NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1840

ANALYSIS OF PROPERTIES OF FOAM

By J. W. McBain, Sydney Ross, and A. P. Brady

Stanford University

NACA

Washington

March 1949

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1840

ANALYSIS OF PROPERTIES OF FOAM

By J. W. McBain, Sydney Ross, and A. P. Brady

SUMMARY

A definition of the term "frothing volume" is given as the amount
of foam formed under the actual conditions imposed by the mechanism of
its production. The practical importance of the total amount of foam,
whether stable or not, is pointed out. The stability of foams is theo-
retically considered and is shown to be intrinsically a property of the
liquid system. The amount of foam, however, depends not only on the
stability but sometimes just as much, or even entirely, on the mechanism
of its production.

INTRODUCTION

Properties of foam, other than stability as measured by rate of
collapse, are to be defined and may be of greater practical importance
than stability. No attempt is on record previous to the time of this
investigation to relate the ease of formation of foam, the amount of
foam formed, and the intrinsic stability of the foam, although these
properties are interdependent and distinguishable. The present report,
based on general experience as well as on a few illustrative data pre-
sented herein, discriminates between these properties and analyzes their
specific meanings, especially with reference to their role in the practical
problem of foaming of oils in aircraft lubricating systems.

SYMBOLS

A height of vertical film

a vertical dimension of idealized foam

b horizontal dimension of idealized foam

d relative foam density $(l/l + g)$

d_o initial value of relative foam density

d_T relative foam density after time T

f total volume of foam $(l + g)$

f_o initial total volume of foam

G gravitational constant

g volume of gas in foam

g_o initial volume of gas in foam

h dynamic height of foam

h_o initial height of foam

K numerical constant

k constant characteristic of foam

L_f average lifetime of foam

L_g average lifetime of gas in foam

L_l average lifetime of liquid in foam

l volume of liquid in foam

l_o initial volume of liquid in foam

l_T volume of liquid in foam after time T

T time after which liquid film becomes unstable

t time

t_B time required for creaming before films commence to rupture at top

t_1 elapsed time before appreciable breakage of foam begins

t_2 time required for successive layers of bubbles to break

u   linear velocity of gas

$\alpha = l_T/l_o$

β constant

δ thickness of film of idealized foam

δ_o initial thickness of film of idealized foam

δ_T thickness of film of idealized foam after time T

η viscosity of liquid in foam

θ complex function of limiting foam density

ν kinematic viscosity of liquid in foam (η/ρ)

ρ density of liquid in foam

Σ unit of foaminess (h/u)

Ease of Foam Formation

The phrase "ease of foam formation" has been used, although without
definition. It is sometimes taken to mean the effort required to produce
a foam, as, for example, by shaking a bottle of liquid. The effect of
viscosity on foam formation is opposite to its effect on foam stability.
More viscous liquids are harder to shake into foam, although the foam
once produced is more stable than that from a less viscous liquid if all
other characteristics are held constant. On the other hand, although mere
shaking does not readily produce a foam with cold or viscous oils,
whipping with an electric kitchen mixer actually produces a greater volume
of foam with such oils than it does with hot or less viscous oils. The
effect of increasing the speed of whipping is sometimes a breakdown of
the foam already formed rather than an increase in the amount of foam.
(See table I of reference 1.)

It is therefore concluded that results obtained with one foam-
producing mechanism cannot be used to predict what will happen when
another one is employed.

Difference of viscosity alone, however, does not serve to distinguish
between foam stability and ease of formation. Thus it is easy to make a
bath full of soapsuds, but it is impossible to produce a pail of froth
from soap and pure water, although the viscosity of the liquid is the
same in both. Clearly in this case, in which the force employed easily
overcomes the viscosity of the liquid, ease of formation simply refers
to the stability of the froth produced.

When a mechanism of foam production which easily overcomes the
viscosity of the liquid is used, the most important factor in the case of
extremely small bubbles or more viscous liquids is the slowness with
which the bubbles can rise through the liquid under the influence of
gravity. It is possible to produce a somewhat temporary emulsion of air
bubbles in pure water if the size of the bubbles is kept below microscopic
dimensions. Similarly, with a highly viscous liquid, ordinary bubbles
might take minutes or hours to rise to the surface under the influence of
gravity. Such systems containing tiny, submerged and separated bubbles
are not usually called foam or froth but are referred to as emulsions.
Their importance in the present connection is the increase in volume of
the system caused by emulsified and entrained air. Emulsified air usually
amounts to only a few percent of the volume of circulating aeronautical
oil, although entrained air may increase by several fold the total volume
of material in the circulating system, as when the scavenge pumps are
pumping more air than oil.

The ease of foam formation usually depends on the method of pro-
ducing the foam as well as on the stability of the foam itself. Still
other factors might be recognized as significant, for example, the rate
of formation of bubble nuclei, as in boiling a liquid or as in the differ-
ence between soda water and properly settled champagne.

Some aspects of ease of formation are illustrated by the aeration-
evacuation tests for foaming of aeronautical oil. In these tests the
foam produced is greatly affected by the preliminary aeration. Without
aeration there is relatively little foam. Aeration produces not only
dissolved air but also emulsified bubbles, both of which supply froth
upon evacuation. This froth may sometimes be very stable, but further
evacuation stretches the bubbles and they may then all break. Voluminous
froths or none may therefore be produced and the result depends on the
technique of production.

In an airplane lubricating system, aeration, evacuation, compression,
entrainment, beating, heating, and cooling occur. The importance of the

actual frothing volume under these complex conditions is emphasized in the following section.

Total Foam Volume and Its Practical Significance

Hitherto, considerations of foam measurement have been chiefly concerned with an account of the stability of the foam and the rate at which foam breaks, either when undisturbed or when exposed to the atmosphere. Units of stability have been devised that are without reference to the initial amount of foam produced and give the same numerical value for a large quantity of foam as for a smaller quantity of the same foam.

It is often more important, however, to have information concerning the initial or total amount of foam that is formed under given conditions. For this reason the term "frothing volume" is introduced. Frothing volume is defined in an empirical but practical manner as the volume percentage of air in the oil system under stated given conditions. Frothing volume is quite different for different conditions, such as beating, circulating, bubbling, and so forth. The most striking case so far encountered is that an aqueous solution containing 30 percent of ethylene glycol produces no foam at all in an electric-mixer test but gives a copious head of foam on bubbling.

It has been pointed out, as a result of previous investigations in this laboratory (reference 2), that ease of foam formation, frothing volume, and stability of the foam that is formed are properties that do not necessarily have any direct relation. However, most writers on the subject have confined their attention solely to the measurement of stability. The limitations of this viewpoint have been referred to recently in a paper by Gray and Stone (reference 3) who emphasize that foam-stability measurements should be taken in conjunction with measurements of foam density. It is easily recognized that initial foam densities, as measured by Gray and Stone, also measure amounts of foam formed in cases where the same starting volumes of liquid are used under stated conditions in which none of the air escapes.

Under certain conditions of testing, the amount of foam formed (that is, the frothing volume) is not independent of the foam stability. It is a fundamental characteristic of Bikerman's dynamic foam meter (reference 4) and the dynamic foam meter of Hoffman and Peters (reference 5), for example, that an equilibrium between formation and collapse be established, whereby the volume of foam formed depends only on the rates of formation and collapse. With a previously determined rate of formation by injection of bubbles, the calculation of foam stability is actually based on the measurement of the volume of foam formed at the steady state.

Under many other conditions encountered both in practice as well as in laboratory tests, however, the amount of foam that can be formed is completely independent of determinations of foam stability. This is the case, for example, in the static methods of foam measurement. The amount of foam produced in static methods is a function of the method by which it is formed; however, the stabilities of the foams produced, even though produced by very different methods, have been shown to give values capable of a high degree of correlation (reference 6).

The stability of any foam is, therefore, largely a function of the type of liquid, while the amount of foam formed (the frothing volume) depends not only on its intrinsic stability or rate of breakage but also on the conditions imposed by the method used to produce it.

Data that are already available (table I) show that values of foam stability for a series of existing oils bear no relation to the amount of foam produced, the frothing volume, or the percentage of air contained in the system after beating the oil. Oils with abnormally great foam stability produce approximately the same amount of foam as oils of average stability.

The amount of foam formed could have been expressed by any one of a series of related values, such as initial foam density, percentage volume increase, or volume percentage of air contained (frothing volume), provided that only foam is under discussion. It has been found that the expression percentage by volume of air contained in the foam is convenient because its meaning can be readily visualized. The volume percentage of gas in the foam, the frothing volume, is obtained by subtracting the weight of 100 cubic centimeters of foam from the known weight of 100 cubic centimeters of the liquid and by dividing the difference by the density of the liquid.

It is indicated in table I that, for more complete information concerning the character of foams made from existing oils, both the foam stability and the amount of foam formed must be given. Since the latter value varies with the method employed to produce the foam, it is desirable to duplicate conditions or to have conditions analogous to the practical problem when specifying the laboratory test.

In the practical case the significance of total foam volume may be even more pertinent to the problem of foaming in aircraft engines than the stability of the foam itself. The formation of a large volume of foam, even if relatively unstable, causes such an increase in total volume that the mechanical system may not be sufficiently large to contain it; the result is a loss of lubricant through the breathers in the crankcase, as has been frequently reported by pilots and observers. On the other hand, the formation of a small total volume of foam, even if the foam is relatively stable, need not be cause for undue concern.

Effect of Antifoaming Agents

An antifoaming agent can modify either or both of the two charac-
teristics of the foam, frothing volume and stability. Agents have been
tested that have no effect on the amount of foam under certain conditions
while considerably reducing its stability (for example, the benzene
eluates described in table III of reference 7). Other agents may reduce
the amount of foam to a very low value while leaving the stability of the
residual foam unchanged or even enhanced. This distinction in the action
of antifoaming agents (the same is also true of foaming agents but the
action is in an opposite direction) has not been previously pointed out.
In order to measure the dual action of chemical agents, it has been
necessary to develop parallel tests, one of them for percentage of air
contained in the foam, as reported in detail in reference 1, the other
for foam stability, reported in reference 8.

In the tables in reference 1, values are given for frothing volume,
expressed as percentage of air contained in the oil and froth, for a
series of concentrations of glycerol - Aerosol-OT mixtures in oil beaten
in an electric kitchen mixer and likewise for different concentrations
of Gulf Agent. The percentage of air contained in the oil can be reduced
to a very low value by the use of certain concentrations of these agents,
without any reference to the ultimate stability of the small volume of
foam that is formed.

Experiments performed by the staff of the Shell Development Company
(Emeryville, California) have been reported in which the presence of
foam-inhibiting agents has resulted in a greater tendency of the oil to
retain very small amounts of air, entrained as a fine emulsion. The
gaseous droplets of this emulsion rise to the surface of the oil much
more slowly than corresponding droplets in untreated oils. The formation
of this "turbid oil" is directly due to the presence of the antifoaming
agent, such as Gulf Agent or the glycerol - Aerosol-OT mixture, and is
not found in pure oils. When the electric-kitchen-mixer test method is
used, this turbidity corresponds to less than 1 percent of entrained air.
Only engine tests can determine whether the formation of turbid oil is
deleterious to performance in actual flight.

Foam Stability and Its Characterizing Factors

The question of foam stability, as distinct from amount of foam,
has received considerable attention. A multiplicity of methods is in
use for determining the foaming of liquids, aqueous and nonaqueous.
In general, they were developed to provide an answer to specific problems
encountered in industrial practice and they have not been completely
correlated or analyzed.

The present report is an attempt to show how far the stability
of foams may be determined, independent of the particular method of
measurement. The theory of foam measurement is analyzed, and the factors
which operate to make one foam differ from another are estimated.

It will be shown that to a very great extent all the methods of
foam measurement yield similar information about the factors involved.
In a few cases the characteristics of the foam may depend upon its mode
of formation. For example, in certain nonaqueous foams formed by re-
ducing the pressure, the froths initially formed are stable until they
are stretched too far by further evacuation, whereupon they collapse.
Certain foams in which the foaming agent produces a surface film of high
viscosity likewise need further study.

Foam-stability units.- Foams may differ greatly according to the
manner in which they are formed. They may be made very wet, as by
incomplete beating or by putting in insufficient gas, or they may be
dried by further input of gas, by stretching, or by drainage; they may
be studied at any of these stages. Alejnikoff (reference 6) introduced
the somewhat arbitrary distinction which designates as dynamic methods
those in which observations are made during formation of the foam and
as static methods those in which the foam is formed before observations
are begun.

In 1936 Bikerman (reference 4) proposed a unit of foaminess for wet
dynamic foams, and again in 1941 essentially the same unit was proposed
by Hoffmann and Peters (reference 5). This unit cannot have the general
significance ascribed to it by Bikerman, that is, the average lifetime
of a bubble in the foam; it does, however, represent the average time
that gas remains entrained in the foam. Generalizing the concept to
apply to all types of foam measurement, Ross (reference 9) proposed the
units L_l and L_g, which represent the average lifetimes (in min) of

liquid and gas in the foam, respectively:

$$L_l = 1/l_0 \int_0^{l_0} t \, dl \qquad \text{(reference 9, p. 266)} \qquad (1)$$

$$L_g = 1/g_0 \int_0^{g_0} t \, dg \qquad (2)[1]$$

where g and l refer to the volumes of gas and liquid at time t, the original volumes being g_0 and l_0. For example, if drainage of liquid were strictly linear with time, all the liquid would be gone at $2L_l$.

In the case of dynamic foams, L_g is measured by the methods described in references 4 and 5; for static foams, both L_l and L_g can be measured either by graphical or analytical methods. It is frequently desired, if possible, to express foam stability as a single number for the purpose of comparing members of a series of samples. A direct comparison of foam stabilities may be made by use of the concept L_f, which represents the average lifetime of the foam in minutes.

$$L_f = 1/f_0 \int_0^{f_0} t \, df = \frac{1}{f_0} \int_0^T f \, dt = \frac{1}{(l_0 + g_0)} \int_0^T l \, dt + \frac{1}{(l_0 + g_0)} \int_0^T g \, dt$$

$$(3)$$

where f is the total volume of foam $(f = l + g)$ at time t and T is the time for total collapse of the foam. This unit is related to L_l and L_g by the introduction of another concept, the relative foam density, defined as

$$d = \frac{l}{f} = \frac{l}{(l + g)} \qquad (4)$$

---

[1]It is frequently more convenient in practice to express these integrals in an equivalent form. Since the curves terminate on both axes, then $\int_0^{l_0} t \, dl = \int_0^T l \, dt$, where T is the time for total collapse of the foam.

Then L_f can be calculated from the equation

or
$$L_f = L_g + d_o \left(L_l - L_g \right)$$
$$\left(g_o + l_o \right) L_f = g_o L_g + l_o L_l$$
$$(5)$$

where d_o is the initial foam density. Equation (5) is readily derived from equations (3) and (4). The value of L_f is always intermediate between L_g and L_l.

The resolution of a single value of L_f into two values, L_l and L_g, provides more detailed information concerning the nature of the foam. The concurrent phenomena of drainage and film rupture occur during the existence of every foam. Some idea of their relative importance in the case of any foam is obtained by a comparison of the values L_l and L_g. If drainage is a more pronounced factor than film rupture, as is normally the case with a freshly formed and therefore wet foam, then liquid is removed from the foam at a faster rate than gas is liberated. Consequently L_g will be greater than L_l. If, on the other hand, film rupture or coalescence of bubbles at the exposed surface of the foam takes place before drainage of the underlying films has had time to take place, then the gas is liberated from the foam more rapidly than the liquid. This happens frequently in the presence of an antifoaming agent capable of destroying relatively thick films before they have time to drain. In this case L_g is smaller than L_l. It is therefore extremely informative in the case of any single foam to have values of both L_g and L_l.

Analysis of factors in characterizing foam stability.- It has proved a useful concept that many liquid films attenuate by the draining out of liquid to a critical thickness at which the films are no longer capable of stable existence. In cases where spontaneous film rupture takes place, it is difficult to find any other mechanism. An approximate theoretical derivation of L_l and L_g can be obtained by employing this idea. The application of Poiseuille's law to the drainage of liquid from between vertical immobile planes results in the following equation for the volume rate of drainage of liquid in the film:

$$-dl/dt = bG\delta^3\rho/12\eta$$
$$(6)$$

where

b   horizontal dimension (large compared to δ)

G   gravitational constant

l volume of liquid in film

δ thickness of film

ρ density of liquid

η viscosity of liquid

If the thinning remains of constant vertical and horizontal dimensions, a and b, during drainage

$$l = ab\delta \tag{7}$$

$$\frac{dl}{dt} = ab(d\delta/dt) \tag{8}$$

Substituting equations (7) and (8) in equation (6) yields

$$-\frac{dl}{dt} = \frac{Gl^3\rho}{\left(12\eta b^2 a^3\right)} \tag{9}$$

The idea of limiting dimensions of the liquid film is now introduced to terminate the existence of the film after a time T.

At time T the limiting volume of liquid in the film l_T is the lower limit for the integration that is made to obtain L_l for this film.

$$L_l = \frac{1}{l_o} \int_{l_T}^{l_o} t \; dl = \frac{1}{l_o} \int_{0}^{T} l \; dt = \frac{12\eta b^2 a^3}{\rho G l_o} \left(\frac{1}{l_T} - \frac{1}{l_o}\right)$$

when $l_T/l_o = \alpha$ and it is recalled that $l_o = ab\delta_o$, then

$$L_l = \frac{\left(\frac{12\eta a}{\rho G \delta_o^2}\right)(1 - \alpha)}{\alpha} \tag{11}$$

If the liquid film is part of an idealized foam, then its final collapse after time T will release the volume of gas enclosed. Therefore $L_g = T$. By integration of equation (4) to obtain the time for total collapse T,

$$L_g = \frac{6\eta a}{\rho G \delta_o^2} \left(\frac{1 - \alpha^2}{\alpha}\right) \tag{12}$$

$$\frac{L_l}{L_g} = \frac{2\alpha}{(1 + \alpha)} \tag{13}$$

Equations (12) and (13) can also be obtained by integration of equation (11) of reference 9.

Equations (11) and (12) of the present report, although highly idealized, are nevertheless of value in their indication of the influence of various factors on foam stability. The influences of gravity and density are immediately obvious even without the mathematical formulation. The influence of viscosity requires more extended mention.

Linear influence of viscosity on life of foam.- Speculations on the influence of viscosity on foam stability are frequent in the literature although the present authors, at the time of this investigation, were not aware of any extensive experimental results. Equations (11) and (12) predicate a linear relation between foam stability and viscosity, all other factors being constant.

In order to demonstrate experimentally the linear relation, the kinematic viscosity of lubricating and white oils was determined throughout a temperature range of 26° to 117° C by means of a Saybolt Universal Viscosimeter. These data were published in reference 10 and show that within each group of oils both L_l and L_g bear an approximate linear relation to the viscosity.

Further confirmation of the linear relation of viscosity and foaminess is found in an aqueous system. The data of Helm (reference 11) on the foam stability of beer at different temperatures have been recalculated by Ross and Clark (reference 12). The unit designated Σ in that paper is in this case equal to L_l. A comparison is made with the viscosity of water at corresponding temperatures in the following table. The ratio of L_l to η is constant within the limits of accuracy of the data.

EFFECT OF VISCOSITY ON AVERAGE LIFE OF LIQUID

IN FOAM L_l FOR PASTEURIZED BEER

Temperature ($^\circ$C)	L_l (min)	Viscosity of water at corresponding temperature (centipoise) (1)	L_l/η
10	4.1	1.31	3.1
15	3.6	1.145	3.1
20	3.35	1.01	3.3

[1]Data from reference 13.

Limiting foam density.- The concept of a limiting film thickness leads to a corresponding idea of a limiting foam density, the final density at which the last remaining films break and, hence, equal to the relative foam density at which the films become unstable. Values of limiting foam density are obtained by extrapolation of foam-density curves to zero amount of liquid in the foam and have been given for a series of oils in reference 10.

The influence of the factor α (equations (12) and (13)) is related closely to the limiting foam density of which it is a monotonic function. The relationship between α and d_T is in the real case more complex than the simple proportionality calculable from the definition of α in the idealized case of a single vertical film.

Values of d_T have been reported (reference 10, p. 56) as being independent of temperature and as being the same for both beating and bubbling methods. This is no less than is expected from equations (12) and (13) for any function of α. These results greatly enhance the probability of the existence of a limiting film thickness, upon which supposition the equations are based.

Influence of height of foam column and generalization of L_g.- Before investigating the influence of the factor α in equations (11) and (12), it will be advantageous to set up a slightly more sophisticated model for a foam. If the foam column is regarded as a series of vertical films of height A, then equation (12) can be applied to obtain the time required for the top film to rupture; if the initial film thickness is δ_0 and the limiting film thickness is δ_T,

$$t_1 = \left(\frac{6\eta A}{G\rho}\right)\left(\frac{1}{\delta_T{}^2} - \frac{1}{\delta_0{}^2}\right) \tag{14}$$

After the top film has broken and the liquid of which it was composed is deposited on the underlying film, the new film exposed will drain and rupture in time t_2; each successive film exposed thereafter will require the same time to rupture. An exaggerated collapse curve for such a foam is diagrammatically shown in figure 1. From equation (14) the expression for t_2 may be derived

$$t_2 = \frac{6\eta A}{G\rho\delta_T{}^2}\left(\frac{\beta^2 - 1}{\beta^2}\right) \tag{15}$$

where

$$\beta = \delta_T - \delta_2 \Big/ \delta_T \tag{16}$$

and δ_2 is the thickness of the penultimate film at the time of collapse of the top of ultimate film. The function β should have the value of 2 or greater. From the geometry of figure 1,

$$L_g = t_1 + \frac{1}{2}\left(T - t_1\right) = \frac{1}{2}\left(T + t_1\right) = t_1 + \frac{1}{2}\left(\frac{t_2}{A} h_0\right) \qquad (17)$$

where h_0 is the initial foam height and t_1 is the elapsed time before appreciable breakage of foam begins. Substituting equations (14) and (15) in equation (17) yields

$$L_g = \frac{6\eta A}{G\rho}\left(\frac{1}{\delta_T{}^2} - \frac{1}{\delta_0{}^2}\right) + \frac{3\eta h_0}{G\rho\delta_T{}^2}\left(\frac{\beta^2 - 1}{\beta^2}\right) \qquad (18)$$

If the effect of creaming is eliminated and $A \ll h_0$, the first term on the right-hand side of equation (18) is negligible. When the foam is produced in the bubbling type of foam meter, there is no period of creaming for the foams herein investigated. For a given liquid β is a constant; hence equation (18) may be written

$$L_g / \nu h_0 = K\theta \qquad (19)$$

where

ν kinematic viscosity (η/ρ)

K numerical constant

θ complex function of limiting foam density

A comparison of the values of $L_g/\nu h_0$ and $L_g/\nu h_0$ for Aeroshell 120 and Standard Aviation oil obtained by the bubbling method is given in table II. Data at different temperatures are included in this table. Since it has already been shown experimentally that d_T is independent of the temperature, an experimental test of equation (19) would be to obtain $L_g/\nu h_0$ also independent of temperature for any given substance. This is indeed shown to be the case in the last column of table II. Thus the average life of the gas in the foam L_g is proportional to the kinematic viscosity and to the height of the foam column. The proportionality constant is independent of temperature, the dimensions of the apparatus, and the amount of liquid charged.

For comparison, some values of L_g/ν are included in table II. These values are found to be approximately constant only for a given apparatus containing a fixed amount of oil (h_0 nearly unchanged).

Bubble size.- The constancy of $L_g/\nu h_0$ can be expected to be maintained only if the character of the foam does not radically change with temperature and if the bubble size is constant. Although equation (19) does not contain bubble size explicitly, it is usually a factor in the limiting foam density d_T. The criterion for constancy of $L_g/\nu h_0$ according to equation (19) is constancy of d_T. An illustration of the influence of the limiting relative foam density is provided by an experiment with Standard Aviation oil where d_T increased to 0.10 on very rapid bubbling at low temperature (as compared with 0.05 in most experiments) because coalescence on the sintered glass bubbler led to larger bubbles. In this case $L_g/\nu h_0$ was 1.0, instead of the mean value 2.0 in table II.

The effect of bubble size on the average life of the gas in the foam has been investigated by Hoffmann and Peters (reference 5) for their dynamic foams. Analysis of their data reveals that L_g was proportional to the -0.86 power of the bubble diameter.

Another influence of bubble size on foam stability is illustrated when stable bubbles are stretched by gradually reducing the pressure during evacuation; after a certain point they become unstable and rapidly break.

Dynamic foams.- The dynamic foam methods of Bikerman (reference 4) and Hoffmann and Peters (reference 5) rely on the existence of a dynamic equilibrium between rates of formation of the foam and its rate of collapse at the top. The unit of foaminess, designated Σ by Bikerman and τ by Hoffmann and Peters is given by the equation

$$\Sigma = h/u \qquad\qquad (20)$$

where h is the dynamic height of the foam and u is the linear velocity
of the gas in the foam.

Hoffmann and Peters observed the same wet foam both by dynamic and
static methods, by shutting off the gas supply after the dynamic foam
height had been observed and allowing the foam to collapse without further
disturbance. Extrapolation of the initial linear rate of collapse to the
time axis yielded an intercept numerically equal to Σ or τ. At equi-
librium the rate of collapse of the foam is equal to the rate of gas flow u;
hence the intercept on the time axis is h/u, which is equal to Σ by

equation (20). It may be noted that in this case L_g' is $\frac{1}{2}\Sigma$. The rela-
tion between static and dynamic methods and between Σ and L_g' is shown
in figure 2. The factor 1/2 arises because in the static measurement the
lifetime of the bubbles is considered to start when the gas is shut off,
although they have already been in existence at that instant for an average

time of $\frac{1}{2}\Sigma$.

In the dynamic method, if the rate of gas input is tripled, for example,
the value of h is also tripled, maintaining the same value of Σ and
of L_g. However, an application of equation (19), in the same way as was
done in the last column of table II, gives values of L_g/vh which are no
longer constant, since $L_g/h = u/2$. Some fundamental difference clearly
exists between the foams of table II, which are uniform and homogeneous,
and the wet foams derived from a dynamic bubbler such as used by Bikerman
and by Hoffmann and Peters. In the foams of table II, all the liquid is
turned into the foam and the height of the foam is independent of the rate
of gas flow, while, in the wet foams derived from a dynamic bubbler, special
precautions are taken to ensure that not all the liquid is converted into
the foam, so that the foam height is proportional to the rate of flow. The
foams treated in table II are therefore initially of uniform film thickness,
while those discussed by Hoffmann and Peters have a gradient of foam density
throughout the column at the start of the experiment. This gradient is
determined by the rate of gas flow. In equation (18) the foam—density
gradient, denoted by its function β (see equation (16)), while rightly
taken as constant for the foams of table II, cannot be so taken for the
nonuniform, non—homogeneous foams discussed by Hoffmann and Peters. In
the nonuniform foams, the foam—density gradient can be calculated by means
of equation (15), since $A/t_2 = u$ and L_g remains constant.

The relation between Σ and L has been tested experimentally.
Previous attempts to find an experimental relation between dynamic and
static methods have failed (reference 14) because no comparable units were
employed. The present analysis makes it clear that in the earlier work Σ
(dynamic) was compared with L_l (static) to which it does not neces-
sarily bear any correspondence. In the following table, values of L_g
(static) are compared with Σ (dynamic). The values of Σ were obtained
from a dynamic foam meter that has a capillary bubbler. As previously

pointed out, the absolute values of the two units cannot be expected to be the same since the foams are not the same, but it can be seen from the last column in the table that the ratio of the foam stability of the lubricating oil to that of the white oil is comparable in the two systems.

COMPARISON OF RESULTS OBTAINED BY

DYNAMIC AND STATIC METHODS

Liquid used	Value at 25° (cgs)	Ratio
ΣN		
White oil	6.3×10^{-2}	1.1
Aeroshell 120	5.8	
$L_g/N h_o$		
White oil	1.56×10^{-3}	1.0
Aeroshell 120	1.57	

Practical problem of foam measurement.- The foregoing theoretical analysis of factors in foam measurement reveals the causes of difficulty in the practical problem. Various investigators have experienced difficulty in obtaining reproducible results especially in the case of bubbling, both for static and dynamic methods. The degree of this difficulty is to some extent an inherent property of the particular foaming liquid, some systems exhibiting it to a greater degree than others. Conflicting statements in the published literature about the efficiency of the method can often be ascribed to this reason. When a foam is formed by bubbling at a high temperature, it is not always possible to secure a pure example of a dynamic equilibrium height. Frequently all the under-lying liquid becomes so suffused with air bubbles that it cannot definitely be stated whether it has been turned into foam. Furthermore, the foam may be expanded and channeled by further bubbling. The theoretical importance of this factor in influencing the value of L_g has already been noted; in dynamic foam measurements L_g/h cannot be constant, nor can any general meaning be attached to the value of L_g/h, even when obtained by a static method, if the foam is non-homogeneous (see section entitled "Dynamic foams"). In practice, care has not always been exercised to obtain a truly homogeneous foam nor to investigate the conditions that lead to the production of comparable foams from different liquids; consequently, experimental values of L_g/h may be found to vary when the conditions are either not standardized or not amenable to control.

Among the more outstanding causes of variance in the practical
measurement is lack of regulation of the rate of air flow. In experi-
ments with the bubbler-type foam meter, it has been found that there are
upper and lower limits to the permissible rates of air flow (15
and 75 cm^3/min, respectively); these limits cannot be extended in either
direction without serious alteration in the character of the foam or in
the value for its stability. Both slower and faster rates of air flow
result in decreased volumes of foam, the faster rate because of less air
and the slower rate because a turbulent formation permits large quanti-
ties of air to escape through the liquid without the formation of films.
A large personal error is also possible in many cases since the measure-
ment of a decreasing volume of foam demands the exercise of a discrimi-
nating judgment to estimate the average position of an interface that may
be considerably depressed or elevated at the center of the tube. Another
source of variance is common, especially in very stable foams, when the
length of time required for the measurement causes non-homogeneity to
occur even in an initially homogeneous foam.

Despite the foregoing difficulties, it has been proved that, with
the proper conditions carefully specified, the bubbling method (static)
when used by a competent operator is capable of yielding comparable and
reproducible results (within ± 3 percent).

A clear-cut static method is more readily obtained by beating than
by bubbling. By the beating method the ambiguity about the character of
the liquid underneath the foam is removed, all the liquid is indubitably
in the foam, the bubble size is uniform, the liquid films are uniform both
in composition and in average thickness, and no air channels occur. For
these reasons, the measurement of foam stability when an electric kitchen
mixer is used (modified Towne test described in reference 10) yields
results of considerably greater reproducibility, which are obtained with
less difficulty. A reference to figures 1 and 2 of reference 8 will
reveal the usual character of the decay curves, both for gas and for
liquid in the foam, when the foam is produced by an electric kitchen mixer.
In figure 2 the time required for creaming before films commence to rupture
at the top t_B is absent in foams produced by the bubbling method. At the
outset, the foam is homogeneous but as creaming continues this homogeneity
is lost, until at the termination of the period t_B the foam lacks complete
homogeneity. It now resembles a foam produced by bubbling (without mixing).
The necessity, both in beating and bubbling, for stirring up the foam to
achieve homogeneity is herein made clear. When the portion of the curve
that follows t_B is compared with its counterpart in the bubbling foam
method, the two methods are found to yield results of the same order of
magnitude for L_g/h. Foams obtained by beating are comparable, necessary
changes having been made, with those produced by bubbling.

The definition of L_g makes it theoretically independent of the
amount of foam used. This has been treated experimentally for this beating

method (by W. W. Woods) by using different amounts of the same foam, all at the same initial height but maintained in tubes of different cross-sectional area. It was found that L_g (hence L_g/h) is experimentally independent of the cross-sectional area and is therefore independent of the initial foam volume. The linear rate of liquid drainage from the oil foams is also independent of the initial amount of foam, confirming the theoretical requirement that L_l as well as L_g should be independent of the initial foam volume.

A method of escaping the onerous standardization necessary for obtaining reproducible values of L_g/h by the bubbling method is to abandon completely the measurement of stability in favor of some empirical but more readily obtained function. This is a reversion to earlier methods for the sake of a rapid estimation of foaming ability. The linear rate of foam formation for a constant rate of air input has been reported as a practical method by Ostwald and Mischke (references 15 to 17) and has been criticized on theoretical grounds by Ross (reference 18) as often lacking significance. As a rapid practical method, however, it does not require elaborate precautions and yields results whose most extreme variation has never been found to be greater than ± 10 percent. Greater accuracy could undoubtedly be obtained by exercising greater care, but in such a case the sole practical advantage of the method would be annulled; the use of one of the methods of greater theoretical significance would be again indicated.

The foam produced by aeration and evacuation is even less amenable to control than that produced by bubbling. The non-homogeneity of liquid films due to stretching on evacuation may result in their rupture, so that too great a reduction of pressure can cause a complete collapse of the foam formed at the initial stage of the evacuation. With care a range of diminished pressures can be ascertained, within which range the resulting foams maintain a reproducible character; but in this case also the inability to ensure complete homogeneity of the foam lessens the usefulness of the method.

None of these arguments concerning the practical difficulties of obtaining reproducible results by certain methods affects the theoretical significance of the units L_l and L_g. Foam stability is completely independent of the method of foam production and the reproducibility of results. Every foam has a stability which is defined quantitatively by L_l and L_g. The question of whether a certain liquid can be made to produce foams of the same stability by different methods has been answered in the affirmative by the painstaking use of these units. The practical problem of devising a rapid method of foam comparison may nevertheless be better solved by the use of some arbitrary test that does not necessarily employ the sophisticated concepts of L_l and L_g.

It is to be admitted that many of the data reported for the comparative foam stabilities of existing oils (reference 10, table on p. 50) can be considered as yielding only approximate evaluations. These data are reprinted in the present report because of the valid illustration they afford of the general trend, more especially the complete lack of correlation between values of stability and foaming volume. It is to be further noted that values of the total life of the foam must be taken as at least twice the value recorded in this table for L_g.

CONCLUSIONS

From an investigation of the properties of foam, the following conclusions were drawn:

1. The stability of foam is intrinsically a property of the liquid system.

2. The amount of foam depends not only on the stability but on the mechanism of its production.

Stanford University
    Stanford University, Calif., January 8, 1945

REFERENCES

1. McBain, J. W., and Ross, Sydney: Quantitative Study of Variations in
     Concentration of Glycerol and Aerosol OT on Foaming Volume of Oil
     at Room Temperature. NACA TN No. 1841, 1949.

2. Ross, Sydney, and McBain, J. W.: Inhibition of Foaming in Solvents
     Containing Known Foamers. Ind. and Eng. Chem. (Ind. Ed.), vol. 36,
     no. 6, June 1944, pp. 570-573.

3. Gray, Philip P., and Stone, Irwin: The Measurement and Study of Beer
     Foam. Wallerstein Lab. Communications on the Sci. and Practice of
     Brewing, vol. III, no. 10, Dec. 1940, pp. 159-171.

4. Bikerman, J. J.: The Unit of Foaminess. Trans. Faraday Soc.,
     vol. XXXIV, pt. 5, May 1938, pp. 634-638.

5. Hoffmann, K., and Peters, H.: A New Method for the Measurement of
     Foaminess. Kolloid-Zeitschr., vol. 97, 1941, p. 161.

6. Alejnikoff, N. A.: Dispergierung der Luft in Wässerigen Lösungen.
     Kolloid-Beihefte, Bd. XXXVI, Heft 1-3, June 20, 1932, pp. 82-122.

7. McBain, J. W., Robinson, J. V., Woods, W. W., and Abrams, I. M.:
     Attempts to Defoam Existing Oils by Processing. NACA TN No. 1845, 1949.

8. McBain, J. W., and Woods, W. W.: Effect of Various Compounds in Use
     with Airplane Engines on Foaming of Aircraft Lubricating Oil.
     NACA TN No. 1843, 1949.

9. Ross, Sydney: Foam and Emulsion Stabilities. Jour. Phys. Chem.,
     vol. 47, no. 3, March 1943, pp. 266-277.

10. McBain, J. W., Ross, S., Brady, A. P., Robinson, J. V., Abrams, I. M.,
     Thorburn, R. C., and Lindquist, C. G.: Foaming of Aircraft-Engine
     Oils as a Problem in Colloid Chemistry - I. NACA ARR No. 4I05, 1944.
     (See also Brady, A. P., and Ross, S., Jour. Am. Chem. Soc., vol. 66,
     1944, p. 1348.)

11. Helm, E.: The Stability of Beer Foam. Woschenschrift für Brauerei,
     vol. 50, 1933, p. 241.

12. Ross, Sydney, and Clark, G. L.: On the Measurement of Foam Stability
     with Special Reference to Beer. Wallerstein Lab. Communications
     on the Sci. and Practice of Brewing, no. 6, Aug. 1939, pp. 46-54.

13. Anon.: International Critical Tables. Vol. V. McGraw-Hill Book Co.,
     Inc., 1929, p. 10.

14. Clark, George L., and Ross, Sydney: Measurement of Static and Dynamic
    Foams in Characteristic Units. Ind. and Eng. Chem. (Ind. Ed.),
    vol. 32, no. 12, Dec. 1940, pp. 1594-1598.

15. Ostwald, Wo., and Mischke, W.: Investigation of Foaming with Partic-
    ular Reference to Applied Chemistry. I. Kolloid-Zeitschr.,
    vol. 90, 1940, p. 17.

16. Mischke, W.: Investigation of Foaming with Particular Reference to
    Applied Chemistry. II. Kolloid-Zeitschr., vol. 90, 1940, p. 77.

17. Ostwald, Wo., and Mischke, W.: Investigation of Foaming with Partic-
    ular Reference to Applied Chemistry. III. Kolloid-Zeitschr.,
    vol. 90, 1940, p. 205.

18. Ross, Sydney: Current Methods of Measuring Foam. Ind. and Eng.
    Chem. (Anal. Ed.), vol. 15, no. 5, May 15, 1943, pp. 329-334.

TABLE I.- COMPARISON OF FOAM TESTS

No. (a)	Frothing volume[b] at 25° ± 1° C (percent)	Liquid	Average life of gas in foam L_g (min)					
			Room temperature			100° C		
			Method[c]					
			1c	2b	3b	2b	3a	3b
1	0.8	Ethylene glycol						
2	5.7	Glycerol						
3	14.7	Castor oil	3.6		5.6			
4	6.1	McKesson's Hydrol						
5	9.9	Squibbs Mineral oil	---	4.6	---	---	---	----
6	41.9	Union SAE 60	18.5	.14	---	0.38	1.8	1.1
7	52.6	Texaco 120	22.3	5.3	---	.64	---	----
8	49.7	Texaco 120 (Moffet Field)	27.3	1.9	1.3	.58	2.2	1.0
9	28.7	Syntholube	31.2	5.1				
10	49.3	NACA Reference Oil 120	51.5	7.8	25	.49	1.7	1.0
11	52.6	McClellan Field 120	91.4	8.2	---	.78	---	----
12	52.0	McClellan Field 120 (used)	65.5	7.8	---	.62	---	----
13	65.5	Barton Grimsley	79.1	9.0	---	.57	---	----
14	51.6	Gulf Airline 120	71.8	9.5	33	.70	---	1.1
15	47.7	Texaco 120 (used 24 hr)	61.3	9.7	---	.62	---	2.2
16	51.3	Aeroshell 120	79.2	10.2	32	.54	2.0	1.15
17	55.9	Standard Aviation 120	103.6	11.7	55	.80	1.4	1.8
18	54.4	Standard Synthetic	231	14.7			1.6	
19	45.3	RPM Aviation 120	4920	40.2	---	6.6	---	>>10
20	50.6	Shell Formula II	2056	60.2	---	---	---	>>10

[a]Values of L_g for liquids 5 to 8, 10 to 17, 19, and 20 were taken from reference 10.

[b]Frothing volume is volume percentage of air contained after beating. (See reference 1 under METHODS.)

[c]Method 1c, Towne test
       2b, aeration and evacuation
       3a, porous stone bubbler
       3b, sintered glass bubbler

[d]These two are the only oils in the list definitely known to contain additives. They were tested without any defoamer such as is now often added by manufacturers.

TABLE II.- DATA FOR COMPARISON OF AEROSHELL 120

AND STANDARD AVIATION OIL

| Test method	Temperature (°C)	ν (centistoke)	L_g (min)	h_o (cm)	L_g/ν	$L_g/\sqrt{h_o}$
Aeroshell 120						
Bubbling (18-mm tube)	56	145	7.2	31.3	49.5×10^{-3}	1.59×10^{-3}
Bubbling (18-mm tube)	78	55	3.0	32.8	54.5	1.64
Bubbling (18-mm tube)	100	26	1.2	30.0	46	1.54
Bubbling (18-mm tube)	100	26	1.75	45		1.50
Bubbling (28-mm tube)	[a]100	26	2.0	48		1.57
Standard Aviation Oil						
Bubbling (18-mm tube)	46	227	17.5	39	77	1.98
Bubbling (18-mm tube)	56	145	10.5	39.5	72.5	1.93
Bubbling (18-mm tube)	64.5	98	6.5	33	66	2.00
Bubbling (18-mm tube)	78	55	3.4	30	62	2.05
Bubbling (18-mm tube)	100	26	1.8	33.5	69	2.03
Bubbling (28-mm tube)	100	26	2.0	38		2.02
Bubbling (18-mm tube)	117	15.3	1.1	31.1		2.02

[a]A larger charge of oil in meter.
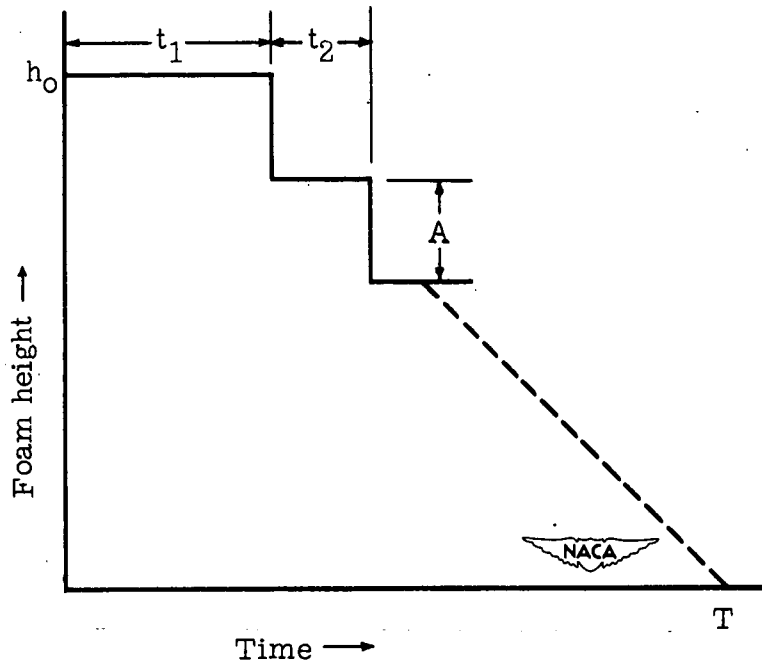
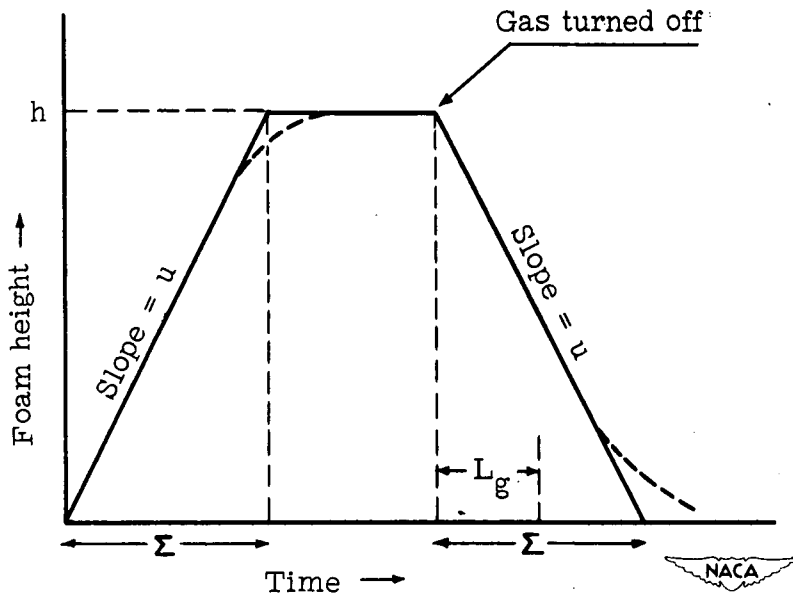Figure 1.- Exaggerated collapse curve for foam.

Figure 2.- Relation between static and dynamic methods of foam measurement.