NASA TECHNICAL
MEMORANDUM

NASA TM X-53551

December 9, 1966

NASA TM X-53551

FACILITY FORM 602

N 67-19021	
(ACCESSION NUMBER)	(THRU)
36	1
(PAGES)	(CODE)
TMX-53551	12
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

CRITERION FOR MASS DROP-OFF MEASUREMENTS BASED UPON PRECISE PRESSURE AND TEMPERATURE MEASUREMENTS

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ABSTRACT

An analytical study was performed to determine if Mass Drop-Off measurements, based upon precise temperature and pressure measurements, could be used successfully for the detection of leaks in complex gas systems on space vehicles.

Leaks under isothermal as well as isobaric conditions were investigated using both the perfect gas law and the virial expansion for the compressibility factors. This study showed that the mass drop-off method is very limited in scope due primarily to the requirement of the temperature measurement.

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METHODS AND RESEARCH SECTION
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ANALYTICAL OPERATIONS DIVISION
QUALITY AND RELIABILITY ASSURANCE LABORATORY

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SUMMARY

An analytical study was performed to determine if Mass Drop-Off measurements, based upon precise temperature and pressure measurements, could be used successfully for the detection of leaks in complex gas systems on space vehicles.

The study showed that this technique could be used to detect leak rates to an accuracy of 1 scim on systems less than 5 cubic feet in capacity, but only if the temperature in the system is uniform and constant throughout the entire volume during the checkout period. This is based upon a minimum detectable pressure decay of 0.1 psi/hr. The magnitude of the detectable leak rates becomes proportionally larger in larger system volumes.

This leak detection technique becomes very ineffective if the temperature environment is not controlled and free of temperature fluctuations and gradients. Under these circumstances, this method could still be used for the detection of very large leak rates or to obtain a general check of the overall status of a closed complex gas system.

Dry air was used as the test media throughout this study, but the same limitations described herein would apply to any compressible fluid.

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*This report was prepared by SPACO, Inc., for the Analytical Operations Division, Quality and Reliability Assurance Laboratory, George C. Marshall Space Flight Center, under Contract No. NAS8-20081.

SECTION I. INTRODUCTION

The technique of detecting the presence of leaks in closed fluid (gas) systems by observing the decay in pressure is not new. It has been widely used in industry to detect leaks in boilers, storage vessels, various components, etc. This technique of detecting leaks, herein called the Mass Drop-Off (MD) technique, is based upon detecting any loss of mass in a closed system. The mass of a system is directly related to the density (mass per unit volume) and it would therefore be desirable to measure this quantity directly. However, direct density measurements are not presently feasible, so the pressure and temperature are measured and related to density by an equation of state. This relationship is discussed in detail in this report.

This study set out to define conditions under which this leak detection technique could be used successfully in the aerospace industry. The degree of accuracy that could be expected was investigated and reported. The accuracy of the MD technique was found to be related to the following parameters:

1. The accuracy of the gas equation of state by which the density is calculated from measured values of pressure and temperature.
2. The accuracy of the pressure measurement.
3. The accuracy of the measurement of the average gas temperature.

The resolution of this technique was found to be related to items 2 and 3 above. The above parameters affecting the outcome of leak detection by the MD technique are discussed in detail in this report.

In the course of this study, it was determined analytically that the technique of detecting leaks with the MD technique is very limited in scope primarily due to the requirement of the temperature measurement.

SECTION II. METHODS

A. THE GAS EQUATION OF STATE

As previously mentioned, an equation relating density to pressure and temperature must be defined. The simplest equation of this kind is the well-known perfect gas law. It is a known fact, however, that the behavior of all real gases depart from a so-called perfect gas. It therefore became necessary to investigate the magnitude of error that could be introduced if the perfect gas law was used as a basis for the Mass Drop-Off (MD) measurements. The real gas behavior of air was investigated by the National Bureau of Standards (NBS) for the pressure range 0.01 atm (0.147 psi) to 100 atm (1470 psi) and the temperature range of 50° K to 300° K (1). The virial or power series expression of Kamerlingh Onnes (2) for the compressibility factor was shown by NBS to accurately describe the behavior of air for pressures and temperatures mentioned above.*

$$Z = \frac{Pv}{RT} = 1 + \frac{B}{v} + \frac{C}{v^2} + \frac{D}{v^3}$$

where

Z = compressibility factor.

Z is an indication of the departure from perfect gas behavior. It is always unity for a perfect gas. If Z = 1, the equation becomes

$$\frac{Pv}{RT} = 1,$$

which is of course the perfect gas law.

P = system pressure
v = specific volume (inverse of density)
T = absolute temperature
R = gas constant
B, C, D are temperature dependent constants (independent of pressure)

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* NBS designated the Kamerlingh Onnes virial expression as the Virial Equation of State and it will therefore be referenced herein by the same name.

The values of these constants for air are reported in appendix A.

Since the real gas equation proposed by NBS has only been validated to pressures up to 1470 psi, it became necessary to limit the comparison with perfect gas behavior to this pressure. The comparison between the two equations will be as follows:

1. Equations relating ΔP and mass lost by leakage for an isothermal process will be derived from both the Virial Equation of State as well as the Perfect Gas Law, and the two results will be compared to each other.
2. Similar equations will be derived for an isobaric process from the same equations, and the two results will again be compared to each other.
3. A system free of leaks but undergoing a temperature and corresponding pressure change will also be investigated using both the Virial Equation of State and the Perfect Gas Law. It will be shown that the latter equation can indicate a leak in a no-leak system. This is of course due to the deviation of a perfect gas from real gas behavior.

Dry air is used as the test media throughout this study, but the MD technique is not limited to this gas. Other gases such as nitrogen or helium could have been used in this study with comparable results. The compressibility factors for other gases as computed from the Virial Equation of State are not identical to those for air, but these differences are small and the same limitations of the MD technique as reported herein would apply for any compressible fluid.

B. LEAK VERSUS CHANGE IN PRESSURE FOR ISOTHERMAL PROCESS

The change in pressure corresponding to a leak for a constant temperature process will now be calculated. This will be done using the Virial Equation of State as well as the perfect gas equation. The two results will be compared and a percent deviation calculated.

Using the Virial Equation of State $\frac{Pv}{RT} = Z\ (P,\ T)$ or

$$\frac{PV}{MRT} = Z\ (P,\ T) \text{ since } v = \frac{V}{M}$$

where

V = Total Volume
M = Total Mass

Initially $$\frac{P_1V}{M_1RT} = Z_1 \qquad (1)$$

After a leak at constant temperature $$\frac{P_2V}{M_2RT} = Z_2 \qquad (2)$$

Subtract equation (2) from equation (1)

$$\frac{P_1V}{M_1RT} - \frac{P_2V}{M_2RT} = Z_1 - Z_2$$

Simplifying,

$$P_1VM_2 - P_2VM_1 = Z_1M_1M_2RT - Z_2M_1M_2RT$$

but,

$M_2 = M_1 - M_L$ where M_L = Mass lost by leakage.

After further simplification, the equation becomes

$$V(P_1 - P_2) = RTM_1\ (Z_1 - Z_2) - RTM_L(Z_1 - Z_2) + P_1V\frac{M_L}{M_1}$$

but,

$$M_1 = \frac{P_1V}{RTZ_1}$$

$$V(P_1 - P_2) = \frac{P_1 V}{Z_1} (Z_1 - Z_2) + RTZ_2 M_L$$

Solve for M_L and simplify $M_L = \frac{V}{RT} \left[\frac{P_1}{Z_1} - \frac{P_2}{Z_2} \right]$ (3)

For a perfect gas, $Z_1 = Z_2 = 1$ and equation (3) becomes

$$M_{L\ \text{perfect}} = \frac{V}{RT} (P_1 - P_2) \tag{4}$$

The percent error introduced by the perfect gas equation will next be calculated,

$$\frac{\text{Percent Error } (M_L)}{100} = M_L - M_{L\ \text{perfect}}$$

Substituting values for M_L and $M_{L\ \text{perfect}}$ from equations (3) and (4) respectively into the above equation, it becomes,

$$\frac{\text{Percent Error}}{100} = 1 - \frac{P_1 Z_1 Z_2 - P_2 Z_1 Z_2}{P_1 Z_2 - P_2 Z_1} \tag{5}$$

C. LEAK VERSUS CHANGE IN TEMPERATURE FOR AN ISOBARIC PROCESS

The leak corresponding to a certain temperature drop will be calculated for an isobaric process. Again, the virial equation will be used, and the error introduced by the perfect gas law will be calculated.

Initially $\frac{PV}{M_1 R T_1} = Z_1$ (6)

After a leak at constant pressure, $\frac{PV}{M_2RT_2} = Z_2$ (7)

Subtract equation (7) from (6) and obtain

$$\frac{PV}{M_1RT_1} - \frac{PV}{M_2RT_2} = Z_1 - Z_2$$

Simplify and substitute, $M_2 = M_1 - M_L$

$$PVT_2 (M_1 - M_L) - PVT_1M_1 = RM_1T_1T_2 (M_1 - M_L) (Z_1 - Z_2)$$

but, $M_1 = \frac{PV}{Z_1RT_1}$

and upon substitution and further simplification,

$$M_L = \frac{PV}{Z_1RT_1} - \frac{PV}{Z_2RT_2} \qquad (8)$$

For perfect gas behavior, $Z_1 = Z_2 = 1$ and equation (8) becomes

$$M_{L\ \text{perfect}} = \frac{PV}{RT_1} - \frac{PV}{RT_2} \qquad (9)$$

The error introducted by assuming perfect gas behavior is calculated below.

$$\frac{\text{Percent Error } (M_L)}{100} = M_L - M_{L\ \text{perfect}}$$

Upon substitution and simplification this becomes

$$\text{Percent Error} = 100 \left[1 - \frac{Z_1Z_2(T_1 - T_2)}{Z_1T_1 - Z_2T_2)} \right] \qquad (10)$$

D. FALSE LEAK INDICATION

It was discovered that by assuming perfect gas behavior, a leak could be indicated in a no-leak system if it undergoes a temperature change followed by a corresponding pressure change. The magnitude of such false leak indication will now be investigated. The original conditions are

$$\frac{P_1 V}{M_1 R T_1} = Z_1$$

After a temperature and pressure change $\frac{P_2 V}{M_2 R T_2} = Z_2$

Solving both equations for mass $M_1 = \frac{P_1 V}{Z_1 R T_1}$, $M_2 = \frac{P_2 V}{Z_2 R T_2}$

change in mass = $M_1 - M_2$

$$M_1 - M_2 = \Delta M = \frac{V}{R}\left[\frac{P_1}{Z_1 T_1} - \frac{P_2}{Z_2 T_2}\right] \qquad (11)$$

For a no-leak system $\Delta M = 0$, thus $\frac{P_1}{Z_1 T_1} = \frac{P_2}{Z_2 T_2}$

and $$P_2 = \frac{P_1 T_2 Z_2}{T_1 Z_1} \qquad (12)$$

P_2 (12) is the pressure of a no-leak system after undergoing a temperature change. Had perfect gas behavior been assumed, this corresponding pressure P_2 would have been calculated to be

$$P_2 = \frac{P_1 T_2}{T_1} \qquad (13)$$

Substituting the last value for P_2 (13) into equation (11) will give the magnitude of a possible false leak by assuming perfect gas behavior.

$$(\text{False } \Delta M) = \frac{VP_1}{RT_1} \left[\frac{1}{Z_1} - \frac{1}{Z_2} \right] \qquad (14)$$

The following example will illustrate:

(1) In a closed system with no leaks, the temperature is measured at 25.0° C and the pressure at 1500 psi. Z for this condition is 0.99248.

(2) After one hour, the temperature is measured at 27.0° C and the corresponding pressure at 1512.4 psi. Z for this condition is 0.99401.

(3) If these values for P, T, and Z are substituted into equation (11) above, ΔM equals zero. This is of course correct for a no-leak system.

(4) By the perfect gas law (equation 14), the indicated change in mass is $12.07\ V \times 10^{-3}$ lb. (where V has units of cubic feet).

(5) A leak of 1 scim reduces the mass in the system by $2.66 \times 10^{-3} \frac{\text{lb.}}{\text{hr.}}$

(6) The above indicated change in mass will therefore correspond to a leak of 4.54 scim per cubic foot of system volume.

(7) The magnitude of the false leak increases with increasing volume.

(8) Had the temperature and pressure change been reversed, the perfect gas law would have shown an increase of mass in the system.

E. DISCUSSION OF ERRORS INTRODUCED BY THE PERFECT GAS LAW

The errors introduced by the Perfect Gas Law for isothermal processes can be calculated from equation (5). Some typical values are shown in table 1. The error is a function of P_1 (initial pressure),

Table 1. Errors Introduced by The Perfect Gas Law Isothermal Processes

T = Temperature (°K)

P_1 = Initial Pressure (Psi)

ΔP = Pressure Decay (Psi)

270°K					310°K				
	% Error					% Error			
P_1 psi	ΔP→0	ΔP = 10	ΔP = 50	ΔP = 100	P_1 psi	ΔP→0	ΔP = 10	ΔP = 50	ΔP = 100
100	0.4	0.8	0.6	---	100	0.1	0.3	0.2	---
300	1.2	2.2	2.1	1.9	300	0.4	0.6	0.6	0.7
600	2.1	3.7	3.7	3.5	600	0.6	0.8	0.8	0.8
900	2.8	4.4	4.4	4.4	900	0.6	0.4	0.3	0.4
1200	3.2	4.4	3.9	4.1	1200	0.4	-0.8	-0.7	0.5
1500	3.2	2.5	2.7	2.9	1500	0	-1.6	-2.0	-2.2

290°K					330°K				
	% Error					% Error			
P_1 psi	ΔP→0	ΔP = 10	ΔP = 50	ΔP = 100	P_1 psi	ΔP→0	ΔP = 10	ΔP = 50	ΔP = 100
100	0.3	0.5	0.4	---	100	0.1	0.1	0.1	---
300	0.7	1.3	1.3	1.2	300	0.1	0.1	0.1	0.1
600	1.2	2.1	2.0	2.0	600	0.1	-0.2	-0.2	-0.1
900	1.5	2.0	2.1	2.1	900	-0.2	-0.2	-0.8	-0.8
1200	1.6	1.1	1.4	1.4	1200	-0.5	-1.7	-2.2	-2.0
1500	1.4	0.3	0.1	0.0	1500	-1.1	-4.2	-4.0	-4.0

ΔP (pressure loss caused by the leak) and T. At low pressures (P1), the deviations are small but increase at higher pressures until a maximum positive value is reached for the error. The deviations then become smaller until they change signs and then become larger and larger as the pressure increases.

It is not recommended to base the MD technique upon the Perfect Gas Law for pressures exceeding 1500 psi. The errors become quite large above this pressure and could be larger than 5 percent at 2000 psi, 7 percent at 2500 psi, and 9 percent at 3000 psi. Below 1500 psi and constant temperature only moderate errors are usually introduced by the Perfect Gas Law, but if very accurate results are desired, an equation better describing the real gas behavior must be utilized even at very low pressures.

Much larger error will generally be introduced for non-isothermal processes. Some typical errors resulting from assuming perfect gas behavior are shown below: These examples are for isobaric leaks only.

(1) With a temperature change from 20° to 21° C at 500 psi, the calculated error is 7.8 percent.

(2) With the same temperature change at 1500 psi, the calculated error is 6.9 percent.

(3) With a temperature change from 15° to 25° C at 1500 psi, the calculated error is 19.4 percent.

As can be seen from the above examples, a relatively large error can be introduced by the Perfect Gas Law even for small temperature changes, and the error becomes correspondingly larger for larger temperature changes. Furthermore, a false leak can be indicated by assuming perfect gas behavior for non-isothermal processes. Not only could a false leak be indicated by assuming perfect gas behavior, but a substantial leak indication could be cancelled by a temperature and corresponding pressure change. In other words, a system with leaks could pass as a no-leak system.

F. FURTHER INVESTIGATION OF THE VIRIAL EQUATION OF STATE

The comparison between real and perfect gas behavior was limited to pressure up to 1500 psi. It is known, however, that the deviation between a real and a perfect gas increases with increasing pressure. It has been shown that to accurately measure leaks by consecutive P and T measurements, an equation that accurately describes the behavior of air is required. The Virial Equation of State proposed by NBS describes the real behavior of air up to 1500 psi with a high degree of accuracy. An investigation was undertaken to determine if the same equation was applicable for pressures up to 3000 psi (for temperature region 270° K to 340°K).

The investigation included:

(a) Solving the Virial Equation of State for compressibility factor (Z) and density for pressures up to 3500 psi.

(b) Compare above results with experimental values obtained by other investigators.

The Virial Equation of State as previously mentioned:

$$Z = \frac{Pv}{RT} = 1 + \frac{B}{v} + \frac{C}{v^2} + \frac{D}{v^3} \qquad (15)$$

It is rather cumbersome and time consuming to solve this equation for density (1/v). It has to be solved by iteration which involves repetitive mathematical operations. A computer program was therefore prepared to solve the above equation. The input data were P, T, M (molecular weight) and the constants B, C, D. The following output data were printed for each combination of pressure and temperature.

Real Gas Density: DVE, units $\frac{lb}{Ft^3}$

Perfect Gas Density: DPE, units $\frac{lb}{Ft^3}$

Compressibility Factor: Z

A library search was undertaken to obtain experimental thermodynamic properties of air. The pressure - volume - temperature relations for air were investigated in the late nineteenth century by Amagat (3) and Witkowski (4); in the early twentieth century by Koch (5), Holborn and Schultze (6), Holborn and Otto (7), and in more modern times by Michels and others (8). The only investigators who had made an extensive investigation of the behavior of air in the region defined herein were those of modern times. Their experimental data were used for comparison with the computer results.

The compressibility factors for dry air obtained from the Virial Equation of State as well as those obtained from Michel's investigation were plotted in figure 1. The deviation between the two values were calculated as follows:

$$\text{Percent Departure} = \frac{\text{Z experimental - Z calculated}}{\text{Z calculated}} \times 100$$

(1) For pressures less than 1500 psi the maximum percent departure was less than 0.03 percent.

(2) For pressures up to 2500 psi, this figure was 0.70 percent.

(3) It was 0.85 percent for pressures up to 3500 psi.

It should be noted that these maximum deviations all occurred at the lowest investigated temperature (270° K). At higher temperatures these deviations decreased substantially.

The agreement between the two sets of data is, in general, good. Below 1500 psi the agreement is extremely good, which it should be since the Virial Equation of State has been proven to describe very accurately the real behavior of air for this pressure region.

However, precise MD measurements above 1500 psi would require an equation which describes the pressure-temperature relation of the gas even more accurately.

Michel's fitted an equation to their experimental data. The equation was of the form

$$\frac{Pv}{RT} = 1 + \frac{B}{v} + \frac{C}{v^2} + \frac{D}{v^3} + \frac{E}{v^4} + \frac{F}{v^5} + \frac{G}{v^6} + \frac{H}{v^7} \qquad (16)$$

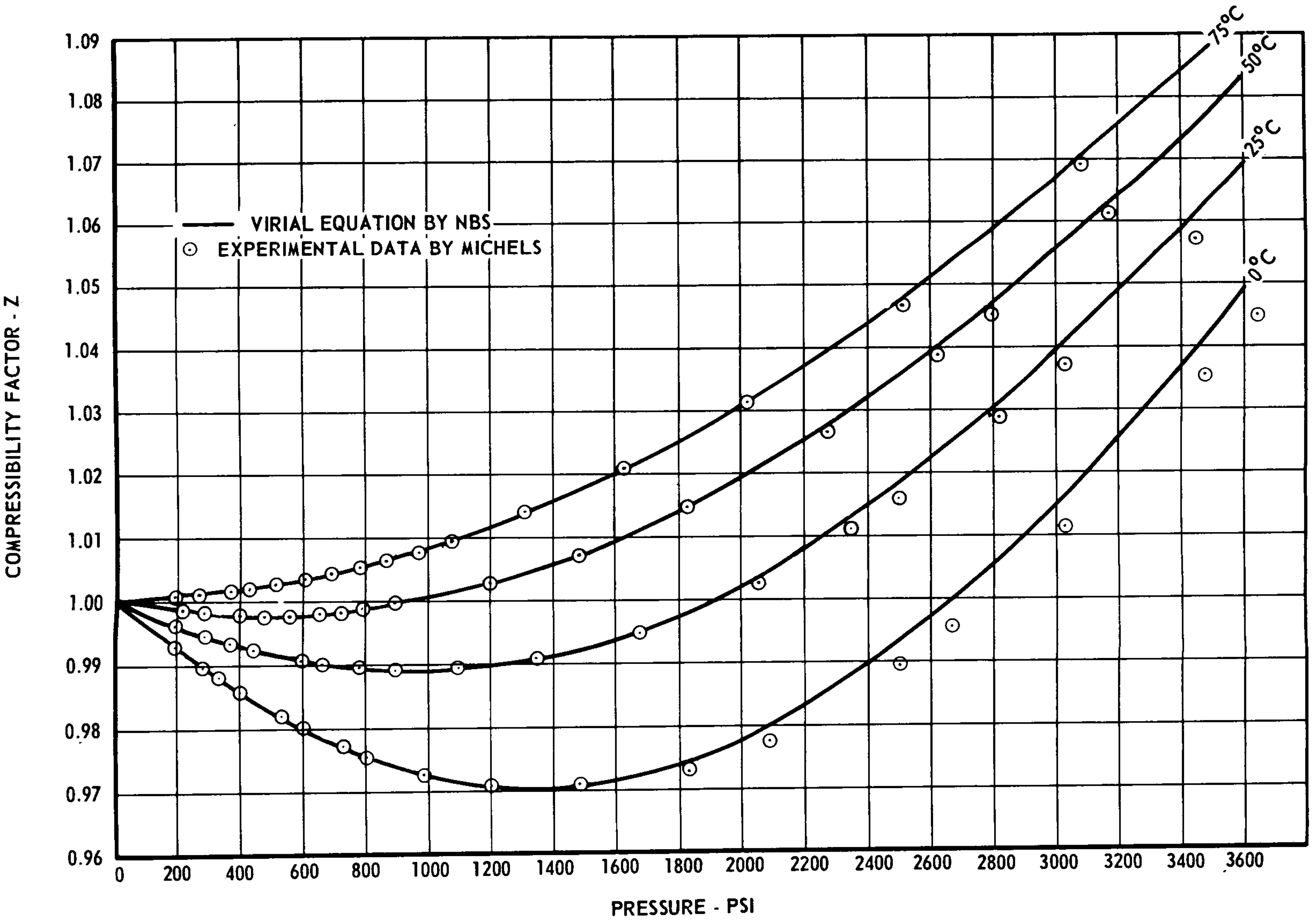

Figure 1. Compressibility Factors for Dry Air

Four additional terms were needed in the series to describe the behavior of air. Michel's experiments included pressures up to 17,000 psi which necessitated the extra terms for a complete description of the gas behavior. The first three coefficients (B, C, and D) are not the same as those used by NBS. The number of terms in the Virial Equation of State increased with increasing pressure range. Four terms were required to describe the behavior of air up to 1500 psi. It was necessary to use eight terms to describe the properties up to 17,000 psi. Therefore, it is reasonable to assume that five or six terms will be required to include pressures up to 3000 psi.

To obtain an equation of state that accurately describes the behavior of air up to 3000 psi, it is suggested to fit an equation to Michel's data up to this pressure. Michel's equation could be used as it stands, but several unnecessary terms would be carried. Furthermore, it would be well to obtain more experimental data for air between 1500 and 3000 psi. The literature search did not yield any more data, and it is suggested that more experimental data be collected to make a fitted equation more reliable.

The MD measurements require that the Virial Equation of State be solved for density. The equations proposed by both NBS and Michel's give the density as an implicit function of pressure and temperature. These equations have to be solved by iteration and therefore are awkward to use as the basis for any MD measurements.

It was shown that the Virial Equation of State can be written in the form

$$\frac{Pv}{RT} = 1 + B_1P + C_1P^2 + D_1P^3 + \dots \qquad (17)$$

This can be done by fitting a polynomial to the curves plotted in figure 2. The constants B_1, C_1, and D_1 are again temperature dependent. Equation (17) can be solved directly for density for known values of pressure and temperature without iteration, and it is therefore better suited as a basis for MD measurements.

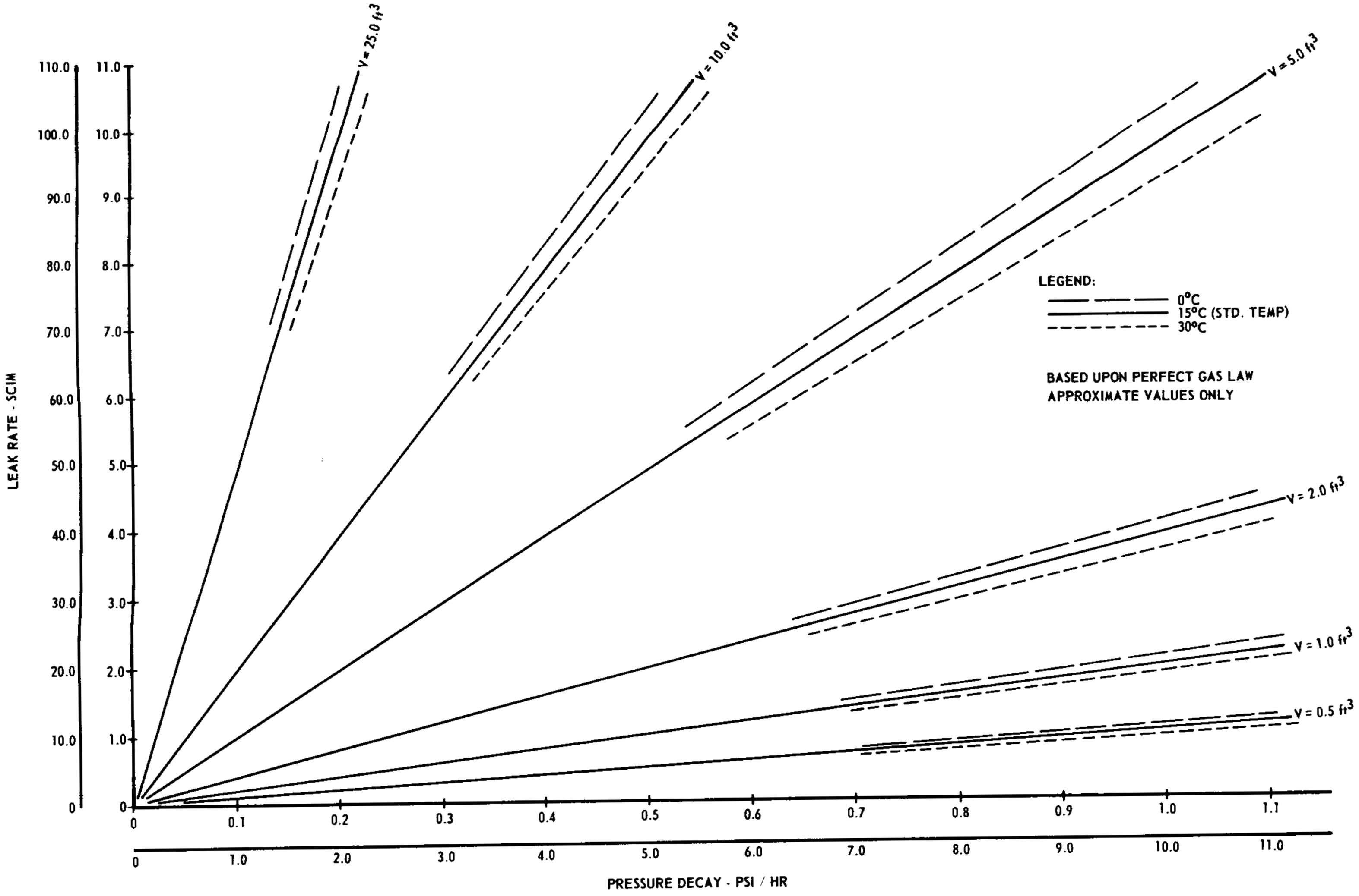

Figure 2. Leak Rate Versus Pressure Decay

SECTION III. MEASURING REQUIREMENTS

Up to now, the requirements of the gas equation have been discussed. In this section the magnitude of the pressure change that must be detected will be investigated. The required resolution of the pressure and temperature measurements and the influence of temperature gradients will also be investigated.

A. LEAK RATE VERSUS PRESSURE DECAY FOR ISOTHERMAL PROCESS

Earlier in the report an equation (3) was derived relating the change in mass to the change in pressure for an isothermal process.

$$(3) \qquad M_L = \frac{V}{RT}\left[\frac{P_1}{Z_1} - \frac{P_2}{Z_2}\right]$$

To investigate the order of magnitude of a pressure change to a corresponding mass change, set $Z_1 = Z_2 = 1$. In other words, perfect gas behavior is assumed. This is not absolutely correct, but quite adequate for investigation of the magnitudes of corresponding changes. Equation (3) becomes

$$M = \frac{V \Delta P}{RT}$$

Leak rates in scims can be directly related to the rate of pressure decay (psi/hr). One standard* cubic inch of air equals 4.4270×10^{-5} lbs. and the gas constant R for air is taken at 0.66687. The equation now becomes

$$\text{Leak rate} = \frac{564.56\ V\Delta P}{T} \qquad (18)$$

The units for the variables in equation (18) are:

Leak Rate = scim
Volume (V) = ft^3
Pressure Decay (ΔP) = $\frac{psi}{hr.}$
Temp. (T) = K°

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*Standard conditions are taken at 1 atm and 51°C (NASA TN 3182)

Equation 18 is plotted in figure 2 for three constant temperatures. The time interval between pressure readings is assumed to be 1 hour. From figure 2 one can readily see that small ΔP's must be measured to detect small leaks. The larger the volume the smaller pressure changes must be measured. The minimum detectable leak is therefore a function of the resolution of the pressure sensor and the capacity of the system. There are commercial quartz pressure transducers on the market with a resolution of 0.1 psi for pressure ranges of 0 to 3000 psi. Even so, a leak of less than 1 scim cannot be measured if the system is larger than 5 ft.^{3}. It is realized that pressure measuring instruments are available with resolutions smaller than 0.1 psi. One such instrument is the fused quartz Bourdon tube with a resolution of 0.0005 percent of full scale readings. This is, however, a laboratory tool and could not be used by technicians at checkout. One could argue that by making the time interval between pressure readings larger than 1 hour, smaller leaks could be detected and measured. However, longer time intervals would make the method impractical by placing greater demands on instrumentation stability and temperature control; furthermore, increased time intervals between readings may cause unreasonable delays in the overall test program.

Up to this point, it was assumed that the pressure is absolutely uniform throughout the system. This is not quite true since for large volumes the weight of the fluid column will induce a small pressure gradient. This gradient is quite small and constant since the geometry of the system does not change. The pressure gradient does not jeopardize the leak detection nearly as much as temperature gradients as will be seen later in this report.

B. PRESSURE CHANGE VERSUS TEMPERATURE CHANGE FOR A NO-LEAK SYSTEM

Both pressure and temperature of the system must be measured before the mass of system can be calculated from the equation of state. Previously, the requirements of the pressure measurements were investigated. In this section, the requirements of the temperature measurements will be investigated. This will be done by deriving an equation relating ΔP and ΔT for a no-leak system.

$$\text{Initial Conditions} \quad \frac{P_1 v_1}{R T_1} = Z_1 \qquad (19)$$

and final conditions $$\frac{P_2 v_2}{RT_2} = Z_2 \qquad (20)$$

Since no leaks are present $v_1 = v_2 = v$

Equation (20) subtracted from (19) yields $\frac{P_1}{T_1} - \frac{P_2}{T_2} = \frac{Z_1 R}{v} - \frac{Z_2 R}{v}$

but $T_2 = (T_1 - \Delta T)$

Upon substitution and simplification the equation becomes

$$\Delta P = \frac{R \Delta Z T_1}{v} - \frac{R \Delta Z}{v} \Delta T + \frac{P_1}{T_1} \Delta T$$

but

$$\frac{P_1}{T_1} = \frac{Z_1 R}{v}$$

and upon substitution and simplification

$$\Delta P = \frac{R}{v} \Delta Z T_1 + \frac{R}{v} Z_2 \Delta T$$

but $v = \frac{RT_1 Z_1}{P_1}$ or $V = \frac{RT_2 Z_2}{P_2}$

By substituting these values for v into the first and second term of the right hand side of the above equation, it becomes

$$\Delta P = \frac{P_2 \Delta T}{T_2} + \frac{P_1 \Delta Z}{Z_1}$$

$$\Delta P = \frac{\Delta T P_1}{T_2} - \frac{\Delta T}{T_2} \Delta P + \frac{P_1 \Delta Z}{Z_1}$$

$$\Delta P \left(1 + \frac{\Delta T}{T_2}\right) = \frac{\Delta T P_1}{T_2} + \frac{P_1 \Delta Z}{Z_1}$$

$$\Delta P \,(T_2 + \Delta T) = \Delta T P_1 + P_1 T_2 \frac{\Delta Z}{Z_1}$$

$$\Delta P \square \frac{\Delta T P_1}{T_1} + \frac{P_1 T_2}{T_1} \frac{\Delta Z}{Z_1} \tag{21}$$

The above equation relates changes in temperature to the corresponding pressure change for a no-leak system. If perfect gas behavior had been assumed, the second term would have vanished since ΔZ for this case is zero. The ΔP corresponding to a small error in temperature can be calculated from equation (21).

Equation (21) is rewritten as

$$(\Delta P)\ \text{Error} = \frac{\text{T Error (P)}}{\text{T}} + \frac{\text{P (T-T Error)}}{\text{T}} \frac{\Delta Z}{\text{Z}} \tag{22}$$

This equation is plotted in figure 3 for four different values of T Error, namely 1.0° C, 0.5° C, 0.1° C and 0.05° C. Temperature (T) was taken to be standard (15° C). The error in ΔP due to an error in the temperature measurement can now be determined from figure 3. This ΔP error can then be used in figure 2 to determine the corresponding error in leak rate.

Commercial temperature transducers are available with a resolution of 0.05° C for this particular temperature region. From figure 3 the corresponding ΔP is 0.75 psi for a 3000 psi system pressure. A pressure decay of 0.75 psi per hour can amount to a substantial leak rate. If a pressure transducer with a 0.1 psi resolution is used, then a temperature transducer should be used with a resolution such that the corresponding ΔP error does not exceed 0.1 psi. For system pressures below 500 psi, a temperature resolution of 0.05° C would be adequate. If the system pressure is 3,000 psi, a temperature resolution of 0.005° C is required. If the resolution of the pressure decay measurements is less than 0.1 psi/hr, the resolution of the temperature sensors must then be correspondingly smaller.

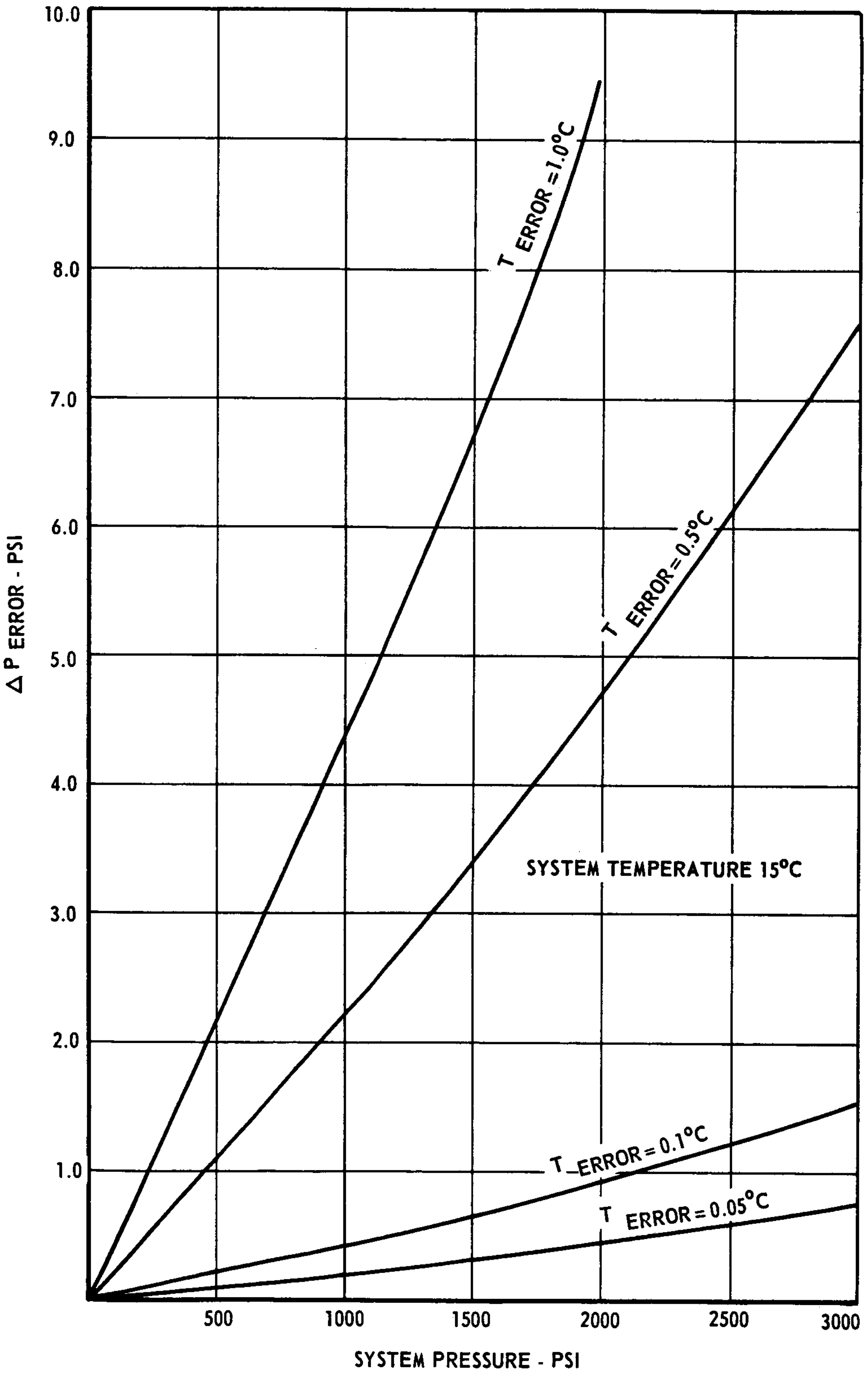

Figure 3. Influence of Temperature Error

C. TEMPERATURE GRADIENTS

It has been shown that a small error in the temperature measurement can amount to large errors in the leak indication. Previously, only the error introduced by the temperature transducer itself was investigated. One may now wonder what temperature to measure. Should no temperature gradients exist in the system, this will present no problem because only one temperature can be measured. However, it is reasonable to assume that temperature gradients will be present in the system since the temperature environment during the checkout period is not a controlled one.

As previously mentioned, the basis for this leak detection technique is to detect any changes in the average density of the whole system. Any change will indicate the presence of leaks and the magnitude of the change will indicate the magnitude of the leaks. Local changes in density can take place without the presence of any leaks. These local density changes are, of course, due to local temperature changes. Therefore, local changes are of no interest when applying the MD techniques and the temperature to be measured must be the one that when substituted into the gas equation will yield the average gas density of the entire system.

The relationship between density and temperature for a constant pressure is not a linear one (figure 4). Therefore, the average gas temperature does not precisely yield the average density. For moderate temperature gradients, however, the relationship between temperature and density can be assumed linear, since the MD technique is based upon measuring changes in the average density rather than absolute densities. Therefore, the small error introduced initially by using the average temperature will be cancelled by subsequent readings. The argument is a valid one but the problem of finding the average temperature still remains. Obviously, the average temperature of the gas in the system is not the average reading of several temperature transducers located at random throughout the system. The average temperature desired is rather the average temperature of all the molecules in the whole system. This becomes impossible if the system is of a complex geometric configuration, such as a multitude of volumes of different capacity connected to each other by small tubing. To determine the average molecular temperature of a complex system, each particular reading must be weighted according to the size of the volume with which the temperature sensor is associated. Under such conditions, the

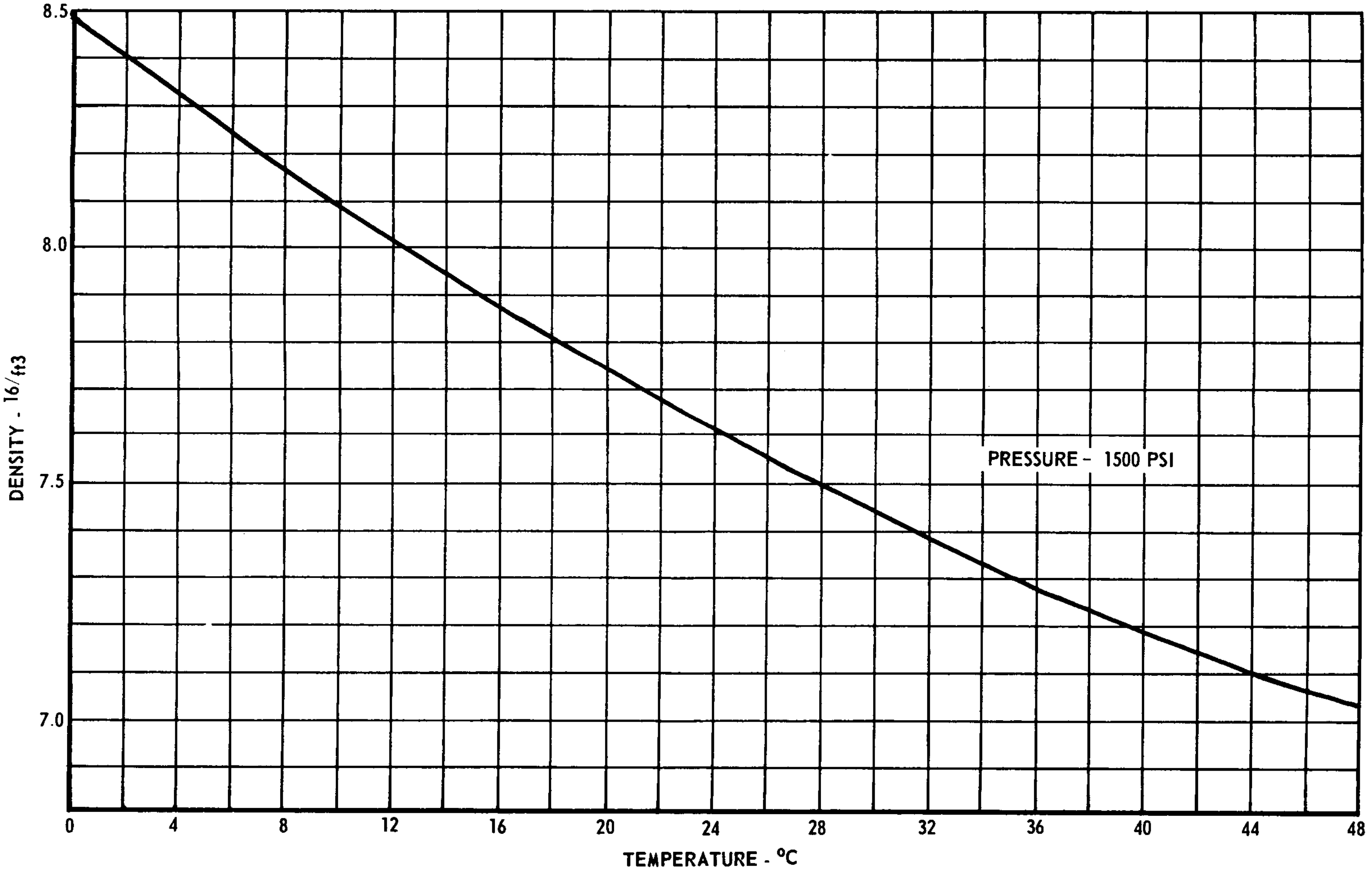

Figure 4. Temperature Versus Density

probability of measuring the average molecular gas temperature with the required precision is very small. It would not be unreasonable to assume that for complex geometric systems with large temperature gradients and temperature fluctuations, the average temperature can only be measured to within ±3° C. Realizing that even minute errors in the temperature measurement can cause large errors in the leak indication, it must be concluded that the confidence level of the leak indication becomes very small if the MD method is applied to systems where temperature gradients and/or fluctuations occur.

SECTION IV. CONCLUSIONS

Successful leak detection with the mass drop-off method requires:

1. An equation relating density to pressure and temperature.
2. Pressure sensors measuring the pressure in the system at any time.
3. Temperature sensors capable of measuring the average temperature of the test gas in the system.

The accuracy and reliability of the mass drop-off method is a function of the aforementioned items. Due to the marked influence of temperature fluctuations, the technique could be subdivided into isothermal and nonisothermal MD measurements.

A. ISOTHERMAL MASS DROP-OFF MEASUREMENTS

Isothermal MD measurements are defined as those taking place in an environment free of temperature fluctuations and temperature gradients during the entire checkout period.

The error introduced by basing isothermal MD measurements upon the perfect gas law can be calculated from equation (5). Some calculated values were also shown in table 1. These errors were moderate at low pressures and even at 1500 psi the errors did not exceed 5 percent, but the errors increase with increasing pressure. These errors could probably be tolerated in some instances. Furthermore, no false leaks can be indicated by assuming perfect gas behavior for isothermal MD measurements. A condition for possible false leak indication is a temperature change during the measuring period.

Should on the other hand very accurate results be required, isothermal MD measurements cannot be based upon the perfect gas law. An equation better describing the real behavior of the test gas must then be defined. The Virial Equation of State can always be utilized but it can also become rather awkward for mathematical manipulations. This is particularly the case at high pressures which require a large number of terms in the equation for an accurate description of the real gas behavior.

The resolution of isothermal MD measurements is a function of the resolution of the pressure sensors. Knowing the latter, the corresponding leak measuring resolution can be calculated from equation (18) or from figure 3. As can be seen from the figure, the ability of measuring small leaks with this technique diminishes rapidly with increasing system volume. However, fairly small leaks could be detected on systems moderate in size, but even the slightest fluctuation of the temperature or the slightest temperature gradient in the system during the checkout period would make this technique quite unreliable. The task of insuring isothermal environment during the measurements may be just as difficult as to actually measure the average gas temperature.

B. NONISOTHERMAL MASS DROP-OFF MEASUREMENTS

The error introduced by assuming perfect gas behavior is in general larger for nonisothermal than isothermal MD measurements. Furthermore, a false leak could be indicated during nonisothermal MD measurements based upon the Perfect Gas Law. Not only could a false leak be indicated, but a substantial leak indication could be cancelled by a temperature and corresponding pressure change. In other words, a system with leaks could pass as a no-leak system. The Perfect Gas Law is therefore not recommended to be used as a basis for nonisothermal MD measurements.

Even a small error in the temperature measurement could amount to large errors in the indicated leak rate as can be seen from equation (21) and figure 3. The largest error will not be caused by the temperature sensors, but rather by any temperature gradients present in the system. The average temperature must be accurately measured which becomes very difficult in a complex system. Due to aforementioned factors, the nonisothermal MD technique becomes very unreliable particularly for the measurement of small leaks.

The nonisothermal MD technique could possibly be used to obtain a general check of the overall status of a closed complex gas system. This is possible if the magnitude of the pressure decay (ΔP actual) caused by the leak is very large compared to the ΔP error introduced by the temperature measurement. Under such conditions, the ΔP error can be considered negligible.

Before any leak detection is performed with the MD technique, the test conductor in charge should consider the following:

1. Determine the magnitude of the smallest leak rate that must be detected and measured.

2. Investigate the temperature environment under which the testing will take place.

3. Estimate to what accuracy the average temperature can be measured.

4. Estimate the resolution of the temperature and pressure sensors to be used.

5. From above items, determine if the mass drop-off technique could be used to advantage and if so decide whether to base the technique upon

    a. The Perfect Gas Law
    b. The Virial Equation of State.

Although leak detection by the MD technique has many limitations and shortcomings, occasions could arise where other methods are impractical or impossible to use. Under these conditions, the MD technique could be used to advantage, but only after a careful consideration has been given to the items listed above.

APPENDIX A

COEFFICIENT FOR THE EQUATION OF STATE FOR AIR

Temperature K°	$cm^3/mole$	$cm^6/mole^2$	$cm^9/mole^3$
260	-16.537	1325.3	41700
270	-13.982	1316.9	39800
280	-11.637	1308.0	38000
290	-9.475	1298.3	36300
300	-7.480	1288.5	34600
310	-5.629	1278.4	33100
320	-3.911	1268.4	31600
330	-2.310	1258.6	30200
340	-0.820	1248.8	28800
350	+0.575	1239.1	27500
360	+1.882	1230.4	26200

APPENDIX B

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December 9, 1966 NASA TM X-53551

APPROVAL

CRITERION FOR MASS DROP-OFF MEASUREMENTS BASED UPON PRECISE PRESSURE AND TEMPERATURE MEASUREMENTS

By

Jan H. Sodergren

The information is this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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