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MODELING AND MEASUREMENT OF THE PERFORMANCE OF A BRANCHED CONDUIT SAMPLING SYSTEM IN A MASS SPECTROMETER LEAK DETECTOR

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ABSTRACT

In the leak testing of a large engineering system, one may distinguish three stages, namely leakage measurement by an overall enclosure, leak location, and leakage measurement by a local enclosure. Sniffer probes attached to helium mass spectrometer leak detectors are normally designed for leak location, a qualitative inspection technique intended to pinpoint where a leak is but not to quantify its rate of discharge. The main conclusion of the present effort is that local leakage measurement by a leak detector with a sniffer probe *is* feasable provided one has: (a) quantitative data on the performance of the mass separator cell (a device interior to the unit where the stream of fluid in the sample line branches); and (b) a means of stabilizing the mass transfer boundary layer that is created near a local leak site when a sniffer probe is placed in its imediate vicinity. Theoretical models of the mass separator cell are provided and measurements of the machine-specific parameters in the formulas are presented. A theoretical model of a porus probe end for stabilizing the mass transfer boundary layer is also presented.

SUMMARY

As I wrote in abstract printed nearby, "Sniffer probes attached to helium mass spectrometer leak detectors are normally designed for leak location, a qualitative inspection technique intended to pinpoint where a leak is but not to quantify its rate of discharge". Most long range sniffer probe sampling systems are of branched conduit type. In such a system, sampled gas enters the tip of the sniffer probe, passes down the length of a long hose, and discharges into a so-called *mass separator cell*, a chamber with one inlet and two outlets. A typical chamber pressure in the mass separator cell is 0.18 atm.

One outlet from the mass separator is across the face of a permeable membrane (also called a *window*), on the other side of which is the very low pressure (say 10^{-7} to 10^{-8} atmospheres) typical of the analysis cell of a mass spectrometer leak detector. The meter reading on the leak detector is affected only by the portion of the sampled gas that passes across this permeable window. The rest of gas that enters the mass separator cell is exhausted to the low pressure port of mechanical vacuum pump. Since the inlet end of the sampling line is at atmospheric pressure, sampled gas will not flow through it unless the pressure at the outlet end is less than one atmosphere. In the present instance, the mechanical vacuum pump furnishes this low pressure at the outlet end of the sampling line.

Thus, of all the gas sniffed by the sniffer probe, only a small portion (say one six-hundredth to one eight hundredth) passes across the window of the mass separator cell where it is measured. The *internal supply-to-sample flowrate ratio* (ISSFR) (also called the *permeation ratio*) is the ratio of the rate of transport of helium *into the probe tip* to the rate of helium transport *across the separator cell window*. One must, of course, have quantitative knowledge of the ISSFR before one can relate the meter reading on a leak detector to the rate of transport of helium into the probe tip.

An interesting question that arises in this context is whether the ISSFR is a constant of the machine, or whether the IFFSR exhibits a functional dependence upon one or more parameters. To address this question, one must model the transport of helium across the mass separator window. If one assumes that the transport of helium across the window is a diffusion phenomenon, then one may argue that the rate of transport is directly proportional to the partial pressure of helium in the mass separator chamber and that the factor of proportionality is $\kappa A/h$, in which κ is the diffusivity if helium in the window material (in, say, $(\text{cm})^2/\text{s}$), A is the effective cross sectional area of the window (in, say $(\text{cm})^3/\text{s}$), and h is the window thicknwess (in, say, cm).

The present investigation yields formulas for the ISSFR in terms of $\kappa A/h$ and various flow parameters. It also furnishes results of measurements of $\kappa A/h$ under a varity of circumstances to determine whether it is indeed a constant of the machine. The results indicate that $\kappa A/h$ varies slightly with changes in chamber pressure of the mass separator, but that the variations are much weaker than the corresponding variations in other flow parameters.

The ratio of the rate of transport of helium from a leak to the rate of capture of that helium by the sniffer probe is the *external supply-to-sample flowrate ratio* (EFFSR). The present investigation involved the determination of the EFFSR in some simple cases (where a plain probe end is held close to a pinhole leak of known discharge rate) and found values in the range 0.20 to 0.95 , though the results are extremely sensitive to currents of air in the laboratory where the tests is conducted.

Stabilization of the mass transfer boundary layer (the region of exceptionally high concentration of helium near the point leak) by a sponge, pad, or other medium through which the sampled gas is forced to seep promises significant reductions in the variations of the EFFSR due to currents in the room air. This report furnishes a model of the mass transport boundary layer when the porous medium exhibits either of two symmetries (cylindrical or spherical). The recommendations include follow-on research on the development of porous medium probe ends for stabilization of the mass transfer boundary layer.

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INTRODUCTION

1.1 THE NEED FOR LEAK TESTING

The storage and transport of fluid is intrinsic to many engineering devices. The ability of such a device to carry out a given mission and to do so safely is often contingent on *leak tightness*. Accordingly, inspection for leak tightness constitutes a significant portion of the time devoted to between-flight testing of the space shuttle orbiter.

1.2 STAGES IN A GENERIC LEAK TESTING PROGRAM

A useful compendium of the technology for leakage testing was prepared in 1968 by J. WILLIAM MARR on behalf of the General Electric Company and was published as a NASA Contractor's Report under the title *Leakage testing handbook* (Ref. 1). In the leak testing of a large engineering system, one may distinguish three stages: (i) leakage *measurement* by an *overall* enclosure; (ii) leak *location*; and (iii) leakage *measurement* by a *local* enclosure.

The between-flight testing of the space shuttle main engine compartment conforms to a paradigm of this sort. Thus, in stage (i), one may seal off all but two openings of the engine compartment. These openings serve as the inlet and the outlet for *purge gas*. Suspect fluid lines in the compartment are pressurized with *tracer gas* such as helium. Leaked helium then becomes a trace contaminant in the effluent. The concentration of this effluent contaminant may be measured by helium mass spectrometry. When data from such measurements are combined with information about the rate of transport of purge gas, one can deduce the total rate of discharge of tracer gas through all of the leaks in all of the fluid lines that had been pressurized with tracer gas. The foregoing description is a rough representation of the *Helium Signature Test* (Ref. 2) that operations personnel at Kennedy Space Center routinely carry out.

One advances to stage (ii) of the leak test program whenever leakage measurement by an overall enclosure reveals the presence of at least one out-of-specification leak somewhere. A hand-held probe attached to the collection system of a helium-mass-spectrometer leak detector—a *sniffer probe*—is a standard device for the location of such individual leaks. According to the classical paradigm as described by MARR, such a *leak-location* effort yields *qualitative* information—whether tracer gas is or is not leaking from a suspect leak site—but does not provide *quatitative* information about the rate of discharge through a leak, once located.

The reason why a generic sniffer probe does not actually measure the discharge rate from an individual leak is obvious. Even if the leak detector is calibrated so as to give accurate information regarding the rate of transport of helium into the probe tip, the user does not know what portion of the tracer gas discharged from the leak actually enters the probe tip and what remaining portion is dispersed in the surrounding environment. In the Final Report of a Summer Faculty Research Fellowship (Ref. 3), the present author suggested the term *external supply-to-sample flowrate ratio* (ESSFR) for the ratio whose numerator is the rate of discharge of tracer gas from the leak and whose denominator is the rate of transport of tracer gas into the probe tip.

To continue the discussion of the classical paradigm for leak testing a large test object, suppose that leakage measurement by an overall enclosure (stage (i)) has indicated the presence of an out-of-specification leak somewere and that inspection of the test object by a sniffer probe (stage (ii)) has pinpointed the location of a local leak site. One thus advances to stage (iii), namely leakage measurement by a local enclosure. In the classical paradigm, such testing involves the installation of a vacuum bag around the leak site to prevent dispersal of the leaked tracer gas into the surrounding environment. If one is confident that all or nearly all of the leaked tracer gas enters the sampling line of the leak detector, then one can make a quantitative measurement of the discharge through the individual leak.

The cramped quarters of the main engine compartment of the shuttle orbiter, the complexity of cable bundles and plumbing therein, and the general inaccessibility of leak sites render the installation of vacuum bags in the main engine compartment ex-

tremely awkward. Thus, vacuum-bag testing in the main engine compartment amounts to a *heroic measure* that operations personnel resort to only when circumstances make it unavoidable.

One may try to estimate the rate of discharge of tracer gas from a local leak site from information furnished by a sniffer probe, provided one is willing to accept the uncertainties associated with poor understanding of the external supply-to-sample flowrate ratio. Some routine inspection procedures employed by operations personnel in the leak testing of the main engine compartment of the space shuttle orbiter are of this latter kind. Acceptability Criteria pertaining to such inspections are described in SPECIFICATION number MF0001-003 titled "Proof pressure and leak detection–Aerospace plumbing systems and assemblies" prepared by D. R. SUEME & K. R. RAVAL on behalf of Rockwell Corportation (Ref. 4).

1.3 INTERNAL PLUMBING OF A PARTICULAR MASS SPECTROMETER LEAK DETECTOR WITH A BRANCHED CONDUIT SAMPLING SYSTEM

Helium mass spectrometer leak detectors equipped with sniffer probes employ sampling systems that one may group into two broad classes according to their internal plumbing. To understand why this plumbing has the form that it has, one must provide some background on the general layout of mass spectrometer leak detectors.

Every helium mass spectrometer leak detector has an *analysis cell*, which acts as a transducer whose signal is proportional to the partial pressure of a particular gas species identified by the charge-to-mass ratio of its positively charged ion. The analysis cell operates only if the gas in it is rarified, *i.e.* if the mean free path is large compared to the spatial dimensions of the device. The total pressure in the analysis cell must thus be on the order of 10^{-7} atm or less. Thus, every mass spectrometer leak detector has a *high vacuum envelope* containing an analysis cell into which some sampled gas must pass if its partial pressure (or, more precisely, if an electrical signal proportional to the partial pressure) is to be measured.

In a typical mass spectrometer leak detector, a sequence of vacuum pumps maintains the very low pressure in the high vacuum envelope. One pump within that sequence has an input port whose pressure is about the same as that of the analysis cell. I will call that port the *lowest pressure port*. The pumping system is designed so as to maintain near constancy (under normal operating conditions) of the volume transport rate $\dot{\Delta}_{max}$ through the lowest pressure port. The product of $p_{He,ac}\dot{\Delta}_{max}$, in which $p_{He,ac}$ is the partial pressure of helium in analysis cell, is a measure of the flowrate of helium through the high vacuum envelope*. If $\dot{\Delta}_{max}$ is indeed constant, then the flowrate $p_{He,ac}\dot{\Delta}_{max}$ is proportional to $p_{He,ac}$, which, in turn, is proportional to the electrical signal generated by the analysis cell. In this respect, the electrical signal generated by the analysis cell is a measure of the flow rate of helium through the high vacuum envelope. Thus, a modern designer of a leak detector may feel justified in equipping his or her device with a *leak flowrate meter*, whose signal is proportional to the electical current through the target electrode in the analysis cell, but whose scale is demarcated in flowrate units such as atm·(cm)^3/sec.

The pumping system in any leak detector has a limited capacity and this limit places a ceiling on the rate at which sampled gas may be admitted into the high vacuum envelope without exceeding the 10^{-7} atm ceiling on the total pressure there. The simplest type of sniffer probe sampling system is one in which all of the sampled gas that enters the probe tip is admitted into the high vacuum envelope of the leak detector. This arrangement is described by the term *direct conduit* sampling system. Owing to the limitations on pumping capacity described in the opening sentence of this paragraph, the rate of flow through the probe in a direct conduit sampling system must be very low. In addition, the sampling hose that runs from the sniffer probe to the leak detector must be part of the high vacuum envelope itself. To avoid excessive leakage by permeation of atmospheric gasses throgh the hose, its must have a rather thick wall and a rather short length.

In recent years a second kind of sampling system has appeared on the market, whose conduit is

* The beginning of subsection 1.3 below provides some motivation for the representation of flowrate through a streamtube as the product of pressure at a particular cross section with volume transport rate across that section.

branched rather than direct. Thus, sampled gas flows through the sampling line into the chamber of a *mass separator cell* which has one inlet and two outlets. Gas flows through the sampling hose owing to the difference in pressure between atmospheric pressure at the probe tip and the somewhat lower pressure (say 0.18 atm) in the mass separator chamber. Since the sampling hose is not part of the low pressure envelope of the leak detector, it is not subject to the limitations on wall thickness and hose length described in the previous paragraph. Hoses in use in the orbiter processing facility, for example, are made of PVC plastic, have an outside diameter of about 0.5 cm and a length of 100ft.

Of the two outlets from the chamber of the mass separator cell, one is a permeable membrane or *window*, across which a small portion of the sampled gas diffuses. The window is a rigid partition that separates the mass separator chamber from the high vacuum envelope of the leak detector. The relatively low diffusive transport of gas across the window prevents the sampled gas from overwhelming the pumping system for the high vacuum envelope. In a branched conduit sampling system, the overwhelming portion of the sampled gas is exhausted into the low pressure port of a mechanical vacuum pump whose high pressure end vents to the atmosphere. One may thus proclaim

> **The distinctive feature of branched conduit sampling system:** *The electrical signal generated by the analysis cell (and displayed on a flow rate meter) is proportional to the rate of transport of helium across the mass separator window, not to the (much larger) rate of transport of helium through the probe tip.*

Fig. 1 is a schematic diagram showing the internal plumbing of a particular helium mass spectrometer leak detector manufactured by Alcatel (type ASM 110 Turbo CL). Point A is the tip of the sniffer probe; point B is a quick disconnect which enables the sniffer probe hose to be detached from the leak detector cabinet; point C is the inlet to the mass separator chamber; point D is the upstream end of the high vacuum conduit that starts at the mass separator window; path DEF is the portion of the sample conduit that passes through the high vacuum envelope; device FG is a turbumolecular pump whose inlet is the lowest pressure port described earlier; path GH is a moderate vacuum conduit; device H is the low pressure stage of a vane

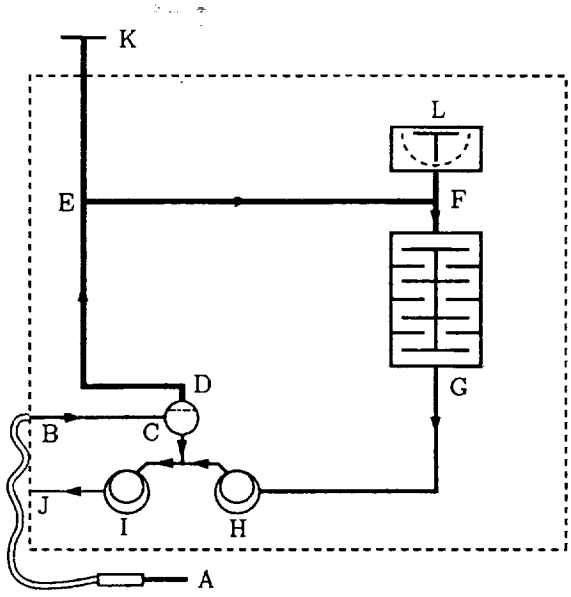

Fig. 1. Internal plumbing of a leak detector featuring a sniffer probe and a branched conduit sampling system.

pump system consisting of two identical statges; device I is the high pressure stage of the pair; station J is the exhaust to the room; device L is the analysis cell; and point K is the a direct input port to the high vacuum envelope (which is capped during normal operation of the sniffer probe).

Most of the sampled gas follows the circuit ABCIJ (the end of which is exhausted to the room), but some of it follows the circuit ABCDEFGHIJ. Only the latter portion affects the signal displayed on the leak flowrate meter.

1.4 INTERNAL AND EXTERNAL SUPPLY-TO-SAMPLE FLOWRATE RATIOS AND THEIR SIGNIFICANCE IN THE INTERPRETATION OF PROBE MEASUREMENTS

Before one can interpret the terms internal supply-to-sample flowrate and external supply-to-sample flowrate, one must clarify what one means by the term *flowrate*. Let $\dot{A}$ (in, say, $(cm)^3/s$) be the rate of trasport of fluid volume across a particular cross section of a streamtube. Let ρ^* (in, say, gm-mole/$(cm)^3$) be the molar density of the fluid averaged over the same cross section. Then the

product $\rho^*\dot{\Delta}$ has the dimensions of gm-mole/s and represents the rate of transport of matter across the streamtube. According to the law of conservation of mass, however, the rate of transport of matter (and thus the product the product $\rho^*\dot{\Delta}$) is the same for all cross sections of the streamtube (even if ρ^* and $\dot{\Delta}$ vary from one station to the next) and is an intrinsic property of the streamtube.

According to the equation of state of an ideal gas,

$$p = \rho^* \mathcal{R} T \,, \tag{1.1}$$

in which p is the pressure (in, say atm), T is the absolute temperature (in, say, °K), and $\mathcal{R}$ is the universal gas constant, whose numerical value is*

$$\mathcal{R} = 82.0560 \, \frac{\text{atm} \cdot (\text{cm})^3}{\text{gm-mole} \cdot {}^\circ\text{K}} \,. \tag{1.2}$$

If one multiplies (1.1) by $\dot{\Delta}$, one obtains

$$p\dot{\Delta} = \rho^* \dot{\Delta} \mathcal{R} T \,. \tag{1.3}$$

It follows that $p\dot{\Delta}$ is directly proportional to the rate of transport of matter $\rho^*\dot{\Delta}$ through the streamtube with a factor of proportionality $\mathcal{R}T$ that depends only on the absolute temperature. Following the standard convention in the leak testing literature, I will refer, here and elsewhere, to the expression $p\dot{\Delta}$ as the *flowrate* through a streamtube.

In subsection 1.2 above, I defined the external supply-to-sample flowrate ratio (ESSFR) to be "the ratio whose numerator is the rate of discharge of tracer gas from the leak and whose denominator is the rate of transport of tracer gas into the probe tip". Thus,

$$\text{ESSFR} = \frac{(p_{\text{He}}\dot{\Delta})_{\text{leak}}}{(p_{\text{He}}\dot{\Delta})_{\text{probe}}} \,. \tag{1.4}$$

By similar reasoning, one may define the *internal supply to sample flowrate ratio* (ISSFR) (also called the *permeation ratio*) by the expression

$$\text{ISSFR} = \frac{(p_{\text{He}}\dot{\Delta})_{\text{probe}}}{(p_{\text{He}}\dot{\Delta})_{\text{window}}} \,, \tag{1.5}$$

in which the subscript in the denominator refers to the streamtube passing through the mass separator window. The flowrate meter on the leak detector furnishes the value of $(p_{\text{He}}\dot{\Delta})_{\text{window}}$.

Suppose that one has a mixture of *calibration gas* whose helium concentration $c_{\text{He}} = p_{\text{He}}/p_{\text{mix}}$ is known (here p_{He} is the partial pressure of helium in the mixture and p_{mix} is the total pressure of all the gases in the mixture). Then

$$p_{\text{He}} = c_{\text{He}} p_{\text{mix}} \,. \tag{1.6}$$

If one multiplies both sides by the volume transport rate of gas mixture into the probe tip $\dot{\Delta}$, one obtains

$$(p_{\text{He}}\dot{\Delta})_{\text{probe}} = c_{\text{He}}(p_{\text{mix}}\dot{\Delta})_{\text{probe}} \,. \tag{1.7}$$

Suppose, further, that one can measure the flowrate $(p_{\text{mix}}\dot{\Delta})_{\text{probe}}$ of calibration gas through the probe tip by a suitable flowmeter. Then both factors in the right member of (1.7) are measurable or known, and so helium transport rate $(p_{\text{He}}\dot{\Delta})_{\text{probe}}$ through the probe tip is expressible in terms of measurable quantities. It follows that the numerator and the denominator in the right member of (1.5) are both measurable and (1.5) furnishes the corresponding value of ISSFR.

It is not obvious that the relation between $(p_{\text{He}}\dot{\Delta})_{\text{window}}$ and $(p_{\text{He}}\dot{\Delta})_{\text{probe}}$ is one-to-one. Even if the relationship is one-to-one, it is not obvious that the relationship is linear. One of the objectives of the present research effort was to determine set of parameters upon which ISSFR depends. Chapter II below addresses this objective in detail.

From the foregoing definitions, one may deduce that

$$\begin{aligned}(p_{\text{He}}\dot{\Delta})_{\text{leak}} &= \frac{(p_{\text{He}}\dot{\Delta})_{\text{leak}}}{(p_{\text{He}}\dot{\Delta})_{\text{probe}}} \cdot \frac{(p_{\text{He}}\dot{\Delta})_{\text{probe}}}{(p_{\text{He}}\dot{\Delta})_{\text{window}}} \cdot (p_{\text{He}}\dot{\Delta})_{\text{window}} \\ &= \text{ESSFR} \cdot \text{ISSFR} \cdot (p_{\text{He}}\dot{\Delta})_{\text{window}} \,. \end{aligned} \tag{1.8}$$

If one has a good model of the action of the mass separator cell, one can relate ISSFR to measurable quantities and to constants of the machine and if the flowrate meter is properly adjusted, one can read $(p_{\text{He}}\dot{\Delta})_{\text{window}}$ from the flowrate meter. Equation (1.8) indicates that one still needs to know the value of ESSFR before one can use a sniffer probe to measure $(p_{\text{He}}\dot{\Delta})_{\text{leak}}$.

* The numerical value for the gas constant was computed from reference values in the *U.S. Standard Atmosphere 1976* (Ref. 5, p3)

The most serious obstacle to the determination of ESSFR is its dependence upon air currents in the environment where the test is taken. If, for example, there is a draft in the room where a sniffer probe is held up to a point leak source, then one would expect the sniffer probe to capture a smaller fraction of the leaked tracer gas (leading to a larger value of ESSFR) than it would capture if there were no such draft. The dynamics of the flow in the neighborhood of a stock sniffer probe and a point leak source in the presence of arbitrary drafts is complicated enough to preclude any quantitative preediction of ESSFR in general. Section III below describes some observations of ESSFR in various conditions, namely (i) when the lealed gas emerges from a duct into which the probe shaft can be inserted; (ii) when the leak is from a point source on a flat surface and the probe is placed at at 45° angle to that surface; and (iii) when the leak is from a point source on a flat surface and the probe shaft is laid flat aganist the surface with the probe tip some 4mm away from the point source. In all these cases, the value of ESSFR depended upon room drafts, but was in the range $0.20 < \text{EFFSR} < 0.95$.

Fortunately, with modifications of the environment through which the tracer gas passes one may expect to reduce the uncertainties considerably. Suppose, for example, that tracer gas leaks from a point on a planar surface. One may construct a hemispherical sponge with a hole along its axis of symmetry that just fits the shaft of the sniffer probe (so the probe tip is at the center of the flat face of the sponge). If one places the sponge flush against the leak surface and centered on the leak, then one may expect the flow of air through the sponge to be affected far more by friction within the sponge than by room drafts. In this respect, one may expect that the use of porous medium probe ends may stabilize the *mass transfer boundary layer*, *i.e.* the region containing helium rich air in the vicinity of the point leak against which the probe tip has been placed.

A second objective of the present research effort was thus to determine (analytically) the distribution of helium through a porous medium probe end. Section IV of this report addresses this objective in detail.

1.5 OBJECTIVES OF THE PRESENT EFFORT

As I have pointed out in the preceeding subsection, the present research effort adressed two main objectives, namely

1. To determine the set of parameters upon which the internal supply-to-sample flowrate ratio (ISSFR) depends and to evaluate the machine specific constants in the formula for ISSFR for a particular device.
2. To determine the distribution of helium concentration in the interior of a porous medium probe end of simple form.
3. To indicate how knowledge of the helium distribution in the porous probe end can be used to design probe ends that promise relativly high values of the external supply-to-sample flowrate ratio (ESSFR).

SECTION TWO

THE MASS SEPARATOR CELL: PERFORMANCE PARAMETERS AND THEIR MEASUREMENT

2.1 GRADIENT-FLUX RELATIONSHIPS IN A GENERIC DIFFUSION PROCESS

Let ρ^*_{He} denote the molar density of helium (in, say gm-moles/(cm)^3) in some background material (which may, for example, be the mass separator window or air). If ρ^*_{He} is nonuniform, one expects that helium will diffuse in the direction of most rapid decrease of ρ^*_{He}. Let $\mathbf{u}_{He}$ (in, say, (cm/s)) denote the migration velocity of helium through the background material. One expects that $\mathbf{u}_{He}$ will, in general, be a function of both position and time. Now the vector $\nabla\rho^*_{He}$ (in, say, gm-moles/(cm)^4) points in direction of most rapid *increase* of ρ^*_{He} and its magnitude $|\nabla\rho^*_{He}|$ equals the slope of the curve of ρ^*_{He} with respect to arc length in that direction. Thus the vector $-\nabla\rho^*_{He}$ points in direction of most rapid *decrease* of ρ^*_{He}. The simplest standard model of diffusion thus asserts that

$$\rho^*_{He}\mathbf{u}_{He} = -\kappa\nabla\rho^*_{He} , \tag{2.1}$$

in which κ is the *diffusivity* of helium through the background material. In view of the units of measurement furnished earlier for ρ^*, $\nabla\rho^*$, and $\mathbf{u}_{He}$ one concludes that the corresponding units for κ compatible with (2.1) are (cm)^2/s.

2.2 DIFFUSION OF HELIUM ACROSS THE MASS SEPARATOR WINDOW

Suppose that the mass separator window has cylindrical symmetry. Let z be an axial coordinate measured along the axis of symmetry. For definiteness, let the plane $z = 0$ be the face of the window that abuts the mass separator chamber and let the plane $z = h$ be the face that abuts the high vacuum envelope of the leak detector. Thus, helium diffuses in the direction of increasing z and the only nontrivial component of the vector equation (2.1) is the z-component. This component reads

$$\rho^*_{He}w_{He} = -\kappa\frac{d\rho^*_{He}}{dz} , \tag{2.2}$$

in which w_{He} is the z-component of $\mathbf{u}_{He}$.

Let A be the cross sectional area of the mass separator window. If one multiplies (2.2) by A, one obtains

$$\rho^*_{He}w_{He}A = -\kappa A\frac{d\rho^*_{He}}{dz} . \tag{2.3}$$

Now $w_{He}A$ is the rate of transport of helium volume, $\dot{\Delta}$, across a typical plane z = constant internal to the window. One may therefore write (2.3) in the form

$$\rho^*_{He}\dot{\Delta} = -\kappa A\frac{d\rho^*_{He}}{dz} , \tag{2.4}$$

In the first paragraph of subsection 1.4 above, I pointed out that $\rho^*_{He}\dot{\Delta}$ is the rate of transport of helium (in, say gm-moles/s) through a streamtube which, in this case, is the tube bounded by the side edge of the mass separator window.

Consider, now, the region between the plane $z = 0$ and any other plane z = constant in the window. If the diffusion is steady in time, there is no accumulation of helium between these planes, *i.e.* inward transport of helium across the plane $z = 0$ is balanced by outward transport of helium across the plane z = constant. It follows that

$$(\rho^*_{He}\dot{\Delta})|_{z=0} = (\rho^*_{He}\dot{\Delta})|_{z=\text{constant}} \tag{2.5}$$

for any z greater than 0 and less than h. One concludes that the left member of (2.4) is independent of z. If one integrates (2.4) with respect to z from $z = 0$ to $z = h$, one obtains, therefore,

$$\rho^*_{He}\dot{\Delta}h = -\kappa A\left(\rho^*_{He}|_{z=h} - \rho^*_{He}|_{z=0}\right) , \tag{2.6}$$

In the present application,

$$\rho^*_{He}|_{z=h} \ll \rho^*_{He}|_{z=0} , \tag{2.7}$$

which expresses the assumption molar density of helium in the high vacuum envelope of the leak detector (where the total pressure is less that 10^{-7} atm) is very much smaller than the molar density of helium in the mass separator chamber (where the total pressure is some modest fraction of an atmosphere, such as 0.18 atm). In view of (2.7), equation one may apporoximate (2.6) by the simpler equation

$$\rho^*_{He}\dot{\Delta}h = \kappa A\rho^*_{He}|_{z=0} , \tag{2.8}$$

or

$$\rho^*_{\rm He}\dot{\Delta} = \frac{\kappa A}{h}\rho^*_{\rm He}|_{z=0} \ , \qquad (2.9)$$

Now the partial density $\rho^*_{\rm He}|_{z=0}$ of helium on the boundary of the mass separator chamber is related to the partial pressure $p_{\rm He}$ of helium there by an equation analogous to (1.1) *i.e.*

$$p_{\rm He} = \rho^*_{\rm He}\mathcal{R}T \ . \qquad (2.10)$$

If one multiplies both sides of (2.9) by $\mathcal{R}T$ and makes use of (2.10), one obtains

$$(p_{\rm He}\dot{\Delta})_{\rm window} = \frac{\kappa A}{h}p_{\rm He}|_{z=0} \ , \qquad (2.11)$$

Equation (2.11) is the model of diffusion across the mass separator window that I have employed in throughout present investigation. The values of A and h are constants for any particular mass separator window. One expects that the diffusivity κ for helium diffusing through the window material should be proportional to some positive power of the absolute temperature T, but not neccesarily to anything else. If κ is indeed dependent only on T, then it should not change from one experiment to the next, provided the experiments are all run at the same temperature. Equation (2.11) suggests that $\kappa A/h$ is a basic performance parameter of the machine. I will discuss methods for the determination of $\kappa A/h$ (suitable units for which are $(\mathrm{cm})^2/s$) in the following subsections.

2.3 TWO STEADY FLOW METHODS FOR MEASURING THE PARAMETER $\kappa A/h$ OF A MASS SEPARATOR WINDOW

2.3.1 A METHOD THAT EMPLOYS TWO RESERVOIR TYPE LEAKS AND ULTRA HIGH PURITY NITROGEN.

Fig. 2, printed nearby, is a schematic diagram of the apparatus that employs two reservoir leaks. The acronyms in the figure have the following interpretations: (i) AC stands for *analysis cell*; TMP stands for *turbomolecular pump*; VP stands for *vane pump*, of which there are two identical stages labeled *first* and *second*; MSC stands for *mass separator cell*; RL stands for *reservoir leak*, of which there are two labeled *internal* and *external* (relative to the high vacuum envelope); PG stands for *pressure gauge*; QD stands for *quick disconnect*; and FM stands for *flowmeter*, of which there one for the probe and one for the vent.

Both of the reservoir leaks are equipped with hand valves. The purpose of the internal reservoir leak is to validate the zero, peak, and gain setting of the flowrate meter, whose signal is proportional to the electrical current of the helium ion beam, but whose scale is demarcated in units of leak flowrate as (*cf.* the discussion in subsection 1.3 above). One may shut off the hand valve on the external reservoir leak bottle and disconnect the sniffer probe, then adjust the flowrate meter to force agreement between the meter reading and the certification label on the internal reservoir leak bottle. When the agreement is satisfactory, one shuts the hand valve on the internal reservoir leak bottle and thenceforth interprets the meter reading as the measured value of $(p_{\rm He}\dot{\Delta})_{\rm window}$.

Once the meter is adjusted and the hand valve on the internal reservoir leak is shut off, one may attach the sniffer probe (keeping the hand valve on the external reservoir leak shut) and begin to flow ultra high purity nitrogen through the sniffer probe line. The arrangement in Fig. 2 is meant to ensure that all of the gas that enters the probe tip is nitrogen and that the pressure of the gas at the probe tip is atmospheric. This condition is achieved if the two flow meters shown are identical, are arranged in the symmetric pattern shown, and if the hand valve on the nitrogen supply regulator is adjusted so that the readings from the two flow meters are equal. In tests under the conditions described in the last paragraph, I have verified that the leak flowrate meter continues to read zero. Thus, any helium contaminant in the ultra high purity nitrogen supply I used this summer is below the noise level in the measurement system.

Next, one opens the hand valve on the external reservoir leak and observes the response of the leak flowrate meter. The effect is usually to release a slug of helium into the system (which produces a transient spike in the flowrate meter reading), followed by a slow decay of the indicated value of $(p_{\rm He}\dot{\Delta})_{\rm window}$. One must often wait for a half hour or more for the signal to appear to stabilize at a resonably steady value. When it does, one may assume that the total number of moles per unit time of gas (both helium and nitrogen) that enter the mass separator cell is equal to $(\mathcal{R}T)^{-1}$ times

$$(p_{\rm He}\dot{\Delta})_{\rm RL,ex} + (p_{\rm N_2}\dot{\Delta})_{\rm probe} \ . \qquad (2.12)$$

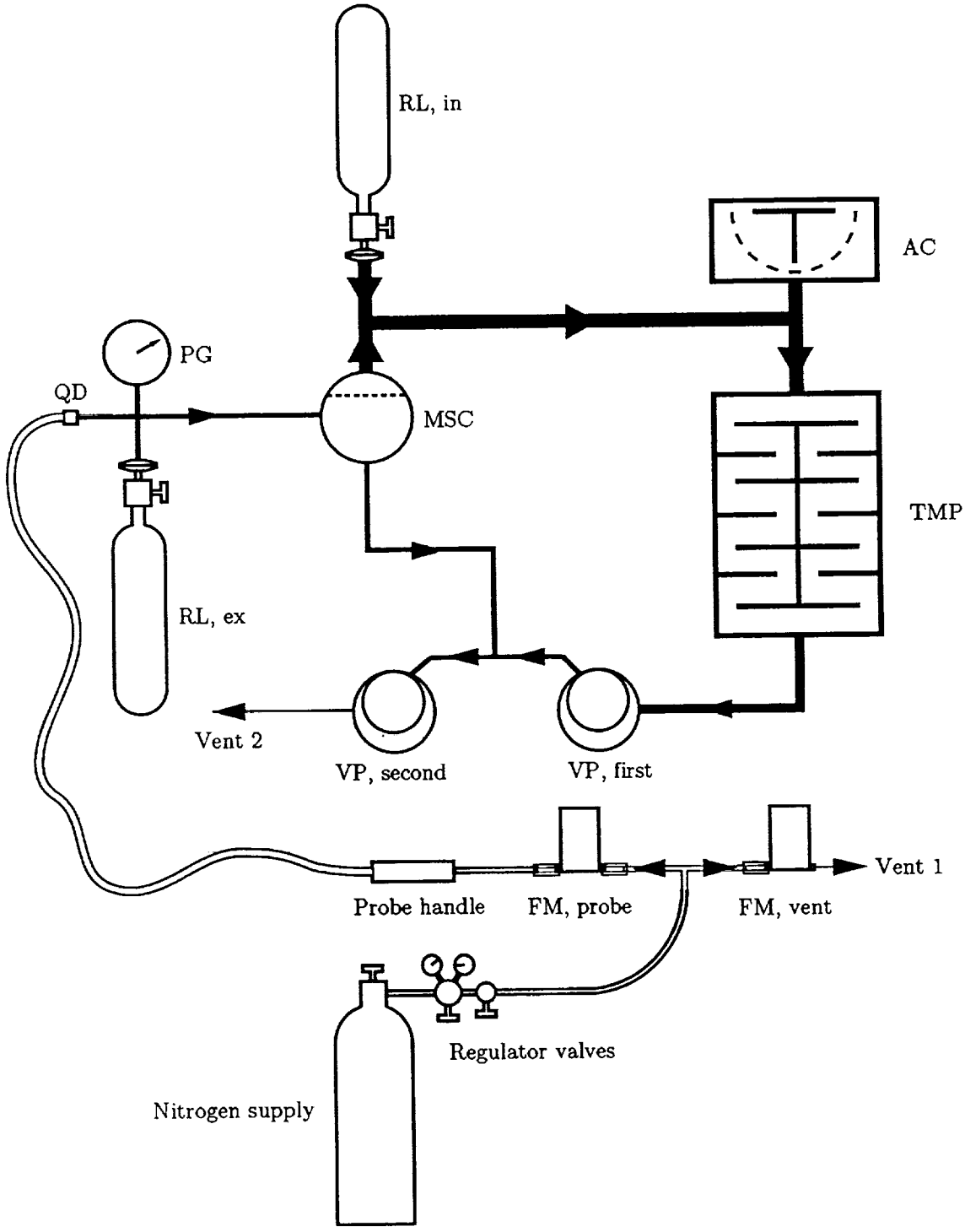

Fig. 2. Schematic diagram of apparatus for tests involving two reservoir leaks

If one assumes that the gas that enters the mass separator cell is a well mixed solution of helium in nitrogen, one may represent the concentration c_{He} of helium in the mass separator chamber by

$$(c_{He})|_{MSC} = \frac{(p_{He})_{chamber}}{(p_{He})_{chamber} + (p_{N_2})_{chamber}} . \quad (2.13)$$

Now the volume occupied by the helium component of a unit mass of a solution of helium in nitrogen is equal to the volume occupied by the nitrogen component. In particular, there is no need to distinguish between the volume transport rate $\dot{\Delta}$ of helium and nitrogen in the mixture that enters the mass separator chamber. One may thus multiply the numerator and the denominator of (2.13) by the common factor $\dot{\Delta}$ to obtain

$$(c_{He})|_{MSC} = \frac{(p_{He}\dot{\Delta})_{chamber}}{(p_{He}\dot{\Delta})_{chamber} + (p_{N_2}\dot{\Delta})_{chamber}} . \quad (2.14)$$

Now all of the helium that enters the chamber must come from the external reservoir leak and all of the nitrogen that enters the chamber must come from the probe tip. It follows that

$$(p_{He}\dot{\Delta})_{chamber} = (p_{He}\dot{\Delta})_{RL,ex} \quad (2.15)$$

$$(p_{N_2}\dot{\Delta})_{chamber} = (p_{N_2}\dot{\Delta})_{probe} \quad (2.16)$$

In view of (2.15) and (2.16), one may write (2.14) in the equivalent form

$$(c_{He})|_{MSC} = \frac{(p_{He}\dot{\Delta})_{RL,ex}}{(p_{He}\dot{\Delta})_{RL,ex} + (p_{N_2}\dot{\Delta})_{probe}} . \quad (2.17)$$

The two flowrates in the denominator of (2.17) differ by a large factor. Thus, in the tests I conducted this summer,

$$(p_{He}\dot{\Delta})_{RL,ex} = 5.0 \times 10^{-6} \text{ atm}\cdot(\text{cm})^3/\text{sec} \quad (2.18)$$

according to the label on the leak bottle (which had been prepared by the Calibration Laboratory at KSC). If there are no obstructions in the sniffer probe line, the probe flowrate meter registers a typical value of

$$(p_{N_2}\dot{\Delta})_{probe} = 3.53 \text{ atm}\cdot(\text{cm})^3/\text{sec} \quad (2.19)$$

The denominator of (2.17) is clearly dominated by the term $(p_{N_2}\dot{\Delta})_{probe}$, and one may approximate (2.17) by the simpler expression

$$(c_{He})|_{MSC} \approx \frac{(p_{He}\dot{\Delta})_{RL,ex}}{(p_{N_2}\dot{\Delta})_{probe}} . \quad (2.20)$$

I have indicated why one may approximate the fraction (2.17) by the simpler fraction (2.20). By the same token, one may approximate the fraction (2.13) by the simpler fraction

$$(c_{He})|_{MSC} \approx \frac{(p_{He})_{chamber}}{(p_{N_2})_{chamber}} . \quad (2.21)$$

It follows from (2.20) and (2.21) that

$$\frac{(p_{He}\dot{\Delta})_{RL,ex}}{(p_{N_2}\dot{\Delta})_{probe}} = \frac{(p_{He})_{chamber}}{(p_{N_2})_{chamber}} . \quad (2.22)$$

One may rearrange (2.22) to give an explicit formula for the partial pressure of helium in the mass separator chamber, *viz.*

$$(p_{He})_{chamber} = \frac{(p_{He}\dot{\Delta})_{RL,ex}}{(p_{N_2}\dot{\Delta})_{probe}}(p_{N_2})_{chamber} . \quad (2.23)$$

According to equation (2.11) above,

$$\frac{\kappa A}{h} = \frac{(p_{He}\dot{\Delta})_{window}}{p_{He}|_{z=0}} . \quad (2.24)$$

If one assumes that

$$p_{He}|_{z=0} = (p_{He})_{chamber} \quad (2.25)$$

(whose right member is given by (2.23)), one may rewrite (2.24) in the equivalent form

$$\frac{\kappa A}{h} = \frac{(p_{He}\dot{\Delta})_{window}(p_{N_2}\dot{\Delta})_{probe}}{(p_{He}\dot{\Delta})_{RL,ex}(p_{N_2})_{chamber}} . \quad (2.26)$$

All the terms in the right member of (2.26) are expressible in terms of data one may read from the apparatus illustrated in Fig. 2. Thus: $(p_{He}\dot{\Delta})_{window}$ is the the reading on the leak flowrate meter; $(p_{N_2}\dot{\Delta})_{probe}$ is the reading of the flowrate meter upstream of the probe tip; $(p_{He}\dot{\Delta})_{RL,ex}$ is the flowrate value given on the label of the external reservoir leak (it cf. (2.18) above); and $(p_{N_2})_{chamber}$ is the reading of the pressure gauge PG illustrated in Fig 2. If the window performance parameter $\kappa A/h$ is indeed constant, then measurement of the expression in the right member of (2.26) should give nearly the same value, even if the individual terms in that fraction are varied.

Table 1. Measurements of $\kappa A/h$ with an apparatus involving two reservoir leaks

$(p_{He}\dot{\Delta})_{window}$ atm·(cm)^3/sec	$(p_{N_2})_{chamber}$ atm	$(p_{N_2}\dot{\Delta})_{probe}$ atm·(cm)^3/sec	$\kappa A/h$ * (cm)^3/s	ISSFR†
6.0×10^{-9}	0.180	3.53	0.0236	833
6.1×10^{-9}	0.180	3.53	0.0239	820
8.4×10^{-9}	0.066	0.933	0.0238	595
8.12×10^{-9}	0.0637	8.67	0.0221	616
5.79×10^{-9}	0.0861	1.33	0.0179	864
5.61×10^{-9}	0.100	1.67	0.0187	891
5.6×10^{-9}	0.138	2.53	0.0206	893
5.1×10^{-9}	0.180	3.47	0.0196	980
7.05×10^{-9}	0.106	1.87	0.0248	709
6.8×10^{-9}	0.105	1.80	0.0233	735

* Calculated from (2.26) with $(p_{He}\dot{\Delta})_{RL,ex} = 5.0 \times 10^{-6}$ atm·(cm)^3/sec

† Here ISSFR=$(p_{He}\dot{\Delta})_{RL,ex}$ /$(p_{He}\dot{\Delta})_{window}$

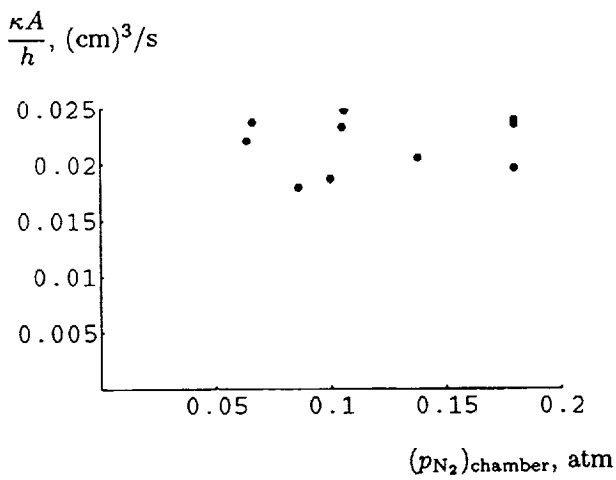

Fig. 3 Window diffusivity parameter $\kappa A/h$ versus chamber pressure in the mass separator cell

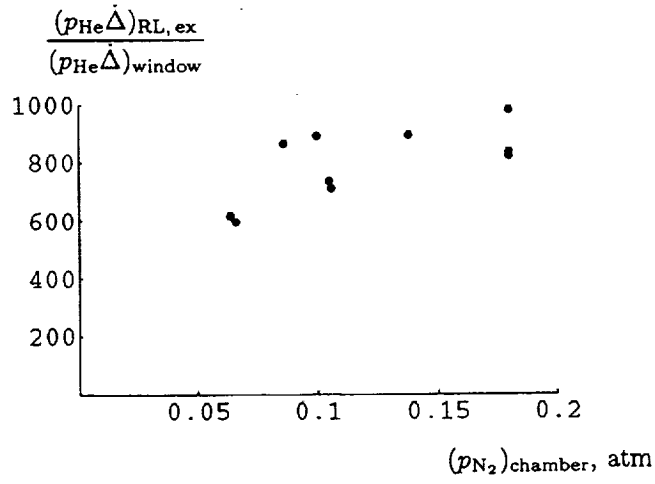

Fig. 4 ISSFR versus chamber pressure in the mass separator

One way of artificially varying the values of the individual terms in the numerator and the denominator of the fraction in the right member of (2.26) is to attach a C-clamp to the plastic tubing between the quick disconnect (labeled QD in Fig. 2) and the mass separator chamber. By tightening the C-clamp, the parameters $(p_{N_2}\dot{\Delta})_{probe}$ and $(p_{N_2})_{chamber}$ both decrease. Table 1 summarizes the results of a test run on July 25, 1994.

The data in Fig. 3 do not indicate any trend that is distinguishable from the scatter. Fig. 4, by contrast, seems to indicate a slight upward trend of ISSFR with increasing pressure in the mass separator chamber.

2.3.2 A METHOD THAT EMPLOYS ONE RESERVOIR TYPE LEAK AND AIR.

Referring again to Fig. 2, suppose that both the regulator valve on the Nitrogen supply and the hand valve on the external reservoir leak are shut off. In this configuration, the sniffer probe sucks atmospheric air, which then flows into the chamber

of the mass separator cell without any addition of helium. Of course, atmospheric air has some helium in it. According to data furnished in the *U.S. Standard Atmosphere, 1976* (Ref. 5), the ambient helium concentration has the average value

$$c_{\mathrm{He,\,air}} = 5.24 \times 10^{-6} \,. \qquad (2.27)$$

If one assumes that the concentration of helium in air does not change between the probe inlet and the mass separator cell, then

$$(p_{\mathrm{He}})_{\mathrm{chamber}} = c_{\mathrm{He,\,air}} (p_{\mathrm{air}})_{\mathrm{chamber}} \,. \qquad (2.28)$$

If one substitutes this result into (2.25) and substitutes the result of that manipulation into (2.24), one obtains

$$\frac{\kappa A}{h} = \frac{(p_{\mathrm{He}} \dot{\Delta})_{\mathrm{window}}}{c_{\mathrm{He,\,air}} (p_{\mathrm{air}})_{\mathrm{chamber}}} \,. \qquad (2.29)$$

As was the case in the experiment described in §2.3.1 above, one may vary the parameters in the problem by adjusting the tightness of a C-clamp on the tubing between the quick disconnect QD in Fig. 2 and the mass separator cell.

On Friday July 22, 1994, a blockage appeared in the tubing between the mass separator chamber and the second stage of the vane pump (*cf.* Fig. 2). Thus, while the chamber pressure in the mass separator cell does not normally rise above 0.185 atm it did so on that Friday and the following Monday until the blockage seemed to clear itself out. The presence of this blockage (which was accidental) presented an opportunity to take data in the case when the chamber pressure in the mass separator cell is well above the value intended by the designers of the device. Table 2 gives data from some tests in this configuration

Fig. 5 is a plot of some of the data in Table 2 Unlike the data in Fig. 3 above, the window diffusivity parameter $\kappa A/h$ *does* indicate a trend that is distinguishable from the scatter, in particular a decrease in $\kappa A/h$ in response to increases in the mass separator chamber pressure in the range 0.2 to 0.8 atmosperes. Apparently, if one is to expect constancy of the window diffusivity parameter $\kappa A/h$, one must ensure that the chamber pressure in the mass seprator cell does not rise above its normal value when the machine is clean and free of blockages.

Table 2. Measurements of $\kappa A/h$ with an apparatus involving one reservoir leak and air

$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}$ atm·(cm)^3/sec	$(p_{\mathrm{air}})_{\mathrm{chamber}}$ atm	$\kappa A/h$ * (cm)^3/s
3.69×10^{-9}	0.0298	0.0236
1.24×10^{-8}	0.0982	0.0241
1.8×10^{-8}	0.0146	0.0235
4.35×10^{-8}	0.725	0.0114
3.38×10^{-8}	0.499	0.0129
2.96×10^{-8}	0.402	0.0140
2.89×10^{-8}	0.387	0.0142
1.93×10^{-8}	0.219	0.0168
1.84×10^{-8}	0.208	0.0168
1.06×10^{-8}	0.0734	0.0275
9.2×10^{-9}	0.0629	0.0279
9.55×10^{-9}	0.0656	0.0277

* Calculated from (2.29) with $c_{\mathrm{He,\,air}} = 5.25 \times 10^{-6}$

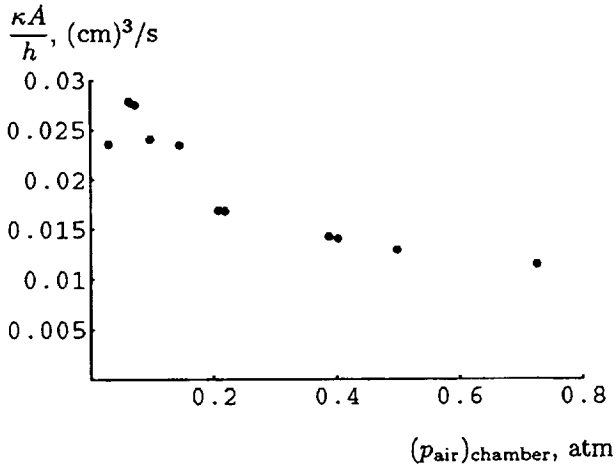

Fig 5. Window diffusivity parameter $\kappa A/h$ versus chamber pressure in the mass separator cell.

I can not think of any good reason why the window performance parameter $\kappa A/h$ should be nonconstant. The best conjecture I can come up with in this instance is that high chamber pressures in the mass separator cell allow relatively higher total pressure in the high vacuum envelope of the leak detector. Such high values of the total pressure in the leak detector may cause the pumping speed

$\dot{\Delta}_{\max}$ (*cf.* §1.3 above) to be nonconstant. If it is, then one can no longer assume that the reading on the leak flowrate meter (which is really proportional to the partial pressure of helium in the analysis cell) is a constant multiple of the helium flowrate through the mass separator window and the results may be skewed accordingly.

2.4 A TIME DEPENDENT FLOW METHOD FOR MEASURING THE PARAMETER $\kappa A/h$ OF A MASS SEPARATOR WINDOW

Fig. 6 illustrates a closed container with a porous stopper. The container is a model of the mass separator cell when the leads into it and out of it are closed and the stopper is a model of the mass separator window.

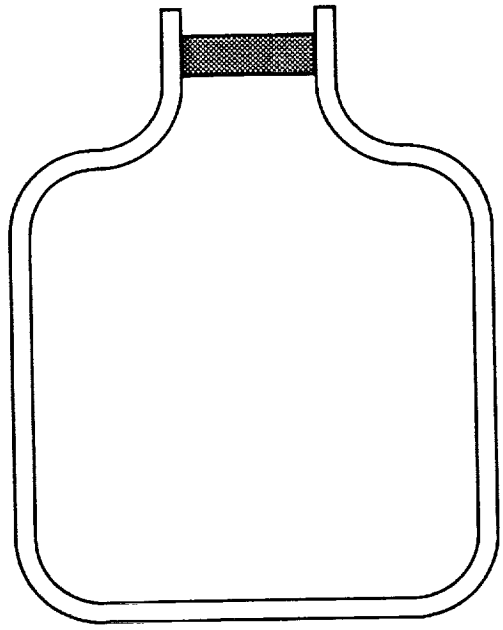

Fig. 6 A closed container with a porous stopper

Let $\mathcal{V}$ be the region interior to the container and let $\partial\mathcal{V}$ be its bounding surface. Let dV denote the differential volume element in $\mathcal{V}$ and let dS denote the differential area element on $\partial\mathcal{V}$. Let $\hat{\mathbf{n}}$ denote the outward unit normal vector at a generic point on $\partial\mathcal{V}$ and let $\mathbf{u}$ denote the helium velocity immediately after it enters the stopper. Now the time rate of change of the total number of moles of helium in $\mathcal{V}$ equals the rate of transport of helium into $\mathcal{V}$ across $\partial\mathcal{V}$, *i.e.*

$$\frac{d}{dt}\left(\iiint_{\mathcal{V}} \rho^*_{\mathrm{He}} dV\right) = \iint_{\partial\mathcal{V}} \rho^*_{\mathrm{He}} \mathbf{u}\cdot(-\hat{\mathbf{n}})\, dS\,. \quad (2.30)$$

I will assume, as before, that the absolute temperature in the mass separator cell and the window is effectively constant. If one multiplies (2.30) by $\mathcal{R}T$ and applies the ideal gas law (2.10), one obtains

$$\frac{d}{dt}\left(\iiint_{\mathcal{V}} p_{\mathrm{He}} dV\right) = \iint_{\partial\mathcal{V}} p_{\mathrm{He}} \mathbf{u}\cdot(-\hat{\mathbf{n}})\, dS\,. \quad (2.31)$$

Now the right member of (2.31) is just the negative of the flowrate through the mass separator window $(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}$, so

$$\frac{d}{dt}\left(\iiint_{\mathcal{V}} p_{\mathrm{He}} dV\right) = -(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}\,. \quad (2.32)$$

In view of the basic diffusion model for the window (*cf.* (2.11)), one may write (2.32) in the equivalent form

$$\frac{d}{dt}\left(\iiint_{\mathcal{V}} p_{\mathrm{He}} dV\right) = -\frac{\kappa A}{h} p_{\mathrm{He}}|_{z=0}\,, \quad (2.33)$$

where, to recall, the subscript $z = 0$ denotes conditions at the face of the window that looks into the mass separator cell.

Let $\langle p_{\mathrm{He}}\rangle$ denote the spatial average of p_{He} throughout $\mathcal{V}$, *i.e.*

$$\langle p_{\mathrm{He}}\rangle \equiv \frac{\iiint_{\mathcal{V}} p_{\mathrm{He}} dV}{\iiint_{\mathcal{V}} dV}\,. \quad (2.34)$$

Let V denote the volume enclosed by the mass separator cell (*i.e.* the denominator in (2.34)). Then one may multiply both sides of (2.34) by V to obtain

$$\langle p_{\mathrm{He}}\rangle V = \iiint_{\mathcal{V}} p_{\mathrm{He}} dV\,. \quad (2.35)$$

If one substuties (2.35) into (2.33) to eliminate the integral contained therein, one obtains

$$\frac{d}{dt}\left(\langle p_{\mathrm{He}}\rangle V\right) = -\frac{\kappa A}{h} p_{\mathrm{He}}|_{z=0}\,. \quad (2:36)$$

Now the container is rigid, so V does not change in time. One may therefore move the factor V outside of the time derivative in (2.36) to obtain

$$\frac{d}{dt}\left(\langle p_{\mathrm{He}}\rangle\right) V = -\frac{\kappa A}{h} p_{\mathrm{He}}|_{z=0} \,. \tag{2.37}$$

If one divides both sides of (2.37) by the product $V p_{\mathrm{He}}|_{z=0}$, one obtains

$$\frac{\frac{d}{dt}\left(\langle p_{\mathrm{He}}\rangle\right)}{p_{\mathrm{He}}|_{z=0}} = -\frac{\kappa A}{hV} \,. \tag{2.38}$$

A natural approximation to introduce at this point is

$$\langle p_{\mathrm{He}}\rangle \approx p_{\mathrm{He}}|_{z=0} \,. \tag{2.39}$$

Before making this approximation, one should point out that it can not hold exactly. To see why it can not, note that the rate at which helium leaves the gas in the container must equal the rate at which helium enters the stopper (or window). If the latter is nonzero, then the the former must be nonzero too. In particular, the rate of diffusion of helium from the core region of the container to the stopper must be nonzero. In view of the gradient-flux relation (2.1), a nonzero helium current due to diffusion can only occur if there is a nonzero gradient of helium concentration (or partial pressure) in the container. But if the gradient of helium partial pressure is nonzero in the core region and the helium current due to diffusion is in the direction from the core to the stopper, one expects that the concentration (or partial pressure) of helium should be lower at the stopper (toward which the helium is diffusing) that in the core region (since in any diffusion process, the diffusion current is in the direction from higher to lower concentration). Such considerations lead one to expect that

$$\langle p_{\mathrm{He}}\rangle > p_{\mathrm{He}}|_{z=0} \,, \tag{2.40}$$

which indicates the algebraic sign of the error introduced by the approximation (2.39).

Having acknowledged the limitations of the approximation (2.39), I am now ready to apply it for what it is worth. Thus, if one eliminates $\langle p_{\mathrm{He}}\rangle$ from (2.38) by means of (2.39), one obtains

$$\frac{\frac{d}{dt}\left(p_{\mathrm{He}}|_{z=0}\right)}{p_{\mathrm{He}}|_{z=0}} \approx -\frac{\kappa A}{hV} \,. \tag{2.41}$$

Equation (2.41) is now a first order ordinary differential equation for $p_{\mathrm{He}}|_{z=0}$ as a function of t. One may write the general solution of this equation in the form

$$\ln\left(C p_{\mathrm{He}}|_{z=0}\right) = -\frac{\kappa A}{hV} t \,, \tag{2.42}$$

in which C is an arbitrary constant with the dimensions of (pressure)$^{-1}$. One may evaluate C by introducing the initial condition

$$p_{\mathrm{He}}|_{\substack{z=0\\t=0}} = p_0 \,. \tag{2.43}$$

If one evaluates (2.42) at $t = 0$, uses the initial condition (2.43) and solves for C, one finds that $C = p_0^{-1}$. If one substitutes this result back into (2.42) and solves for $p_{\mathrm{He}}|_{z=0}$, one obtains

$$p_{\mathrm{He}}|_{z=0} = p_0 \exp\left(-\frac{\kappa A}{hV} t\right) \,. \tag{2.44}$$

Equation (2.44) indicates that $p_{\mathrm{He}}|_{z=0}$ decreases by one power of e during a time interval t_e defined by

$$t_e = \frac{hV}{\kappa A} \,. \tag{2.45}$$

If one can determine t_e experimentally, then (2.45) indicates that the experimental value of the window performance parameter $\kappa A/h$ must be

$$\frac{\kappa A}{h} = \frac{V}{t_e} \,. \tag{2.46}$$

Table 3 gives the results of some measurements of $\kappa A/h$ by this time-decay method.

Table 3. Measurements of the decay of $(p_{\mathrm{He}})_{\mathrm{window}}$ *with respect to* t

$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}} \times 10^8$ atm·(cm)^3/sec	t s	t_e^* s	$\kappa A/h$† (cm)^3/s
$10e^{0} = 10.00$	0	–	–
$10e^{-0.5} = 6.07$	18	–	–
$10e^{-1.0} = 3.68$	34	34	0.018
$10e^{-1.5} = 2.23$	50	32	0.019
$10e^{-2.0} = 1.35$	67	33	0.018
$10e^{-2.5} = 0.82$	90	40	0.015

*t_e is here defined to be the difference between the present t and the value of t when $(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}$ was one power of e higher

†Calculated from equation (2.46) with $V = 0.599$ (cm)^3

The mass separator cell was disassembled and the dimensions of its chamber were measured with a precision caliper. The value of container volume V given in Table 3 is the result of these measurements. This figure for V is the sum of the volume of the main cylidrical cavity plus the volumes enclosed by two metal tubes that branch off of it. During a typical test, the tubing to the mass separator cell was briefly exposed to atmospheric air. As soon as a test run was to begin, the tubing branches extending from the cell were stopped off with rubber stoppers.

The values of $\kappa A/h$ found here are lower than those of Table 1 but in the range of those in Table 2. Since each time-decay test was begun by exposing the mass separator cell to atmospheric air, one would expect the measured value of the window performance paramter $\kappa A/h$ to be similar to those in Table 2 with relatively high chamber pressures. Chamber pressures between 0.2 and 0.3 atm in Table 2 do indeed correspond to values of $\kappa A/h$ in the same range as those of the time decay tests.

If I had more time to conduct tests this summer, I would repeat the time decay tests but with a lower starting pressure, (say 0.18 atm). I would also use valves to seal off the leads to the mass separator cell rather than rubber stoppers. Repeated attachment and detachment of the stoppers allowed rubber shavings to be sucked into the tubing branches and to risk fouling the line to the vacuum pump. I would expect the time decay measurements of $\kappa A/h$ in the case of lower starting pressure to more nearly resemble the values in Table 1.

SECTION THREE

SOME OBSERVATIONS OF EXTERNAL SUPPLY-TO-SAMPLE FLOWRATE RATIO (STANDARD PROBE TIP)

Fig. 7 illustrates three different experimental configurations in which I measured the external supply to sample flowrate ratio.

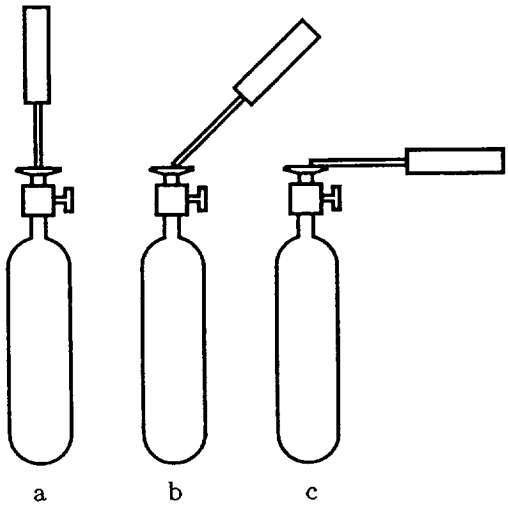

Fig. 7 Probe held in various attitudes relative to flange of a reservoir leak

As a preliminary step, I verified that the probe was drawing atmospheric air withough any apparaent obstructions. To this end, I measured the flowrate of atmospheric air into the probe tip (with a Sierra flowmeter mounted to the probe end as in Fig. 2 above but with the nitrogen shut off) and obtained the value

$$(p_{\text{air}}\dot{\Delta})_{\text{probe}} = 3.40 \text{ atm}\cdot(\text{cm})^3/\text{sec} . \quad (3.1)$$

I also noted that the chamber pressure in the mass separator cell was 0.179 atm (according to the pressure gauge PG illustrated in Fig. 2). These values are consistent with the normal functioning of the device I had access to this summer (the Alcatel ASM 110 Turbo CL leak detector in Room 117 of the Engineering Development Lab). I also adjusted the zero and the gain of the leak flowrate meter to force agreement between the meter reading and the internal reservoir leak labeled "RL, in" Fig. 2. In these tests, I employed an internal reservoir leak having the posted leak rate

$$(p_{\text{He}}\dot{\Delta})_{\text{RL, ex}} = 5.05 \times 10^{-8} \text{ atm}\cdot(\text{cm})^3/\text{sec} . \quad (3.2)$$

The choice of reservoir leak ensured that no change in scale of the leak flowrate meter would be required between the time the meter was adjusted and the time the measurements were taken.

With the meter duly adjusted and the internal reservoir leak shut off, I noted that the flowrate meter (with the probe tip exposed to clean air) read

$$(p_{\text{He}}\dot{\Delta})_{\text{window}} = 2.54 \pm 0.05 \times 10^{-8} \text{ atm}\cdot(\text{cm})^3/\text{sec} . \quad (3.3)$$

If one substitutes these data (along with the usual assumption $c_{\text{He, air}} = 5.25 \times 10^{-6}$) into equation (2.29) for the window performance parameter $\kappa A/h$, one finds

$$\frac{\kappa A}{h} = 0.0270 \frac{(\text{cm})^3}{\text{s}} . \quad (3.4)$$

This value is in the range of values in the left margin of Fig. 5.

From the data quoted above, one may also deduce that

$$\begin{aligned}(p_{\text{He}}\dot{\Delta})_{\text{probe}} &= c_{\text{He, air}}(p_{\text{air}}\dot{\Delta})_{\text{probe}} \\ &= 1.785 \times 10^{-5} \text{ atm}\cdot(\text{cm})^3/\text{sec} .\end{aligned} \quad (3.5)$$

It follows that

$$\text{ISSFR} \equiv \frac{(p_{\text{He}}\dot{\Delta})_{\text{probe}}}{(p_{\text{He}}\dot{\Delta})_{\text{window}}} = 703 . \quad (3.6)$$

At this point, one should note the change in the flowrate meter reading that one would expect to observe if the probe tip were placed in the vicinity of a reservoir leak and were able to capture all of the leaked helium. The label on the reservoir leak I used indicated

$$(p_{\text{He}}\dot{\Delta})_{\text{RL}} = 5.0 \times 10^{-6} \text{ atm}\cdot(\text{cm})^3/\text{sec} . \quad (3.7)$$

If the probe captured all of the helium discharged from this leak, then the meter reading should increase by

$$\begin{aligned}\Delta[(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}] &= \frac{(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}}{(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{probe}}} \times \Delta[(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{probe}}] \\ &= \frac{1}{\mathrm{ISSFR}} \times (p_{\mathrm{He}}\dot{\Delta})_{\mathrm{RL}} \\ &= \frac{5.0 \times 10^{-6}\ \mathrm{atm{\cdot}(cm)^3/sec}}{703} \\ &= 7.11 \times 10^{-9}\ \mathrm{atm{\cdot}(cm)^3/sec}\ . \end{aligned} \tag{3.8}$$

3.1 PROBE END INSERTED LOOSELY IN THE OPENING OF A RESERVOIR LEAK

The opening of the external reservoir leak in Fig. 7 is large enough for the probe tip to fit loosely in it to a depth of about one inch. I inserted the probe end into this well (*cf.* panel a of Fig. 7) and let the meter stabilize. The stabilized value was

$$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}} = 3.16 \pm 0.07 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec}\ . \tag{3.9}$$

This value exceed the clean air reading given in equation (3.3) by

$$\begin{aligned}\Delta[(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}] &= 0.62 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec} \\ &= 6.2 \times 10^{-9}\ \mathrm{atm{\cdot}(cm)^3/sec}\end{aligned} \tag{3.10}$$

This figure is 87% of the figure for complete capture of the leaked gas given in (3.8) above. Alternatively, the external supply-to-sample flowrate ratio ESSFR is the quotient whose numerator is the figure in (3.8) and whose denominator is the figure in (3.10), *viz.*

$$\mathrm{ESSFR} = \frac{7.11}{6.2} = 1.15\ . \tag{3.11}$$

Evidently, the shelter provided by the well into which the probe tip was inserted in this test helped to achieve such a low value of ESSFR. If one could arrange that the ESSFR were as small as the value given in (3.11) for general placement of the probe tip, there would be no problem in the use of a sniffer probe for local leakage measurement.

3.2 PROBE END HELD AT A FOURTY-FIVE DEGREE ANGLE TO A FLAT SURFACE WITH A PINHOLE LEAK

In the next test, I covered the well on the reservoir leak with a Band-Aid™ *shear spot* (a covering that does not have any perforations). I then punctured the Band-Aid with a pointed object to create a pinhole leak on an otherwise flat surface. I then placed the probe tip as shown in panel b of Fig. 7 and allowed the meter reading to stabilize.

This time, the stabilized value was

$$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}} = 3.03 \pm 0.13 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec}\ . \tag{3.12}$$

This value exceed the clean air reading given in equation (3.3) by

$$\begin{aligned}\Delta[(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}] &= 0.49 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec} \\ &= 4.9 \times 10^{-9}\ \mathrm{atm{\cdot}(cm)^3/sec}\end{aligned} \tag{3.13}$$

This figure is 69% of the figure for complete capture of the leaked gas given in (3.8) above. Alternatively, the external supply-to-sample flowrate ratio ESSFR is the quotient whose numerator is the figure in (3.8) and whose denominator is the figure in (3.13), *viz.*

$$\mathrm{ESSFR} = \frac{7.11}{4.9} = 1.45\ . \tag{3.14}$$

Evidently, the unsheltered environment of the pinhole leak and the probe tip illustrated in panel b of Fig. 7 allows more helium to disperse to the surrounding air than in the case illustrated in panel a.

3.3 PROBE SHAFT HELD FLUSH AGAINST A FLAT SURFACE WITH A PINHOLE LEAK ABOUT 4mm FROM THE PROBE END

In the third test, placed the probe tip as shown in panel c of Fig. 7 and allowed the meter reading to stabilize.

This time, the stabilized value was

$$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}} = 2.74 \pm 0.11 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec}\ . \tag{3.15}$$

To allow for the possibility of drift in the instrumentation, I exposed the probe tip to clean air a second time to see if the value returned to the value given by (3.3) above. This time the stabilized value was

$$(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}} = 2.49 \pm 0.09 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec}\ , \tag{3.16}$$

which is satisfactorily close to the value given in (3.3).

This test value given by (3.15) exceeds the clean air reading given in equation (3.16) by

$$\begin{aligned}\Delta[(p_{\mathrm{He}}\dot{\Delta})_{\mathrm{window}}] &= 0.25 \times 10^{-8}\ \mathrm{atm{\cdot}(cm)^3/sec} \\ &= 2.5 \times 10^{-9}\ \mathrm{atm{\cdot}(cm)^3/sec}\end{aligned} \tag{3.17}$$

This figure is 35% of the figure for complete capture of the leaked gas given in (3.8) above. Alternatively, the external supply-to-sample flowrate ratio ESSFR is the quotient whose numerator is the figure in (3.8) and whose denominator is the figure in (3.17), *viz.*

$$\mathrm{ESSFR} = \frac{7.11}{2.5} = 2.84\ . \tag{3.18}$$

Again, the unsheltered environment of the pinhole leak and the probe tip illustrated in panel c of Fig. 7 allows more helium to disperse to the surrounding air than in the case illustrated in panel a.

SECTION FOUR

CONCEPT OF A DRAFT DAMPER TO MINIMIZE DISPERSAL OF LEAKED HELIUM IN THE ROOM AIR

4.1 PRELIMINARY REMARKS

The results of section III above indicate that the external supply-to-sample flowrate ratio (ESSFR) obtained by an unmodified mass spectrometer hand probe held up to a leak may be as low as 1.15 if the probe tip is sheltered from drafts. The aim of the present section is to pursue the implications of this observation. Thus, one may shelter the probe tip from room drafts and inhibit buoyant convection at the same time by surrounding the probe tip with a sponge or other flexible porous material, provided the small pressure gradients needed to cause sniffed air to seep through it are still large compared to pressure gradients associated with the dynamic pressure of room drafts or the bouyant force per unit volume ρg (in which ρ is the mass density of the air and g is the acceleration due to gravity).

In this section, I will solve a convection-diffusion problem for the distribution of helium concentration in the interior of a porous medium probe end in the case when the probe end exhibits either of two symmetries, namely cylindrical or spherical. In each case, one supposes that the end of the sniffer probe is placed as closely as possible to a pinhole leak. Thus, the nonuniformity of helium concentration due to the relatively high concentration near the pinhole leak leads to diffusion of helium in the direction from higher to lower concentration, *i.e.* away from the pinhole leak. At the same time, the inward flow of air to supply the sucking action of the probe causes helium to drift toward the probe tip (which, you will recall, is placed as closely as possible to the pinhole leak). Thus, the helium transport is affected by inward drift with the air and by outward diffusion through it, leading to a steady state nonuniform helium distribution to be determined by solution of a suitable differential equation for the helium concentration as a function of the radial coordinate r in either cylindrical or spherical geometry.

To determine the arbitrary constants in the general solution of such a differential equation, one must have a boundary condition for the helium concentration at the low-r extremity of the solution domain (*i.e.* the range of values over which the solution is sought). To fix such a boundary condition, consider the steady input-output balance for helium:

$$\rho^*_{\mathrm{He,\,air}}\dot{\Delta}_{\mathrm{air}} + \rho^*_{\mathrm{He,\,leak}}\dot{\Delta}_{\mathrm{leak}} = \rho^*_{\mathrm{He,\,effl}}\dot{\Delta}_{\mathrm{effl}} \ , \qquad (4.1)$$

in which the subscript "air" refers to the room air that enters the porous medium probe end; the subscript "leak" refers to the gas emanating from the leak; and the subscript "effl" refers to the effluent, *i.e.* the gas that enters the sample line of the leak detector. One may write (4.1) in the equivalent form

$$c_{\mathrm{He,\,air}}\rho^*_{\mathrm{air}}\dot{\Delta}_{\mathrm{air}} + c_{\mathrm{He,\,leak}}\rho^*_{\mathrm{leak}}\dot{\Delta}_{\mathrm{leak}} = c_{\mathrm{He,\,effl}}\rho^*_{\mathrm{effl}}\dot{\Delta}_{\mathrm{effl}} \ , \qquad (4.2)$$

in which c_{He} is the nondimensional helium concentration, *i.e.* the ratio whose numerator is the molar density of helium in some mixture and whose denominator is the molar density of the mixture as a whole.

One may also write down an equation of balance for for all the gases, namely

$$\rho^*_{\mathrm{air}}\dot{\Delta}_{\mathrm{air}} + \rho^*_{\mathrm{leak}}\dot{\Delta}_{\mathrm{leak}} = \rho^*_{\mathrm{effl}}\dot{\Delta}_{\mathrm{effl}} \ , \qquad (4.3)$$

In equations (4.4) and (4.3), however,

$$\rho^*_{\mathrm{air}} = \rho^*_{\mathrm{leak}} = \rho^*_{\mathrm{effl}} = \frac{p}{\mathcal{R}T} \ , \qquad (4.4)$$

which expresses AVOGADRO'S principle that "equal volumes of gas at the same temperature and pressure have equal numbers of molecules" (*cf.* (1.1) above).

One may thus cancel several common factors in (4.2) and (4.3) to obtain, respectively,

$$c_{\mathrm{He,\,air}}\dot{\Delta}_{\mathrm{air}} + c_{\mathrm{He,\,leak}}\dot{\Delta}_{\mathrm{leak}} = c_{\mathrm{He,\,effl}}\dot{\Delta}_{\mathrm{effl}} \ , \qquad (4.5)$$

$$\dot{\Delta}_{\mathrm{air}} + \dot{\Delta}_{\mathrm{leak}} = \dot{\Delta}_{\mathrm{effl}} \ , \qquad (4.6)$$

If one eliminates $\dot{\Delta}_{\mathrm{air}}$ from (4.5) by means of (4.6), one obtains

$$c_{\mathrm{He,\,air}}(\dot{\Delta}_{\mathrm{effl}} - \dot{\Delta}_{\mathrm{leak}}) + c_{\mathrm{He,\,leak}}\dot{\Delta}_{\mathrm{leak}} = c_{\mathrm{He,\,effl}}\dot{\Delta}_{\mathrm{effl}} \ . \qquad (4.7)$$

If one divides through by $\dot{\Delta}_{\text{effl}}$, one obtains

$$c_{\text{He, air}}\left(1-\frac{\dot{\Delta}_{\text{leak}}}{\dot{\Delta}_{\text{effl}}}\right)+c_{\text{He, leak}}\frac{\dot{\Delta}_{\text{leak}}}{\dot{\Delta}_{\text{effl}}}=c_{\text{He, effl}}\,. \tag{4.8}$$

As an example, suppose that

$$\dot{\Delta}_{\text{leak}}=5.0\times10^{-6}\ \text{atm}\cdot(\text{cm})^3/\text{sec}$$

and $\dot{\Delta}_{\text{effl}}=3.4\ \text{atm}\cdot(\text{cm})^3/\text{sec}$. Suppose further that $c_{\text{He, air}}=5.25\times10^{-6}$ and $c_{\text{He, leak}}=1$. Then equation (4.8) yields

$$\begin{aligned}c_{\text{He, effl}}&=5.25\times10^{-6}\left(1-\frac{5.0\times10^{-6}}{3.40}\right)\\&\quad+(1)\frac{5.0\times10^{-6}}{3.40}\\&=6.72\times10^{-6}\ \text{atm}\cdot(\text{cm})^3/\text{sec}\end{aligned} \tag{4.9}$$

4.2 PADDED DIAPHRAGM PROBE END

Consider a porous medium probe end in the form of a cylinder of thickness h. Let $\dot{n}$ denote the molar transport of helium across a cylinder of radius r (in, say, gm-moles/s). If the flow is steady then helium does not accumulate between coaxial cylinders of different radii. It follows that the transport of helium into the gap betweeen the cylinders must be balanced by the transport of helium out of that gap and one concludes that $\dot{n}$ is independent of r.

Now there will be two distinct contributions to $\dot{n}$, namely diffusion of helium through the air and drift of helium with the air. Summing these two effects, one obtains

$$\dot{n}=(2\pi rh)\left(-\kappa'\frac{d\rho^*_{\text{He}}}{dr}\right)+(-\dot{\Delta}\rho^*_{\text{He}})\,. \tag{4.10}$$

In (4.10), the expression $2\pi rh$ is the area of the cylinder of height h and radius r across which helium diffuses. The expression within large parentheses is the intensity of the helium current due to diffusion (in say gm-moles per square centimeter per second). The paramter κ' is the diffusivity of helium in air (not to be confused with the diffusivity of helium in the window material introduced in (2.2) above). MARR (Ref. 1, p93) furnishes a value for κ', namely 2.7 $(\text{ft})^2/\text{hr}$, at $T=0°$ Celsius. Converting to CGS units, one obtains $\kappa'=0.6968$ $(\text{cm})^2/\text{s}$ at that temperature. CHAPMAN & COWLING (Ref. 6, p264) indicate that the diffusivity varies as a positive power of the absolute temperature and furnish the value 1.691 for the exponent. If one takes $T=300\ °\text{K}$ as a typical value for the temperature in the laboratory, one finds that the

$$\begin{aligned}\kappa'|_{T=300\,°\text{K}}&=\kappa'|_{T=273.15\,°\text{K}}\left(\frac{300}{273.15}\right)^{1.691}\\&=0.8165\ (\text{cm})^2/\text{s}\end{aligned} \tag{4.11}$$

One may rearrange (4.10) to the equivalent form

$$0=(2\pi rh)\left(-\kappa'\frac{d\rho^*_{\text{He}}}{dr}\right)-\dot{\Delta}\left(\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}\right)\,, \tag{4.12}$$

so

$$0=(2\pi rh)(-\kappa')\frac{d}{dr}\left(\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}\right)-\dot{\Delta}\left(\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}\right)\,, \tag{4.13}$$

so

$$\frac{\frac{d}{dr}\left(\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}\right)}{\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}}=\frac{-\dot{\Delta}}{2\pi h\kappa'}\frac{1}{r}\,, \tag{4.14}$$

the general solution of which is

$$\rho^*_{\text{He}}+\frac{\dot{n}}{\dot{\Delta}}=Ar^{-\dot{\Delta}/(2\pi h\kappa')}\,, \tag{4.15}$$

in which A is an arbitrary constant.

As $r\to\infty$, equation (4.15) takes the form

$$(\rho^*_{\text{He}})_\infty+\frac{\dot{n}}{\dot{\Delta}}=0\,, \tag{4.16}$$

so

$$\dot{n}=-(\rho^*_{\text{He}})_\infty\dot{\Delta}\,. \tag{4.17}$$

If one substitutes this expression for $\dot{n}$ into (4.15), one obtains

$$\rho^*_{\text{He}}-(\rho^*_{\text{He}})_\infty=Ar^{-\dot{\Delta}/(2\pi h\kappa')}\,. \tag{4.18}$$

If

$$\rho^*_{\text{He}}|_{r=r_1}\equiv\rho^*_{\text{He}}(r_1)\,, \tag{4.19}$$

one may deduce from (4.18) that

$$\rho^*_{\text{He}}(r_1)-(\rho^*_{\text{He}})_\infty=A(r_1)^{-\dot{\Delta}/(2\pi h\kappa')}\,. \tag{4.20}$$

If one divides (4.18) by (4.20), one obtains

$$\frac{\rho^*_{\mathrm{He}} - (\rho^*_{\mathrm{He}})_\infty}{\rho^*_{\mathrm{He}}(r_1) - (\rho^*_{\mathrm{He}})_\infty} = \left(\frac{r}{r_1}\right)^{-\dot{\Delta}/(2\pi h\kappa')} . \quad (4.21)$$

If one divides the numerator and the denominator of the left member of (4.21) by the molar density of the mixture of helium and air (which equals $p/\mathcal{R}T$ according to (4.4)), and recalls the definition of concentration (*cf.* the text immediately after (4.2)), one obtains

$$\frac{c(r) - c_\infty}{c(r_1) - c_\infty} = \left(\frac{r}{r_1}\right)^{-\dot{\Delta}/(2\pi h\kappa')} . \quad (4.22)$$

One may apply this equation to the design of a padded diaphragm. To illustrate the idea, suppose that the left member of (4.22) is to take the value 0.01 at the radius $r = R = 5r_1$ and that $\dot{\Delta} = 3.40$ $(\mathrm{cm})^3/\mathrm{s}$ and κ' is given by (4.11) above. Then from (4.22), we have

$$\frac{c(R) - c_\infty}{c(r_1) - c_\infty} = \left(\frac{R}{r_1}\right)^{-\dot{\Delta}/(2\pi h\kappa')} . \quad (4.23)$$

If one solves for h, one obtains

$$\begin{aligned} h &= \frac{\dot{\Delta}}{2\pi\kappa'} \frac{\ln(R/r_1)}{\ln\left(\frac{c(r_1)-c_\infty}{c(R)-c_\infty}\right)} \\ &= \frac{3.40(\mathrm{cm})^3/\mathrm{s}}{2\pi(0.8165(\mathrm{cm})^2/\mathrm{s})} \frac{\ln 5}{\ln 100} \\ &= 0.2316\ \mathrm{cm} \end{aligned} \quad (4.24)$$

To add further detail to the example, one may identify the radius r_1 with the radius of the smallest disk that can completely cover both the pinhole leak and the probe end. If one imagines that r_1=1mm, then R = 5mm so the diameter of the padded diaphragm probe is 1cm. Such a probe is small enough to be practical, although there is some doubt about usefulness of the device when the test surface is not flat.

4.3 POROUS PROBE END IN THE FORM OF A SPHERICAL WEDGE

Consider next a steady convection-diffusion problem with the helium transport denoted by $\dot{n}$ as before.

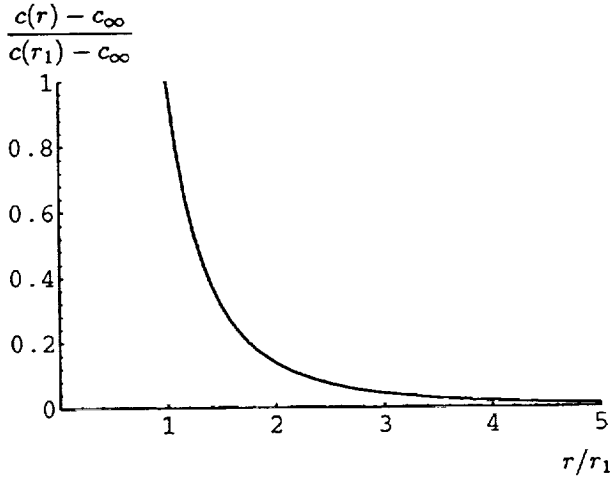

Fig. 8 Structure of the diffusion boundary layer within a padded diaphragm probe (*cf.* (4.22)) corresponding to the values κ'=0.8165 $(\mathrm{cm})^2/\mathrm{s}$, $\dot{\Delta}$=3.40 $(\mathrm{cm})^3$, h=0.2316 cm, and r_1=1mm.

This time the helium flow is between hemispheres, quarter spheres, or other kinds of *spherical wedges*. For the purposes of the present analysis, the only parameter that distinguishes one kind of spherical wedge from another is the *view factor* Ω, *i.e.* the fraction of the celestial sphere visable to a hypothetical observer at the center of the wedge. Thus, for the hemisphere $\Omega = 1/2$, for the quarter-sphere, $\Omega = 1/4$, and so on.

Consider now the flow of helium between two concentric spherical wedges. By assuming that the flow is steady, one concludes that inflow of helium into the gap must be balanced by outflow of helium from it. An equation analogous to (4.10) is

$$\dot{n} = (4\pi r^2\Omega)\left(-\kappa' \frac{d\rho^*_{\mathrm{He}}}{dr}\right) + (-\dot{\Delta}\rho^*_{\mathrm{He}}) , \quad (4.25)$$

in which $4\pi r^2\Omega$ is the area of the spherical wedge of radius r.

One may write (4.25) in the equivalent form

$$0 = (4\pi\Omega\kappa')(-r^2)\frac{d\rho^*_{\mathrm{He}}}{dr} - \dot{\Delta}\left(\rho^*_{\mathrm{He}} + \frac{\dot{n}}{\dot{\Delta}}\right) , \quad (4.26)$$

so

$$0 = (4\pi\Omega\kappa')(-r^2)\frac{d}{dr}\left(\rho^*_{\mathrm{He}} + \frac{\dot{n}}{\dot{\Delta}}\right) - \dot{\Delta}\left(\rho^*_{\mathrm{He}} + \frac{\dot{n}}{\dot{\Delta}}\right) , \quad (4.27)$$

so

$$\frac{\frac{d}{dr}\left(\rho^*_{He}+\frac{\dot{n}}{\dot{\Delta}}\right)}{\rho^*_{He}+\frac{\dot{n}}{\dot{\Delta}}}=\frac{\dot{\Delta}}{(4\pi\Omega\kappa')(-r^2)}=\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\right)\frac{d}{dr}\left(\frac{1}{r}\right) \quad (4.28)$$

the general solution of which is

$$\rho^*_{He}+\frac{\dot{n}}{\dot{\Delta}}=A'\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r}\right), \quad (4.29)$$

in which A' is an arbitrary constant.

As $r\to\infty$, (4.29) becomes

$$(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}=A' \quad (4.30)$$

so (4.29) becomes

$$\rho^*_{He}+\frac{\dot{n}}{\dot{\Delta}}=\left[(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}\right]\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r}\right), \quad (4.31)$$

or, equivalently,

$$[\rho^*_{He}-(\rho^*_{He})_\infty]+\left[(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}\right]=\left[(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}\right]\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r}\right). \quad (4.32)$$

If one collects common factors of $(\rho^*_{He})_\infty+\dot{n}/\dot{\Delta}$ on the right hand side, one obtains

$$\rho^*_{He}-(\rho^*_{He})_\infty=\left[(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}\right]\times\left[\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r}\right)-1\right]. \quad (4.33)$$

If one evaluates this equation at $r=r_1$, one obtains

$$\rho^*_{He}(r_1)-(\rho^*_{He})_\infty=\left[(\rho^*_{He})_\infty+\frac{\dot{n}}{\dot{\Delta}}\right]\times\left[\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1\right], \quad (4.34)$$

If one divides (4.33) by (4.34), one obtains

$$\frac{\rho^*_{He}-(\rho^*_{He})_\infty}{\rho^*_{He}(r_1)-(\rho^*_{He})_\infty}=\frac{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1}{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1}. \quad (4.35)$$

If one divides the numerator and the denominator of the left member by the common factor ρ^*_{air}, and recalls the definition of concentration given in the text after equation (4.2) above, one obtains

$$\frac{c(r)-c_\infty}{c(r_1)-c_\infty}=\frac{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r}\right)-1}{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1}. \quad (4.36)$$

One may use equation (4.36) in the design of a draft damper. Suppose, for example, that ϵ is some given small number, such as 0.01. One may choose the radius of the draft damper such that the left member of (4.36) equals ϵ when $r=r_\epsilon$, *i.e.* r/ϵ is subject to the following constraint

$$\epsilon=\frac{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_\epsilon}\right)-1}{\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1}. \quad (4.37)$$

If one solves (4.37) for r_ϵ, one obtains

$$r_\epsilon=\frac{\frac{\dot{\Delta}}{4\pi\Omega\kappa'}}{\ln\left\{1+\epsilon\left[\exp\left(\frac{\dot{\Delta}}{4\pi\Omega\kappa'}\frac{1}{r_1}\right)-1\right]\right\}} \quad (4.38)$$

Suppose, for example, that

$$\dot{\Delta}=3.40\ \text{atm}\cdot(\text{cm})^3/\text{sec},$$

κ'=0.8165 $(\text{cm})^2/\text{s}$, and Ω=1/2. Then

$$\frac{\dot{\Delta}}{4\pi\Omega\kappa'}=0.6627\ \text{cm}. \quad (4.39)$$

If ϵ=0.01 and r_1=1mm, equation (4.38) gives

$$r_\epsilon=\frac{0.6627\ \text{cm}}{\ln\left\{1+0.01\left[\exp\left(\frac{0.6627\ \text{cm}}{0.1\ \text{cm}}\right)-1\right]\right\}}=0.3089\ \text{cm} \quad (4.40)$$

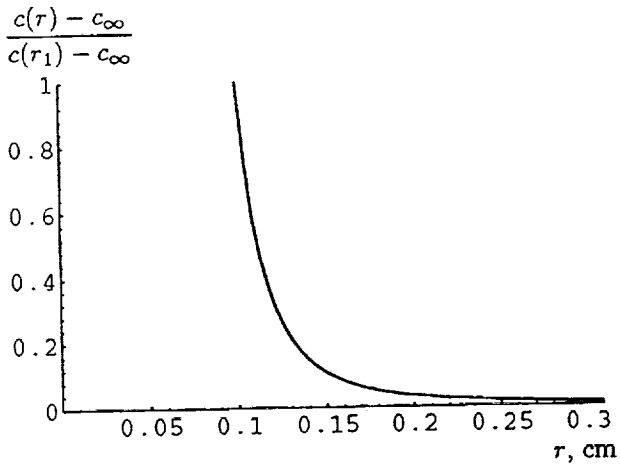

Fig. 9 Structure of the diffusion boundary layer within a draft damper shaped like a hemisphere (*cf.* (4.36)) corresponding to the values κ'=0.8165 $(\text{cm})^2/\text{s}$, $\dot{\Delta}$=3.40 $(\text{cm})^3$,r_1=1mm, and Ω=1/2.

SECTION FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. The internal supply-to-sample flowrate ratio is not a constant for a given mass separator cell.
2. The window diffusion performance parameter $\kappa A/h$ *is* a constant of the machine provided the absolute temperature does not change significantly and the total pressure in the mass separator chamber is not above 0.018 atm.
3. The external supply to sample flowrate ratio ESSFR may be as low as 1.15 if the probe tip is sheltered by solid walls (as it is when the test leak is at the bottom of a slender hole into which the probe tip fits). Even if the probe tip is unsheltered, the ESSFR may be as low as three, provided the test leak emerges from a pinhole, the probe tip is placed less than 4mm from it, and the drafts in the room are not artifically large.
4. If a mass spectrometer hand probe is equipped with a porous medium probe end (such as a sponge) and if the sponge is either cylidrically symmetric or spherically symmetric and centered over a point leak, then one may solve the linear convection-diffusion probem for the distribution of helium concentration within the sponge. The solutions are expressible in terms of elementary functions and exhibit boundary layer character (*i.e.* the concentration is largest near the point source but drops off rapidly in the direction away from it). A modest size probe end (whose diameter is one centimeter or less) can shelter the region in which 99% of the drop in helium concentration occurs.
5. For some mass spectrometer leak detectors (including the one I used to conduct the tests I reported in sections II and III above), the leak flowrate meter reading is unreliable unless the zero and gain settings are adjusted with an internal reservoir leak whose order of magnitude matches that of the meter readings in the subsequent tests.

5.2 RECOMMENDATIONS

1. The measurement of the numerical value of the window performance parameter $\kappa A/h$ should be part of the routine qualification a new mass spectrometer leak detector or modification of an old one (*e.g.* after the mass separator cell has been replaced).
2. A pressure gauge should be attached to monitor the chamber pressure in the mass separator cell. Only with this information (and knowledge of the constant value of $\kappa A/h$) can one relate the helium transport rate across the separator window to the concentration of helium in the separator chamber. The pressure gauge for the separator chamber also provides a strong indication of the presence or absence of obstructions in the internal and external fluid transport lines.
3. Followup work should address the optimization of draft dampers to enable local leakage measurement with mass spectrometer hand probes. The present work supplies most of the necessary formulas. What is needed is to fabricate prototypes and test them.
4. In particular, the sensitivity of external supply to sample flowrate (ESSFR) to room drafts should be tested quantitatively. Thus, hand probe equipped with draft dampers should be placed in a wind tunnel and the dependence of the ESSFR upon tunnel speed should be measured.
5. Test should be conducted to determine the repeatability of local leakage measurments made with draft damper equipped hand probes in the case when the measurements are taken by relatively unskilled personnel (such as undergraduate students).
6. Some further work should seek an analytical solution of the convection-diffusion problem of a spherical draft damper equipped hand probe placed in a wind tunnel. The tests mentioned in item 2 above should be compared with such theoretical predictions.

REFERENCES

1. MARR, J. WILLIAM 1968 *Leakage testing handbook.* Prepared by General Electric, Schenectady, N.Y. for Jet Propulsion Laboratory, Pasadena, CA. NASA Contractor Report CR-952, April 1968 (xx + 392 pages, with appendices).
2. BILARDO, VINCENT J., IZQUIERDO, FRANCISCO, & SMITH, R. KENNETH 1987 Development of the Helium Signature Test for orbiter main propulsion system revalidation between flights. AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 12–15 1987. AIAA Paper 87-0293 (9 pages).
3. RUSSELL, J.M. 1993 Interpretation of discrepancies in mass spectrometry data obtained from different experimental configurations. *1993 Research Reports, NASA/ASEE Summer Faculty Fellow Program*, NASA Contractor Report CR-194678, pp 403–432 (edited by E. RAYMON HOSLER, CAROL VALDES, & TOM BARRON.
4. ANONYMOUS 1992 Proof pressure and leak detection–Aerospace plumbing systems and assemblies. Rockwell International specification (prepared by D.R. SUEME, & K.R. RAVAL). SPECIFICATION number MF0001-003 (Code Indent. No. 03953), Sept 27, 1992.
5. ANONYMOUS 1976 *U.S. Standard Atmonsphere 1976*, National Oceanic and Atmospheric Administration, National Aeronautics and Space Adminstration, United States Air Force, number NOAA-S/T 76-1562 (xv+227 pp).
6. CHAPMAN, SYDNEY & COWLING, T.G. *The mathematical theory of non-uniform gases.* 3rd edition, Cambridge University Press, 1970.