GAS INTERCHANGE IN FREIGHT CONTAINERS

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ABSTRACT: Factors leading to gas interchange between container and external atmosphere are detailed and their relative significance discussed. An approximate quantitative value is given for various ambient conditions and container leakiness. Under poor sealing conditions through flow phenomena such as caused by wind are dominant. Under more gastight situations cyclic phenomena became important (e.g. diurnal temperature variation).

Equivalent hole sizes for a range of containers are presented which can be used for prediction of the interchange rate; the influence of hole size is discussed in relation to fumigation and ventilation of commodities in containers.

Introduction of containerisation for the handling of both bulk and bagged stored products has been recognised to have a number of advantages. Importantly from the point of view of the stored product entomologist it provides a fumatorium for disinfestation of the commodity and then a barrier which prevents subsequent reinfestation from external sources. There is a continuing hazard of infestation by residual insect population [1] and the transport of pests inland into agricultural and economically sensitive areas which is not as acute when transhipment of the commodity is performed at the ports. In-container fumigation overcomes this hazard and provides an economical method of ensuring an insect-free commodity. From the quarantine point of view it is important that fumigations be highly efficient.

Recently it has been realised that in-container fumigation is not always successful and has even been rejected as unreliable by some authorities [2]. Nevertheless the method is widely and routinely used for shipment of some raw agricultural products (e.g. rice export from Australia). This paper seeks to understand the phenomena giving rise to gas loss from an ISO general purpose freight container or other transport vehicle such as a rail box car, thereby enabling prediction of the fumigant concentrations achievable under any given circumstances. The concentration of fumigant present at different times must be known for an adequate assessment of a fumigation for insecticidal efficiency. This knowledge also determines what procedures may be necessary for safety during the fumigation and subsequent unloading or handling.

The problem is parallel to that of air leakage into refrigerated container vehicles which has received some attention (e.g., [3] [4] [5] [6] [7]) but has not yet been fully described.

Published research ([2] [8] [9] [10] [11]) and unpublished reports available to the authors on in-container and box-car fumigation have been carried out without objective assessment of the leakiness of the body. In addition most trials have been static yet fumigations are frequently carried out in transit giving high and variable relative air velocities and pressures. Interpretation of these trials and generalisation from them is not possible without measurement of several additional parameters as we will show below.

The factors leading to fumigant loss from a container atmosphere can be summarised as follows ([4] [6] discuss some of these phenomena in relative to insulated containers):

EXTERNAL FACTORS LEADING TO BULK GAS INTERCHANGE: (1) Pressure changes from diurnal and long term barometric changes. (2) Pressure changes caused by diurnal temperature variation of the internal atmosphere. (3) Pressure differences between the roof and floor of the container from gas density differences (different internal composition or temperature to external). (4) Pressure difference between different areas of the container surface caused by movement of air relative to the structure (either wind or transport induced). (5) Short-term pressure fluctuations from wind gusts. (6) Short-term pressure fluctuations caused by vibration of the container surfaces and flexing from wind buffeting or road vibrations.

INTERNAL FACTORS LEADING TO FUMIGANT LOSS: (7) Reversible sorption/desorption by the commodity or container fabric. (8) Irreversible reaction with the commodity or container fabric.

INDEPENDENT FACTORS: (9) Diffusion.

In addition some fumigants are not released suddenly but generated over a period of time (e.g., the phosphine-generating aluminium phosphide preparations) giving a gain period which must be incorporated into any model.

Table I gives estimated contributions of all the external factors leading to gas interchange except that from vibrations of the container surfaces. These figures rely on a number of assumptions, given with relevant calculations in Appendix, and must be taken as very approximate only. The gas loss caused by vibration of the body wall, flexing with volume alteration and the influence of shock waves generated from passing objects while in transit is said to be substantial [6] for refrigerated containers but has not yet been determined.

The influence of leakiness of the container is immediately apparent. The reduction of the effective leak size, CoA, from a

TABLE I ESTIMATED CONTRIBUTIONS OF THE VARIOUS FACTORS CAUSING GAS INTERCHANGE FOR TWO DIFFERENT LEAKINESSES

	Range for calculation	Estimated effect (% interchange/day) For equivalent hole size:-	Estimated effect (% interchange/day)	Dependent on
		CoA = $0.1 \times 10^{-3} m^2$	CoA = $0.5 \times 10^{-3} m^2$	
Barometric cycling	1010 - 1005 mb (2 x daily)	1	1	pressure difference
Temperature cycling	10 - 40°C	11	11	temperature range
Wind through two opposite holes	5 m/sec wind	16	81	wind speed, leak size, distribution leak.
Pulsing wind on one face	0-5 m/sec 30x per hr	1	5	wind speed, pulsation frequency size, orientation leak.
Chimney effect	Internal 40°C External 20°C	6	33	Temperature differential, size distribution leak.
Diffusion	Path length 0.3×10^{-3}m External concentration, zero.	0.2	0.8	Path length, leak size.

mid-range value for general purpose freight containers we have tested ($0.5 \times 10^{-3} m^2$) to a value close to the specification for refrigerated containers ($0.1 \times 10^{-3} m^2$) alters the relative importance of the various factors dramatically. In particular the influence of Factor (4) the chimney effect, becomes much less important and the wind induced leakage becomes comparable with that predicted for temperature effects.

The precise effect of wind is difficult to estimate as it is very dependent on distribution of holes. If a through path is eliminated the major effect is nullified. The estimate is based on a low wind speed and much higher transport-induced speeds can be expected greatly increasing even this large figure. A number of workers (e.g., [7] [8] [11]), have found large losses of fumigant from rail box cars and trailers while in transit. These losses are directly attributable to the velocity of transport. The full effect of actual velocity induced pressures and consequent gas exchange will not be found in trains as the slipstream of the leading vehicle will substantially reduce the relative air speed for the following bodies and their resultant drag coefficients (cf. [12]).

The effects of load on these factors are at present under investigation.

THE DETERMINATION OF LEAKINESS OF A CONTAINER: A relevant and objective measure of leakiness is important to any model of gas loss from a container. The methods available for the determination of leakiness of bodies such as freight containers have been critically discussed [6]. For practical purposes a quick method is required. Static pressure testing is unsually used. The method suffers from the disadvantage that total leakiness is measured without regard to the number and distribution of the holes and has been rejected [7] by other workers. For more accurate assessment a tracer method is applicable and either a fumigant itself or an inert gas may be used. The latter is preferable as the influences of factors (7) and (8) are eliminated.

PRACTICAL TRIALS: (a) Pressure tests - A number of empty ISO freight containers, representing several types of construction, were leak tested by applying a constant pressure of air and measuring the rate of leakage. The leak rates observed with applied pressures of 25Pa for a number of containers are given in Figure 1. It can be seen that the measured leak rates for general purpose freight containers vary widely, providing an explanation for the discrepancies reported by various workers when describing in-container fumigation trials.

The observed relationship between the applied pressure and the gas leakage rate does not follow a square root relationship, but is better described by the expression $P = kQ^n$, $n = \approx 1.7$. This relationship is similar to that observed [5] for two insulated containers.

Using this relationship between pressure and leak rate, with a value of 1.7 for the exponent, the ISO draft specification

[13] for insulated containers of not more than 9.4 cfm at $1^3/_{64}$" w.g. is equivalent to a leak rate not exceeding $2.8 \times 10^{-3} m^3/sec$ at an applied pressure of 125 Pa or $1.1 \times 10^{-3} m^3/sec$ at 25 Pa.

(b) Tracer Tests - A series of eight empty containers was flushed with nitrogen containing 2% argon, a mixture with density very close to that of air, until the internal atmosphere contained about 2% oxygen. The trial was conducted outside during two sunny and relatively calm days (wind < 2 m/ sec and usually calm) in Sydney, Australia. The rate of air ingress was determined from the increase in oxygen concentration using formula (1) which assumes complete mixing of small inputs of air with expulsion of the same volume of the consequent mixture. The data was fitted to an equation (formula (2)) corresponding to a linear trend with a daily sinusoidal purturbation (see Fig. 2). Slightly better line fits were obtained with a linear trend and 12 and 24 hr period harmonics (formula (3)). The slope thus determined was used for calculation (Table II).

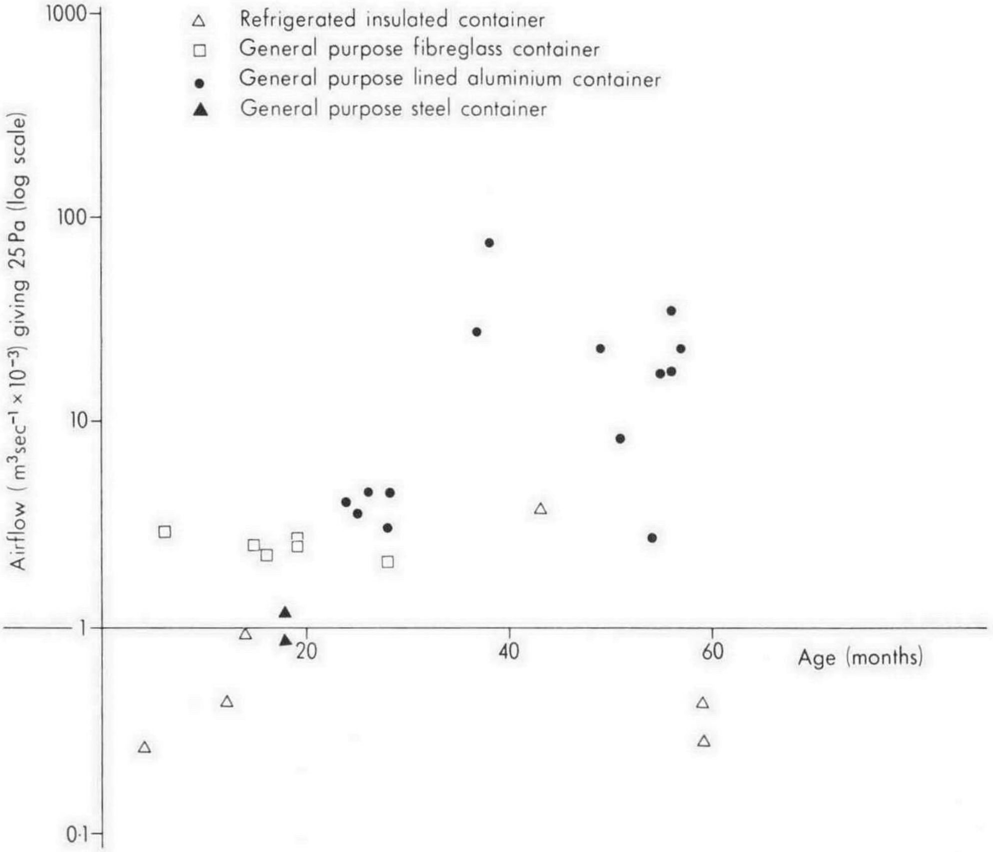

FIGURE 1. Variation of leakiness observed with different types of container.

The calculated ingress may be corrected for factors like the known diurnal barometric and temperature fluctuations.

The internal air temperatures of the containers varied widely under the sunny conditions of the test (approximately 18°C-40°C for general purpose containers and about 21°C-32°C for

TABLE II. Gas Interchange Attributable To Temperature Cycling, Barometric Pressure Changes and Other Factors.

	Container number	Temperature dependent exchange	Barometric pressure exchange	Total exchange	Line fit	Residual	Flow
			%/day	%/day	calc %/day	%/day	$m^3 \times 10^{-3}$ giving 125 Pa
1	AJCL JRF 01136	3.37	0.52	3.89	4.05	0.16	0.78
4	OCL LFC 01357	2.91	0.52	3.43	3.62	0.19	1.25
5	OCLU 269022	4.52	0.52	5.05	5.44	0.39	2.05
6	OCL LFL 01353	2.94	0.52	3.46	3.14	-0.32	0.88
7	OCLU 025957	8.36	0.55	8.91	20.03	11.12	13.9
8	OCLU 024914	8.16	0.55	8.71	20.04	11.33	14.7
9	OCLU 026579	8.16	0.55	8.71	13.76	5.05	6.7
11	OCLU 026909	7.11	0.55	7.66	13.50	5.84	7.6
12	OCLU 022128	6.93	0.55	7.48	14.56	6.08	6.5

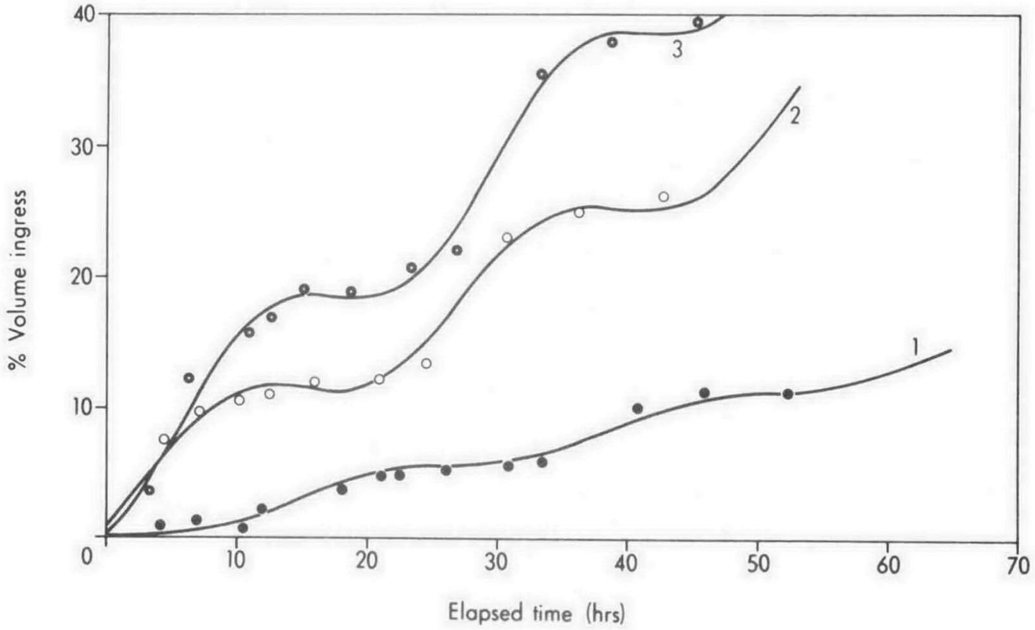

FIGURE 2. Computer fitted trend for air ingress in 3 empty containers (insulated (1) general purpose (2, 3)) over two days.

insulated ones) (See Figure 3). This fluctuation causes expansion and contraction of the internal gas causing gas interchange. Barometric fluctuations (Figure 4) have a lesser but similar effect. Table II gives the estimates of these effects on the test containers.

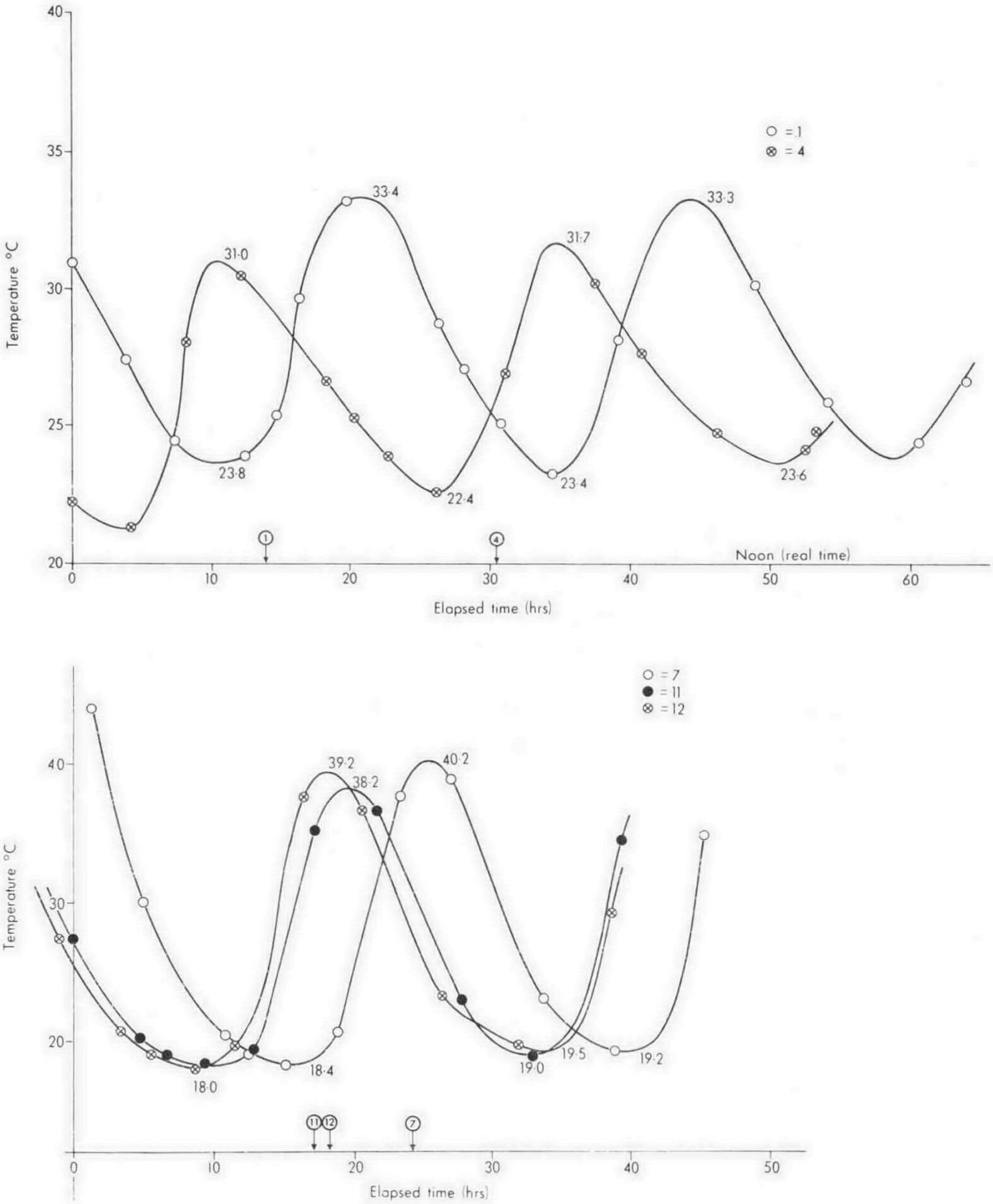

FIGURE 3. Internal temperature variation in five empty containers under clear weather conditions. Containers 1, 4 are insulated, containers 7, 11, are lined aluminium, container 12 is lined fibre glass construction.

The residual interchange after subtraction of the known

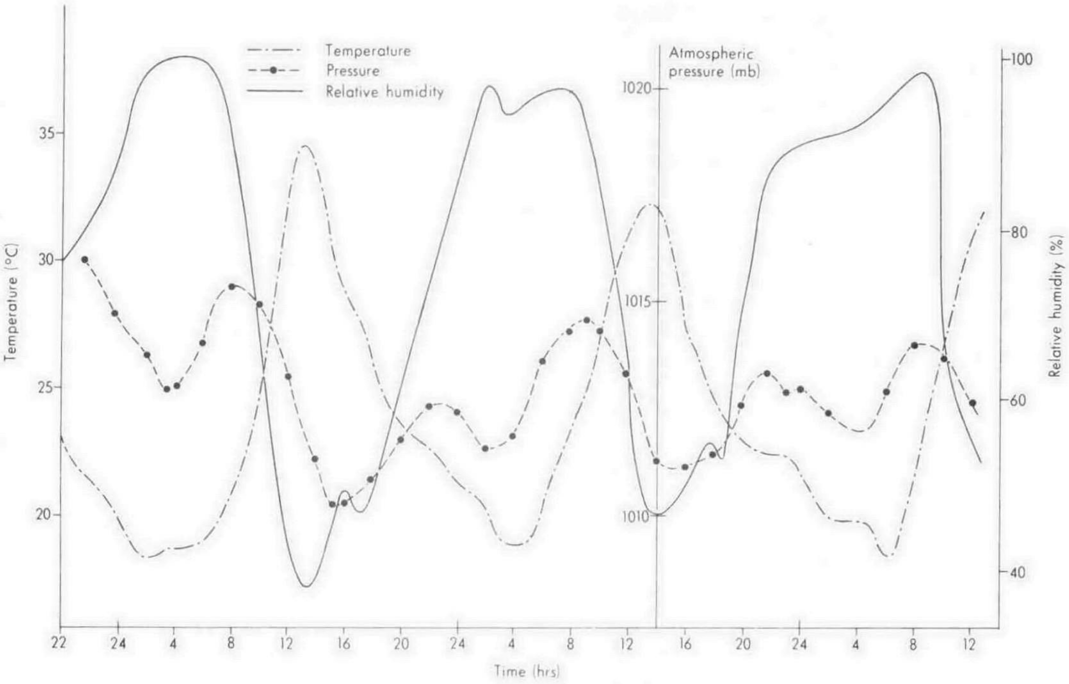

FIGURE 4. Barometric pressure, external temperature and relative humidity variation during the leakage trial.

effects is seen to be proportional to the leak rate determined by pressure testing (Figure 5). This result is important since it demonstrates that under the static conditions of this trial the pressure test provides a reasonable measure of the rate of gas interchange after the subtraction of diurnal meteorological factors and thus the leaks appear to be positioned such as to make a similar difference to the total gas loss. It also substantiates the assumption made for the estimates of relative importance of various factors on air ingress. Except for diurnal temperature and barometric pressure cycling (factors (1) and (2)) the external factors are all theoretically expected to be proportional to effective leak size.

SUMMARY: (1) Factors influencing gas loss from a container are detailed and their magnitude estimated.

(2) Wind and transit-induced pressures are the main factors for fumigant loss from leaky containers.

(3) The importance of a knowledge of the effective leakiness of a freight container undergoing fumigation is stressed.

(4) Under field conditions with empty ISO freight containers, it is shown that pressure testing gives a useful measure of leakiness.

(5) Under the static conditions of this trial, discrepancies in leak rate, after allowance for diurnal temperature and pressure cycling, are proportional to container leakiness determined by pressure test.

(6) Diurnal temperature and pressure changes induce gas losses which may be accurately modelled.

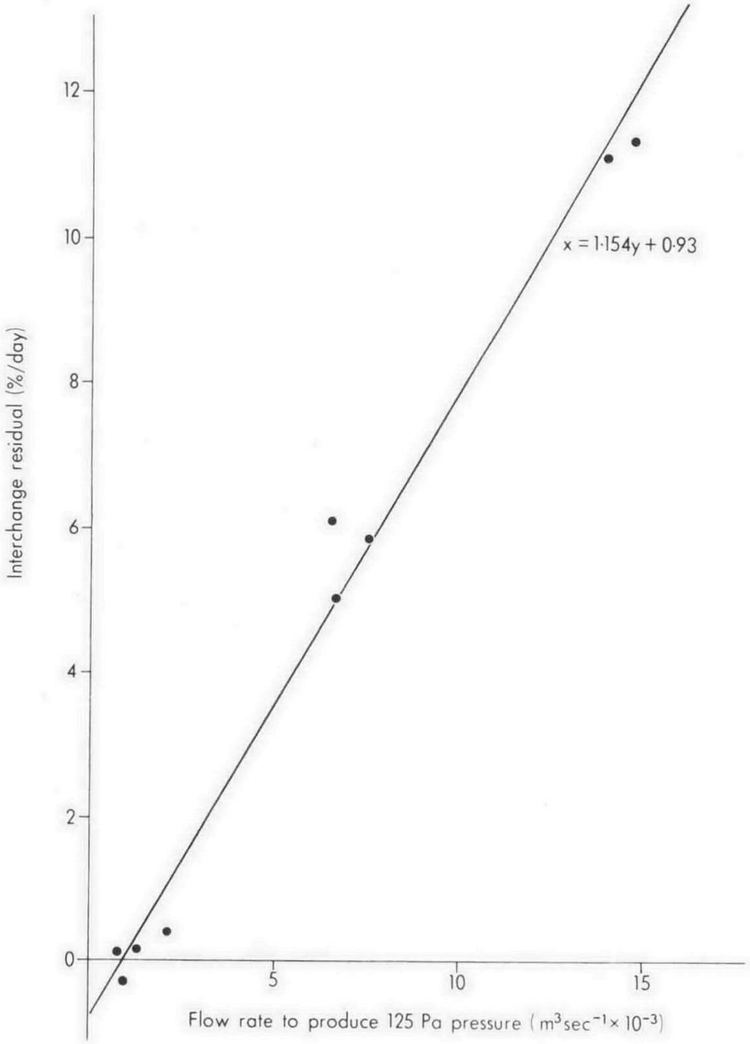

FIGURE 5. Discrepancy in predicted interchange against leakiness assessed by pressure test.

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APPENDIX CALCULATION OF EFFECTS OF VARIOUS FACTORS ON GAS INTERCHANGE IN CONTAINERS

Formulae used:-

Air interchange

$$\% \text{ air ingress} = 100 \log_e \left(\frac{21 - C_t}{21 - C_i} \right) \tag{1}$$

Equations used for data fitting

$$y = a + bx + c \sin 2\pi \left(\frac{x - t}{24} \right) \tag{2}$$

$$y = a + bx + c \sin \frac{2\pi x}{24} + d \cos \frac{2\pi x}{24} + e \sin \frac{2\pi x}{12} + f \cos \frac{2\pi x}{12} \tag{3}$$

Air flow through two orifices in series obeying Bernonilli's equation

$$\Delta p = \frac{\rho Q^2}{2} \left(\frac{1}{(CoA_1)^2} + \frac{1}{(CoA_2)^2} \right) \tag{4}$$

Symbols used

C_t = final concentration
C_i = initial concentration
Δp = pressure difference
p = pressure
ρ = density of air
Q = volumetric flow rate
Co = orifice coefficient
An = area of the nth orifice
C_D = drag coefficient
v = velocity of motion
k = constant
n = exponent

Assumptions:-

That the apertures responsible for the leak are equally distributed over the six surfaces of the container.

That perfect mixing occurs within the container.

(1) + (2) Effect of barometric pressure and internal temperature changes were calculated using simple gas laws.

(3) *Chimney effect*

For an ambient temperature of 20°C and an internal temperature of 40°C. (40% rh, 1013 mb)

Density of air [15] 20°C 40% rh = 1.200 kg/m^3
40°C 40% rh = 1.116 kg/m^3

Height of ISO freight container (8') = 2.44 m
= density difference
x head

Pressure difference between top and bottom
= (1.200 - 1.116) x 2.44 kgf/m^2
= 2.01 Pa

Assuming only leaks at top and base are relevant formula(4) gives

$$2.01 = \frac{1.2}{2} \times Q^2 \left[\left(\frac{6}{0.5 \times 10^{-3}} \right)^2 + \left(\frac{6}{0.5 \times 10^{-3}} \right)^2 \right]$$

$Q = 1.078 \times 10^{-4}\ m^3/sec$
$= 9.3\ m^3/day$
= 33% per day.

(4) *Wind effects through two holes*

It is assumed that only the windward and leeward faces are important and that the pressure drop across these faces combined is $C_D \times \frac{1}{2} \rho v^2$. The value of C_D, the drag coefficient is given [12] [14] as 0.86 for vehicles similar in shape to freight containers. With an allowance of 0.06 for skin friction, a coefficient of 0.80 will be used here (for model [4] $C_D = 0.75$ calculated from recorded pressures).

For a 5 m/sec wind

$$\Delta p = C_D \times \frac{1}{2} \rho v^2$$

$$= 0.8 \times \tfrac{1}{2} \times 1.2 \times 5^2 = 12 \text{ Pa.}$$

With a total equivalent leakage area of $0.5 \times 10^{-3} m^3$, uniformly distributed, the effective leak for one entry and one exit surface is assumed to be $\frac{1}{6} \times 0.5 \times 10^{-3}\ m^2$ each.

Formula (4) gives

$$12 = \frac{1.2}{2}\ Q^2 \left[\left(\frac{6}{0.5 \times 10^{-3}} \right)^2 + \left(\frac{6}{0.5 \times 10^{-3}} \right)^2 \right]$$

$Q = 2.6 \times 10^{-4} m^3/sec$
$= 22.8\ m^3/day$
= 81%

(5) *Wind pulsing effects*

For a single orifice CoA = $\frac{0.5 \times 10^{-3}}{6}$

and a wind pulsing 30x per hour from 0-5 m/sec with full mixing and pressure equalisation. An internal pressure of one half that of the velocity head is assumed (see [4])

$$\Delta p = \frac{1}{2} \rho v^2 \text{ gives}$$

$$\Delta p = \frac{1}{2} 1.2 \times 5^2 \text{ Pa.}$$

$$= 15 \text{ Pa.}$$

Internal pressure increase is $0.5 \times \Delta p = 7.5$ Pa.

At atmospheric pressure of 1×10^5 Pa, the % interchange/ day

$$= \frac{7.5 \times 10^2}{10^5} \times 30 \times 24$$

$$= 5.4\%$$

(9) *Diffusion*

Assuminga diffusion coefficient of 1.5×10^{-5} m^2/sec (appropriate to phosphine) and that the depth of the diffusion path is 3×10^{-3}m with complete mixing either side of this.

$$\text{Diffusion flux} = 1.5 \times 10^{-5} \times \frac{C}{3 \times 10^{-3}} \text{ units/m}^2\text{/sec}$$

Over an area of 0.5×10^{-3}m^2 C = concentration/m^2

$$\text{Mass moved} = 1.5 \times \frac{10^{-5} \times C \times 0.5}{3} \text{ units/sec}$$

$$= 2.5 \times 10^{-4} C \text{ units/sec}$$

$$= 0.22\ C \text{ units/day}$$

Mass originally present (volumne = 28 m^3) = 28C

Diffusion movement

$$= \frac{0.22}{28c} C \times 100\%\text{/day}$$

$$= 0.8\%\text{/day.}$$