NASA Technical Paper 1170

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APRIL 1978

NASA

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NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1978

SUMMARY

A gas inlet system is described for generating precise gas pressures that are to be used as calibration references for the mass spectrometers aboard the dual air density (DAD) Explorer satellites. This gas inlet system was developed as an in-flight calibration technique in which a known amount of onboard gas is released in the satellite cavity and is detected by the mass spectrometer. Although several flight mass-spectrometer experiments have been proposed, none make use of the in-flight calibration technique described in this report. Laboratory measurements and calibration of the metering leak technique for the gas inlet systems are discussed. The systems tested have metering leak rates between 2 and 4 μl/sec at 298 K for argon-40, and they produce molecular flow up to 100 torr, which is the highest test pressure in this experiment. One set of equations is presented that can be used to predict the satellite calibration pressures as a function of time during the metered gas flow. Another set of equations is also presented to predict the satellite pressure during the time the metered gas flow is terminated. These equations are useful for designing similar systems for future applications and for extending data comparisons beyond the limits tested in this program. Test data show that metering leak rates are reproducible within 1 percent of established means for helium-3, helium-4, and argon-40.

INTRODUCTION

When the purpose of an investigation is to measure the density, constituents, and seasonal changes of the atmosphere by using stationed mass spectrometers in orbiting satellites, a method of in-flight calibration is highly desirable. The DAD Explorers were equipped with mass spectrometers to measure the number density of exospheric neutral particle constituents over a 2-year period. A gas inlet system for the in-flight performance evaluation and calibration of the mass spectrometers was developed for the DAD satellites. The two satellites, one a 0.762-m-diameter aluminum sphere and the other a 3.66-m-diameter aluminized Mylar[1] inflatable balloon sphere, were to be placed into coplanar polar orbits at elevations of 350 km to 750 km and 750 km to 1500 km, respectively (ref. 1). The satellites were functionally similar in design, as shown in figure 1 by the artist's concept of the satellites in orbit. They were fabricated with a large number of uniformly distributed, small-diameter perforations that constitute about 1 percent of their surface areas. The perforations allowed free exchange of molecules from the atmosphere to within the satellite shells and insured that the number density of atmospheric constituents within the satellite shells where the mass spectrometer was located would be the same regardless of satellite orientation. The gas inlet metering systems employed argon-40 and the helium-3 isotope as calibration gases for the in-flight calibration processes. The gas inlet system design was similar to the laboratory systems that are discussed in references 2, 3, and 4 and that have been used with considerable success for several years.

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[1] Mylar: Registered trademark of E. I. du Pont de Nemours & Co., Inc.

The purpose of this report is to describe the onboard gas metering leak systems developed for DAD, to describe briefly the characteristic operation, and to present some results observed in the laboratory. This report is limited to laboratory results for the inlet system since they are the only results available. Launch of the DAD Explorer experiment was unsuccessful because of failure of the Scout rocket.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

SYMBOLS

C	conductance, l/sec
C_c	conductance for calibration gas, l/sec
C_o	conductance for reference gas, l/sec
M_c	molecular weight of calibration gas, g/mol
M_o	molecular weight of reference gas, g/mol
n	number of calibrations
p	pressure, torr (1 torr = 133.3 Pa)
$p_{t=0}$	pressure at time equal zero, torr
$p(t)$	pressure as a function of time, torr
$p(t)_{sc,n}$	pressure in storage cylinder as a function of time for the nth calibration, torr
Q_1	gas flow rate from storage cylinder into satellite, torr-l/sec
Q_2	gas flow rate from atmosphere into satellite, torr-l/sec
Q_3	gas flow rate from satellite to atmosphere, torr-l/sec
t	time, sec
T_c	temperature of calibration gas, K
T_o	temperature of reference gas, K
V	volume, l
τ	plateau time, sec

Subscripts:

is	inside satellite
os	outside satellite
l	porous metal metering leak
s	satellite
sc	storage cylinder
t	trapped

IN-FLIGHT CALIBRATION SYSTEM

The major components of the DAD in-flight calibration system are the gas inlet system and the perforated satellite shell. These two components act to establish an accurate time history of calibration gas pressure within the spherical volume enclosed by the shell of the satellite. The known parameters of these components provide all the information needed to accurately determine the calibration gas pressure at any instant during a calibration process. The parameters are discussed and the gas pressure equations are developed in detail in the following section. One of the important parameters needed was the time required for the pressure inside the satellites to reach equilibrium. Pressure equilibrium is maintained in the satellites when the flow of gas from the inlet system is equal to the flow of gas exiting through the perforations of the satellite shell; for free-molecular flow conditions, the pressure equation simplifies to

$$p(t)_{is} = p(t)_{sc} \frac{C_l}{C_s} \tag{1}$$

This pressure equilibrium occurs approximately 1.39 sec after initiating the calibration gas input for the 0.762-m-diameter satellite, and approximately 5.51 sec after initiating the gas input for the 3.66-m-diameter satellite. Two gases were chosen for calibration purposes; argon-40 was used for the high mass calibration, and the helium-3 isotope was used for the low mass calibration so that the mass spectrum would not be confused with atmospheric helium-4. A command control signal from a ground station was transmitted to the satellite telemetry to activate the sequential timing circuits of the gas calibration system that were associated with the instrumentation electronics. When the inlet-system latching solenoid valve opens, gas flows from the inlet-system storage cylinder (V = 5 cl), through the porous metal metering leak, into the satellite volume, and out through the satellite skin perforations. The 1-percent surface-area perforations of the DAD satellite shell are equivalent to C_s = 1.75 kl/sec for the 0.762-m satellite and 41.9 kl/sec for the 3.66-m satellite. The satellite conductances given here apply for argon-40 at 298 K.

THEORY AND DESIGN PARAMETERS

To provide the pressure-time relationship of the calibration gases in the two satellites, it was necessary to derive equations showing their functional dependence on the gas inlet-system parameters. Consider the schematic shown in figure 2 for a calibration gas flowing from the inlet-system storage cylinder, through a metering leak of conductance C_1, into the perforated satellite shell, and out into the surrounding space. The storage cylinder pressure at any time t after the valve is opened is described by the expression

$$p(t)_{sc} = p_{t=0,sc} \exp\left(-\frac{C_1}{V_{sc}} t\right) \tag{2}$$

Inside the sphere, the pressure is described by the equation of flow

$$V_s \frac{dp(t)_{is}}{dt} = C_1 p(t)_{sc} - C_s p(t)_{is} + C_s p_{os}$$

Multiplying through by $V_s^{-1}\,dt$ and substituting from equation (2) gives the following equation:

$$dp(t)_{is} + \frac{C_s}{V_s} p(t)_{is}\,dt = \frac{C_1}{V_s} p_{t=0,sc} \exp\left(-\frac{C_1}{V_{sc}} t\right) dt + \frac{C_s}{V_s} p_{os}\,dt \tag{3}$$

Using the integration factor as given by

$$\exp\left(\int \frac{C_s}{V_s}\,dt\right) = \exp\left(\frac{C_s}{V_s} t\right) \tag{4}$$

to solve the differential equation and integrating equation (3) gives

$$\begin{aligned} p(t)_{is} \exp\left(\frac{C_s}{V_s} t\right) = {} & \frac{C_1}{V_s} p_{t=0,sc} \int \exp\left[-\left(\frac{C_1}{V_{sc}} - \frac{C_s}{V_s}\right)t\right] dt \\ & + \frac{C_s}{V_s} p_{os} \int \exp\left(\frac{C_s}{V_s} t\right) dt + k \end{aligned} \tag{5}$$

where k is an arbitrary integration constant.

Solving the integrals of equation (5) gives

$$p(t)_{is} \exp\left(\frac{C_s}{V_s} t\right) = - \frac{\frac{C_l}{V_s} p_{t=0,sc} \exp\left[-\left(\frac{C_l}{V_{sc}} - \frac{C_s}{V_s}\right)t\right]}{\frac{C_l}{V_{sc}} - \frac{C_s}{V_s}} + p_{os} \exp\left(\frac{C_s}{V_s} t\right) + k \tag{6}$$

At $t = 0$,

$$p_{t=0,is} = \frac{C_l}{V_s} \frac{p_{t=0,sc}}{\frac{C_s}{V_s} - \frac{C_l}{V_{sc}}} + p_{os} + k \tag{7}$$

Therefore, the arbitrary integration constant is obtained from the initial conditions as

$$k = p_{t=0,is} - \frac{C_l}{V_s} \frac{p_{t=0,sc}}{\frac{C_s}{V_s} - \frac{C_l}{V_{sc}}} - p_{os}$$

When the integration constant is substituted into equation (6), the following equation is obtained:

$$p(t)_{is} \exp\left(\frac{C_s}{V_s} t\right) = \frac{C_l}{V_s} p_{t=0,sc} \frac{\exp\left[-\left(\frac{C_l}{V_{sc}} - \frac{C_s}{V_s}\right)t\right]}{\frac{C_s}{V_s} - \frac{C_l}{V_{sc}}} + p_{os} \exp\left(\frac{C_s}{V_s} t\right)$$

$$+ p_{t=0,is} - \frac{C_l}{V_s} \frac{p_{t=0,sc}}{\frac{C_s}{V_s} - \frac{C_l}{V_{sc}}} - p_{os} \tag{8}$$

After multiplying through by $\exp\left(-\frac{C_s}{V_s} t\right)$ and combining terms, equation (9), which gives the functional relation for $p(t)_{is}$, is obtained:

$$p(t)_{is} = \frac{C_l}{V_s} p_{t=0,sc} \frac{\left[\exp\left(-\frac{C_l}{V_{sc}} t\right) - \exp\left(-\frac{C_s}{V_s} t\right)\right]}{\frac{C_s}{V_s} - \frac{C_l}{V_{sc}}} + p_{os}\left[1 - \exp\left(-\frac{C_s}{V_s} t\right)\right] + p_{t=0,is} \exp\left(-\frac{C_s}{V_s} t\right) \qquad (9)$$

When the valve shown in figure 2 is closed in the calibration procedure, the constant V_{sc} is replaced by V_t, which is the trapped volume between the valve and the porous metal metering leak. Each time the valve is opened, the pressure in the storage cylinder is expanded into the trapped volume between the valve and the porous metal metering leak such that the pressure in the storage cylinder is reduced by a small amount given by the constant 0.999. This constant must be introduced to account for the pressure reduction in the storage cylinder which occurs when the expanding gas from the storage cylinder fills the void between the storage cylinder and the porous metal metering leak. This would then yield a general expression that can be used when the calibration intervals are the same (that is, when the valve is open for the same increment of time).

It is necessary to know $p(t)$ after the valve had been opened for a specified time so that the pressure in the satellite could reach a maximum and the valve could then be closed. After the pressure in the satellite has reached a maximum, the pressure is described by equation (9), with V_{sc} replaced by V_t. In this mode of operation, $p_{t=0,sc}$ in equation (9) must be interpreted as being the pressure in the storage cylinder at the instant the valve is closed.

Typical pressure-time relationships for the argon-40 calibration gas at 298 K for the two satellites are shown in figures 3 to 6. Figures 3 and 5 show the pressure-time curves for the 0.762-m and 3.66-m satellites, respectively, when the valve is opened and remains open until the pressure inside the satellite is equilibrated to the pressure outside. These curves show that $p(t)_{is}$ reaches a plateau and remains essentially constant for several minutes. The programed open time for the inlet-system valves for an orbit calibration sequence was 16 sec, and the plateau times were 1.39 and 5.51 sec for the 0.762-m and 3.66-m satellites, respectively. Thus, there is ample time for calibrating the mass spectrometers inside the satellites. Calibrations can be repeated at the pressure plateau when the valve is left open long enough for $p(t)_{is}$ to reach a maximum. The curves shown in figures 3 and 5 were plotted in order to get an idea of how long $p(t)_{is}$ remains approximately constant after it reaches a maximum.

It appears that $p(t)_{is}$ remains essentially constant for approximately 1000 sec, which means that there is plenty of time for repeated calibration sequences. The preferred program operation for repeated calibrations is to open the valve separating the storage cylinder from the sphere and allow

$p(t)_{is}$ to reach a maximum, with the valve open only long enough to make a calibration (approximately 16 sec). After the valve is closed, there is additional calibration time (as shown in figs. 4 and 6) so that $p(t)_{is}$ can be monitored as it decreases from a maximum to a minimum. From figures 3 and 5, it can be seen that $p(t)_{is}$ reaches a maximum at approximately 1.39 and 5.51 sec for the 0.762-m and 3.66-m satellites, respectively. The time required for the pressure in each satellite to reach a maximum is a constant and is a function of the volumes and conductances involved for each satellite. This plateau time τ is obtained by differentiating $p(t)_{is}$ in equation (9) with respect to time and setting it equal to zero. When this is done, the plateau time is given by the following expression:

$$\tau = \frac{\ln\left(\frac{C_l V_s}{V_{sc} C_s}\right)}{\frac{C_l}{V_{sc}} - \frac{C_s}{V_s}} \tag{10}$$

Substituting for the system parameters from table I gives the plateau times, as shown in figures 3 and 5.

There are essentially two programed modes of operation, and they are determined by the open or closed position of the valve separating the storage cylinder from the satellite. The condition for the valve in the open position has been described. It is useful to consider the condition when the valve has been opened long enough for the pressure inside the satellite shell to reach the plateau level and is then closed. As previously mentioned, the pressure inside the satellites is then given by equation (9), with V_{sc} replaced by V_t. Therefore, when the valve is closed, the equation expressing the pressure in the satellite becomes

$$p(t)_{is} = \frac{\frac{C_l}{V_s} p_{t=0,sc}\left[\exp\left(-\frac{C_l}{V_t}t\right) - \exp\left(-\frac{C_s}{V_s}t\right)\right]}{\frac{C_s}{V_s} - \frac{C_l}{V_t}} + p_{os}\left[1 - \exp\left(-\frac{C_s}{V_s}t\right)\right] + p_{t=0,is}\exp\left(-\frac{C_s}{V_s}t\right) \tag{11}$$

From the data given in table I, C_l/V_t is equal to 0.02 $\sec^{-1}$ and C_s/V_s is equal to 7.563 and 1.635 $\sec^{-1}$ for the 0.762-m and 3.66-m satellites, respectively. The exponential factor $\exp\left(-\frac{C_l}{V_t}t\right)$ has the largest influence of all the exponential terms on $p(t)_{is}$ as time is increased. Pressure as a function of time inside the satellite will reach a minimum pressure outside the satellite when the term $\frac{C_l}{V_s} p_{t=0,sc} \frac{\exp\left(- \frac{C_l}{V_t} t\right)}{\frac{C_s}{V_s} - \frac{C_l}{V_t}}$ is small (5×10^{-15} torr) with respect to p_{os}. This occurs at approximately 813 sec for the 0.762-m satellite and at 770 sec for the 3.66-m satellite. In order to illustrate this computation, the pressure outside the satellite in figures 4 and 6 was taken to be 10^{-12} torr. Since the pressure outside the satellite enters in these pressure-time curves as a boundary condition, it would be necessary to reconsider these conditions for experiments in which a pressure different than 10^{-12} torr would be encountered. As long as the pressure outside the satellite is much less than the maximum (plateau) pressure expected in the satellites, the pressure equilibration times and pressure plateau would not change for the case when $p(t)_{is}$ is increasing from minimum to maximum. However, when $p(t)_{is}$ is decreasing from a plateau level to a minimum p_{os}, the equilibration time and minimum pressure expected inside the satellites are strongly dependent on p_{os}.

GAS INLET SYSTEM

In figure 7, the four major components of the DAD Explorer satellite gas inlet system are shown. They are the gas storage cylinder, the solenoid valve, the porous metal metering leak, and the pressure transducer. The function of the first three components is to store and to deliver, upon command, either of the calibration gases (helium-3 or argon-40) at a rate that can be accurately predicted. The fourth component was used as a part of the spacecraft monitoring system only.

The storage cylinder pressure for the nth programed calibration $p(t)_{sc,n}$ was used to establish gas flow into the satellite shell and is accurately given by the expression

$$p(t)_{sc,n} = (0.999)^n p_{t=0,sc} \exp\left(- \frac{nC_l}{V_{sc}} t\right) \tag{12}$$

In equation (12), the constant 0.999 is introduced to account for a pressure reduction in the storage cylinder that was caused by the calibration gas expanding into the trapped volume (0.5 ml) between the valve and the porous metal metering leak. Then, by knowing the initial pressure in the storage cylinder $p_{t=0,sc}$, the volume of the storage cylinder V_{sc}, the porous metal metering leak conductance C_l, the time t that the flow is sustained, and the number of calibrations n, the pressure in the storage cylinder $p(t)_{sc}$ can be resolved for any particular instant. In order to test and evaluate the system performance experimentally and to check the precision of equation (12), several inlet systems were assembled. The data in table II show the results of several calibrations for four inlet systems. In the DAD experiment, it was expected that approximately 24 in-orbit calibrations would be made during the mission duration, and each calibration would last for 16 sec. The data in table II show that a sufficient supply of calibration gas from the inlet system would be available. After 30 calibrations, the pressure in the storage cylinders was greater than 90 percent of the original value.

For the gas storage cylinder, a 5-cl cylinder made of AISI type 304 stainless steel was selected. It consisted of two sections machined from solid material and welded by an electron beam at the equator. After welding, each cylinder was vacuum fired at 1123 K (just below the annealing temperature) to remove contaminants and to open any voids in the material that would later cause leak problems.

An electrically operated double latching solenoid valve was selected because of its low power consumption and extremely low leak rate. The valve operated from either an open or closed test position that requires an 8 to 16 V dc pulse and draws a peak current of about 1 A at 8 V. Typically, the time duration of the voltage pulse required to operate the valve was approximately 12 msec. The power requirements to operate the valve were within specifications because the satellite instrumentation power supply system permitted normal power supply fluctuations of 11 to 15 V. The valve leak rate was less than 10^{-10} atm-cm^3/sec as determined by a laboratory helium leak detector.

The precision porous metal metering leak shown in figure 8 had a nominal conductance C_l between 2 and 4 μl/sec for argon-40 at 298 K. The metering leaks were installed at the gas exit side of the valve. The metering leak was made of porous stainless steel and was encapsulated in a small cylinder (0.64 × 0.64 cm) formed from AISI type 304 stainless steel; the cylinder was pressed into an undersized aluminum adapter (0.637 cm), as shown in figure 8. The adapter was fastened to the valve body with eight #2-56 machine screws that use heli-coil locking devices. A silver-coated clamshell seal was used to make the sealing surface between the adapter and the valve body.

The pressure transducer was attached to the gas inlet systems to monitor the storage cylinder pressure in flight. However, the transducer was also used to detect possible system malfunctions such as incorrect or inoperative valve functions or leaks. The transducer accuracy was not good enough for precise determination of the storage cylinder pressure because each calibration sequence reduced the storage cylinder pressure by only 1 part in 1000, and the transducer accuracy was about 2 parts in 100.

The storage cylinder, the pressure transducer, and the latching solenoid valve were welded together using stainless steel tubing that had an outside diameter of 0.32 cm. The completed assembly was then tested for overall leak rates of less than 10^{-10} atm-cm^3/sec.

After the leak testing was completed, the 330-g inlet system was attached to the laboratory test system shown in figure 9 without its porous metal metering leak installed. The system pressure was then reduced to 75×10^{-9} torr, and the temperature of the inlet system within the controlled-temperature environmental chamber was raised to 343 K. The inlet-system outgassing products, principally water, were examined with a quadrupole mass-spectrometer residual gas analyzer. Higher baking temperatures could not be used because the pressure transducer and the rare Earth magnetic core of the solenoid valve were highly susceptible to deterioration.

After the outgassing pressure reduced to within 5 percent of its former pressure level, valves 5 and 1 were closed. Gas from the calibration gas supply was used to purge the inlet system through valves 2 and 3. At this point, the quadrupole mass-spectrometer residual gas analyzer showed only traces of carbon monoxide, water, hydrogen, and methane. The inlet system was then cooled to room temperature and charged to the appropriate pressure by using 20-ppm impurity argon-40 or helium-3 isotope as required. Nominal values of charging pressure were 7.50 torr for the 0.762-m satellite system and 75.02 torr for the 3.66-m satellite system.

The porous metal metering leaks in their adapters were then installed on each gas inlet system, and a final inspection of storage cylinder gas purity was performed.

LABORATORY APPARATUS

Figure 10 is a block diagram of the laboratory system used to calibrate the porous metal metering leaks, and figure 11 is a photograph of the laboratory test hardware. The test system consists of a calibration gas supply, a manifold with an arrangement of valves allowing for isolation of each component, a quadrupole mass-spectrometer residual gas analyzer, a capacitance manometer, a controlled-temperature environmental chamber, and a gas storage cylinder similar to the flight-type inlet-system gas storage cylinder. Typically, the pressure in the manifold could be reduced to the range of 75×10^{-9} torr by using a combination of mechanical, oil-diffusion, and cryogenic pumping.

Calibration gas supply: Research grade argon-40 and helium-4 gases with an impurity level of less than 20 ppm for calibrations.

Main manifold: Stainless steel with an inside diameter of 4.45 cm and a length of 35.6 cm.

Residual gas analyzer: Laboratory quadrupole mass spectrometer with a mass range of 1 to 500 atomic mass units and a minimum detectable partial pressure equal to 10^{-6} of the total pressure.

Capacitance manometer: Capacitance pressure sensor with a prestressed diaphragm. Total range is from 0.01 torr to 997.6 torr.

Controlled-temperature environmental chamber: Range 200 to 588 K, chilled with CO_2, heated with electrical elements. Temperature stability during tests is ±0.56 K.

Pumping system: Includes 10-cm oil diffusion pump with a mechanical backing pump, liquid nitrogen cold trap, and 15-cm gate valve. Approximate pumping speed is 500 l/sec.

Valves: Valves 1 and 5 in figures 9 and 10 are right-angle ultrahigh vacuum type with a rated conductance of 32 l/sec in the fully opened position. Valve 2 is a low-conductance metering type used for regulating calibration gas flow rates into the manifold and associated volume. Valve 6 is a small latching-solenoid type similar to the type used in the flight systems. Valves 3 and 4 are standard laboratory-type test valves.

SYSTEM TESTING AND RESULTS

Metering Leak Calibration

One of the most critical parameters of the calibration gas inlet system is the conductance of the porous metal metering leak. The conductance of each leak was accurately measured before it was installed into a gas inlet system.

Calibrations of the flight gas inlet-system metering leaks were performed with the laboratory apparatus shown in figure 11. A flight gas inlet system that was modified by having the pressure transducer replaced with a stainless steel tubing connection to the sensitive capacitance manometer was located within the controlled-temperature environmental chamber. Each leak to be calibrated was installed on the inlet-system valve adapter and sealed to the vacuum manifold with a Teflon[2] gasket.

During laboratory system tests and calibration, valves 2, 3, and 5 remained closed until the system pressure was reduced to 75×10^{-8} torr. The temperature in the controlled-temperature environmental chamber was increased to 343 K and was held there until the temporary increase in pressure due to outgassing from heating was reduced to less than 75×10^{-9} torr and until the residual gas analyzer showed trace levels of the constituents hydrogen, methane, water, and carbon monoxide. Typically, this required 8 hr. The controlled-temperature environmental chamber was then reduced to room temperature, and the test system was monitored for several hours by using the sensitive capacitance manometer and the residual gas analyzer to check for leaks or further outgassing.

After the system was determined to be free of any contaminants, a small sample of the calibration gas (helium-3 or argon-40) was examined with the residual gas analyzer for purity.

The porous metal metering leak calibrations were performed by establishing the appropriate pressure level in the test system manifold for the calibration gas being used when the manifold pumping system valve was off. The sensitive capacitance manometer was used to determine the manifold pressure level, and the controlled-temperature environmental chamber was used to set the metering leak temperature to a specified typical satellite condition. The metering leak under calibration, the test storage volume, and the sensitive capacitance manometer were then shut off, and the test manifold evacuated by the pumping system. After waiting 15 min (minimum time) for the pressure and temperature to stabilize, leak calibrations were initiated. The initial pressure and the

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[2] Teflon: Registered trademark of E. I. du Pont de Nemours & Co., Inc.

immediate pressure change were recorded, and valve 6 of figure 10 was opened to permit calculation of the trapped volume between the valve seat and the porous metal metering leak being calibrated. The pressure decrease as a function of time during the gas flow decay was recorded until the pressure was approximately half its initial value. These data were then used to compute the conductance of the porous metal metering leak from the relation

$$C_l = -\frac{V_{sc}}{t} \ln \frac{p(t)_{sc}}{p_{t=0,sc}} \qquad (13)$$

This procedure was repeated for several calibrations by using helium-4 as the calibration gas at temperatures of 261 K, 262 K, 308 K, and 309 K, which was the range expected in the DAD Explorer satellites in orbit. At least one or more calibrations with either argon-40 or helium-3 was then performed. Results of the computed conductances (in the range of 10^{-6} l/sec) for these test data for four flight systems are presented in figures 12 and 13. Each data point is normalized to 298 K for argon-40 by using the relationship

$$C_o = C_c \sqrt{\frac{T_o M_c}{T_c M_o}} \qquad (14)$$

The data obtained indicate a relative standard deviation of less than 0.5 percent from the mean.

Volume Measurements

Three volumes are critical for establishing the calibration pressure expected in the satellite shells where the mass spectrometers are situated. Two of these volumes are located within the inlet system itself. They are the small trapped volume between the valve seat and the porous metering leak, and the gas storage cylinder volume, which includes all the interconnecting tubing, the transducer, and the valve cavities. The third is the effective volume of the satellite itself, which also affects the transient characteristics of the satellite calibration pressure.

Measurements of the laboratory test inlet-system volume were made with a precision piston-cylinder volumetric micrometer that was capable of measuring displacements within 700 μm. It was determined from measurements of the piston and cylinder diameters that errors in the volume measurements were approximately 220 μl.

The precision piston-cylinder volumetric micrometer was attached to the inlet-system test manifold at valve 2 (fig. 10). This device was then used to compress the gas at atmospheric pressure in the test manifold, and the total volume was calculated according to Boyle's law from the measured pressure and volume changes. The volume of the test manifold was determined to be 0.6004 l, which was within 0.33 percent of the mean of 12 measurements. The inlet-system storage volume was determined by expanding the calibration gas from its volume into the test manifold volume. These measurements yielded a mean value of 0.0693 l, within 0.14 percent, for the inlet-system volume.

Similar techniques were used to determine the volume of the main manifold section in figure 9, including the sensitive capacitance manometer appendage. The volume of the main manifold section was determined to be 0.5491 l, within 0.02 percent.

The flight inlet-system storage volume measurements were determined by expanding gas into the main manifold ($V = 0.5491$ l). Flight inlet system volumes obtained with this technique averaged 5.11 cl, within 0.39 percent. Errors accumulated from the volume measurements were determined to be within 0.4 percent. Therefore, the volume of the flight calibration gas storage cylinder is 5.11 ± 0.04 cl.

An evaluation of measurement errors (ref. 5) yielded a cumulative relative uncertainty of less than 1 percent in the volume, pressure, and time parameters for the 0.762-m satellite and less than 0.5 percent for the 3.66-m satellite.

FLIGHT QUALIFICATION AND ACCEPTANCE TESTS

A prototype gas inlet system was subjected to the environmental specification for the Scout Vehicle launch and to the expected environment for the DAD Explorer satellites in orbit and performance tests. The gas inlet system was cycled through more than 200 calibration sequences with no deterioration. All four flight units and the two backup units were operational and unaffected during and after the satellite program flight acceptance tests.

LONG-TERM STORAGE RESULTS

Two inlet systems designated as backup units were evacuated to 7.5×10^{-8} torr, stored for 370 days, and then attached to the laboratory test system of figure 10. The pressure P_i of the storage systems was then determined from the expression

$$P_i V_i = P_f (V_i + V_m) \qquad (15)$$

where P_i and V_i are the initial pressure and volume of the inlet system, P_f is the final pressure of the inlet manifold system, and V_m is the volume of the manifold system. The initial pressure of one unit had increased to 0.59 torr, and the residual gas analyzer mass spectrometer showed the gas to be H_2O. The initial pressure of the other unit had increased to 8.28 torr, and the residual gas analyzer showed the gas to be an undetermined substance, neither air nor water. It was presumed that the latter system had not been properly cleaned. Fabrication records showed that neither of these inlet-system storage cylinders had been vacuum fired during construction assembly; this suggested that test contaminants in the system evolved during the storage time. This contamination could have been eliminated if the units had been vacuum fired before final assembly.

CONCLUSIONS

The measurements and tests of the gas inlet systems developed for the DAD Explorer satellites led to the following conclusions:

1. Precision gas inlet systems suitable for use in calibrated pressure devices on satellites have been developed and are practical.

2. The DAD Explorer precision gas inlet systems can produce about 30 16-sec timed calibration sequences before the stored calibration gas pressure has been reduced to 90 percent.

3. Calibration gas flow rates can be produced with 1-percent accuracy and repeatability.

4. Porous metal metering leaks having conductances in the range of 10^{-6} l/sec were developed and shown to be practical for repeated cycling and long-term use in space flight conditions.

5. Since the pressure outside the satellites (p_{os}) is not precisely known, a complete error analysis cannot be given. However, collectively the data indicate that a fractional error of about 8 percent can be quoted.

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March 8, 1978

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TABLE I.- DESIGN CRITERIA DATA COMPUTED FOR ARGON-40 AT 298 K

	0.762-m satellite	3.66-m satellite
C_l, μl/sec	10	10
C_s, kl/sec	1.75	41.9
V_s, hl	2.31	256
V_{sc}, cl	5	5
V_t, ml	0.5	0.5
C_l/V_{sc}, $msec^{-1}$	0.2	0.2
C_l/V_s, $nsec^{-1}$	43.3	0.39
C_l/V_t, sec^{-1}	0.02	0.02
C_s/V_s, sec^{-1}	7.563	1.635
$p_{t=0,sc}$, torr	10	100

TABLE II.- INLET-SYSTEM CALIBRATION DATA FOR ARGON-40 AT 298 K

Number of calibrations	Total calibration time, sec	$p(t)_{sc,n}/p_{t=0,sc}$ at system -			
		1	2	3	4
1	16	0.9983	0.9981	0.9976	0.9982
10	160 (10 × 16)	.9832	.9807	.9768	.9821
20	320 (20 × 16)	.9667	.9617	.9541	.9646
30	480 (30 × 16)	.9505	.9430	.9320	.9471

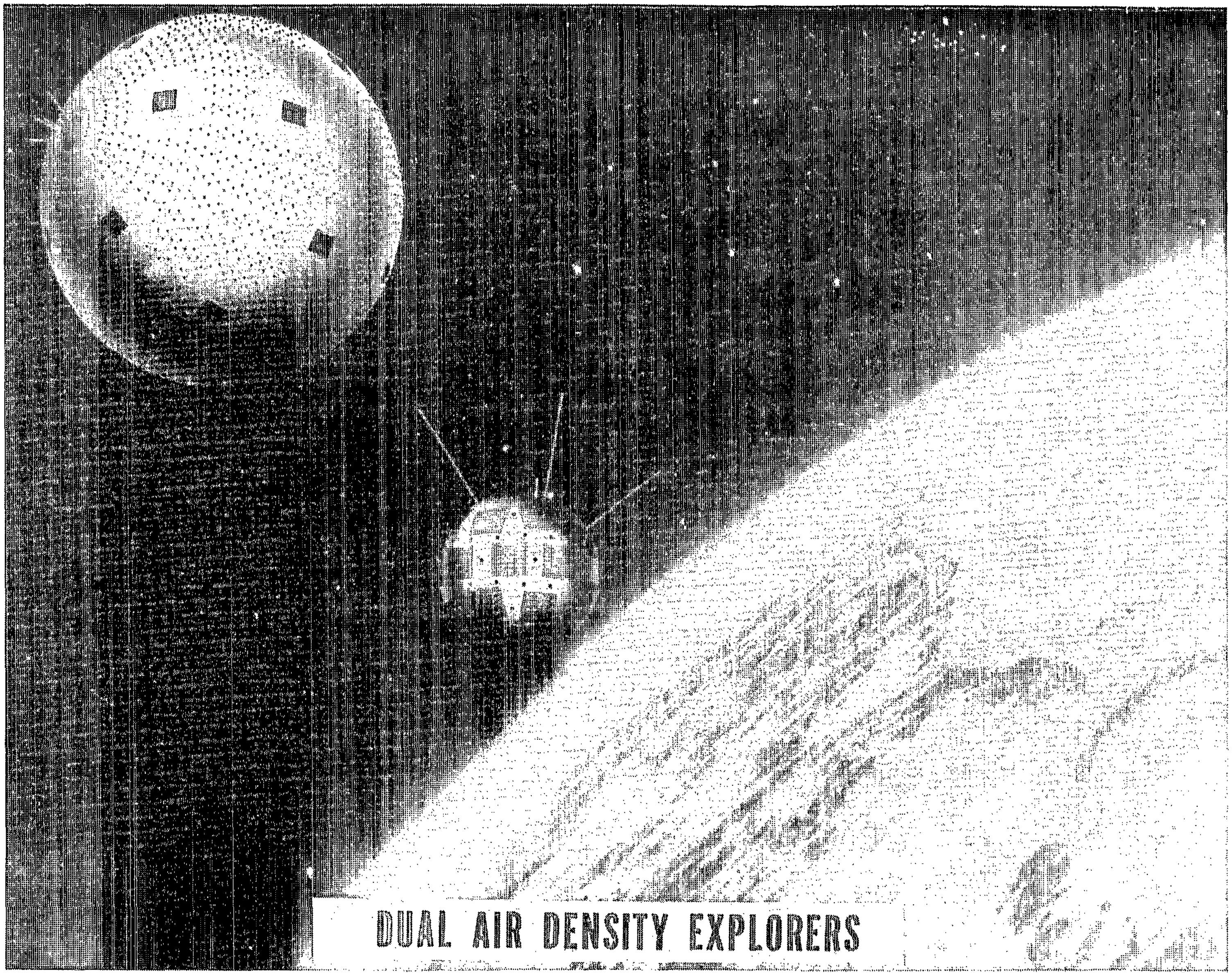

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Figure 1.- Artist's concept of DAD Explorer satellites in orbit.

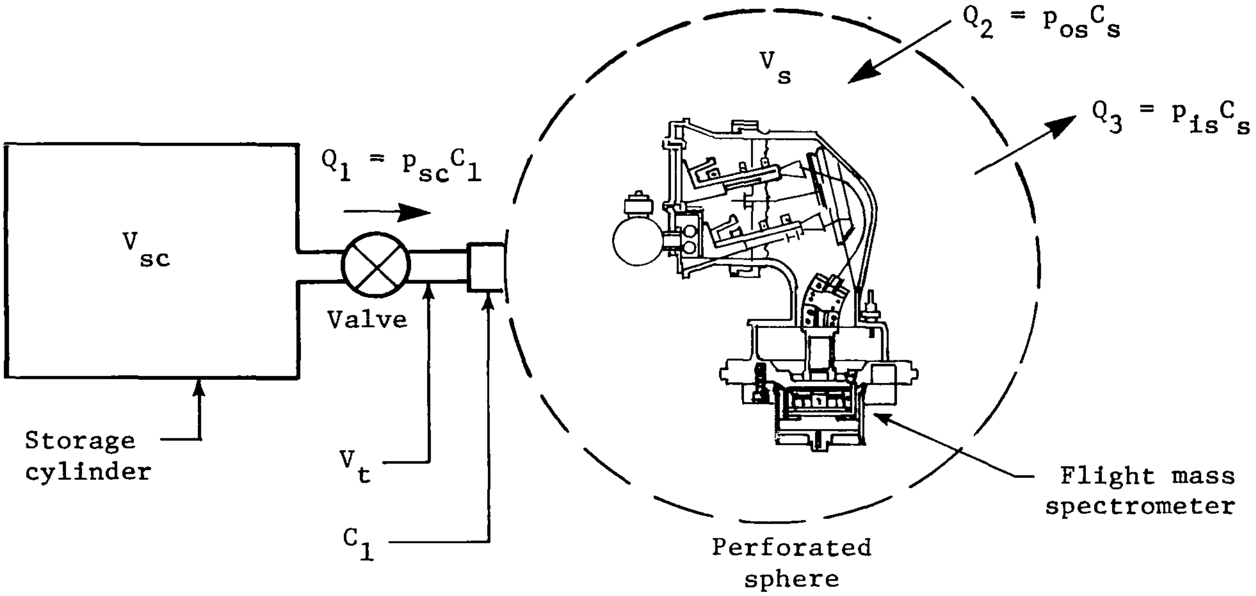

Figure 2.- Schematic of inlet system and flight mass spectrometer.

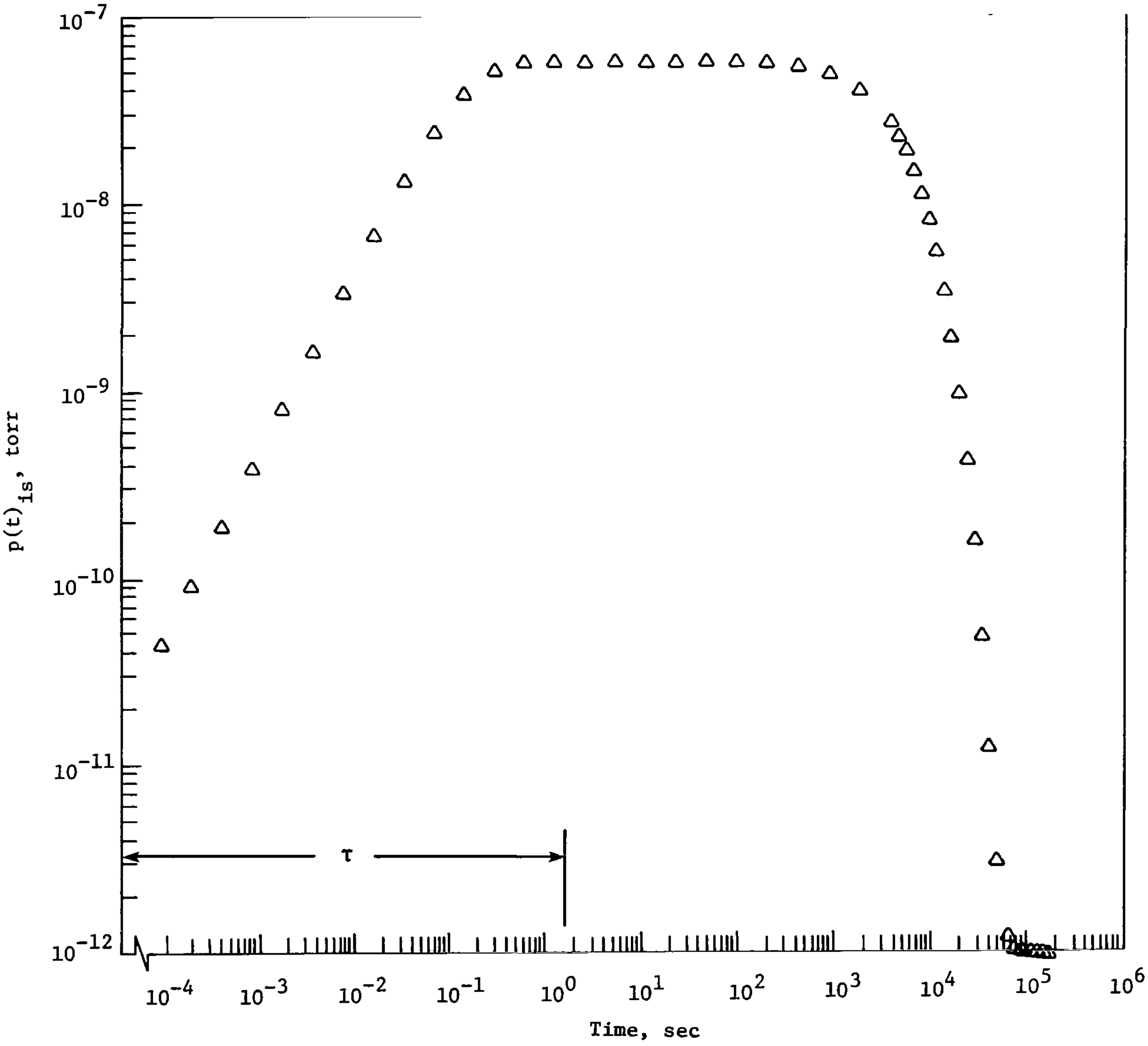

Figure 3.- Relationship between calibration gas pressure and time for argon-40 at 298 K in 0.762-m satellite. Valve open.

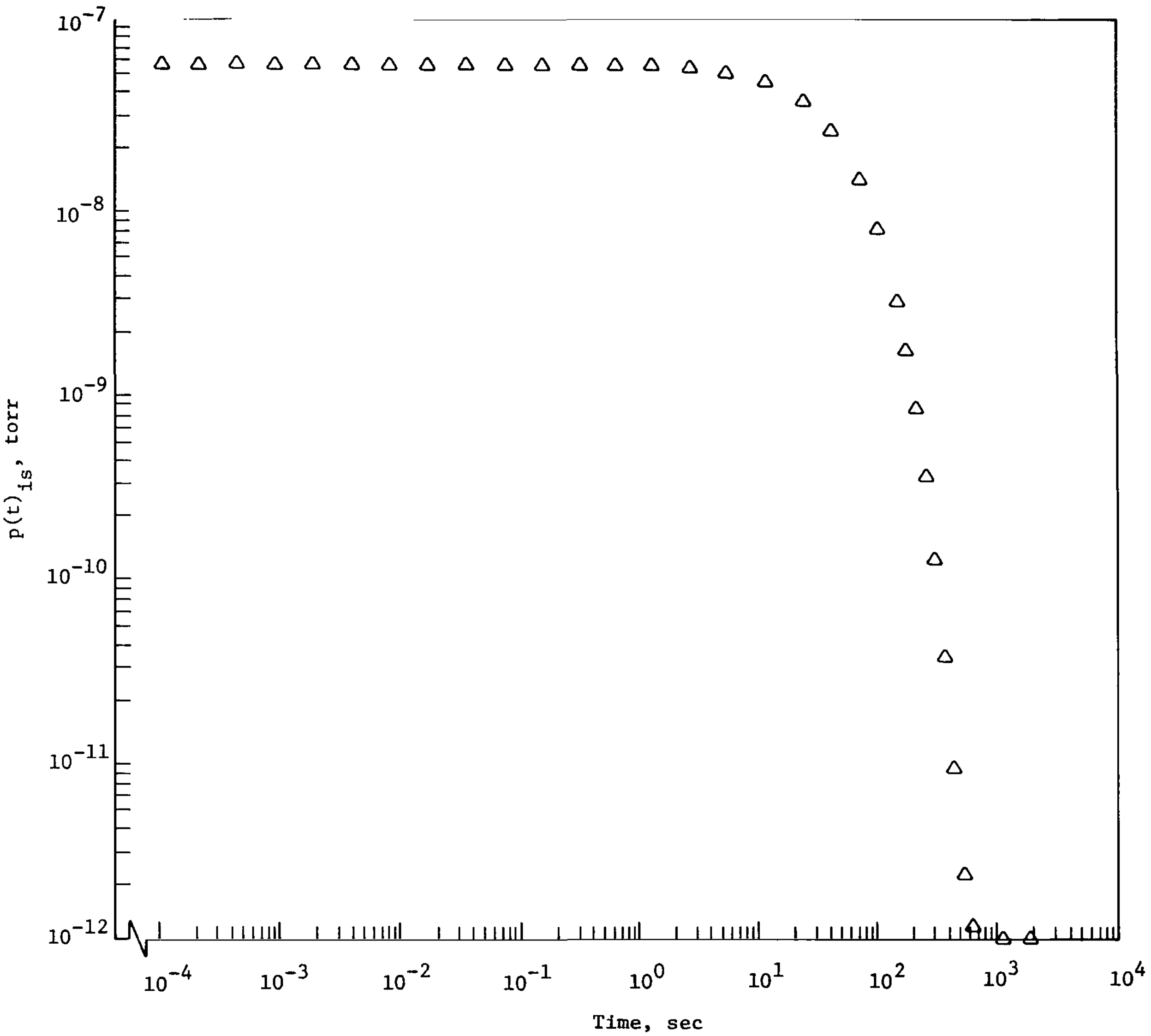

Figure 4.- Relationship between calibration gas pressure and time for argon-40 at 298 K in 0.762-m satellite. Valve closed.

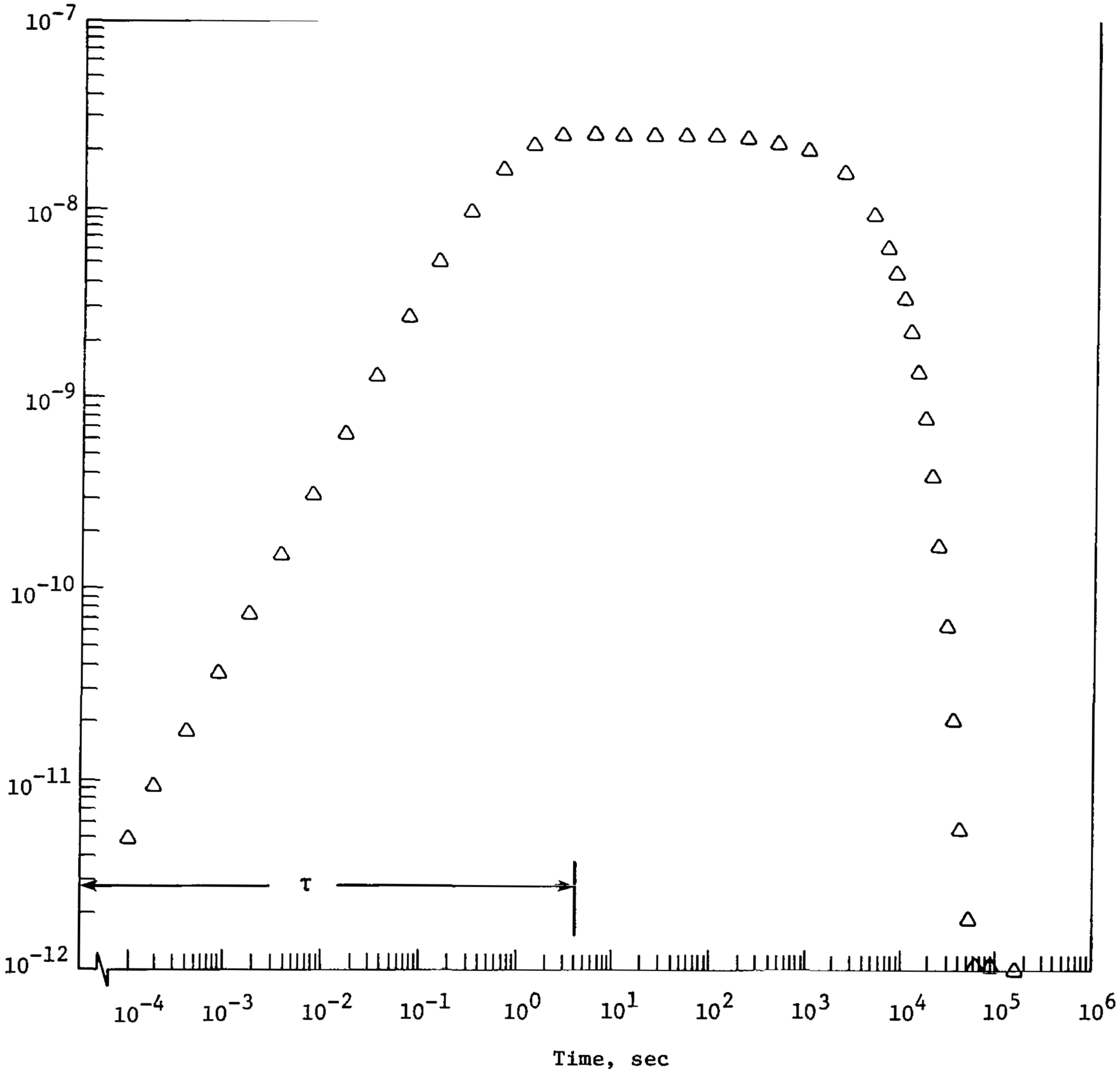

Figure 5.- Relationship between calibration gas pressure and time for argon-40 at 298 K in 3.66-m satellite. Valve open.

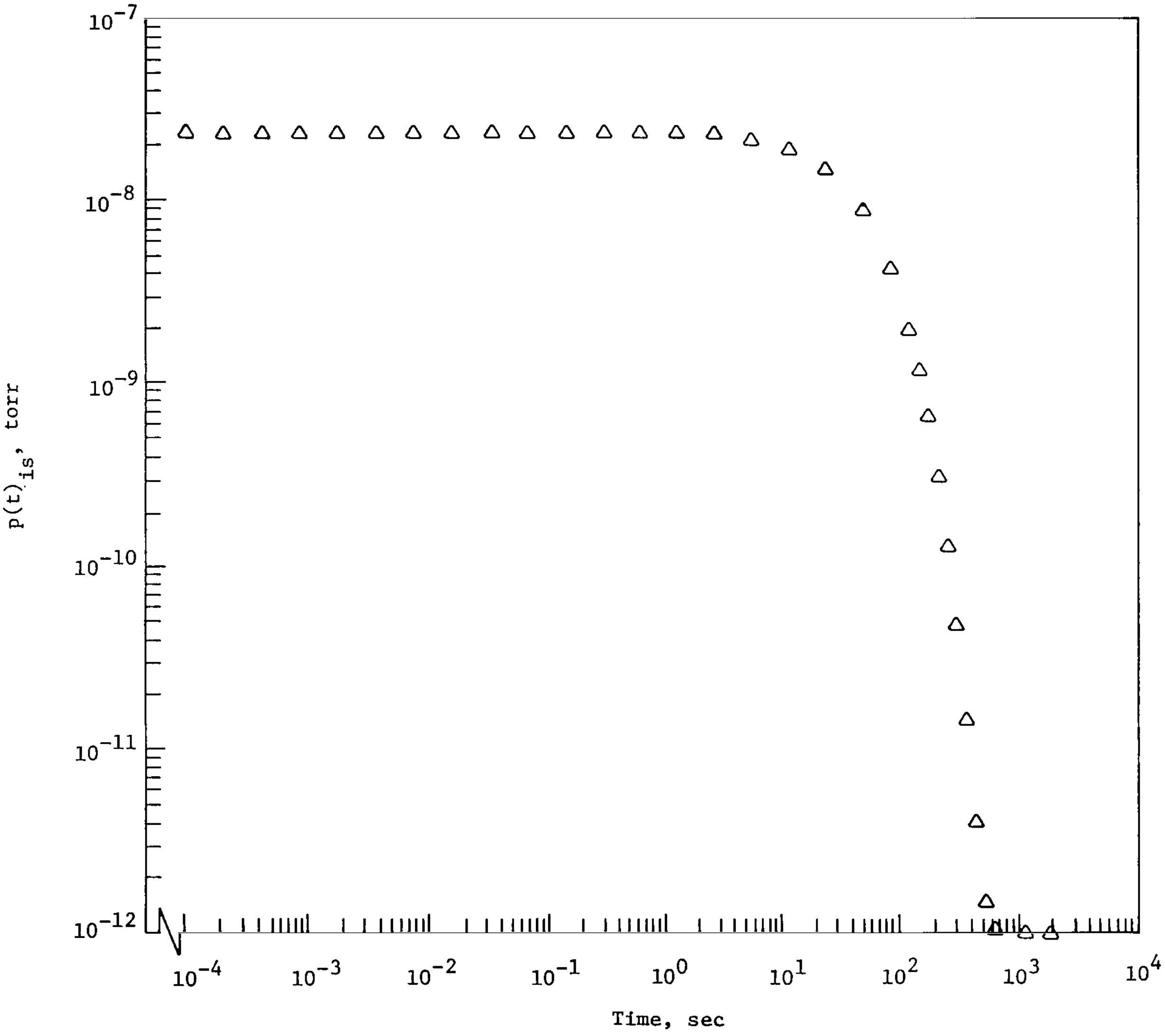

Figure 6.- Relationship between calibration gas pressure and time for argon-40 at 298 K in 3.66-m satellite. Valve closed.

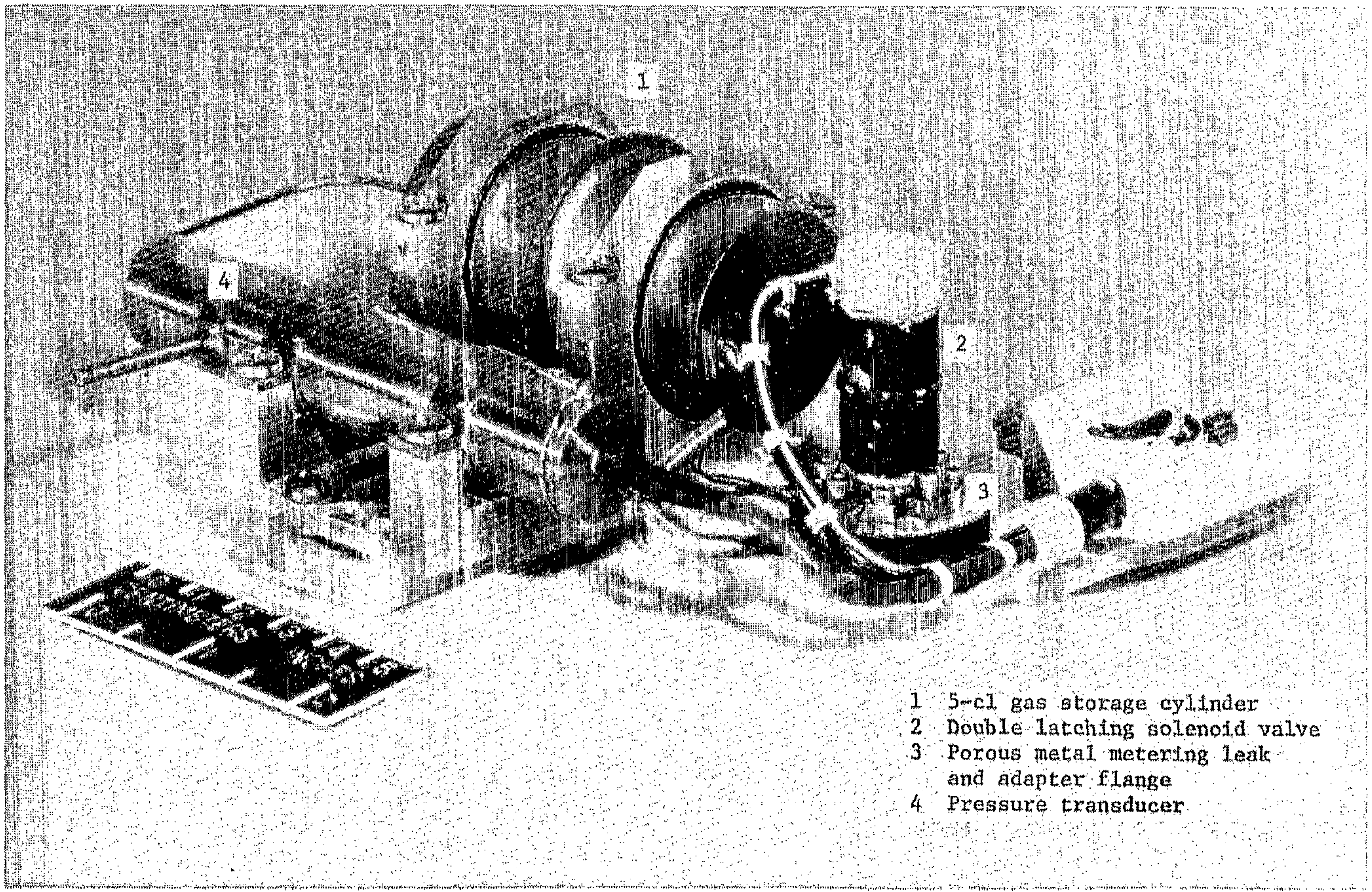

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Figure 7.- In-flight gas calibration system.

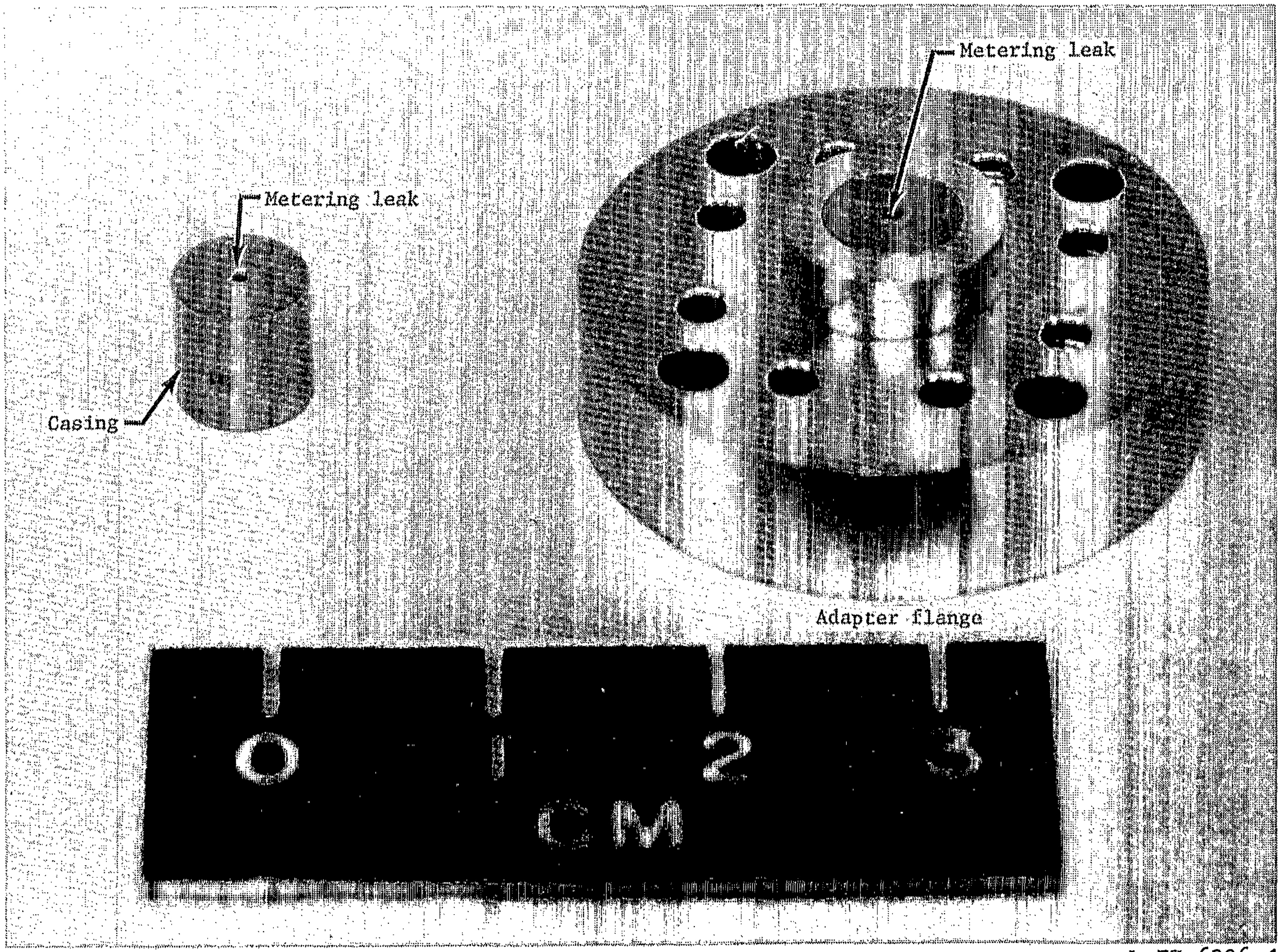

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Figure 8.- Porous metal metering leak and adapter flange.

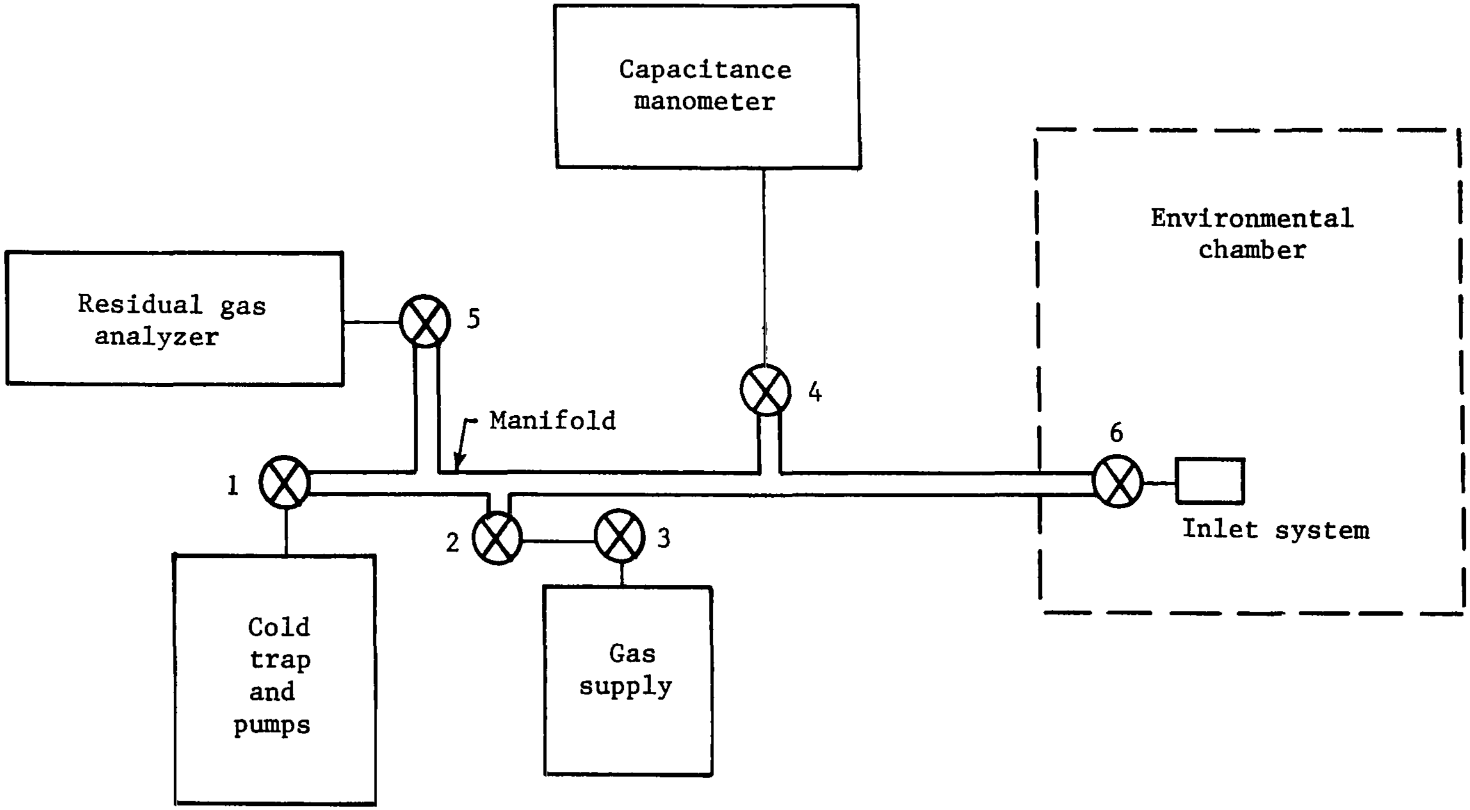

Figure 9.- Laboratory system used to prepare gas inlet system.

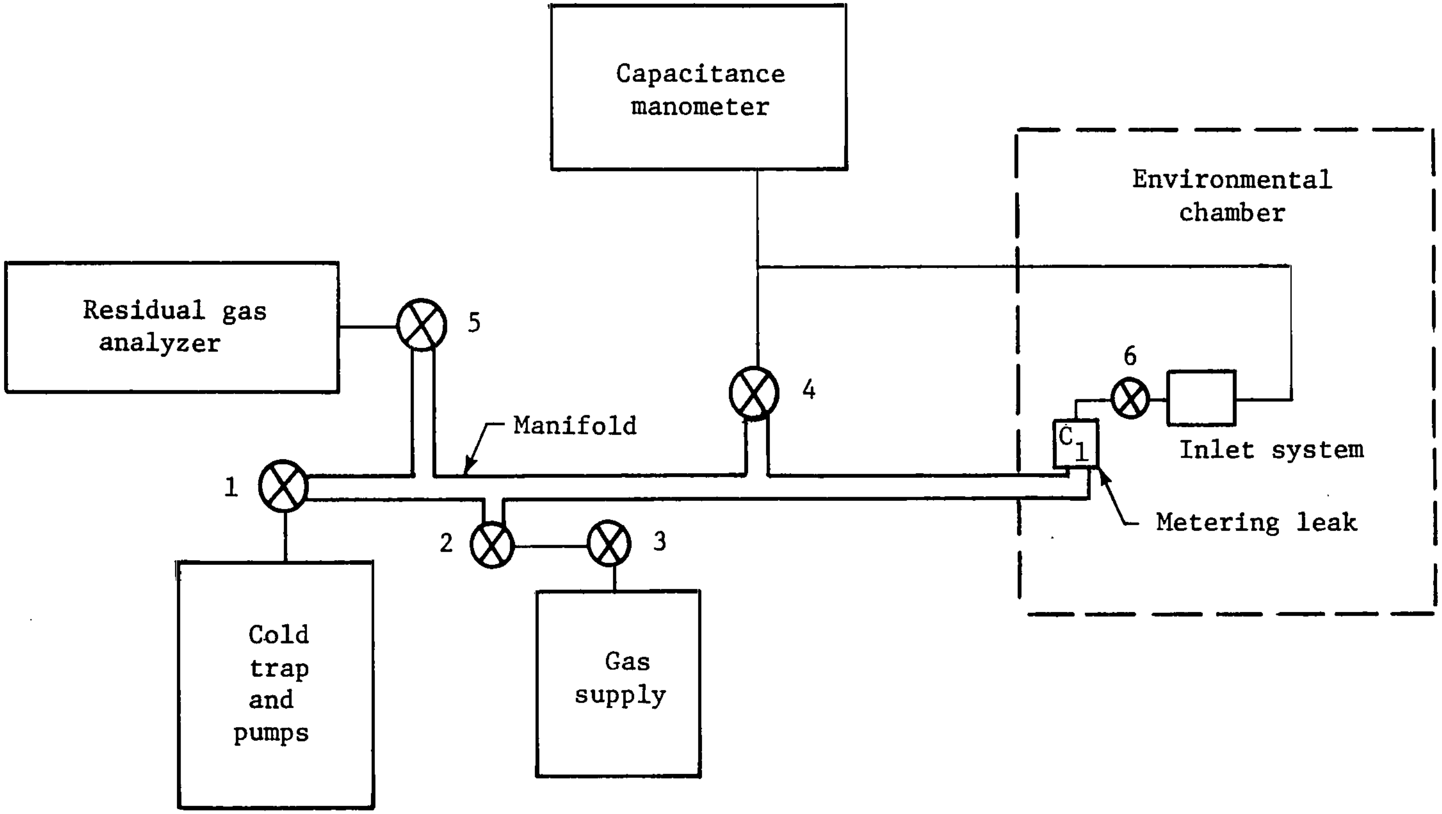

Figure 10.- Laboratory system for calibration of porous metal metering leak.

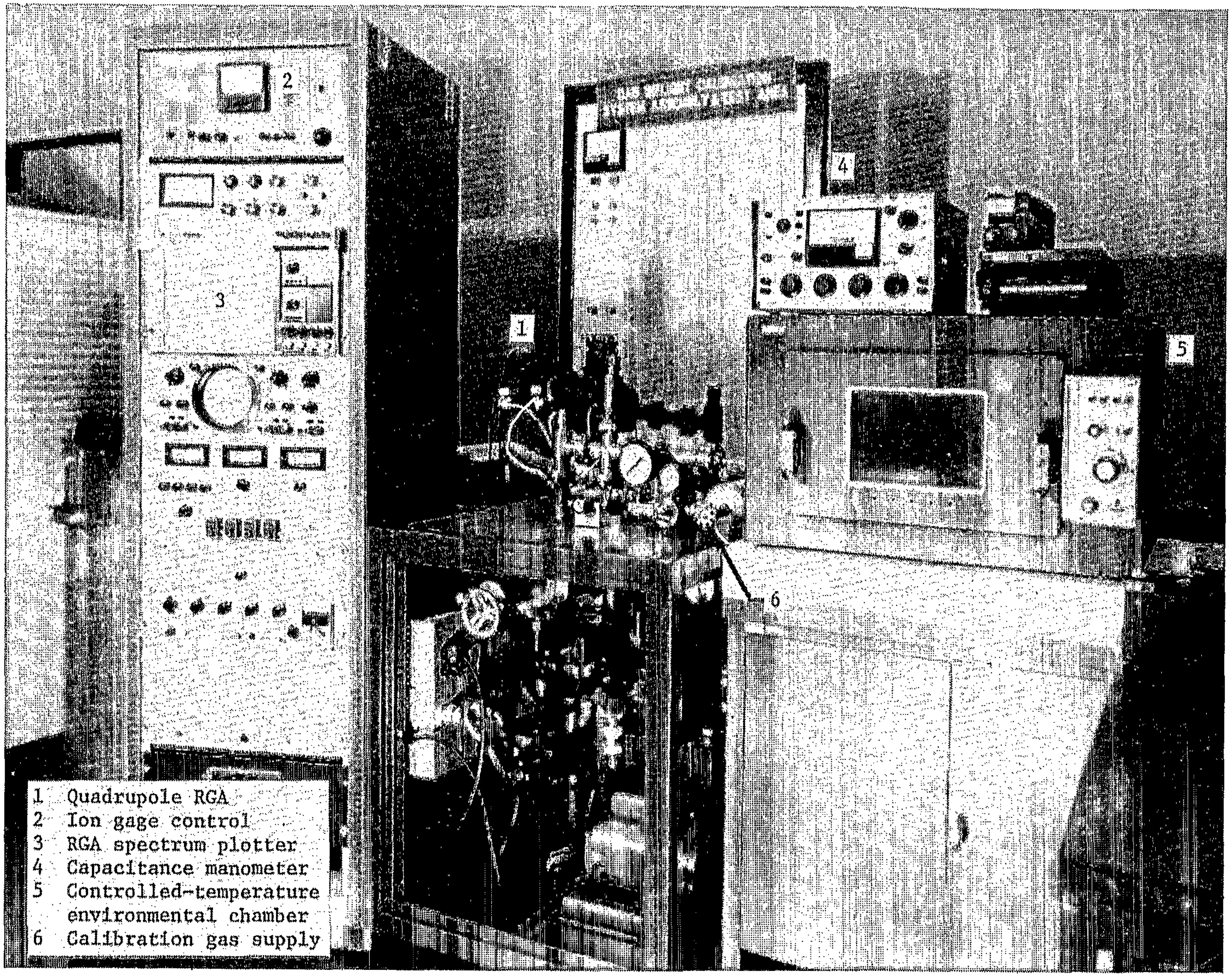

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Figure 11.- Laboratory calibration system. (The abbreviation RGA denotes residual gas analyzer.)

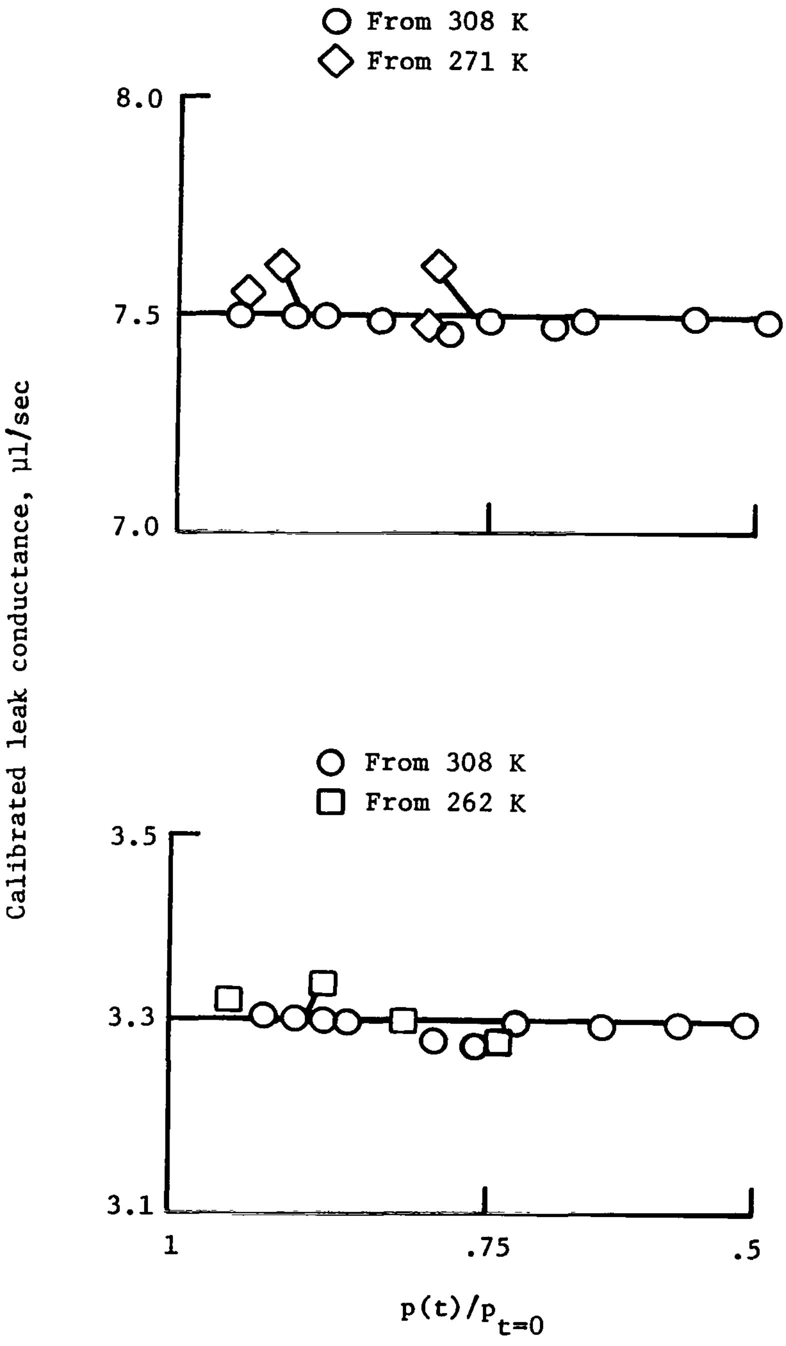

Figure 12.- Conductance for helium-3. Data in each plot are for different porous metal metering leak.

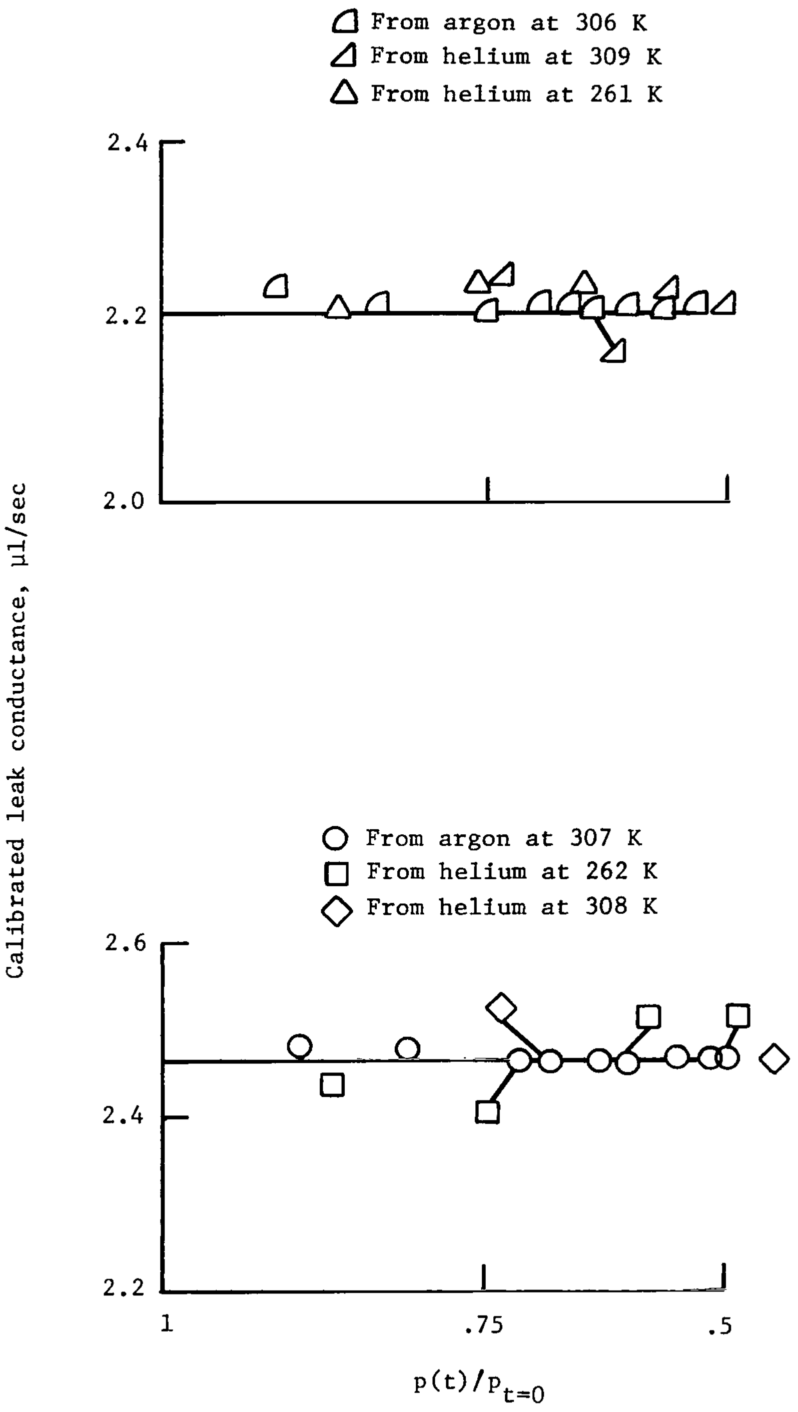

Figure 13.- Conductance for argon-40 and helium-4. Data in each plot are for different porous metal metering leak.

1. Report No. NASA TP-1170	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle A SMALL GAS INLET SYSTEM FOR ORBITAL MASS-SPECTROMETER CALIBRATIONS		5. Report Date April 1978	
		6. Performing Organization Code	
7. Author(s) Alphonsa Smith and Richard E. Stell		8. Performing Organization Report No. L-11988	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 505-05-43-01	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Paper	
		14. Sponsoring Agency Code	
15. Supplementary Notes			

16. Abstract

A gas inlet system is described for generating precise gas pressures that are to be used as calibration references for the mass spectrometers aboard the dual air density (DAD) Explorer satellites. This gas inlet system was developed as an in-flight calibration technique in which a known amount of onboard gas is released in the satellite cavity and is detected by the mass spectrometer. Although several flight mass-spectrometer experiments have been proposed, none make use of the in-flight calibration technique described in this report. Laboratory measurements and calibration of the metering leak technique for the gas inlet systems are discussed. The systems tested have metering leak rates between 2 and 4 μl/sec at 298 K for argon-40, and they produce molecular flow up to 100 torr, which is the highest test pressure in this experiment. Test data show that metering leak rates are reproducible within 1 percent of established means for helium-3, helium-4, and argon-40.

17. Key Words (Suggested by Author(s)) Mass spectrometer Calibration Inlet system		18. Distribution Statement Unclassified - Unlimited Subject Category 35	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	22. Price* $4.50

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1978

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