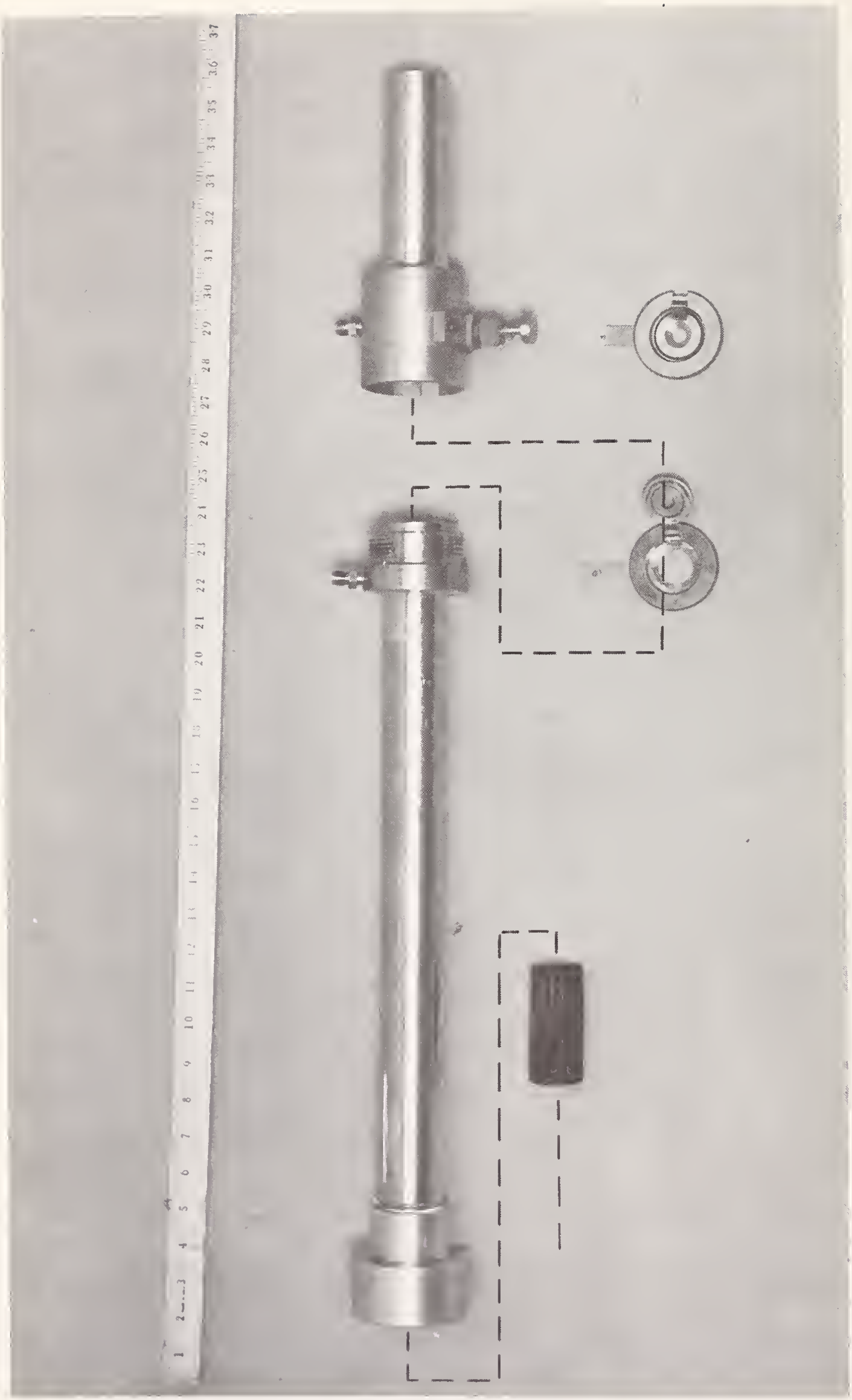


Figure 3-1. Flowmeter--Exploded View

Figure 3-2. Flowmeter Dual Orifice--Large-Orifice, Low-Pressure Position

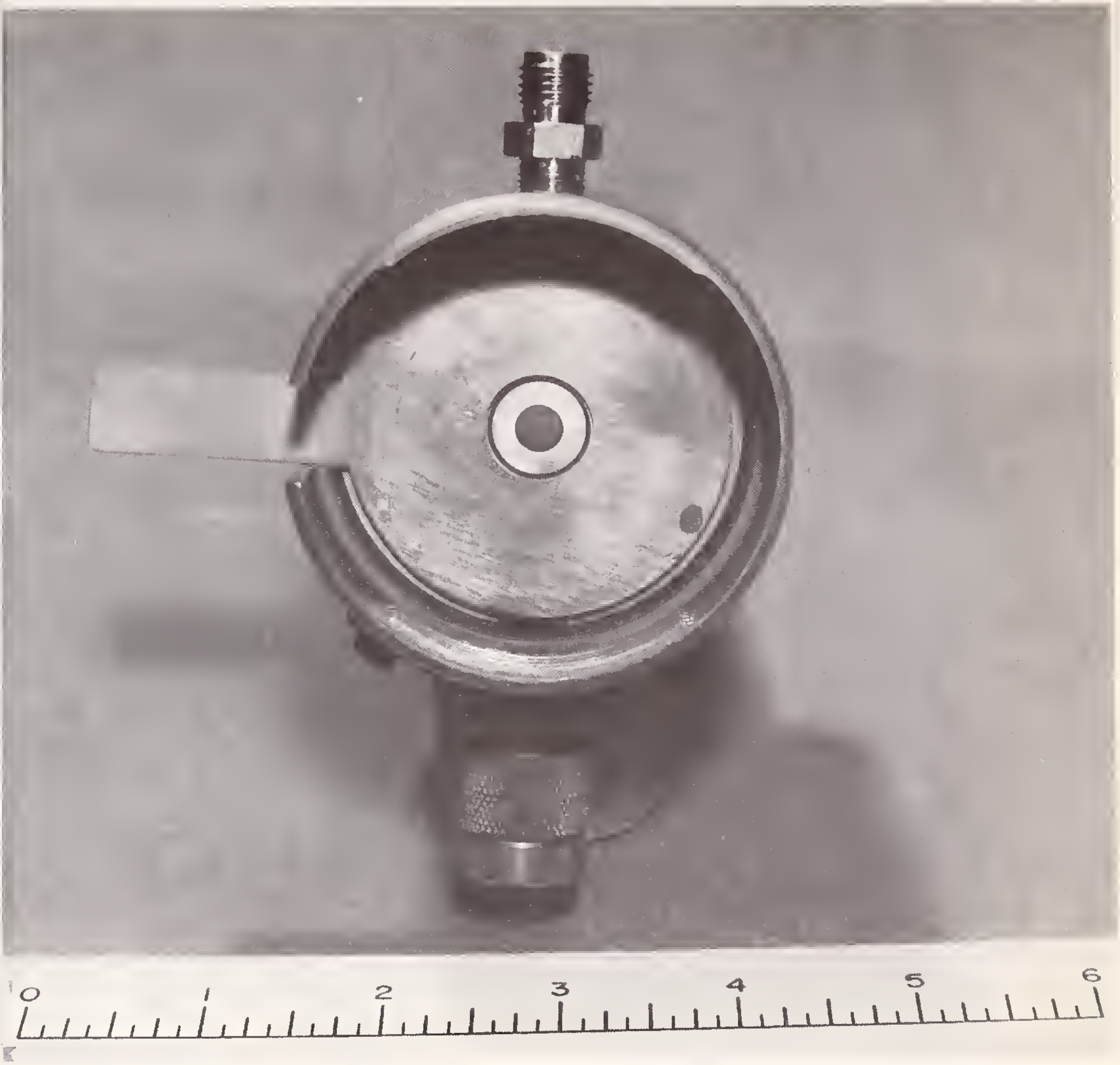


Figure 3-3. Flowmeter Dual Orifice--Small-Orifice, High-Pressure Position

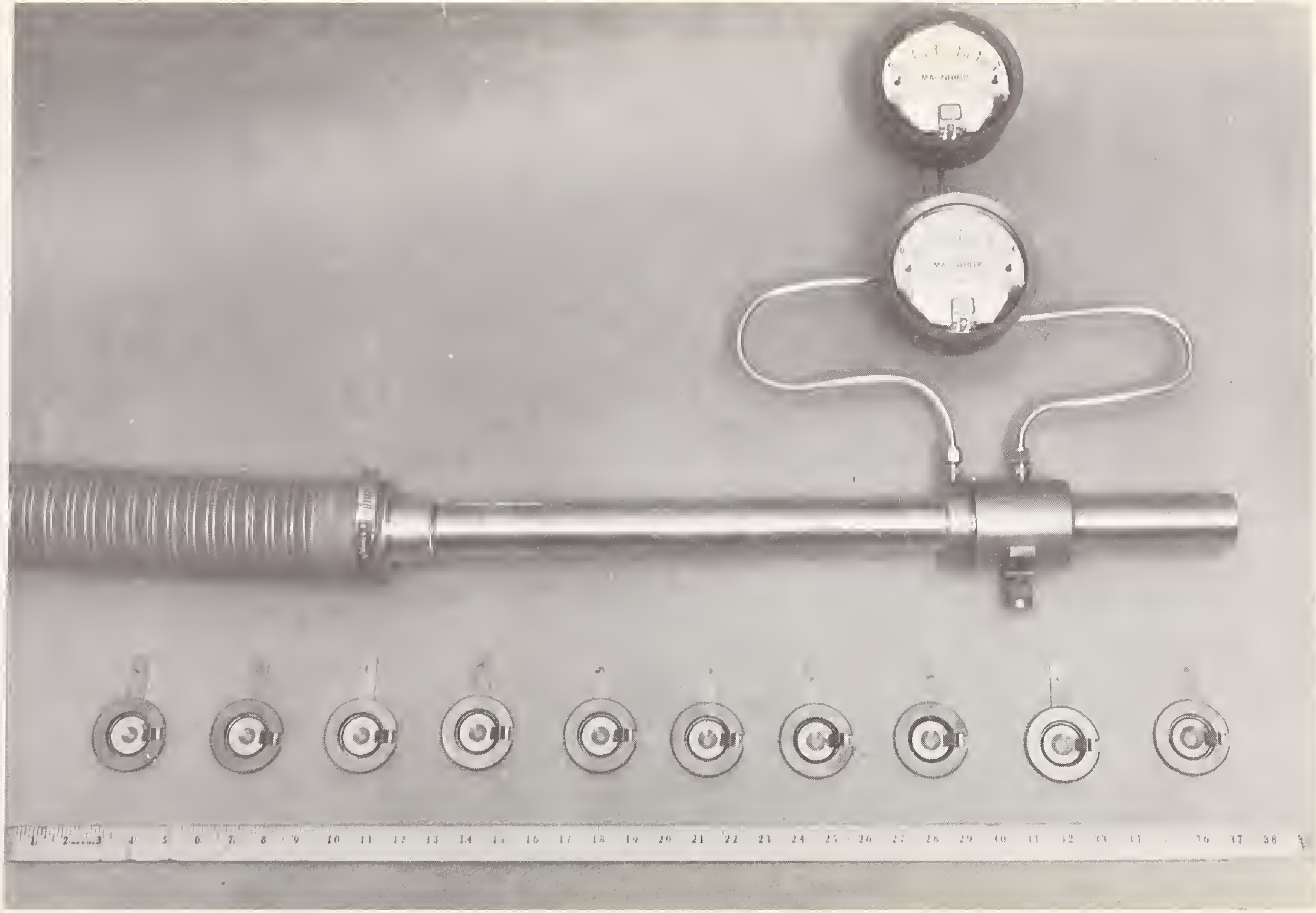


Figure 3-4. Engineering-Model Field-Test Kit--Assembly View

to right hand, respectively. Longitudinal and transverse scales are shown to indicate the dimensions of the components. At the right-hand end of the male portion of the joint can be seen the O-ring which forms a pressure seal against the upstream face of the stationary larger-orifice plate.

Figures 3-2 and 3-3 are upstream views of an orifice assembly installed in operating position in the downstream portion of the flowmeter body, but with the upstream portion of the body removed. Figure 3-2 shows the actuating pin in retracted position for a large-orifice low-pressure test; looking through the larger orifice, the smaller orifice can be seen lying in its recess in the downstream body member, out of the flow path. Figure 3-3 shows the actuating plunger pressed in to swing the smaller orifice up into test position. The upstream face of the smaller-orifice plate, in the vicinity of the orifice itself, is nominally flush with the face of the larger, stationary-orifice plate. However, the annular clearance groove between these two faces is readily apparent. This groove is one of the major departures from the rigid ASME specifications,[4] pertaining to orifice-plate configuration, which necessitated individual-flow calibration of the orifice pairs for this engineering-model flowmeter.

Furthermore, consideration of the orifice-assembly configuration as shown in figures 3-1 and 3-3 will make it apparent that sealing of the gas-flow path between the smaller- and larger-orifice plates is accomplished by a metal-to-metal face contact. Clearly, this is not an absolute seal although in these orifices the mating appears to be quite good. The small amount of leakage, and the inevitable variation therein, which must occur probably is responsible for some of the scatter in calibration data, especially at 0, 1/16- and 1/8-inch leak conditions. At larger leaks, upstream pressure is much lower and leakage caused by incomplete sealing at this orifice closure should be greatly reduced. Consideration was given to installing an O-ring in the smaller-orifice member to provide a better seal at this point. However, this is a difficult position in which to restrain mechanically an O-ring, and the fabrication of the orifice assemblies would have been made more difficult and expensive. The results of the calibration and automobile use tests reported below indicate that the present configuration functions adequately.

Figure 3-4 shows the flowmeter test kit, with complete range of calibrated orifice assemblies, ready for attachment to an automotive exhaust system. The only items required for field use which have not been provided (because they were not required for development and sufficient time was not available) are: a simple support stand for the pressure gages, a protective storage box for the orifice assemblies, and the quick-acting universal coupling for attachment to automobile tailpipes mentioned above in section 3.2.

The orifice sizes included in this kit were calculated from earlier measurements made on the Chevelle test car cited above, using the earlier prototype flowmeter with single orifice plates. The new orifices were intended to span the entire 4-cycle automobile engine range from about 90 to 490 cid, including variations in carburetion, idle speed, etc. The orifices were calculated to have overlapping ranges, as determined by the desired 3- to 5-psig range of Δp across the smaller orifice of each pair at 0 leak condition. The larger orifice of each pair was intended to provide a pressure-drop ratio $R = \Delta p$ (small orifice)/Δp (large orifice) of between 16 and 20 at 0 leak. The orifice sizes fabricated for the prototype test kit are listed below and the orifice equations are given in appendix A.

ORIFICE-PAIR DIAMETERS FOR ENGINEERING-MODEL
EXHAUST-SYSTEM LEAK-TEST KIT

ORIFICE PAIR NO.	SMALLER, SWING-ORIFICE DIAMETER, INCH	LARGER, STATIONARY-ORIFICE DIAMETER, INCH
*1	0.157	0.354
2	0.175	0.393
3	0.194	0.437
4	0.218	0.486
5	0.240	0.540
6	0.267	0.600
7	0.294	0.661
8	0.323	0.727
9	0.355	0.800
10	0.391	0.880

*Not used.

3.5 FLOWMETER CALIBRATION

3.5.1 Flow-Calibration System

The necessity for direct flow calibration of the orifice pairs for the engineering-model leak-test flowmeter has been discussed above in section 3.4. A flow system was required which would permit variation of gas-flow rate over a wide range but still provide essentially constant flow at any setting independent of back-pressure within the range from 0 to about 10 psig. The temperature of the flowing gas (presumably air) should be approximately equal to ambient room temperature to preclude effects of temperature change during calibration. A 2- or 4-cylinder 1-stage air compressor would have been ideal; however, a 2-cylinder 2-stage compressor of adequate capacity was available and was used for this purpose. This compressor would be operating at well under its intended maximum pressure (hence, power demand) at all times, and therefore could be expected to function well as a constant displacement pump.

Rotameters of appropriate sizes to measure the expected range of airflows were available. A problem existed in relating the flow rate of room-temperature air to engine-exhaust flow rate when exhaust temperature could differ substantially from one vehicle to the next. Therefore, measured air-flow rates could not be used to specify precisely which orifice pair should be used for a given size engine. Rather, the rotameters were to be used primarily as proof of constant-volume operation during a test, and also, to verify overlap of relative flow ranges between adjacent orifice pairs. If adjustment of original orifice sizes should be required, flow readings would be a useful guide.

The use of room-temperature air instead of hot exhaust gas for calibration should not distort the relationship between the two orifices of a pair (since essentially constant-temperature conditions would be maintained during either calibration or leak testing).

Unfortunately, the same is not true of apparent leak size as indicated by this test. It was noted above in section 2.2 that mass loss through an exhaust leak is inversely proportional to the square root of absolute temperature of the gas. Section 3.3.1 above showed that exhaust-gas absolute temperature in a single car decreased by about 25 percent in passing from exhaust manifold to tailpipe at nominally zero backpressure. This could result in a variation of almost 12 percent in indicated leak area, or 6 percent in indicated leak diameter, depending on location of the leak along the length of the exhaust system. This effect was actually observed in the operational evaluation of the engineering-model leak-test device, as reported below in section 3.6. The magnitude of this error will vary somewhat with different vehicles and ambient temperatures, and is inevitable; however, discrepancies on the order of 6 percent or less in indicated leak diameter (less than 1/32 inch for a 3/8-inch leak) are not considered serious for the purpose of this test, namely, safety inspection.

To vary the flow rate obtained from the constant-speed, constant-displacement pump (compressor), a throttling valve was installed downstream of the rotameters in the pump inlet line to "starve" the pump inlet. At a given steady-state flow, the average inlet pressure to the pump would be constant (below atmospheric). The constant-speed pump could take in only the constant mass of gas per stroke defined by intake gas density and cylinder volume. Variations in pump-discharge pressure would be effectively isolated from pump inlet by the pump valves. Preliminary tests of the system when first assembled showed this to be true; however, excessive oscillations in intake pressure and flow rate at pump speed were observed. This occurred because the volume of the intake line between throttling valve and pump inlet was approximately equal to the swept volume of the pump cylinder. To correct this situation, a 30-gallon air-receiver tank was installed in the intake line between valve and pump to damp out flow surges; this measure proved quite satisfactory. Similarly, the 80-gallon air tank of the compressor suitably damped discharge flow pulsations.

The automotive exhaust system to which the flowmeter would be connected in normal operation was simulated in the calibration system by a length of about 14 feet of 2-inch Schedule 40 steel pipe between the compressor tank and the flowmeter inlet hose. Artificial "leaks" of known sizes in this line were desired to permit direct evaluation of the effect of leak size on pressure drop ratio R. Holes of 1/16, 1/8, 1/4, 3/8, and 1/2 inch (+0.002/ -0.000 inch) were drilled into the pipe and were fitted with quick-acting toggle clamp seals. The pipe-wall thickness at each "leak" was reduced to about 1/16 inch to approximate the thickness of an exhaust-system pipe.

A schematic of the flow-calibration system is shown in figure 3-5.

A test bench and vertical support wall for the rotameters, exhaust flowmeter, and associated piping was constructed; this assembly is shown in figure 3-6. A worktable adjacent to the test bench supported the chart recorder and isolated it from compressor vibrations. The exhaust-system flowmeter was connected to the calibration system by a 4-foot length of the reinforced silicone rubber/fiberglass hose to be used for attaching the flowmeter to automobile-exhaust systems. Two rotameters connected in parallel (with separate 1/4-turn valves to permit the use of either one individually) can be seen on the wall at the left of the operator's station. The discharge ports of both rotameters are connected by a pipe leading down to the throttling valve to the right of the rotameters. The intake line surge tank can be seen projecting above the left corner of the support wall. No picture of the system on the opposite side of the wall was taken because details of the flow system would not have been evident.

In figure 3-6 immediately to the right of the flow-control valve is the pressure-sampling manifold. This manifold was used to select the desired pressure-tap lines and connect them to the Baratron pressure-sensing head. The Baratron head is the small object to the right of the manifold on the auxiliary shelf under the clock. The other items on the shelf are the digital voltmeter

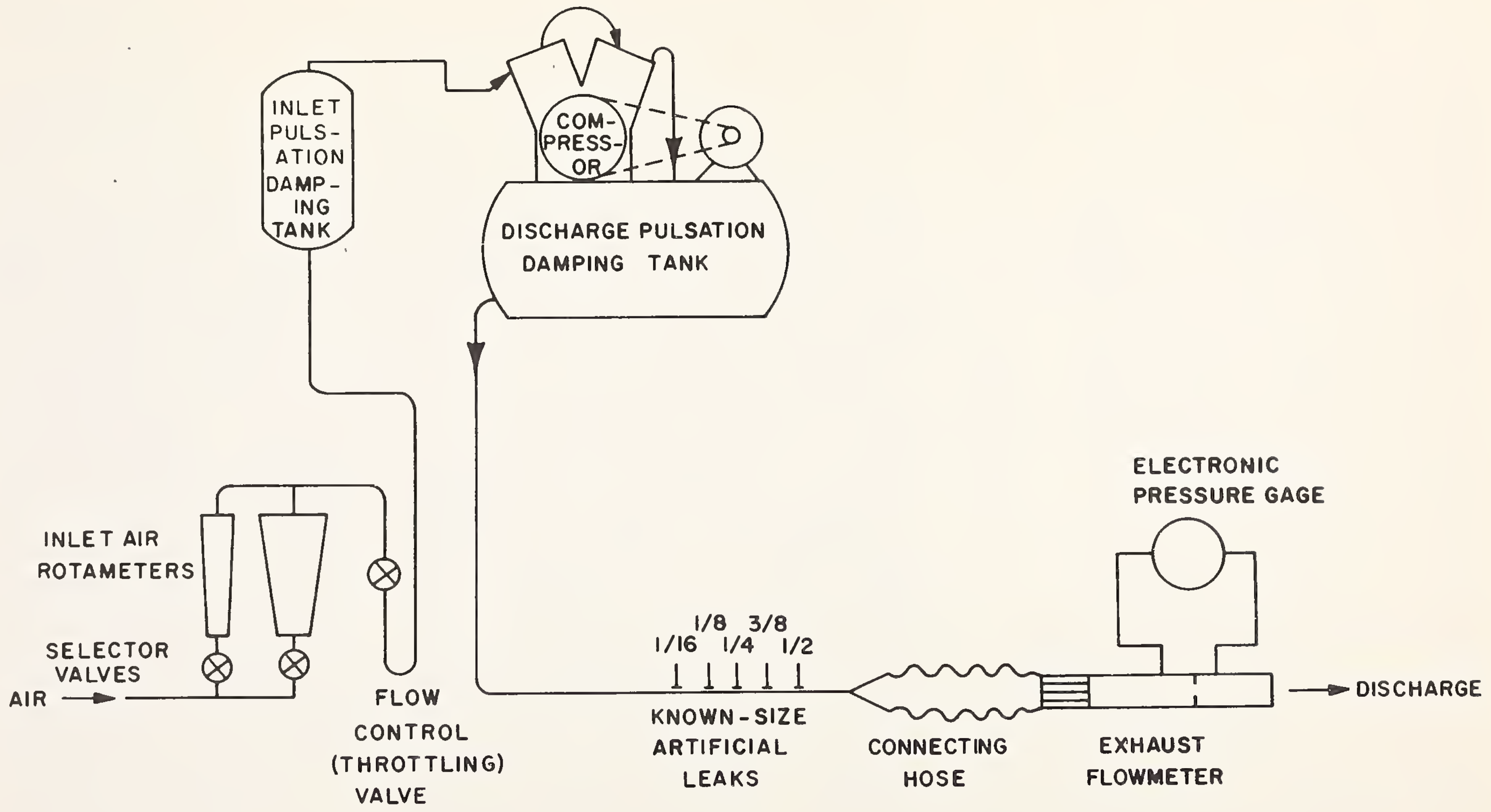


Figure 3-5. Flow-Calibration-System Schematic

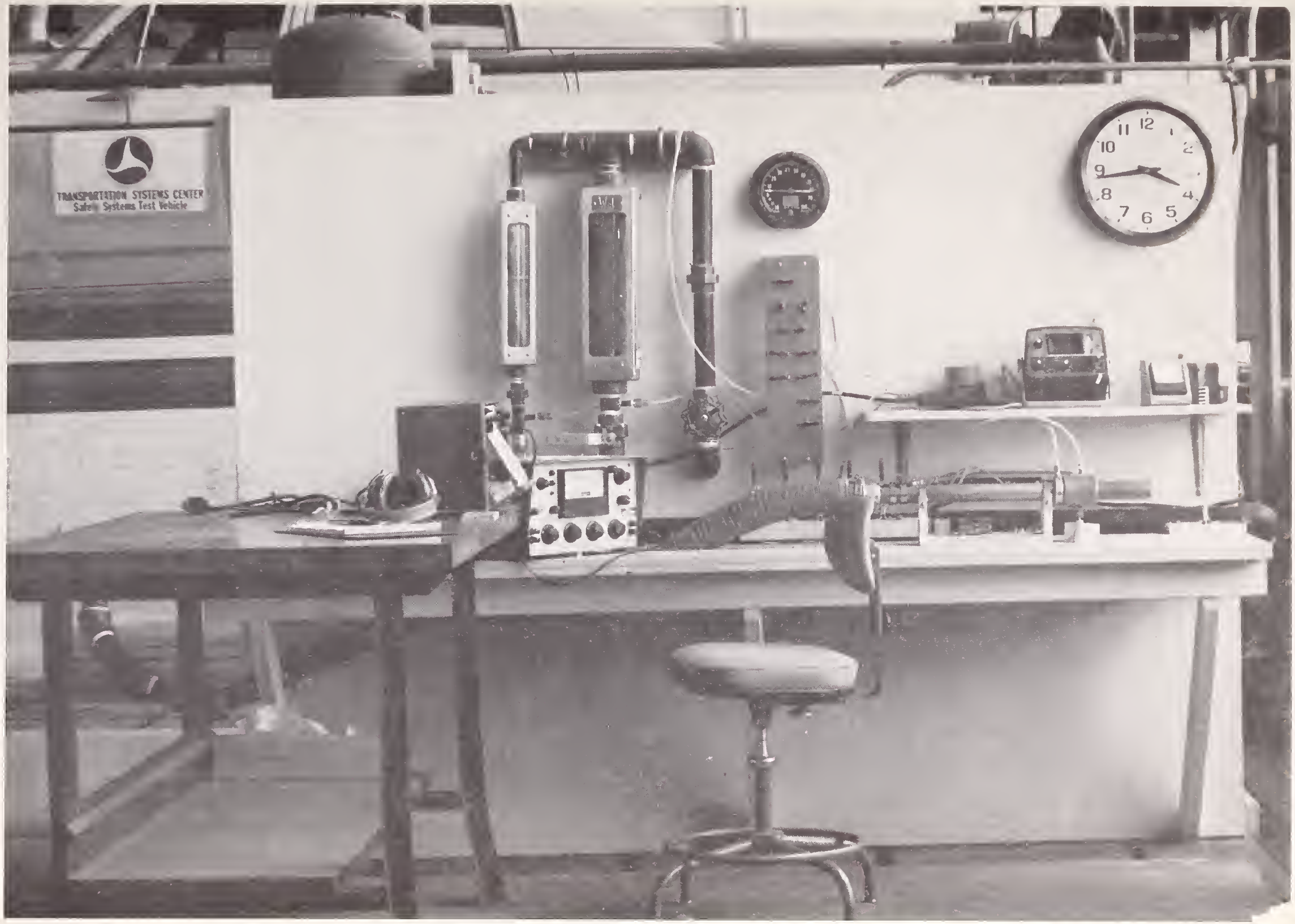


Figure 3-6. Flow-Calibration-Test Bench

and associated components used occasionally to measure system air temperature. Beneath the pressure manifold, the flexible hose is attached to the exhaust system flowmeter; this hose passes down through the bench and is attached to the simulated exhaust system which curves down around the left end of the bench. Behind the hose and exhaust flowmeter can be seen the handles of the toggle clamps which seal the artificial leaks. Above the pressure manifold is a gage which indicates air pressure in the compressor storage tank.

Figure 3-7 is a close-up view of the artificial leak installation. Two of the leaks are shown uncovered for illustrative purposes although normally only one was opened at a time. This arrangement proved to be very convenient and speedy in changing leak sizes.

The two large surge tanks in the calibration-flow system interacted with the flow restrictions of the throttling valve, exhaust flowmeter orifices, and artificial leaks to act as fluid-mechanical analogs of electrical resistor-capacitor (R-C) networks. After any change in flow rate (throttle-valve setting) or back-pressure (orifice or leak size), several minutes were required for the system to stabilize. While this caused a considerable increase in calibration-procedure time, it did not degrade accuracy from the quick-change procedure intended for test operation. During the calibration, air flow was at essentially room temperature at all times, and thus there were no temperature fluctuations resulting from orifice or leak-size changes which the orifice quick-change feature was designed to suppress. To maintain the smaller orifice in the operating position, a wood wedge was inserted between the test bench and orifice-actuating pin. This wedge may be seen in place in figure 3-6.

3.5.2 Flow-Calibration Procedure

The primary calibration effort was devoted to testing each orifice pair at least twice over its normal operating range. In addition, one typical orifice pair was evaluated over a pressure

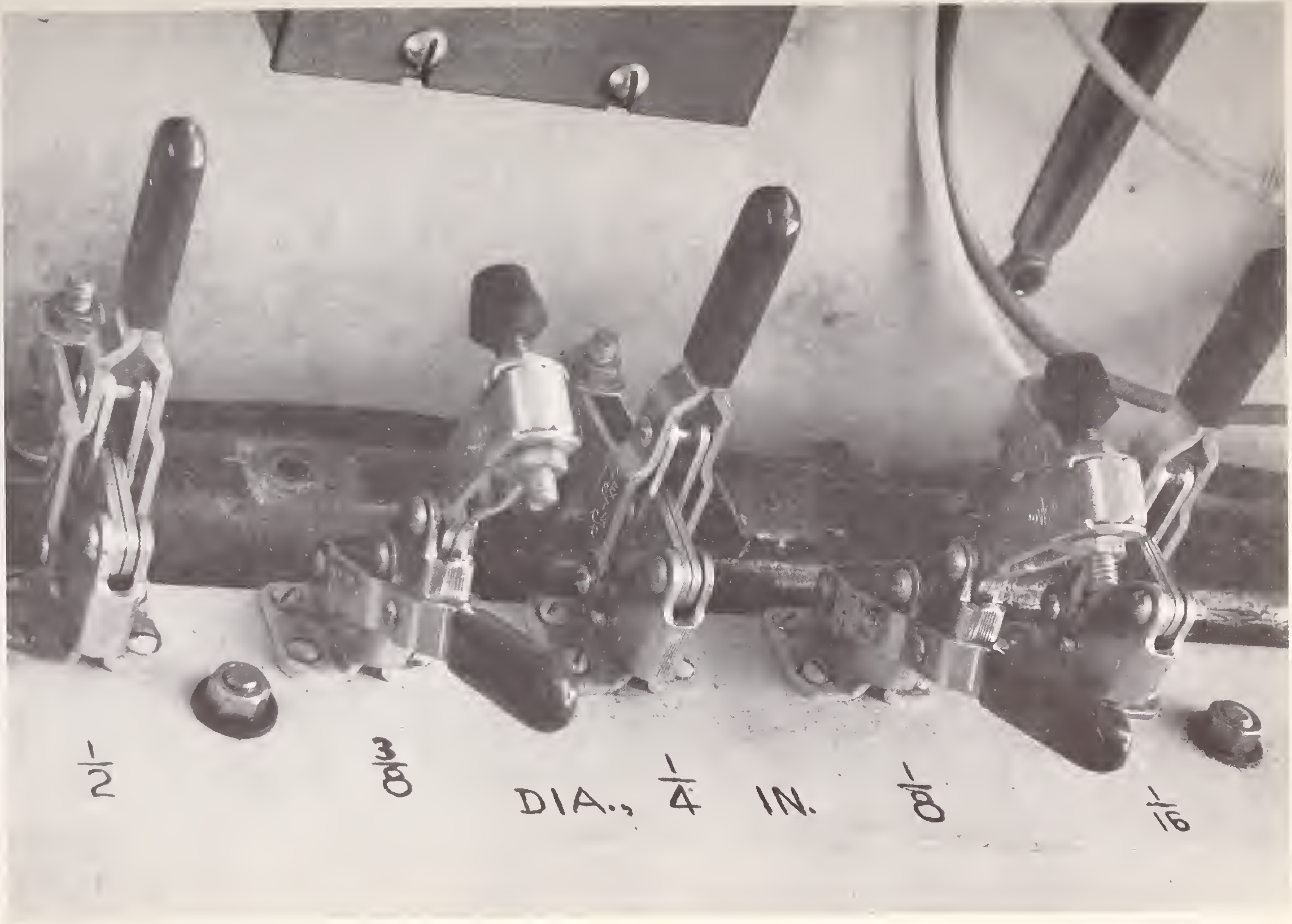


Figure 3-7. Flow-Calibration-System Artificial-Leak Installation

drop (and flow rate) range far exceeding its intended span to provide better insight into the operating characteristics of this device. A repeatability test made on the same orifice pair was comprised of five replications of the standard calibration series. Finally, one abbreviated series was run (again, on the same orifice pair, for consistency) using a maximum-leak size equivalent to an 11/16-inch hole to evaluate the sensitivity of the test to holes larger than the 1/2-inch size which was maximum for the bulk of the calibration work. In all, a total of over 2500 pressure-drop readings were taken. These test efforts are described in detail in the following sections.

3.5.2.1 Normal-Range Calibration - The normal operating range for each orifice pair was defined as that range of flow rates which produce pressure drops between 3.0 and 5.0 psig across the smaller orifice for each pair with zero leaks. This flow range was determined experimentally for each orifice pair. Calibration of both small and large orifices of the pair was conducted at six flow rates approximately evenly distributed by pressure increment over this range.

To illustrate this calibration procedure concisely, two special pressure-drop recordings were prepared using the test equipment and one typical orifice pair (the same one used for all the non-standard tests).

A test series was started by installing the desired orifice pair in the flowmeter on the test bench. The orifice-actuating pin was wedged up to bring the smaller orifice into measuring position. With the compressor running, the air-inlet throttling valve of the calibration system was adjusted to give a Δp (small orifice) of 5.0 ± 0.1 psi and the system was allowed to stabilize. The flow rate was trimmed if necessary to obtain the desired Δp; and the orifice-actuating pin was released and rewedged for two or three cycles, after this had been found to aid in eliminating a slow, long-term drift in flow rate which apparently was caused by the exponential character of flow stabilization after any change in flow rate.

When stability at the chosen Δp (small orifice) had been achieved, the chart recorder was started and the air-flow rate was entered on the chart. This point is shown by the right-hand end of the top trace in figure 3-8, where Δp = 5.0 psi at 0 leak and flow rate = 11.8 SCFM.

After a suitable length of reference trace was recorded, the 1/16-inch artificial leak was opened with the recorder running, and operation continued until the trace was stable at the new level. Flow rate was checked frequently and logged on the chart to ensure constancy of flow. The next larger leak was opened and the previous size closed quickly, and pressure recording continued until trace stability was again achieved. This sequence was carried on until the largest (1/2-inch) leak had been used, and produced a trace corresponding to the entire top curve of figure 3-8.

Then, without stopping the recorder (in normal operation, not as in figure 3-8), the wedge was removed to release the smaller orifice and all artificial leaks were closed. The system was allowed to stabilize at zero leak with the same flow rate as had been determined experimentally for the small orifice. The sensitivity of the Baratron pressure gage was changed to give the best chart record. This condition is shown at the right end of the top trace in figure 3-9. The sequence of recording pressures for each leak size from 0 to 1/2 inch which is described above for the smaller orifice was now repeated for the larger orifice, at the same flow rate, as shown in the entire top trace of figure 3-9. In a normal calibration-chart record, the top trace of figure 3.8 was followed in a continuous record by the top trace of figure 3-9. At that point, the test was halted and the previously observed pressure levels were determined by an internal-pressure calibration procedure for the Baratron; the pressure-calibration results were recorded directly on the test record. The chart then was torn off in preparation for starting a new run.

The smaller orifice was returned to operating position and air flow was adjusted to produce the next lower Δp (small orifice), in this case 4.5 ± 0.1 psi, at zero leak. The entire above test sequence was then repeated for both small and large orifices. (For this

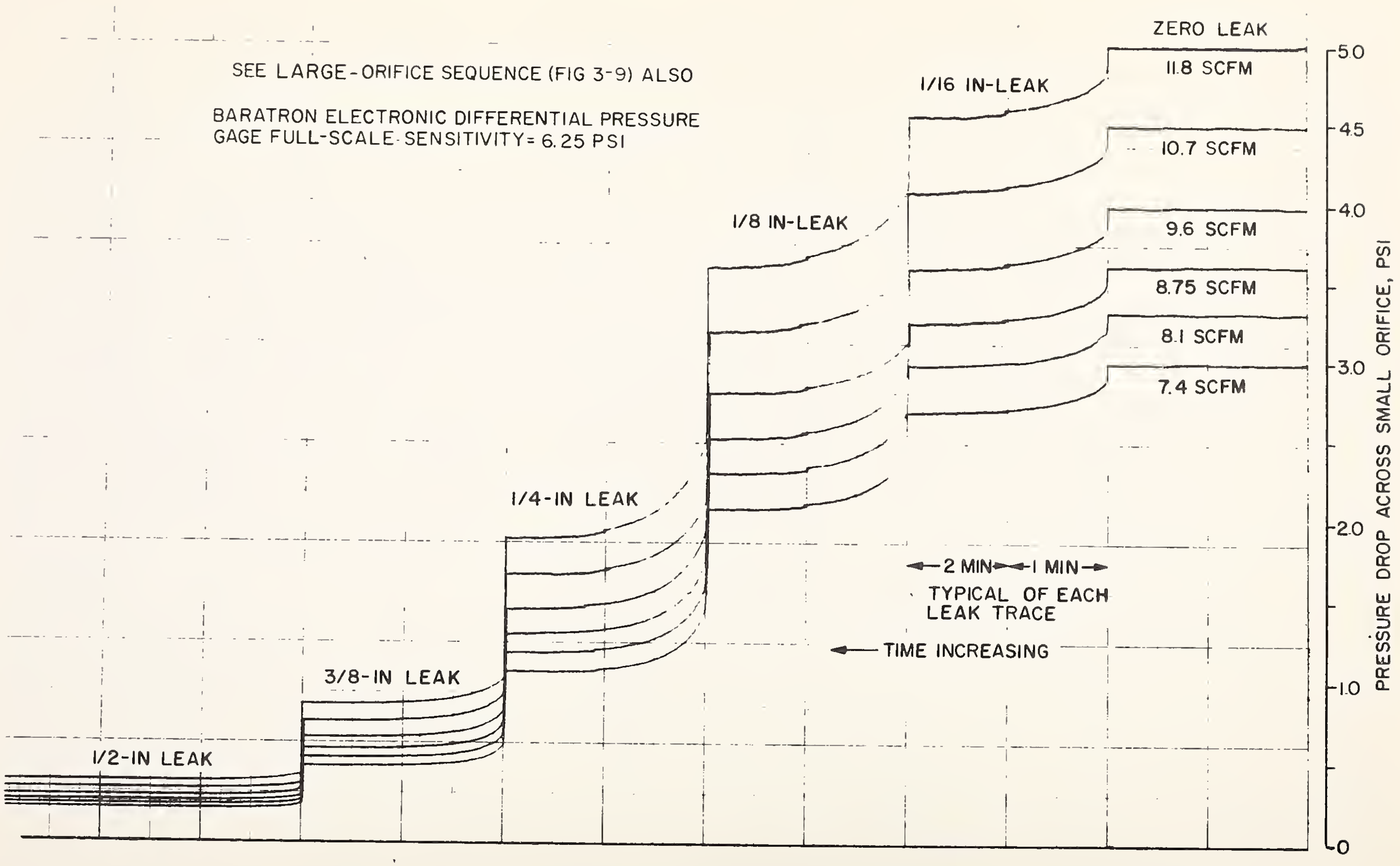
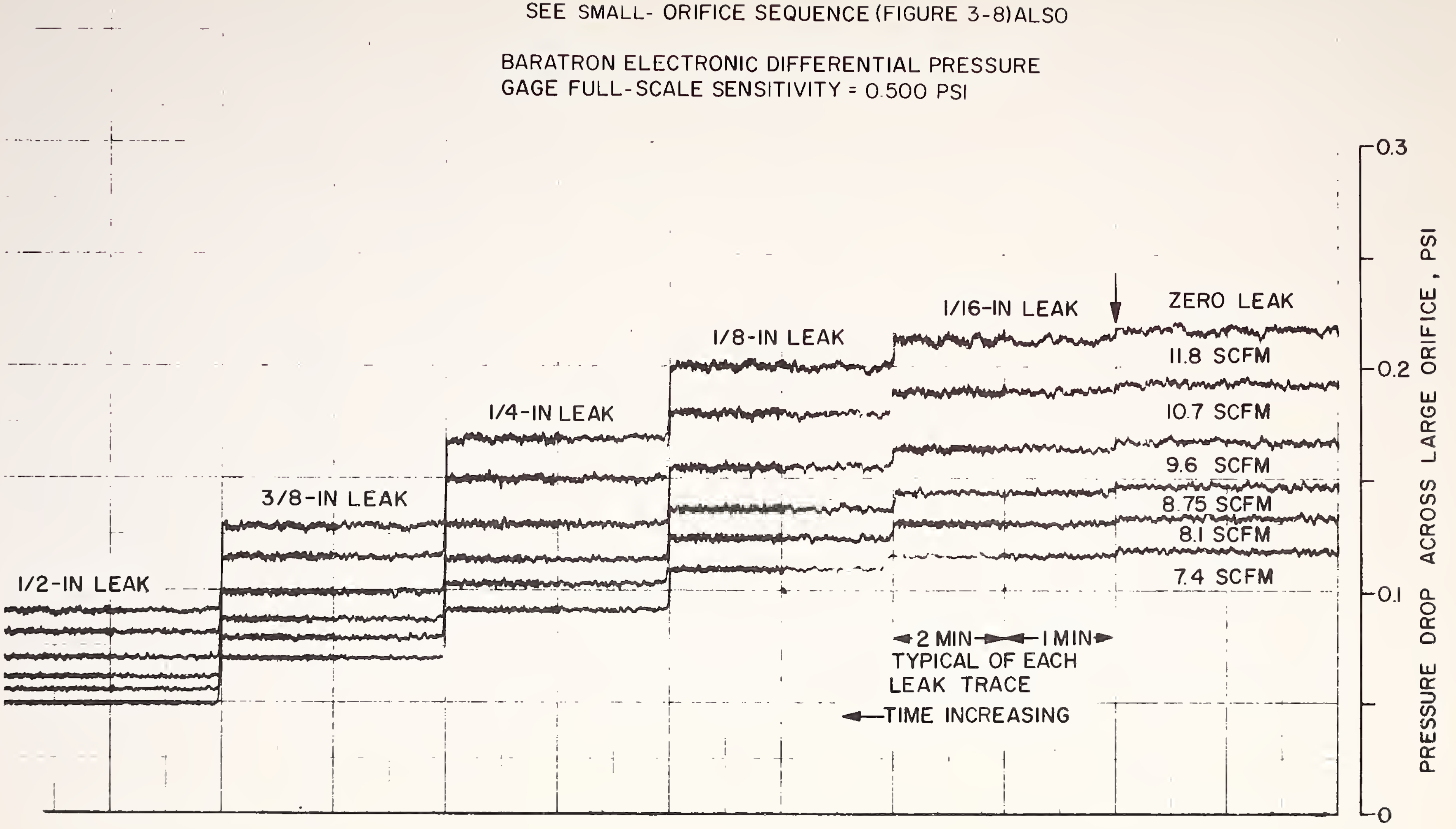


Figure 3-8. Flow-Calibration Series for Small Orifice of Dual-Orifice Pair No. 7



SEE SMALL- ORIFICE SEQUENCE (FIGURE 3-8) ALSO

BARATRON ELECTRONIC DIFFERENTIAL PRESSURE
GAGE FULL-SCALE SENSITIVITY = 0.500 PSI

Figure 3-9. Flow-Calibration Series for Large Orifice of Dual-Orifice Pair No. 7

illustration, the second sequence is shown as the second-highest traces in figures 3-8 and 3-9, at 10.7 SCFM.) Subsequent charts were made, and flow rates recorded, at Δp (small orifice) zero-leak levels of approximately 4.0, 3.65, 3.3, and 3.0 psi; these were the criteria that determined the flow rates at which the orifices of each pair would be calibrated.

Such operational test records were each several feet long and did not always clearly illustrate visually the overall performance of the system. Baratron sensitivity was frequently changed to give the largest on-scale deflection for best legibility. To illustrate the entire calibration procedure better, the relative sensitivity to various leak sizes, and the effects of flow changes, these special records (figures 3-8 and 3-9) were prepared in which the traces were superimposed on the same sections of chart paper. The small-orifice records were made separate from those for the large orifice to permit the use of different Baratron sensitivities for better visualization of each set. When comparing the two figures, it should be noted that the instrument sensitivity in figure 3-9 is 12.5 times that in figure 3-8.

3.5.2.2 Wide-Pressure-Range Calibration -- Four test series were conducted with orifice pair No. 7 as described in section 3.5.2.1, except that a larger number of flow rates was selected to span the Δp (small orifice) zero-leak range from 1 to 10 psi. The purpose of these series was to observe the performance of this leak-test technique well beyond the intended operating limits to provide better interpretation of the routine calibration data.

3.5.2.3 Wide-Leak-Size-Range Calibration - One abbreviated test with orifice pair No. 7 was conducted using leak sizes of 0, 1/4, 1/2, and 11/16 inch, and two flow rates which produced Δp (small orifice) levels of about 5 and 3 psig at 0 leak. The 11/16-inch leak size was provided by opening in parallel the 1/2-, 3/8-, 1/4-, and 1/8-inch leaks, the total area of which equals that of a single 11/16-inch hole. This leak constituted essentially the largest size the calibration system could provide without installing larger holes which would be more difficult to seal properly. The purpose of this test was to indicate the rapidity with which size sensitivity of this technique fell off beyond the standard 1/2-inch maximum calibration leak.

3.5.2.4 Repeatability Test - To evaluate the degree of repeatability which could be expected from this technique, a replication sequence of five calibration series was made with orifice pair No. 7. The elapsed time which this test covered was three weeks although not all the time was devoted exclusively to this test. A total of 372 pressure-drop measurements was made in this sequence.

An added test of reproducibility was afforded incidentally by the wide-leak-size-range calibration described in section 3.5.2.3. This wide-size-range work was performed with the same orifice pair, at three of the same leak sizes and two of the same flow rates used in the replication sequence, but by a different operator and at a later time. Thus, a rather extended period of time and at least two operators, one of them only recently trained to use this method, were involved in the assessment of reproducibility.

3.5.3 Calibration Results

This section will discuss the calibration results in general with a few illustrative examples. The normal range calibration data for all orifice pairs are tabulated in appendix A. Detailed calibration graphs for each individual orifice pair are given in appendix B. For clarity, those calibration graphs show only the calculated best-fit lines for each leak size without individual data points.

Subsequent to flow-calibration tests as described above in section 3.5.2, the raw pressure-drop data were transcribed from strip chart records. Pressure units were converted to psi (the Baratron pressure gage was calibrated in millimeters of mecury) and the ratio $R = \Delta p$ (small orifice)/Δp (large orifice) was calculated for each leak size and flow rate. Usually, the data for both calibration runs on each orifice pair were combined (in a few cases, the earliest calibration runs were found to have been made when there were unknown leaks in the calibration flow system, and only the later calibration series was used to prepare the final graph). The values of R were plotted against Δp (large orifice) on a semi-log coordinate system, as shown in figure 3-10. This particular figure presents the results of the reproducibility test series, but is illustrative here of the data-output format. For each leak size, a straight line which best fits the data was calculated by a least-squares technique. Occasionally, one or two data points which were clearly inconsistent with the rest of the points in a set were discarded as probably erroneous; the number of such rejections has been very small however.

The wide-pressure-range-test results shown in figure 3-11 provided considerable insight into the general nature of this system's performance as flow rate, pressure drop, and leak size were varied. The approximate limits of normal operating range for this orifice pair have been added to this figure to illustrate the degree of range extension employed in this test. It is clear, from this figure, that the data do fit a straight-line relationship on a semi-log plot, and that the slope of the lines for increasing leak sizes does become less negative. The increased scatter of data points at the right (high flow and pressure-drop) end of the lines for 0, 1/16-, and 1/8-inch leaks, where pressure drop across the smaller orifice ranged from 6 to 10 psi, is easily explained. It was noted in section 3.4 above that ASME orifice-meter specifications[4] require orifice-pressure drop be held to 20 percent or less of upstream pressure for best accuracy. At these high flow rates, pressure drop ranged from about 30 to 40 percent of upstream pressure, and lesser accuracy accordingly could be expected. However, it is evident that system performance is quite stable well beyond the upper and lower operating limits, which provides further confidence in this technique.

Results of the wide-leak-size-range test are shown in figure 3-12, where they are superimposed on the data from the reproducibility test (fig. 3-10) which used the same orifice pair. This

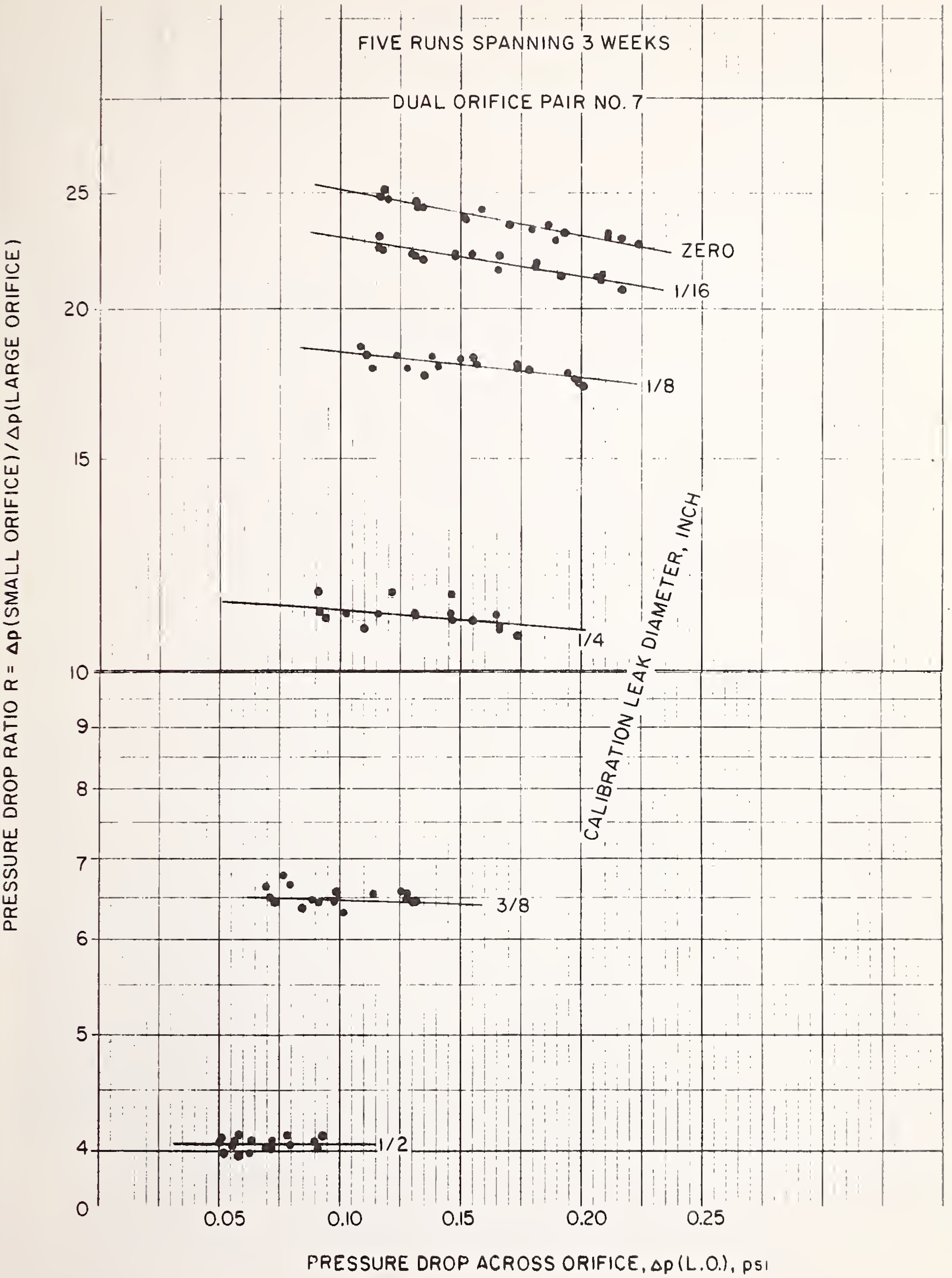


Figure 3-10. Orifice-Calibration Data: Repeatability Series

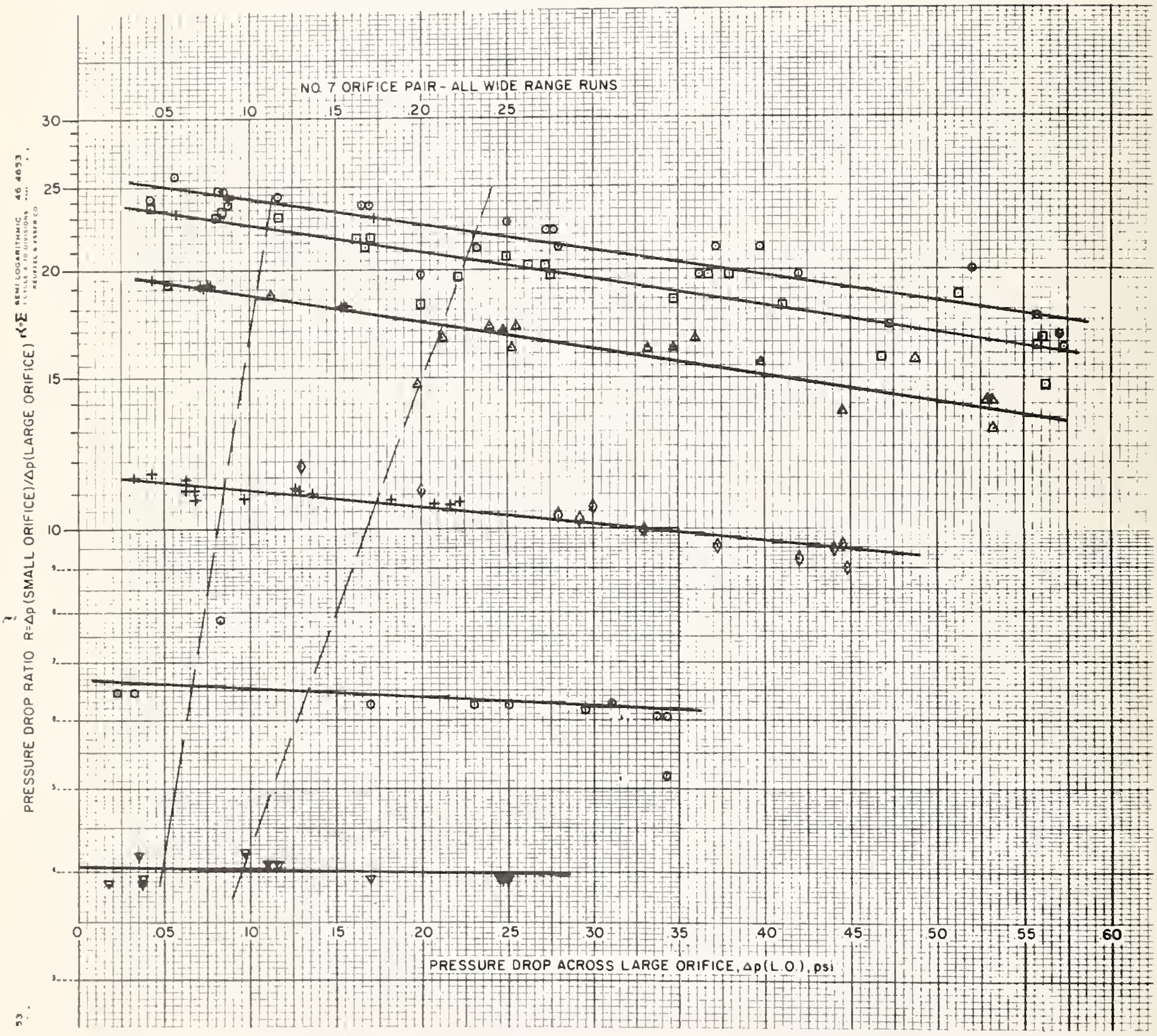


Figure 3-11. Orifice-Calibration Data: Wide-Pressure-Range Test.

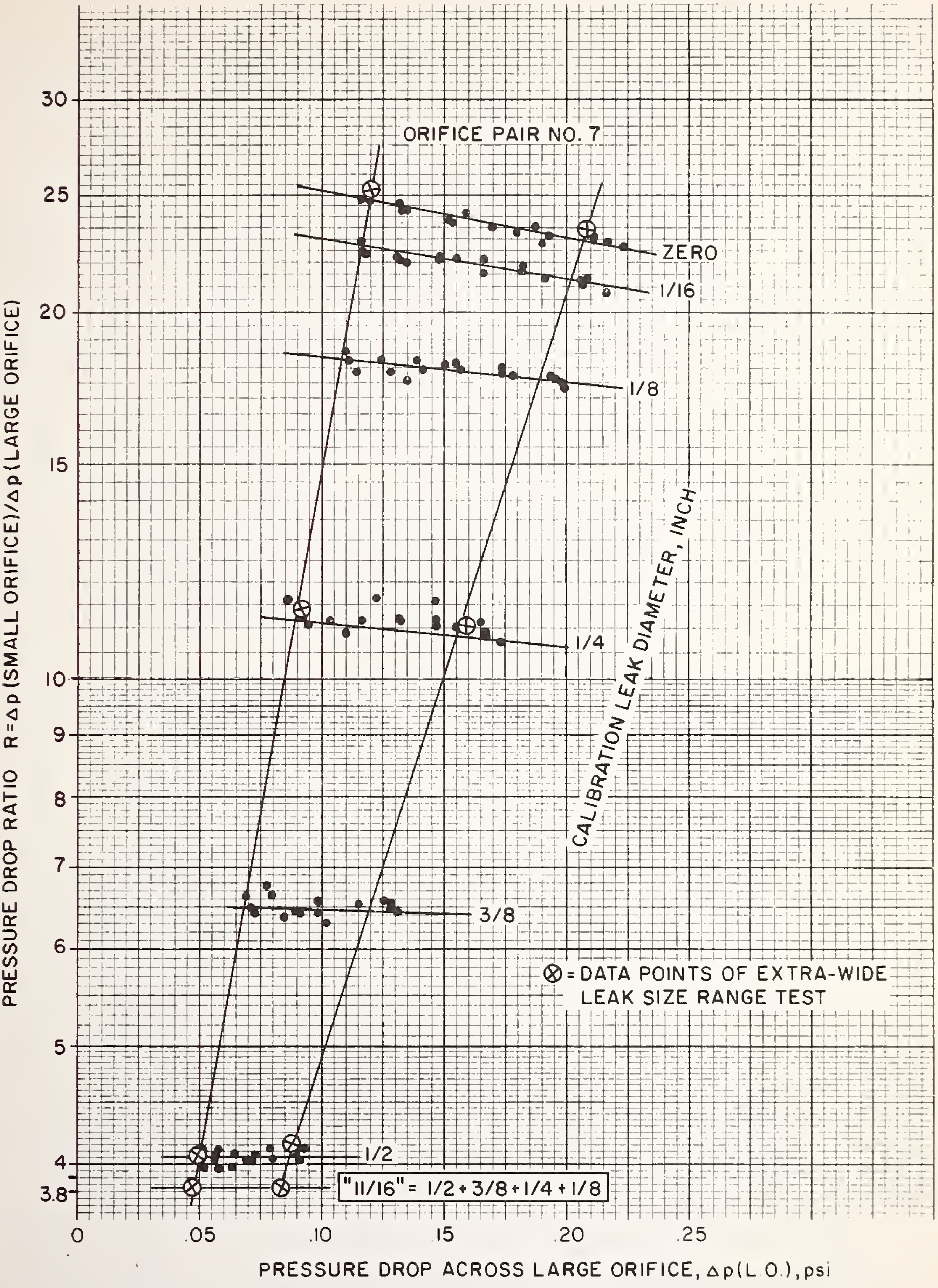


Figure 3-12. Orifice-Calibration Data: Wide-Leak-Size-Range Test

wide-size-range test was made by a newly trained operator who was not involved in the earlier study, and his results at the three smaller-leak sizes agree with the previous operator's work within the limits of experimental error. The drop of only 5.7 percent in R when leak size increased from 1/2 to 11/16 inch, compared with a decrease of 38.5 percent when leak size was increased from 3/8 to 1/2 inch, indicates that the sensitivity range of the present leak-test kit does not extend much beyond 1/2 inch, at least for this orifice pair (No. 7) and smaller sizes. Note from table 3-1 in section 3.4 above that the smaller-and larger-orifice diameters for pair No. 7 are only 0.294 and 0.661 inch, respectively.

The results of the reproducibility test already have been shown in figure 3-10, which was used to illustrate the format employed for data presentation. The close grouping of the data points around each line demonstrates the excellent repeatability obtained. In several instances, two to four points fell precisely upon the top of each other and appear as one point. Only 8 measurements out of the total of 372 made in this test were rejected as erroneous; and of these, 5 were on a single test run which had a consistent error spanning all leak sizes.

3.6 OPERATIONAL EVALUATION

Only a brief operational evaluation of the exhaust-system leak-test kit could be conducted. The test car mentioned above in section 2.2 was used; the exhaust system of this car supposedly was completely sealed except for known-size artificial leaks which could be opened or closed at will. However as reported in section 2.2, the heat riser of this system, ahead of the newly installed components, had been found to leak somewhat when the exhaust system was pressurized with the engine not operating. The effective size of this heat-riser leak was not determined prior to this evaluation of the engine-pressurized test method.

The engineering-model exhaust flowmeter was attached to the test-vehicle tailpipe and the engine was warmed up. The orifice pair to be used was selected according to the pressure drop across the large orifice, as would be done in a typical PMVI test. Orifice pair No. 6 had been expected to be correct for this car, but No. 8 was found to be the right size.

The initial leak test was made with all artificial leaks sealed, and pressure drops across the large and small orifices were measured in that order, with the small orifice being moved rapidly into position and peak pressure drop then read within a few seconds. Both pressure-drop readings were repeated as a check, and the same values were observed. Subsequent tests were made with increasing leak sizes made up of individual holes and of two or three holes in parallel, as indicated on the right side of figure 3-13. This figure is a plot of data from one calibration series for orifice pair No. 8, with the operational test data superimposed. In the figure, the diameters of the known exhaust-system leaks are shown in quotation marks because they necessarily included the effect of the unknown heat-riser leak, and thus are only approximately correct.

The test data clearly indicate a small unintentional leak existed in the exhaust system (it probably was in the heat riser); the size of this leak apparently was equivalent approximately to a 3/32-inch hole. However, it may have been larger and indicated this size because of high exhaust temperature at that location. The effect of this unintentional leak on the test results can be seen to diminish as the known leak size was increased and the relative flow from the accidental leak became less in comparison. The excellent discrimination between actual exhaust-system leak sizes larger than 1/8-inch diameter is evident, and is comparable to that observed in the calibration tests.

Figure 3-13 also shows the variation in sensitivity of this test method to leak location along the length of the exhaust system. The second and third hexagonal points below the 1/4-inch calibration line represent the same total leakage area in the test car exhaust; namely, the sum of one each 1/8- and 1/4-inch holes (plus the unknown leak). The 1/8-inch hole was located ahead of the muffler for both tests, while the 1/4-inch hole was

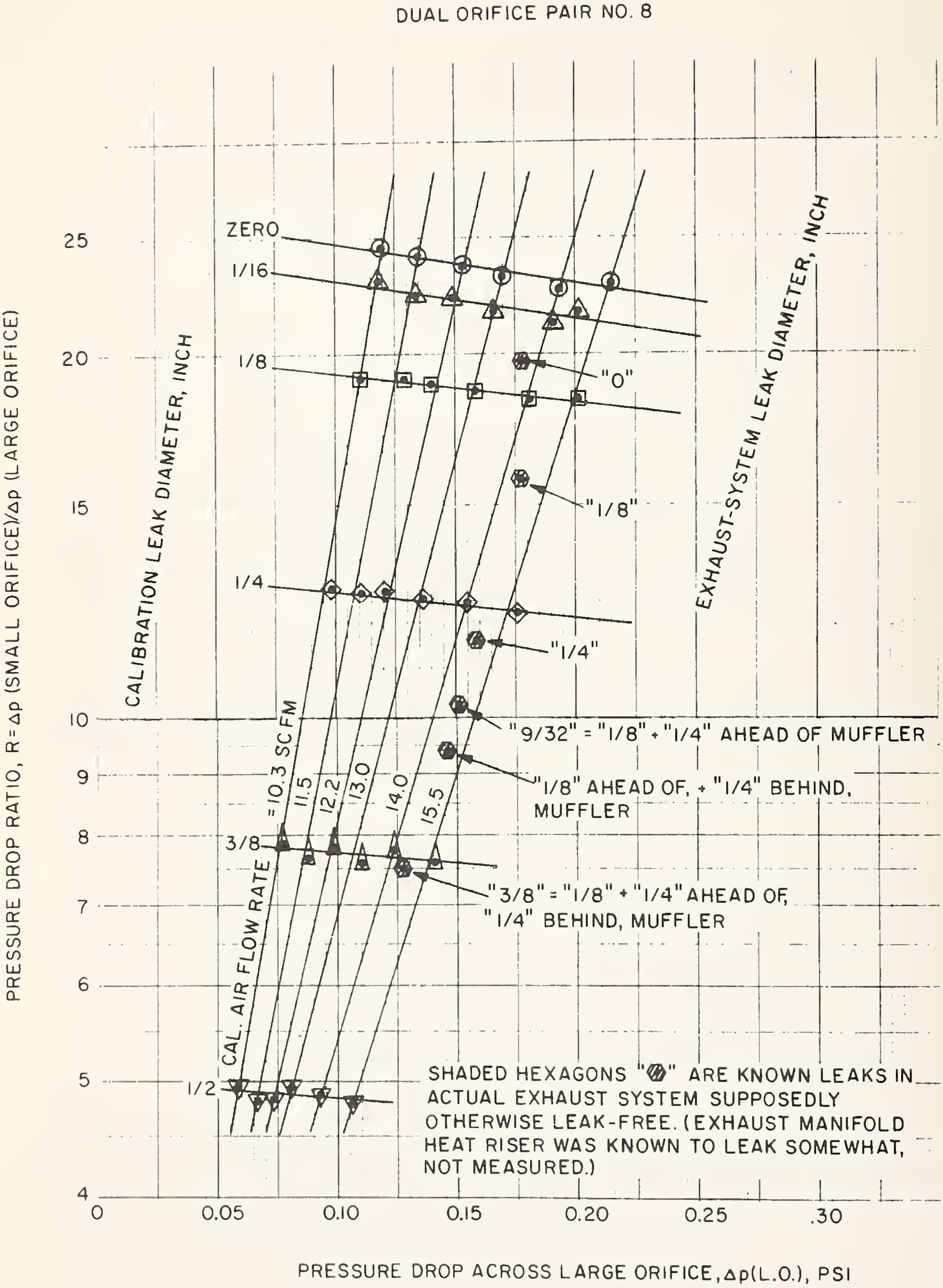


Figure 3-13. Test Data: Operational Evaluation of Engineering-Model Test Device

adjacent to the 1/8-inch hole for one test and near the end of the tailpipe for the other, as indicated in the figure. Clearly, the test is more sensitive to holes near the rear of the system than near the front; this is unfortunate since presumably holes near the front are more likely to contaminate the passenger compartment. The effect is inevitable, however, since it is related to the cooling of the gas as it passes along the exhaust system. For a given pressure drop across an orifice (the leak), mass flow is inversely proportional to the square root of the absolute temperature of the gas, as noted earlier.

Thus, the cooler the gas, (i.e., the farther back along the exhaust system), the larger the leak "looks" to this technique. The magnitude of this effect will vary slightly with different vehicles and with ambient temperature. However, for the larger sizes of leaks shown in the figure, the discrimination between leak sizes is sufficiently great that it should be possible to make adequate allowance or tolerance for this phenomenon.

Lack of time prevented further evaluation of the technique on other cars. However, it was felt that this one test demonstrated sufficient agreement between calibration with room-temperature air and actual use on hot exhaust to validate the concept.

An approximate correlation between calibration air-flow rate and engine displacement can be obtained from figure 3-13. The operational leak-test data points correspond in general to an air-flow rate of approximately 14.5 SCFM. The test car had an engine with 230 cid; idle speed for this test was not measured, but generally was in the range of from 900 to 1000 revolutions per minute (rpm). Based on these data and the calibration air-flow rates observed for each orifice pair over their normal operating ranges, approximate engine-displacement ranges for each orifice pair were calculated. These displacement ranges are listed below, and are plotted on a logarithmic scale in figure 3-14. The horizontal width of the range blocks in figure 3-14 has no significance and was chosen only for convenience and legibility.

ESTIMATED ENGINE-DISPLACEMENT RANGES OF EXHAUST-SYSTEM LEAK-TEST ORIFICE PAIRS

(4-cycle engines)

ORIFICE PAIR NO.	ENGINE DISPLACEMENT RANGE CUBIC INCHES
2	2.7 - 30.0
3	14.6 - 40.0
4	39.7 - 78.0
5	60.0 - 102.0
6	89.5 - 140.0
7	126.0 - 192.0
8	167.0 - 251.0
9	214.0 - 314.0
10	301.0 - 452.0

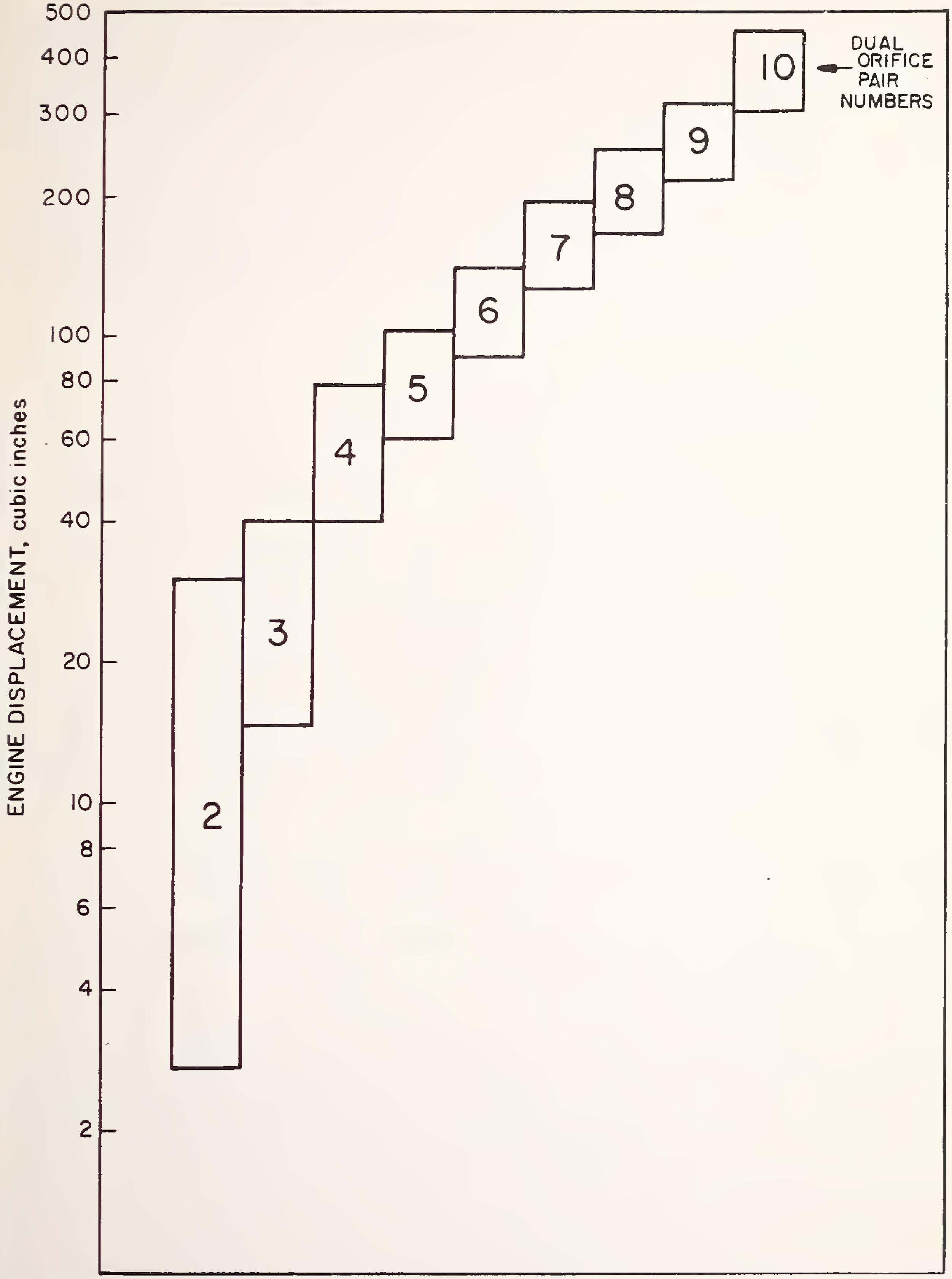


Figure 3-14. Estimated Engine-Displacement Ranges of Exhaust-System Leak-Test Orifice Pairs

It is evident from figure 3-14 that orifice pairs Nos. 2 and 3 are too small for virtually any passenger-car engine. Furthermore, the overlap in ranges between pairs Nos. 4 and 5, 6 and 7, and 8 and 9 is somewhat greater than necessary although not enough to justify remachining and recalibrating these sizes. Had sufficient time remained at the end of this program, orifice pairs Nos. 2 and 3 would have been remachined to sizes larger than pair No. 10 and recalibrated; this would have ensured coverage of the largest automotive engine sizes with ample allowance for variations in carburetion, idle speed, etc.

3.7 EXHAUST-SYSTEM LEAK-TEST PROCEDURE

A detailed test procedure for use of this exhaust-system leak-test kit is included in appendix B. This test procedure contains individual charts for each orifice pair based on calibration results reported above and tabulated in appendix A. By means of these charts, the leakage from any exhaust system tested can be related to the leakage which would result from a single round hole of up to 1/2-inch diameter. A nomograph also is provided for rapid determination of the ratio $R = \Delta p$ (small orifice)/Δp (large orifice) with a straight edge rather than by numerical calculation.

3.8 POSSIBLE ALTERNATIVE NON-QUANTITATIVE LEAK TEST

The experience with automotive exhaust systems gained during the work described above suggested an even simpler, less expensive, but non-quantitative, exhaust-system leak test for mass application. This approach presently is purely conceptual and untested. It is a modification of the present generally used exhaust-system inspection method in which the tailpipe exit is partially obstructed with a rag or other object and the tester listens and/or looks for leaks in the system.

Aside from not giving quantitative results, a major objection to this present practice is that the backpressure imposed on the system is unknown and unreproducible. Furthermore, the degree to which the normal exhaust noise is attenuated to aid the tester in hearing the sounds of possible leaks also is variable. The modified technique would completely obstruct the tailpipe exit with a tapered rubber plug fitted with a calibrated relief valve that would pressurize all exhaust systems to within specified limits (e.g., within 3 to 5 psig), and all exhaust gases leaving the relief valve would be discharged through a silencer or muffler. It has been determined that the sound of exhaust escaping from even a 1/4-inch diameter hole at 3 to 5 psig is quite audible if ambient noise is minimal. Thus while this modified technique would not provide either quantitative or objective evaluation criteria, it would offer reproducible stress levels and acoustical muffling; and it is believed that leaks of potentially serious size would be quite easily detected.

3.9 RECOMMENDATIONS FOR FIELD EVALUATION OF TEST KIT

Now that an engineering model of a quantitative exhaust-system leak-test device has been developed and calibrated, there are perhaps three principal questions concerning the device which can best be answered by an evaluation in the field on a large number of vehicles: (a) What are the limits of variability in exhaust-system leak-evaluation presently being achieved by conventional inspection methods? (b) How large an exhaust-system leak should be legally defined as permissible? (c) Is the degree of sophistication (and cost) represented by the engine-pressurized test method described here really necessary?

To answer the first question, it is suggested that the engineering-model test kit be used in conjunction with present exhaust-system inspection techniques in one or more automobile inspection stations. The test kit should be used to check the condition of entering vehicles before or after the normal inspection is performed. Any rejected vehicle on which exhaust-system repairs are made should be retested with the test kit after the repairs to evaluate the adequacy of the work and the degree of improvement. To avoid as far as possible biasing the operators who use conventional techniques, it is very important that these operators not be allowed to learn anything about the quantitative evaluation of their inspections. Therefore, a separate operator should use the quantitative method and should not give the other operator any hint of the findings of the new technique. More than one operator using standard techniques, and preferably more than one inspection station, should be so evaluated. Important results of this study should include: the mean size of leak which results in rejection; the range of variation in this rejection size, and the relative frequency of rejection vs. size; and a determination if the size distribution vs. frequency is Gaussian or skewed in nature.

As to the second question, no active investigation has been conducted at TSC to obtain the answer. Calculations were made of the approximate leakage rate from a 1/8-inch diameter hole upstream of the muffler at exhaust-system pressures and temperatures typical of passenger-car road loads at 30 and 60 miles per hour (mph). Flow rates of about 0.01 and 0.02 cubic feet per second, respectively, were found.

When it is considered that these flow rates are being discharged into ambient slipstreams of about 45 and 90 feet per second, respectively, this size leak does not seem to be unduly hazardous. Criteria will have to be developed for determining what leakage rates are considered hazardous and under what operating conditions. Perhaps then, a reasonably defensible maximum acceptable size for an exhaust leak can be established.

The answers to the first two questions should then provide a reasonably sound answer to the third, and most important, question. If such a quantitative exhaust-system leak test is found to be necessary, the work reported above will have provided at least one feasible technique. In any case, this work will have produced the means by which to answer the first question. If the non-quantitative test method suggested in section 3.8 is included in the tests outlined above for answering the first question, it may be found that this simpler test, or possibly even the present crude inspection technique, affords an adequate measure of exhaust-system condition.

3.10 RECOMMENDATIONS FOR FIELD RECALIBRATION OF PMVI TEST KITS

The discussion in section 3.4 indicated that orifice meters in general are very sensitive to the physical condition of the orifices. Any damage, even a slight nick or rounding, to the upstream edge of the orifice can change the flow characteristics significantly. Experience during the present program has shown that orifices exposed to engine exhaust tend to accumulate deposits at least on the orifice faces; whether substantial deposits occur also on the inside circumference of an orifice has not been definitely established. It is possible that even face deposits may alter flow characteristics. Careless handling of orifices in PMVI stations very likely could damage orifices seriously. Therefore, it seems reasonable to expect that periodic recalibration, or at least recertification, of PMVI orifice assemblies will be required to maintain legal validity of the test.

The number of such orifice assemblies in the field in even a single State (at least where inspection is performed in franchised service stations rather than in State-operated facilities) would be quite large. If a State has only one or two specified periods during the year when all vehicles must be inspected, presumably recertification could be accomplished during the off-seasons. However, for States which have staggered inspections to spread the work load evenly throughout the year, station operators would not want to have their test orifices tied up for any significant period of time. Perhaps, one acceptable reasonably efficient recalibration scheme would be to have State-operated flow-calibration trucks visit the inspection stations and check out the orifices on site. If off-season recalibration were to be performed by the State (or by private firms under State supervision), a similar recalibration flow system would be required although it need not be mobile. The intent of this section is to offer recommendations, based on experience with the present calibration system, as to features which might be desirable in such a flow calibration system.

To reduce the system response time to changes in flow rate, orifice or leak size, the storage volume throughout the system should be minimized. This will tend to increase the magnitude of pressure oscillations produced by piston-type pumps which, if substantial, will degrade the accuracy of flow and pressure measurements. Therefore, an ideal pump would be a continuous-flow type. However, a positive-displacement pump is almost mandatory for this application; this eliminates centrifugal pumps and turbines, which offer the most uniform rates of discharge. The Roots type of rotary impeller is nearly positive-displacement but will produce a pulsating flow, and probably is more expensive than a piston-type pump of comparable capacity. The recommended pump is a piston-type compressor, single stage with a relatively high speed (e.g., four to eight cylinders running at approximately 1800 to 3600 rpm). An inlet-throttling valve can be used to vary the mass-flow rate, as in the present calibration system. Three or more rotameters and selector valves connected in parallel, installed in the intake line upstream of the throttling valve, can span the required flow range with satisfactory accuracy and resolution. Perhaps, only two or three artificial leaks will be required, one at the legislated maximum leak size and one each larger and smaller than the first. Two pressure gages, one each for the low and high ranges, can be used as on the engineering-model flowmeter.

Such a system should prove to be a very convenient, fast, and economical way of recalibrating or recertifying large numbers of orifice assemblies. Systems could be stationed in one or more central locations or mounted on light trucks and driven to the individual stations on a scheduled basis.

4. REFERENCES

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2. Lavery, A.L., A.J. Broderick and E.C. Klaubert, Automotive Exhaust System Leak Test, Invention Disclosure, DOT Case No. TSC-10044.
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4. Leary, W.A. and D.H. Tsai, Metering of Gases by Means of the ASME Square-edged Orifice with Flange Taps, MIT, Cambridge, MA, July 1951.

APPENDIX A

ORIFICE EQUATIONS AND ORIFICE-FLOW CALIBRATION DATA

A.1 ORIFICE EQUATIONS

The following material is taken largely verbatim from [3], but has been modified as used specifically in development of the engine-pressurized exhaust-system leak test.

The basic form of the practical equation for the weight rate of discharge adopted by the ASME Special Research Committee of Fluid Meters for use with gases is

$$w = q_1\rho_1 = CYS_2 \sqrt{2g_c\ (p_1 - p_2)\ \rho_1/(1 - \beta^4)}, \qquad \text{(A-1)}$$

where C = coefficient of discharge (no dimensions); in the intended range of operation, C tends to be approximately constant at about 0.61,

g_c = dimensional constant = 32.1740 (lb <u>mass</u>) (ft)/(lb <u>force</u>) (sec^2),

P_1, P_2 = pressures at upstream and downstream static pressure taps, respectively, lb <u>force</u>/sq ft,

q_1 = volumetric rate of discharge measured at upstream pressure and temperature, cu ft/sec,

S_2 = cross-sectional area of the dischage opening, sq ft,

w = weight rate of discharge, lb <u>mass</u>/sec,

Y = expansion factor, see below (no dimension),

β^2 = ratio of cross section of constriction, D_2, to that of upstream channel, D_1; for circular openings in circular pipes, $\beta = D_2/D_1$, and

ρ_1 = density at upstream temperature and pressure, lb <u>mass</u>/cu ft.

For gases, $Y = 1 - [(p_1 - p_2)/p_1 k](0.41 + 0.35\beta^4)$, (A-2)

where $k = C_p/C_v$, the ratio of specific heats; for air, $k = 1.40$, while for typical exhaust mixtures, k is about 1.38.

When the above equations are combined and expressed in convenient units, p is expressed in terms of average molecular weight, absolute temperature, and pressure, and letting $(p_1 - p_2) = \Delta p$, (A-1) becomes

$$w = 0.1604\ CY(D_2)^2\ \sqrt{Mp_1 \Delta p / T_1 (1 - \beta^4)}, \qquad \text{(A-3)}$$

where T_1 = upstream absolute temperature, $^{\circ}R$,

D_2 is in in.,

p_1 is in psia (psi absolute), and

Δp is in psi.

Equation (A-3) is the final form of the orifice equation used to calculate w when the other parameters are known,

It is instructive, in understanding orifice relationships, to transpose (A-3) so as to express the relationship for the pressure drop across the orifice, Δp:

$$\Delta p = F\ T_1 \left[\frac{w}{Y}\right]^2 \frac{(1 - \beta^4)}{p_1 (D_2)^4}, \qquad \text{(A-4)}$$

where $F = [1/M(0.1604)^2(0.61)^2]$ = constant

(assuming C is constant at 0.61 and M is constant).

Thus, it may be seen that Δp varies directly with absolute temperature T_1; directly with the square of mass flow rate, w; and approximately inversely with the fourth power of orifice diameter, D_2 (there is a small effect of D_2 in the $(1 - \beta^4)$ factor). Large changes in flow conditions may also affect Y and C.

It must be emphasized that these expressions, and especially the value of C, are very sensitive to the physical configuration of the orifice and orifice plate. Thus, they are useful in interpreting results and as a guide in calculating orifice sizes or pressure drops but, in general, do not yield highly precise values.

APPENDIX A-2

ORIFICE-FLOW CALIBRATION DATA

ORIFICE-FLOW CALIBRATION DATA

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM*	Zero			1/16-in.			1/8-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
2	1.38	4.92	0.240	20.49	3.79	0.220	17.21	2.11	0.188	11.18
2	1.11	4.34	0.213	20.40	3.35	0.199	16.83	1.88	0.171	10.98
2	0.85	4.06	0.195	20.84	3.11	0.181	17.16	1.73	0.156	11.08
2	0.67	3.86	0.180	21.43	2.96	0.168	17.59	1.61	0.145	11.07
2	0.383	3.43	0.1580	21.69	2.63	0.149	17.71	1.42	0.128	11.10
3	2.47	4.87	0.226	12.55	3.86	0.212	18.18	2.33	0.188	12.35
3	2.25	4.35	0.209	21.71	3.62	0.197	18.38	2.16	0.175	12.35
3	1.83	3.93	0.184	21.37	3.17	0.174	18.20	1.91	0.154	12.40
3	1.57	3.59	0.168	21.36	2.93	0.159	18.45	1.77	0.140	12.63
3	1.20	3.23	0.145	22.24	2.57	0.137	18.85	1.54	0.122	12.69
3	1.28	3.31	0.150	22.09	2.61	0.142	18.44	1.59	0.125	12.67
3	0.91	2.99	0.131	22.90	2.34	0.124	18.91	1.39	0.109	12.69
4	4.7	4.95	0.255	19.42	4.18	0.243	17.17	2.80	0.219	12.83
4	4.4	4.47	0.236	18.97	3.79	0.226	16.81	2.55	0.203	12.58
4	3.7	3.97	0.196	20.42	3.33	0.192	17.34	2.24	0.174	12.92
4	3.2	3.62	0.174	20.78	3.02	0.166	18.22	2.01	0.152	13.27
4	2.9	3.35	0.157	21.28	2.79	0.152	18.39	1.85	0.135	13.69
4	2.6	3.06	0.142	21.47	2.57	0.135	19.00	1.68	0.122	13.70

*SCFM = Standard cu. ft./min., i.e. at 70°F, 1-atmosphere absolute pressure

ORIFICE-FLOW CALIBRATION DATA

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM*	1.4-in.			3/8-in.			1/2-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
2	1.38	0.605	0.177	5.18	0.186	0.0656	2.83	0.0667	0.0346	1.93
2	1.11	0.544	0.107	5.07	0.169	0.0584	2.89	0.0600	0.0313	1.91
2	0.85	0.499	0.0975	5.12	0.154	0.0553	2.78	0.0553	0.0288	1.92
2	0.67	0.464	0.0913	5.08	0.144	0.0511	2.81	0.0509	0.0266	1.92
2	0.383	0.406	0.0795	5.11	0.126	0.0437	2.87	0.0445	0.0228	1.95
3	2.47	0.766	0.126	6.08	0.252	0.0770	3.26	0.0925	0.0422	2.19
3	2.25	0.711	0.117	6.09	0.234	0.0708	3.30	0.0855	0.0387	2.21
3	1.83	0.629	0.104	6.07	0.207	0.0631	3.28	0.0766	0.0352	2.18
3	1.57	0.638	0.0961	6.64	0.188	0.0578	3.26	0.0696	0.0321	2.17
3	1.20	0.496	0.0818	6.06	0.164	0.0491	3.34	0.0596	0.0275	2.17
3	1.28	0.511	0.0847	6.03	0.168	0.0509	3.31	0.0619	0.0286	2.16
3	0.91	0.448	0.0756	5.92	0.147	0.0449	3.28	0.0549	0.0248	2.22
4	4.7	1.11	0.159	7.02	0.398	0.103	3.88	0.154	0.0603	2.54
4	4.4	1.04	0.147	7.12	0.368	0.0948	3.88	0.141	0.0561	2.51
4	3.7	0.870	0.126	6.93	0.312	0.0801	3.90	0.119	0.0482	2.46
4	3.2	0.774	0.109	7.12	0.274	0.0720	3.80	0.104	0.0414	2.51
4	2.9	0.696	0.0979	7.11	0.248	0.0629	3.94	0.0948	0.0385	2.46
4	2.6	0.623	0.0890	7.00	0.223	0.0580	3.84	0.0851	0.0346	2.46

ORIFICE-FLOW CALIBRATION DATA (CONT'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	Zero			1/16-in.			1/8-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
5	6.3	4.95	0.240	20.68	4.27	0.232	18.42	3.04	0.216	14.08
5	5.7	4.41	0.212	20.80	3.81	0.205	18.59	2.71	0.188	14.43
5	5.1	3.95	0.184	21.50	3.38	0.175	19.32	2.38	0.164	14.54
5	4.6	3.56	0.160	22.28	3.06	0.155	19.57	2.13	0.145	14.73
5	4.1	3.25	0.148	21.99	2.79	0.143	19.46	1.95	0.133	14.72
5	3.8	3.00	0.135	22.27	2.75	0.130	19.73	1.80	0.121	14.90
6A	8.8	4.85	0.238	20.41	4.35	0.232	18.75	3.31	0.213	15.55
6A	7.8	4.45	0.211	21.06	3.95	0.201	19.62	3.00	0.191	15.72
6A	6.9	3.95	0.175	22.62	3.48	0.172	20.22	2.61	0.161	16.23
6A	6.5	3.60	0.168	21.48	3.17	0.161	19.76	2.42	0.152	15.90
6A	5.8	3.26	0.146	22.35	2.89	0.139	20.76	2.15	0.132	16.32
6A	5.25	2.98	0.135	22.00	2.63	0.129	20.42	1.95	0.122	16.03
6B	8.6	4.87	0.216	22.54	4.29	0.211	20.37	3.21	0.196	16.40
6B	7.8	4.43	0.197	22.45	3.93	0.193	20.43	2.92	0.180	16.23
6B	7.0	3.97	0.174	22.78	3.50	0.167	20.92	2.61	0.157	16.63
6B	6.5	3.64	0.159	22.93	3.17	0.152	20.81	2.38	0.144	16.49
6B	5.9	3.31	0.143	23.11	2.92	0.135	21.57	2.17	0.132	16.42
6B	5.3	2.94	0.126	23.31	2.75	0.122	21.04	1.91	0.112	17.07

ORIFICE-FLOW CALIBRATION DATA (CONT'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	1/4-in.			3/8-in.			1/2-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
5	6.3	1.33	0.166	8.03	0.516	0.166	4.45	0.212	0.0716	2.96
5	5.7	1.16	0.149	7.81	0.453	0.0828	5.47	0.186	0.0634	2.93
5	5.1	1.02	0.125	8.13	0.397	0.0870	4.56	0.160	0.0545	2.94
5	4.6	0.909	0.110	8.30	0.346	0.0774	4.48	0.140	0.0472	2.98
5	4.1	0.832	0.102	8.17	0.317	0.0708	4.48	0.128	0.0437	2.92
5	3.8	0.760	0.0940	8.09	0.290	0.0634	4.57	0.117	0.0391	2.99
6A	8.8	1.62	0.175	9.28	0.677	0.130	5.22	0.294	0.0851	3.45
6A	7.8	1.45	0.154	9.42	0.619	0.115	5.41	0.263	0.0758	3.47
6A	6.9	1.26	0.130	9.70	0.522	0.0948	5.51	0.221	0.0631	3.51
6A	6.5	1.16	0.122	9.49	0.487	0.0894	5.45	0.206	0.0596	3.46
6A	5.8	1.03	0.105	9.78	0.426	0.0774	5.50	0.182	0.053	3.46
6A	5.25	.928	0.0967	9.60	0.391	0.0735	5.32	0.166	0.0487	3.41
6B	8.6	1.53	0.159	9.62	0.642	0.116	5.53	0.271	0.0774	3.50
6B	7.8	1.36	0.145	9.36	0.584	0.106	5.51	0.249	0.0723	3.44
6B	7.0	1.22	0.130	9.40	0.512	0.0940	5.45	0.218	0.0615	3.54
6B	6.5	1.22	0.116	9.67	0.464	0.0828	5.61	0.200	0.0573	3.49
6B	5.9	1.01	0.106	9.45	0.426	0.0774	5.50	0.176	0.0509	3.46
6B	5.3	.870	0.0917	9.49	0.368	0.0652	5.64	0.155	0.0445	3.48

ORIFICE-FLOW CALIBRATION DATA (CONT'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	Zero			1/16-in.			1/8-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
6C	8.63	4.88	0.210	23.20	4.30	0.206	20.92	3.19	0.193	16.58
6C	7.90	4.42	0.188	23.51	3.89	0.182	21.34	2.88	0.171	16.87
6C	7.18	3.93	0.166	23.72	3.46	0.161	21.54	2.56	0.151	16.92
6C	6.55	3.58	0.149	24.04	3.16	0.145	21.84	2.33	0.135	17.24
6C	6.05	3.26	0.135	24.21	2.83	0.129	22.05	2.10	0.120	17.55
6C	5.60	2.99	0.120	24.90	2.62	0.117	22.45	1.92	0.111	17.34
7	11.8	4.87	0.226	21.58	4.45	0.219	20.28	3.56	0.207	17.16
7	11.0	4.41	0.206	21.43	4.02	0.201	20.00	3.21	0.193	16.67
7	10.0	3.97	0.183	21.72	3.64	0.177	20.57	2.90	0.169	17.16
7	9.0	3.62	0.155	23.38	3.27	0.152	21.50	2.55	0.145	17.60
7	8.5	3.29	0.139	23.61	2.96	0.135	21.86	2.32	0.132	17.65
7	8.0	2.96	0.127	23.39	2.69	0.123	21.79	2.11	0.116	18.17
8	15.5	4.93	0.215	22.99	4.54	0.209	21.73	3.73	0.202	18.45
8	14.0	4.39	0.193	22.70	4.04	0.191	21.20	3.33	0.182	18.30
8	13.0	3.95	0.170	23.23	3.62	0.166	21.74	2.96	0.159	18.61
8	12.2	3.62	0.153	23.70	3.33	0.149	22.34	2.71	0.143	18.92
8	11.5	3.27	0.135	24.14	3.00	0.134	22.40	2.44	0.128	19.09
8	10.3	2.94	0.120	24.52	2.71	0.118	23.03	2.19	0.114	19.15

ORIFICE-FLOW CALIBRATION DATA (CONT'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	1/4-in.			3/8-in.			1/2-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
6C	8.63	1.51	0.155	9.75	0.630	0.114	5.54	0.267	0.0770	3.47
6C	7.90	1.36	0.137	9.92	0.567	0.100	5.66	0.238	0.0685	3.45
6C	7.18	1.20	0.121	9.94	0.497	0.0888	5.60	0.210	0.0598	3.51
6C	6.55	1.08	0.110	9.88	0.448	0.0793	5.65	0.189	0.0545	3.46
6C	6.05	.975	0.0967	10.08	0.403	0.0721	5.58	0.169	0.0484	3.50
6C	5.60	.890	0.0890	10.00	0.367	0.0654	5.62	0.154	0.0435	3.54
7	11.8	1.90	0.175	10.84	0.872	0.134	6.52	0.389	0.0948	4.10
7	11.0	1.74	0.161	10.82	0.800	0.122	6.54	0.355	0.0863	4.12
7	10.0	1.55	0.139	11.10	0.679	0.109	6.25	0.311	0.0754	4.13
7	9.0	1.33	0.118	11.27	0.617	0.0925	6.67	0.269	0.0654	4.11
7	8.5	0.890	0.108	8.24	0.549	0.0851	6.45	0.245	0.0580	4.21
7	8.0	1.09	0.108	10.09	0.493	0.0774	6.38	0.220	0.0534	4.12
8	15.5	2.17	0.176	12.29	1.08	0.143	7.60	0.509	0.106	4.80
8	14.0	1.93	0.155	12.49	0.967	0.124	7.79	0.454	0.0932	4.87
8	13.0	1.70	0.136	12.52	0.851	0.112	7.59	0.402	0.0812	4.95
8	12.2	1.57	0.123	12.78	0.774	0.0990	7.81	0.312	0.0749	4.84
8	11.5	1.41	0.111	12.72	0.677	0.0882	7.68	0.322	0.0669	4.82
8	10.3	1.25	0.0979	12.76	0.611	0.0774	7.89	0.287	0.0580	4.95

ORIFICE-FLOW CALIBRATION DATA (CONCL'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	Zero			1/16-in.			1/8-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
9	19.0	4.91	0.193	25.47	4.56	0.190	24.03	3.86	0.183	21.09
9	17.5	4.37	0.169	25.78	4.06	0.167	24.33	3.42	0.161	21.27
9	16.1	3.90	0.149	26.14	3.64	0.147	24.73	3.06	0.141	21.64
9	15.2	3.57	0.134	26.56	3.32	0.132	25.09	2.78	0.128	21.74
9	14.3	3.29	0.120	27.45	3.06	0.118	25.86	2.56	0.115	22.20
9	13.3	2.98	0.108	27.70	2.75	0.107	25.78	2.30	0.102	22.67
10	27.0	4.95	0.212	23.29	4.67	0.210	22.21	4.09	0.203	20.10
10	26.5	4.44	0.207	21.52	4.14	0.203	20.38	3.69	0.197	18.73
10	23.5	3.94	0.172	22.96	3.72	0.170	21.93	3.25	0.164	19.74
10	22.0	3.64	0.155	23.50	3.42	0.154	22.18	3.01	0.150	20.09
10	20.3	3.22	0.136	23.62	3.05	0.135	22.50	2.65	0.132	20.15
10	19.5	3.03	0.126	23.99	2.86	0.125	22.91	2.50	0.121	20.62

ORIFICE-FLOW CALIBRATION DATA (CONCL'D)

Pressure Drop Measurements and Ratios vs. Leak Diameters

Orifice Pair No.	Nominal Air Flow SCFM	1/4-in.			3/8-in.			1/2-in.		
		ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R	ΔP_{SO}	ΔP_{LO}	Ratio, R
9	19.0	2.37	0.162	14.61	1.26	0.135	9.33	0.630	0.105	6.02
9	17.5	2.11	0.143	14.80	1.11	0.118	9.41	0.555	0.0932	5.96
9	16.1	1.87	0.126	14.87	0.986	0.104	9.46	0.487	0.0808	6.02
9	15.2	1.70	0.113	15.04	0.892	0.0942	9.47	0.44	0.0739	5.99
9	14.3	1.55	0.101	15.29	0.812	0.0843	9.63	0.400	0.0661	6.[illegible]
9	13.3	1.39	0.0903	15.40	0.722	0.0760	9.50	0.355	0.0580	6.12
10	27.0	2.77	0.184	15.07	1.64	0.158	10.38	0.890	0.128	6.[illegible]
10	26.5	2.53	0.179	14.18	1.51	0.155	9.75	0.827	0.124	6.66
10	23.5	2.22	0.150	14.81	1.31	0.128	10.24	0.711	0.103	6.90
10	22.0	2.03	0.135	15.00	1.20	0.116	10.32	0.650	0.0940	6.[illegible]
10	20.3	1.80	0.118	15.25	1.06	0.102	10.45	0.573	0.0820	6.[illegible]
10	19.5	1.68	0.110	15.26	0.988	0.0948	10.43	0.536	0.0772	6.[illegible]

APPENDIX B

AUTOMOTIVE EXHAUST-SYSTEM LEAK TEST--DETAILED TEST PROCEDURE

Note: Appendix B was intended to be suitable for operational use as an independent document separate from this report.

UNITED STATES DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION

EXPERIMENTAL TEST PROCEDURE

AUTOMOTIVE EXHAUST-SYSTEM QUANTITATIVE LEAK TEST

Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, MA 02142

CONTENTS

ILLUSTRATIONS

1. SCOPE

1.1 This automotive exhaust-system quantitative leak-test procedure presents a description of the engineering-model exhaust flowmeter, detailed test methods, and test-data-evaluation charts to be used for determining the rate of exhaust leakage from automotive exhaust systems.

1.2 This test procedure and equipment neither comprise a Safety Standard nor are related to any safety standard, at this time. The procedure does not set or suggest limits on exhaust-leakage rate; it merely permits determination of the total area of system leaks within the range equivalent to a single round hole between 1/16- and 1/2-inch diameter.

2. PURPOSE

2.1 At the present time, procedures for inspection of automotive exhaust systems (when used at all) vary widely from state to state. In general, they impose unknown and unreproducible stresses on the exhaust systems tested, and are highly subjective in evaluation of test results. The degree of variability in the limiting exhaust-leakage rate (or leak area) which determines whether a vehicle is passed or rejected is unknown; both the maximum and minimum limiting leakage rates also are unknown.

2.2 This engineering-model exhaust-system leak test was developed to provide a quantitative measurement of exhaust leakage. This test may be used in conjunction with present exhaust-system inspection techniques to evaluate both the absolute magnitude and the variability of leakage rates which result in passage or rejection of typical exhaust systems by present inspection methods.

2.3 To better evaluate the capabilities of presently used inspection techniques, it is desirable to avoid (as far as possible) biasing the judgment of test operators who used these existing methods. Therefore, it is recommended that this quantitative test be performed by a separate operator and that no hint or indication of any findings of this new technique be communicated to operators using standard methods.

3. DESCRIPTION OF TEST SPECIMEN

The test specimen consists of the complete exhaust system on any vehicle to be tested; this includes exhaust manifolds, heat riser/valve assemblies, crossover pipes, manifold-to-muffler pipes, mufflers, tailpipes, gaskets or seals, and any other items forming part of the exhaust-muffling and discharge system of the vehicle.

4. TEST SEQUENCE

The test specimen shall be subjected to the tests in the order outlined below:

Test	Section
Receiving Inspection	7.2
Standard Leak Test	Not herein
Quantitative Leak Test	7.
Repeat Quantitative Leak Test after Repair	7.

5. TEST CONDITIONS

5.1 Test-Data Sheet

No format for a test-data sheet is included in this procedure since this procedure was prepared by an organization other than the one which supports a field evaluation of this technique and equipment. Such supporting organization will provide standard data sheets which will specify the vehicle identification and test data desired; all information requested on such test-data sheets should be entered. It is suggested that three particularly important entries be included: engine displacement and idle speed during the test (at large orifice condition), and orifice pair number. These data may be used, after a significant body of data has been accumulated, to revise the engine-displacement boundaries of the individual orifice-pair operating regions in the Orifice-Pair Selection-Guide graph. The boundaries shown in that figure are estimated from air-flow measurements and from tests on only one vehicle, and may prove to be somewhat inaccurate; all displacement boundaries will be affected somewhat by engine-idle speed.

5.2 Standard Ambient Conditions

There appear to be no strong justifications for requiring control of ambient conditions during performance of this exhaust-system leak test. A given leaking-exhaust system, if tested in the same physical condition but once in a warm environment, and once in a cold environment, will show a slightly larger apparent leak in the cold ambient. However, the magnitude of this effect varies somewhat with different exhaust systems, and in any case, is expected to be small. Therefore, the requirements of efficient operation, available floor space (indoors or outdoors), and working conditions acceptable to the operators should be allowed to dictate the degree of control exercised over ambient test conditions.

5.3 Instrumentation and Test-Equipment Calibration

5.3.1 Calibration of the pressure gages used to read the pressure drops across the large and small orifices is a routine, simple matter for any installation suitably equipped for normal gage testing.

5.3.2 Recalibration of the orifice pairs by direct-flow technique should be performed at intervals consistent with the number of tests made, more frequently at first, to determine whether buildup of exhaust deposits causes changes in orifice-flow characteristics. During the development of this test technique, the amount of testing in an actual automotive exhaust stream was insufficient to indicate whether this would be a problem. (For recommendations regarding a suitable flow-calibration system, see E. C. Klaubert, Report No. DOT-TSC-NHTSA-72-10, "Exhaust-System Leak-Test: Quantitative Procedure," DOT/Transportation Systems Center, Cambridge, MA, Section 3.10.)

5.4 Orifice-Assembly Maintenance

5.4.1 Before each test, the orifice assembly to be used should be examined visually to determine that it is clean, free of oil and loose deposits, that the swinging (smaller) orifice plate operates freely, and, most important, that the upstream (facing flow) edges of both large and small orifices are free of nicks, burrs, fibers of wiping materials, and rounding. Any damage to the upstream edges of an orifice can have a profound effect upon orifice performance; downstream edges have relatively little effect so long as there are no projections into the flow stream.

5.4.2 After one or more tests, whenever an orifice assembly is removed from the exhaust flowmeter, the assembly should be wiped carefully with a clean, soft paper or cloth wiper. Special care should be taken to avoid wiping from the upstream face of each orifice into the bore of the orifice in a manner which would tend to round off the sharp upstream edge of the orifice; loose exhaust deposits on the face of the orifice may be abrasive. The bore of the orifice should be wiped out only from the downstream face of the orifice. All orifice assemblies should be stored in a compartmented box or chest lined with a soft material and should be placed in the compartments with the upstream face down. Then, if a tool or another orifice assembly should accidentally be dropped onto a stored orifice, only the downstream face of the stored orifice is likely to be nicked, which should be inconsequential.

5.5 Testing for Connection Leaks

All connections associated with the exhaust-system leak-test equipment should be checked periodically for leaks while under a pressure of at least 2.0 psi. One convenient way of doing this is to connect to a reasonably leak-free exhaust system in normal test configuration with the engine running and the small orifice in measuring position. In such a case, the metal parts involved will be relatively hot, and a high-temperature leak-detecting liquid (e.g., Leak Tec Formula No. 415, American Gas and Chemicals, Inc., New York, N.Y., or equivalent) should be used. In particular, the joint between the exhaust-system tailpipe and the flowmeter hose-to-tailpipe universal adapter should be checked before <u>each</u> test, but only <u>after</u> verifying that the correct orifice assembly has been installed, to prevent over-pressurizing the exhaust system to be tested. At least once daily the connections between the hose and the tailpipe adapter, the hose and the flowmeter, and the pressure connections between flowmeter and pressure gages should be checked.

6. TEST EQUIPMENT

6.1 The test equipment shown in figure 1 consists of an orifice-type flowmeter body, nine interchangeable dual-orifice assemblies, two differential-pressure gages with ranges of 0 to 0.4 and 0 to 5 psi (the 0- to 0.4-psi gage can be overranged to at least 5 psi without injury), and a wire-reinforced silicone rubber/fiberglas hose suitable for operation at temperatures to 450°F. Additional required items, not shown in figure 1, include: (a) a universal adapter to connect the hose to various sizes and shapes of exhaust tailpipes (not all are round); (b) extra hoses with a Y-connector and two universal adapters to combine the discharges from a dual-exhaust system; (c) a plug

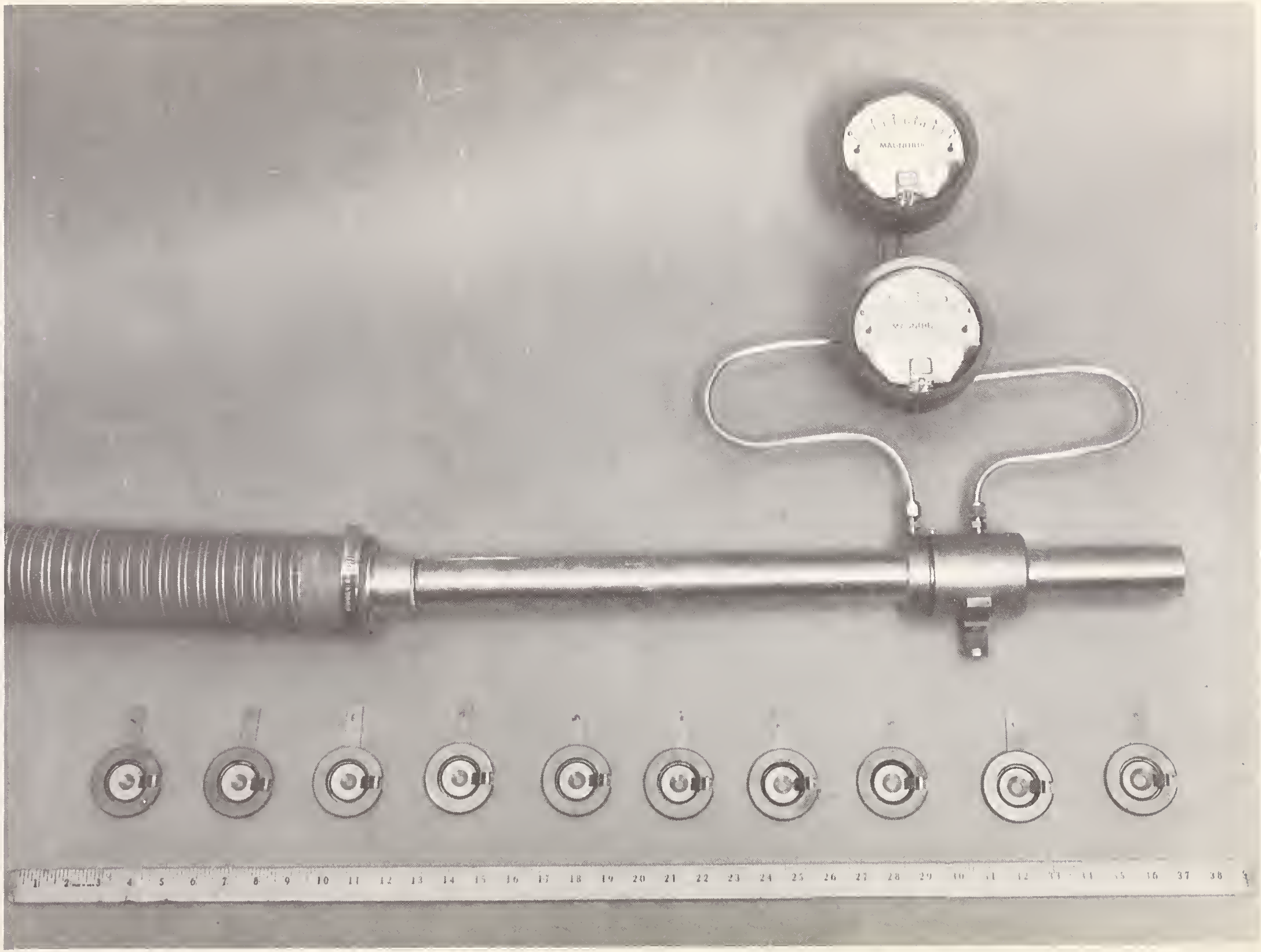

Figure 1. Engineering-Model Field-Test Kit--Assembly View

to seal off one side of a dual-exhaust system which has a common upstream section; (d) a storage box for the several orifice assemblies; and (e) a support for the two pressure gages. These items not shown must be provided by the user. Note also that the flowmeter body normally is covered with fiberglas or asbestos pipe insulation to protect the operator from contact with metal surfaces at from 250° to 300°F exhaust temperatures, and also to minimize heat loss from the flowmeter (hence, cooling of exhaust gases). The insulation was omitted from the pictures for clarity.

6.2 The test equipment causes all engine exhaust discharged from the tailpipe to flow through either of two different-size orifices, and measures the resulting pressure drop across each orifice. To provide maximum readability of pressures, separate gages are used to span the two different ranges of interest. Several orifice assemblies are supplied to accommodate the wide range of automotive engine displacements while maintaining pressure drops within the desired limits. The engine of the car serves as a nearly constant-output pump, at constant-throttle position (idle, warmed up). Note that engine-exhaust output remains nearly constant (within a very few percent) even when engine speed decreases by as much as 15 percent as exhaust backpressure is increased to 5 psi. If there are leaks in the exhaust system, a relatively small portion of the exhaust escapes from the leaks at the low backpressure generated by the larger orifice; therefore, the pressure drop across the large orifice is slightly less than if there were no leaks. The smaller orifice is designed to produce a backpressure of 3 to 5 psi when there are no leaks. If there are leaks, a much greater portion of the exhaust escapes from the leaks when the small orifice is in place than when the large orifice is used. The sizes of the smaller orifices of the assemblies are quite small, from 0.157- to 0.391-inch diameter. These sizes are comparable to, or even smaller than, the leaks this test is intended to measure. Thus, the test serves to "magnify" the size of system leaks (when the orifice diameter is compared to typical tailpipe diameters of 1 to 2 inches). The basic principle of the test, after measuring the exhaust flow rates from the tailpipe at two substantially different pressures, is to relate the leak size to the difference in exhaust leakage caused by the pressure change. In actual operation, however, all that is necessary is to read the two pressure drops, calculate the ratio of the two, and refer to the leak-size determination chart for the orifice pair used. (These charts are included in section 7 of this procedure.) Even numerical calculation is not required; a nomograph is provided in this procedure to permit determining this ratio simply by laying a ruler or other straightedge (a piece of paper) across the three scales of the nomograph.

6.3 Interchange of orifice assemblies in the exhaust flowmeter is easily and quickly accomplished because of the 1/4-turn breechblock joint in the flowmeter body. Orifices may be changed even while the flowmeter is connected to an exhaust system with the car's engine running.

6.4 The larger orifice of a pair is always in place when the flowmeter is assembled. Normally the smaller orifice lies in its recess in the downstream body, out of the flow stream, and the actuating pin protrudes the maximum distance from the bottom of the flowmeter (see figure 2). When the smaller orifice is to be used, the actuating pin is pressed into the meter body and this swings the smaller orifice plate up against the downstream face of the larger orifice (see figure 3).

6.5 The orifice meter body contains straightening vanes (a bundle of small tubes) in its upstream end (see figure 4). These vanes serve to stop any rotary, swirling flow of exhaust, which may have been induced by bends in the exhaust system and the hose, before the exhaust approaches the orifice. This cancellation of swirl is essential to accurate measurements, and hence, the straightening vanes must be in place when any leak test is performed.

Figure 2. Flowmeter Dual Orifice--Large-Orifice, Low-Pressure Position

Figure 3. Flowmeter Dual Orifice--Small-Orifice, High-Pressure Position

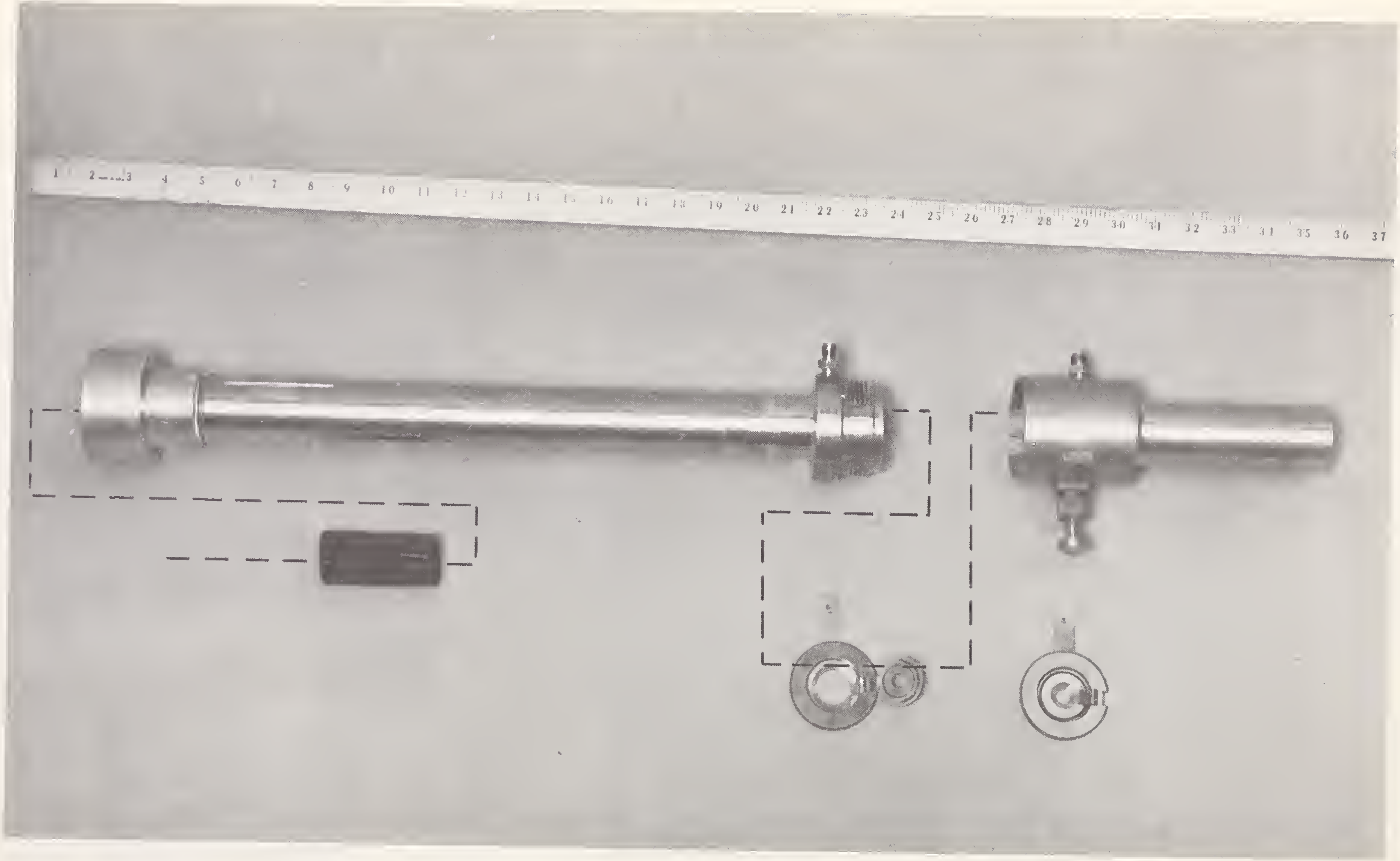

Figure 4. Flowmeter--Exploded View

7. LEAK-TEST PROCEDURE

7.1 Drive the vehicle, whose exhaust system is to be tested, to the test location; park the vehicle with the transmission in "PARK," if an automatic transmission, in "NEUTRAL," if manual; and with the parking brake fully applied. Leave the engine running.

7.2 Receiving Inspection

Record all required vehicular identification data, ambient conditions, and other specified information on the test-data sheet.

7.3 If a tachometer is to be used to measure engine speed, attach signal leads as required.

7.4 Connect exhaust flowmeter, with NO orifice-assembly installed, to vehicle exhaust system as follows:

NOTE: It is assumed that the exhaust hose already has been connected to the exhaust flowmeter and to the universal tail-pipe adapter.

7.4.1 <u>If the exhaust system discharges from a single tailpipe</u> (except for leaks): Attach the universal adapter, which is connected to the flowmeter by the hose, to the vehicle tail-pipe, and complete the seal.

7.4.2 <u>If the exhaust system consists of two entirely independent pipe-and-muffler assemblies with no cross-connection</u>: Attach the two universal adapters of the Y-hose assembly to the two tailpipes, attach the universal adapter of the flowmeter hose to the common discharge of the Y-hose assembly, and complete all seals.

7.4.3 If the exhaust system discharges through two tailpipes but has a common section upstream (so all exhaust may exit through either tailpipe): Either connect as in 7.4.2 above; or attach one universal adapter to one tailpipe, insert plug into this adapter to block discharge of exhaust, attach the universal adapter of the flowmeter hose to the other tailpipe, and complete all seals.

NOTE: Many exhaust systems of this type tend partially or totally to plug on one of the two sides and discharge entirely or mainly from the other tailpipe. If such a case is observed, be sure to plug the obstructed tailpipe and connect the flowmeter to the tailpipe which discharges the major portion of exhaust. If the Y connection is used, this comment is not applicable.

7.5 Refer to the orifice-pair-selection guide (figure 5). Locate on the bottom scale the displacement of the engine of the vehicle being tested. Find in which of the orifice-pair envelopes this displacement falls near center or to the right of center, but within the right-hand boundary. Take this orifice assembly from the storage box.

CAUTION: USE EXTREME CARE AT ALL TIMES TO AVIOD ANY, EVEN SLIGHT, DAMAGE TO THE UPSTREAM EDGES OF THE ORIFICES.

7.6 Grasp the exhaust flowmeter with one hand on the upstream portion, and the other on the downstream portion, and rotate the downstream portion 1/4-turn counterclockwise (viewed from the discharge end) until the slot for the orifice tab in the downstream portion lines up with the pressure tab in the upstream portion. Slide the two portions apart, and set the upstream portion down. Hold the downstream portion nearly horizontal but with the joint slightly upward, and with the actuating pin pointing upward; hold the pin pulled out from the body as far as it will go. Pick up the orifice assembly by the tab with the tab to the right and with the swinging (smaller) orifice plate toward the downstream portion of the flowmeter. This will cause the swinging orifice to swing

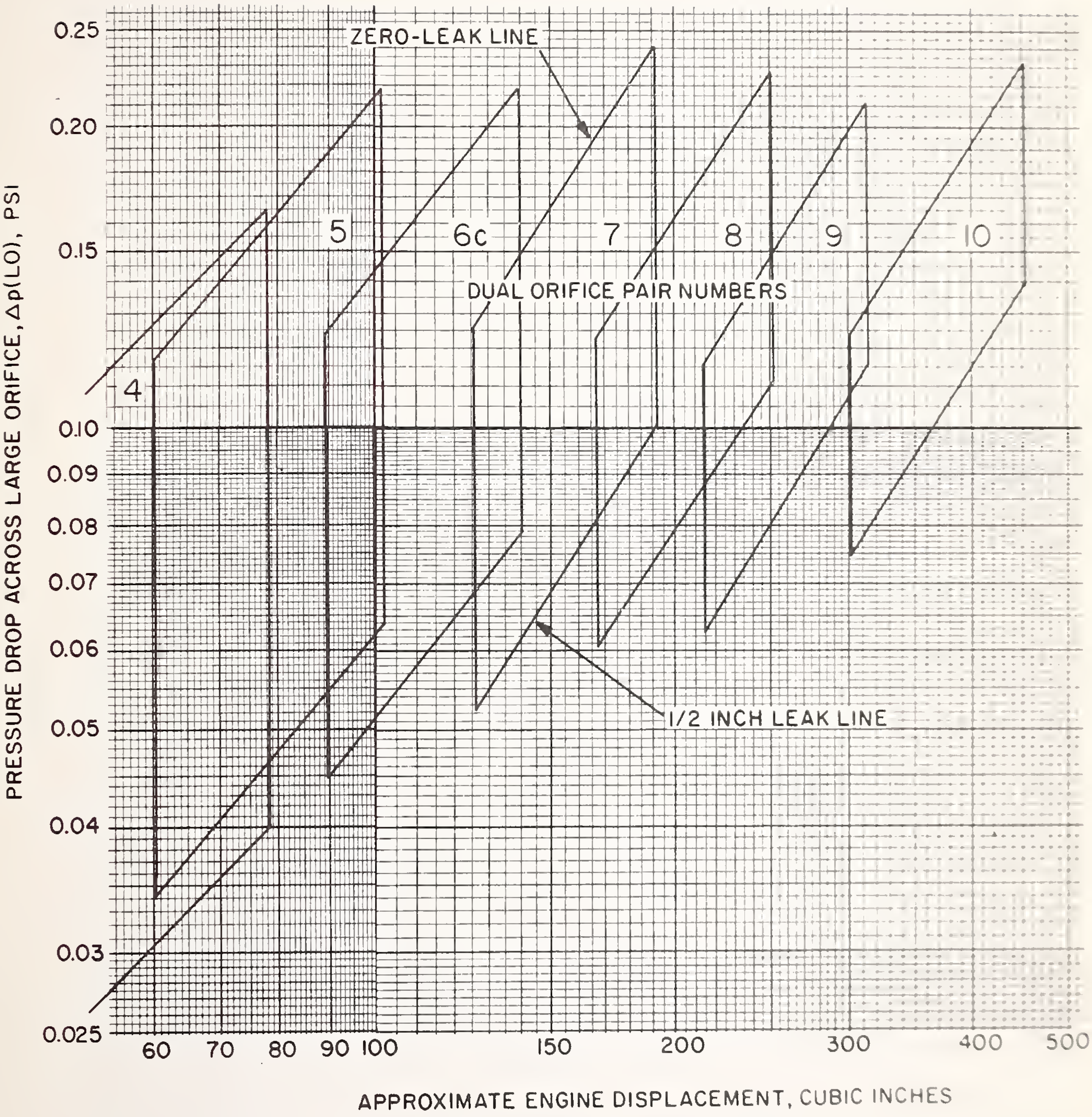

Figure 5. Orifice Pair-Selection Guide

loosely against the larger, stationary orifice plate. Insert the orifice assembly into the joint of the downstream flowmeter portion, with the orifice tab in its slot, until the orifice assembly seats in the body. Hold the orifice assembly in place with one or two fingers, not touching the orifice opening. Tip the discharge end of the flowmeter afterbody down, and see that the swing orifice drops into its recess. While still holding the orifice assembly in place, press on the actuating pin, and see that the swing orifice pivots up against the stationary orifice plate so that the raised face of the swing-orifice plate is flush with the upstream face of the stationary-orifice plate. Allow the small orifice to drop back into its recess. Check the upstream portion of the flowmeter body to ensure that the O-ring has not fallen out of its groove. Align the tab slot in the downstream meter portion with the pressure fitting in the upstream body, and slide the two parts together. The gap between the edge of the downstream member and the shoulder of the upstream portion should be about 1/8-inch; if the O-ring is not seated in its groove, a gap of 1/4-inch or more will be seen. If the correct gap is observed, rotate the downstream member 1/4-turn clockwise until it seats firmly against the upstream member. Do not press the actuating pin to bring the small orifice into measuring position. NOTE: A very tight bottoming is unnecessary since the O-ring seals against the stationary-orifice plate before metal-metal contact is made; wringing the two portions together tightly will only make subsequent disassembly more difficult. The joint cannot be assembled when indexed 1/2-turn out of correct orientation because the thread interruptions intentionally were made unequal in angular width. It is possible to engage the threads one or more pitches out of correct engagement depth, but when rotated 1/4-turn no tightening will be observed and the downstream body can be screwed one or more full turns farther until it bottoms. This could adversely affect the pressure tube to the gages.

7.7 The exhaust flowmeter is now operational in the large-orifice, low-pressure condition. Observe the pressure drop indicated on the lower, 0-to 0.4-psi gage. Refer to the orifice-pair selection guide (figure 5). For the orifice pair in use, does the large orifice-pressure drop, Δp (LO), fall between the slanting upper (zero-leak) and lower (1/2-inch leak) boundaries? If so, proceed to 7.8; if not, proceed as follows. If the observed Δp (LO) falls above the upper, zero-leak boundary, replace the orifice assembly with the next larger size; if Δp (LO) falls below the lower, 1/2-inch leak boundary, substitute the next smaller orifice pair. Observe the new value of Δp (LO) and act according to the above instructions until a satisfactory pressure is obtained. Note that when changing to a different orifice pair, it will not be possible to continue to enter the selection guide at the actual displacement value for the engine in use. The need to change to a different orifice pair suggests that (a) the estimated engine displacement scale on figure 5 is in error, (b) the exhaust system being tested has a total leakage greater than a 1/2-inch hole, or (c) the idle speed of the engine is substantially different from that upon which figure 5 is based. It will be necessary to gain some experience with this technique, acquired largely by trial and error, before becoming adept at establishing and interpreting orifice-selection criteria. The point of greatest importance in selecting an orifice pair is to avoid exceeding a backpressure of 5 psi when the smaller orifice is used. It is desired to stress an apparently acceptable exhaust system to between 3 and 5 psi to indicate that it still possesses sufficient structural integrity so as not to suffer catastrophic failure before the next inspection period. However, most automotive exhaust systems will not actually develop pressures of 5 psi under normal operation. Therefore, it would not be reasonable to destroy a system which can withstand 5 psi by overpressuring it to 7 to 10 psi. Next in importance to this precaution is the need to develop sufficient pressure with the larger orifice to provide reasonable accuracy in reading.

7.8 When it is believed that the correct orifice assembly has been installed, press the actuating pin to swing the smaller orifice into measuring position while watching the 5-psi gage. Be prepared to release the small orifice quickly if Δp (SO) exceeds 5 psi. If Δp (SO) stays below 5 psi, apply leak-detector liquid to the joint between the universal adapter(s) and the tailpipe(s) to determine if these joints are adequately sealed. Tighten the adapter(s) if necessary. Release the small orifice and ensure, by observing the pressure gages, that the small orifice did in fact retract. (There is a tendency, with some orifice assemblies, for the small orifice to remain almost in closed position even when not held there by the actuating pin, when a pressure of 3 or more psi has been developed. Normally, such pressure would develop a force that would tend to push the small orifice away from the stationary-orifice plate. It is believed that this apparent "sticking" of the smaller orifice is caused by aerodynamic forces resulting from high-velocity leakage flow between the adjacent surfaces of the small-and large-orifice plates which causes the small-orifice plate to "fly" against the large plate. In such instances, the small orifice can be released either by a sharp blow with the hand on the discharge end of the flowmeter which jars the small-orifice plate away from the stationary plate, or by momentarily capping the open end of the flowmeter with the hand to build up pressure downstream of the smaller orifice, and then, releasing this pressure quickly.) When it has been established that the correct orifice assembly has been installed, that the leak test equipment is free of leaks, and that the small orifice has been returned to its rest position, the actual exhaust-system leak test may be made.

7.9 Read and record on the test-data sheet the value of Δp (LO). If a tachometer is being used and the test-data sheet calls for engine speed at Δp (LO), read and record this item.

7.10 Quickly and firmly press the actuating pin to snap the smaller orifice into measuring position, and observe the pressure on the 5-psi gage as soon as it reaches a steady maximum (within about 10 seconds after deploying the smaller orifice). Press somewhat more firmly on the actuating pin and note whether Δp (SO) increases; if it does, the small-orifice plate was not seated sufficiently against the stationary-orifice plate. It is important to take the reading of Δp (SO) as quickly as possible after deploying the small orifice; changes in cooling of the exhaust during its passage through the exhaust system, as internal pressure is changed, can cause the value of Δp (SO) to fall off within 20 to 30 seconds. Release the small orifice. Record on the test-data sheet the observed value of Δp (SO).

7.11 If the test-data sheet calls for repeated readings of Δp (LO) and Δp (SO), allow the system to stabilize at Δp (LO) for about 30 seconds before repeating 7.9 and 7.10.

7.12 Determine the ratio $R = \Delta p(SO)/\Delta p(LO)$. This may be done conveniently with accuracy sufficient for test purposes by using the nomograph for calculating ratio of pressure drops (figure 6). Find, on the right-hand scale, the observed value of Δp (LO). With a straightedge (ruler, or simply the edge of the test-data sheet), connect this point with the observed value of Δp (SO), found on the central scale. Where the straightedge crosses the left-hand scale, read the value of R for this test. Enter the value of R on the test-data sheet. (For illustration of this technique, two such determinations have been drawn on figure 6. The solid line (Example A) represents $\Delta p(SO)/\Delta p(LO) = 2.0/0.08 = 25 = R$, while the dashed line (Example B) shows $\Delta p(SO)/\Delta p(LO) = 1.0/0.30 = 3.33 = R$. If the accuracy of this determination is not considered sufficient (e.g., if the owner of the vehicle tested, assuming an operational State-inspection situation, protested a measurement which showed that his vehicle just barely missed passing), the value of R can be calculated numerically.

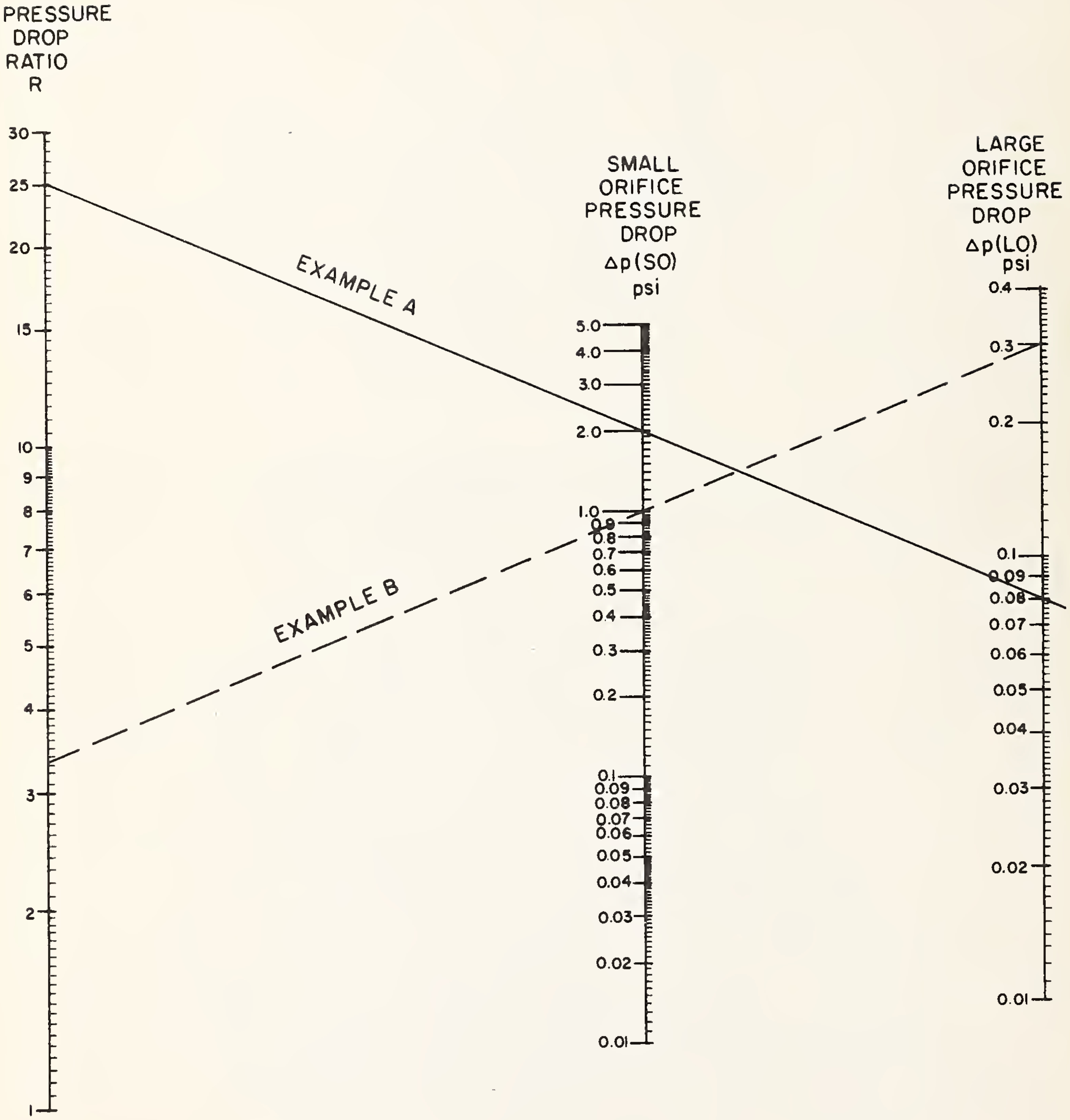

Figure 6. Nomograph for Calculating Ratio of Orifice-Pressure Drops

7.13 Refer to the equivalent single-hole dize-determination chart--one of figures 7-15-- for the orifice assembly used in this test (charts for all orifice assemblies are included at the end of section 7). On the horizontal scale, find the value of Δp (LO) observed in this test. Follow this value vertically upward to the value of R just calculated. Normally the point just located should fall between the steeply sloping lines indicating the boundaries of the normal operating range (for this orifice pair); however, should the point fall somewhat outside these boundaries, the nearly horizontal lines for the various equivalent leak sizes can be extended as shown in the charts. Estimate (to about 1/16-inch) the size of a single round hole which would have leakage equivalent to the combined leaks in the system just tested, by observing the relative distance between the leak size lines given in the chart, taking that fraction of the difference between the size lines immediately above and below the test point, and adding this increment to the diameter for the first line above the test point. For example, if the test point fell approximately halfway between the 1/4- and 3/8-inch-diameter leak lines, the increment would be 1/2 of (3/8 - 1/4 = 1/8), or 1/16-inch; add 1/16 to 1/4, and the equivalent single-hole diameter would be 5/16-inch. Enter the equivalent leak size on the test data sheet. To aid in understanding the size-determination charts, consider the following: Assume a vehicle has a completely leak-free exhaust system and its engine displacement is such that the zero-leak value of R falls just halfway between the normal operating range boundaries. Then, assume a leak of steadily increasing size were made in the exhaust system. The values of Δp (LO) and R for these increasing leaks would decrease in such proportions that they would fall (approximately) along a sloping straight line that would remain halfway between the operating range boundaries all the way down to the bottom of the chart. For other engine sizes within the operating range of this orifice pair, similar lines with proportionately greater or less slope, for smaller or larger engines falling to left or right of center respectively, would be observed. Thus in estimating the fractional distance of an experimental point between two given size lines, the slant distance along a line of appropriate slope is the correct basis for interpolating leak sizes. However in most instances, the slopes of the given leak-size lines are so nearly horizontal that little error will be incurred in taking the vertical distance fraction.

7.14 When the leak test has been completed, remove the orifice assembly from the flowmeter, wipe carefully per paragraph 5.4.2, and return the orifice assembly to the storage box. Remove the leak test equipment from the vehicle which has been tested.

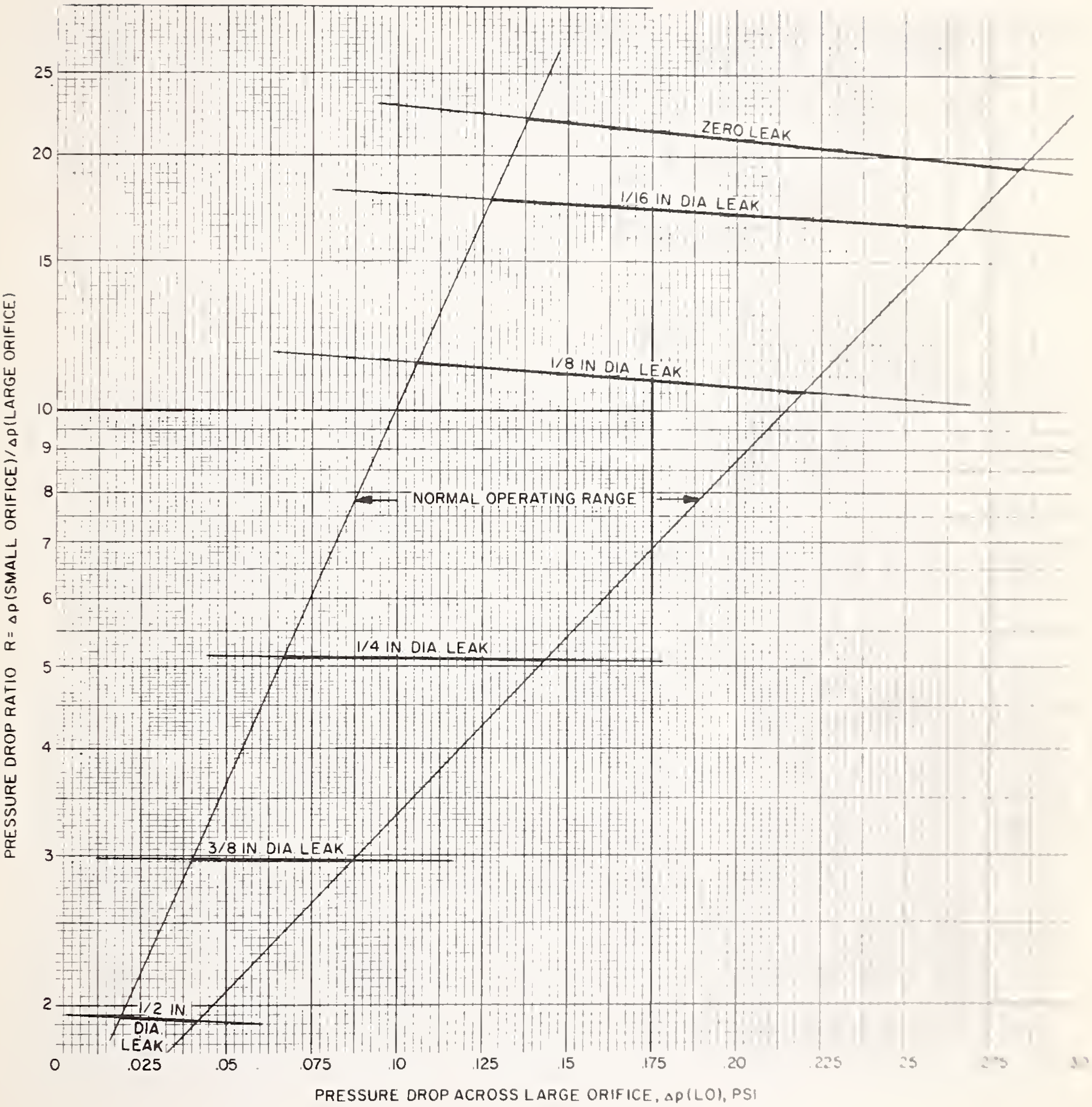

Figure 7. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 2

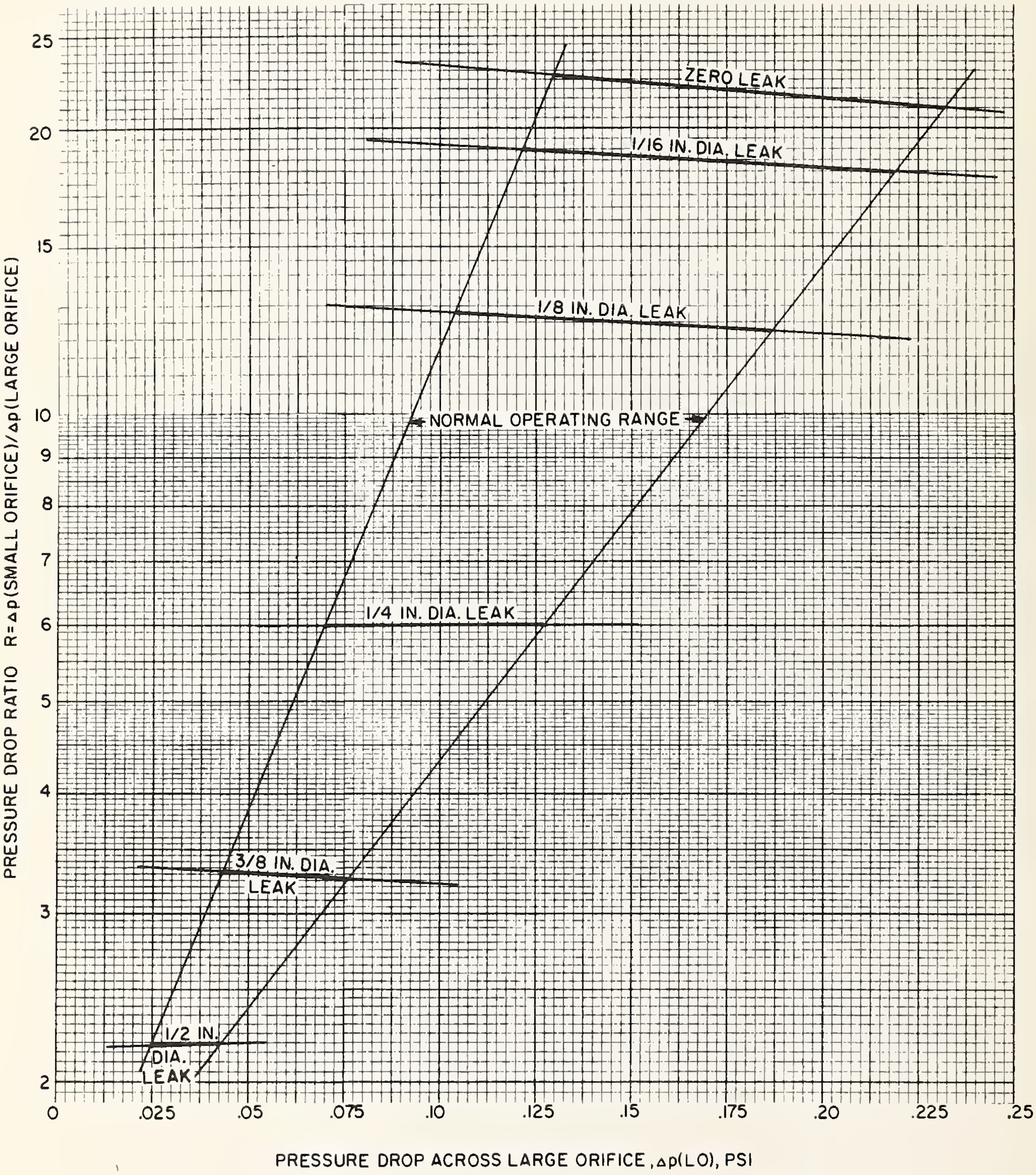

Figure 8. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 3

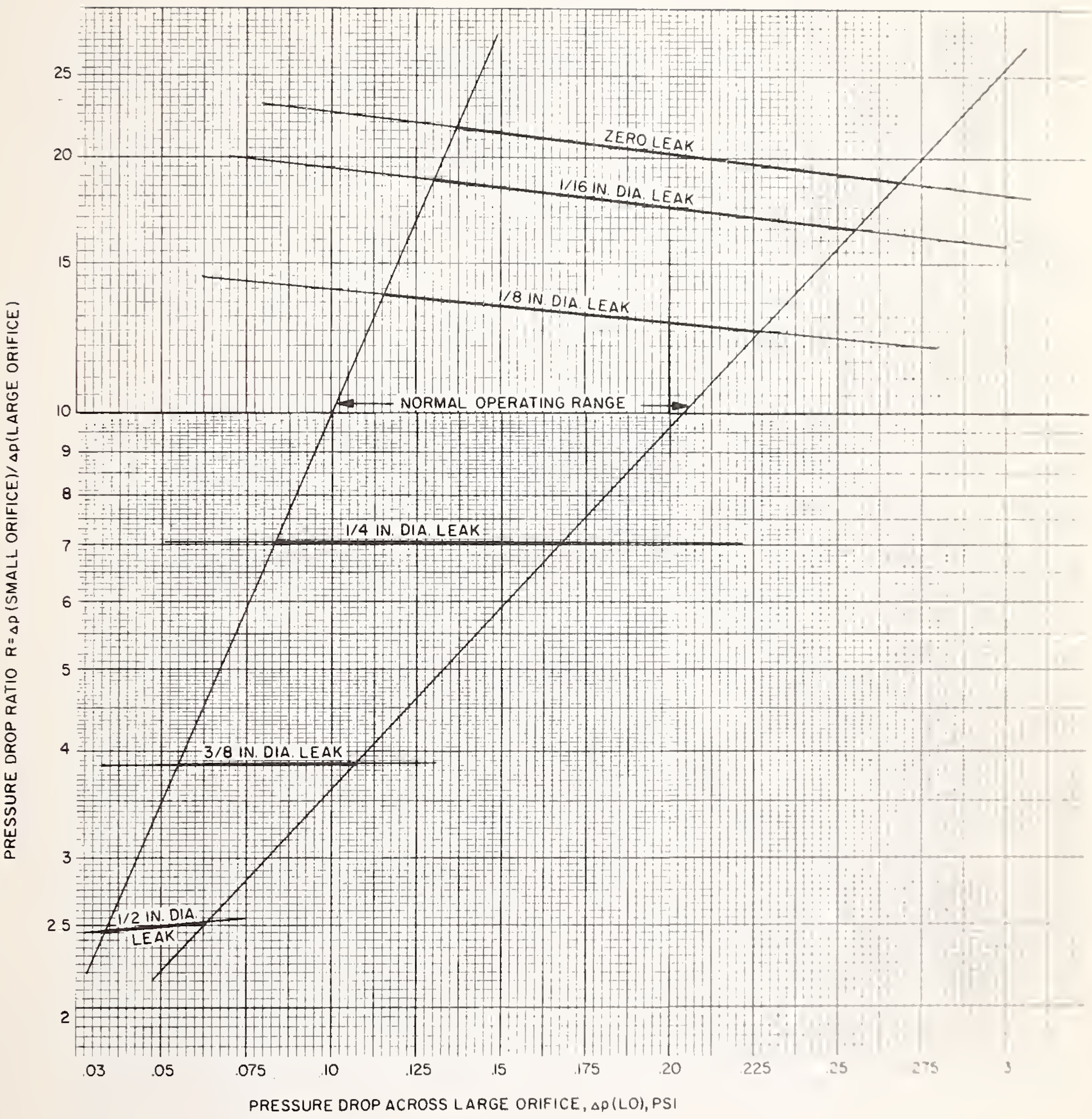

Figure 9. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 4

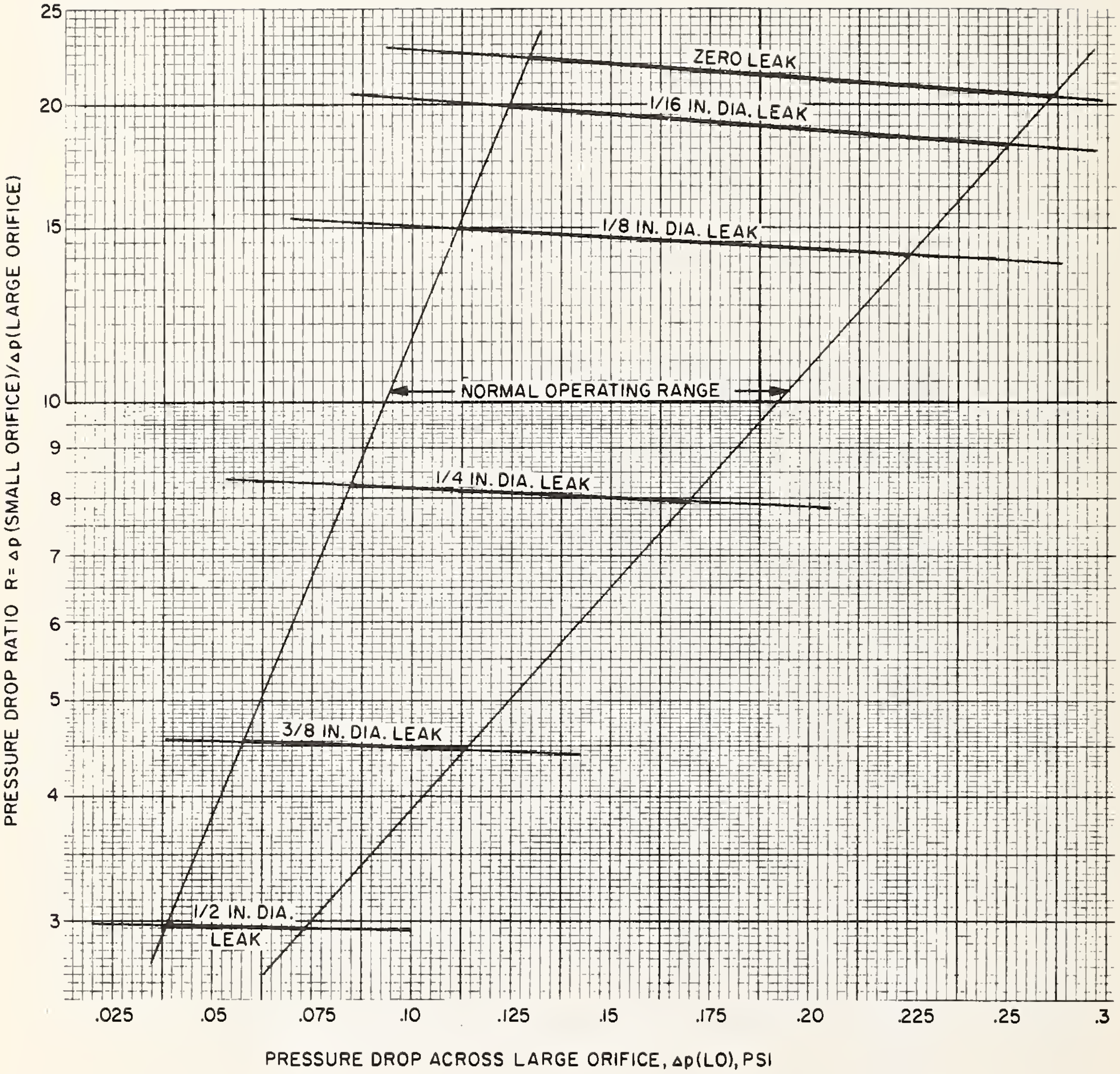

Figure 10. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 5

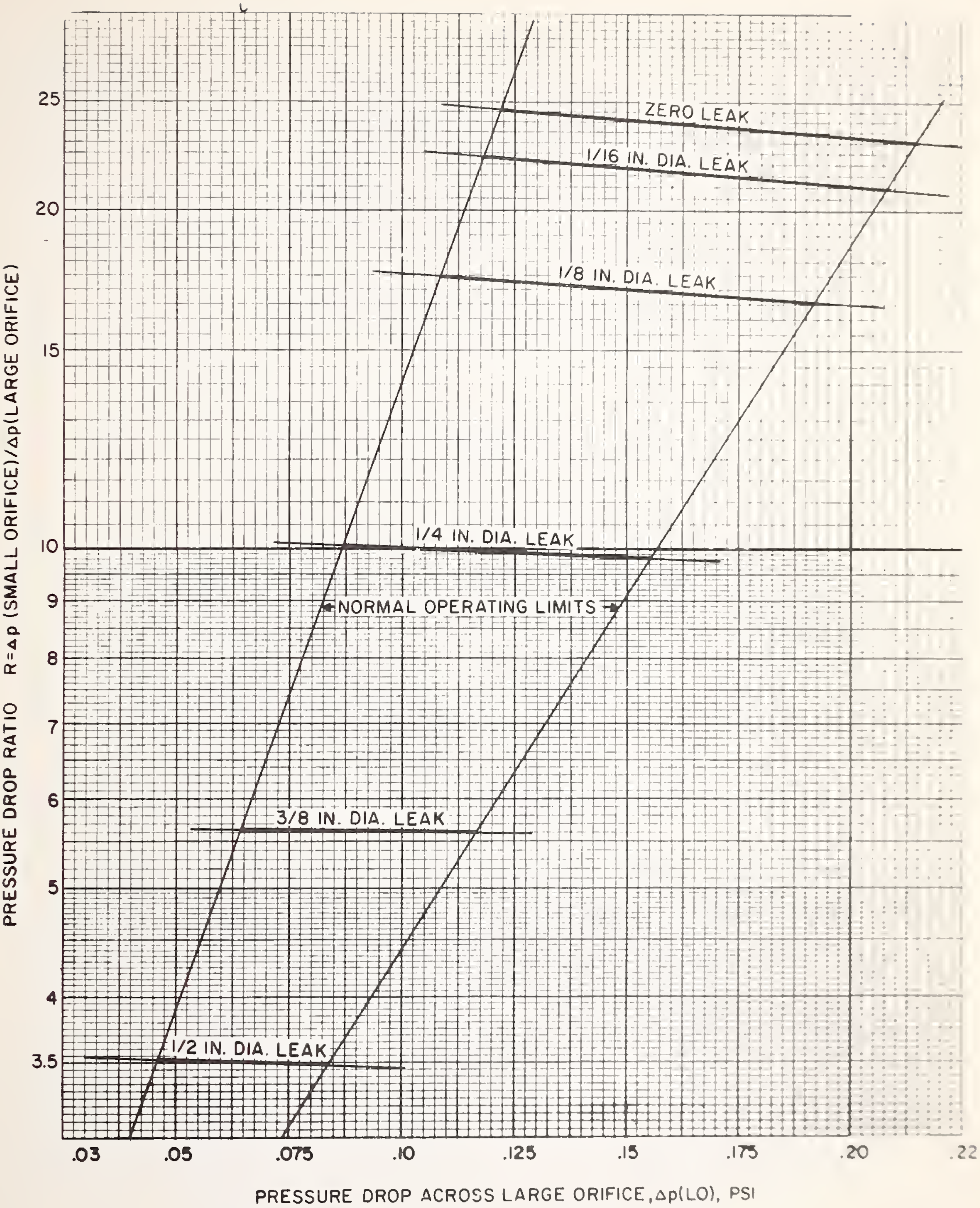

Figure 11. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 6C

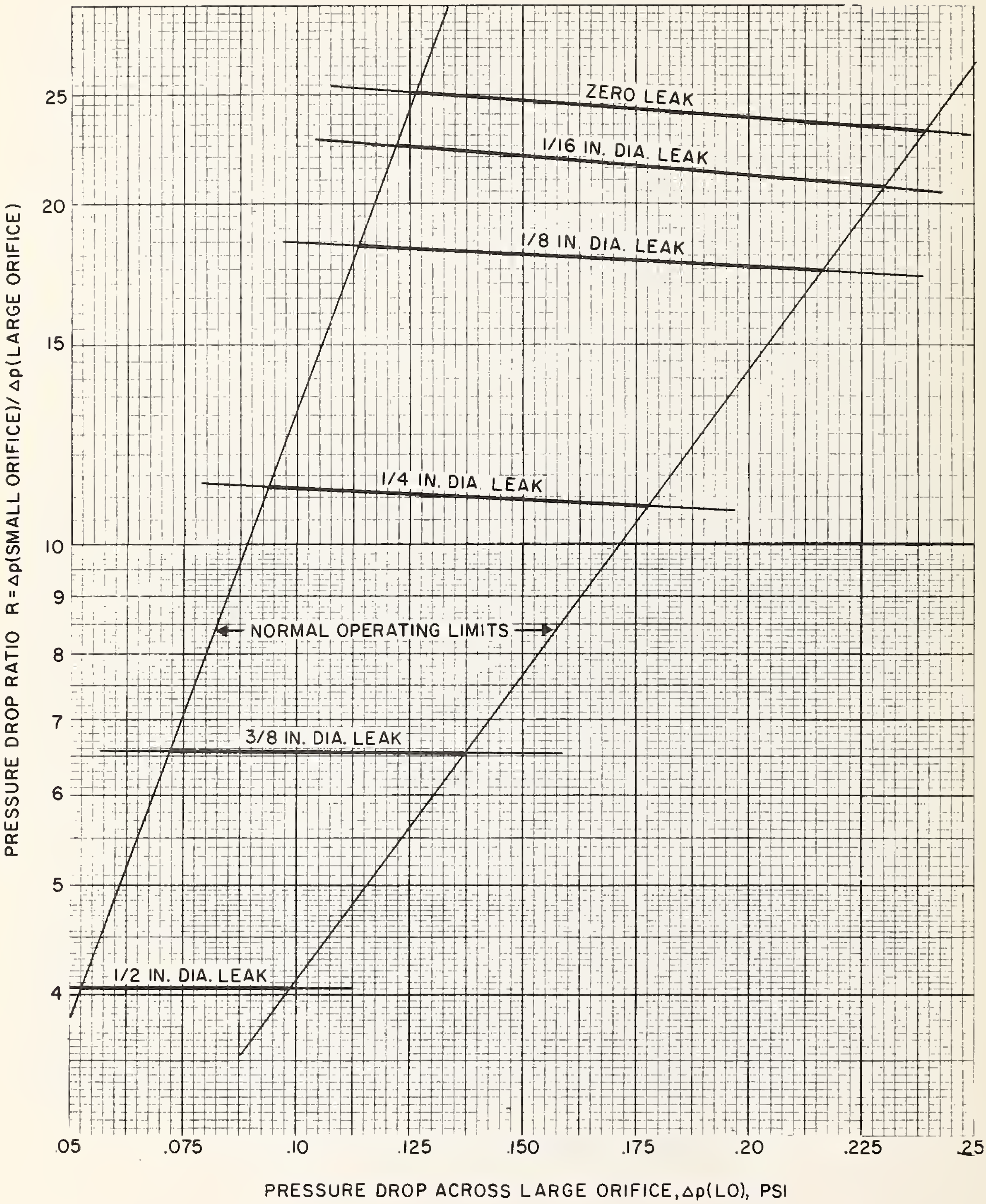

Figure 12. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 7

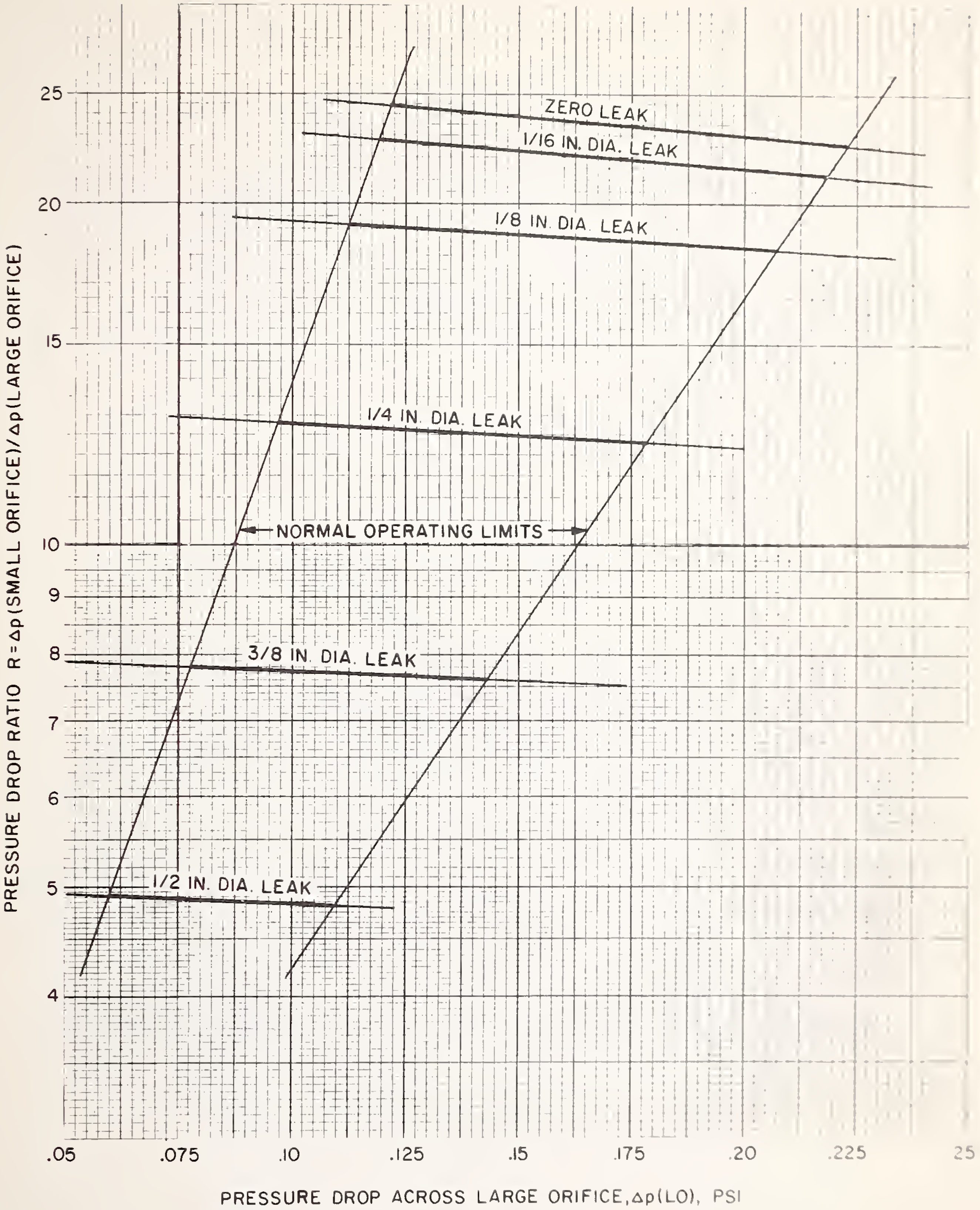

Figure 13. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 8

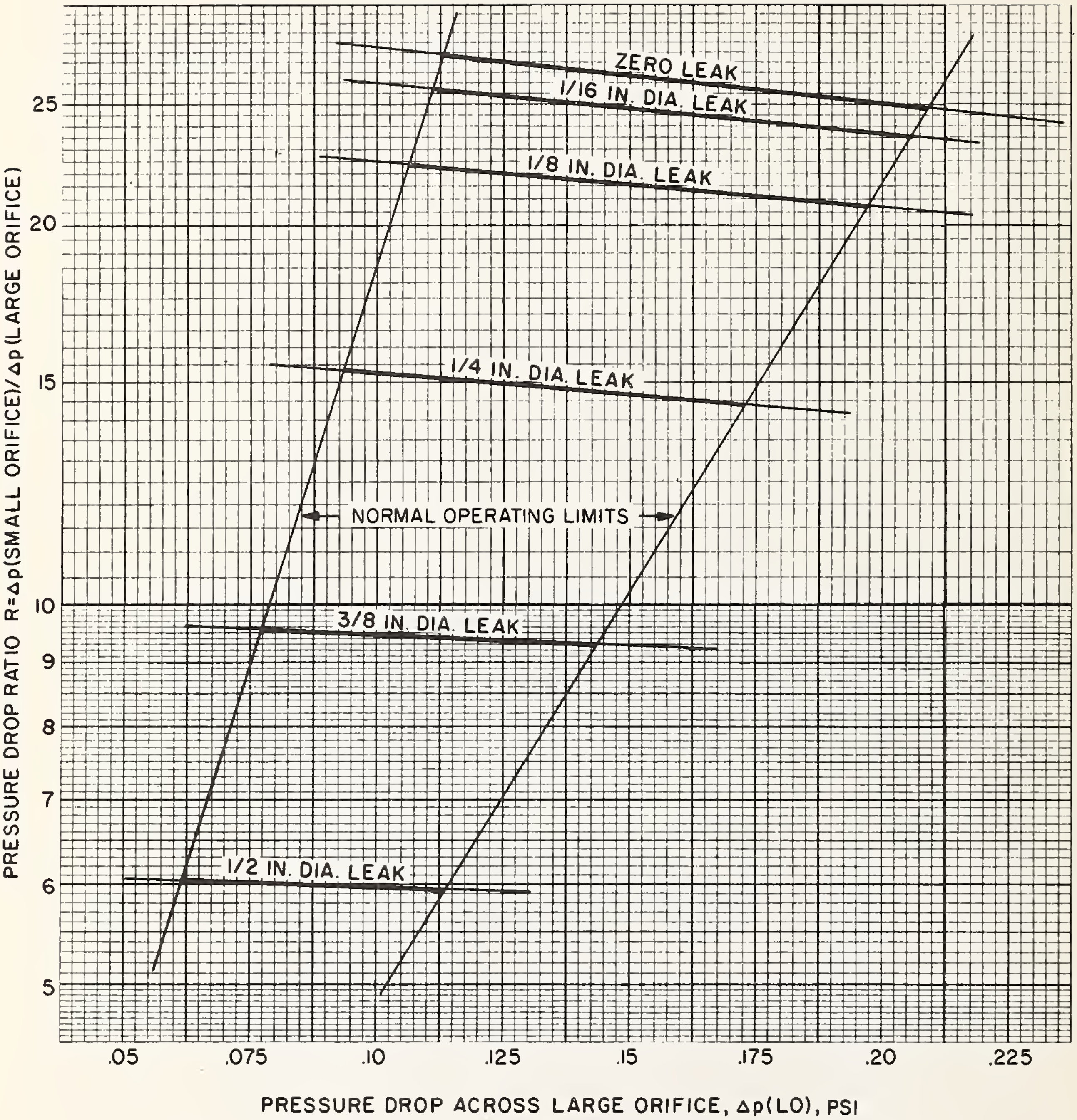

Figure 14. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 9

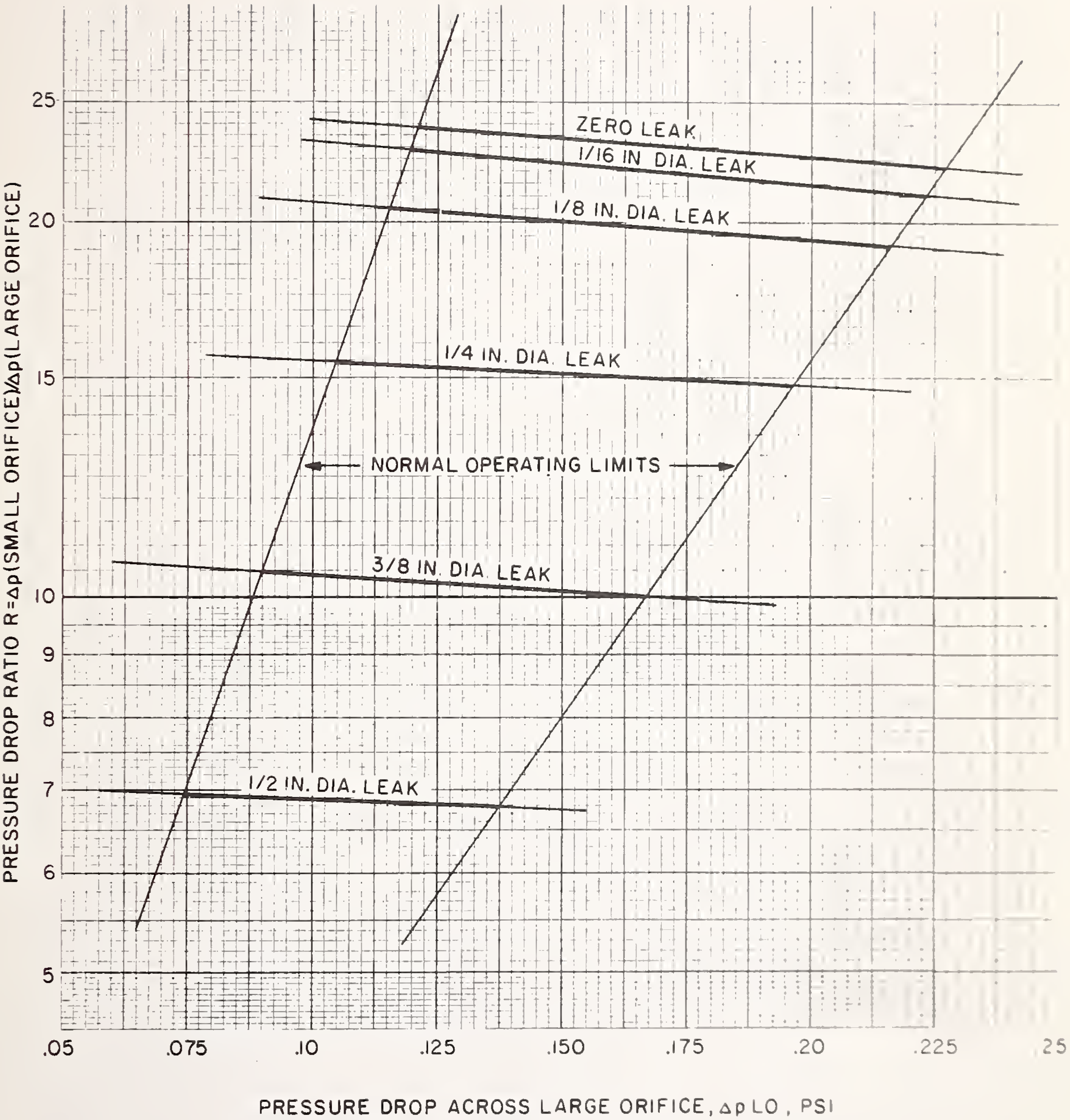

Figure 15. Equivalent Single-Hole Size-Determination Charts Dual-Orifice Pair No. 10