

**EUR 2982.e**

**EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM**

**CONVERSION OF LEAK FLOW-RATES FOR VARIOUS  
FLUIDS AND DIFFERENT PRESSURE CONDITIONS**

by

J. AMESZ

**1966**



ORGEL Program

Joint Nuclear Research Center  
Ispra Establishment - Italy

Engineering Department  
Technology

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## SUMMARY

This report contains in a concise form the development of rules for conversion of gas and liquid leakages. In many cases, for reasons of convenience, leaktightness of components is tested by means of a gaseous medium, although they actually operate with a liquid medium. As leak mechanisms of a liquid and a gas are often principally different, conversion requires the application of appropriate correlations. Based on theoretical considerations, such correlations are derived and presented in this paper.

## 1. INTRODUCTION

The primary requirement for a sealing will be a maximum degree of leaktightness. Several methods of measuring both gas-leakages and liquid-leakages will be discussed shortly, since quantitatively, the leaktightness of a sealing can only be determined by measuring leakages. However, often the circumstances and conditions during measuring are not identical to those during operation. Consequently, in many cases it will be necessary to convert leak data obtained with a certain measuring system, to conditions equal to actual operating conditions. In making such conversions the following parameters should be taken into account:

### Test-fluid (gas and liquid)

Fluid flow conversion is often necessary for one of the following reasons:

- In many cases a measuring method for liquid leaks is not sensitive enough or does not exist, so a gas is used as a test medium instead of the liquid itself.
- Sometimes leaks are measured with a special test gas, as for instance, helium, when a mass-spectrometer is used as leak-test apparatus.

### Pressure (vacuum, atmospheric-pressure and over-pressure)

Conversion of leak flow-rates at different pressures will be needed mainly for the following reason:

Most of the gas leakages are measured either by means of the mass-spectrometer or with the differential-pressure method, consequently under vacuum. However, at operation conditions the working-pressure will not be a vacuum, but an over-pressure.

### Temperature

For ease and accuracy, leak-measurements are mostly performed at ambient temperature, which in most cases does not correspond with reality.

In this report conversion theories will be presented, giving leak flow-rate-formulae for and relationships between the above mentioned parameters.

## 2. LEAK DETECTION FACILITIES

In order to measure or to detect a gas leak, of the many existing possibilities, the following methods are chosen either because of the simplicity, the sensitivity or the handiness:

- the differential-pressure method
- the He mass-spectrometer
- the "Speedivac" leak-detector.

With these few methods small leakages can be measured as well as larger ones.

### 2.1. The differential-pressure method

The object which has to be tested for leakages is evacuated. When the pressure is low enough, a valve is closed separating the object from the vacuum pump. Then the total leakage can be calculated from the pressure-rise during a certain time interval with the following formula:

$$Q = \frac{V}{t} \cdot \Delta p \text{ lusec,}$$

in which V = volume of the object in litres

t = time interval in sec

$\Delta p$  = pressure-rise in  $\mu\text{Hg}$  during t sec.

With this method the measurements are often influenced by outgassing and background leakages of the vacuum system. A theoretical relation has been derived by means of which the outgassing and background leakages can be eliminated. Therefore various measurements at different fill-pressures should be performed (see chapter 5).

It will be clear that the method will be more sensitive for a smaller volume and a higher fill-pressure. In that case very small leaks, in the order of magnitude of

$10^{-4}$  lusec, could be measured.

On the other hand an object under over-pressure can be tested by measuring the pressure-drop at the fill-pressure side of the leak. In this case, the total leakage is also calculated by means of the above mentioned formula.

## 2.2. The He mass-spectrometer

The principle of the mass-spectrometer is based on the fact that gas ions, being in a magnetic field, will follow a circular path of which the radius depends on their charge and mass. Gas ions with a certain molecular weight can thus be separated from other ions in a mixture. The spectrometer can only be operated at low pressure (about  $10^{-1}$   $\mu$ Hg), so that an extensive vacuum installation will be needed, consisting of at least a fore-pump and a diffusion pump in series. In order to measure the leakage a calibrated leak should be placed in the system. The mass-spectrometer is the most sensitive leak test apparatus. Already with a pressure difference of 1 atm over the leak, leak flow-rates of  $10^{-8}$  lusec can be measured. An inherent disadvantage is the use of a test-gas, in most cases helium. Thus, conversion of the leak flow-rate for another gas will be nearly always necessary.

## 2.3. The "Speedivac" leak-detector

In the case where leaks should be localized one can use this industrial apparatus. It has also to be used in combination with a test-gas like helium or argon, since the principle is based on the difference in thermal conductivity of the test-gas and the air. Leaks also can be determined quantitatively, however within a rather large margin of accuracy.

## 2.4. Liquid leak measurements

Although a leak measurement of a liquid is less accurate than that of a gas, such measurements are nevertheless

often applied. The main reason is the need of leak measurements during operation, since the leaking medium is a liquid. Another reason often is the difficulty of converting a measured gas flow-rate to a flow-rate to be expected for a liquid. However, the next chapters will show that this conversion is quite possible. Some methods for determining a liquid leakage directly or indirectly are:

- Volume and weight measurements

By means of a capillary tube small quantities of a liquid can be measured by volume. Also the weight increase of an absorbent material (for instance silicagel and water) can be taken as a measure of a leakage.

If it is possible to remove the liquid by a carrier gas, for instance by evaporation at a higher temperature, depending on the partial-pressures, then the liquid leakage can be measured indirectly in the gaseous phase. The next methods are developed on these lines, especially concerning the measurement of an organic liquid leak (terphenyl  $OM_2$ ).

- Flame ionization method

The organic vapour is removed by nitrogen and is burned in a hydrogen flame, giving an ionization current which gives a signal on the recorder via an amplifier. The apparatus used is a modified Aerograph gas-chromatograph. The smallest amount to be measured is of the order of magnitude of  $10^{-5}$  mg org/cc  $N_2$ .

- U.V. absorption method

The principle is based on the fact that the organic vapour absorbs a part of an UV beam. The other part, depending on the concentration of organic vapour/carrier gas, transmits a signal via a photomultiplier to the recorder.

### 3. THE FLOW-RATE THROUGH A LEAK

Formulae for the leak flow-rate at different conditions are mostly known, or can easily be derived. So, it would be ideal that leak flow-rates could be directly calculated. However, one of the parameters which enters in such calculation is the geometry of the leak. Since it is impossible to estimate the latter with sufficient accuracy, leak flow-rates will be always determined by measuring them.

On the other hand, the knowledge about the geometry of the leaks is sometimes of importance in making conversion of leak flow-rates. Then, one is forced to determine this parameter through the experimental determination of the leak flow-rate (see next chapter), and the application of the known formulae for the leak flow-rate. In this chapter, therefore, formulae of the leak flow-rate for various fluids and different pressure conditions will be presented.

#### 3.1. Gas leakages

Firstly we will define the unit in which a gas leak flow-rate should be expressed.

The definition of the various leak units, as lusec, atm cc/sec, etc. can be derived directly from the already mentioned formula:

$$\text{leak flow-rate} = \frac{\Delta p \cdot V}{t}, \text{ in which}$$

$\Delta p$  is the pressure-drop or pressure-increase due to a leak of the "sealed" volume  $V$ , during a certain time  $t$ .

Then we can define the lusec (or  $\mu$  litre/sec) as follows:

When the pressure in a volume of 1 litre under vacuum increases with 1  $\mu$  Hg (or  $10^{-3}$  mm Hg) in 1 sec, this pressure increase is caused by a leak of 1 lusec.

Likewise we find that:

A leak of 1 atm cc/sec causes in a volume of 1 cc at a certain pressure higher than atmospheric pressure a pressure drop of 1 atm in 1 sec.

The interpretation of leak data often gives rise to confusion. This is due to the fact that the definition of the leak unit does not contain the influence parameters.

Actually the leak unit is a normal flow-rate unit, for which in case of a gas leakage the gas quantity has to be defined more precisely by the product of pressure and volume, i.e. the weight quantity of a certain gas volume depends on the pressure. So, this pressure does not relate to the pressure difference over the sealing or the pressure in the sealed volume. That means one has always to mention the parameters under which a certain leak has been measured. These influence-parameters are:

1. Fill- and exit-pressure; in case of a gas leak two different types of leakage have to be distinguished, either a leak from a high pressure to atmospheric pressure or a leak of atmospheric or higher pressure to vacuum.
2. The temperature not only changes the physical properties of the leaking medium but also effects the geometry of the leak.
3. The leaking medium itself.
4. The sealed length over which the leak is measured.

In vacuum technique the lusec is mostly used as leak unit. In case of sealings against an over-pressure the unit atm cc/sec is used.

The conversion of the various units can easily be performed by means of the above mentioned formula: for instance

$$1 \text{ lusec} = 10^{-3} \text{ torr l/sec} = 1,32 \cdot 10^{-3} \text{ atm cc/sec.}$$

By way of simplification it will be assumed that leaks always occur through a number of small capillaries of circular cross-section with an average diameter  $D$  and a length  $L$ . In chapter 5.1. the justification of this assumption will be given. Depending on the diameter and pressure the nature of the flow through the capillary will be viscous, molecular or in the transition range between these. If  $pD > 0,5$  torr cm, the flow is viscous, and for  $pD < 1,5 \cdot 10^{-2}$  torr cm molecular. That means for a capillary of  $10^{-2} \mu$  the flow will be molecular over the whole length of the capillary, while for a diameter of  $10 \mu$  there will be successively molecular, transition and viscous flow.

Generally, leaks of  $10^{-4}$  atm cc/sec and smaller, which are just of the order of magnitude of the leaks being measured, can be in the transition range between viscous and molecular flow. However, very small leaks around  $10^{-9}$  atm cc/sec are predominately molecular. For instance in the case of a diameter of  $0,1 \mu$ , the flow is 90% molecular, which is in agreement with the fact that the mean free path of the molecules is of the same order of magnitude, i.e. for atmospheric air  $0,0669 \mu$ . In the case of very small capillaries ( $< 0,01 \mu$ ) a third kind of flow appears, i.e. surface flow. The amount of surface flow, influenced largely by the type of gas molecule and the nature of the surface of the capillary-wall, cannot generally be predicted, owing to the absence of data concerning surface adsorption and surface diffusion. Thus leak flow-rate calculations will only be based on viscous and molecular flow.

The flow-rate of a gas leak from atmospheric or higher pressure to vacuum can be calculated with the following basic formulae for molecular and viscous flow through a capillary. For pure molecular flow by means of Knudsen's law:

$$Q_g = \frac{1}{6} \sqrt{2\pi} \cdot 10^{-9} \sqrt{\frac{R_0 T}{M}} \cdot \frac{D^3}{L} (p_1 - p_2) \text{ atm cc/sec} \quad (1)$$

For viscous flow by means of Poiseuille's law:

$$Q_g = \frac{\pi}{256} \cdot 10^{-8} \cdot \frac{D^4}{L} \cdot \frac{p_1^2 - p_2^2}{\eta_g} \text{ atm cc/sec} \quad (2)$$

A general formula for the flow-rate of gases in the transition range can be found by the sum of the basic formulae for molecular and viscous flow, so that:

$$Q_g = 10^{-6} \frac{D^3}{L} \left\{ 0,093 \frac{D}{\eta_g} (p_1^2 - p_2^2) + 2,88 \sqrt{\frac{T}{M}} (p_1 - p_2) \right\} \text{ lusec} \quad (3)$$

in which the diameter of the capillary  $D$  in  $\mu$ ,  
 the length  $L$  in cm,  
 the dynamic-viscosity of the gas  $\eta_g$  in cP and  
 the fill-pressure  $p_1$  in atm and  
 the exit-pressure  $p_2$  in atm.

Theoretical comparison of leak flow-rates by this formula (3) and the next formula (4) given by Knudsen <sup>+</sup>, only gives an appreciable difference at very small diameters ( $D < 0,1\mu$ , see table I)

$$Q_g = 10^{-6} \frac{D^2}{L} \left\{ 5,3 D^2 \frac{\eta_1}{\eta_g} + 7,5 D \sqrt{\frac{M_1}{M_g}} + 0,91 \frac{\eta_g}{\eta_1} \cdot \frac{M_1}{M_g} \right\} \text{ lusec} \quad (4)$$

This formula gives the leak flow-rate of a gas from atmospheric to vacuum pressure in which  $L$  in cm,  $D$  in  $\mu$ ,  $\eta_1$  and  $\eta_g$  are respectively the dynamic-viscosity at 20°C of air and of the relative gas in cP.

Formula (3) can be simplified to:

$$Q_g = 10^{-6} \cdot \frac{D^3}{L} (p_1 - p_2) \left\{ C_1 D (p_1 + p_2) + C_2 \right\} \text{ lusec} \quad (5)$$

in which:

$$C_1 = 5,15 \text{ and } C_2 = 9,15, \text{ for air of } 20^\circ\text{C}$$

$$C_1 = 4,9 \text{ and } C_2 = 24,6, \text{ for helium of } 20^\circ\text{C}.$$

<sup>+</sup>) Vacuum Equipment and Techniques by A. Guthrie and R.K. Wakerling.

In table I the product of leak flow-rate and length is given for several diameters of the capillary. From this table it can be deducted that the leaks of frequent occurrence, being of the order of  $1 - 10^{-6}$  lusec, are related to capillaries with diameters varying from  $0,1\mu$  to  $10\mu$ .

Introducing a new parameter  $\psi$ , being the logarithmic difference of the leak flow-rate-pressure gradient, one can determine how far a leak flow is molecular or viscous. For pure molecular flow  $\psi = 1$  and for only viscous flow  $\psi = 2$ . As  $\psi$  is a function of the diameter of the capillary, one is also able to predict the diameter of the capillary, knowing the value of  $\psi$ .

Generally: 
$$\psi = \frac{\log Q_{gA} - \log Q_{gB}}{\log p_A - \log p_B} \quad (6)$$

in which  $Q_{gA}$  and  $Q_{gB}$  are the leak flow-rate respectively at leak fill-pressure  $p_A$  and  $p_B$  (see table I).

By means of formulae (3) and (6) the average diameter of the capillaries can be defined as follows:

$$D = 31 \eta_g \sqrt{\frac{T}{M}} \cdot \frac{1 - (p_A/p_B)^{\psi-1}}{p_B (p_A/p_B)^{\psi-1} - p_A} \mu \quad (7)$$

or directly in  $Q_{gA}$ ,  $Q_{gB}$ ,  $p_A$  and  $p_B$ .

$$D = 31 \eta_g \sqrt{\frac{T}{M}} \cdot \frac{p_A Q_{gB} - p_B Q_{gA}}{p_B^2 Q_{gA} - p_A^2 Q_{gB}} \mu \quad (8)$$

Also the leak exit-pressure (vacuum) is dependent on the diameter of the capillary. This pressure has a minimum when the velocity of the gas at the end of the capillary is maximum and thus equal to the sound velocity, as

$$Q_g = \frac{\pi}{4} D^2 \cdot v \cdot p_2$$

Consequently:

$$p_2 \text{ min} = \frac{Q_g}{\frac{\pi}{4} D^2 v_s}$$

or

$$p_2 \text{ min} = 3,7 \cdot 10^6 \frac{Q_g}{D^2} \cdot \mu\text{Hg} \quad (9)$$

in which  $Q_g$  is expressed in lusec and  $D$  in  $\mu$ . So to each diameter belongs a certain minimum exit-pressure (see table I).

Gas leaks from an over-pressure to atmospheric pressure can be calculated by the basic formula of viscous flow, being:

$$Q_g = 9,3 \cdot 10^{-8} \frac{D^4}{L} \cdot \frac{1}{\eta_g} (p_1^2 - p_2^2) \cdot \text{lusec} \quad (10)$$

in which  $D$  in  $\mu$ ,  $L$  in cm,  $\eta_g$  in cP,  $p_1$  and  $p_2$  in atm.

The mean free path of the molecules at 1 atm or higher is in most cases smaller than the diameter of the capillary which justifies the neglect of molecular flow.

### 3.2. Liquid leakages

Before giving the general formula for calculating a liquid leak flow-rate two phenomena should be considered in more detail, i.e.

- surface tension effects
- evaporation of the liquid during leaking

The effect of surface tension will set up a pressure according to

$$p_s = \frac{40 \sigma \cos \phi}{D} \text{ atm} \quad (11)$$

in which is:  $\sigma$  = the surface tension in N/m  
 $\phi$  = the contact angle  
 $D$  = the diameter of the capillary in  $\mu$

The surface tension effect will hold the liquid if the pressure difference over the leak is less than this pressure. The value of the contact angle  $\phi$  is a measure of the degree of wetting of the capillary by the liquid. Mainly liquid leakages through very small capillaries will be influenced by this effect.

When the temperature of the liquid exceeds the saturation temperature which corresponds to the exit-pressure of the leak the liquid will evaporate - and the vapour will possibly superheat - travelling down the capillary. Consequently, a combined liquid-gas flow will occur.

The basic formula for a laminar liquid flow is:

$$Q_L = 2,45 \cdot 10^{-10} \cdot \frac{D^4}{L} \cdot \frac{1}{\eta_1} (p_1 - p_2) \text{ cc/sec} \quad (12)$$

in which D in  $\mu$ , L in cm,  $\eta_1$  in cP and  $p_1$  and  $p_2$  in atm.

For a liquid which evaporates during leaking, the leak flow-rate formula can be derived as follows:

Under steady conditions, the interface between the liquid and its vapour takes up a fixed position somewhere along the length of the capillary. We may therefore divide the length L of the capillary into two parts, one part of length x containing the liquid and the remaining length (L - x) containing the vapour.

Considering first the mass flow of the liquid  $\phi_1$  along the part x, we make use of equation (12)

$$\phi_1 = 2,45 \cdot 10^{-10} \cdot \frac{D^4}{x} \cdot \frac{\rho_1}{\eta_1} (p_1 - p_v) \text{ gr/sec}$$

where  $p_v$  is the vapour pressure in atm, and  $\rho_1$  the density of the liquid in gr/cc.

For the vapour, the mass flow  $\phi_v$  along the part (L - x) may be derived by means of equation (10):

$$\Phi_v = 1,225 \cdot 10^{-10} \frac{D^4}{(L-x)} \cdot \frac{(p_v^2 - p_2^2)}{p_v} \cdot \frac{\rho_v}{\eta_v} \text{ gr/sec}$$

where  $\rho_v$  is the density of the vapour in gr/cc.

Under steady conditions, the vapour mass flow-rate  $\Phi_v$  is equal to the liquid mass flow rate  $\Phi_l$  and therefore

$$\Phi_l = 2,45 \cdot 10^{-10} \cdot \frac{D^4}{L} \left\{ (p_1 - p_v) \frac{\rho_l}{\eta_l} + \frac{(p_v^2 - p_2^2)}{2 p_v} \cdot \frac{\rho_v}{\eta_v} \right\} \text{ gr/sec (13)}$$

When the influence of surface tension is expected to be considerable, formula (12) has to be corrected, insofar as the leak fill-pressure  $p_1$  should be lowered by an amount as given by equation (11) (in case of a pure liquid leak). However, when evaporation in the capillary occurs, the leak fill-pressure  $p_1$  in formula (13) should be increased by this amount.

D in $\mu$	$(p_1 - p_2)$ atm $p_2 = 0$	$Q_{air} \cdot L$ in lusec-cm		$\psi$	$p_2$ min in mm Hg	$Q_{gas}/Q_{air}$		
		form(3)	form(4)			form.(3) He	form.(4) He	CO <sub>2</sub>
0,01	1	$9,2 \cdot 10^{-12}$	$9,9 \cdot 10^{-11}$	1,021	$3,7 \cdot 10^{-3}$	-	7,3	0,55
	10	$9,67 \cdot 10^{-11}$						
0,1	1	$9,67 \cdot 10^{-9}$	$1,7 \cdot 10^{-8}$	1,17	$6,3 \cdot 10^{-3}$	2,5	5,3	0,68
	10	$1,43 \cdot 10^{-7}$						
1	1	$1,43 \cdot 10^{-5}$	$1,4 \cdot 10^{-5}$	1,628	$5,2 \cdot 10^{-2}$	2,06	2,3	0,94
	10	$6,07 \cdot 10^{-4}$						
10	1	$6,07 \cdot 10^{-2}$	$6 \cdot 10^{-2}$	1,936	2,2	1,2	1,2	1,2
	10	5,24						
100	1	$5,24 \cdot 10^2$	$4,7 \cdot 10^2$	1,989	170	-	0,93	1,24
	10	$5,1 \cdot 10^4$						

T A B L E I

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#### 4. THE GEOMETRY OF A LEAK

From the foregoing chapter we learned that instead of determining the leak flow-rate theoretically through the geometry of the leak (which cannot be measured), an average leak geometry can be calculated on the basis of the experimentally determined leak flow-rate.

The geometry, i.e., the diameter of the capillaries of which a leak consists, may, as previously mentioned, vary from about  $0,1\mu$  to  $10\mu$ . So, a certain measured leak may consist of many small capillaries as well as one or more larger capillaries. The following example will illustrate this. The leak flow-rates of air from atmospheric to vacuum pressure for two different sealings 1 and 2 are respectively  $Q_{g1}$  and  $Q_{g2}$ , while  $Q_{g1} > Q_{g2}$ . For the same sealings the leak flow-rate of organic liquid  $Q_{L1}$  can be smaller as well as higher than  $Q_{L2}$ . This depends on the composition of the leak; if the leak of sealing 1 consists of many small capillaries and of sealing 2 one or more larger capillaries,  $Q_{L1}$  will be smaller than  $Q_{L2}$  (see also chapter 5.2). That means, the leak flow-rate of a certain gas and a certain liquid for different leaks is not constant but depends completely on the composition and the geometry of the relative leaks

The following methods can give an estimation of the geometry of a leak.

##### - Leak measurements at different fill-pressures

A log-plot of the leak-rate versus pressure will give the logarithmic gradient  $\psi$  (see formula 6), from which the average diameter of the capillaries can be calculated (see formula 7). Also known is then the leak flow-rate through one capillary of that diameter (see table I) and so the number of capillaries divided by the length follows from the total measured leak flow-rate. In chapter 5.1. it will be shown that for purposes of conversion of leak-rates one may assume the same diameter for all

the capillaries of which a leak consists.

- Leak measurements with two different gases

The leak flow-rate ratio of two different gases for the same leak also depends on the diameter of the capillary, i.e. the kind of flow (molecular-viscous) through a capillary of a certain diameter depends on the molecular weight and the viscosity of the relative gas. For instance, a leak with an air flow-rate of 0,01 lusec from 1 atm to vacuum of which in case of helium the leak flow-rate is 0,053 lusec, will consist of about  $10^6$  capillaries ( $L = 0,1$  cm) with a mean diameter of  $0,1 \mu$ .

- Measuring the pressure on the vacuum side of the leak

As can be seen from Table I the vacuum which can be obtained - of course with a sufficient pumping speed - also depends on the diameter of the capillary. A relative high leak flow-rate with a low vacuum would point to many small leakages.

It should be emphasized that the above mentioned methods can only be applied in cases where vacuum is used. If the leak exit-pressure is atmospheric, the leak flow-rate will be always viscous, thus proportional with  $D^4$ . In that case gas-liquid flow-rate conversion will not be influenced by the geometry of the leak.

5. CONVERSION OF VARIOUS FLUID FLOW-RATES

On the basis of the above mentioned flow-rate formulae, relationships can be presented which permit direct conversion of the flow-rate of a particular fluid at known pressure conditions to the flow-rate to be expected for another fluid at the same or different pressure conditions. By means of these relationships the conversion can be made mathematically as well as graphically.

5.1. Mathematical conversion of leak flow-rates

5.1.1. Gas and liquid flow-rates

There are two possibilities to be considered, depending on the gas pressure on the lower pressure side of the leak, the exit-pressure, which can be:

- a) vacuum pressure ( $p_2 = 0$ ), or
- b) atmospheric pressure ( $p_2 = 1$ ).

In both cases it is important to find a relation between the liquid leak-flow-rate and the gas leak-flow-rate in such a way that it is not necessary to know the geometry of the leak. While in case a) with, for instance, the differential-pressure method one should also have the possibility of eliminating the influence of outgassing and background leaks.

- a) In this case, leaks to vacuum pressure, it will be possible to eliminate both factors by measuring the gas leak flow rate at three different fill-pressures, being  $Q_{gA}$  at pressure  $p_A$ ,  $Q_{gB}$  at pressure  $p_B$  and  $Q_{gC}$  at pressure  $p_C$ . The general formula of  $Q_g$  is (see formula 3):

$$Q_g = 10^{-6} \frac{D^3}{L} \left\{ 0,093 \frac{D}{\eta_g} (p_1^2 - p_2^2) + 2,88 \sqrt{\frac{T}{M}} (p_1 - p_2) \right\} \text{lusec}$$

The measured leak is equal to the actual leak ( $Q_g$ ) plus outgassing plus background leaks.

Denoting the outgassing plus background leaks as  $R$ , being independent on the fill-pressure, then the above mentioned formula, for a fill-pressure  $p_A$ , can be written in the following general form:

$$Q_{gA} = a_A x + b_A y + R \quad (I)$$

with  $x = n \frac{D^4}{L}$ ,  $y = n \frac{D^3}{L}$ ,  $a_A = 10^{-6} \cdot \frac{0,093}{\eta_g} p_A^2$  and

$$b_A = 10^{-6} \cdot 2,88 \sqrt{\frac{T}{M}} \cdot p_A.$$

n is the number of leaks (capillaries) with mean diameter D and length L, while  $p_2$  is assumed to be 0.

Also analogous will be:

$$Q_{gB} = a_B x + b_B y + R \quad (II)$$

$$Q_{gC} = a_C x + b_C y + R \quad (III)$$

The formula for the liquid leak  $Q_L$  can be transformed with formula (12) to:

$$Q_L = dx \quad (IV)$$

with 
$$d = 2,45 \cdot 10^{-10} \cdot \frac{\Delta p_L}{\eta_L}$$

These 4 equations (I), (II), (III) and (IV) with 4 unknowns  $Q_L$ , x, y and R give:

$$Q_L = 9,5 \frac{\eta_g}{\eta_L} \cdot \Delta p_L \frac{(p_B - p_A)(Q_{gC} - Q_{gB}) - (p_C - p_B)(Q_{gB} - Q_{gA})}{(p_C - p_A)(p_C - p_B)(p_B - p_A)} \text{ cc/h} \quad (14)$$

In this formula the geometry of the leak has been eliminated. The outgassing and background leaks also have been eliminated, because in the formula only differences of gas leak flow-rates appear.

$p_A$  being atmosphere-pressure and the next two fill-pressures being an equal number of atmospheres higher, for instance  $p_B = 1 + \Delta p_g$  and  $p_C = 1 + 2 \Delta p_g$ , then formula (14) can be simplified into:

$$Q_L = 9,5 \frac{\eta_g}{\eta_L} \Delta p_L \frac{Q_{gA} - 2 Q_{gB} + Q_{gC}}{2 \Delta p_g^2} \text{ cc/h} \quad (15)$$

For the outgassing and background leaks the next formula

can be derived:

$$R = \frac{p_B p_C \cdot Q_{gA}}{(p_C - p_A)(p_B - p_A)} - \frac{p_A p_C \cdot Q_{gB}}{(p_C - p_B)(p_B - p_A)} + \frac{p_A p_B \cdot Q_{gC}}{(p_C - p_A)(p_C - p_B)} \text{ lusec} \quad (16)$$

Also the mean diameter D can be expressed in the leak flow-rates and fill-pressures:

$$D = 31 \eta_g \sqrt{\frac{T}{M}} \left\{ \frac{p_B(Q_{gC} - Q_{gA}) - p_A(Q_{gC} - Q_{gB}) - p_C(Q_{gB} - Q_{gA})}{p_A^2(Q_{gC} - Q_{gB}) - p_B^2(Q_{gC} - Q_{gA}) + p_C^2(Q_{gB} - Q_{gA})} \right\} \mu \quad (17)$$

However, formula (14) cannot be applied when the gas leak flow-rate at only one fill-pressure is known. In that case  $Q_L$  can only be directly calculated from formula (3) and (12). The mean diameter D has to be determined either according to the methods of chapter 4 or by assumption. Thus

$$Q_L = 9,5 \cdot \frac{\eta_g}{\eta_L} \cdot \Delta p_L \frac{Q_g}{p_1 \left( p_1 + 31 \frac{\eta_g}{D} \sqrt{\frac{T}{M}} \right)} \text{ cc/h} \quad (18)$$

- b) In the second case of a gas leak to atmospheric pressure the liquid gas leak-ratio is determined by means of formula (10) and (12) so that:

$$Q_L = 9,5 \cdot \frac{\eta_g}{\eta_L} \Delta p \frac{Q_g}{(p_1^2 - 1)} \text{ cc/h} \quad (19)$$

The geometry of the leak does not matter in this case, as both flows are viscous.

5.1.2. The average diameter of the capillaries

One may ask whether it is correct to assume all capillaries to be of the same diameter where the leak flow-rate is caused by capillaries of various diameters. As it is shown subsequently, this does not affect the conversion of gas-liquid leak flow-rates.

$Q_{g1}$  and  $Q_{gp}$  being respectively the measured gas leak flow-rates at atmospheric pressure and a pressure  $p$  ata, through  $n$  capillaries of diameter  $D$ , then:

$$Q_{g1} = n \frac{D^3}{L} (C_1 D + C_2) \quad (I)$$

$$\text{and } Q_{gp} = n \frac{D^3}{L} p (C_1 D p + C_2) \quad (II)$$

Supposing  $Q_{g1}$  and  $Q_{gp}$  flows through  $n_1$  capillaries of diameter  $D_1$ ,  $n_2$  capillaries of diameter  $D_2$  etc.; thus, generally through  $n_x$  capillaries of diameter  $D_x$  with  $n = 1, 2, 3, \dots$ , then also:

$$Q_{g1} = \sum_{x=1}^{\infty} n_x \frac{D_x^3}{L} (C_1 D_x + C_2) \quad (III)$$

$$\text{and } Q_{gp} = \sum_{x=1}^{\infty} n_x \frac{D_x^3}{L} p (C_1 D_x p + C_2) \quad (IV)$$

In both cases the liquid leak flow-rate can be expressed by:

$$Q_{LA} = C_3 n \frac{D^4}{L} \quad (V)$$

$$\text{and } Q_{LB} = \sum_{x=1}^{\infty} C_3 n_x \frac{D_x^4}{L} \quad (VI)$$

If equation (I) is multiplied by  $p$ , we find together with equation (II):

$$n \frac{D^4}{L} = \frac{Q_{gp} - p Q_{g1}}{(p^2 - p) C_1}$$

Similarly, with equations (III) and (IV):

$$\sum_{x=1}^{\infty} n_x \cdot \frac{D_x^4}{L} = \frac{Q_{gp} - p Q_{g1}}{(p^2 - p) C_1}$$

Thus

$$n \frac{D^4}{L} = \sum_{x=1}^{\infty} n_x \frac{D_x^4}{L}$$

so that with (V) and (VI)

$$Q_{LA} = Q_{LB}$$

That means, the composition of the leak does not affect the conversion of gas-liquid leak flow-rates. For instance an air leak-rate of 0,01 lusec from 1 atm to vacuum and 0,6 lusec from 10 atm to vacuum ( $\psi = 1,778$ ) may consist of 45 capillaries ( $L = 1$  cm) with a mean diameter of  $2,22 \mu$ . However, it is also possible that the leak consists of one capillary with a diameter of  $5,2 \mu$  and 305 capillaries ( $L = 1$  cm) with a mean diameter of  $1,04 \mu$ . In both cases the conversion from an air leak rate to a liquid leak rate gives the same leak flow-rate, for instance, for water  $0,9 \text{ mm}^3/\text{h}$ .

## 5.2. Graphical conversion of leak flow-rates

A method for graphically converting a measured leak flow-rate to another leak flow-rate for both a different fluid and different pressure conditions would be very useful. Although it is impossible to fit all parameters into one graph, in several ways an approach can be made. A nomographic solution has been given by D.J. Santeler and T.W. Moller <sup>+</sup>). In this nomograph the pressure difference

<sup>+</sup>) 1956, National Symposium on Vacuum Technology Transactions

is plotted against the respective gas and liquid leak flow-rates for viscous flow. A connection for the geometry and molecular flow is given on the basis of an assumed length and the fill-pressure, expressed in the parameter  $L \cdot p_1^2$ .

Another graphical method which is more accurate, particularly concerning the influence of the geometry of the leak, but more complicated, as for each pair of fluids to be converted one has to consider another graph, will be explained subsequently.

In graph II the conversion of an air or He leakage to an organic liquid leakage is taken as an example. The dotted lines give the relationship between the diameter of the capillary and the air or He leakage through one capillary of this diameter at different fill-pressures. The full lines give the organic liquid leakage through one capillary depending on the diameter and the fill-pressure. In order to convert, for instance, a measured air leakage of  $10^{-2}$  lusec to an organic liquid leakage a vertical line is drawn at  $10^{-2}$  lusec on the leak flow-rate scale. Then, the distance between the leak-lines of air and organic liquid at the corresponding fill-pressure is drawn to the right from this vertical line along the relative diameter line. For instance, if an air leak consisting of capillaries with an average diameter of  $0,1 \mu$  and a flow-rate of  $10^{-2}$  lusec from 1 atm to vacuum (A) should be converted to an organic liquid leak from 20 atm to atmospheric pressure (B), the distance AB is drawn to the right from C. When the average diameter would be  $1 \mu$ , the distance A'B' is drawn to the right from C' etc. In this way a line is found which gives the liquid leak flow-rate depending on the diameter of the capillary for an air leak of  $0,01$  lusec. On graph II it is shown that in this case the organic liquid leak flow-rate varies from  $5,8 - 92$  mg/h for respectively D varying from  $0,1 \mu$  to  $10 \mu$ . Referring to the example of chapter 4 concerning the composition and the geometry of a leak, it follows from the graph that for  $Q_{g1} = 10^{-2}$  lusec

(with  $D = 0,1 \mu$ ) and  $Q_{g2} = 5 \cdot 10^{-3}$  lusec (with  $D = 1 \mu$ ),  $Q_{L1}$  and  $Q_{L2}$  are respectively 6 mg/h and 18 mg/h. Consequently  $Q_{L2} > Q_{L1}$ , while  $Q_{g2} < Q_{g1}$ . It should be noticed that the horizontal distance (AC) between the leak-line for one capillary and the total leak-line (vertical) gives the number of capillaries. For instance, A''C'' is equal to 1, A'C' to about 720 and AC to about  $10^6$  capillaries. In the same way the example given in chapter 5.1.2. is illustrated and explained in graph I.

### 5.3. Conversion of gas flow-rates at vacuum and atmospheric exit-pressure

By means of the formula (3) and (10) the conversion of two gas flow-rates can be determined for different cases and various pressure conditions.

The following possibilities are to be considered:

- a) Both gas leaks from atmospheric or higher pressure to vacuum.
- b) Both gas leaks from a higher pressure to atmospheric pressure.
- c) One gas leak according to case a) and the other one according to case b).

- a) First of all the average diameter of the capillary has to be determined (see chapter 4). If two leak flow-rates of the relative leak at two different fill-pressures are known, D also can be calculated with formula (8). With formula (3), we find:

$$Q_{g1} = \frac{\eta_{g2}}{\eta_{g1}} \cdot \frac{p_{g1}}{p_{g2}} \left\{ \frac{p_{g1} + 31 \frac{\eta_{g1}}{D} \sqrt{\frac{T}{M_{g1}}}}{p_{g2} + 31 \frac{\eta_{g2}}{D} \sqrt{\frac{T}{M_{g2}}}} \right\} Q_{g2} \text{ lusec (20)}$$

- b) Following formula (10) in this case the leak ratio will be:

$$Q_{g1} = \frac{\eta_{g2}}{\eta_{g1}} \cdot \frac{(p_{g1}^2 - 1)}{(p_{g2}^2 - 1)} Q_{g2} \text{ lusec} \quad (21)$$

c) A combination of the formulae (20 and (21) gives:

$$Q_{g1} = \frac{\eta_{g2}}{\eta_{g1}} \cdot \frac{p_{g1}}{p_{g2}^2 - 1} \left\{ p_{g1} + 31 \frac{\eta_{g1}}{D} \sqrt{\frac{T}{M_{g1}}} \right\} Q_{g2} \text{ lusec} \quad (22)$$

## 6. CONVERSION FOR DIFFERENT PRESSURE CONDITIONS

The conversion of a leak flow-rate for other pressure conditions can be easily derived by means of the formulae found in the foregoing chapter.

For a gas leak to vacuum, formula (20) is transformed into:

$$Q_{gA} = \frac{p_A}{p_B} \cdot \frac{p_A + 31 \frac{\eta}{D} \sqrt{\frac{T}{M}}}{p_B + 31 \frac{\eta}{D} \sqrt{\frac{T}{M}}} Q_{gB} \text{ lusec} \quad (23)$$

and for a gas leak to atmospheric pressure, formula (21) gives:

$$Q_{gA} = \frac{p_A^2 - 1}{p_B^2 - 1} Q_{gB} \text{ lusec} \quad (24)$$

This formula can also be used for conversion of a liquid leak at other pressure conditions. Finally a gas leak to vacuum can be converted to a gas leak to atmospheric pressure, or the inverse, by using formula (22):

$$Q_{gA} = \frac{p_A}{p_B^2 - 1} \left\{ p_A + 31 \frac{\eta}{D} \sqrt{\frac{T}{M}} \right\} Q_{gB} \text{ lusec} \quad (25)$$

where  $Q_{gA}$  is the gas leak flow-rate to vacuum with  $p_A$  being the fill-pressure in that case.

From the foregoing it follows that even for pressure conversion one should know in certain cases the mean diameter of the capillaries. In fact, according to these simple formulae it should be noted once more that since the geometry of the leak determines the type of flow, no two leaks, even though they may have the same leak flow-rate at a particular pressure, need to be identical at other pressures.

## 7. THE INFLUENCE OF THE TEMPERATURE ON THE LEAK FLOW-RATE

The influence of the temperature on various leak parameters can be approximated theoretically. However, the influence of the temperature on the geometry of the leak can be established only experimentally for reasons of differential thermal expansion and flow phenomena of the materials at elevated temperatures. These two effects are very complex and particularly in the case of leak measurements on sealings, cannot be predicted theoretically.

Excluding the effect of the temperature on the leak geometry one may set up the following relationships:

a) for gas leaks:

- the molecular part of the leak flow-rate is proportional to  $\sqrt{T}$
- the viscous part is inversely proportional to  $\eta$ .

In fact  $\eta = a \cdot T^x$ ; for instance for  $N_2$   
 $a = 3,2 \cdot 10^{-6}$  and  $x = 0,702$ .

b) for liquid leaks:

The leak flow-rate is also inversely proportional to or proportional to  $T$ , since

$$\eta = \frac{a}{T} - b .$$

For instance for organic liquid (Gilotherm OM<sub>2</sub>)  
 $a = 2,2 \cdot 10^3$  and  $b = 4,75$ .

Whenever leak measurements are performed above ambient temperature, attention should be given to correct the measured value for density variations when this should be expressed in atm cc/sec.

Finally, with particular respect to vacuum leaks, one has to take into account the effect of the temperature on the outgassing.

### 8. APPLICATION EXAMPLES OF LEAK FLOW-RATE CALCULATIONS AND CONVERSIONS FOR ORGANIC LIQUID (TERPHENYL OM<sub>2</sub>)

Most of the leaktightness tests are performed with a test gas, for instance air or helium, while in fact tightness against a liquid is required. Therefore, some conversion examples will be given especially concerning leak flow-rate conversion of a gas and the reactor coolant Gilo-therm OM<sub>2</sub>, an organic liquid.

- To convert a known air-leakage to an organic liquid leakage we can use formula (18), thus:

$$\frac{\Phi_L}{Q_g} = 9,5 \rho_L \frac{\eta_g}{\eta_L} \cdot \frac{\Delta p_L}{p_{g1} (p_{g1} + 31 \frac{\eta_g}{D} \sqrt{\frac{T}{M_g}})} \text{ g/h/lusec} \quad (26)$$

For Gilotherm OM<sub>2</sub> we use the following data:

	$\rho$ (g/cc)	$\eta$ (cP)	$p_v$ (atm)	$\sigma$ (N/m)
Organic liquid at 400 °C	0,8	0,24	2,3	$12 \cdot 10^{-3}$
Organic liquid at 200 °C	0,955	0,9	< 1	$27 \cdot 10^{-3}$
Organic vapour at 400 °C	0,02	0,05	-	-

For air at 20°C:  $\eta_g = 0,018$  cP and  $M_g = 29$

Then:

$$\frac{\Phi_L}{Q_g} = \frac{0,57 \cdot \Delta p_L}{p_{g1} \left( p_{g1} + \frac{1,76}{D} \right)} \text{ g/h/lusec (org.liq.at } 400^\circ\text{C)} \quad (27)$$

For the leak-ratio in the case of organic liquid at 20 atm gage pressure and an air leakage measured from atmospheric pressure to vacuum, we find the following correlation, assuming a mean diameter of the capillaries of  $1 \mu$ :

$$\frac{\Phi_L}{Q_g} = 3,9 \text{ g/h/lusec (org. liq. at } 400^\circ\text{C)} \quad (28)$$

The same leak-ratio can be found from graph II.

- The pressure  $p_s$  due to the surface tension of the liquid can be calculated with formula (11). It has been assumed that in this case the liquid wets completely the wall of the capillary. For Gilotherm OM2 we find:

at $400^\circ\text{C}$ for $D = 0,1 \mu$	→	$p_s = 4,8 \text{ atm}$
and for $D = 1 \mu$	→	$p_s = 0,48 \text{ atm}$
at $200^\circ\text{C}$ for $D = 0,1 \mu$	→	$p_s = 10,8 \text{ atm}$
and for $D = 1 \mu$	→	$p_s = 1,08 \text{ atm}$

In order to check the influence of surface tension and evaporation on the leak flow-rate, the product  $\Phi_L \cdot L$  of Gilotherm OM2 is calculated by means of formulae (12) and (13) for various diameters of the capillary and at different fill-pressures. They are given in Table II and III for respectively a temperature of  $400^\circ\text{C}$  and  $200^\circ\text{C}$ .

From these tables it is clear that there is only a significant difference in the leak flow-rates calculated by formula (12) or formula (13) for:

- a) small capillary diameters,  $D < 0,1$
- b) a fill-pressure below about 20 atm
- c) a temperature much lower than  $400^\circ\text{C}$ .

T A B L E II

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$\Phi_1.L$  in mg/h.cm of Gilotherm OM2 at 400° C

D in $\mu$	$p_1$ in atm				
	2,3	5	10	20	30
0,1	x	$1,18 \cdot 10^{-6}$	$2,65 \cdot 10^{-6}$	$5,58 \cdot 10^{-6}$	$8,53 \cdot 10^{-6}$
0,1 <sup>+) )</sup>	$3,26 \cdot 10^{-8}$	x	$3,7 \cdot 10^{-6}$	$6,6 \cdot 10^{-6}$	$9,55 \cdot 10^{-6}$
1	x	$1,18 \cdot 10^{-2}$	$2,65 \cdot 10^{-2}$	$5,58 \cdot 10^{-2}$	$8,53 \cdot 10^{-2}$
1 <sup>+) )</sup>	$3,26 \cdot 10^{-4}$	$9,7 \cdot 10^{-3}$	$2,43 \cdot 10^{-2}$	$5,38 \cdot 10^{-2}$	$8,3 \cdot 10^{-2}$
10	x	1,18	265	558	853
10 <sup>+) )</sup>	3,26	82,6	230	523	820

+ ) These values of  $\Phi_1.L$  are corrected for surface tension effects and evaporation.

T A B L E III

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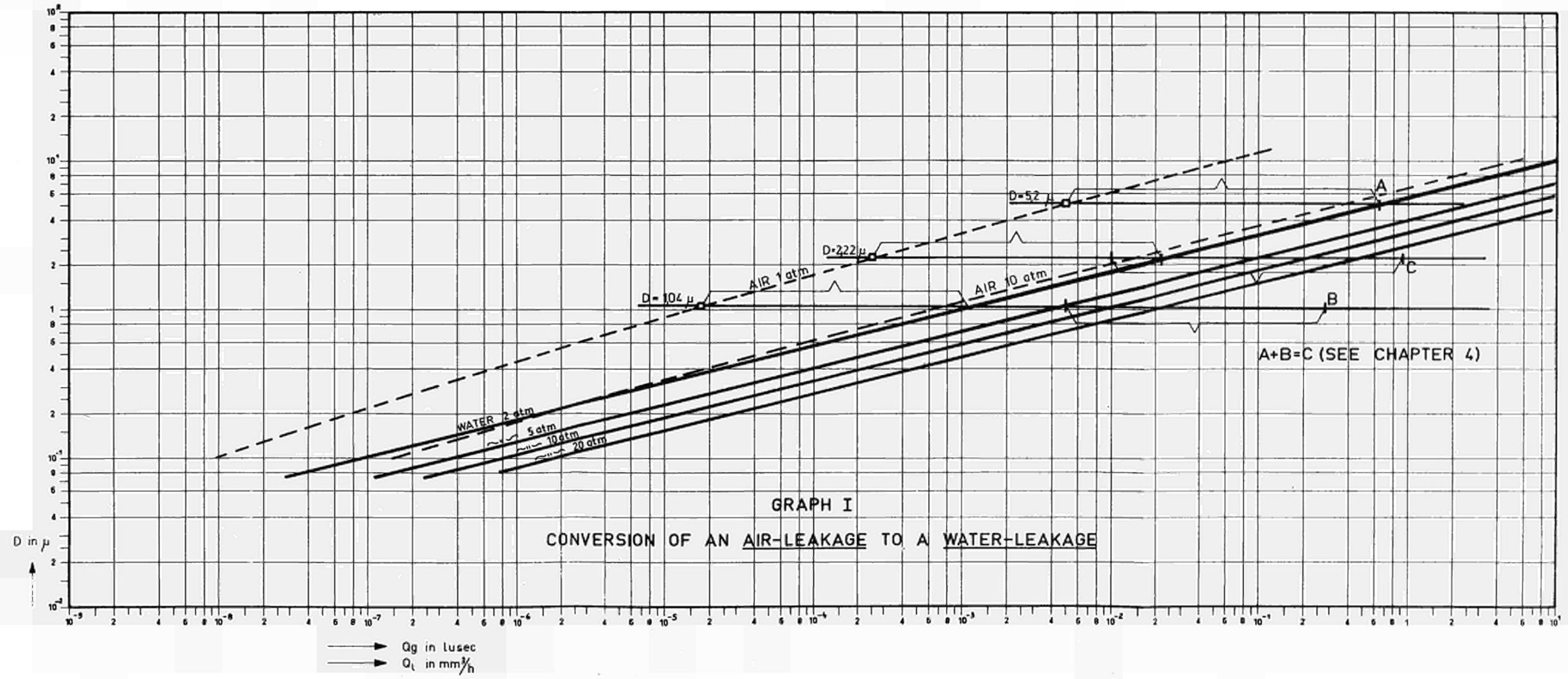
$\Phi_1.L$  in mg/h.cm of Gilotherm OM2 at 200°C

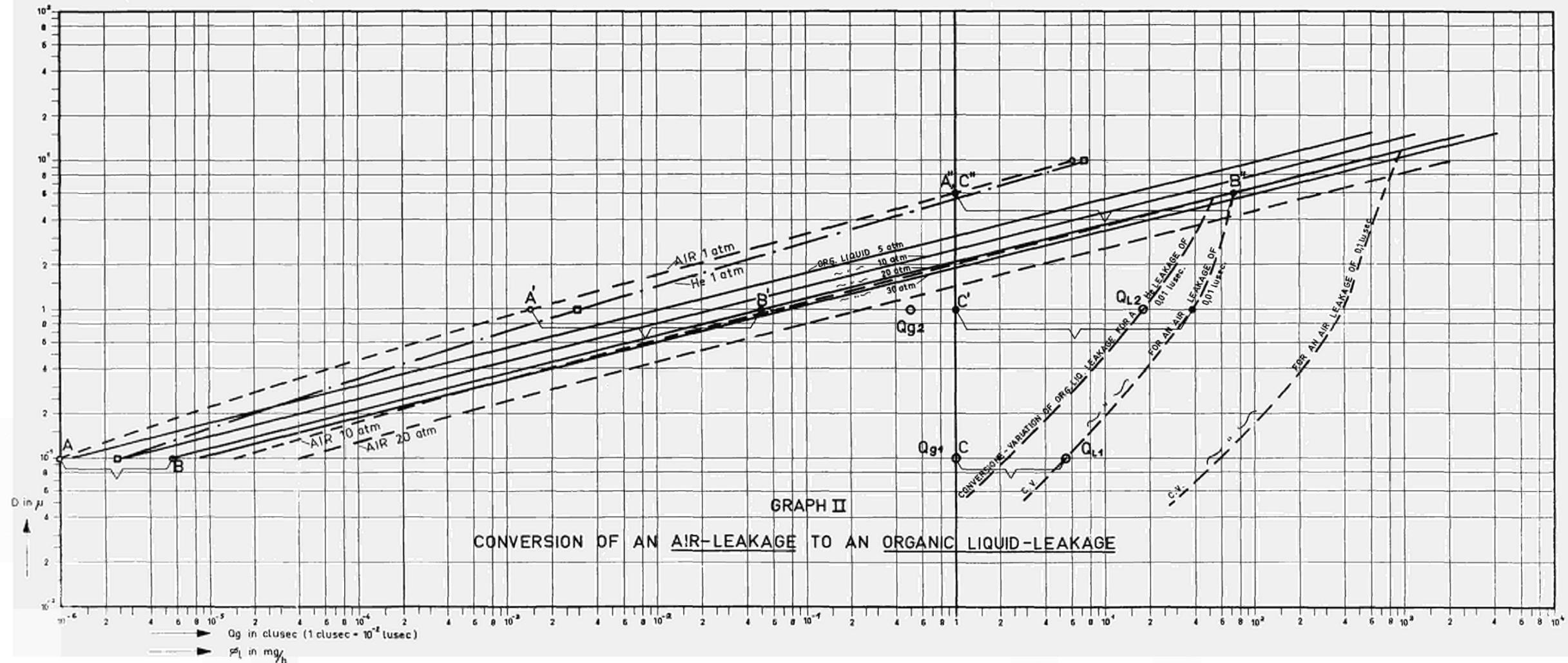
D in $\mu$	$p_1$ in atm				
	2	5	10	20	30
0,1	$9,35 \cdot 10^{-8}$	$3,74 \cdot 10^{-7}$	$8,4 \cdot 10^{-7}$	$1,78 \cdot 10^{-6}$	$2,72 \cdot 10^{-6}$
0,1 <sup>+) )</sup>	0	0	0	$7,67 \cdot 10^{-7}$	$1,7 \cdot 10^{-6}$
1	$9,35 \cdot 10^{-4}$	$3,74 \cdot 10^{-3}$	$8,4 \cdot 10^{-3}$	$1,78 \cdot 10^{-2}$	$2,72 \cdot 10^{-2}$
1 <sup>+) )</sup>	0	$2,74 \cdot 10^{-3}$	$7,4 \cdot 10^{-3}$	$1,67 \cdot 10^{-2}$	$2,62 \cdot 10^{-2}$
10	9,35	37,4	84	178	272
10 <sup>+) )</sup>	9,35	37,4	84	178	272

+ ) These values of  $\Phi_1.L$  are corrected for surface tension effects and evaporation.

## 9. CONCLUSIONS

1. In general one is able to convert by means of the derived formulae leak data for various fluids and different pressure-conditions (see chapters 5 and 6).
2. Under vacuum conditions the influence of the leak-geometry on fluid-flow conversion is not to be neglected (see graph II).
3. It is possible to determine the leak-geometry by means of leak-measurements at different fill-pressures (see formula 18).
4. The outgassing and background leaks can easily be corrected for and even calculated (see formulae 14 and 16).
5. For fluid-flow conversion it is correct to assume a leak-geometry as being a number of capillaries of the same diameter (see chapter 5.1.2.).
6. The influence of surface tension and evaporation of a leaking liquid can be considerable, mainly in the case of a low fill-pressure and small capillary diameters. This subject is still under investigation.
7. The application of the foregoing conversion-correlations is illustrated and compared to experimental values in a next report which is in preparation.





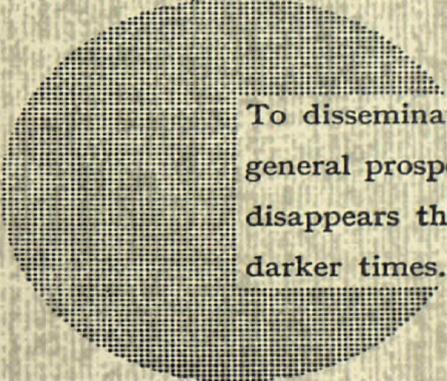
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Alfred Nobel

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