NASA TM-80091

NASA Technical Memorandum 80091

NASA-TM-80091 19790019291

A Study of Response Time of Pitot Pressure Probes Designed for Rapid Response and Protection of Transducer

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May 1979

NASA
National Aeronautics and
Space Administration

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A STUDY OF RESPONSE TIME OF PITOT PRESSURE PROBES DESIGNED FOR RAPID RESPONSE AND PROTECTION OF TRANSDUCERS

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SUMMARY

A study was made in a small shock tube of the response time of pitot pressure probes designed both for rapid response and to protect the transducer from flow-particle damage. Parameters varied were the initial driven-gas pressure in the shock tube, the pitot probe orifice diameter, the conductance of the protective baffle, and the volume of the cavity ahead of the transducer. Experimental results were compared with a simple theory.

The change in response time of the pitot pressure probes as the parameters were changed was, in general, predicted by theory. The simplifying assumptions in the theory did not permit accurate predictions of the actual values of response time in many cases. The response time decreased as the orifice diameter increased and as the volume of the cavity ahead of the transducer decreased. Changes in conductance of the baffle had little effect on the response time.

An eight-orifice probe, designed to protect the transducer without the use of a baffle, was compared to a standard orifice-baffle probe in the small shock tube and in the expansion tube under normal run conditions. In both facilities, the response time of the eight-orifice probe was considerably better than the standard probe design.

INTRODUCTION

As indicated in reference 1, the test times in the Langley 6-inch expansion tube are extremely short, on the order of 400 microseconds or less.

Pitot pressure measurements require the use of pressure transducers with rise times of 1 to 3 microseconds in response to a step increase in pressure. A probe design in which the pressure-sensing surface of the transducer is flush with the front surface of the probe would give the best response. However, as indicated in reference 1, particles from the primary and secondary diaphragms arrive following the test flow and impinge on this front surface, thus endangering the transducer.

Methods of protecting the transducer include offsetting the transducer and the installation of an annular baffle, as described in reference 2. In these designs, the volume ahead of the transducer cannot be reduced enough to obtain the very short time response to pressure that is required. Two methods that have been used in the expansion tube are the overlapping baffle, described in reference 1, and the orifice-disk baffle of reference 3. Both of these probes provided adequate protection for the transducer, but the time response to pressure change was on the order of 50 to 100 microseconds.

Consideration must also be given to the orifice size and length of passages leading from the point of measurement to the sensing element. In reference 4, it has been determined that the time response to pressure change in tubing depends directly on the length of the tubing and the volume of the cavity ahead of the sensing element, and inversely on the pressure and the fourth power of the internal diameter of the tubing. Thus, a short response time requires that the pressure sensing transducer be located as close as possible to the point being measured and that the volume ahead of the transducer be minimal and coupled to the point of measurement with a large diameter orifice.

The purpose of the present study was to determine the effects of probe geometry and pressure on the time response to a step increase in pressure of pitot pressure probes designed to protect the transducer from damage due to particles in the flow being measured. Geometric parameters varied were the size of the orifice, the volume of the chamber ahead of the transducer, and the conductance of the protective baffles. The flow conditions in the shock tube were varied by changing the initial value of the pressure in the driven section of the tube. A comparison is made between the experimental results obtained and results of a simplified theoretical analysis of the time response of an orifice-cavity configuration to a step increase in pressure.

SYMBOLS

A	area
a	speed of sound
K	constant defined by equation (3)
l	length of sleeve ahead of transducer
$\dot{m}$	mass flow rate
M	Mach number, U/a
n	number of holes in baffle
p	pressure
R	gas constant
T	temperature
t	time
U	velocity
$U_{s,1}$	incident shock velocity in shock tube
V	volume

γ	ratio of specific heats of gas
ρ	density
ε	ratio of effective orifice area to geometric orifice area

Subscripts:

1	conditions ahead of incident shock in shock tube
2	conditions behind incident shock in shock tube
t	total conditions, assuming gas brought to rest
o	orifice
b	baffle
c	cavity

Superscripts:

'	conditions in cavity ahead of transducer in probe

DESCRIPTION OF APPARATUS

Probes

The pitot pressure probes used during previous investigations in the Langley 6-inch expansion tube are shown in figure 1(a) and the pitot pressure probes used in the present study are shown in figure 1(b). The pressure transducers used in all probes were piezoelectric quartz or ceramic types, with a response time of 1 to 3 microseconds. All probes, except the eyelid probes, were composed of a short forward tip portion enclosing the transducer, sleeve, and baffle, and a longer supporting cylinder. The eyelid probe was a one-piece cylinder with the same overall length as the other probes. The eight-orifice probe with no internal baffle was designed to minimize the internal volume and give adequate protection for the transducer from all but the smallest particles. This design was developed from results obtained during the present study.

The geometrical properties of the probes used in the present study are given in table I. Probe tips were made for each orifice diameter, and sleeves of different lengths were used to change the volume of the cavity ahead of the transducer. The conductance of the baffle was varied by changing the number of holes drilled through the baffle, each hole being 1.092 mm diameter. The total volume of the baffles includes the volume of the holes and the volume of the cavity ahead of the holes.

TABLE I. - GEOMETRIC PROPERTIES OF PITOT PROBES USED IN PRESENT STUDY

ORIFICE			BAFFLE			TRANSDUCER CAVITY	
d_o, mm	A_o, cm	V_o, cm^3	$n^{(1)}$	A_b, cm^2	$V_b^{(2)}$, cm^3	l, mm	V_c, cm^3
0.508	0.00203	0.00026	3	0.02810	0.01439	0.381	0.00934
0.889	0.00621	0.00079	4	0.03747	0.01545	0.889	0.02180
1.321	0.01370	0.00174	5	0.04684	0.01651	1.397	0.03426
1.702	0.02275	0.00289	6	0.05621	0.01757	1.905	0.04672
2.057	0.03325	0.00422	7	0.06557	0.01863	2.413	0.05918
2.438	0.04670	0.00593	8	0.07494	0.01969	2.921	0.07164
<u>8-ORIFICE</u>			(1) holes 1.092 mm dia.				
0.889	0.04960	0.00631	(2) V_b includes volume of holes and volume of cavity ahead of holes.				

TEST APPARATUS

The present study was conducted in a small 15.24 cm diameter shock tube, shown schematically in figure 2. The tube was designed for a maximum pressure of 0.69 M Pa. For the present tests, the driver gas was helium at approximately 0.35 M Pa and the driven gas was air. Separating the driver section from the driven section was a 0.0508 mm thick diaphragm of mylar. The initial pressure of the driven gas, p_1, was varied to give the desired conditions for the test. Conditions in the shock tube for the present study are listed in table II.

TABLE II. - NOMINAL TEST CONDITIONS IN SHOCK TUBE

p_1 Pa	$\frac{U_{s,1}}{a_1}$	$\frac{p_2}{p_1}$	$\frac{T_2}{T_1}$	M_2	$p_{t,2}$ K Pa	T_2 °K	$T_{t,2}$ °K
106.7	4.6	25.02	5.05	1.62	14.5	1515	2297
2670	2.7	8.34	2.34	1.27	58	703	911

For the tests, four probes were mounted in the end plate, equally spaced around the center on a 6.35 cm diameter circle. The probes protruded 4.763 cm into the driven tube, measured from the end plate. One probe, with the pressure transducer mounted flush with the front surface of the probe, was used as a reference for the time of flow establishment and the magnitude of the measured pressure.

The output of each pressure transducer was processed through a charge amplifier and recorded by an oscilloscope and camera. The velocity of the incident shock was determined from the reading of a microsecond counter triggered by successive wall-pressure transducers.

RESULTS AND DISCUSSION

The theory of reference 2 is applicable to laminar flow in the tubing connecting the transducer cavity to the point at which the pressure is being measured. The probes in the present study were designed so that the length of passage from the point of pressure measurement to the transducer cavity was only 1.27 mm, hence, the length is too short for the theory of reference 2 to apply. Therefore, a simple theory was developed to predict the time response of an orifice-cavity configuration to a step increase in pressure.

The assumption was made that, after the passage of the initial incident shock, the region ahead of the pitot probe was equivalent to a stagnation reservoir and the orifice was a throat ahead of an evacuated reservoir. As long as the pressure in the cavity ahead of the transducer was below 0.528 times the stagnation reservoir pressure, the flow in the orifice was assumed to be at sonic velocity. When the pressure in the transducer cavity exceeded 0.528 times the stagnation reservoir pressure, the flow through the orifice was assumed to be subsonic. Computation of the mass flow into the transducer cavity was based on these assumptions.

Writing for the mass flow, from reference 5, page 204:

$$\dot{m} = \frac{\varepsilon A\, p_t}{(R\, T_t)^{\frac{1}{2}}} \left(\frac{2\gamma}{\gamma-1} \left[\left(\frac{p}{p_t}\right)^{2/\gamma} - \left(\frac{p}{p_t}\right)^{\frac{\gamma+1}{\gamma}} \right] \right)^{\frac{1}{2}} \tag{1}$$

or

$$\dot{m} = \frac{\varepsilon A\, p_t}{(T_t)^{\frac{1}{2}}}\, K \tag{2}$$

where

$$K = \left(\frac{2}{R(\gamma-1)} \left[\left(\frac{p}{p_t}\right)^{2/\gamma} - \left(\frac{p}{p_t}\right)^{\frac{\gamma+1}{\gamma}} \right] \right)^{\frac{1}{2}} \tag{3}$$

For the present tests in air, $\gamma_{t,2} = 1.4$ and

$$K = 0.15585 \left[\left(\frac{p}{p_t}\right)^{1.4286} - \left(\frac{p}{p_t}\right)^{1.7143} \right]^{\frac{1}{2}} \tag{4}$$

Assuming the pressure in the cavity is given by

$$p' = \rho' R T' = \frac{RT'}{V} \int_{o}^{t} \dot{m} \, dt \tag{5}$$

and substituting the expression for $\dot{m}$ from equation (2)

$$\frac{p'}{p_t} = \varepsilon R \frac{A}{V} \frac{T'}{(T_t)^{\frac{1}{2}}} \int_{o}^{t} K(t) \, dt \tag{6}$$

For $p'/p_t < 0.528$, sonic flow exists in the orifice, and when the value of p/p_t for M = 1 is substituted into equation (4), the value of K is 0.04033. Putting this value of K into equation (6)

$$\frac{p'}{p_t} = 11.624 \, \varepsilon \frac{A}{V} \frac{T'}{(T_t)^{\frac{1}{2}}} \, t \tag{7}$$

For $p'/p_t > 0.528$, the flow in the orifice is assumed to be subsonic, and it is further assumed that the pressure in the cavity is equal to the pressure in the orifice. The value of K is then determined by equation (4) and is a function of the Mach number in the orifice.

In computing the variation of p'/p_t with time, equation (7) is used for p'/p_t less than or equal to 0.528. For values of p'/p_t greater than 0.528, an iterative procedure is used with equations (4) and (6). The values of A and V are determined by the particular orifice-cavity configuration. The value of T' in the cavity is assumed to be the static temperature in the flow just ahead of the probe.

The orifice-cavity theory was modified to include the effect of the initial shock wave moving down the shock tube entering the cavity of the probe. The portion of this shock wave ahead of the orifice of the pitot pressure probe is assumed to enter the orifice, reflect from the transducer surface, or baffle surface when baffle is in, and move back out into the flow ahead of the probe. Calculations indicate that under the conditions of the present tests, this takes on the order of 2 to 10 microseconds. The gas affected by this shock is assumed to be in the volume enclosed by the column from the orifice opening to the transducer or baffle surface reflecting the shock. This volume of gas is assumed to expand into the total internal volume of the pitot probe after the reflected shock exits the probe. The resulting pressure is assumed to be the initial pressure in the transducer cavity for the calculation of the mass flow through the orifice.

The simplified orifice-cavity theory, with no baffles, is compared to experimental results, with no baffles, for initial driven tube pressures of 106.7 Pa and 2.67 K Pa in figure 3. The results are presented for three orifice diameters and three values of the volume of the cavity ahead of the transducer. The theory agrees generally with the trend of the experimental data for the indicated values of orifice coefficient, ε. The initial overshoot of the pressure for the larger diameter orifices at the higher initial driven tube pressure indicates the reflection of the initial incident shock from the face of the transducer, since the orifice diameter is roughly 40 percent of the diameter of the transducer. With this overshoot, there is generally an oscillation of the pressure in the cavity around the calculated value of the total pressure.

The simplified orifice-cavity theory is compared with the experimental data with various baffles installed for initial driven tube pressures of 106.7 Pa and 2.67 K Pa in figure 4 for different diameter orifices. Again, the theory generally follows the trend of the experimental data. The addition of the baffle has dampened the initial overshoot in the pressure for the larger orifices that was noted in the data for no baffles installed. Increasing the conductance of the baffles from four holes to eight holes has no measurable effect on the response of the orifice-cavity-baffle configuration. For the lowest values of the initial driven tube pressure, even the largest diameter orifice probe had poor response time to pressure input with a baffle installed. At the higher value of initial driven tube pressure, the response of the largest diameter orifice probe with baffle was adequate.

Comparing the data with and without baffles for the same orifice diameter and initial driven tube pressure indicates a definite deterioration in the response time of the probe when the baffle is present. This is not due entirely to an increase of total internal volume of the probe, since at the lower value of initial driven tube pressure for the same orifice diameter and total cavity volume (i.e., figures 3(c) and 4(b)), the time response of the probe without the baffle was better than the probe with the baffle.

In order to take advantage of this effect, a probe was designed to protect the transducer without a baffle and with a minimal total internal volume of the pitot probe. To provide protection for the transducer, the area of the orifice was divided into eight small diameter orifices located at a distance from the center of the probe that was just less than the radius of the transducer sensitive area. This design gives considerable protection for the transducer, although not as good as the baffle single-orifice configuration, and reduces the total volume of the cavity ahead of the transducer to about the absolute minimum.

Comparison of the data from this eight-orifice probe with the data from a probe with a single orifice of about the same area with a baffle installed is shown in figure 5 for initial driven tube pressures of 106.7 Pa and 2.67 K Pa. Also included is the simplified theory for an orifice-cavity configuration. The time response to pressure for the eight-orifice probe was considerably better than the time response of the orifice-baffle probe, especially at the lower value of initial driven tube pressure. At this condition, the time response of the eight-orifice probe, with the total volume of the cavity ahead of the transducer, increased to a slightly larger value than for the single orifice-baffle configuration, was much better than the single orifice probe with baffle. For the higher value of initial driven tube pressure, the eight-orifice probe showed an initial overshoot in pressure followed by an oscillation around the theoretical value of pitot pressure being measured. This also occurred for the larger diameter orifice probe without baffle at the same condition, figure 3(f).

A comparative study was made in the Langley 6-inch expansion tube of the standard orifice-baffle probe and the eight-orifice probe without baffle. Air was used as the test and acceleration gas. Initial pressures used were those found best in reference 4, namely, 3.45 K Pa for the initial pressure of the test gas and 6.6 Pa for the initial pressure of the acceleration gas. Helium at a pressure of 34.5 M Pa was the driver gas. The approximate free stream conditions were a pressure of 1.931 K Pa and temperature of 1327 K. The conditions behind a standing normal shock were stagnation pressure of about 140 K Pa and a stagnation temperature of about 6200 K.

The experimental data for the two probes are shown in figure 6. The eight-orifice probe responds to the pitot pressure being measured within 20 microseconds, whereas the standard orifice-baffle probe responds in the time frame of 80 to 100 microseconds. This corresponds roughly to the response of the two probes in the small shock tube at the lower value of initial driven-tube pressure.

CONCLUDING REMARKS

A study has been made of the effects of pressure and of probe geometry on the time response of pitot pressure probes designed to protect the pressure transducer from damage due to impingement of flow particles. Parameters varied were the initial driven gas pressure in the shock tube, the diameter of the probe orifice, the volume of the cavity ahead of the transducer, and the conductance of the protective baffle. The experimental results were compared with a simplified theory.

The change in the time response of the pitot pressure probes as the parameters were changed was, in general, predicted by the theory. However, the simplifying assumptions in the theory did not permit accurate predictions of the actual values of the time response in many cases. As expected, the time required to respond to a step increase in pressure decreased as the orifice diameter increased and the volume of the cavity ahead of the transducer decreased. Changes in the conductance of the baffle, within the limits encountered in the present study, did not affect the time response of the pitot pressure probe. The time to respond to an increase in pressure became larger as the initial driven gas pressure was decreased.

An eight-orifice probe, designed to protect the transducer without the use of a baffle, was compared with a standard orifice-baffle probe in the small shock tube and under normal run conditions in the expansion tube. In both facilities, the response time of the eight-orifice probe was considerably smaller than the standard probe design.

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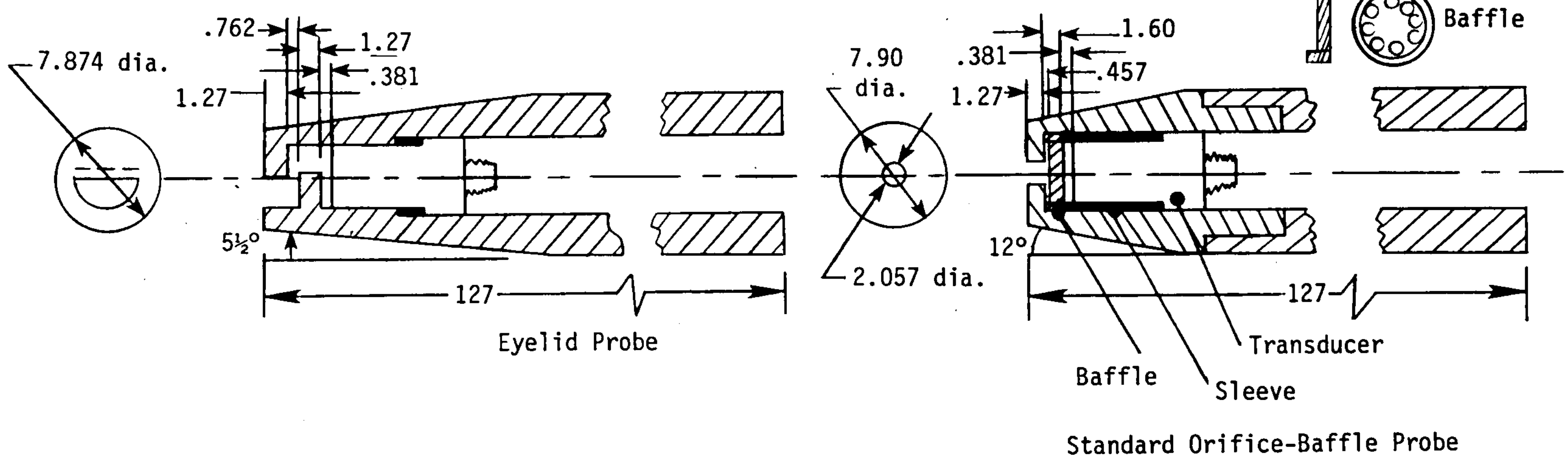
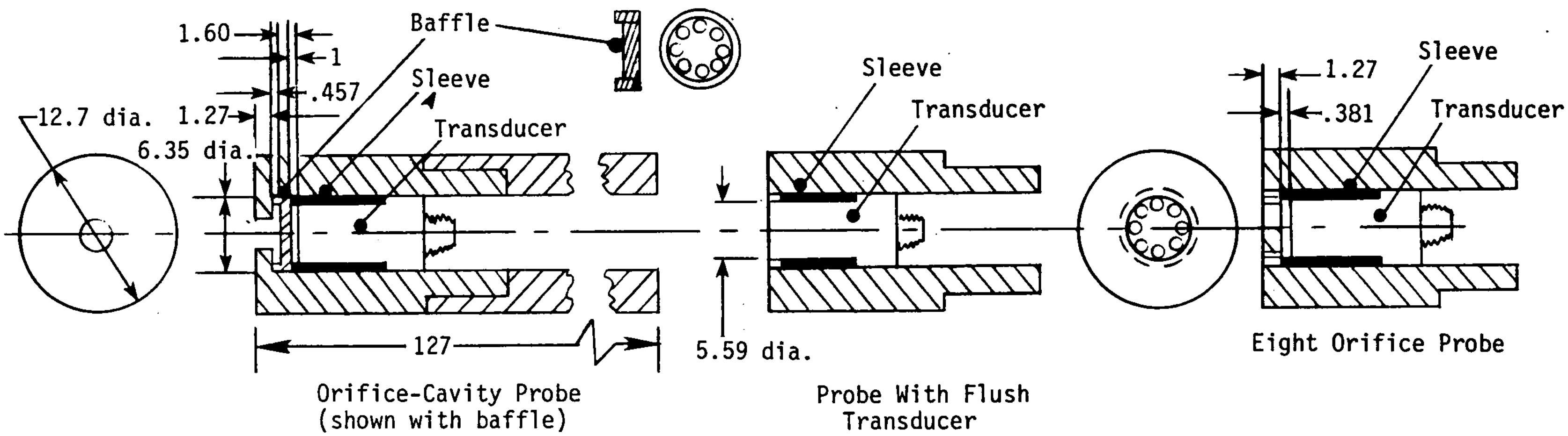
All dimensions - millimeters.



(a) Probes used in Langley 6-inch Expansion Tube.

Figure 1.- Sketches of pitot pressure probes.

All dimensions - millimeters.



(b) Probes used in present study.

Figure 1.- Concluded.

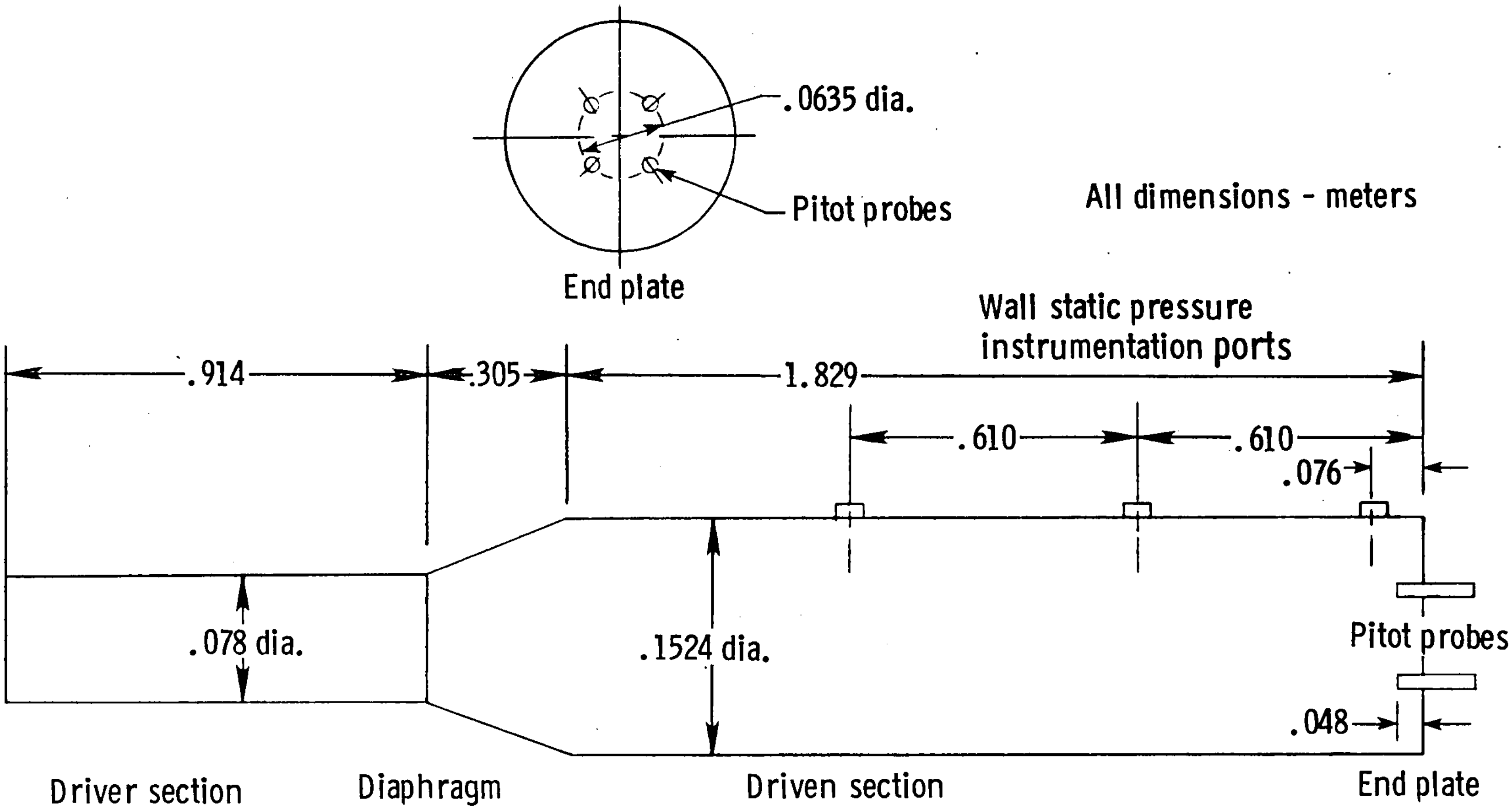
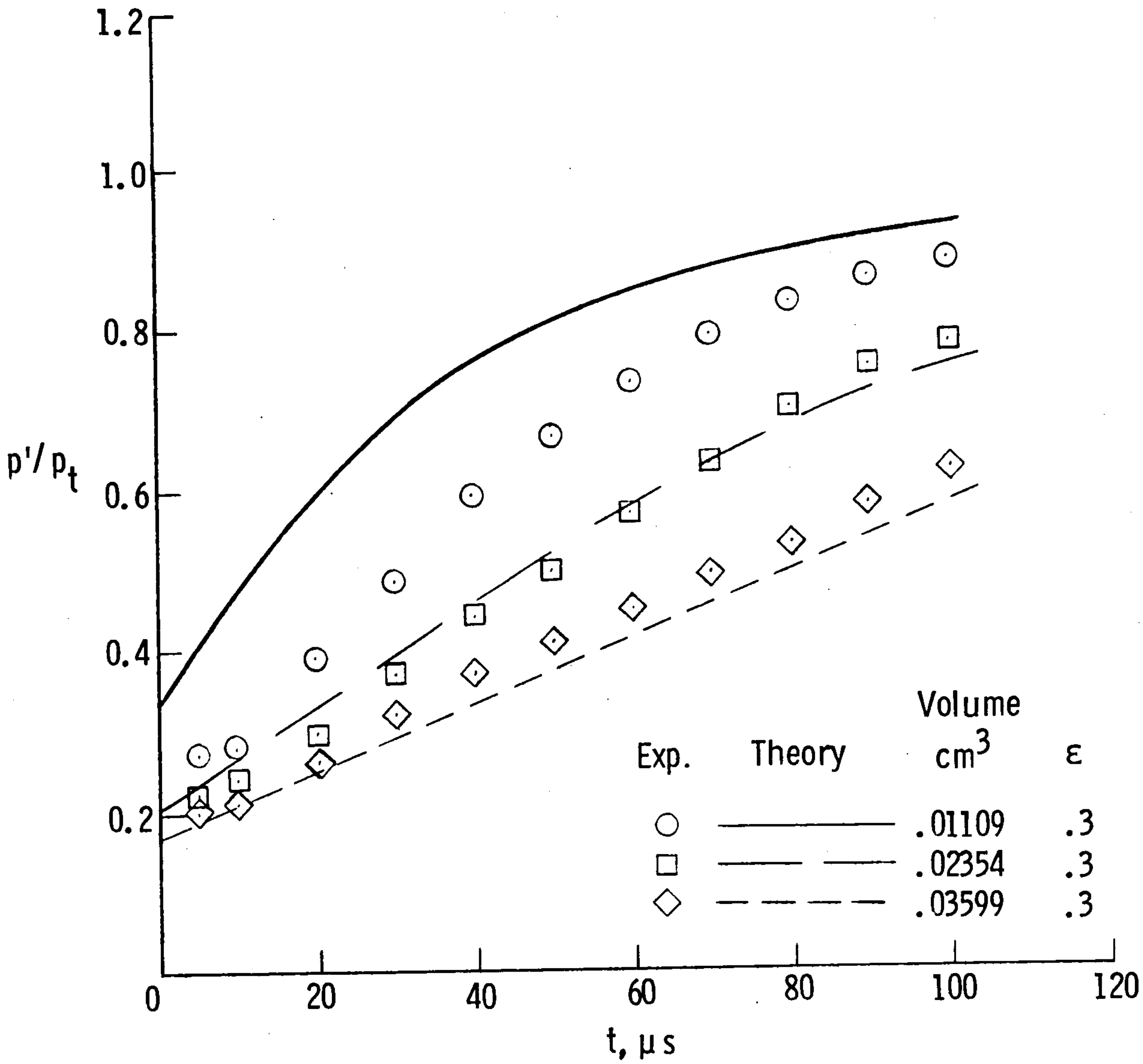
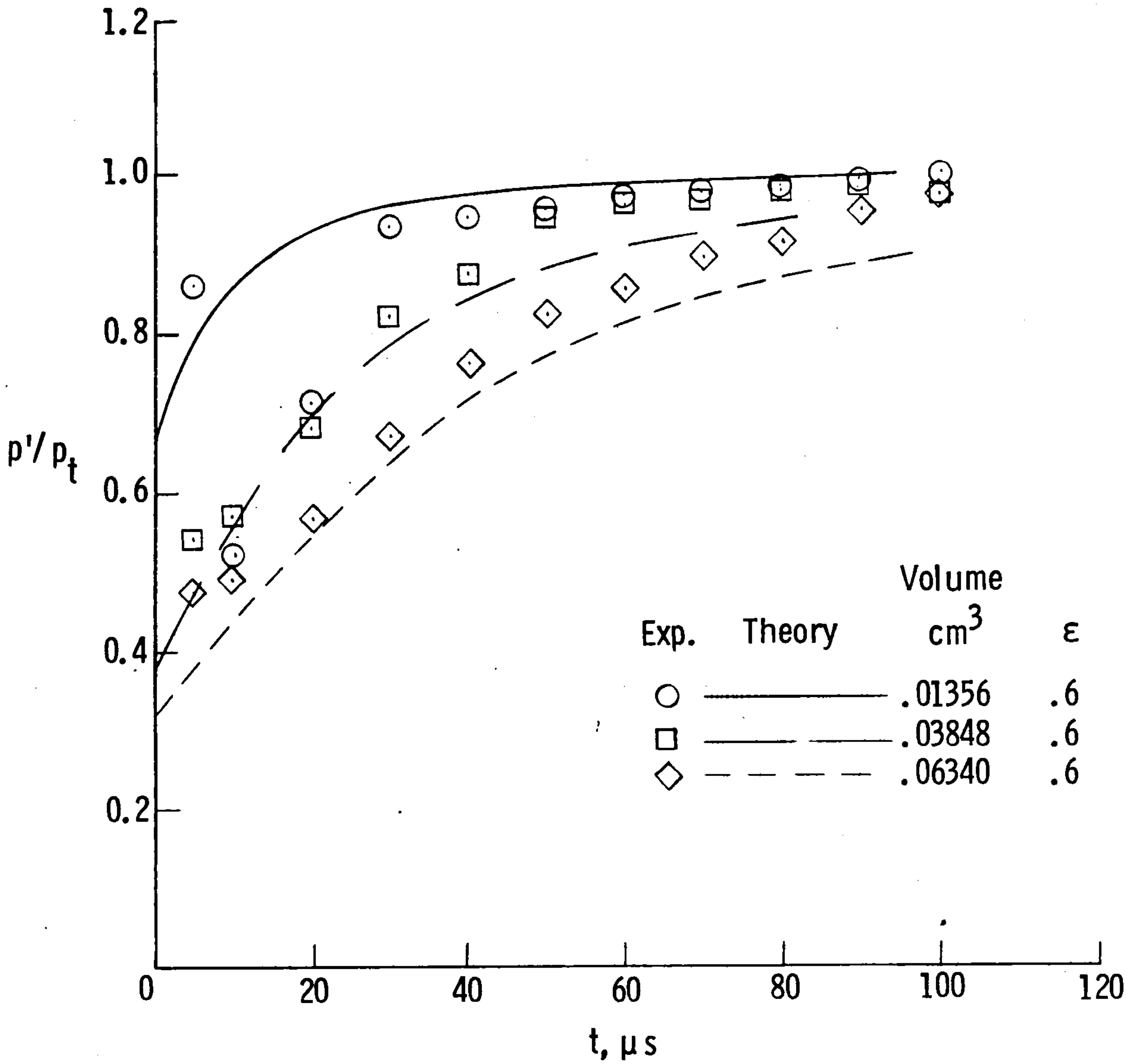


Figure 2. - Sketch of small shock tube test facility.



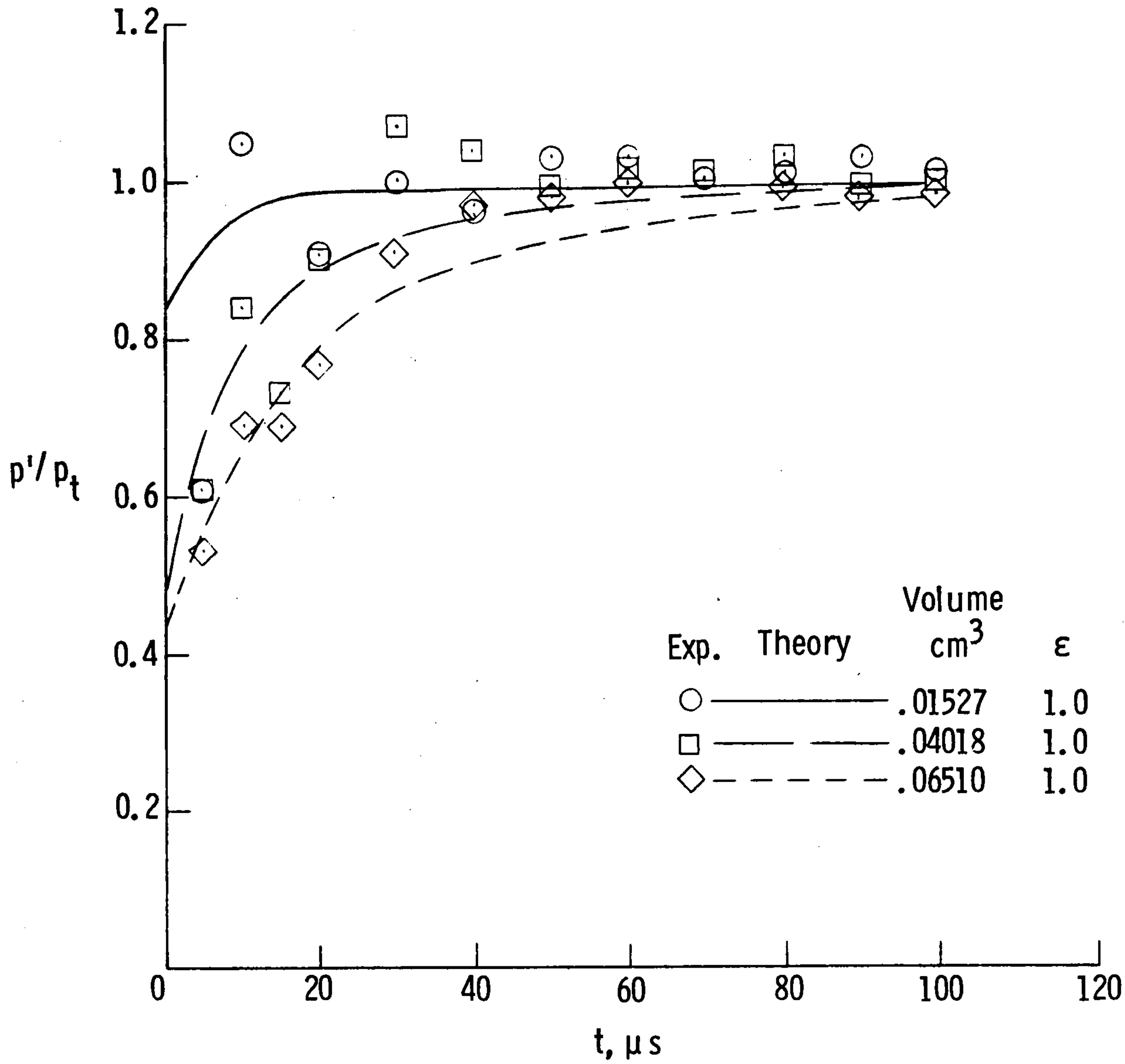
(a) Orifice diameter 1.321 mm, p_1 = 106.7 Pa.

Figure 3. - Variation of the ratio of the probe cavity pressure to total pressure with time for probes without baffles.



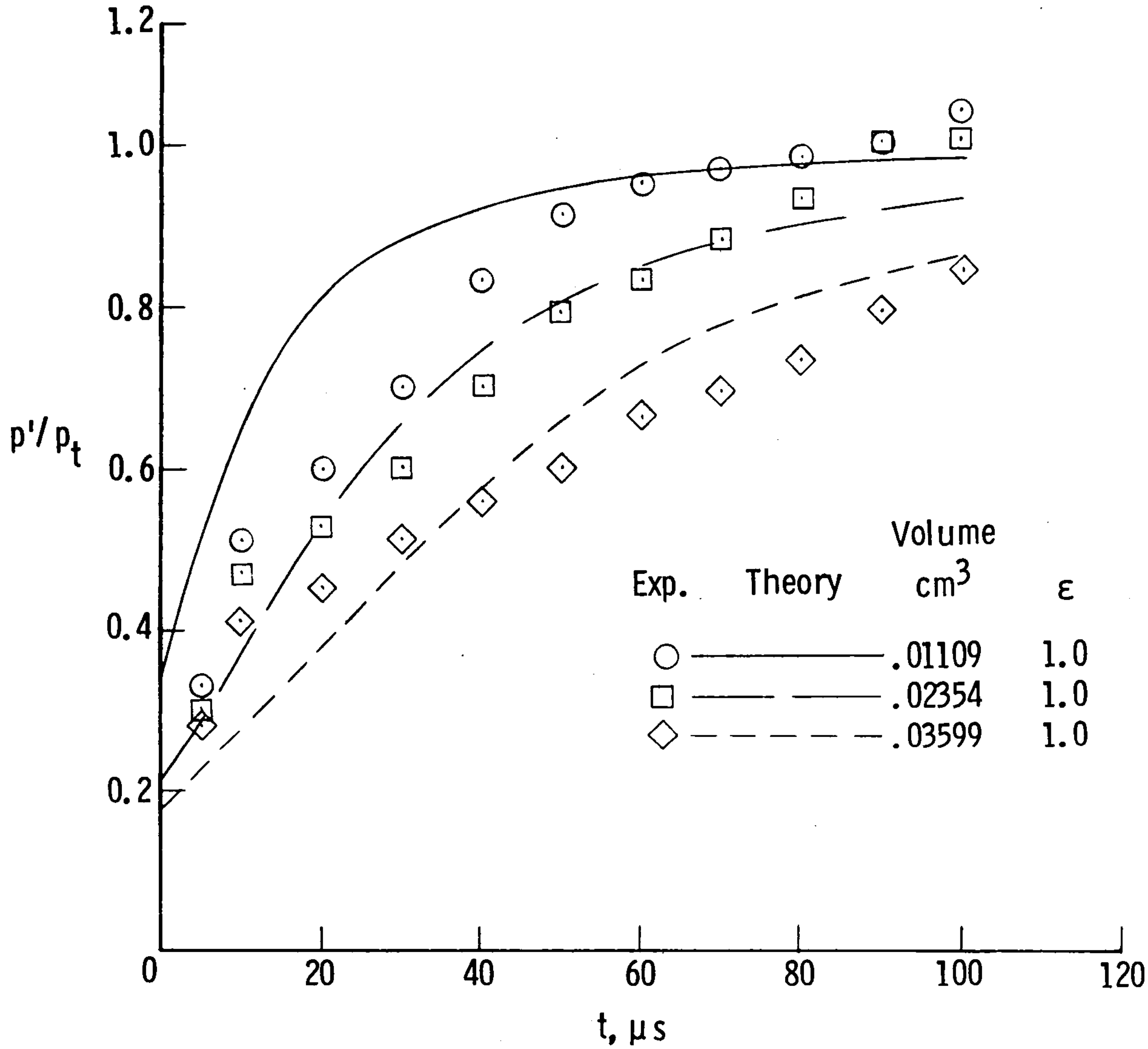
(b) Orifice diameter 2.057 mm, p_1 = 106.7 Pa.

Figure 3. - Continued.



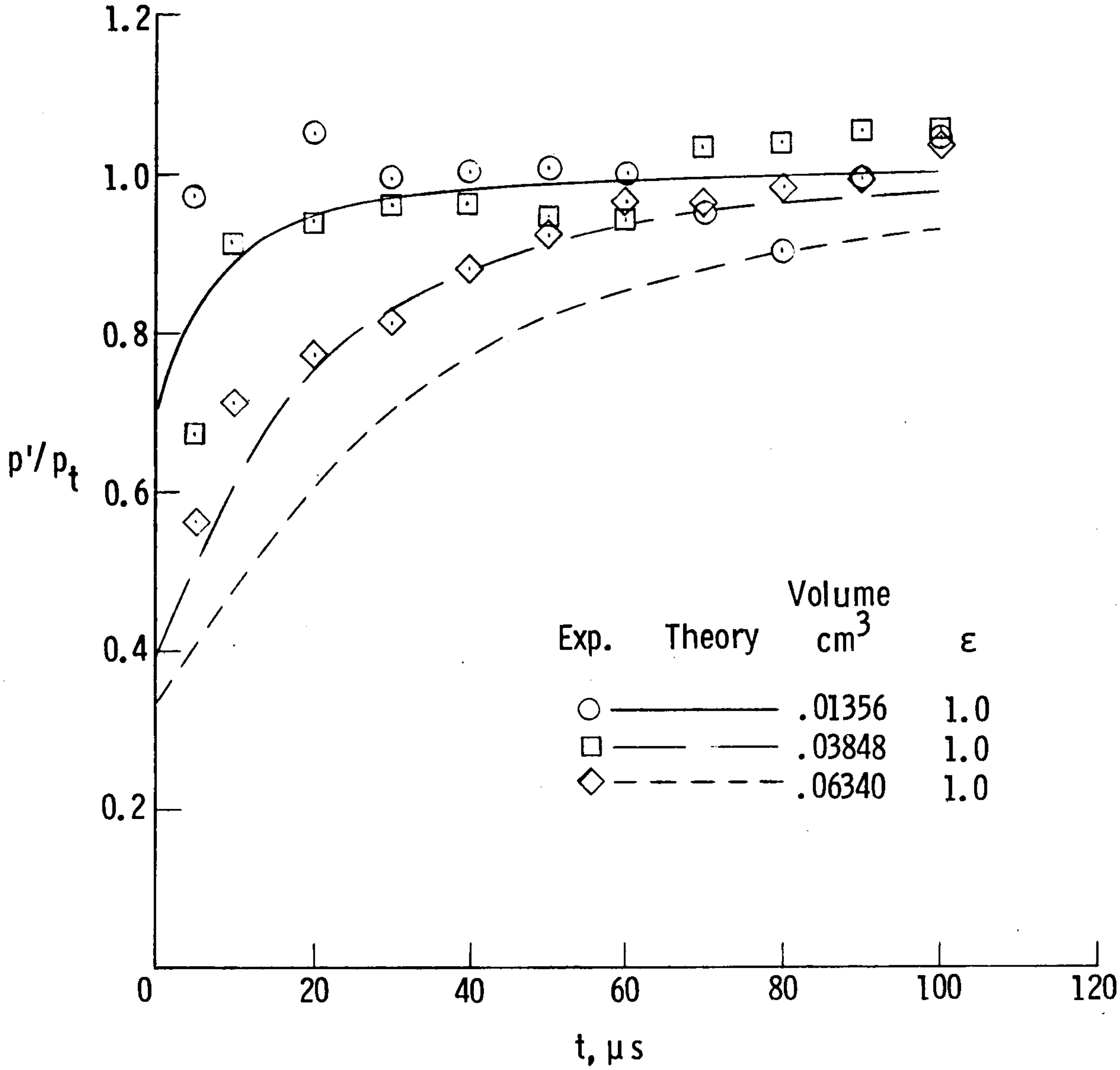
(c) Orifice diameter 2.438 mm, p_1 = 106.7 Pa.

Figure 3. - Continued.



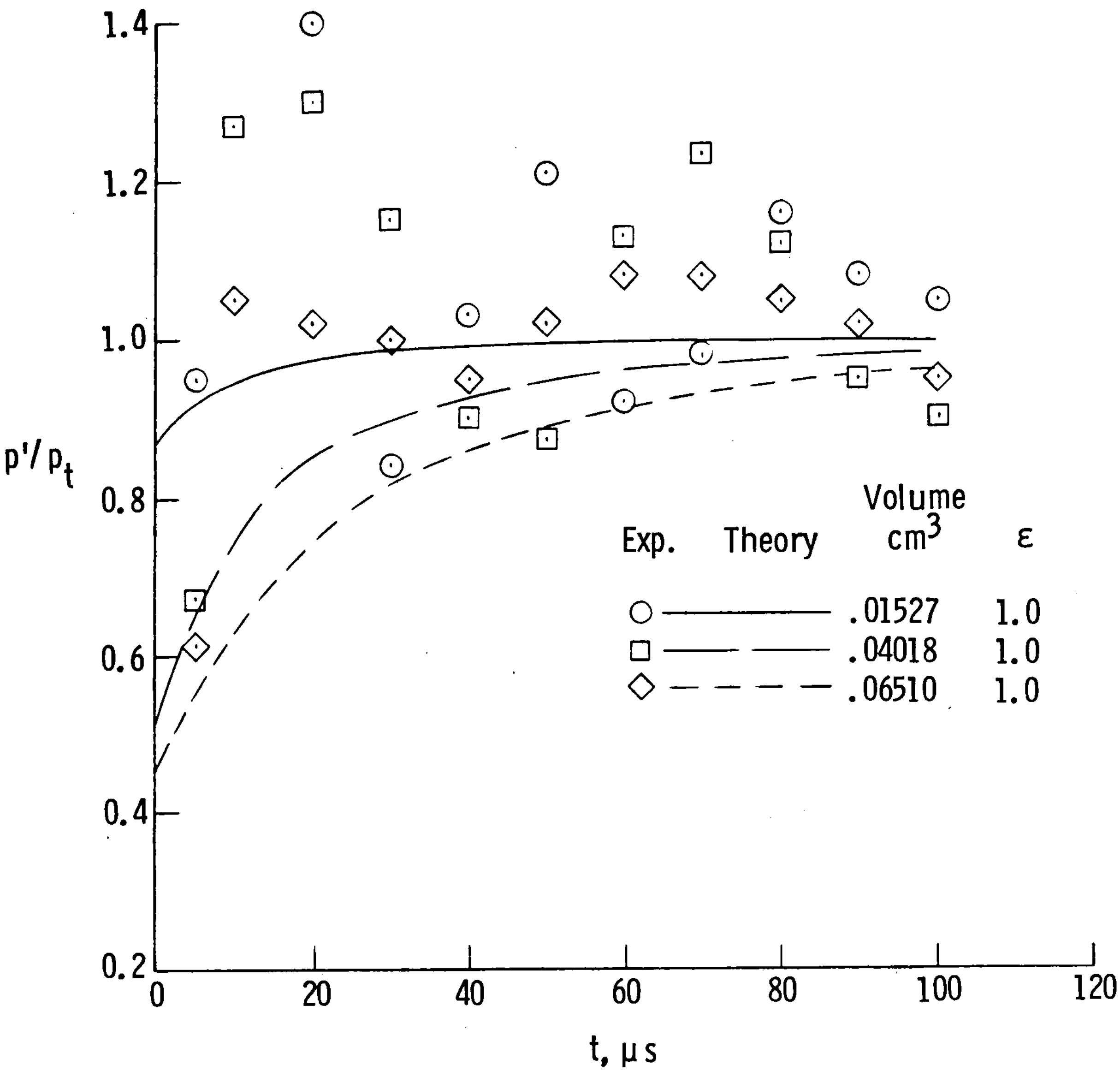
(d) Orifice diameter 1.321 mm, p_1 = 2670 Pa.

Figure 3. - Continued.



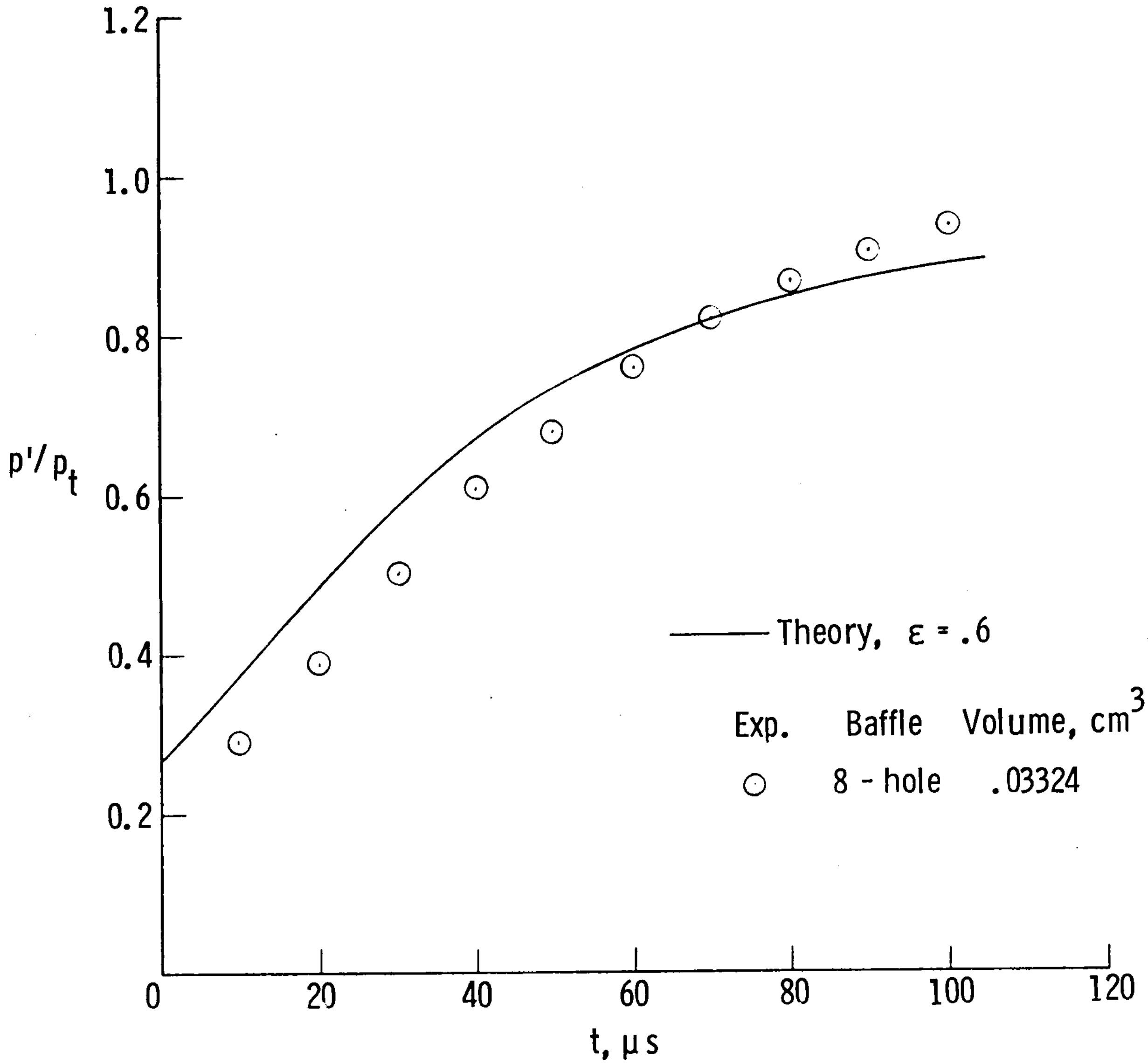
(e) Orifice diameter 2.057 mm, p_1 = 2670 Pa.

Figure 3. - Continued.



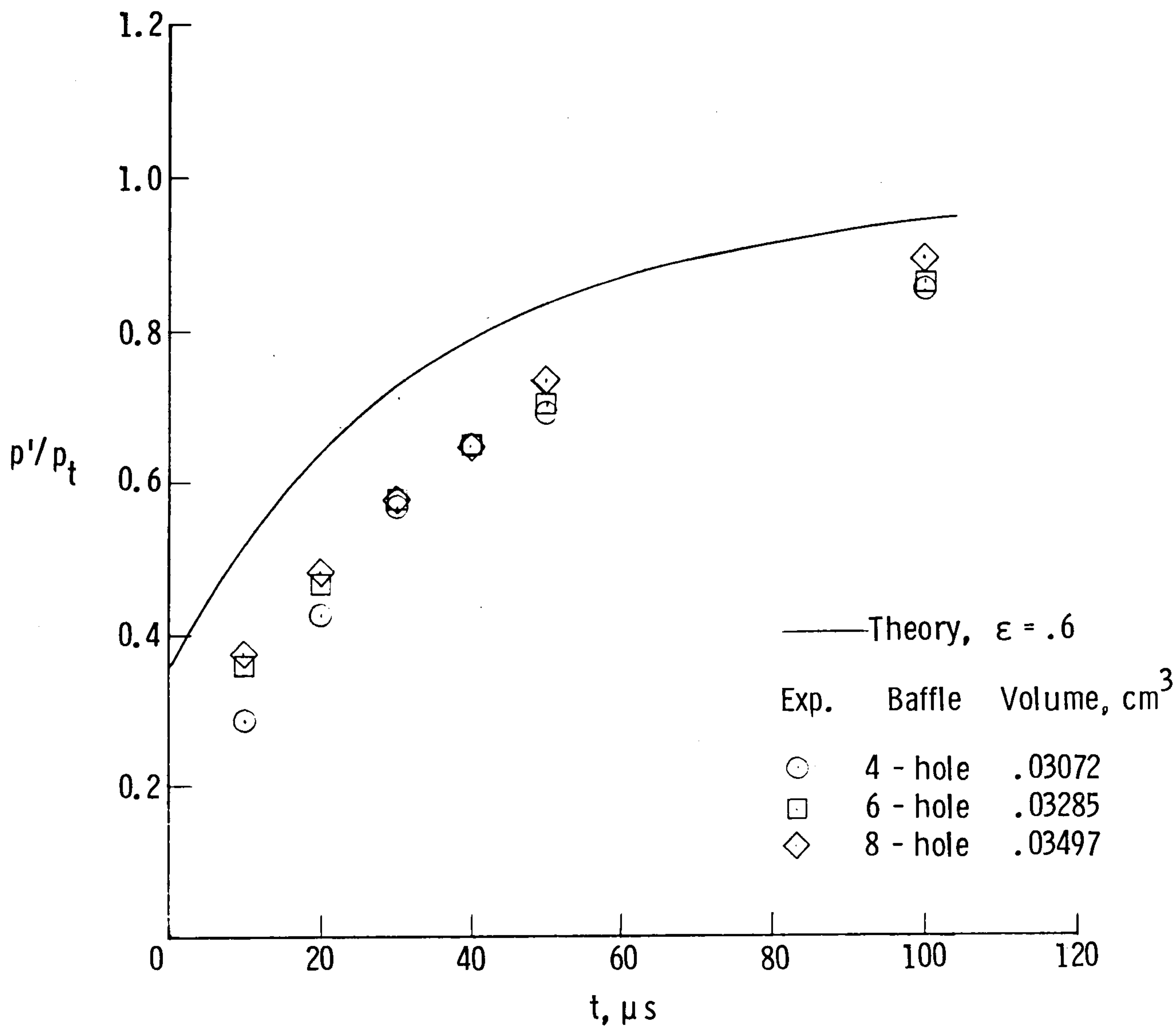
(f) Orifice diameter 2.438 mm, p_1 = 2670 Pa.

Figure 3. - Concluded.



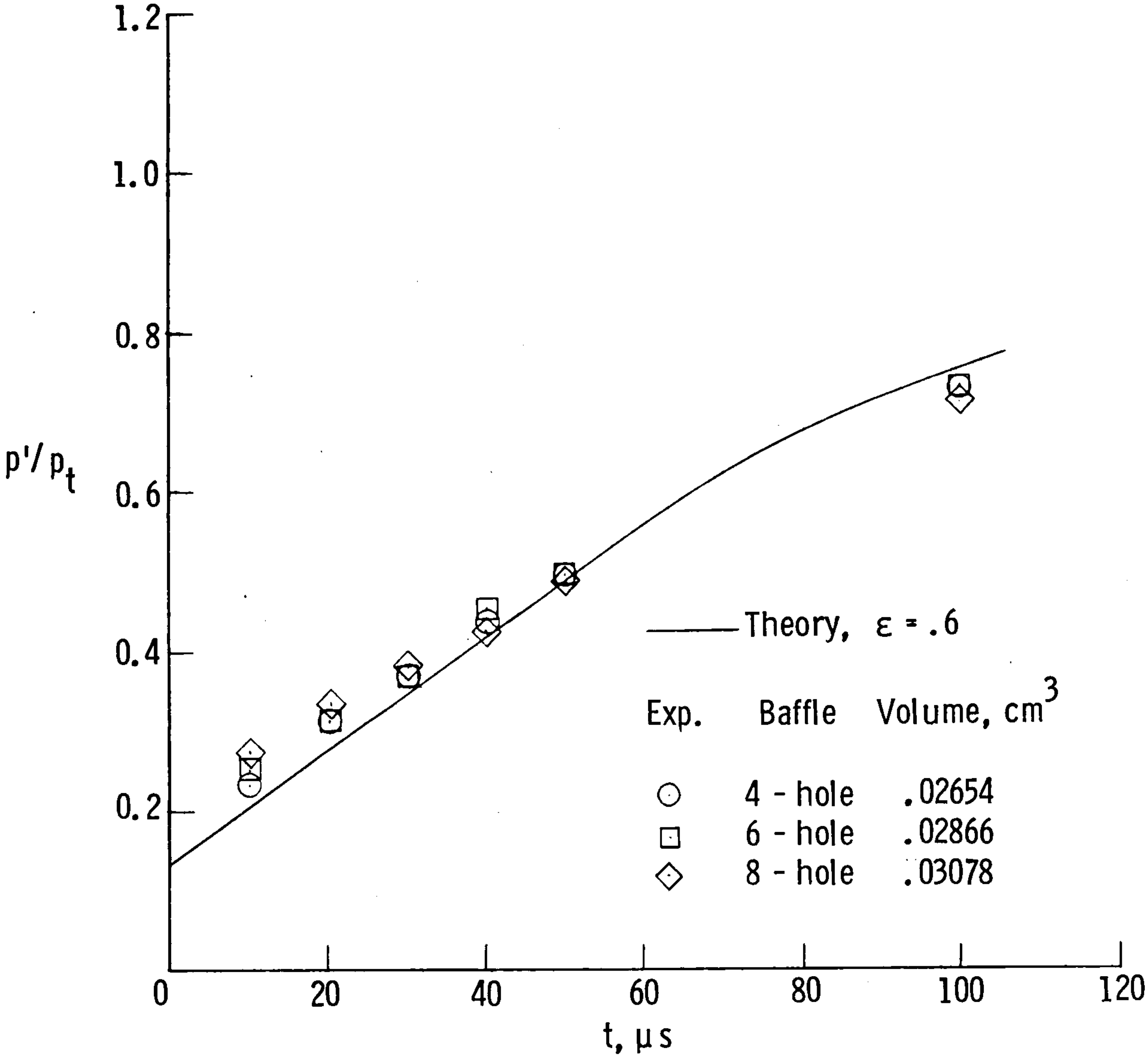
(a) Orifice diameter 2.057mm, p_1 = 106.7 Pa.

Figure 4. - Variation of the ratio of probe cavity pressure to total pressure with time for probes with baffles.



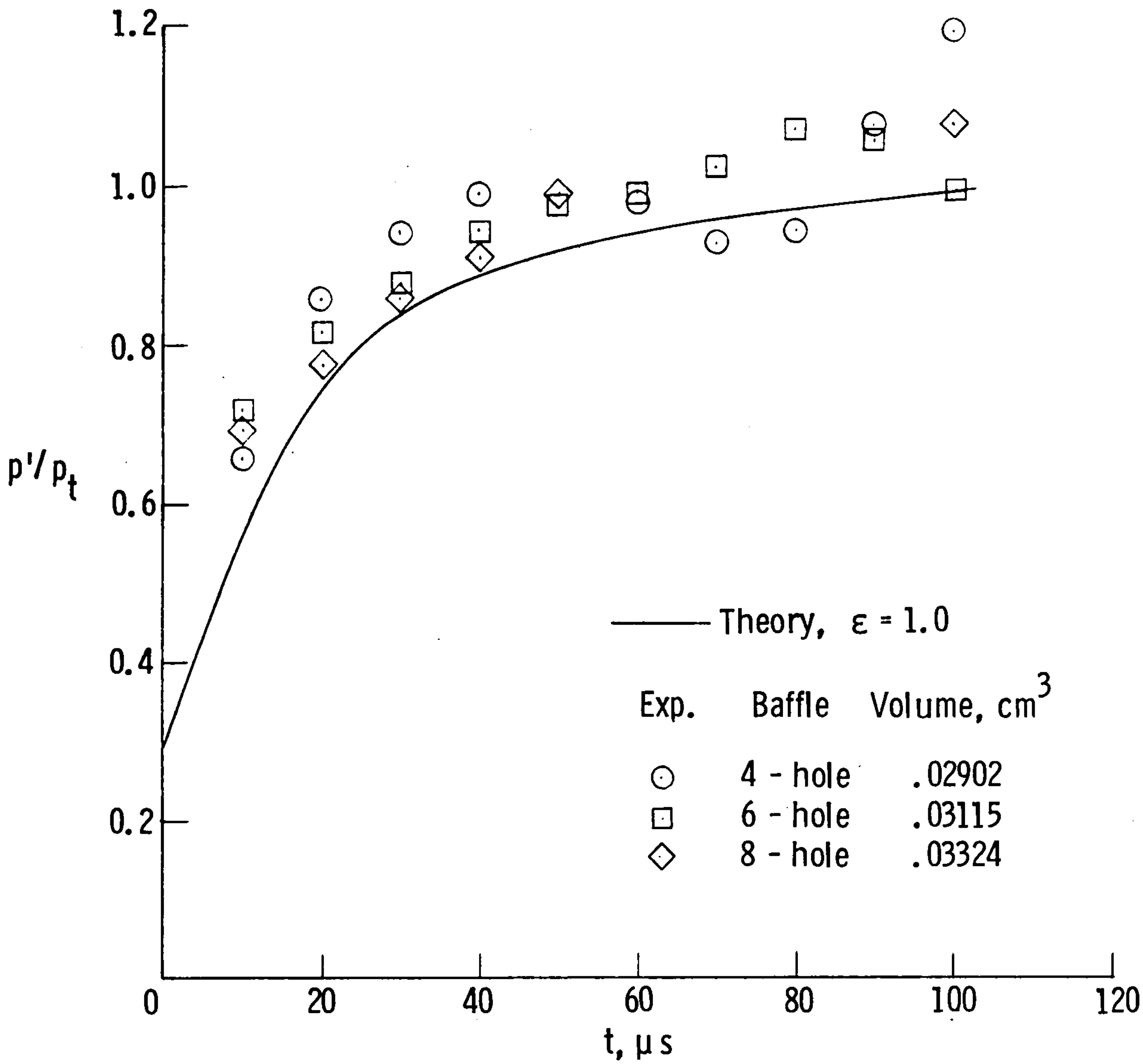
(b) Orifice diameter 2.438 mm, p_1 = 106.7 Pa.

Figure 4. - Continued.



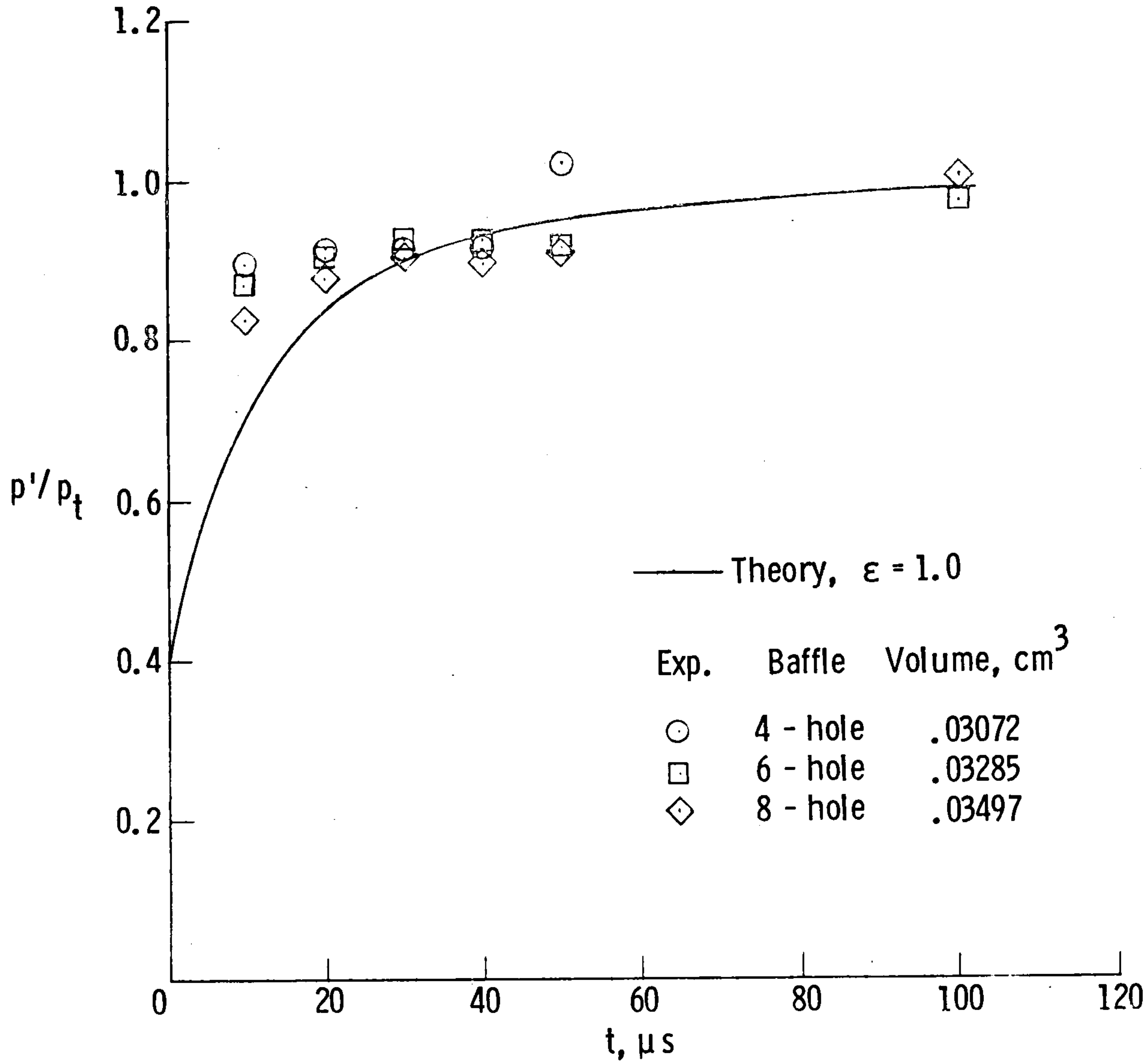
(c) Orifice diameter 1.321 mm, p_1 = 2670 Pa.

Figure 4. - Continued.



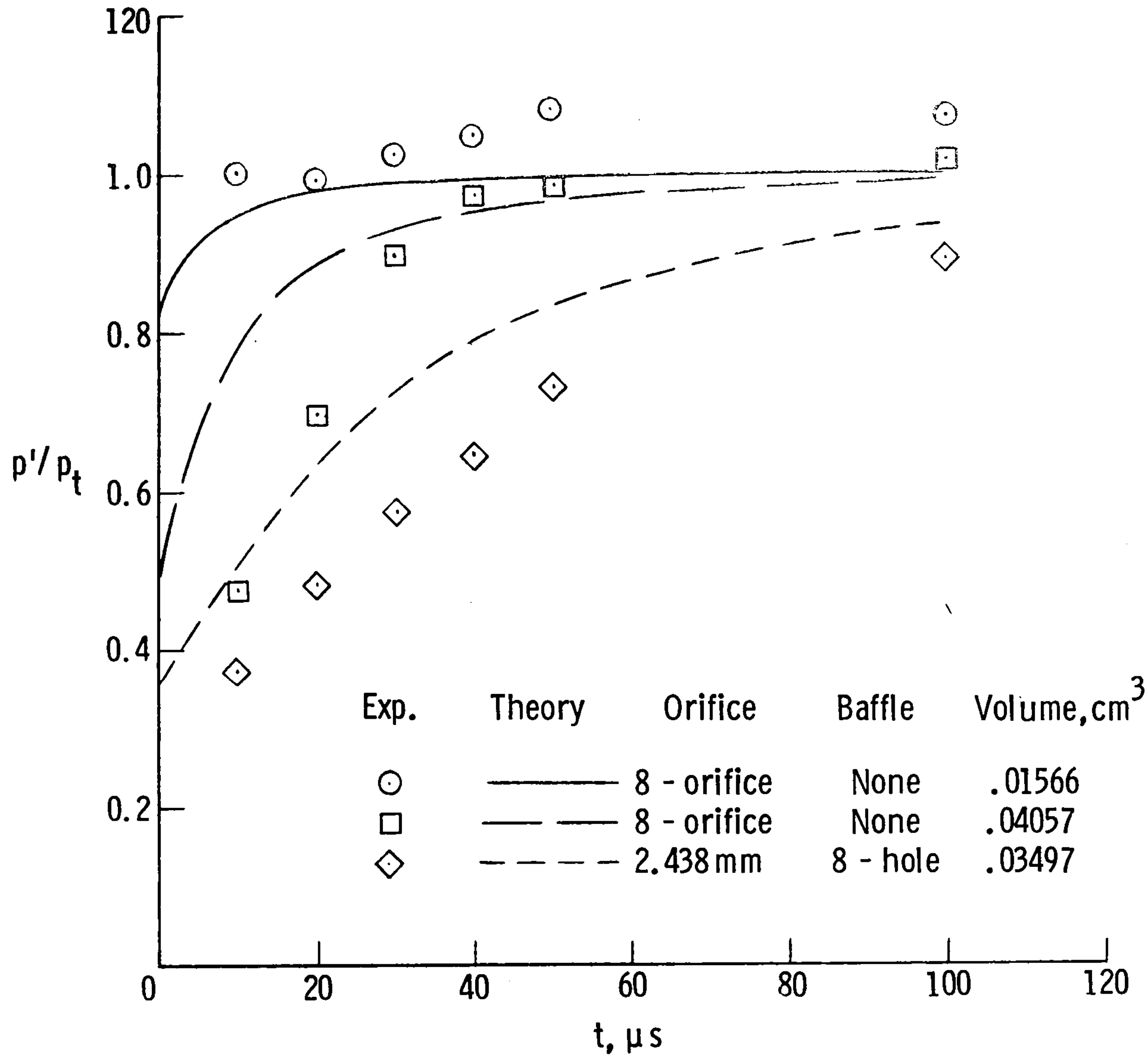
(d) Orifice diameter 2.057 mm, p_1 = 2670 Pa.

Figure 4. - Continued.



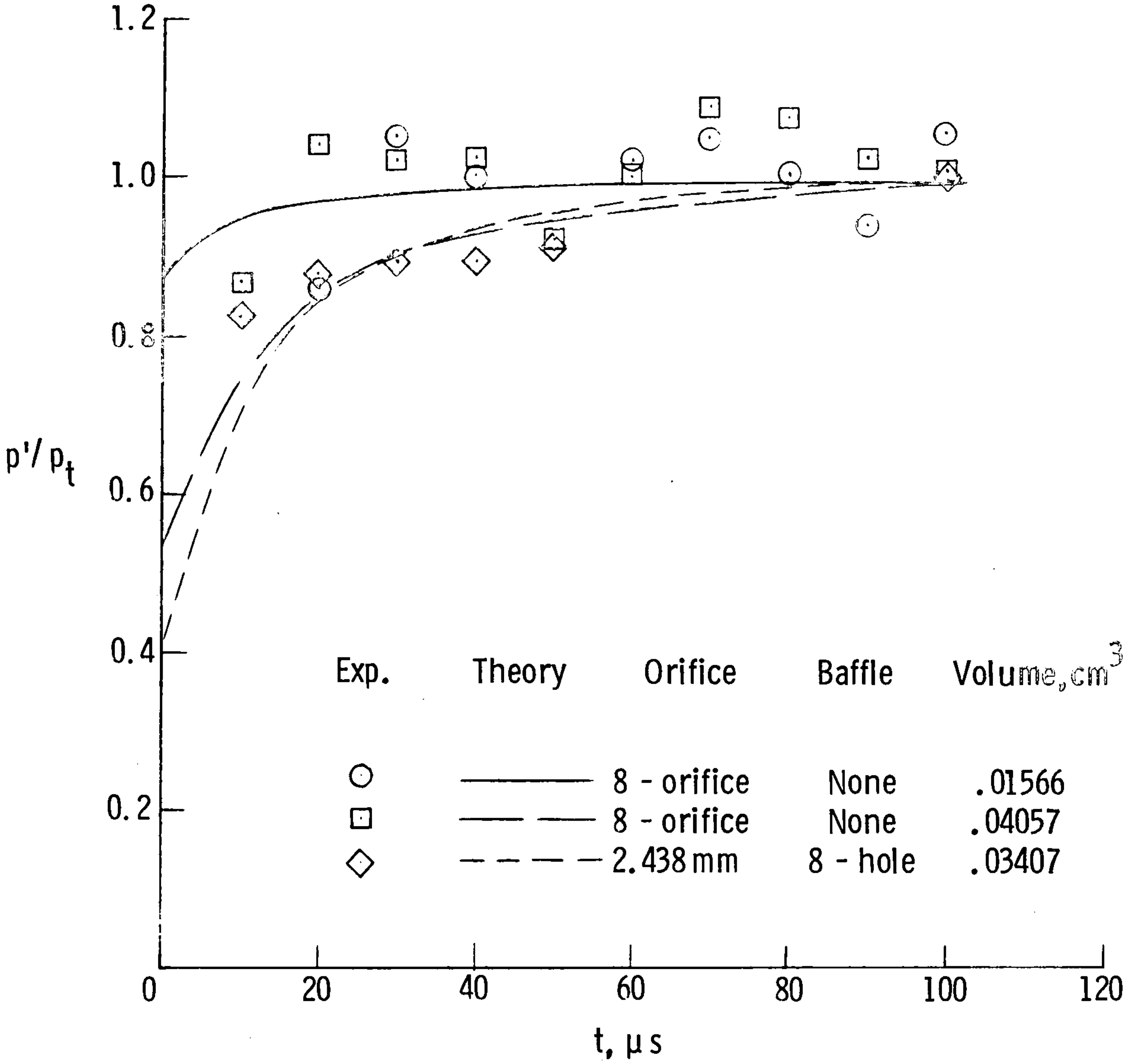
(e) Orifice diameter 2.438 mm, p_1 = 2670 Pa.

Figure 4. - Concluded.



(a) $p_1 = 106.7$ Pa.

Figure 5. - Comparison of 8 orifice probe without baffle and standard single-orifice probe with baffle.



(b) $p_1 = 2670$ Pa.

Figure 5. - Concluded.

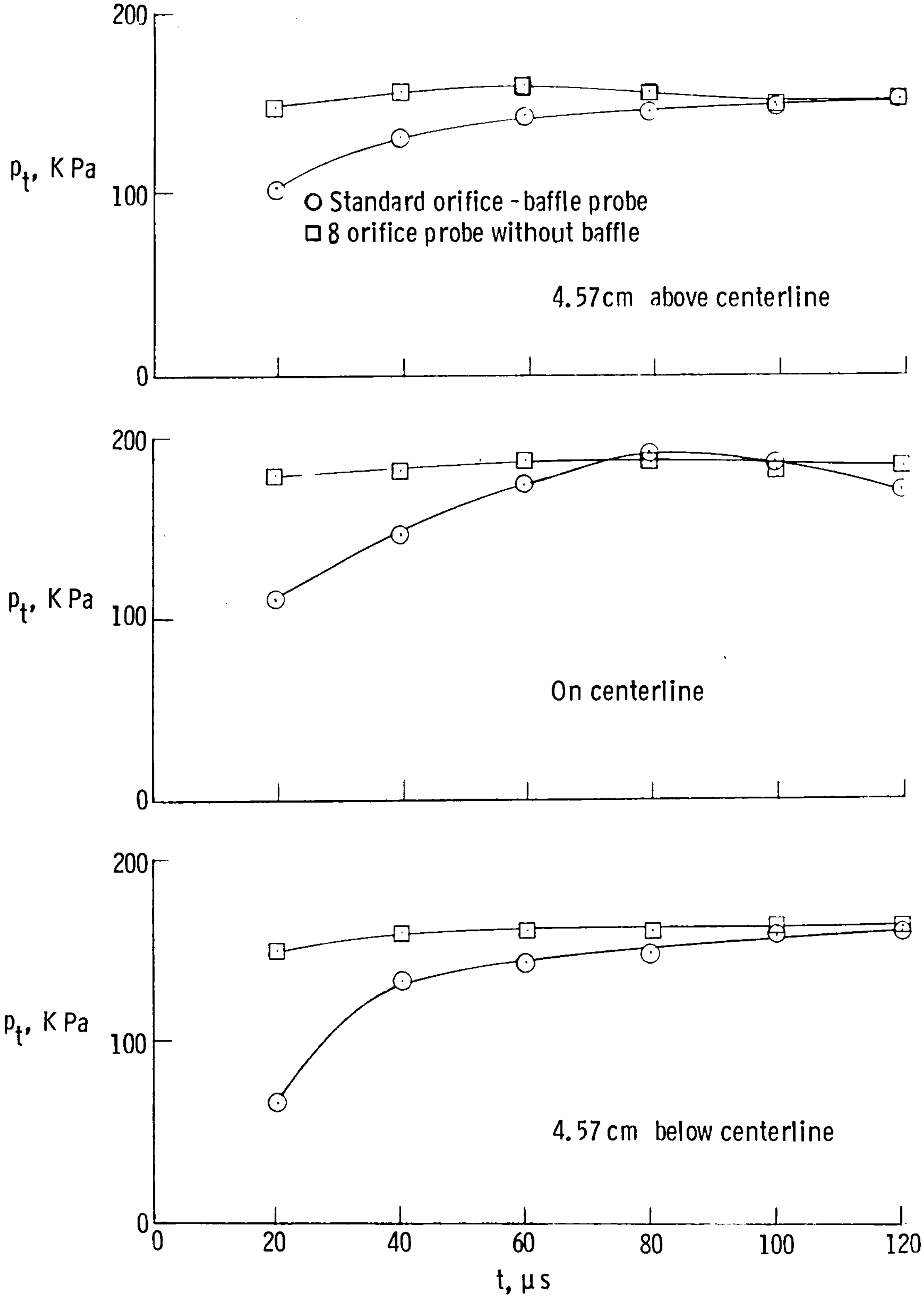


Figure 6. - Comparison of 8 orifice probe without baffle and standard single - orifice probe with baffle in the Langley 6 - inch Expansion Tube.

1. Report No. NASA TM 80091	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Study of Response Time of Pitot Pressure Probes Designed for Rapid Response and Protection of Transducer		5. Report Date May 1979
		6. Performing Organization Code
7. Author(s) J. A. Moore		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A study was made in a small shock tube of the response time of pitot pressure probes designed both for rapid response and to protect the transducer from flow-particle damage. Parameters varied were the initial driven-gas pressure in the shock tube, the pitot probe orifice diameter, the conductance of the protective baffle, and the volume of the cavity ahead of the transducer. Experimental results were compared with a simple theory.

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17. Key Words (Suggested by Author(s)) Pitot pressure probe; Shock tube instrumentation	18. Distribution Statement Unclassified - Unlimited; Subject Category: 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
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