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AERONAUTICAL LUBRICATING OILS

By W. W. Woods and J. V. Robinson

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SUMMARY

Comparative data are presented on the volume of foam and the stability of foams of aeronautical lubricating oils (new and used) produced at 100° C (212° F) by the air-bubbling method. All of the data were obtained using the same foam meter, by a standard technique and at various rates of air flow. The percentage volume increase, when foams are produced by the beating method at 25° C, has been included for comparison, as obtained from the previously reported frothing volumes.

A function $V = kA(1 - e^{-at})$ is proposed to relate volume increase during bubbling V , rate of air flow A , and continued bubbling time t . The constants k and a are discussed and calculated for several oils from averaged experimental data. The constant k appears to be an inverse function of the bubble size and a is related to the rate at which the steady state of foam volume is reached.

The foam-stability function L_g/h_0 (where L_g is the average lifetime of the gas in the foam and h_0 is the increase in height of the foaming system due to the inclusion of air at the instant bubbling ceases) has been investigated using carefully selected experimental data and is shown to be nearly linearly related to the rate of air flow.

It is shown that aeronautical oils froth more than do medicinal paraffin oils, as would be expected from their higher viscosities. The volume of froth produced by beating is 10 times greater and the lifetime of the gas in the foam, even divided by the volume of foam, is definitely greater. Bubbling does not exhibit such a wide difference as beating, but, even so, the volumes of foam produced by aeronautical oils are many times greater than those obtained from medicinal paraffin oils.

The aeronautical oils definitely differ from each other, and even different batches from the same company may be markedly different. The percent volume increase on beating ranges from 72 to 127, and on bubbling shows as great a range; beating and bubbling do not give parallel values, nor does either follow the same order as the stability of the foam produced.

Reproducibility of the bubbling method using porous stone and fritted-glass bubblers is discussed, and improvements are suggested.

INTRODUCTION

Oil-foaming troubles are greatly aggravated by flying at altitude; the effects of these troubles are well known, but the control of them is incomplete. Study of these problems includes the study of anti-foaming agents and the study of refinement of oils so as to make them nonfoaming. As part of the general problem, the present paper compares data on the foaming characteristics of various new and used aeronautical lubricating oils and some medicinal paraffin oils.

This work was conducted at Stanford University under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

A	rate of air input to bubbler at 95° C, cubic centimeters per minute
a	constant for a given oil and a given rate of air input
e	base of natural logarithms
h	increase in height of foaming system due to inclusion of air (i.e., height at any time t of top of foam above original oil level), centimeters; note that this is not the same h used by Brady and Ross (reference 1)
h_0	value of h at the instant bubbling ceases (i.e., in all these tests, 8 min. after bubbling commences)
k	constant for a given oil and given rate of air input
L_g	average lifetime of gas in foam, seconds
t	time while air is bubbled into foaming system during formation of foam, minutes
V	increase in volume of foaming system due to inclusion of air, cubic centimeters; in a uniform tube this is equal to h times horizontal cross section of foam

$\frac{100V}{O}$ percentage volume increase, O being volume of oil used

$\frac{L_g}{h_o}$ foam stability

APPARATUS AND EXPERIMENTAL METHOD

The apparatus used was the foam meter diagrammed in figure 1, consisting essentially of a jacketed Pyrex glass tube about 30 inches long and having an internal cross section of 7.84 square centimeters. Metered air was bubbled into 50-cubic-centimeter oil samples at 100° C through a porous stone sphere (Cenco "gas diffusing stone") connected to a delivery tube having an external cross section of 0.28 square centimeter. In one series of tests a Pyrex vertical-type, fritted-glass, gas-dispersion tube of 20-millimeter disk diameter and "coarse" porosity was substituted for the Cenco stone sphere. The rate of air flow was computed from the pressure drop across a calibrated capillary tube in the air supply line.

The experimental procedure consisted of noting the rise in the level of the top of the foam at definite time intervals up to 8 minutes after bubbling commenced. At the end of 8 minutes the air was shut off and the uppermost level of the collapsing foam noted at definite time intervals, usually 15 seconds, until no foam remained. Preliminary experiments showed that the foam height was within 10 percent of its steady-state value after 8 minutes.

RESULTS

The data from the measurements upon oil foams are summarized in tables I to III.

The volume increase was related to the air input and duration of bubbling by the function $V = kA(1 - e^{-at})$. The parameters k and a are dependent upon the rate of air input A .

The dependence of foam stability upon rate of air input was likewise studied.

The findings from these investigations are reported as follows: Constant k against air input (fig. 2), constant a against air input (fig. 3), and foam stability L_g/h_o against air input (fig. 4).

Reproducibility of Foam Tests

Tables I and II were made up considering all available experimental data. Where several determinations have been made, the extreme range of values is reported. It should be noted that there is an over-all variation of about 75 percent in the foam-stability measurements and of about 50 percent in the foam-volume measurements. The reproducibility of these measurements appears to be governed primarily by the condition of the porous stone bubbler. Any reduction in the effective number of pores (resulting from clogging with oil, additives, residues, etc.) tends to produce larger bubbles which are less stable. Ordinary cleaning methods, such as washing with petroleum ether, are often not effective, and drastic treatment such as burning out the contamination in an air stream occasionally results in small cracks and may leave a residual ash. The construction of the Cenco bubbler (a metal stem cemented into the porous stone) prohibits the use of acid oxidizing agents in cleaning. Consequently, the condition of the stone bubbler is indeterminate except by empirical comparisons on a reference oil, and not controllable except by selection of bubblers.

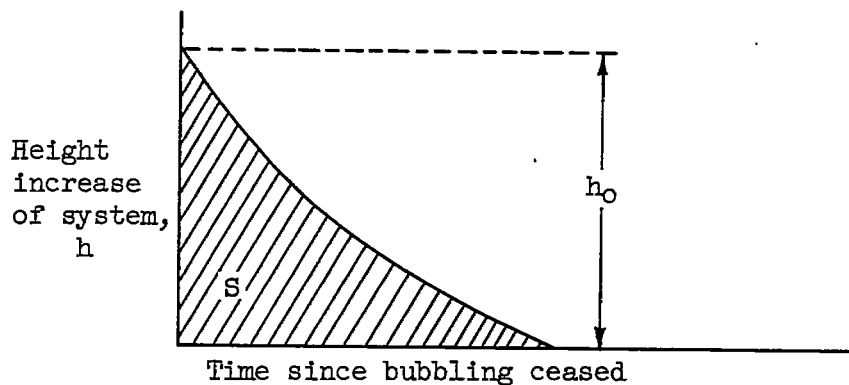
A Pyrex, fritted-glass, gas-dispersion tube was substituted for the Cenco porous stone sphere in a series of five successive tests on Aeroshell 120 designed to compare the reproducibility of the two bubbler types. The resulting experimental data were converted into percentage volume increase and values of L_g/h_0 by the calculations explained below, and the results presented in table III for comparison with similar data obtained using the Cenco bubbler.

Except for the difficulty of cleaning the stone bubbler, the experimental factors affecting reproducibility are readily controlled. The data in table III indicate that, with a fixed bubbler condition, the variation in either percentage volume increase or foam stability is less than 10 percent. The much greater ease of cleaning the fritted-glass disk makes its use preferable to that of the stone sphere. Partial clogging of the pores of the stone sphere may cause a change of nearly 100 percent in foam stability.

Treatment of Data

The foam height used to calculate the values of percentage volume increase listed in tables I, II, and III was measured 8 minutes after bubbling commenced. The volume increase at any given time is equal to the height increase (in cm) multiplied by the annular cross section (in sq cm) of the tube occupied by foam. The percentage volume increase $\frac{100V}{O}$ is 100 times the ratio of volume increase to the original oil volume.

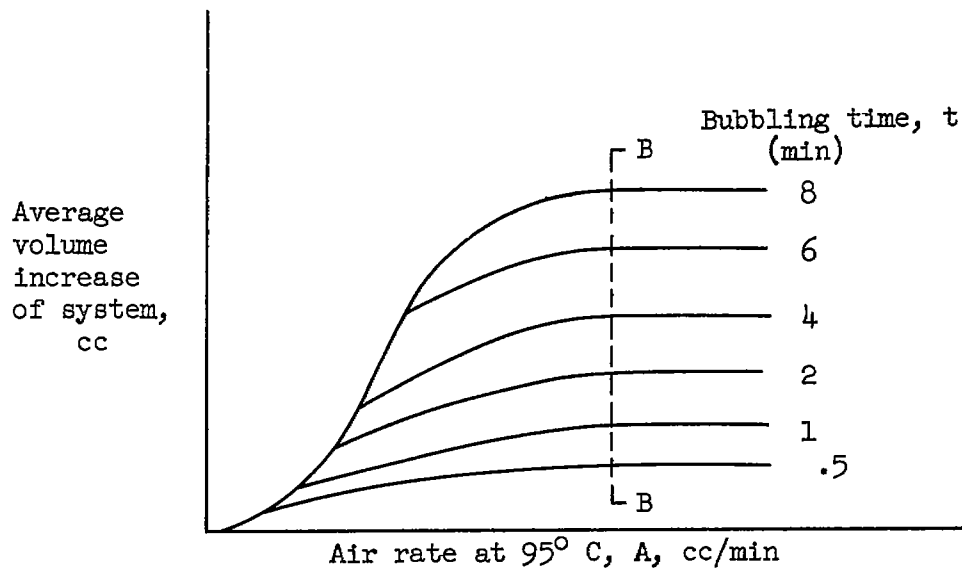
The ratio L_g/h_o , as reported in tables I, II, and III, is a derived unit representing foam stability, and is known (from unreported data) to be independent of the amount of exposed foam surface. The average lifetime of the foam L_g was determined as shown in the following diagram, with $L_g = \frac{S}{h_o}$ and $\frac{L_g}{h_o} = \frac{S}{h_o^2}$.



The area S was calculated by means of Simpson's rule from the experimental foam heights measured during collapse. To simplify the calculation, the foam heights were measured at 15-second intervals; hence the equation for this area becomes

$$S = 15 \left(\frac{h_1 + h_2}{2} + \frac{h_2 + h_3}{2} + \frac{h_3 + h_4}{2} + \dots \right)$$

An attempt mathematically to relate foam with rate and duration of air flow was subsequently made, using data obtained with the porous stone bubbler. Because of the aforementioned lack of experimental reproducibility, it was found necessary to average the data (to obtain "average volume increase") from a large number of foam tests on each oil (in the case of Aeroshell 120, 61 foam tests were used). These data were first plotted as shown in the following diagram.



Sections such as B-B (see diagram) indicate the volume increase at different bubbling times for any rate of air input. It was found that, for any such section as B-B, rate of air input, volume increase, and duration of bubbling could be related by the function $V = kA(1 - e^{-at})$.

The constants k and a were computed for each rate of air input (i.e., a particular section B-B) by successive trial and approximation, assuming values of a at 0.05 intervals and then calculating the value of k for each bubbling time indicated on the preceding diagram. When a was correctly assumed, k remained constant for all values of t . The degree of constancy was determined by the average percentage deviation from the mean k . For the selected values of a , the corresponding values of k did not vary more than 10 percent. Data on three Navy 1120 specification oils and one synthetic oil were treated in this manner. The variation in the constants k and a with air input for these oils treated in this manner are shown in figures 2 and 3, respectively.

Table I indicates that in most cases foam stability (expressed as L_g/L_0) decreases with increasing rates of air input during foam formation. As the over-all experimental reproducibility for L_g/h_0 was poorer than for foam volume, and as less data were available, it was considered impractical to average values of L_g/h_0 as was done in the case of values of percentage volume increase. Therefore, only those foam data were selected for which the foam volume was within

12 percent of the average (8-minute) foam value for that air flow. Using this procedure, and defining "nearly average" volume increases as those within 12 percent of the actual average, selected measurements of L_g/h_0 on Aeroshell 120 were obtained. These data are plotted in figure 4, which shows that the variation of L_g/h_0 with rate of air flow is nearly linear.

DISCUSSION

In considering the function $V = kA(1 - e^{-at})$, it should be noted that as t tends toward infinity $kA(1 - e^{-at})$ becomes kA ; hence k is the determining factor in equilibrium foam height. The exponent a , on the other hand, is related to the time required to reach equilibrium.

Previous experience in this laboratory has indicated that, for a given oil, steady-state foam volume is a function of bubble size as well as of rate of air input. At a certain rate of air input, small bubbles will form a definite foam, but larger bubbles will not. The factor k , therefore, appears to be a function of bubble size. Small bubbles form more foam than slightly larger bubbles; hence, as bubble size decreases, k increases. The Cenco gas diffusing stones used in this study do not produce bubbles of the same diameter for all rates of air flow. At low rates there is a tendency for all of the air to pass through the larger pores, and at high rates considerable bubble coalescence on or near the surface of the stone is encountered. Consequently, at either high or low air flows, there is a higher proportion of large bubbles than at intermediate air flow. This explains the maximum in the k -curve of figure 2. Furthermore, at high rates of air flow, moderate turbulence occurs in the foam column, a condition favorable to bubble coalescence into larger and less stable bubbles.

Figure 2 indicates that the arrangement of oils in the order of their foaming volume may be altered by changes in the rate of air flow. The best reproducibility is given by the lowest air flow that produces a satisfactory head of foam, since turbulence in the column is avoided. An air flow of approximately 100 cubic centimeters per minute produces a maximum of foam with little turbulence (compare fig. 2).

It is apparent that the bubbling method at 100° C using the Cenco bubbler must be rigorously controlled to achieve reproducibility. Experience in this laboratory has indicated that even new stones vary markedly when compared on a reference oil. Table III indicates that Pyrex fritted-glass bubblers may be substituted for the porous-stone

type and yield nearly the same amount of foam with better reproducibility. The Pyrex bubbler can be easily cleaned with acid oxidizing agents after the customary solvent treatment, whereas proper cleaning of the Cenco bubbler is extremely difficult.

The data of table I indicate some interesting facts. The nonhydrocarbon liquids - ethylene glycol, glycerol, and castor oil - foam much less than the lubricating oils, even making allowances for the viscosity differences. However, only the ethylene glycol does not foam; the axiom "pure liquids do not foam" (meaning single chemical species) demands the assumption that the glycerol and castor oil were not pure liquids, which seems very likely for the glycerol and certain for castor oil.

Of the three synthetic oils, two of which are hydrocarbon in nature, two foam less than the 120-grade military aeronautical lubricating oils (see table I-Concluded) and one (a hydrocarbon) foams more. The nonhydrocarbon oil was of much lower viscosity, so the lesser foaming of it is partially accounted for on that basis.

The medicinal oils foam less than the lubricating oils (see table I-Concluded), but this is accounted for by the difference in viscosities, as has been previously pointed out (fig. 5, p. 1352, reference 1).

Table I-Concluded indicates that the foaming characteristics of the aeronautical lubricating oils used by the armed services vary within extremes that have approximately a twofold range, both as to foam stability and foam volume.

Table II shows that less froth is produced from used oils, either by beating or by bubbling; but the stability of the froth so produced is in every case greater. The volumes of froth produced from used oils differ more than those from oils before use, but the foam stabilities become similarly high.

CONCLUDING REMARKS

Data on the comparative foaming characteristics of lubricating oils, both new and after use, have been redetermined and calculated by a standard procedure. They are found to differ significantly from each other. This comparison is believed to be much more reliable than previously made ones.

For the most reliable foam measurements on oils, the beating method at room temperature and the bubbling method at 100° C using

the fritted-glass-disk bubbler, as specified, are recommended. It is believed that much of the variation in the results reported for the bubbling method at 100° C would be eliminated by redetermination using the fritted-glass disk in place of the porous stone sphere actually used.

An empirical expression has been developed by which the rate of foam rise may be predicted from a known rate of aeration, by making use of two parameters characteristic of the oil. It is believed that this expression might be adapted to engineering calculations on foaming volume.

Stanford University

Stanford University, Calif., June 25, 1945

REFERENCE

1. Brady, A. P., and Ross, Sydney: The Measurement of Foam Stability. Jour. Am. Chem. Soc., vol. 66, no. 8, Aug. 1944, pp. 1348-1356.

TABLE I.- COMPARATIVE FOAMING CHARACTERISTICS OF UNUSED AERONAUTICAL LUBRICATING OILS, MEDICINAL OILS, AND A FEW OTHER LIQUIDS

Sample	Volume increase (percent)				Foam stability, L_g/h_0 ; air-bubbling method at 100° C for air flow of -		
	Air-bubbling method at 100° C for air flow of -			Beating method at 25° C	Foam stability, L_g/h_0 ; air-bubbling method at 100° C for air flow of -		
	100 cc/min	150 cc/min	200 cc/min		100 cc/min	150 cc/min	200 cc/min
Ethylene glycol	0	0	0	0.7	-----	-----	-----
FPO-265 Synthetic ^a	30	80	290	7.0	6.6	2.6	1.5
McKesson's Hydrol	60	100	200	6.0	1.9	1.9	1.3
RPM Aviation 120 (9/15/44) ^b	180	136	130	3.0	7.2	20.9	16.4
Squibb mineral oil	100	230	340	11.0	2.3	1.4	1.3
Glycerol	220	340	270	6.0	3.0	1.9	1.3
Castor oil	220	330	370	17.0	1.7	1.3	1.4
Shell Syntholube	340	400	500	23.0	1.8	1.5	1.4
RPM Aviation 120 (1942)	490	400	390	83.0	(b)	(b)	(b)
Texaco 120 (1944)	400	430	460	72.0	3.4	3.2	2.8
Aeroshell 120	370-590	420-650	420-800	105.0	2.6-4.0	2.3-4.4	1.8-3.7
Moffett Field (1943 Texaco 120)	400-580	470-730	470-800	98.0	2.5-3.1	2.1-3.0	1.7-3.2*
Barton Grimsley 60	420	500	600	190.0	2.8	2.3	1.9
Gulf Airline 120	450	580-620	620-850	106.0	3.3	2.6	2.2
Texaco 120 (1942)	450-600	480-740	540-840	111.0	2.1-3.6	2.0-3.1	2.1-2.9
McClellan Field (1942)	490	550	570	111.0	3.2	3.0	2.9
Moffett Field (1944 Gilmore 120)	500	620	740	92.0	2.5	2.4	2.1
RPM Aviation 120 (6/28/44) ^b	640	610	590	104.0	(b)	(b)	(b)
NACA Reference Oil 120 (Texaco 120)	630-670	750-780	790-850	98.0	2.8-3.2	2.3-2.7	2.2-2.4
Shell Formula II ^b	600	810	860	102.0	1.2	1.0	.9
Standard Aviation 120	580-700	650-970	740-1020	127.0	2.4-3.3	2.6-2.9	2.2-3.4
Standard Synthetic 120	810	850	750	119.0	2.0	1.7	1.4

^aThis oil is not comparable with the other synthetics, having abnormally low viscosity.

^bThese three are the only oils in the list known to contain additives. RPM Aviation (1942) and Shell Formula II were tested without any defoamer such as is now often added by manufacturers as, for example, in RPM Aviation (9/15/44). RPM Aviation 120 (1942) and (6/28/44) drain rapidly, leaving dry foams of great stability.



TABLE I.- COMPARATIVE FOAMING CHARACTERISTICS OF UNUSED AERONAUTICAL OILS - Concluded

Sample	Volume increase (percent)				Foam stability, L_g/h_o ; air-bubbling method at 100° C for air flow of -		
	Air-bubbling method at 100° C for air flow of -			Beating method at 25° C	100 cc/min	150 cc/min	200 cc/min
	100 cc/min	150 cc/min	200 cc/min				
McKesson's Hydrol	60	100	200	6	1.9	1.9	1.3
Squibb mineral oil	100	230	340	11	2.3	1.4	1.3
Aeroshell 120	370-590	420-650	420-800	105	2.6-4.0	2.3-4.0	1.8-3.7
Gulf Airline 120	450	580-620	620-850	106	3.3	2.6	2.2
McClellan Field (1942)	490	550	570	111	3.2	3.0	2.9
Gilmore 120 (Moffett Field, 1944)	500	620	740	92	2.5	2.4	2.1
Standard Aviation 120	580-700	650-970	740-1020	127	2.4-3.3	2.6-2.9	2.2-3.4
Texaco 120 (Moffett Field, 1943)	400-580	470-730	470-800	98	2.5-3.1	2.1-3.0	1.7-3.2
Texaco 120 (1942)	450-600	480-740	540-840	111	2.1-3.6	2.0-3.1	2.1-2.9
Texaco 120 (1944)	400	430	460	72	3.4	3.2	2.8
NACA Reference Oil 120	630-670	750-780	790-850	98	2.8-3.2	2.3-2.7	2.2-2.4


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TABLE II.- EFFECT OF USE IN AIRPLANE FLIGHT ON FOAMING CHARACTERISTICS OF
AERONAUTICAL LUBRICATING OILS

Sample	Volume increase (percent)				Foam stability, L_g/h_0 ; air-bubbling method at $100^{\circ} C$ for air flow of -		
	Air-bubbling method at $100^{\circ} C$ for air flow of -			Beating method at $25^{\circ} C$	100 cc/min	150 cc/min	200 cc/min
	100 cc/min	150 cc/min	200 cc/min				
McClellan Field (Gulf); new (1942)	490	550	570	111	3.2	3.0	2.9
McClellan Field (Gulf); used (1942)	420	470	490	108	3.6	3.4	3.3
Moffett Field (Texaco); new (1943)	400-580	470-730	470-800	98	2.5-3.1	2.1-3.0	1.7-3.2
Moffett Field (Texaco); used 7 hours (1943)	360	420	420	---	3.7	3.2	3.4
Moffett Field (Texaco); used 25 hours (1943)	330	340	360	91	3.4	3.6	3.5
Moffett Field (Gilmore); new (1944)	500	620	740	92	2.5	2.4	2.1
Moffett Field (Gilmore); used 29.5 hours (1944)	370	390	410	79	3.1	3.0	3.0

TABLE III.- COMPARISON OF BUBBLER TYPES, USING
AEROSHELL 120 AS A REFERENCE OIL

Bubbler	Volume increase at air flow of 200 cc/min (percent)	Foam stability, Lg/h_0 (Foam produced by air flow of 200 cc/min)
Pyrex fritted- glass disk	546	2.77
	562	2.61
	624	2.30
	593	2.57
	640	2.42
	Mean 593 \pm 31	2.53 \pm 0.14
Cenco porous stone sphere	609	2.77
	671	2.42
	818	2.63
	702	2.34
	Mean 700 \pm 60	2.54 \pm 0.16



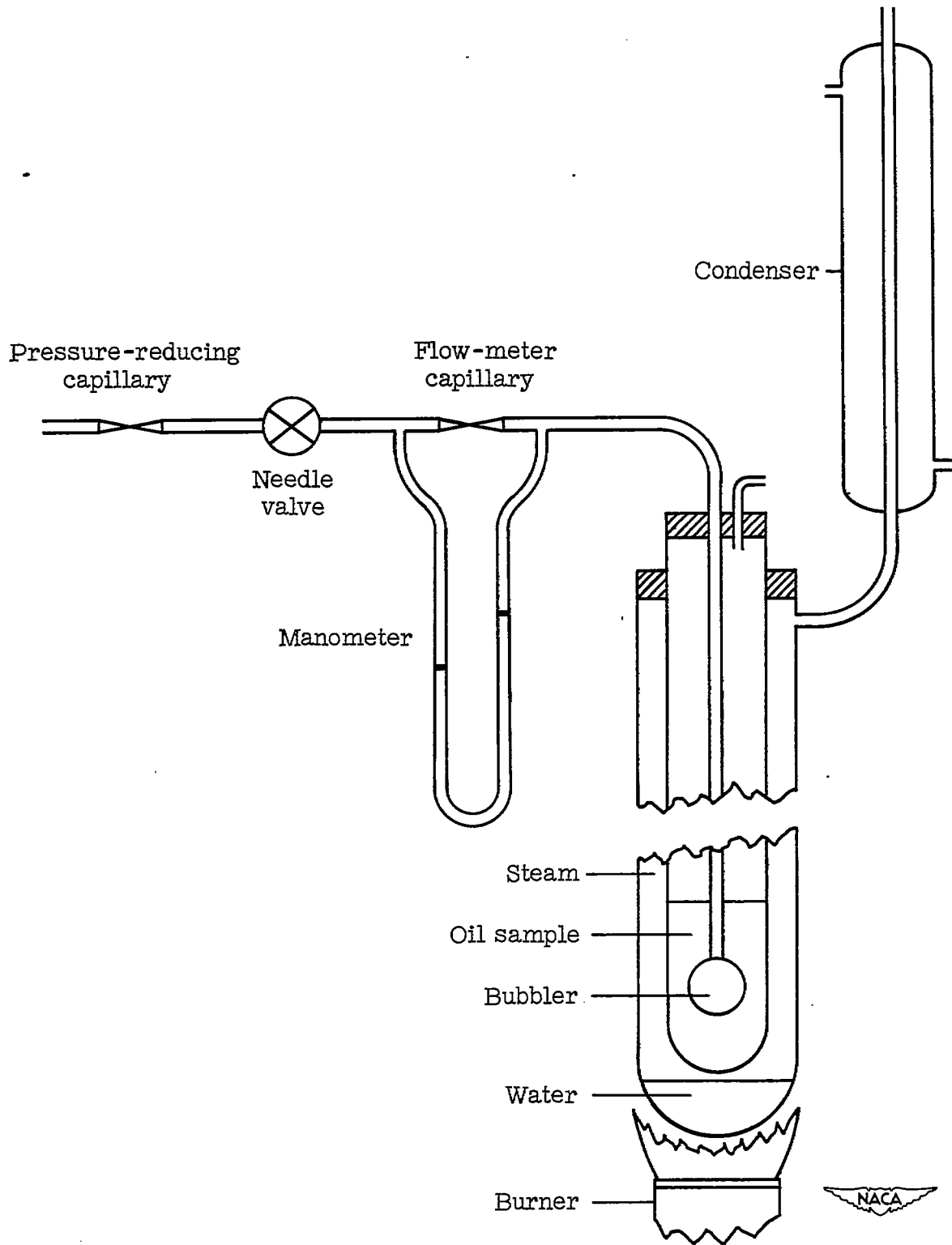


Figure 1.- Foam meter.



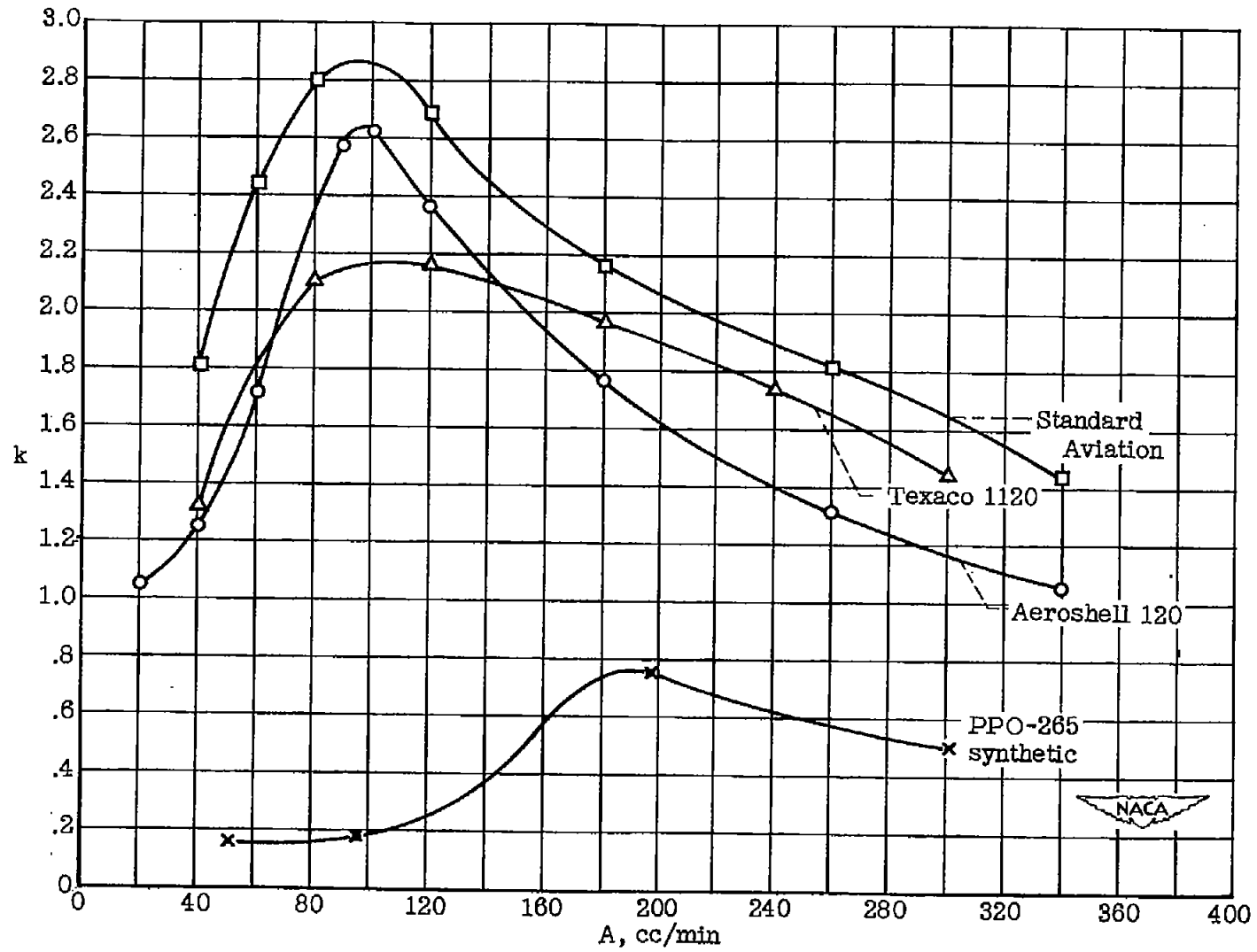


Figure 2.- Constant k against rate of air input at 95° C. $V = kA(1 - e^{-at})$.

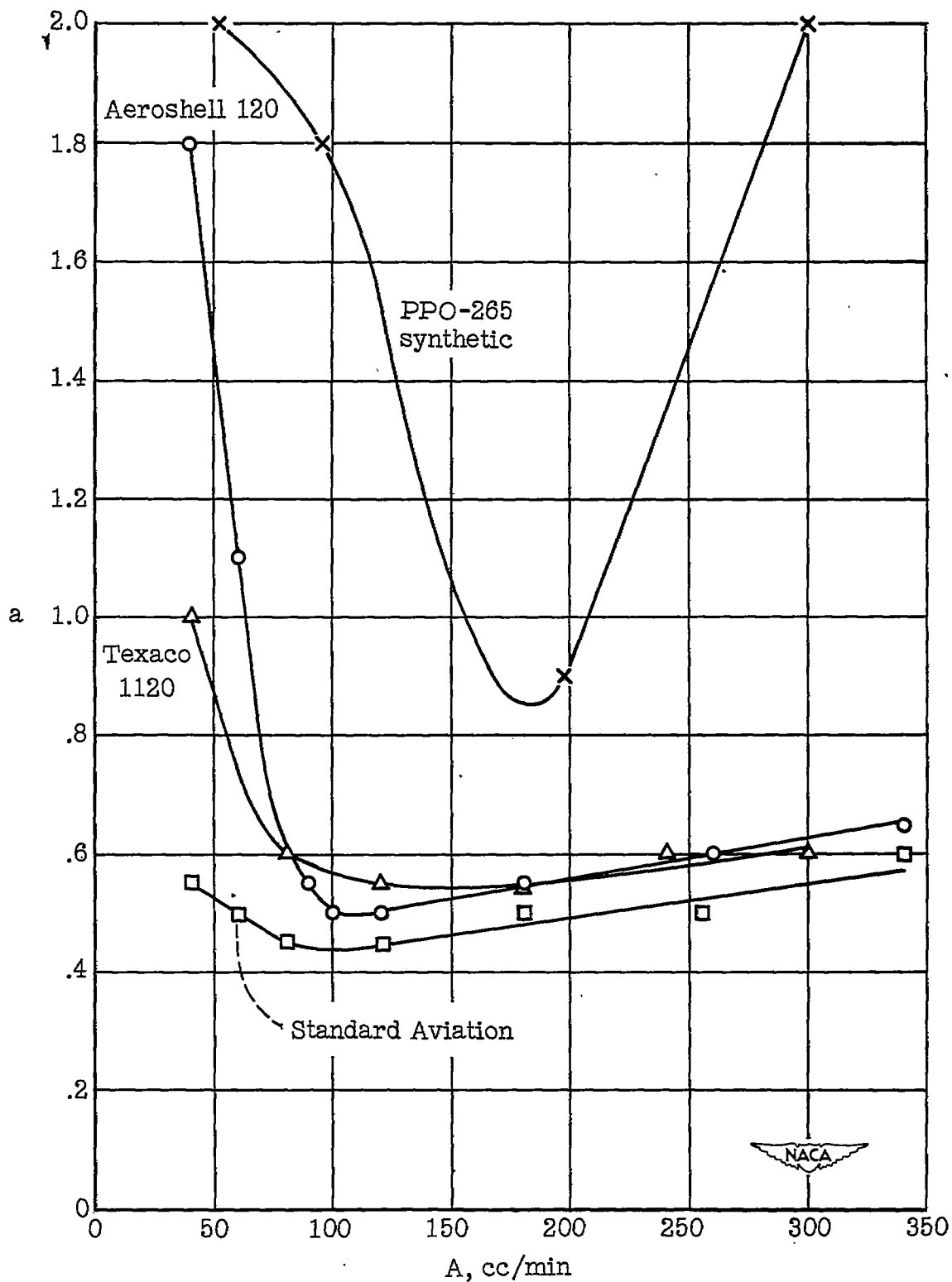


Figure 3.- Constant a against rate of air input at 95° C. $V = kA(1 - e^{-at})$.

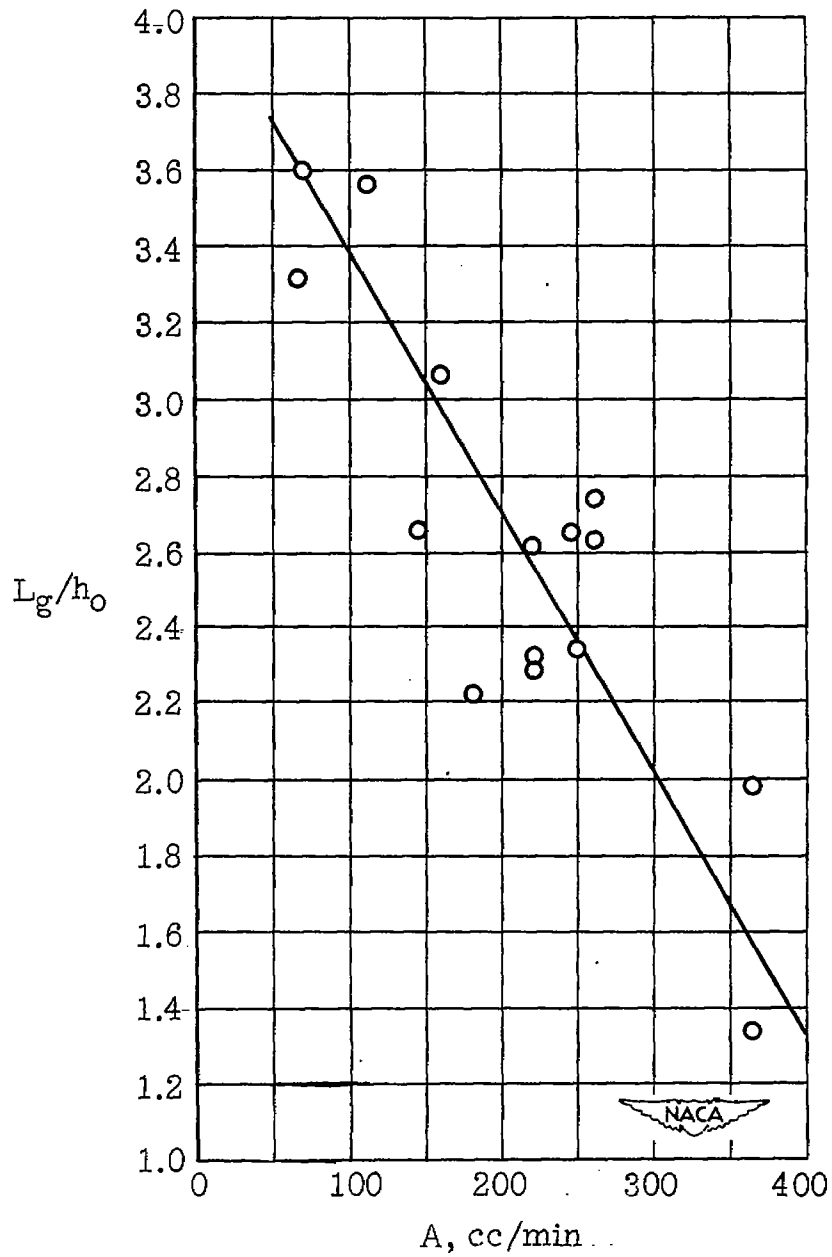


Figure 4.- Foam stability against rate of air input at 95° C for Aeroshell 120.