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No. 1844

SURFACE PROPERTIES OF OILS

By J. W. McBain and James V. Robinson

Stanford University



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SUMMARY

The surface properties of oils were studied in a short series of experiments upon their film viscosities and surface tensions. Information about film formation in general was obtained from the behavior of single bubbles upon the surface and from the coalescence of pairs of bubbles below the surface of various pure and binary liquids.

The principal object of the investigation was to discover whether an excessive viscosity in the films was responsible for their stability. In the case of ordinary, only moderately stable, oil foams, this was found not to be the case, but in the case of certain modified oils adsorption at the air interface caused the formation of solid films responsible for stabilizing the foams. Foam inhibitors, on the other hand, increased, left unchanged, or slightly decreased the film viscosity.

Another object of the study was to learn whether mixtures of hydrocarbons could of themselves form stable films or whether a surface-active "foaming agent" must be present. The time of coalescence of pairs of bubbles held below the surface of various liquids indicated that, while pure liquids could not form stable films, some of the binary mixtures thereof formed films of finite, although limited, stability. The inference is not excluded that the observed foaming ability of unmodified lubricating oils may be due partly to the mixture of hydrocarbons.

Another object of the study was to determine whether foam stabilizers and foam inhibitors added to lubricating oils acted by their effect upon the surface tension. Such was not the case; in only one instance did an additive materially affect the surface tension, although the foaming was greatly changed.

INTRODUCTION

The work described in this paper represents one experimental approach to the general theory of oil-foaming. The physical properties

of the bulk of the oil, notably viscosity, are important factors in determining the foaming characteristics but are not sufficient to account for them. It seems apparent, therefore, that other controlling physical factors should be sought at the oil surface.

Plateau (reference 1) in 1869 suggested that film stability was the result of the balance of the forces of surface tension, tending to disrupt the film, and of "superficial" viscosity, tending to stabilize the film. The present study is an attempt to evaluate this hypothesis. The difficulty of measuring superficial viscosity is great, since the surface may extend to a depth of only a few molecules. Early attempts by Rayleigh and others (reference 2) to detect excessive superficial viscosities on pure liquids failed. Successful measurements of an excessive viscosity at the surface of pure water on which floated molecular films of insoluble substances to which the viscosity was attributed have been reported in references 3 to 5. The present method of raising a thin film of liquid below the torsion pendulum represents a distinct refinement which reduces the drag due to the bulk of the liquid below the surface and increases the chance of detecting small excessive viscosities. The change of the surface with undisturbed age complicates the measurement.

The presence of cybotactic structure in liquids has been well established (reference 6), and peculiar behavior of liquid bubbles, which maintain their identity on surfaces of liquid of the same composition as themselves, has been noted as evidence for cybotactic surface structure (references 7 and 8). Observations made at this laboratory upon the drainage of liquid from oil foams indicate that the films may retain large quantities of liquid relative to those necessary for films of a thickness of a few molecules. The likelihood of deep surface forces, as postulated by Hardy (reference 9) and McBain (reference 10), is thus indicated.

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APPARATUS AND PROCEDURE

Surface Viscosimeter

The surface viscosimeter was a torsion pendulum. A hollow cylindrical bob 1.35 centimeters in outside diameter terminated in a knife edge at the lower end and a solid cone at the upper end. To the tip of the cone was attached, with sealing wax, the lower end of a 103-centimeter-long quartz fiber. The upper end of the fiber was similarly attached to the

point of a downward-pointing pin so mounted in a simple bearing that it could be axially rotated to impart a twist to the fiber. A tiny mirror was mounted rigidly in a vertical plane, with sealing wax, to the cone tip of the bob. A telescope was mounted radially at the circumference of a semicircular galvanometer scale in such a position that a portion of the scale could be viewed through the telescope by reflection from the little mirror on the bob. A cross hair in the telescope served as a reference line for reading the scale. The quartz fiber was so delicate that even a raised film on the oil was sufficiently viscous to damp the pendulum completely.

To determine viscosity, a twist of slightly less than 90° was given to the upper suspension of the fiber, the bob being in contact with the oil to some carefully measured depth. When the scale was viewed through the telescope, the rate of travel of the scale image was timed at close intervals with a stop watch. This rate was proportional, of course, to the angular velocity of the bob. For a completely damped torsion pendulum, the velocity is continuously decreasing; so the timed intervals must be small. The rest position of the pendulum is determined as the final reading, and from it the torsion, in scale units, at the center of each of the timed intervals is counted. The ratio of torsion to velocity is the viscous drag and, for a given depth of immersion, is directly proportional to the viscosity coefficient (reference 11).

The ratios of force to velocity are left in the arbitrary units of torsion in scale divisions and velocity is left in scale divisions per second. The torsion constant of the quartz fiber was 0.995 dyne-centimeter per radian, or, in terms of the scale units, 0.0688 dyne-centimeter per division.

For determining the viscosity of the liquid below the surface, a flat disk 2.2 centimeters in diameter and about 0.5 millimeter in thickness was substituted for the hollow-cylinder bob. With this disk, the calibration of the torsion-velocity ratio into absolute-viscosity units was easily made.

The liquid was set under the bob in a small crystallizing dish on a little table, whose height was adjustable with a screw and measurable by a micrometer caliper clamped alongside. The "zero" height was that at which the bottom of the bob first touched the oil surface. Film viscosity was measured by lowering the surface from the "zone" height, thus drawing out a cylindrical film below the edge of the bob.

Surface Tensiometer

Surface tension was determined by the maximum pull on a platinum-iridium ring of 4-centimeter circumference, such as is supplied for the Cenco-Du Nouy tensiometer. The pull was measured on a Chainomatic

balance from which the pans had been removed to reduce the moment of inertia of the beam. A small pan (weight, 5 grams) was hung on one arm of the balance, and a counterweight and the ring, supported by a short wire, on the other. The balance beam is maintained horizontal, as the pull on the ring is increased, by lowering the oil surface.

The oil was contained in a 12-centimeter fused-silica watch glass, cleaned by heating to redness. The silica watch glass rests on a small adjustable-height table such as is supplied with the Cenco-Du Nouy tensiometer, a fine screw providing the adjustment. The entire balance was set in an air thermostat maintained near 25° C.

Surface tensions were calculated by the conversion tables of Harkins and Jordan (reference 12).

Bubble-Coalescence Apparatus

The time of coalescence of two air bubbles beneath the surface of a liquid was determined by means of an accessory piece mounted on the single-bubble apparatus described in reference 13.

The assembly provides a means by which two bubbles of measured volume may be introduced below the surface of a liquid without possibility of surface contamination and trapped beneath a "spoon" which maintains them in juxtaposition until they coalesce. The whole apparatus can be disassembled for cleaning, and the liquid comes in contact only with glass.

In place of the single jet of the apparatus, used in reference 13, a reservoir of heat-resistant glass was connected to the bubble-volume meter through the ground-glass joint. The air tube passes vertically through a ring seal at the bottom of the reservoir, thence to a jet inside. The reservoir consists of an inverted 250-milliliter Florence flask sealed at the neck to the female part of a large ground-glass joint. The male (lower) half of the joint is drawn down at its lower end to the ring seal through which the air tube passes. The central tube has a ground joint at its upper end, at a level just above the large ground joint around it, to permit interchanging the jet tips. In the bottom of the inverted flask (the top of the assembly) is sealed a 25-millimeter open tube, about 2 inches long, at a 45° angle. Through this tube a glass spoon is inserted into the reservoir below the liquid surface and held in place by a stopper through which the handle passes.

A bubble of air of metered volume was released from the jet of the bubble-coalescence apparatus and caught under the glass spoon. A second bubble of the same size was then released and caught and a stop watch was started upon contact of the two bubbles. When the two bubbles coalesced the watch was stopped, the time being the "time of coalescence."

RESULTS AND DISCUSSION

Direct Comparison of Viscosity at Surface and in Bulk

For the determination of viscosity at the surface and in the bulk, the flat disk was used for the torsion-pendulum bob. It was immersed to various depths, from 13 millimeters to the surface (only one side of the disk in contact), in a 45-millimeter-diameter crystallizing dish with the oil 26 millimeters deep. The viscosities, in poises, obtained from these measurements are listed in table I for comparison of viscosity at the surface and in the bulk. The viscosimeter was calibrated against castor oil, which is known to behave as a Newtonian fluid.

The temperatures of the determinations were measured to about $\pm 0.3^{\circ}$ C. Since the viscosity varies greatly with temperature, these comparisons are not very accurate at the point at which the disk just touches the surface, the disk would not be immersed halfway up the edges, except for the raising of the meniscus, which does not exert much drag since it is above the surface. This inaccuracy and the temperature consideration would tend to account for the high ratio of bulk-to-surface viscosity. Therefore, the ratio would probably approach 2.0 if the conditions were adjusted to constant temperature and immersion of exactly half of the disk in the surface determinations for the three examples in table I. These determinations, therefore, indicate that a strong excessive viscosity is nonexistent in the surface region of the unmodified oils.

Demonstration of Anomalous Film Viscosity

The modified oils tested, which formed more stable foams than the unmodified oil, showed an anomalous and excessive viscosity. This anomaly was in the direction of an increasing viscosity as the rate of shear decreased, similar to Bingham's "plastic-flow" diagrams (reference 14). The demonstration of a tendency of certain surfaces to set when undisturbed, or at low rates of shear, provides one type of mechanism for the stabilization of films in foams.

The viscosity of RPM Aviation 120 oil is anomalous in the bulk as well as in films. The viscosities of other modified oils showing anomalous film viscosity were not measured in the bulk with varying rate of shear. Such an anomalous bulk viscosity was not expected. In this case, the tendency to set evidently extends through the entire mass of the oil, whereas the tacit assumption made in planning the experiments and in the present discussion was that the anomalous viscosity was confined to the surface region and was the result of adsorption of the foaming agent. The result was further surprising in that such a "plastic" flow was considered undesirable in a lubricant. The theoretical implication

that a relatively small amount of agent can change the viscosity of the oil, again demonstrating long-range molecular forces, is also interesting.

Table II illustrates the increase of viscosity coefficient at low rates of shear for RPM Aviation 120 oil and also the tendency of the surface to set on aging while undisturbed. After standing overnight, the surface became rigid. By contrast, the viscosity coefficients for castor oil and Aeroshell 120 showed no systematic change but a random variation of about 5 percent due to experimental inaccuracy.

Other anomalous film viscosities are reported in table III, but only the range of viscosity coefficient observed is given. The applied torsion in all cases was in the scale-division range of 45 to 0.

Effect of Added Agents upon Viscosity of Oil Films

Although evidence of excessive film viscosity could not be obtained for unmodified oils, the addition of foaming agents gave a very large increase in film viscosity, which was greatest at low rates of shear. The range of viscosity observed with varying rates of shear is indicated in table III. Where a single value is given, the viscosity was Newtonian. A few agents of unusual foaming effect were tested, and the film viscosity was found to be roughly parallel to the foaming behavior.

An early sample of Paranox 56 stabilizes the foam of Aeroshell 120 tremendously. However, a more recent sample, stated by the manufacturer to be corrected for foaming, inhibits the foaming. The film viscosity of the early sample, the foamer, shows anomalous viscosity, which indicates the formation of a plastic film at the surface in $2\frac{1}{2}$ hours. The defoamed sample, however, does not show such anomalous viscosity after 24 hours, although eventually, after 200 hours, the plastic film forms.

The commercial additive Lamepon 4C has a peculiar action in that sometimes it acts as a defoamer, although usually as a foamer. When first dispersed into the oil, the agent may defoam it. As the oil is bubbled with air at 100° C, a foam of increasing stability forms and is finally much more stable than that of the unmodified oil. This may be due to the volatile solvent in the Lamepon 4C. The film viscosity is actually decreased by the agent, for the first 24-hour aging of the surface. After 24 hours, anomalous viscosity appears; this indicates the formation of a plastic film, which however is soft compared with that formed by Paranox 56 (foamer). When the mixture is subjected to air bubbling at 100° C for about 2 hours, its film-viscosity characteristics are somewhat changed. The viscosity of the relatively fresh film is greater than that of films of the original oil, although Newtonian. This sample was not aged to determine if a plastic film would develop.

Stearic acid has been observed to increase the rate of drainage from an Aeroshell foam, although it has little effect upon the foam stability. The film viscosity of Aeroshell containing stearic acid was enhanced for the fresh films, but upon aging the viscosity dropped to about 6 percent below that of the unmodified Aeroshell. This change is small, and it is impossible from present knowledge to say whether it is of a magnitude sufficient to effect the noted increase in drainage rate. However, it seems significant that the change is in the right direction and, for a series of four viscosity measurements, is greater than the experimental variation.

Standard 31072R formed an extremely stable foam with Aeroshell 120 and likewise showed a tendency to form plastic films at the surface, as manifested by the anomalous viscosity of the 21-hour-old film. The slight foamer, Rustban 606, did not appreciably affect the viscosity of fresh films of Aeroshell.

The samples of Aeroshell 120 defoamed by charcoal treatment, 1A1F and 2ALEPE, had a slightly increased viscosity, which may have been due to a fractionation of the oil by the charcoal treatment. The bulk viscosity of the samples was not taken.

Surface Tensions of Oils and Modified Oils

The surface-tension data in table IV represent a comparatively nonfoaming oil of another system (castor oil), a lubricating oil (Aeroshell 120), Aeroshell 120 plus foam destroyers (Gulf Agent and the newer Paranox 56A) and foam stabilizers (Lamepon 4C, Paranox 56, and Standard 31072R), and Aeroshell 120 strongly defoamed by charcoal treatment (27A10F plus 28A10EB). The surface tensions of the other lubricating oils are repeated to show the remarkably similar values. This list of oils represents a wide range of foam stability. With the exception of the Aeroshell containing Gulf Agent, the surface tensions are almost identical. It must therefore be concluded that surface tension and viscosity alone cannot account for the foam stability of all liquid systems.

Coalescence of Bubbles in Binary Mixtures of Liquids

Table V shows the time for coalescence of bubbles in binary mixtures of liquids. The stability of the films between bubbles in the mixed liquids is seen from this table to be many times that in the separate liquids. Although the reagents used were not especially purified, they are free of surface-active materials, as shown by their failure to form films separately. Therefore, the ability to form films becomes a property of the simple binary mixtures. This idea has been previously set forth and confirmatory data have been adduced by Foulk (reference 15) on other systems of carefully purified liquids.

Foaming of Binary Mixtures of Liquids

The foaming of pure liquids and binary mixtures was observed by beating 100 milliliters of the liquid for 3 minutes in the smaller bowl of an electric kitchen mixer at full speed. All the foams were fleeting and were estimated by watching after the mixer was turned off. In cases of no foam, bubbles would not even stay below the surface of the liquid while the machine was running. The results are presented in table VI. This test is not sufficiently sensitive to detect very slight tendencies to form films. For diethylene glycol plus water, a definite foaming tendency is exhibited by the mixture that was not demonstrated by either of the liquids separately. The rest of the experiments are essentially negative.

Effect of Aging on Life of Single Bubbles of Mineral Oil

A preliminary model of the apparatus described for bubble coalescence was used to study single bubbles. The principal difference in the two apparatus was that the reservoir holding the oil for the single-bubble tests was sealed at the bottom with a cork instead of a glass joint. The cork, of course, is a likely source of contamination and may furnish the contamination evidenced in the following description.

A sample of Squibb mineral oil was used to fill the 250-milliliter reservoir. A glass spoon was arranged over the jet so that bubbles could be caught under it and held for any interval before being released to the surface or could be allowed to rise immediately to the surface. The progress of the experiment is given in table VII.

Although the fluctuations in single-bubble life confuse the results, 5-minute aging beneath the surface appears to have little effect on bubble life. There is some indication that the condition of the upper surface is the cause of fluctuation in bubble life and that the condition is not completely dependent upon the age of the surface in itself but also upon incidental contamination. Table VII shows that the bubble lives fluctuate less as the oil stands in the apparatus and the surface is subjected to sweeping. The unswept surface also appears to give roughly two or three times the bubble life of the swept surface and the bubble life seems to increase as the swept surface ages but not to the values of the original dirty oil.

Spreading of Oils and Modified Oils upon Water

An interesting approach to the study of surface properties of lubricating oils is afforded by the methods of Zisman (reference 16) in observing the spreading of films from drops placed upon an aqueous surface. This method has hitherto not been tried in this laboratory. A preliminary experiment has shown that a drop of Aeroshell spreads slowly upon 0.01 N aqueous sodium hydroxide but that if defoamers are present

(Gulf Agent or glycerol plus Aerosol OT) it spreads very rapidly. A foamer (Lamepon 4C) also increased the rate of spreading but not so much as the defoamers. This method is simple and convincing for detecting an interfacial-active agent, with the possibility that it may be correlated in some more quantitative way with a foaming property.

SUMMARY OF RESULTS

From an investigation of the surface properties of oils, the following results were obtained:

1. The viscosities of Aeroshell 120, Squibb mineral oil, and castor oil are independent of the rate of shear (i.e., they are Newtonian liquids), both in the bulk and in films consisting of menisci lifted 0.25 centimeter above the liquid surface. A disk supported by a torsion fiber experienced approximately half the viscous drag when resting on the surface as it did when immersed. Evidently the drag was dependent only upon the surface of the disk in contact with the oil. Therefore, there is no excessive surface viscosity responsible for the foaming of these oils.

2. The viscosity of RPM Aviation oil was anomalous, both in the bulk and in films consisting of menisci lifted above the surface. The viscosity increased at low rates of shear. The actual values of the viscosities of films depended upon the age of the undisturbed surface. With sufficient age the surface became "solid," with a yield point as the shearing stress was increased. This oil formed a foam that was indefinitely stable, a fact attributable to the formation of solid films.

3. Oils to which agents stabilizing the foam had been added likewise showed anomalous film viscosity, which indicated the formation of "plastic" films at the surface.

4. Foam-inhibiting agents may increase, have no effect on, or decrease the film viscosity of the unmodified oil. This is consistent with the possibility that foam inhibitors may operate because they are in a separate phase, causing film inhomogeneity and instability. The explanation of foam stability in terms of film viscosity would appear to be limited to homogeneous systems.

5. The surface tension of Aeroshell 120 is unaffected by either foam-enhancing or foam-inhibiting agents, with the exception of Gulf Agent, which greatly lowers the surface tension. Charcoal treatment only slightly changes the surface tension. The surface tensions of the lubricating oils from different companies are essentially the same.

6. The stability of foams in general cannot be accounted for solely on the basis of the viscosity, either in the films or in the bulk, and the surface tension of the foaming liquid.

7. The life of a single bubble of Squibb mineral oil on the surface was unaffected by the length of time the air bubble was held under the surface before release. The surface of the oil was subject to incidental contamination, which greatly increased the life of the bubble.

8. The time for coalescence of bubbles beneath the surface of pure liquids and binary mixtures of liquids (propylene glycol-water, cumene-toluene, cumene-naphthalene, toluene-naphthalene, and cumene-toluene-naphthalene) was too small to be observed for the separate liquids, but the mixtures had coalescence times of several seconds.

9. The bubble-coalescence results indicate that the resistance of bubbles to coalescence under the liquid surface may be caused by the mixture of major components in the oil and not necessarily by a definite foaming agent.

10. Mixtures of pairs of liquids were tested for foaming by a beating method. No actual froth was obtained, but a delay in the bubble collapse greater than that obtained with the liquids separately was observed in one case. The indication is that mixtures of pure miscible liquids may be able to foam.

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TABLE I.- COMPARISON OF VISCOSITY AT SURFACE AND IN BULK

Oil	Depth of immersion (mm)	Temperature (°C)	Viscosity (poise)	Ratio of bulk-to-surface viscosity
Castor oil	3	22.5	8.12	2.18
	13	22.5	8.12	
	0	22.5	3.72	
Squibb mineral oil	5	25.0	1.55	2.06
	0	----	.754	
Aeroshell 120	5	25.5	8.95	2.48
	0	27.0	3.61	



TABLE II.- VARIATION OF VISCOSITY COEFFICIENT WITH RATE OF SHEAR

[Cylindrical bob; film height, zero]

Castor oil		Aeroshell 120		RPM Aviation 120			
Torsion (scale division)	Torsion Velocity	Torsion (scale division)	Torsion Velocity	Fresh surface		1-hour surface	
				Torsion (scale division)	Torsion Velocity	Torsion (scale division)	Torsion Velocity
40.2	50.3	33.1	63.6	39.5	86.9	41.0	571
32.2	53.1	26.1	60.0	32.5	95.9	39.0	562
26.2	52.5	21.1	63.3	27.5	100.3	37.0	555
20.2	52.5	16.1	64.4	23.5	102.2	35.0	659
15.2	53.1	12.1	63.7	19.5	109.0	33.0	863
11.2	53.6			15.5	115.0	31.0	1200
7.7	53.9			12.0	118.0		
5.7	52.8			10.0	117.0		
				8.0	118.0		
Av.	52.7	Av.	63.0	5.0	119.0		



TABLE III.— FILM VISCOSITY OF AEROSHELL 120 OIL CONTAINING ADDITIVES

[Height of film, 1 mm above surface; viscosities corrected to 25.0° C; coefficient of viscosity of Aeroshell 120, 51]

Additive	Percent of additive	Coefficient of viscosity (arbitrary)	Undisturbed age of surface (hr)	Remarks
Paranox 56 (foamer)	0.5	40	1/4	Foamer
		30 to 87	$2\frac{1}{2}$	
		329 to 5110	$21\frac{1}{2}$	
Paranox 56A (defoamed)	.5	50	1/6	Foam inhibitor
		46	24	
		75 to 684	200	
Lamepon 4C	.1	42	1/2	Defoamer at first, then foamer
		46	26	
		33 to 110	42	
Lamepon 4C	.08	70	1/3	Do. (after 2-hr bubbling at 100° C)
		61	2/3	
		59	2	
Stearic acid	.1	67	1/4	Increases rate of drainage
		48	120	
Standard 31072R	.5	50	1/6	Foamer
		54	$2\frac{1}{3}$	
		84 to 1660	21	
Rustban 606	.1	54	1/2	Slight foamer
^a 1A1F		58	1/2	} Defoamed by charcoal treatment
^a 2A1EPE		55	1/2	

^a Not true additives; charcoal-defoamed Aeroshell 120.



TABLE IV.- SURFACE TENSIONS

Oil	Temperature (°C)	Corrected surface tension (dynes/cm)	Remarks
Aeroshell 120	25.0	31.65	
plus 0.045 percent glycerol plus 0.015 percent Aerosol OT	25.0	31.8	
plus 1/2 percent Gulf Agent.	25.1	22.72	Defoamed
plus 0.2 percent Lamepon 4C	25.3	31.46	Foamer
plus 0.1 percent Lamepon 4C	25.0	31.4	Do.
plus 0.5 percent Paranox 56 (first) (foamer)	25.0	31.2	Do.
plus 0.5 percent Paranox 56A (later; defoamed)	25.0	31.2	Defoamed
plus 0.5 percent Standard 31072R	25.0	31.4	Foamer
27A10F plus 28A10EB	25.2	31.45	Defoamed
Standard Aviation 120	25.0	31.6	
RPM Aviation 120	25.0	31.6	
Sinclair GX 120	25.0	31.4	
Gulf Airline 120	25.0	31.3	
Used Texaco 120	25.0	31.5	
Castor oil	25.0	34.47	Nonfoaming

TABLE V.— COALESCENCE OF BUBBLES IN BINARY MIXTURES OF LIQUIDS

Liquid	Time of coalescence (sec)
Propylene glycol	< 1/10
Distilled water	< 1/10
50 percent propylene glycol plus 50 percent distilled water	1 to 8
Toluene	< 1/10
77 percent toluene plus 23 percent naphthalene	< 1/2 > 0
Cumene	< 1/10
85 percent cumene plus 15 percent naphthalene	.5 to 1.4
51 percent cumene plus 31 percent toluene plus 18 percent naphthalene	.5 to 1.0


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TABLE VI.— FOAMING OF BINARY MIXTURES OF LIQUIDS

Liquids (components in equal volumes)	Foaming
Diethylene glycol plus water	No foam
plus methanol	Slight foam; very unstable
n-Butyl phthalate	No foam
plus nitrobenzene	Do.
plus naphthalene (2 gm/100 cc)	Very slight, unstable foam
Nitrobenzene	No foam
Benzene	Very slight, unstable foam
Toluene	No foam
Benzene plus toluene	Do.
Benzene plus carbon tetrachloride	Do.
Carbon tetrachloride plus carbon disulfide	Very slight foam; breaks rapidly
Methanol plus water	Do.
Cumene	Do.
Cumene plus naphthalene (2 gm/100 cc)	Do.


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TABLE VII.-- LIFE OF SINGLE BUBBLES OF MINERAL OIL

Time (hr)	Delay in rising (min)	Life (sec)	Remarks
0	0 1	7, 75, 105, 70 225, 315, 190, >980	Surface not swept
16	0 6	95, 25, 60, 10, 165 20, 165, 540, 720	Small amount of fresh oil added to raise level
17	0	110, 110, 90, 10, 15, 27	Surface swept
	--do--	12, 7, 18, 43, 90, 120, 15	Surface swept again
18	5 0	3, 7, 3, 3 6, 5, 6, 6, 6, 2, 95	Oil added before swept
40	5 0	92, 80, 2 70, 40, 67, 100, 80, 83	Oil level down 1 mm
41	5 0	300, 34, 115 1, 44, 39	Oil added Surface swept
42	5 0	62, 45 30, 133, 155	Surface swept
	5	37, 45	Surface swept 3 sec before bubble released
90		82	Bubble aged 48 hr; surface swept 30 sec before bubble released

