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SUMMARY

Measurements were made to evaluate the performance of water-vapor jets in the thrust range from 5 to 200 dynes. It was found necessary to reduce the ambient pressure to less than 1 micron to obtain results applicable to a space environment. Under these conditions, the steady-state specific impulse was 58 to 65 percent of the value expected for isentropic flow regardless of nozzle size. The specific impulse measured for a train of pulses was always found to be less than that for steady thrust. For pulses lasting 1/2 to 5 seconds, the measured specific impulse was 10 to 25 percent less than the steady-state value.

INTRODUCTION

Disturbances encountered by unmanned spacecraft causing errors in attitude and in orbital position are inherently small. Analyses of jet systems for controlling attitude have shown that the mass of propellant required is minimized when the impulse delivered by the control system is sufficient to just overcome the disturbances. Control of orbital position, or station keeping, also requires very low impulses. For example, the yearly impulse for station keeping in a synchronous equatorial orbit corresponds to a change in the satellite velocity of only 2 m/sec.

The impulse imparted during a thrust pulse can be controlled by varying either the thrust level or pulse duration. If a small impulse is required, it is often advantageous to use low thrust levels, thereby avoiding the need for extremely short pulses. For low thrust levels, a condensible vapor has inherent advantages. The proper selection of a vapor can result in a low-volume, low-pressure system in which no pressure regulators are required. In contrast, a gaseous propellant requires high pressure storage with pressure regulators to reduce the pressure at the nozzles to a lower level than the storage pressure. On the other hand, the use of a condensible vapor introduces other difficulties not present when the propellant is gaseous. First, vapor pressure and, therefore, jet thrust are strongly dependent upon temperature. Second, the temperature differences within the system must be controlled to prevent condensate from collecting in the lines leading to the nozzles. Either active or passive temperature control is therefore required for vapor systems.

Water is a possible choice of a propellant for a vapor-jet system from the standpoints of specific impulse, vapor pressure, and corrosiveness. The steady-state performance of water-vapor jets was reported in reference 1.

During the course of the current study, it was discovered that the ambient pressure had an unpredictable effect on the performance of the smaller nozzles and that the ambient pressure must be 1 μ or less for the results to be applicable to the nearly perfect vacuum environment of space. The earlier experiments (ref. 1) correspond to an ambient pressure from 30 to 50 μ and, therefore cannot be extrapolated to zero pressure. For this reason, the earlier experiments were repeated and the results presented herein include the steady-state performance applicable to a space environment as well as information on the performance of the jets when operated in a pulsed mode.

NOTATION

d_T	nozzle throat diameter, cm
g	gravitational acceleration, 980 cm/sec^2
I_{sp}	specific impulse, thrust/gm/sec, sec
$I_{sp(isen)}$	specific impulse for one-dimensional isentropic flow
$\dot{m}$	mass flow rate, gm/sec
P_c	nozzle chamber pressure, dynes/cm^2
T	temperature of vapor in the vapor generator, $^\circ$C
ϵ	area ratio of nozzle, exit area divided by throat area
μ	pressure in microns, 10^{-3} mm Hg

TEST EQUIPMENT

Test equipment was designed and constructed for measuring either the steady-state or transient performance of small vapor jets. The equipment consisted of an instrument capable of measuring either total impulse or steady thrust, two thrustor units, and a vacuum chamber.

An instrument was designed for measuring the total impulse delivered to a target placed in the nozzle jet. The basic operation of the instrument is analogous to that of a ballistic galvanometer (ref. 2). The total impulse delivered to a target is measured by observing the total swing of a torsional pendulum with a known spring constant and moment of inertia. The spring constant and moment of inertia are determined by measuring the natural frequency of the pendulum for several known increments of the moment of inertia of the arm. From the dynamics of the pendulum, a relationship can be derived which gives the impulse delivered to the target on the arm; that is,

$$\text{Impulse} = \theta_{max} \frac{\sqrt{kI}}{d}$$

where

θ_{max} maximum angular deflection of the pendulum

k torsional spring constant of the suspension wire

I moment of inertia of the pendulum arm

d distance from the center of suspension to the center of the target

This relationship is exact for pulses of zero duration; for pulses of finite duration, little error is introduced, provided the pulse is short relative to the period of the pendulum. To permit accurate measurement for pulses of up to 5 seconds duration the pendulum period was varied from 10 to 60 seconds by changing the moment of inertia.

Figure 1 is a photograph of the instrument. The relationship given above for determining the total impulse requires that the initial swing of the torsional pendulum be undamped. After the maximum amplitude was reached, the damping coils shown in the photograph were energized to critically damp the return motion of the pendulum.

Maintaining sufficient sensitivity to measure small total impulse required that the spring constant and moment of inertia of the rotating member be small. Both of these requirements precluded placing a thrustor on the rotating arm. It was necessary, therefore, to use an indirect technique in which the force of the nozzle jet was measured as it impinged on a target mounted on the rotating member (see fig. 1). A relationship between the thrust of the jet and the force it exerts when impinging on the target is therefore needed. The establishment of this relationship required that the instrument be operated to measure steady-state force either with a thrustor mounted on the arm as in figure 2 or with the thrustor attached to the vacuum tank closure plate as in figure 1, for then the force on the target could be calibrated against the reaction thrust. For either steady-state measurement, the jet force was opposed by the force transducer shown in figure 2. This transducer consisted of a permanent magnet within a direct current solenoid. The transducer was calibrated with dead weights.

For the steady-state measurement the thrustor had to be light, so that it could be mounted on the balance arm without breaking the suspension wire (see fig. 2). A small unit with a low propellant capacity and a minimum of instrumentation was built to satisfy this requirement. A larger unit, with additional features and vapor capacity, was constructed for measuring the transient performance during pulsed-mode operation when the jet impinges on the target (see fig. 1). In each thrustor, the water was absorbed into cellulose sponges, arranged to provide sufficient area from which evaporation could take place. The jet was controlled by a soft-seated, normally closed solenoid valve that was actuated by 8 to 10 W. Once the valve was open, it remained open until the power was reduced to less than 1/2 W. This permitted the heat delivered to the nozzle region to be regulated between 1/2 and 10 W for steady-state operation. The temperature of the vapor generator portion of each thrustor was controlled with heating coils wrapped around the outside of the units. Temperature was measured by a thermistor mounted so that it would determine the temperature of the vapor. When a separate pressure measurement was not made, pressure was inferred from the unique temperature-pressure relationship for saturated vapors.

Several additional features were available in the larger thrustor. This thrustor consisted of two main parts -- a plenum chamber and a vapor supply chamber. For continuous thrusting, unrestricted flow was permitted from the vapor generator to the plenum chamber. To investigate pulse shaping, the flow between the vapor generator and plenum was constricted by an orifice (see fig. 3). Also, provision was made for manually adjusting the plenum volume. The pulse shape could then be varied by changing the plenum volume and orifice size. Pressure time histories during a thrust pulse were obtained from a pressure cell. This cell could be located to measure the pressure in the plenum as illustrated in figure 3 or between the valve and nozzle as shown in figure 1.

Four flat-faced convergent-divergent nozzles and one sharp-edged orifice were machined (see fig. 4). The nozzles had been designed with an expansion ratio of 100, an entrance cone angle of 60°, and an exit cone angle of 30°. The nozzle with sharp edges on the exit cone was machined to match the dimensions of one of the flat-faced nozzles. After the machining process, the inside dimensions of all nozzles were measured with a microscope. The dimensions varied slightly from those that had been specified and resulted in different area ratios (fig. 4).

The balance and the various thrustors were operated in a small vacuum-chamber and bell-jar combination that permitted the balance deflections to be observed visually. A mechanical pump and a diffusion pump were used to evacuate the stainless steel vacuum tank containing the apparatus. Ambient pressure in the vacuum tank was measured either with a thermocouple gage or an ion gage. The ambient pressure was kept below 1 μ for all experiments intended to simulate a vacuum environment. A liquid nitrogen cold trap was used to maintain pressures below 1 μ during continuous thrusting periods.

RESULTS AND DISCUSSION

Ideal Nozzle Performance

One-dimensional isentropic flow is a convenient standard for comparing nozzle performance. Well-designed nozzles of the size usually used in rockets or turbines approach this performance within a few percent. For calculating the ideal performance of the nozzles of this study, the fluid entering the nozzle is assumed to be dry steam. As the vapor is expanded through the nozzle, first some liquid phase will be formed and entrained in the stream. As the pressure falls below the triple point, the solid phase will be formed. For calculating the ideal specific impulse, at any given point in the expansion, all phases present were assumed to be at the same temperature. This cannot occur physically since insufficient time is available for heat to be transferred from the liquid or solid phases as the expansion proceeds. An alternative assumption, representing the opposite extreme, is that the liquid and solid phases remain at the temperature at which they were formed as the gas about them cools during the expansion. Neither of the two assumptions is realistic, but the difference in the calculated performance based on either assumption is only a few percent. The ideal specific impulse based on the isentropic expansion assumption and the geometric area ratio is shown in figure 4 for each of the test nozzles.

There are several reasons for expecting that the measured performance will not approach the ideal. By definition, one-dimensional isentropic flow does not consider the effects of viscosity. For nozzles of the size of interest, the effects of viscosity might be expected to reduce the performance from the ideal value. Performance will also be reduced if the liquid phase is present in the fluid entering the nozzle. Liquid will be present if the passages leading to the nozzle are cooler than the vapor generator where the steam is formed. An estimate given in reference 1 showed that if the fluid entering the nozzle is 20 percent water the specific impulse will be reduced by about 10 percent.

Measured Steady-State Performance

The measured steady-state thrusts for the various nozzles are shown in figure 5(a) and the corresponding mass flow rates are shown in figure 5(b). The vapor temperature range for these results was between 18° and 38° C. The heat input to the valve was always sufficient to keep the valve and nozzle region at a temperature sufficiently greater than the rest of the thrustor unit to insure that no condensed fluid entered the nozzle. The thrust and mass flow rate were assumed to vary as $(\text{pressure})^n$ and the best fit, in the least squares sense, to the results was found. The curves of $I_{sp}/I_{sp(isen)}$ versus thrust in figure 6 have been calculated from the least squares fit data of figures 5(a) and 5(b). The specific impulse was normalized to theoretical specific impulse for isentropic flow to account for differences in area ratio. The ratio of $I_{sp}/I_{sp(isen)}$, generally, increased from about 0.58 to 0.65 as the thrust increased over the range recorded for each nozzle tested (fig. 6). These results fall in the same band as the results reported by R. John and A. Jonath (refs. 3 and 4) for nozzles that use ammonia as a propellant.

The nozzles tested were nearly identical to those described in NASA TN D-1302 (ref. 1) and it was therefore anticipated that the steady-state results would match the earlier work. This, however, was not the case since the earlier results indicated the specific impulse tends toward zero as the thrust level is decreased. The discrepancy between the two sets of results was traced to a difference in the ambient pressure in the test chamber. The ambient pressure of the current tests was 1 μ or less, in contrast to 30 to 50 μ for earlier tests. The effect of this ambient pressure difference on measured thrust is illustrated in figure 7. Note that, for each nozzle, the thrust increases by about 15 dynes as the pressure is decreased from about 10 to 1 μ and appears to remain nearly constant with further reduction in ambient pressure. Some increase in thrust with decreasing pressure is to be expected because of the reduction in ambient pressure force over the nozzle exit. However, this force is small compared to the measured thrust increase. For instance, the ambient pressure force is only about 2 dynes at an ambient pressure of 10 μ for the larger of the two nozzles for which results are presented in figure 7. The increase in thrust with decreasing pressure causes a corresponding increase in specific impulse since the mass-flow rate does not vary with changes in ambient pressure below 50 μ (see fig. 5(b)). The increase in specific impulse becomes greater as the nozzle throat diameter is reduced since the additional thrust becomes a greater part of the total.

The increase in thrust with decreasing ambient pressure was observed when the indirect measurement technique was used as well as when the thrustor was mounted directly on the balance arm. It was established that the thrust increase was attributable to the thrust of the jet and not to spurious forces on the balance arm induced by operation of the jet within the vacuum chamber. To verify the absence of spurious forces the thrustor was mounted in various positions with the jet directed away from the target. When this was done, the jet caused no deviation of the balance arm from the null position, regardless of ambient pressure level.

Subsequent tests established that the thrust increases with decreasing ambient pressure for orifices as well as for convergent-divergent nozzles (see fig. 8). This fact led to the suggestion that the peculiar variation of thrust with ambient pressure might be related to desorption of a film of vapor from the flat surface that surrounds the exits of both the nozzles and the orifice. This explanation was disproved by testing the sharp-edged nozzle shown in figure 4. In this instance, the same variation of thrust with ambient pressure was observed as for the flat-faced nozzles.

Measured Transient Performance

The specific impulse obtainable under steady-state conditions was found to fall in a band between 58 and 65 percent of theoretical $I_{sp(isen)}$ regardless of nozzle size. Whether the specific impulse remained the same under pulse mode operation required further investigation.

The tests to study the operation of the jet in a pulsed mode required that the force exerted by the jet upon a target be related to nozzle thrust. Several experiments were made to observe the effect of target size and nozzle-to-target distance on the force on the target. For a 5 cm diameter target, there was a region of nozzle-to-target distance between 1.3 and 1.8 cm over which the force on the target was constant. With this spacing, the ratio of target thrust to nozzle thrust was about 1.4 for all nozzles tested (see fig. 9).

Once the target calibration factor was established, the total impulse from the thrustor was obtained from the maximum deflection of the pendulum. Figure 10 shows that these measurements agree quite well with the total impulse calculated from the time history of the nozzle chamber pressures and the average thrust coefficient (determined from the steady-state measurement with the assumption that the thrust coefficient is independent of the upstream pressure). The total impulse was calculated from the time history of the nozzle chamber pressures as follows:

$$\text{Impulse} = \int A_t P_c C_f \, dt$$

where

A_t nozzle throat area

P_c measured nozzle chamber pressure

C_f average steady-state thrust coefficient determined for each nozzle from the data of figure 5(a), $\frac{\text{thrust}}{A_t P_c}$

The specific impulse of several of the nozzles when operated in the pulsed mode was determined. For these tests the time between pulses was kept constant at 20 seconds while the pulse duration was varied from 1/2 to 5 seconds. The equipment was operated over a sufficient time interval to expend enough propellant to permit measurement of the mass loss. Individual pulses were monitored from time to time to measure total impulse per pulse. The only variations observed in the pulse were those which would be anticipated because of small deviations from the desired temperature of the vapor generator. The results of the measurements are shown in figure 11. For each nozzle the scatter of the test points, which was traced to the mass flow measurement, is roughly 10 percent of the theoretical specific impulse. The results indicated that specific impulse is reduced from 10 to 25 percent from the steady-state value for pulse durations of from 1/2 to 5 seconds.

Throughout the tests there was no condensation to interfere with performance because the temperature in the region of the nozzle was always higher than that of the vapor generator. The source of heat was the power for operating the valve. This situation was purposely reversed by heating the vapor generator, thereby raising the temperature and pressure of the vapor. Hence, as the temperature difference progressively decreased between the vapor generator and a point near the entrance to the passage leading to the nozzle (see fig. 3), the thrust level produced by the nozzle increased. Attention, however, should be focused on the character of the decay of thrust following the closure of the valve (see fig. 12). When the measured temperature difference was 1.1° C or greater, the thrust decayed rapidly immediately upon closure of the valve. As the temperature difference was decreased, the decay to zero pressure was delayed. This delay became more pronounced as the temperature difference was decreased to 0.4° C. In some of the records (not shown here) it appeared that the valve failed to close for a period of time after it was de-energized. For these cases it is surmised that the poppet was held open by ice crystals. It is inferred from these results that the observed effects on pulse shape resulted from vapor condensing in the passage leading to the nozzle. The consequences of condensation are obvious. First, the specific impulse will decrease. Second, and perhaps more important, a timed pulse will no longer yield the desired impulse.

The feasibility of shaping the pulse was investigated briefly. Pulse shaping has been proposed by R. S. Gaylord (ref. 5) as a method of damping for "on-off" type space vehicle attitude control systems that employ fixed switching boundaries that depend on attitude alone. The best pulse shape for damping "on-off" systems is an ideal impulse of zero duration followed by a steady low-level thrust. In the absence of switching hysteresis, the impulsive decrease in angular velocity of the vehicle will determine the velocity reduction per cycle and the lower limit of angular velocity likely to be attained. The level of the estimated external torques on the controlled spacecraft will determine the low-level thrust requirement. The use of shaped pulses, therefore, affords a method by which the angular rate of a spacecraft can be decreased without resorting to sensitive rate measuring equipment or other logic elements commonly used in the mechanization of "on-off" type control systems.

The desired pulse shape can be approached by constricting the flow into a chamber that lies between the valve and vapor generator (see fig. 3). When the valve opens, the initial thrust is determined by the static pressure within the system. The rate at which thrust decays is governed by the chamber volume and the ratio of the diameters of nozzle throat and of the orifice that constricts the flow into the chamber. For the experiment, the chamber was made as small as possible. Its volume was mostly that of the line leading to the pressure transducer (see fig. 3).

The largest ratio of nozzle throat diameter to orifice size yielded a ratio of initial to final thrust of approximately 40 (see fig. 13). The values of thrust plotted in figure 13 were calculated from plenum pressure measurements combined with an average value of thrust coefficient and the known throat area of the nozzle. The time constant (time to 1/3 of initial value) of the decay of the initial thrust was about 1/2 second for the two smallest orifices. No difficulty was encountered in repeating any of the pulse shapes shown.

CONCLUSIONS

Measurements to evaluate the performance of water-vapor jets, for nozzles in the thrust range from 5 to 200 dynes, indicate the following:

1. Ambient pressure must be less than 1 micron for the results to be applicable to a space environment.

2. The steady-state specific impulse varies from 58 to 65 percent of the theoretical value for isentropic flow.

3. The specific impulse measured for a train of pulses lasting 1/2 to 5 seconds is 10 to 25 percent less than the steady-state value.

4. Condensation, caused by heat transfer from the steam to the passages leading to the nozzle, must be avoided to ensure that a given timed pulse always yields the same impulse and to prevent a reduction in specific impulse.

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National Aeronautics and Space Administration
Moffett Field, Calif., May 4, 1966

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5. Gaylord, Robert S.: Differentiating Gas Jet for Space Attitude Control. Journal of ARS, Jan. 1961, pp. 75-76.

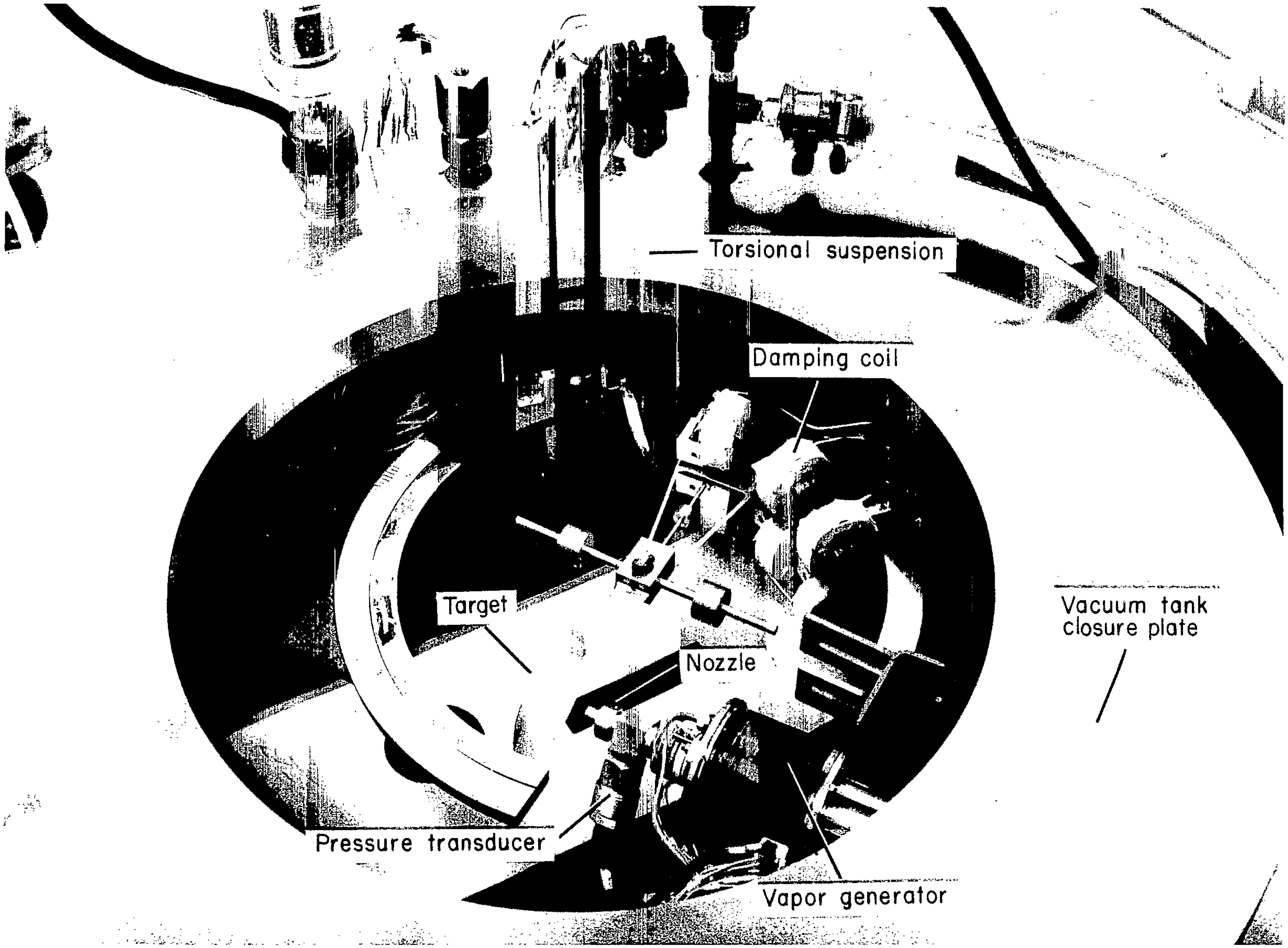

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Figure 1.- Arrangement of apparatus for measuring total impulse.

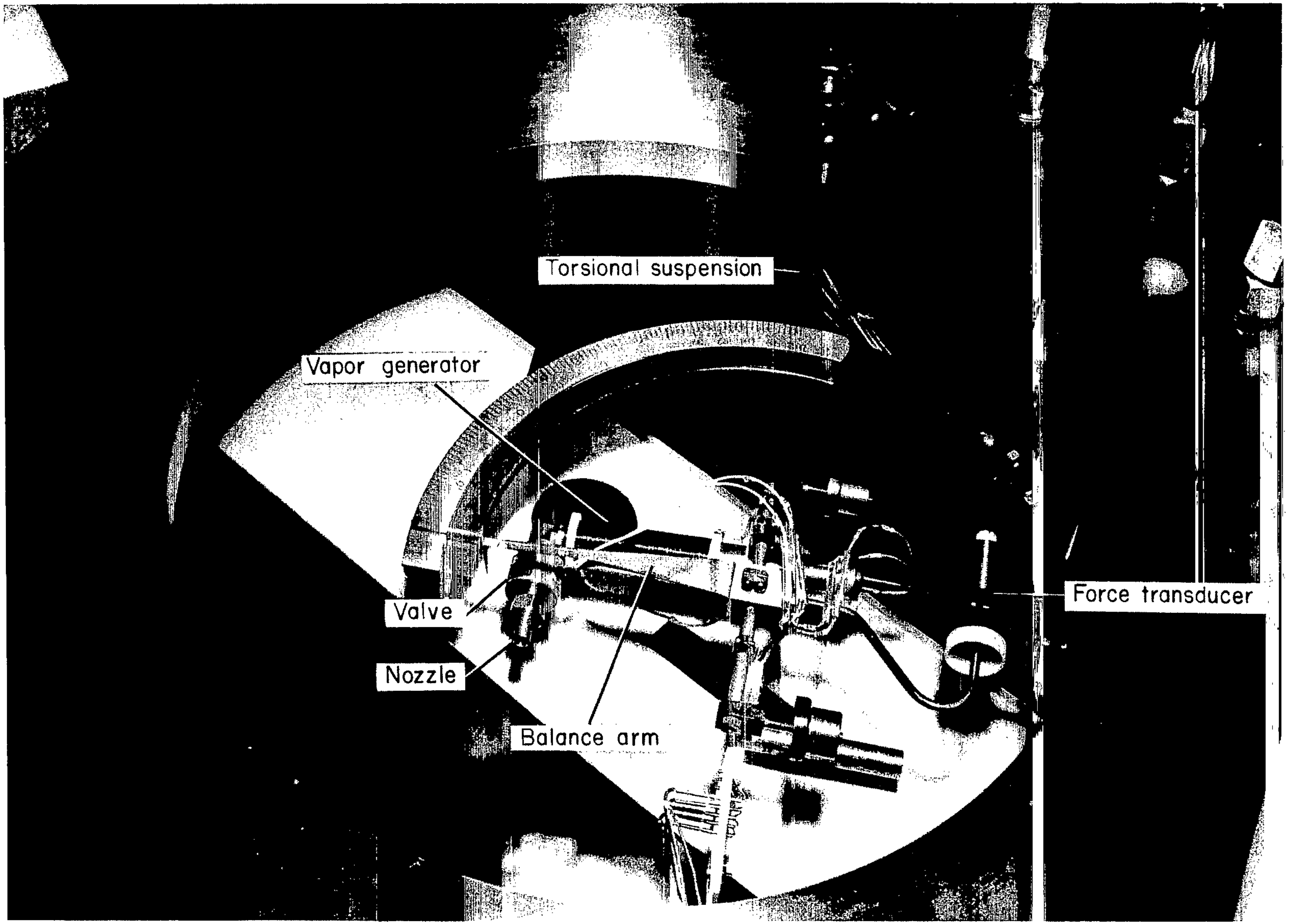

Figure 2.- Arrangement of apparatus for measuring direct nozzle thrust.

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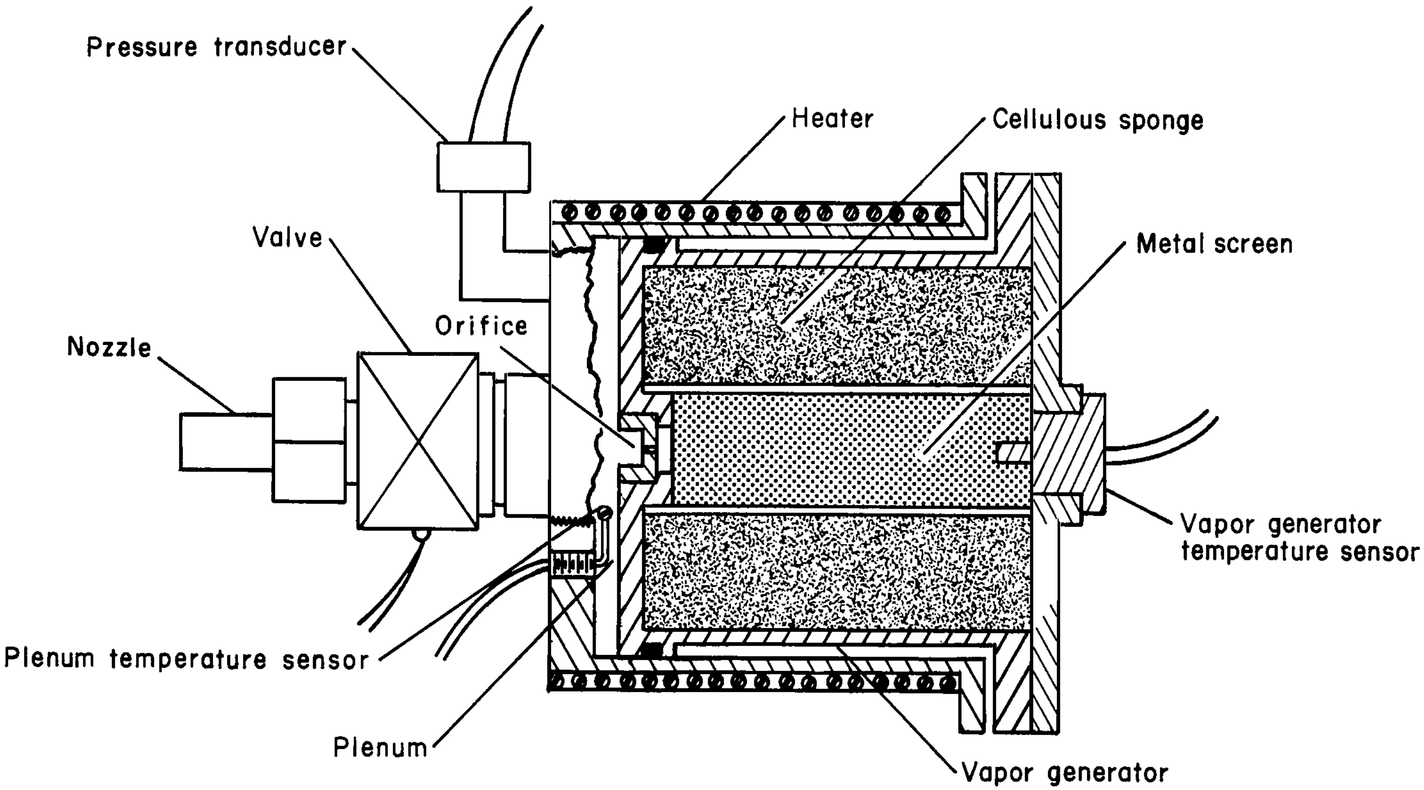
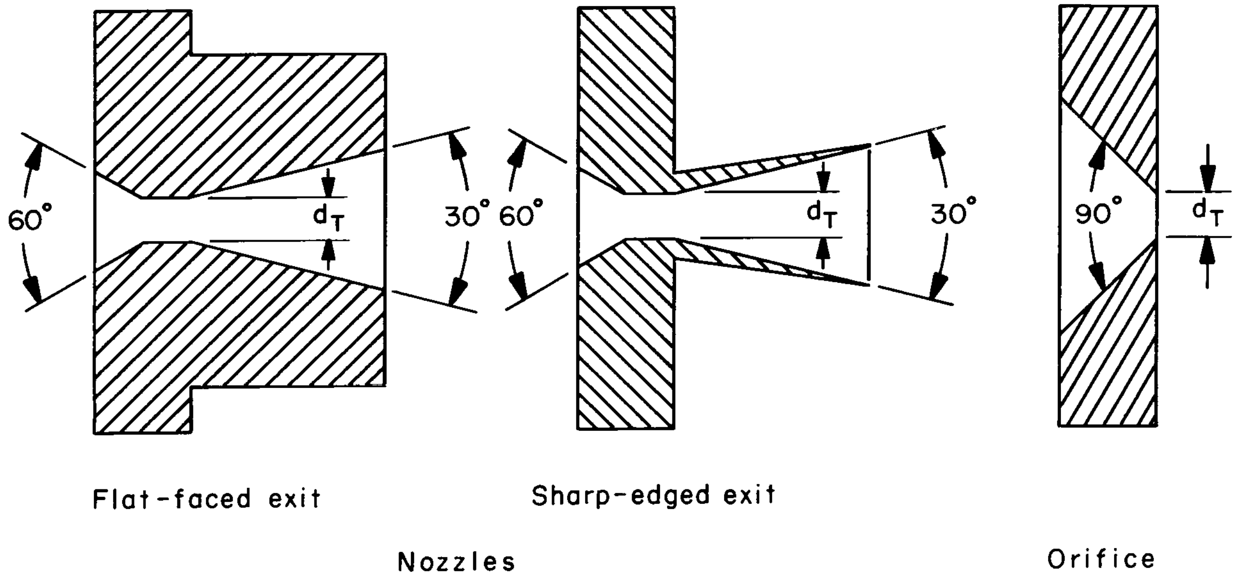
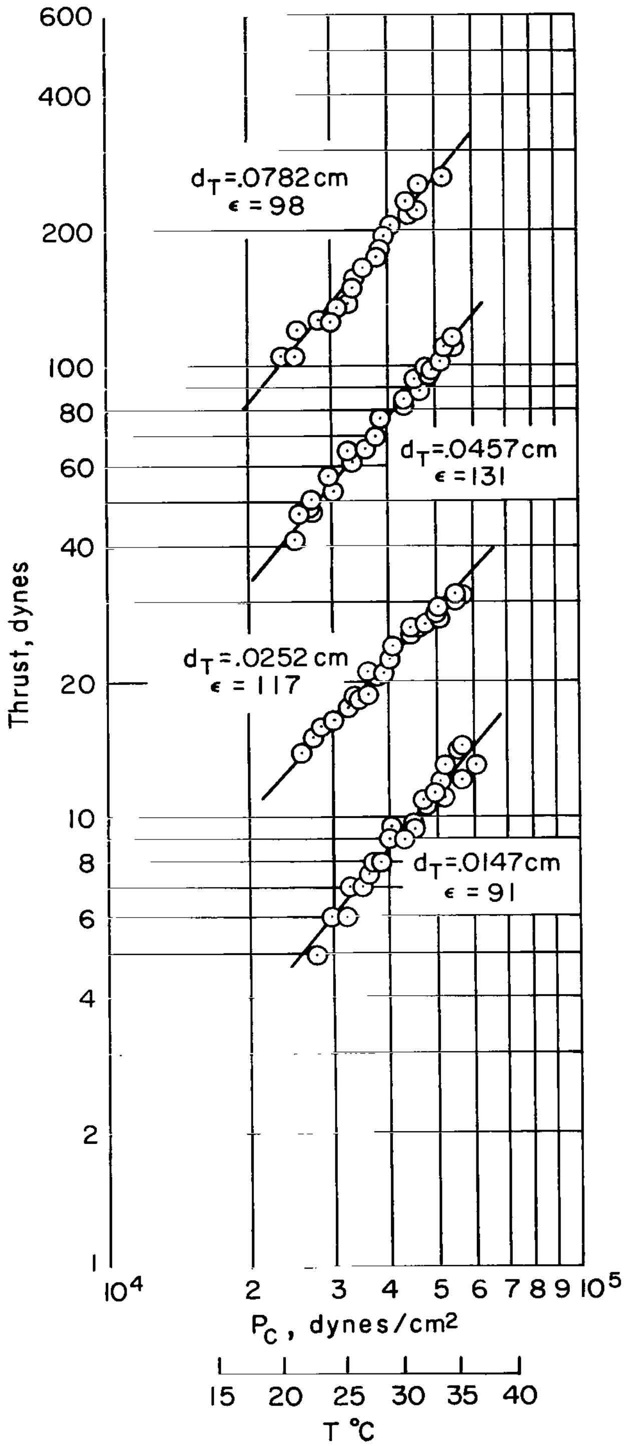


Figure 3.- Thrustor assembly.



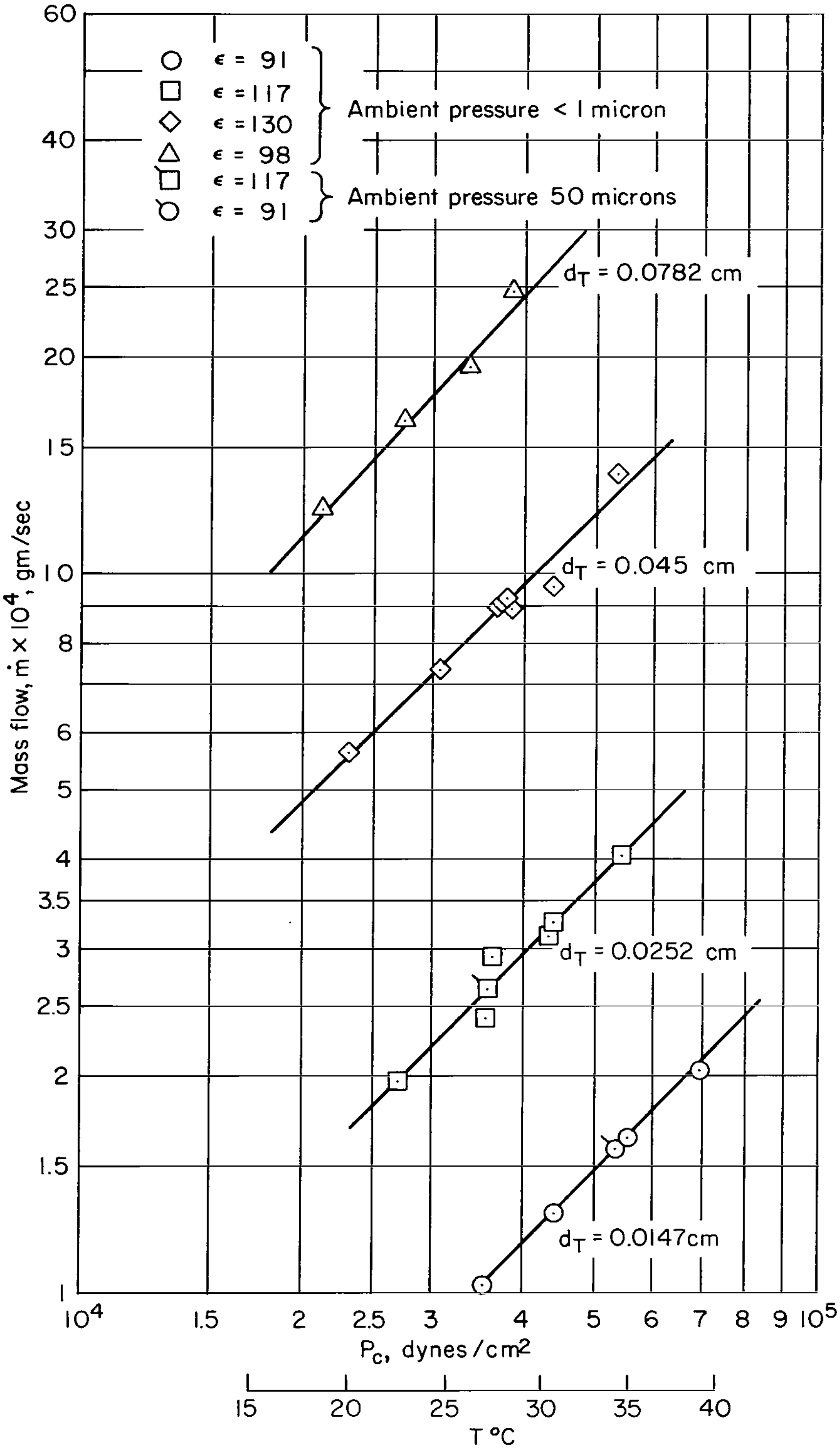
	Throat diameter d_T, cm	Area ratio ϵ	$I_{sp(isen)}$ at 25°C
Flat-faced nozzle	0.0147	91	121.1
	0.0252	117	123
	0.0457	131	123.8
	0.0782	98	121.6
Sharp-edged nozzle	0.0252	98	121.6
Orifice	0.027	—	71.0

Figure 4.- Dimensions and theoretical specific impulse of nozzles tested.



(a) Thrust.

Figure 5.- Typical test results for convergent-divergent nozzles.



(b) Mass-flow rate.

Figure 5.- Concluded.

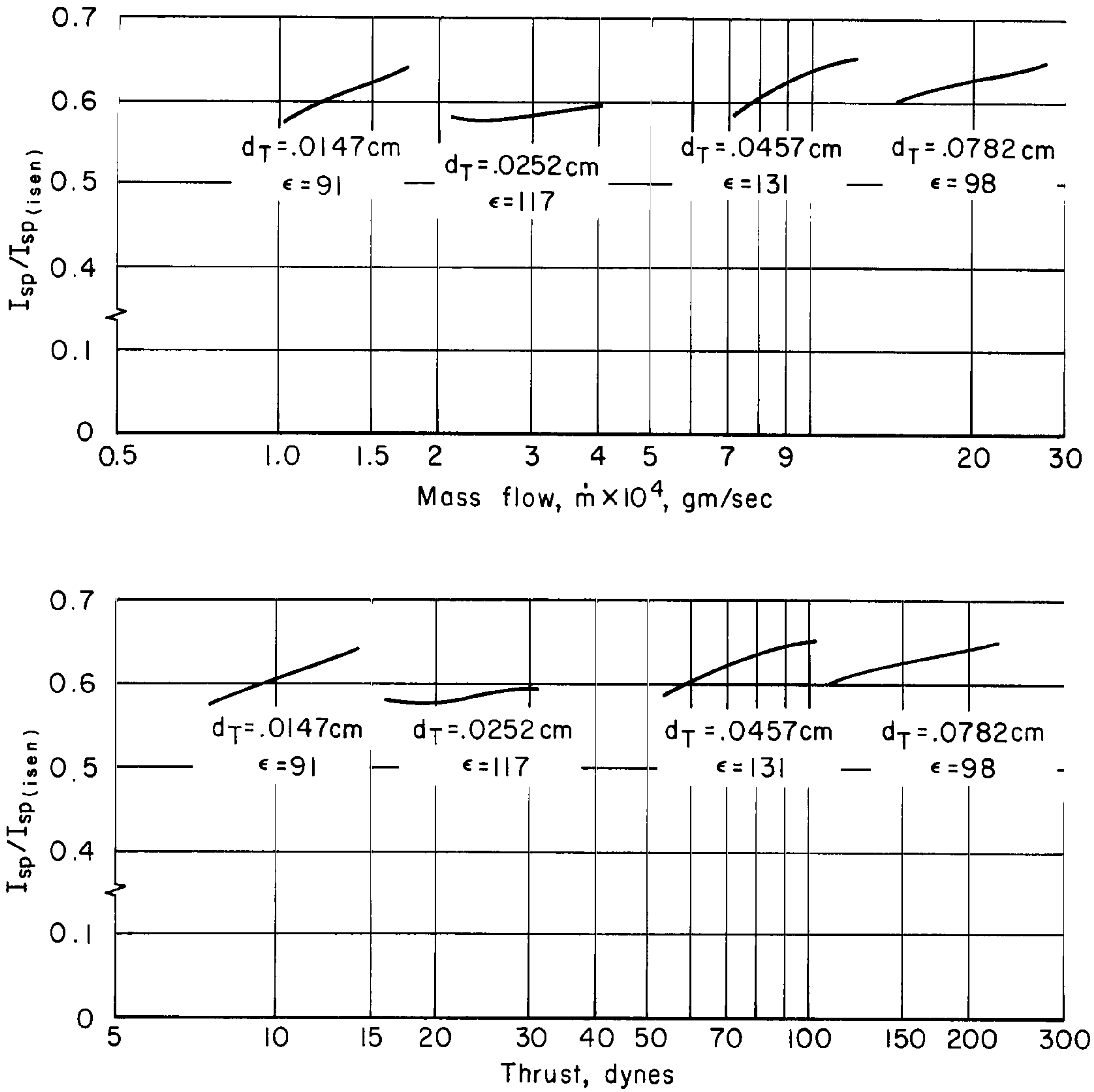


Figure 6.- Correlation of specific impulse with mass loss and thrust.

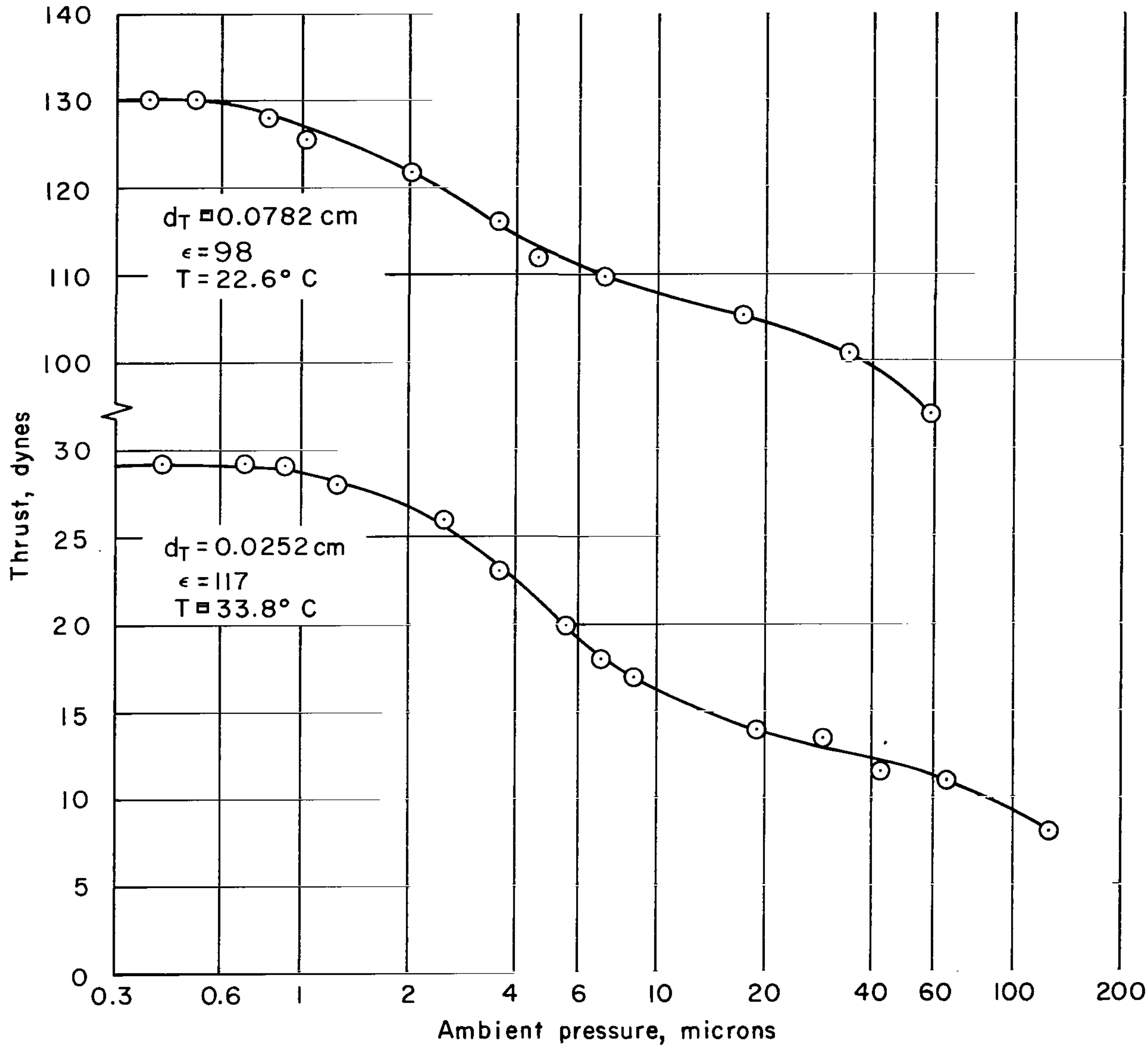


Figure 7.- The effect of ambient pressure on thrust.

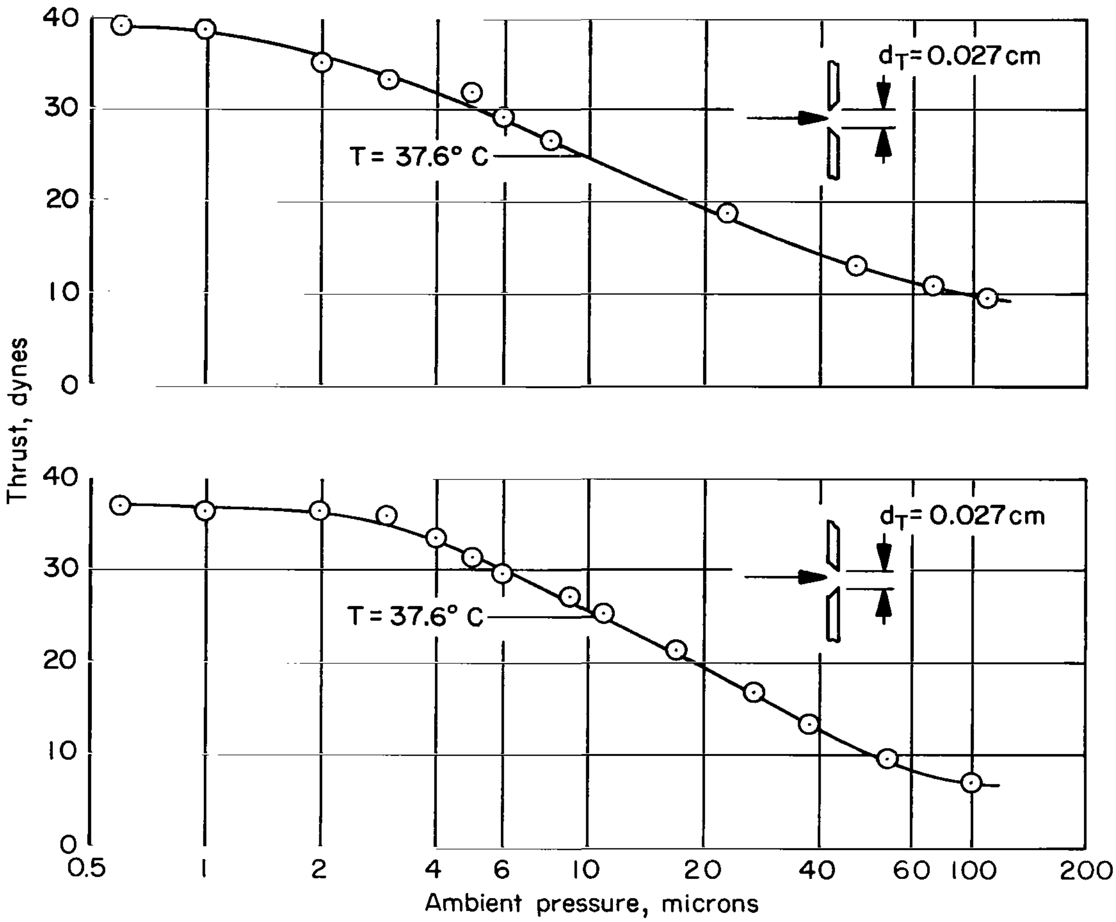


Figure 8.- The effect of ambient pressure on thrust for an orifice.

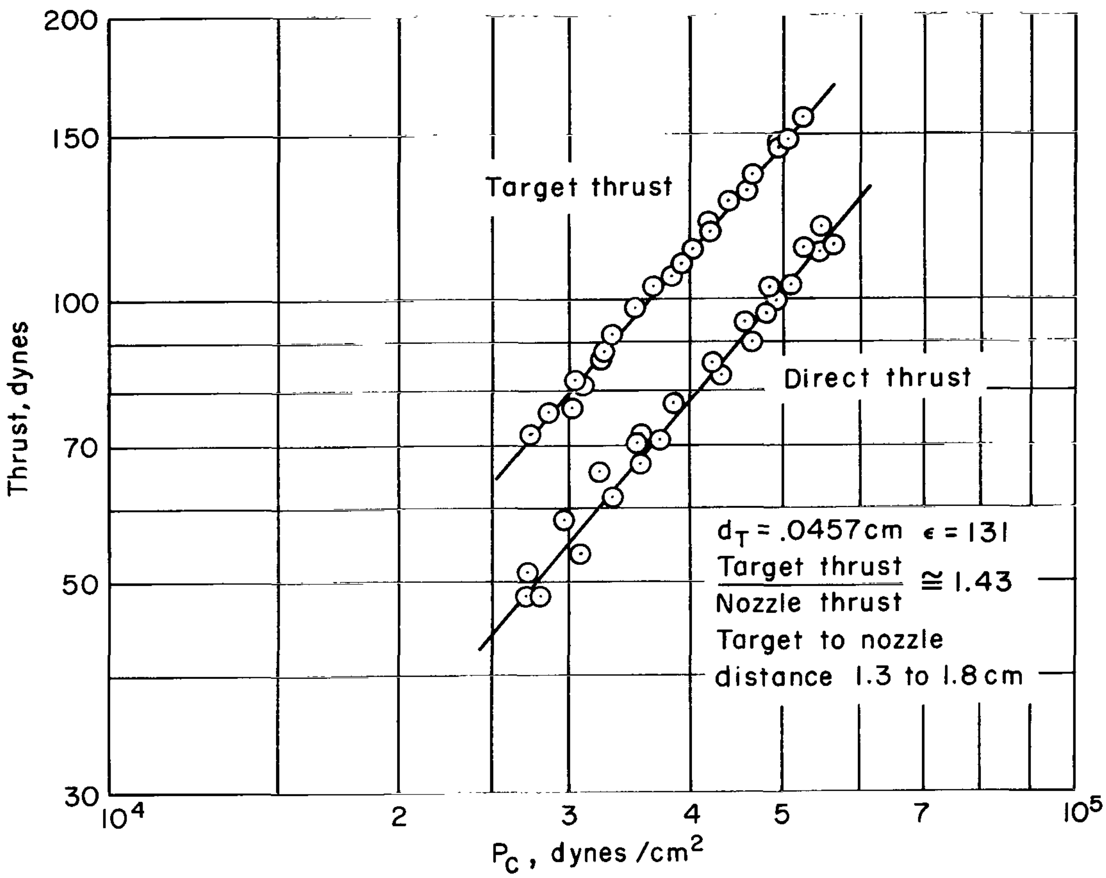


Figure 9.- Correlation of direct and target thrust measurements.

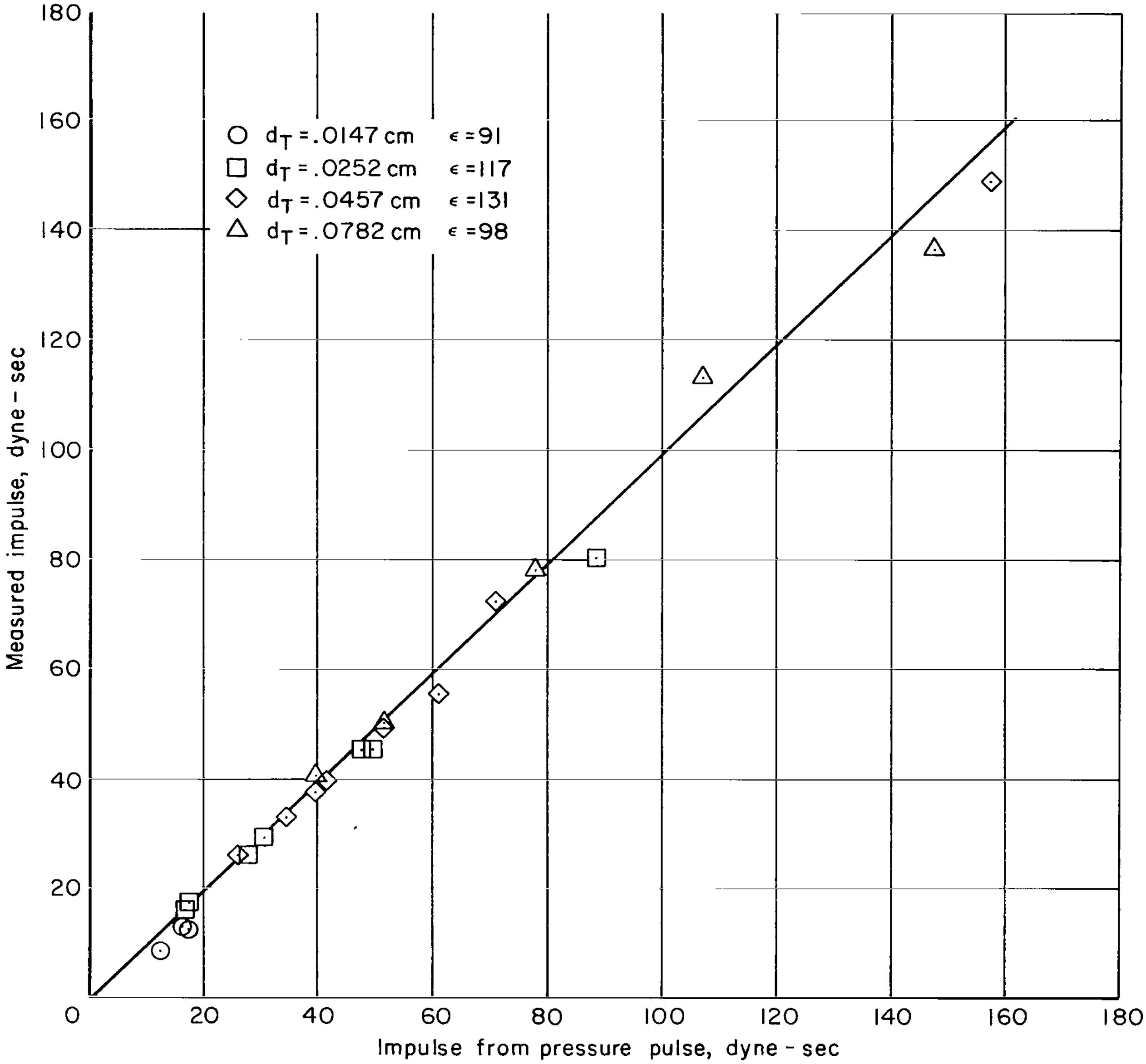


Figure 10.- Correlation of pendulum impulse with pressure pulse.

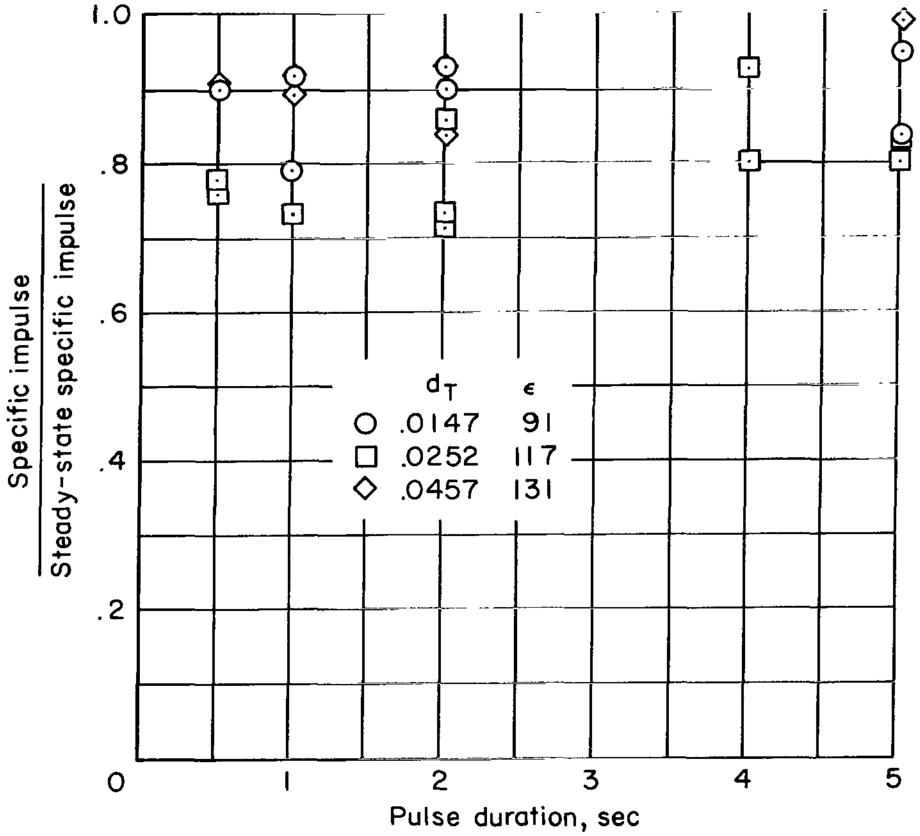


Figure 11.- Measured effect of pulse duration on specific impulse.

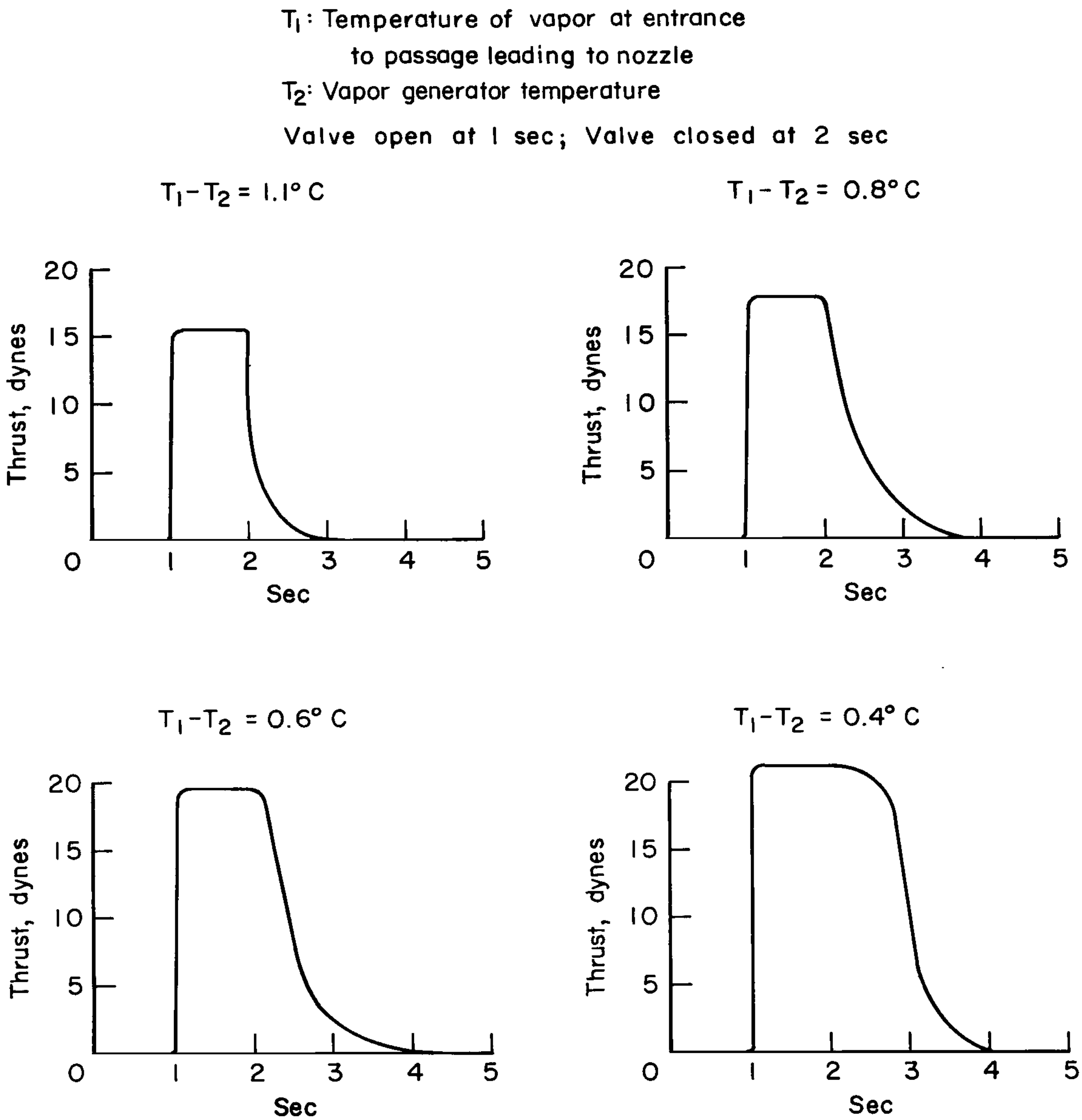


Figure 12.- Effect of condensation on pulse shape.

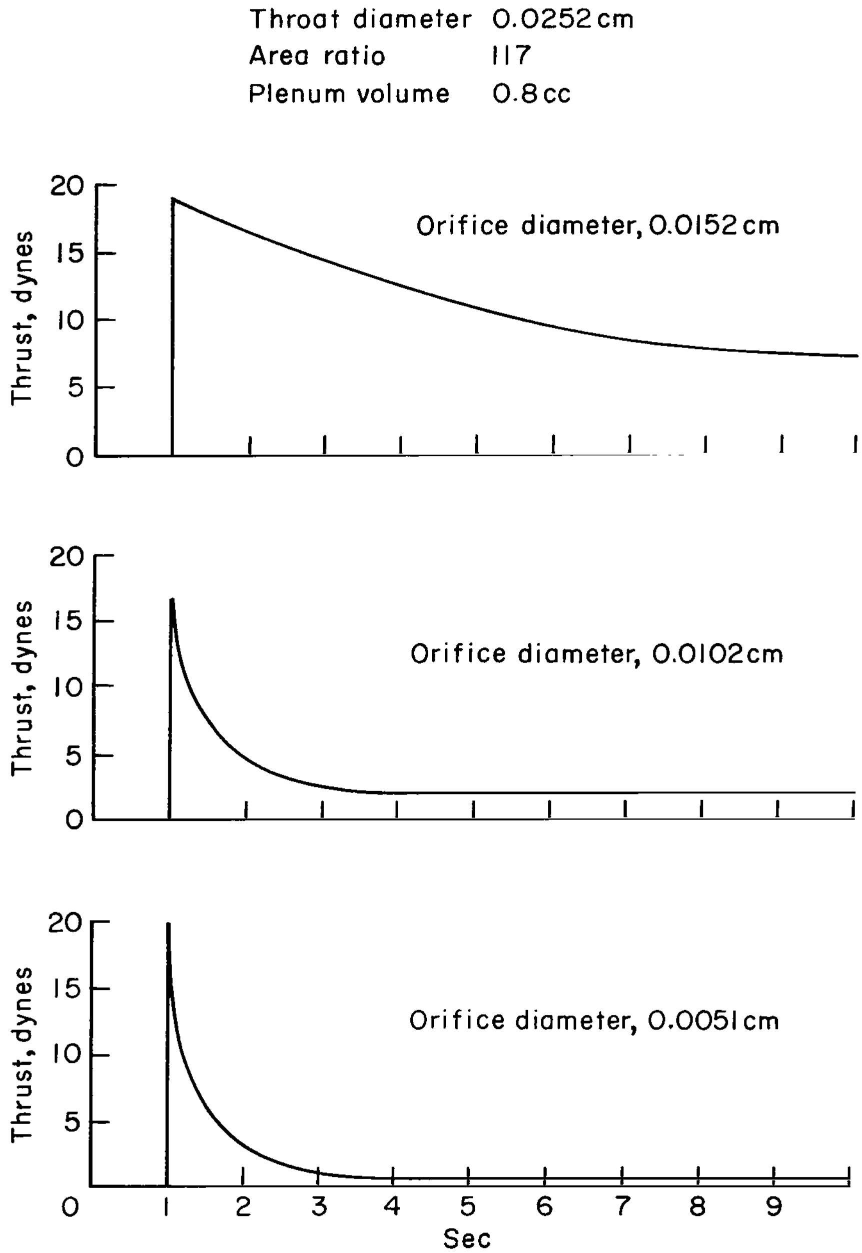


Figure 13.- Pulse shapes for various orifice diameters.

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