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ABSTRACT

An empirical equation is developed from vacuum evaporation tests on two lubricating fluids which relates to container geometry. Methods of presenting data are discussed which cautions against use of percent to describe weight loss of a fluid in vacuum. Data from numerous tests are presented in various forms resulting in a more effective comparison constant which is better suited in selecting lubricants for space applications.

INTRODUCTION

Effective lubrication of critical components over a prolonged time period remains a source of concern in present and future spacecraft applications. Ball bearings, a prime example, are used extensively throughout a spacecraft in motor mountings, star trackers, recorders and other rotating members. The acceleration of lubricant evaporation rates due to the low pressure space environment has caused premature failures in mechanical systems due to the resulting loss of lubrication.

Various methods have been used in attempts to restrict this evaporation. Geometric designs incorporating baffles to increase the flight path of escaping molecules or apertures to reduce the effective areas are included in these methods. More recently, in bearing applications, oil impregnated sintered nylon or phenolic retainers have replaced previously used metal retainers to provide an extra oil reserve in direct contact with the balls of the bearings. Reservoir materials affording an extra supply of lubricating fluids placed in unused space in proximity to parts in need of lubrication are yet another alternative.

Although evaporation rates can be predicted by the familiar Langmuir equation;

$$G = 5.83 \times 10^{-2}\, p \sqrt{\frac{M}{T}}$$

where

G = evaporation rate, g/cm^{2}s,

p = vapor pressure, torr,

M = molecular weight,

T = temperature, deg K.

this equation does not account for geometric restrictions placed on the evaporation process. In addition, use of this equation requires that the vapor pressure and molecular weight of the lubricant be known.

Whereas most experiments have been concerned with the surface area of the sample fully exposed to the low pressure space environment, this investigation deals with the effects of container geometry on the evaporation rates of lubricating oils. Tests were conducted on two lubricating oils, dioctyl adipate and Bray Company NPT-4, in glass containers having different heights and surface areas.

In addition to exploring geometric effects, the presentation of results from outgassing experiments is to be examined. Many experiments report rates of evaporation of materials, including oils, as a percentage of the original sample weight. Others report the evaporation rate as a direct weight rate change. Two oils were selected for these experiments to explore these effects, namely dioctyl adipate and Bray Company NPT-4.

Experiments

Evaporation rates for dioctyl adipate oil at 100°F were established for ten samples. Each sample was carefully weighed in glass containers of differing geometry; length and exposed surface area. Figure 1 shows typical containers used in these tests. The samples were placed in a vacuum chamber and held at a pressure of 2×10^{-4} Torr at the indicated test temperature. The samples were removed, cooled to room temperature, weighed and returned to the test conditions. This procedure was periodically repeated until a total time of approximately 300 hours had elapsed. Weights were determined with an accuracy of 0.1 milligrams.

The dioctyl adipate tests were conducted in three groups: A) the first four samples were in containers whose areas were the same and whose length varied, B) the next four samples were tested in containers whose lengths were the same and the areas were varied and C) two additional samples were conducted in two widely different sized containers for additional confirmation of results.

Weight versus time curves were prepared for each sample and weight loss rates were measured in the linear portions of the curves. Figures 2 through 7 presents these curves for the dioctyl adipate oil. The linear slopes of the curves were determined by the least mean square method using all points in the linear region.

Five similar tests were conducted using Brayco NPT-4 oil. After an initial period of 90 hours at 100°F, the test temperature was increased to 150°F in order to produce significant weight changes. Figures 14 and 15 presents the weight versus time curves for these tests.

Tables 1 and 2 list the experimental results as well as the pertinent test parameters including container size, original sample weight and rate of weight loss.

Results and Discussions

The sample weights versus vacuum exposure times were plotted for all dioctyl adipate samples. Figures 2 through 6. Each point presented represents an individual weight determination made by removing the test container from the vacuum chamber, weighing at ambient temperature, and subsequent resumption of the test. The principal test parameter that was varied was the test container geometry with all containers being cylindrical glass vials of differing lengths and diameters. Note that the original weights of the dioctyl adipate samples ranged from one to fifteen grams and the slopes of the curves varied from 0.00034 to 0.01337 grams per hour under the same environmental conditions of 100°F and a pressure of 4×10^{-4} torr. The evaporation rate decreased when the container length increased and the rate increased when the container area increased just as would have been anticipated. Figure 7 shows a schematic of all ten tests indicating their relative positions plotted against common coordinates. All ten samples showed a linear weight decrease throughout the time duration of the tests.

Outgassing data is sometimes presented in percentage weight loss according to

$$\%\ \text{weight loss} = \frac{\omega_0 - \omega}{\omega_0} \times 100 \qquad (2)$$

where

ω_0 = original weight
ω = weight at time t.

Figures 8 and 9 present the data in this form for the dioctyl adipate oil showing the same samples as were given in earlier figures on a weight basis. These curves produce the impression that some samples had bad outgassing properties while others were acceptable. For example, in Figure 9, samples 5 through 8 were tested in containers whose areas became progressively larger and whose evaporation rates should be expected to increase proportionately. An apparent contradiction appears in the case comparing samples 7 and 8 where it appears that 7 evaporates faster than 8, even though the container area of 8 is larger than that of 7. On a direct weight basis, Figures 4 and 5, the rates of weight loss are in proportion to their respective exposed areas. An explanation of this contradiction follows.

Figure 10 makes a comparison between samples 4 and 9 on both a percentage as well as a change in weight basis. The containers used in these tests were approximately the same physical size. The upper curve, on a change in weight basis, indicates that both samples lose weight at close to the same rate. The lower curve, based on a percent weight loss, indicates that sample 4 loses at a rate four times greater than that of sample 9. An examination of the data revealed the cause for the apparent discrepancy, which was the difference in the original sample weight and its relationship in equation 2. Equation 2 can be rewritten as

$$\% = \frac{1}{\omega_0} (\omega_0 - \omega) \times 100 \qquad (3)$$

where it becomes obvious that the original weight is an inverse function of percent. The contradictions of Figures 9 and 10 was caused by the differences in original sample weights even though the weight loss, $(\omega_0 - \omega)$, due to evaporation in the samples of Figure 10 were indeed the same.

Since the percent weight loss exhibits these aforementioned contradictions, subsequent data was treated on a weight or rate of weight loss basis only. The rates for the ten samples were calculated using the least mean square method and considering all rates to be linear.

The geometry of the containers was considered next. Evaporation rates for six samples in containers having the same exposed area is shown in Figure 11(a) plotted against the reciprocal container length. This curve suggested an exponential form which lead to the log plot, Figure 11(b). The resulting slope of approximately 0.5 further suggested that the relationship between evaporation rate and container length might be a function of the square root of the container length, $1/\sqrt{\ell}$. Figure 11(c) confirms this relationship. The rates of the remaining four samples, in containers of similar length but of different areas, were plotted in Figure 12 showing that the rate is directly proportional to the exposed area.

Finally the rates of all ten samples were plotted against the combined geometric function, $A/\sqrt{\ell}$, resulting in Figure 13.

This produced the following linear relationship:

$$\frac{d\omega}{dt} = c\,\frac{A}{\sqrt{\ell}} \qquad (5)$$

where

$\frac{d\omega}{dt}$ = evaporation rate, grams/hour

A = surface area, cm^2.

ℓ = container length, cm.

c = slope of Figure 13.

Equation 4 leads directly to

$$\omega = \omega_0 - c\,\frac{A}{\sqrt{\ell}}\,t \qquad (6)$$

where

t = exposure time, hours

W = weight remaining after time t, grams

W_0 = original weight, grams

In order to confirm the previous results and to gain additional information, another lubricant, Brayco NPT-4, was selected and tested in similar fashion using the same techniques. Figure 14 shows the total loss in weight for five tests in which the container geometry was varied. Figure 15 presents the same data for the lower four curves of Figure 14 for clarity and to better measure the evaporation rates by increasing the sensitivity of the ordinate. The rates obtained from these curves are used in Figures 16 and 17 resulting in the same linear relationship between the evaporation rate and the geometric function, $A/\sqrt{Z}$, for the Brayco NPT-4 oil as was determined earlier for the dioctyl adipate.

CONCLUSIONS

This series of tests clearly demonstrates the importance of container geometry on evaporation rates of liquid lubricants in spacecraft applications. A convenient empirical equation has resulted that can be used to determine the amount of oil remaining in a vacuum environment after prolonged time periods:

$$W = W_0 - C \frac{A}{\sqrt{Z}} t$$

This equation is presently limited by temperature and pressure parameters. Additional testing would be required to better define these effects. However, the same test method is applicable to develop a family of curves for different temperatures and pressures.

In the evaluation or comparison of candidate lubricants, the constant c, in the above equation is a direct measure of the evaporation or outgassing characteristics of the fluids. The smaller the value of c, the less evaporation will occur under the temperature and pressure at which c was determined. Comparison of c eliminates the effects of test container geometry and original sample weight. For example; in the case of the two lubricants tested here the values of c are as follows:

for dioctyl adipate at 100°F and 2×10^{-4} torr
$c = 0.00073$

and for the Bray Co. NPT-4 at 150°F and 2.7×10^{-4} torr
$c = 0.000087$

This indicates that the Bray Co. NPT-4 at 150°F has an outgassing characteristic that is lower by a factor of ten than the dioctyl adipate at 100°F.

The data presented also illustrates the pitfalls that exist with regards to the method of presentation. Many sources use percent as a measure of evaporation loss. Although this data is meaningful, extreme care should be exercised with an awareness of its shortcomings. If, for instance, a particular material is reported to have a loss of 2%, then it is not known how much material has actually been evaporated unless the original sample weight is known. In a direct rate of weight loss the amount evaporated can readily be computed. If a smaller sample is tested under duplicate conditions, then it erroneously appears, in percent form, to have lost more than a larger sample tested under identical circumstances. Curves based on percent have validity only on a comparative basis only when all test parameters including original weight and container geometry have been kept constant for all fluids under consideration.

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3. Buckley, D. H., Johnson, R. L., "Evaporation Rates for Various Organic Liquid and Solid Lubricants in Vacuum to 10^{-8} Millimeter of Mercury at 55° to 1100° F," NASA Technical Note TN D-2081, December 1963.
4. ASTM designation (D2715-68T), "Tentative Method for Measurement of Volatilization Rates of Lubricants in Vacuum," 1969.

Table 1

Tabulation of the dioctyl adipate tests listing geometric parameters and rates of weight loss.

Sample Number	Container Geometry length, cm. A area, cm^2					Rate of Weight Loss	Original Sample Weight gms
		A	$\frac{1}{}$	$\frac{1}{}$	$\frac{A}{}$	= rate, gms/hr	$_0$
1	3.68	5.29	0.272	0.521	2.76	0.00210	0.9983
2	5.84	5.29	0.171	0.413	2.18	0.00171	0.9936
3	7.24	5.29	0.138	0.372	1.97	0.00130	0.9842
4	9.40	5.29	01106	0.372	1.73	0.00113	1.0772
5	3.04	1.17	0.329	0.575	0.673	0.00024	0.6520
6	3.09	3.49	0.324	0.569	1.99	0.00115	1.6990
7	3.12	5.29	0.320	0.565	2.98	0.00207	2.0228
8	4.06	32.7	0.246	0.495	16.2	0.01239	14.7677
9	8.50	5.29	0.118	0.342	1.81	0.00120	4.9656
10	1.27	20.3	0.787	0.925	18.8	0.01337	4.9907

Table 2

Tabulation of the Bray Co. NPT-4 oil tests listing geometric parameters and rates of weight loss.

Sample Number	Container Geometry ℓ = length, cm A = area, cm^2					Rate of Weight Loss $\dot{w}$ = rate, gms/hr	Original Sample Weight gms
	ℓ	A	$\frac{1}{\ell}$	$\frac{1}{\sqrt{\ell}}$	$\frac{A}{\sqrt{\ell}}$		w_0
1	1.02	1.37	0.980	0.990	1.36	0.00017	0.4588
2	1.27	5.29	0.787	0.885	4.68	0.00050	1.1997
3	1.14	62.1	0.876	0.934	58.0	0.00494	6.5082
4	4.45	1.37	0.225	0.473	0.648	0.00006	0.5828
5	9.65	5.29	0.104	0.322	1.70	0.00018	2.0322

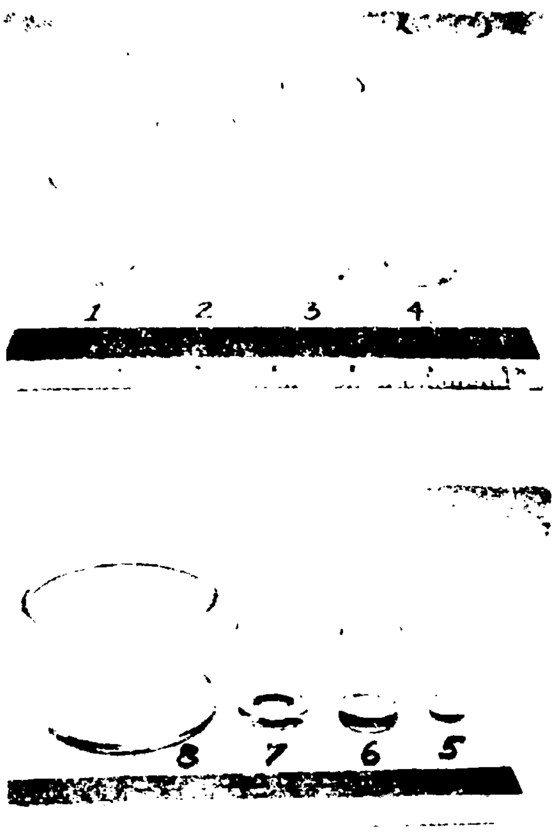


Figure 1. Typical containers used in evaporation tests of dioctyl adipate and Bray Co NPT4 lubricants

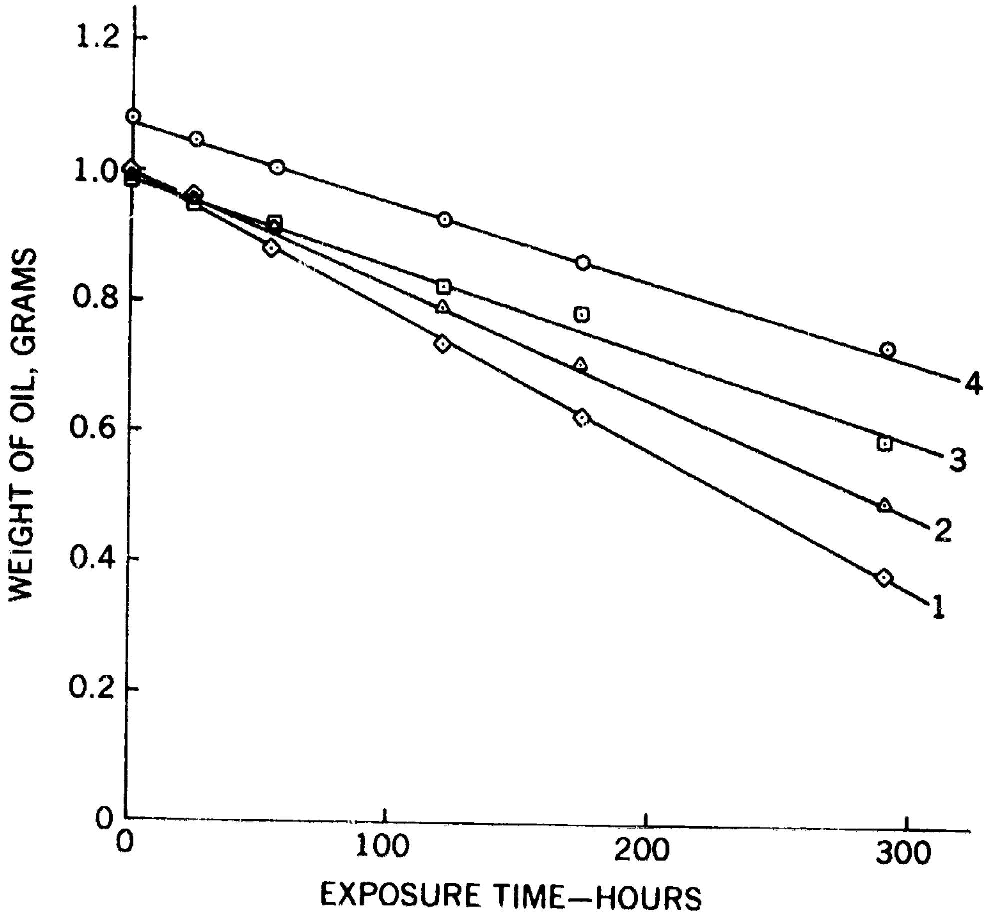


Figure 2. Loss in weight of dioctyl adipate oil at 100°F at a pressure of 2 × 10^{-4} torr – Samples 1 through 4

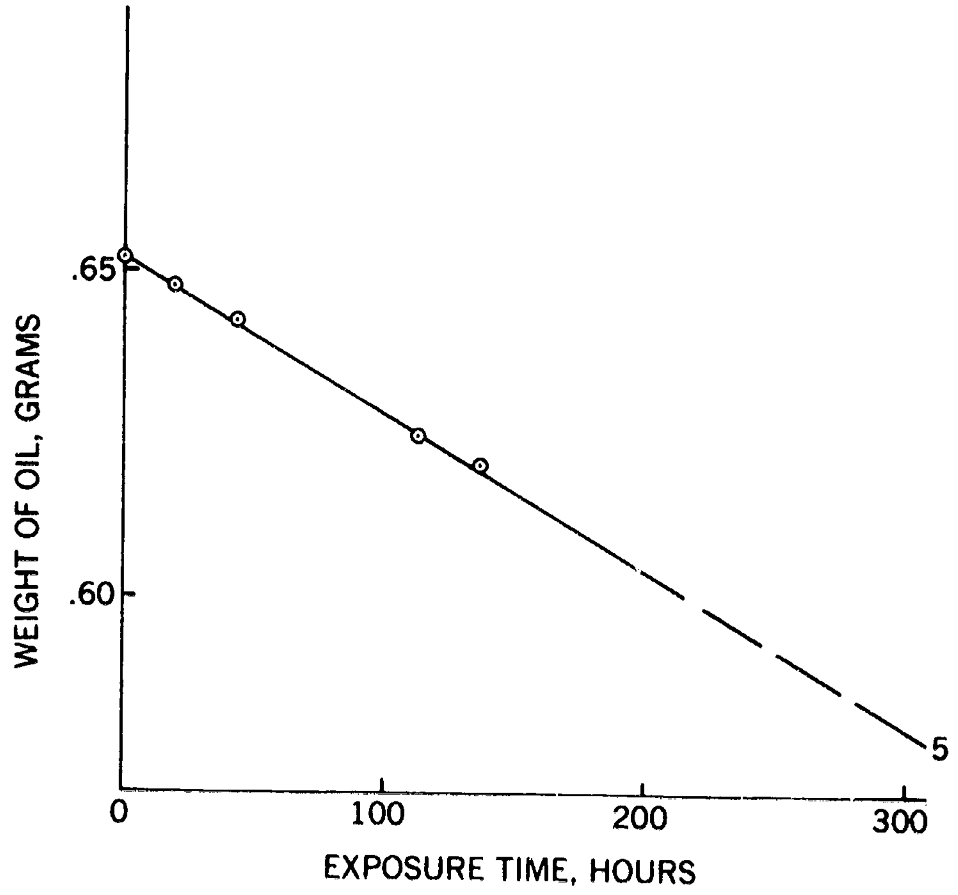


Figure 3. Loss in weight of dioctyl adipate oil at 100°F at a pressure of 2×10^{-4} torr – Sample 5

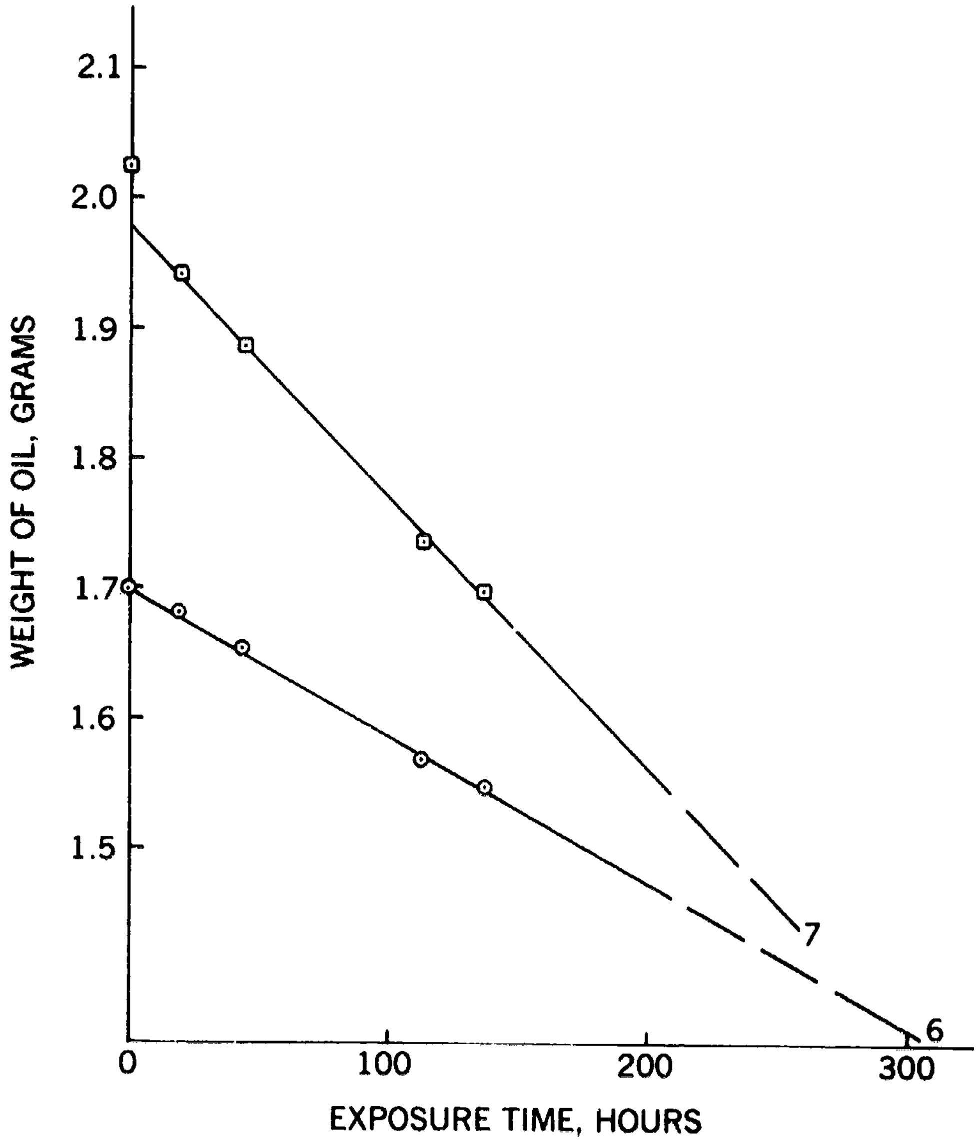


Figure 4. Loss in weight of dioctyl adipate oil at 100°F at a pressure of 2×10^{-4} torr – Samples 6 and 7

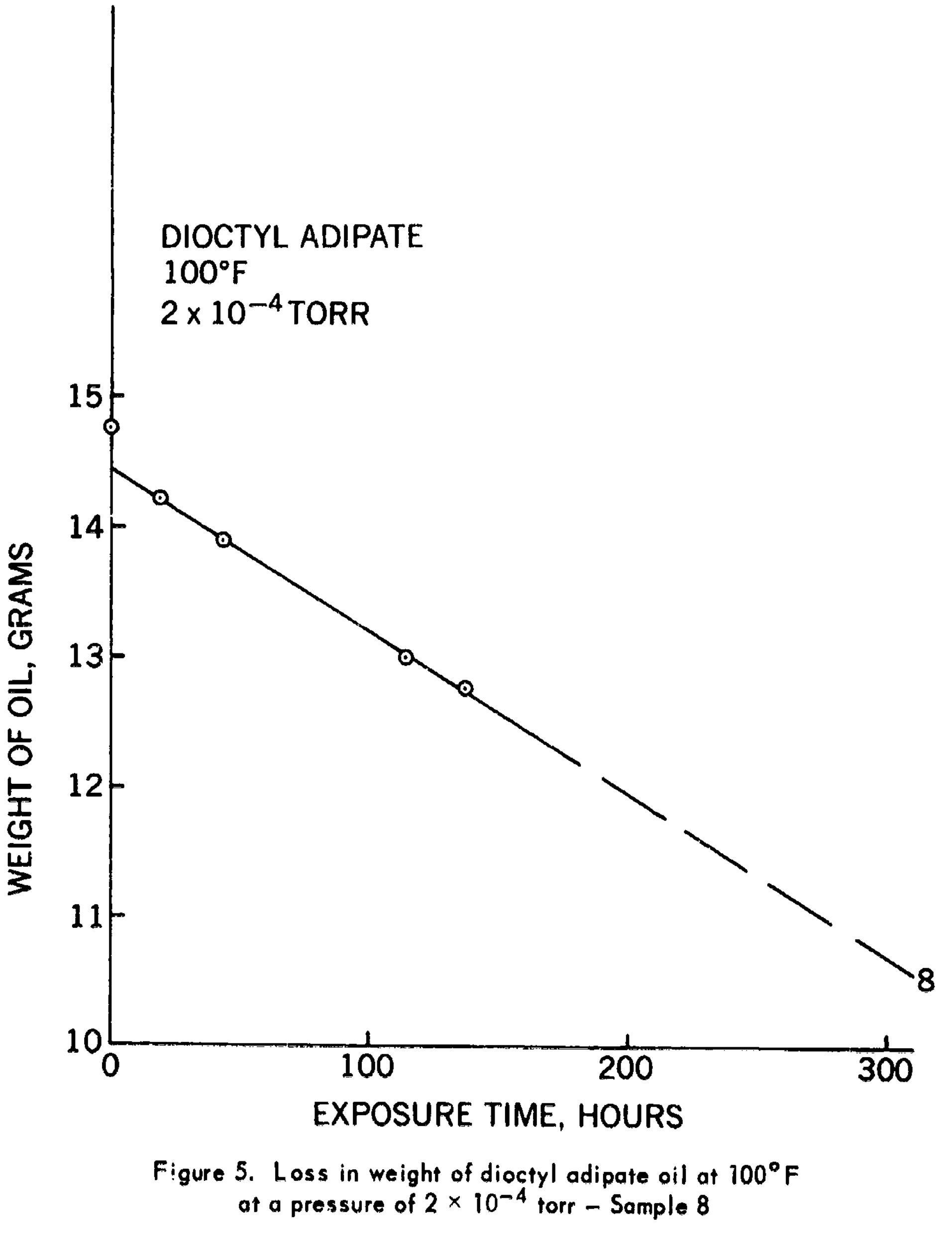


Figure 5. Loss in weight of dioctyl adipate oil at 100°F at a pressure of 2×10^{-4} torr – Sample 8

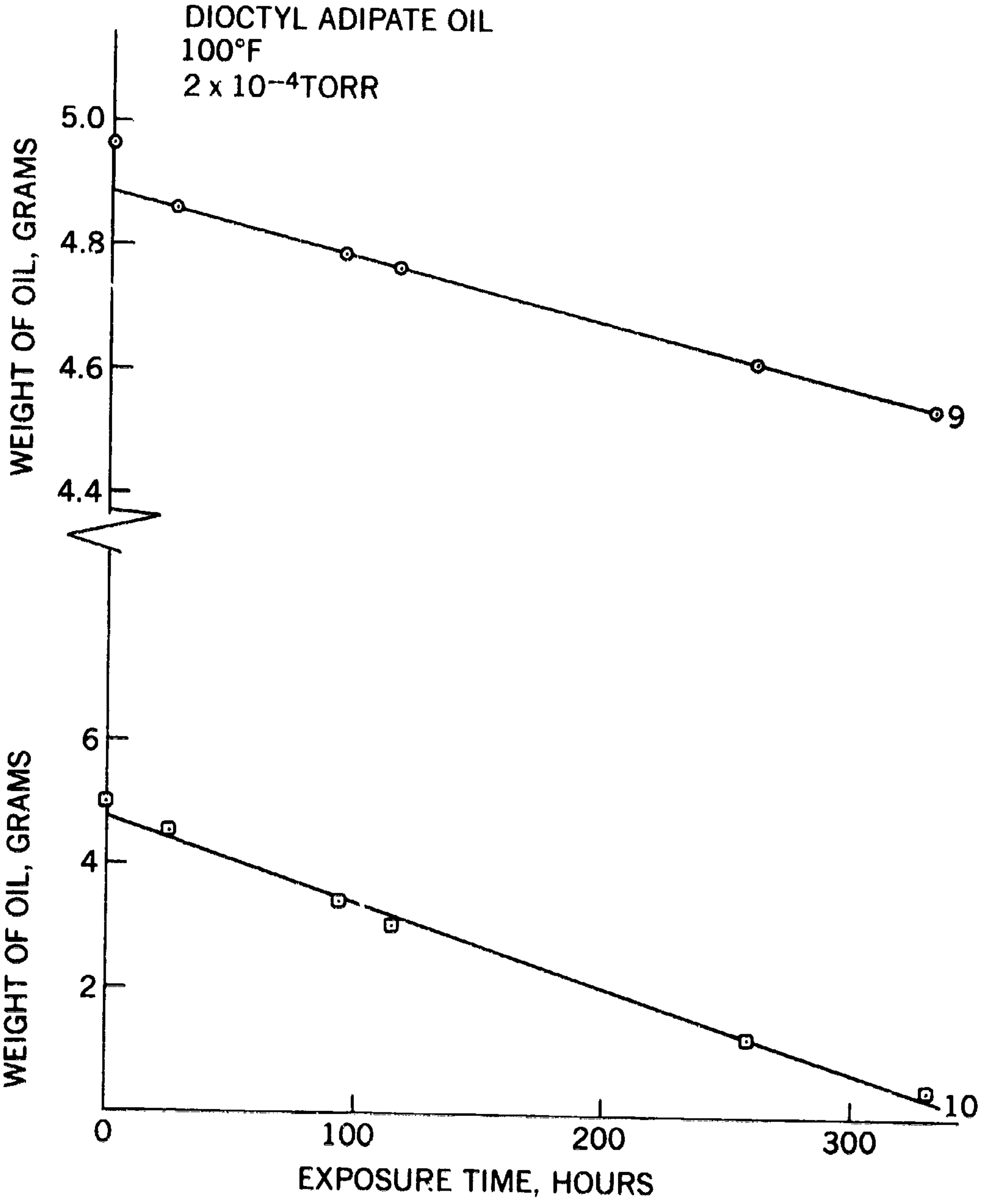


Figure 6. Loss in weight of dioctyl adipate oil at 100°F at a pressure of 2×10^{-4} torr – Samples 9 and 10

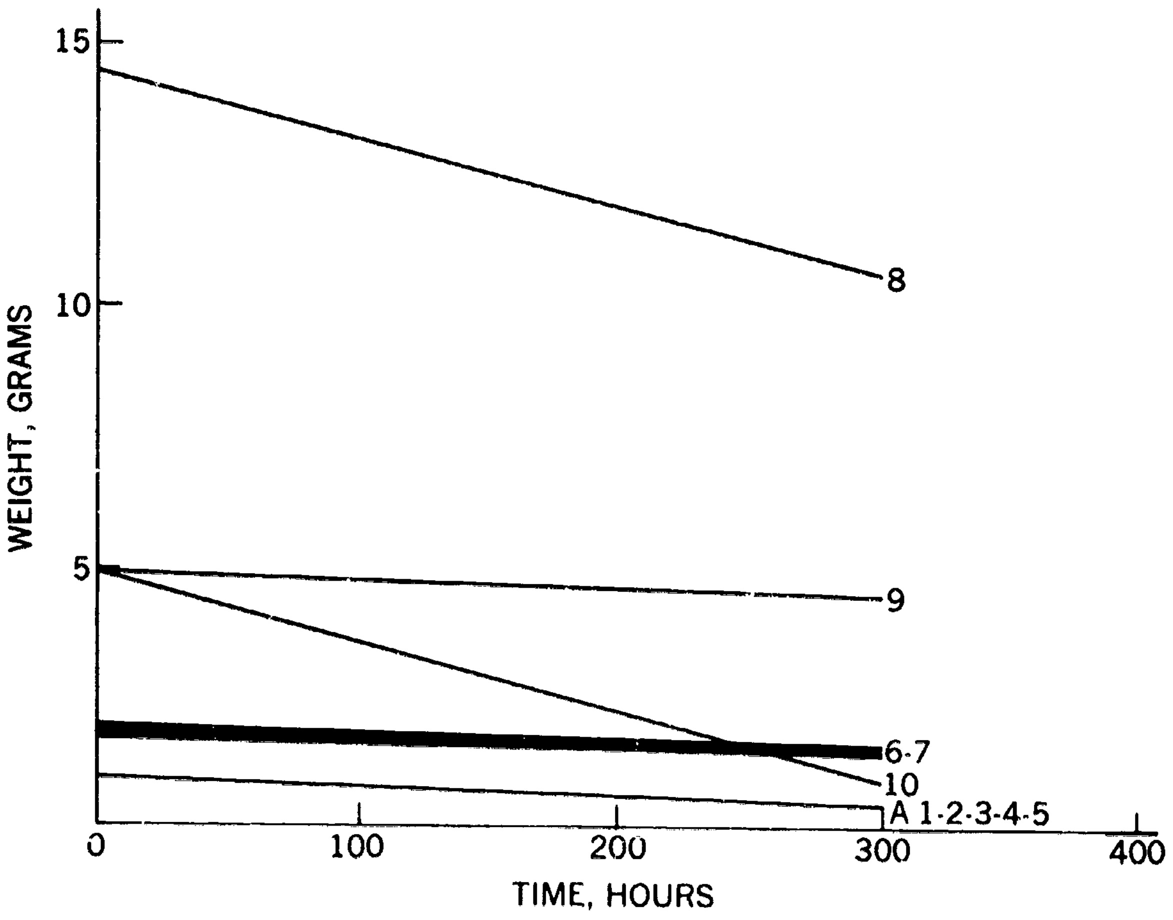
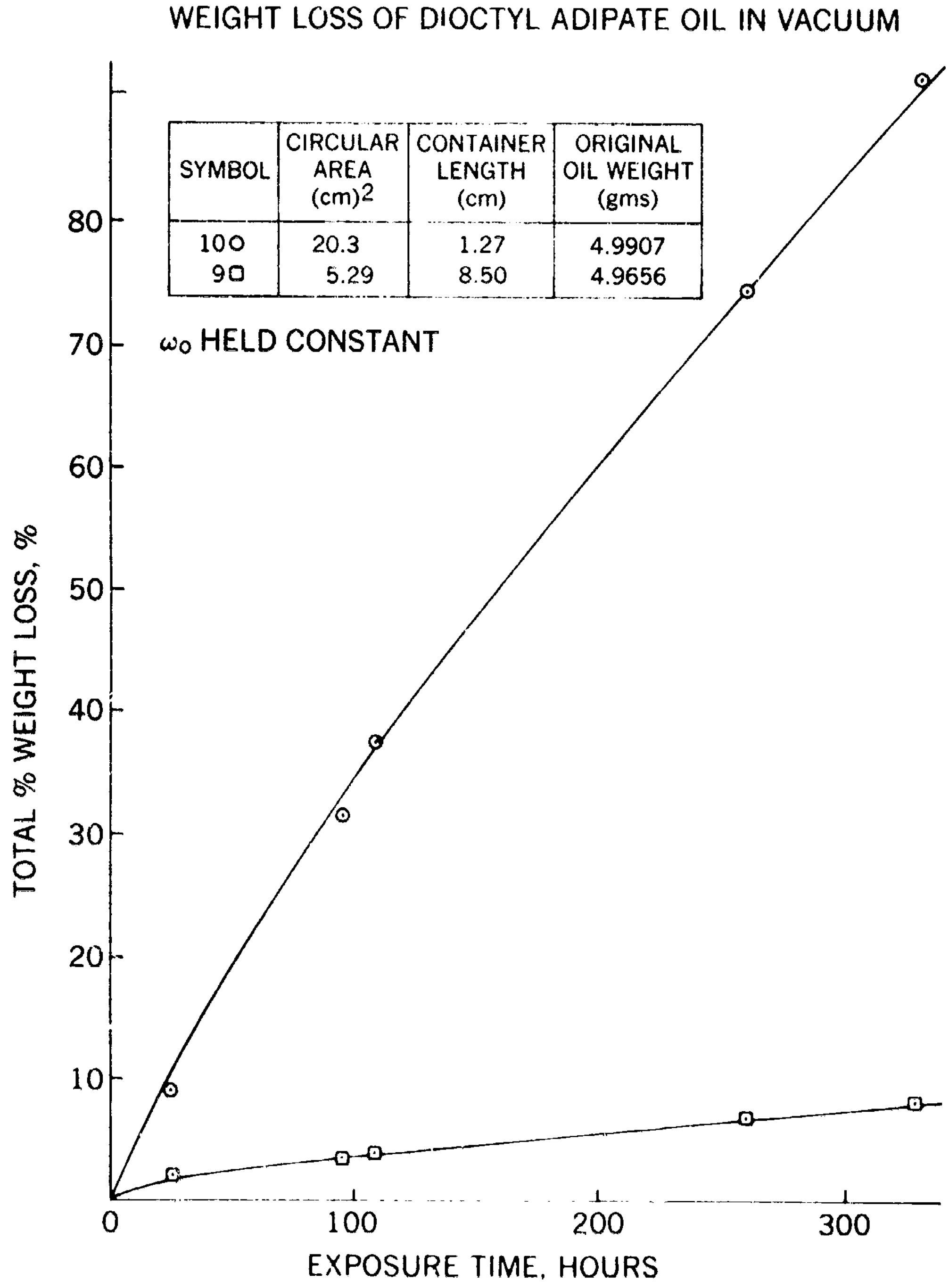
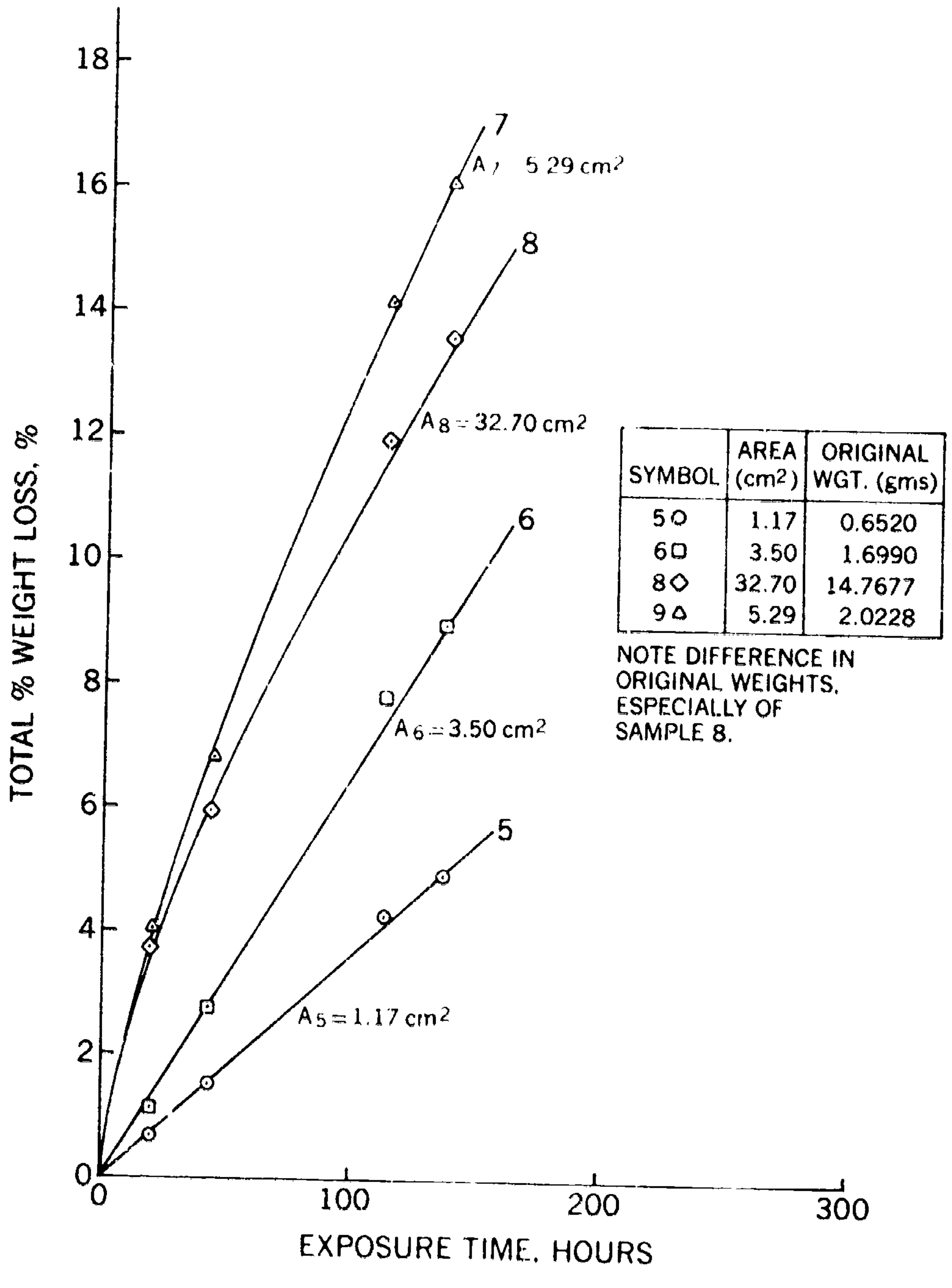


Figure 7. Schematic weight versus time curve for all ten dioctyl adipate vacuum evaporation tests showing relative regions covered by the tests



SYMBOL	CIRCULAR AREA $(cm)^2$	CONTAINER LENGTH (cm)	ORIGINAL OIL WEIGHT (gms)
10○	20.3	1.27	4.9907
9□	5.29	8.50	4.9656

Figure 8 Percent weight loss of dioctyl adipate oil samples 9 and 10



SYMBOL	AREA (cm²)	ORIGINAL WGT. (gms)
5 ○	1.17	0.6520
6 □	3.50	1.6990
8 ◇	32.70	14.7677
9 △	5.29	2.0228

NOTE DIFFERENCE IN ORIGINAL WEIGHTS, ESPECIALLY OF SAMPLE 8.

Figure 9. Percent weight loss of dioctyl adipate oil as a function of area

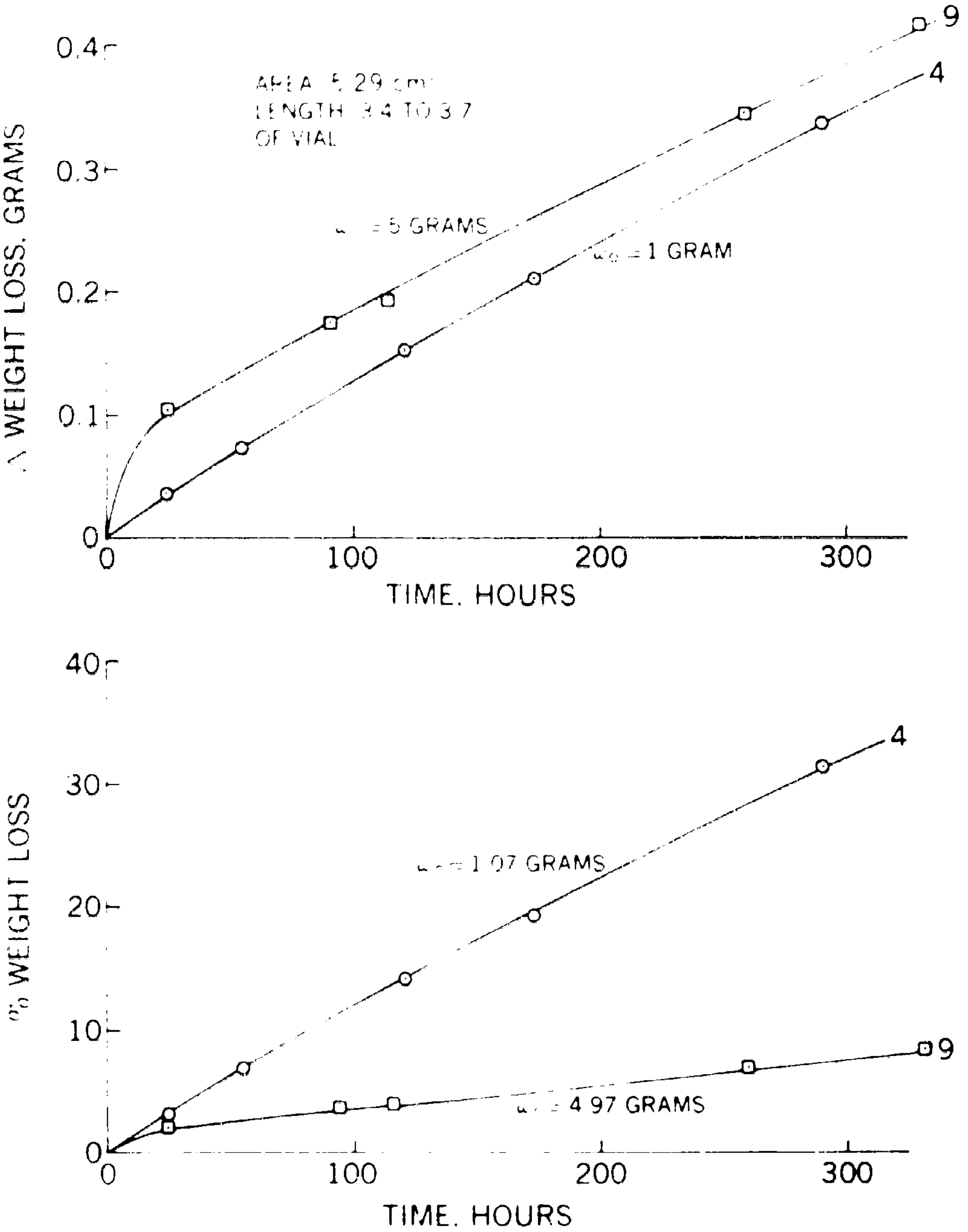


Figure 10. Comparison of outgassing data for dioctyl adipate between weight change and percent weight loss

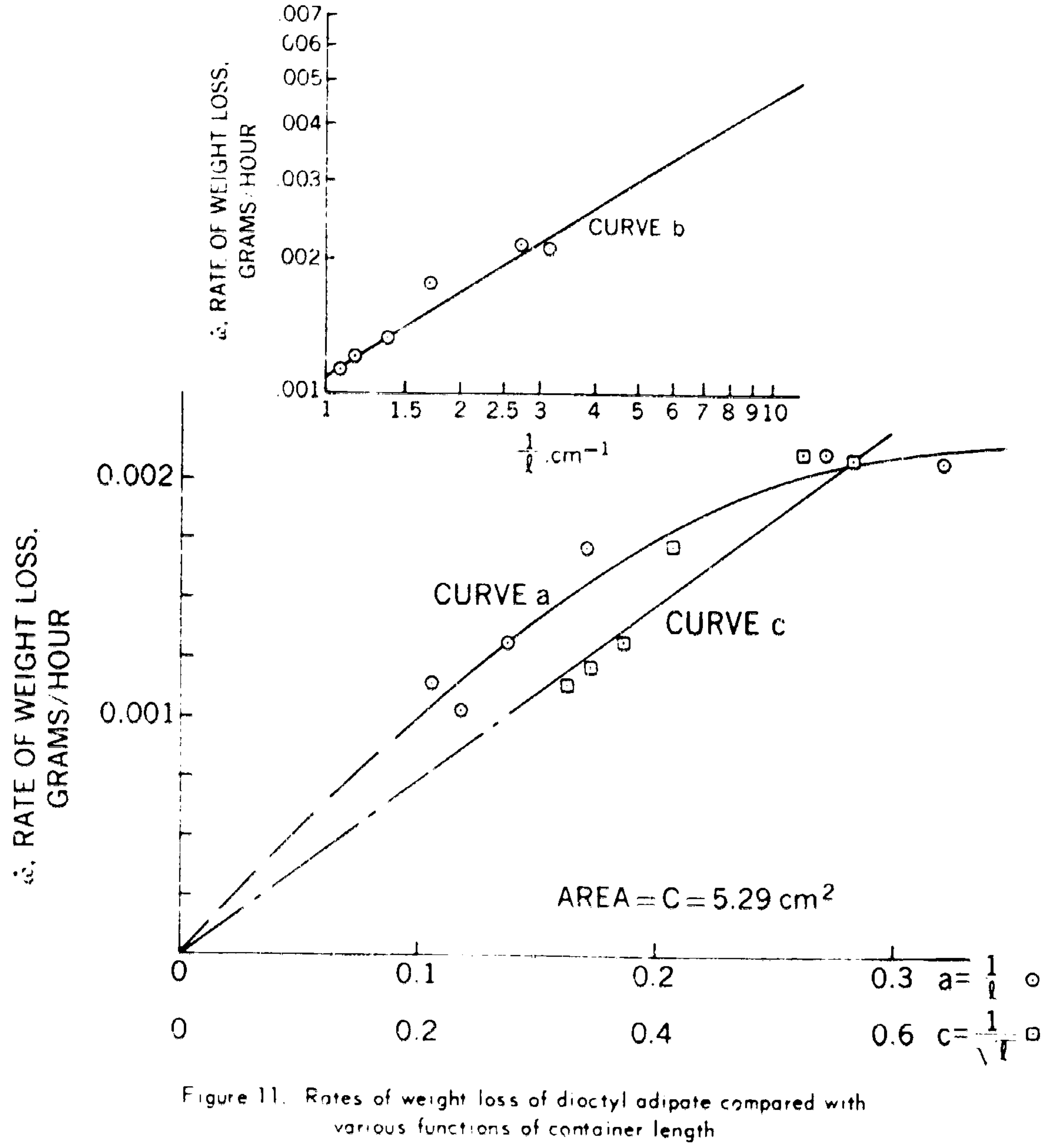


Figure 11. Rates of weight loss of dioctyl adipate compared with various functions of container length

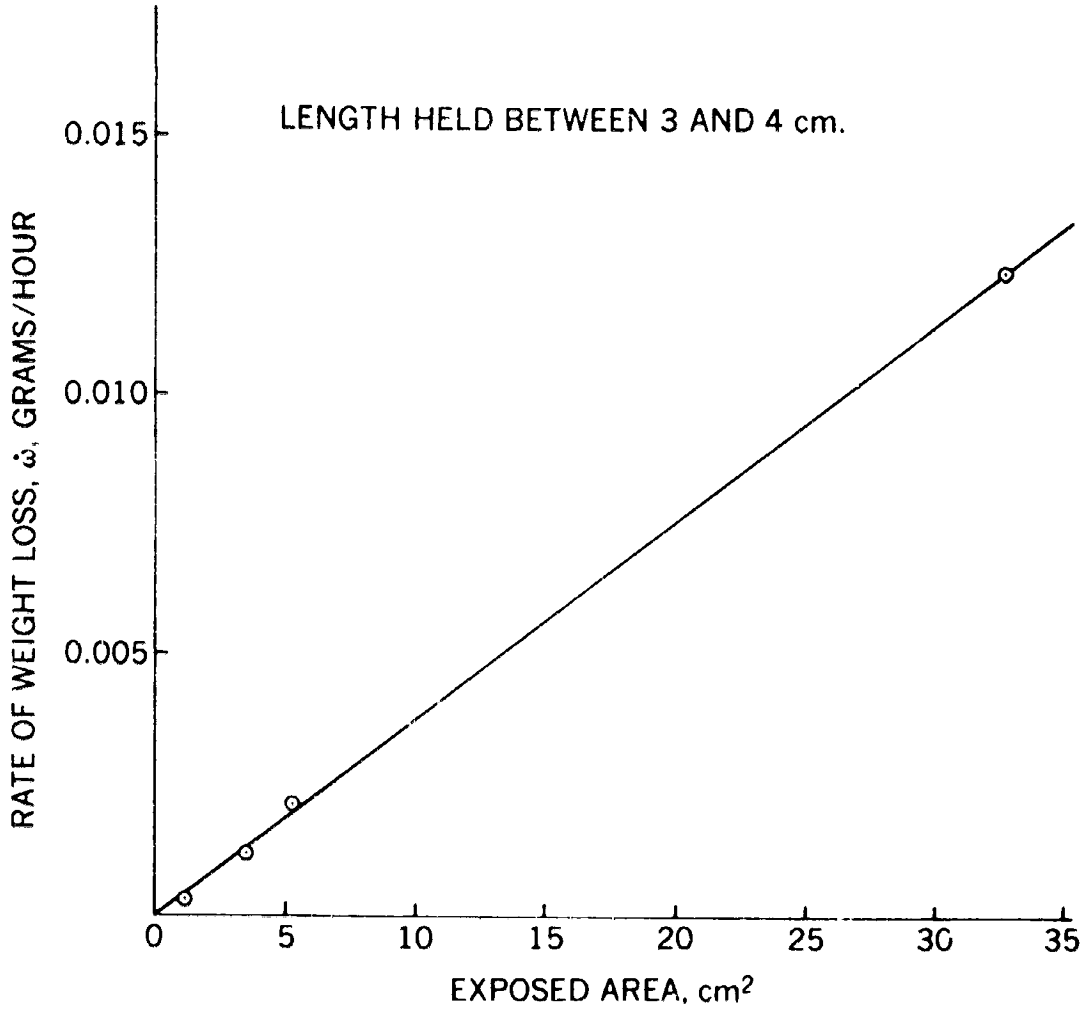


Figure 12. Rates of weight loss of dioctyl adipate compared with container area

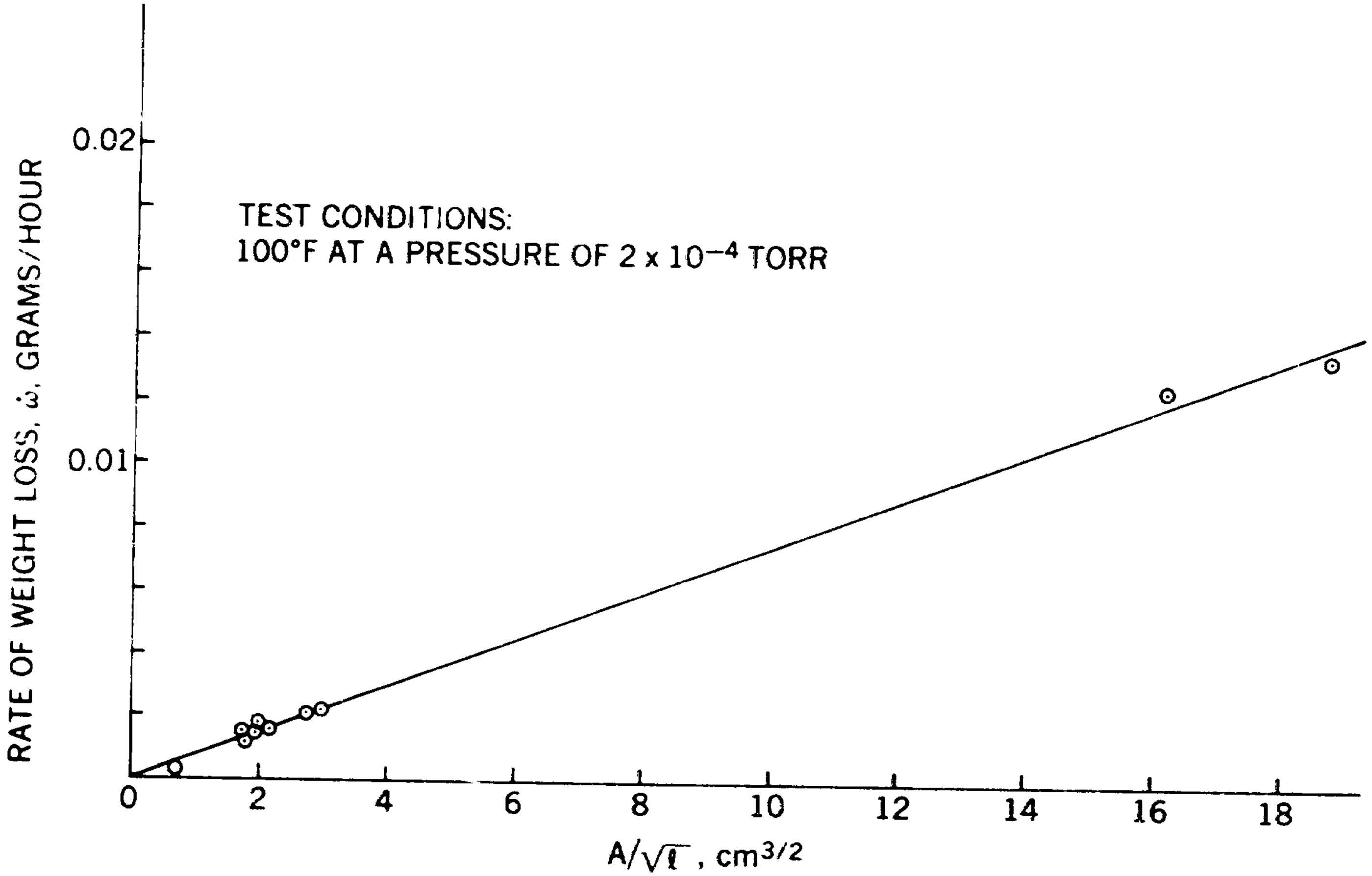
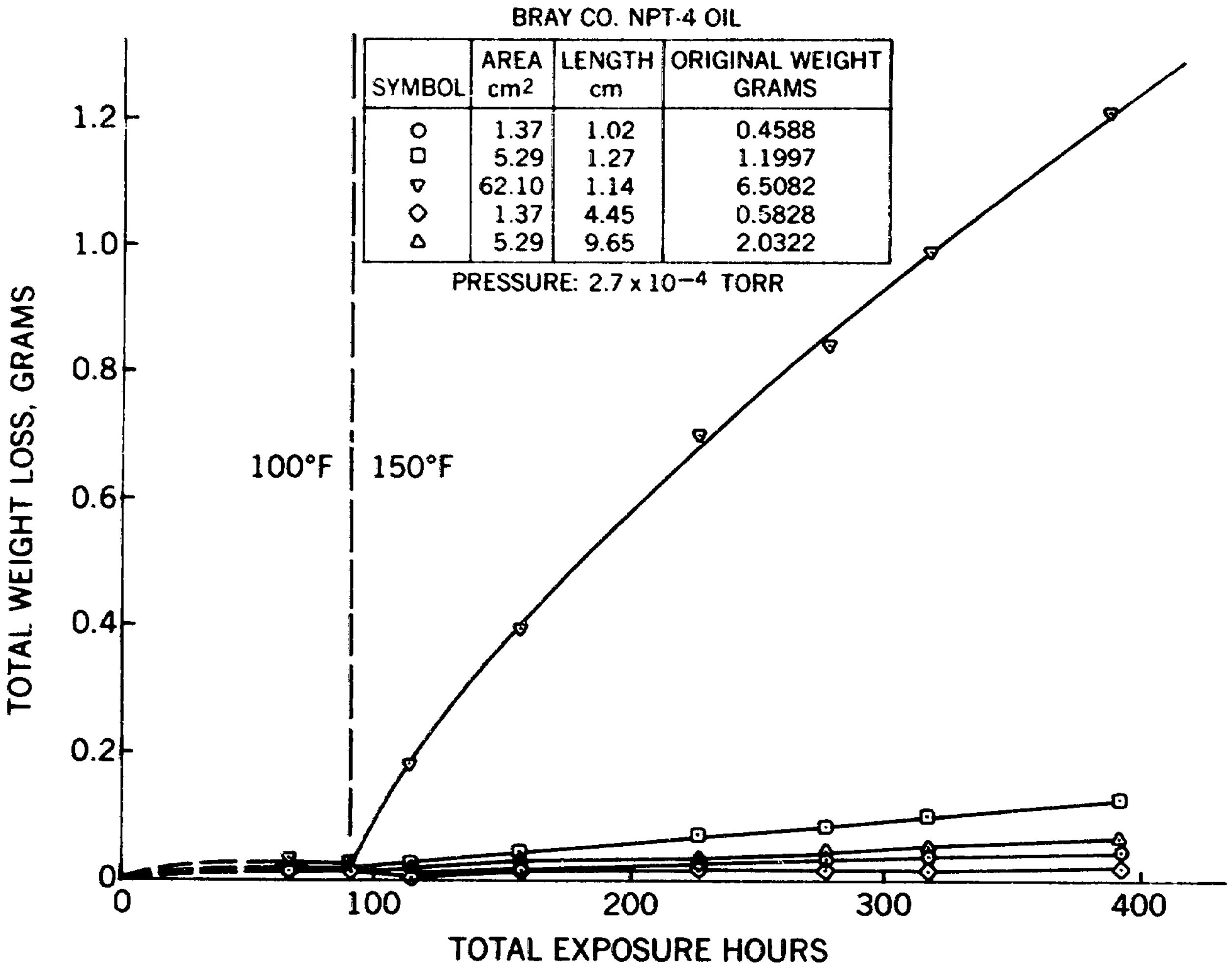
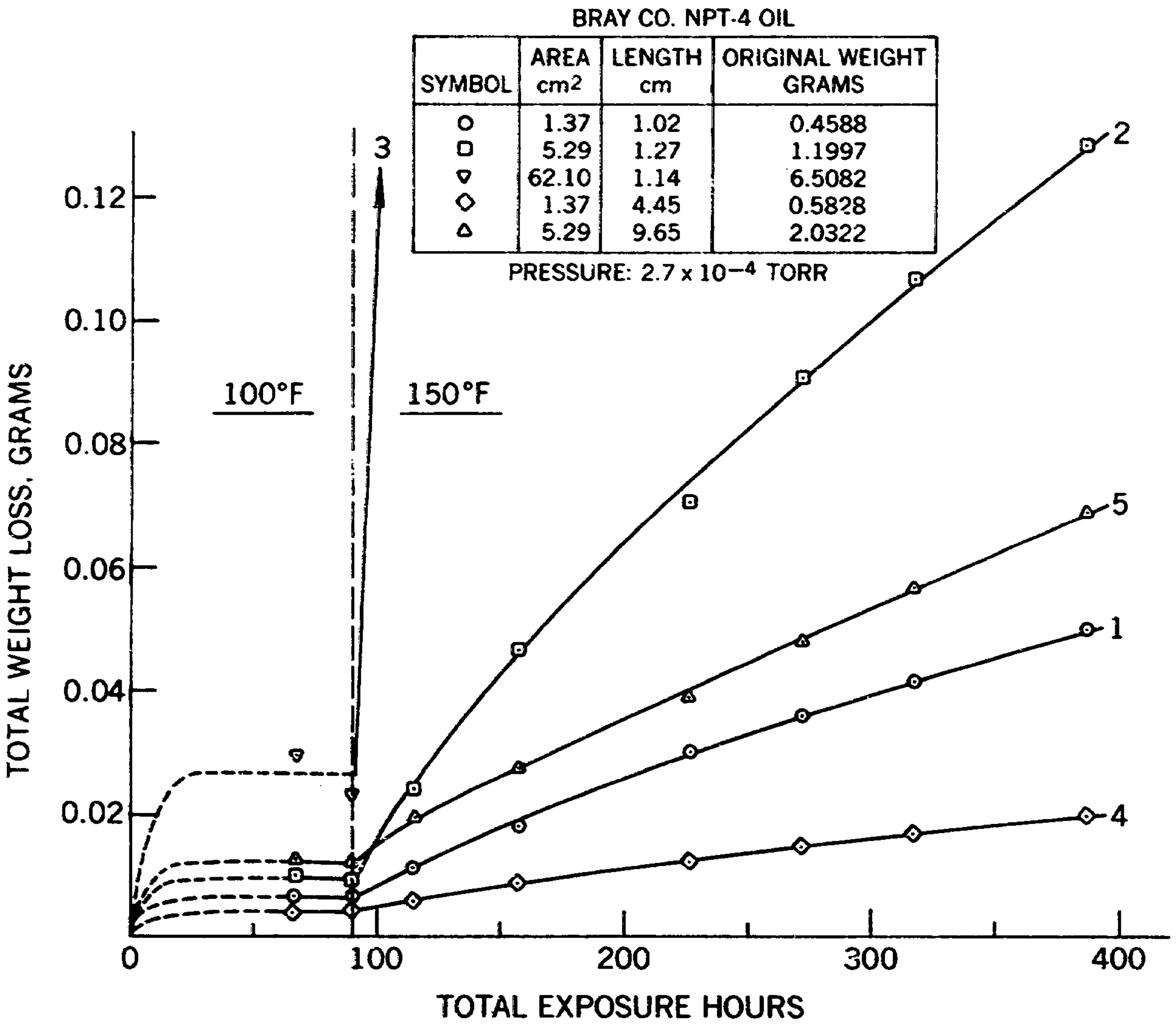


Figure 13. Rates of weight loss of all dioctyl adipate tests as a function of the geometric term $A/\sqrt{e}$



SYMBOL	AREA cm2	LENGTH cm	ORIGINAL WEIGHT GRAMS
○	1.37	1.02	0.4588
□	5.29	1.27	1.1997
▽	62.10	1.14	6.5082
◇	1.37	4.45	0.5828
△	5.29	9.65	2.0322

Figure 14. Outgassing tests on Brayco NPT-4 oil in vacuum of 2.7×10^{-4} torr in containers of different geometry



SYMBOL	AREA cm2	LENGTH cm	ORIGINAL WEIGHT GRAMS
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▽	62.10	1.14	6.5082
◇	1.37	4.45	0.5828
△	5.29	9.65	2.0322

Figure 15. Outgassing of Brayco NPT-4 oil at pressure of 2.7×10^{-4} torr in containers of differing areas and heights

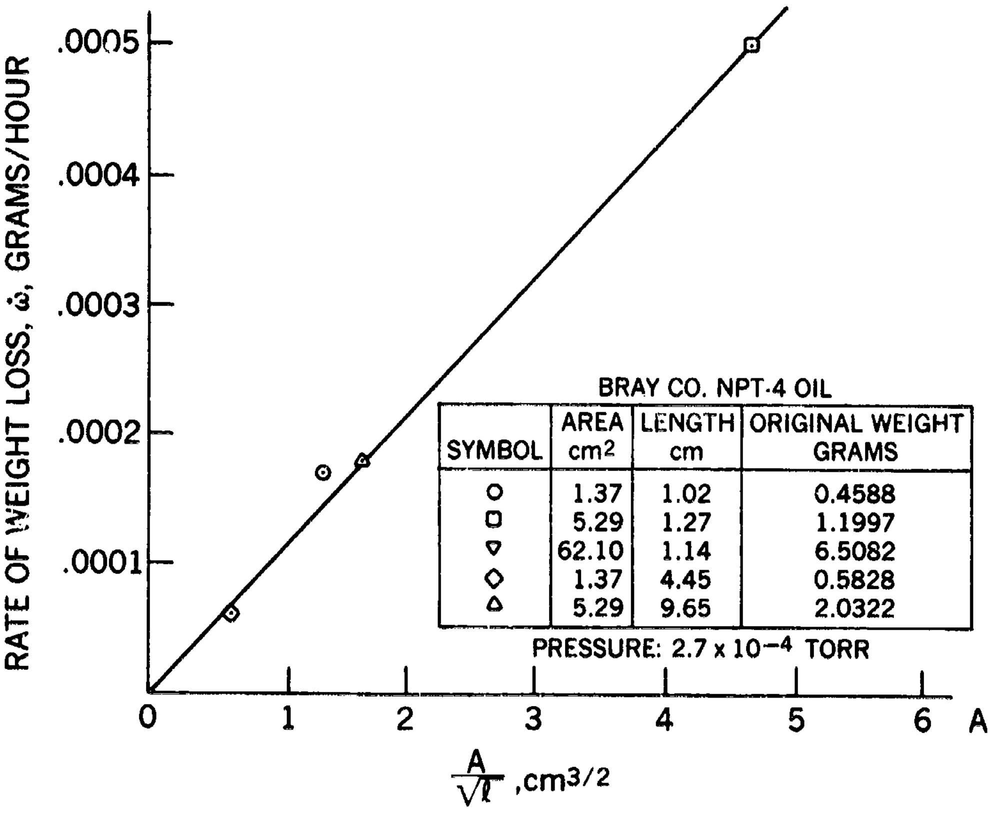
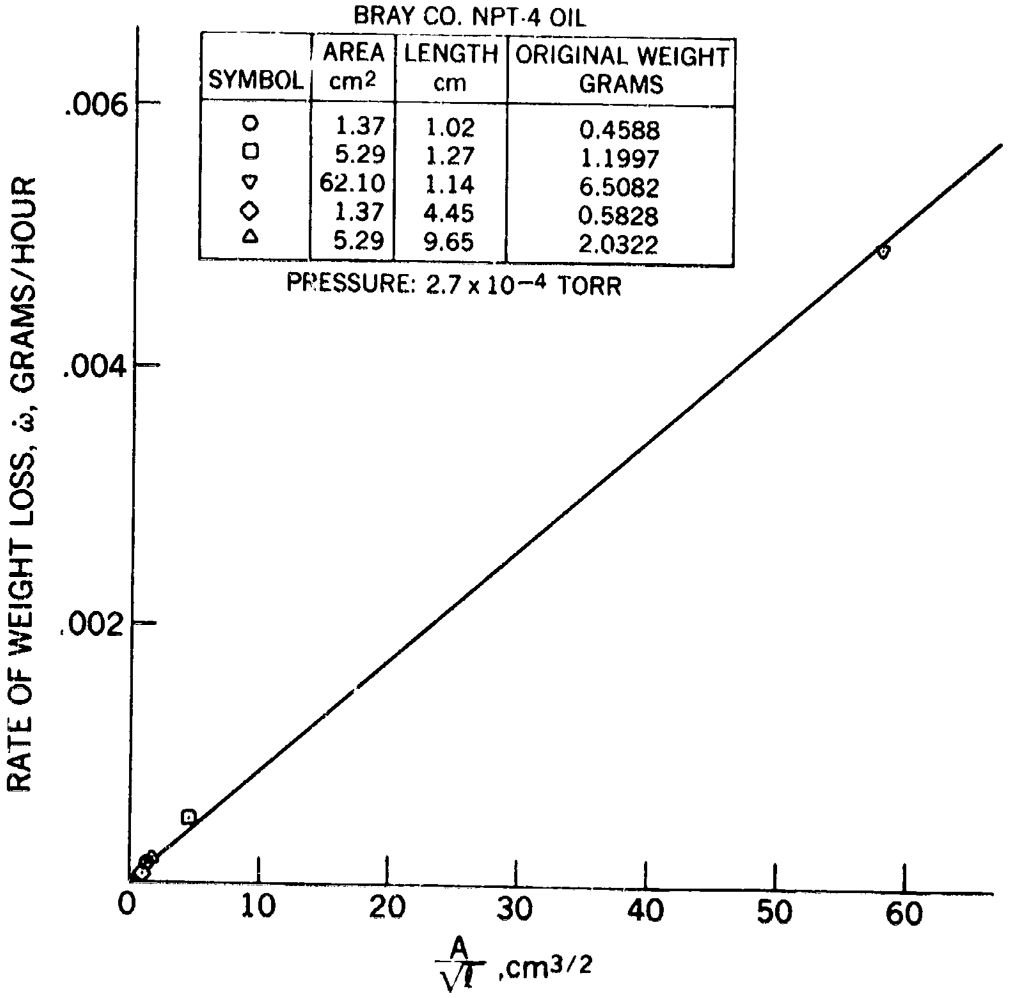


Figure 16. Bray Co. NPT-4 Oil outgassing tests as a function of geometry



SYMBOL	AREA cm2	LENGTH cm	ORIGINAL WEIGHT GRAMS
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Figure 17. Bray Co. NPT-4 Oil outgassing tests as a function of geometry