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ENHANCED OIL RECOVERY BY CO₂ FOAM FLOODING

First Annual Report

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New Mexico State University
Las Cruces, New Mexico

U. S. DEPARTMENT OF ENERGY

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ENHANCED OIL RECOVERY BY CO₂ FOAM FLOODING

First Annual Report

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OVERVIEW

Objective: Identify commercially available additives which are effective in reducing the mobility of carbon dioxide, CO₂, thereby improving its efficiency in the recovery of tertiary oil, and are low enough in cost to be economically attractive.

Summary: An extensive review of the literature revealed that the use of foam to lower the mobility of gases used to displace oil has been considered since 1956. Although early work was related mainly to light hydrocarbons, it is natural to extend the concept to the CO₂ flooding process. Samples of foaming agents, compatible with oil reservoir environments, were obtained from major manufacturers. Ninety-three samples were tested both alone and in admixture in a static screening test to identify the suitable candidates. The most promising class of additives appears to be ionic surfactants and, more specifically, those produced by ethoxylation of a linear alcohol followed by sulfation. Surfactants having this molecular structure were supplied by three manufacturers and all displayed consistently superior performance. One of the best, Plura-foam NO-2N was tested in a linear sandpack and found to reduce the mobility of gas relative to water an average of 300-fold.

Viscosity measurements of the foam at varying shear rates were made to help explain the dramatic change in gas mobility in the linear flow

model. The foam is non-Newtonian but many-fold more viscous than the liquid from which it is generated at all reasonable shear rates. Viscosities exceeding 1000 centipose are routinely obtained.

Addition of water-soluble polymers to the foaming liquid greatly enhances the stability of the foam. Five different polymer structures were tested all of which had a common cellulosic type backbone. Of this group hydroxypropyl cellulose and xanthan gum appear to be the most promising candidates. The superiority of these polymers lies primarily in their stability at reservoir conditions in the acid environment created when carbon dioxide dissolves in water.

SECTION ONE

INTRODUCTION

1.1 General

For more than 30 years recovery experts have known that carbon dioxide possess a unique ability to displace crude oil from reservoir rock. Although many gases have been tested for their crude-displacing efficacy, only carbon dioxide has the ability to reduce residual oil saturations to near zero and also to produce significant quantities of tertiary oil in models that have been previously water flooded to the economic limit. Early studies have provided the fundamental understanding required to explain the high efficiency of carbon dioxide, and yet the depressed price of crude until recently has made most, if not all, CO₂ field applications appear to be unprofitable.

Oil displacement by gas can occur under both miscible and immiscible phase conditions. CO₂ is unique in that it can effectively displace oil in both modes with the determining factor being largely the depth of the reservoir which controls the pressure at which the flood is conducted. All factors being equal it is desirable to conduct the flood under miscible conditions when at all possible.

A common failing among gas-driven oil recovery processes is the severe gas channeling which occurs in the reservoir due to excessively high gas mobility. Optimistic oil recoveries obtained in laboratory flow tests using small diameter, linear models have never been achieved

in the field. Both miscible and immiscible drive processes suffer because gas channeling causes most of the oil reservoir to be bypassed and the oil left behind.

Because of the high potential for miscible drives using enriched gas mixtures, considerable study was undertaken in the late 1950's on techniques to mitigate gas channeling. A few visionary investigators considered the use of foams as a possible solution to the problem. The earliest reported work was conducted by Bond and Holbrook whose 1958 patent describes the use of foams in gas drives processes [106]. Because of the high cost of carbon dioxide relative to crude oil during this period, carbon dioxide processes were ignored. The use of foams in conjunction with carbon dioxide was not contemplated until much later when rising crude prices revived interest in the carbon dioxide displacement technique.

1.2 Background

Before embarking on the experimental phase of this research project, an extensive literature review was undertaken to evaluate the current state-of-the-art and identify techniques, both good and bad, that had been investigated in the past. The resulting bibliography is included in this report.

The majority of both field and laboratory results which appear in the literature have been summarized by Patton [50] and are presented in Figure 1.1. These data have been normalized to a constant CO₂ injection equal to 0.2 pore volumes. It is apparent that above an oil viscosity of 2 centipoises the experiments indicate an almost constant displacement efficiency for carbon dioxide processes.

Figure 1.1 Carbon dioxide required to produce tertiary oil

The earliest work relative to the problem of lowering the mobility of carbon dioxide does not involve carbon dioxide at all. Carbon dioxide exists as a gas or super critical phase under reservoir conditions; therefore, experiments on controlling gas mobility are usually applicable to carbon dioxide even though they may have been conducted with nitrogen, methane or even air. Concurrent with Bond and Holbrook's work, whose 1958 patent describes the use of foams, Fried, working at the Bureau of Mines Laboratory in San Francisco, demonstrated the potential of foam to lower the mobility of an injected gas phase [25].

Fried generated the foam in a cylinder by dispersing fine air bubbles beneath the surface of a surfactant solution. This foam was flowed but only with much difficulty through a highly permeable matrix. A high foam viscosity was indicated suggesting that, indeed, foam might be the answer to mobility control in gas drive processes. Oil displacement tests in an Aloxite core showed that foam could reduce the saturation of a 350 centipoise oil to half the value obtained by waterflooding. The reduction in oil saturation was purely a viscous flow effect as the waterflood contained the same surfactant concentration as the foam.

Fried conducted additional studies in a 30 cm glass bead pack, 0.78 cm diameter, that indicated foam might be too good as a mobility control agent. Although the permeability of the pack was about 12 darcys, the foam was too viscous to flow even at a pressure gradient of 15 psi/ft. Microscopic examination of the linear model indicated that the injected foam coalesced and was regenerated as the gas and water moved through the tiny pores. The regenerated foam had smaller bubbles and had

presumably, a much higher viscosity. After a substantial amount of regenerated foam had been formed, the mobility was lowered to the point that steady-state flow could not be maintained. From these experiments Fried concluded that a highly stable foam would not be desirable in an oil recovery process.

Fried's work was followed by some excellent work by Bond, Benard and Holm [5,7,8,35] whose experimental technique involved in situ foam generation promoted by injecting alternate slugs of surfactant solution and gas. Especially pertinent is their patent related to the use of foam for mobility control in CO₂ processes [104].

Laboratory work was encouraging enough that Union Oil Company conducted a field test in the Siggins Field, Illinois [32]. Foam generation by alternate slug injection as well as simultaneous gas-solution injection was tested. This test indicated that the foaming agent, a modified ammonium lauryl sulfate, concentrations below 1%, did not produce an effective foam. Above 1%, reduced gas mobility was obtained; however, at least 0.06 PV of surfactant solution had to be injected to achieve lasting mobility control. Inasmuch as the tests were conducted sequentially with the higher concentrations injected last, it is possible that the required amount of surfactant may be understated. Possibly a tenth of a pore volume bank might be more realistic for lasting mobility control. The results also indicate that adsorption may reduce the effectiveness of a surfactant. Future tests might benefit by selection of agents which are less strongly absorbed than lauryl sulfate.

Work from the mid-60's to the early 70's proceeded sporadically due to the low incentive provided by the depressed price of crude oil. Interest was maintained largely by the impressive attempt by Chevron to commercialize the CO₂ process at Sacroc. Although this project suffered from the same gas channeling noted earlier, CO₂ was effective in displacing commercial quantities of oil. Sacroc is regarded as the pioneering success for CO₂ processes.

The recent publications are especially pertinent. The first by Kanda and Schecter, [40] corroborated much of the earlier work by Union, Amoco, and Professor Marsden at Stanford University and served to highlight the mechanisms and pertinent variables relative to foam mobility control. Specifically they concluded that:

1. Displacement efficiency of foams is inversely related to the surface tension between the gas and liquid constituents.
2. High surface viscosities are beneficial in improving displacement efficiency.
3. Permeability reduction, interpreted as meaning mobility control, is achieved more by films forming across the pore openings than by the physical movement of foam past mineral surfaces in the pore matrix.
4. By far the most important variable is the ability of the surfactant solution to wet the mineral surfaces in the matrix.

This last item has not been widely recognized and bears additional discussion. Experiments were conducted in sand packs conditioned to provide varying degrees of water-wetness. When the matrix was oil wet, drastic reduction in displacement efficiency occurred. The mere presence of oil had little influence on mobility control; however, when

the oil was initially allowed to contact the dry sand surfaces; it reduced water-wetness and subsequent displacement efficiency. A similar result was obtained when the sand grain surfaces were treated with an oil-wetting silicone prior to being saturated with water.

Interpretation of these results in terms of reservoir performance is hazardous because of two factors. First, the displacement tests were conducted in a sand pack having a permeability of 27 darcys and a porosity of 42%. The pore dimensions in this media are unrealistically high and may have caused anomalous experimental results. The second factor involves the very low concentration of surfactants employed. Danda & Schechter believe surfactant concentrations above the critical micelle concentrations are of no advantage and, hence, used very dilute solutions, about 10^{-3} M. Tests by Holm and others indicate that there is a concentration effect and that this variable should be investigated in the future.

A more recent theoretical study by Slattery [65] suggests that displacement efficiency is proportional to surface tension. It then follows that the optimum foaming agent is one which lowers surface tension only the minimum required for spontaneous foaming to occur in the reservoir. Slattery's predictions are supported in part by experimental observations reported by other authors [32,40,43]. It is possible that deviations from theory are the result of grossly different pore dimensions utilized by the different investigators. Slattery's work also supports the dominant effect wettability exerts on the control of CO₂ mobility by foam.

SECTION TWO

ADDITIVE SELECTION

2.1 Contact with Suppliers

The research team assembled for this project represents many years of experience and widely diverse backgrounds. The collective expertise of this staff allowed instant access to manufacturers of surface-active chemicals whose products have a multitude of applications ranging from shaving cream to oil well drilling. The specific requirements of an additive for reducing the mobility of CO₂, together with the oil reservoir environment in which it must be effective, was discussed with over 20 commercial manufacturers. Of these 17 submitted one or more samples for evaluation in the project. Ninety-three individual surfactant types were received.

It was immediately evident, that if even three or four pieces of data were recorded on each sample, record keeping would become laborious and interpretation of the data extremely difficult. For this reason it was decided to record the data permanently in lab notebooks but at the same time store it in the computer for easy recall and analysis. To facilitate computer analysis each of the additives was coded using a two-part number separated by a colon. The number to the left of the colon represents the company and the number to the right identifies the individual surfactant. This coded surfactant index is included in Appendix A for easy reference.

The same selection procedure was followed with respect to foam stabilizers; however, polymer manufacturers are not as numerous nor are there many polymer types suitable for application in an oil reservoir. For this reason only 6 companies were identified and only 15 polymer samples received for testing. Due to the limited number of polymer samples to be studied, they have not been coded and stored in the computer as of this time.

2.2 Static Foam Evaluation of Surfactant Additives

Initial foam tests were conducted in accordance with the standard ASTM test D35 1976. In this test a solution containing the additive is blended in a commercial Waring blender, and the height of the foam generated in blender container measured. It was soon found that the height-to-diameter ratio of the blender container was too low to allow precise evaluation of the additive under test. Accordingly, the apparatus was modified by constructing a special blender chamber three inches in diameter and twenty-eight inches high shown in Figure 2.1. The increased height-to-diameter ratio greatly eliminated the human error in reading the foam height and improved the reproducibility of the test. In order to use the special blender chamber it was necessary to utilize a machine having a screw-base rather than a fixed-blade arrangement common to the Waring machine. A Osterizer 10-speed commercial blender was tested and found to be satisfactory and comparable to the Waring apparatus. It was purchased and used for all subsequent tests in the project. The standard blender foam test which evolved from the preliminary experimentation is included in Appendix B.

Figure 2.1 Research associate Holbrook explains static foam generator to graduate student Dellinger

Due to the lack of any published information relative to a correlation between foam characteristics and mobility control, several pieces of data were recorded during each foam test. The intent was to identify the relationship between static foaming data and mobility control observed in reservoir models. The variable having the best

correlation would then be used for subsequent tests and data analysis. Foam heights as a function of time were recorded together with miscellaneous comments regarding foam appearance and breakout mechanisms. From these data foam height after 16 minutes, ratio of initial to final foam heights and the half-life of the foam were calculated. The quantitative data were stored in the computer for ease in analysis. Data were collected at surfactant concentrations of 0.1% wt. and 0.5% wt. at 75° and 120 F° and pH's of 2.5 and unadjusted (about neutral). Random scatter in the data as well as the unknown influence of experimental parameters made the selection of a single superior additive impossible. For this reason the computer was utilized to serially rank the top 25 additives with respect to the various parameters, calculated or measured. Data for foam height and half-life are included in Appendix C.

In general, anionic surfactants appear superior in the static foam tests. Sulfate esters of ethoxylated linear alcohols were slightly better as a class than alkylated aromatic sulfonates. The sulfonates do not appear compatible with even small amounts of calcium and suffer from this deficiency.

2.3 Synergism

Before embarking on dynamic stability tests it was deemed advisable to explore the possible synergistic interactions between the various additives being tested. 25 of the better foaming agents were tested in admixture with additives known to have a beneficial effect in other foam stability applications. The possible synergistic agents tested were Aromox DM16, Monamide 150AD, Dowfax 3B2 and Dispersant 425. None of the additives had a significant effect on the initial foam height as can be seen in

the tabulated data. However, the effect of a cosurfactant on foam stability was occasionally dramatic. The most consistent positive effect was obtained with Monamide 150AD. Of particular note is its effect on Alipal CD28 where the foam showed no decrease in 10 minutes as opposed to a 25% decrease for the Alipal alone or in admixture with Dowfax 3B2 or Aromox DM15. The Monamide 150AD had a similar effect on most of the Plurafoam additives tested. The results of the admixture tests are given in Appendix D.

2.4 Foam Stabilization Additives

The fifteen samples of water-soluble polymers selected as most promising for foam stabilization represented five distinct chemical structures. All structures have a common cellulosic backbone. Since cellulose is not soluble in water, each polymer type represents a different substitution required to achieve water solubility. These polymers are well known and several have been used in other petroleum applications. They are as follows: 1) hydroxyethyl cellulose 2) hydroxypropyl cellulose 3) carboxymethyl cellulose 4) carboxymethyl hydroxyethyl cellulose 5) xanthan gum.

The initial screening test was to dissolve each polymer in 3% NaCl brine containing 100 ppm calcium. All polymers dispersed easily; however, the carboxymethyl cellulose appeared not to dissolve completely and precipitated after standing for several days. CMC does not appear to be applicable as a stabilizer for brine foams.

The four remaining candidates were tested further by adjusting the pH to 2.5 with hydrochloric acid. At 120°F HEC and CMHEC both showed drastic viscosity loss and were eliminated from further screening tests. In tests lasting four weeks, xanthan demonstrated distinct thermal

stability superiority and would appear to be the preferred stabilizer, except for one feature. Whereas all other polymers produced clear, solution-like, dispersions in brine, the xanthan dispersion is cloudy, indicative of incomplete dissolution of the polymer aggregates. Based on previous work, it is doubtful that xanthan, as now manufactured, can be propagated through reasonably tight petroleum formations and, hence, hydroxypropyl cellulose holds the most promise at this time. Additional experiments will be undertaken to evaluate the five polymer types more quantitatively.

There is also the possibility that permeability may influence the selection of the proper polymeric stabilizer. Xanthan could conceivably be superior in loose, unconsolidated reservoirs.

SECTION THREE

DYNAMIC FOAM STABILITY TEST

3.1 Apparatus

The tests for dynamic foam stability were conducted in a linear sand pack 1.5 inches in diameter 5 ft. long. The model, a glass pipe packed with sand, was covered with fine, wire mesh for safety. The apparatus including two transfer cylinders is shown in Figure 3.1 with the students who built it.

A review of the literature and prior experience both dictated that the permeability of the model should be low to avoid anomalous interfacial tension effects. After much searching, an acceptable quality, fine silica was obtained from Perma Sand Company in Midland, Texas. The sand was tested in some experimental packs and found to have a permeability of less than 100 millidarcys. There was a large quantity of fines less than 400 mesh that tended to plug the model and caused widely varying permeabilities throughout the length. To develop a more uniform model the bulk sand was sized by controlled settling to remove the particles below 20 microns in diameter. The resulting material packed nicely to a permeability of around 300 millidarcys and appears to have flow properties similar to that of many unconsolidated oil reservoirs.

Figure 3.1 Conoco fellow, Brad Phillip, advises Phillips' fellow, John Laurent on transfer cylinder adjustment

The model was connected so that it could be fed liquid at a constant volume using a Ruska proportioning pump (Figure 3.2), liquid at a constant pressure using a pressure flow cell or gas at a constant pressure. Pressure is measured at each end of the model and no intermediate taps are available.

Figure 3.2 Undergraduate students, Bob Watkins and Karen Taylor, check operation of Ruska pump with P.I., Dr.J.T. Patton

Originally it had been planned to use carbon dioxide as the gas phase in the low pressure experiments. This proved to be poor choice because at low pressure there is a large percentage variation in pressure along the length of the model. These large relative pressure changes affect the CO_2 solubility equilibrium and make it impossible to adjust the flowing gas-liquid ratio in a consistent fashion.

To remedy this problem it was decided that carbonic acid would be simulated by lowering the pH of this solution to 3 with HCl. The effect of the gas would be simulated by utilizing insoluble nitrogen in place of soluble carbon dioxide. Tests in model and also the capillary viscometer demonstrated that the analogue fluids were adequate and, in fact, were more representative of the CO₂ process at low pressures.

3.2 Fluids

All dynamic flow tests were conducted in a sea water type brine containing 100 ppm calcium and 3.0% sodium chloride. This fluid was selected to provide the necessary adverse influence of salinity and divalent cations and yet pose no problems from supersaturation and precipitation in the model. To clean the model between runs the deionized water prepared by reverse osmosis was utilized to thoroughly remove both surfactants and salt content. It was determined that flooding several pore volumes of RO water through the model between duplicate runs produced reproducible data. However, when changing surfactant types hydrogen peroxide or other oxidizing agent will be used to remove any traces of the previous surfactant.

3.3 Model Characterization

To provide a base line from which to judge the performance of additives in reducing the mobility of CO₂, gas-liquid permeability curves were measured for the five-foot linear, unconsolidated sand pack. The results of this experiment, shown in Figure 3.3, are typical curves with the gas permeability at Scw being slightly higher than the water permeability at 100% saturation.

Figure 3.3 Gas-Water permeabilities of linear sand pack

The irreducible water saturation in the presence of gas was a surprisingly high 62%. It is possible that this saturation might be slightly high; however, water production was less than 1 cc per day at that saturation, well below the detectable level. Points at intermediate water saturations were obtained by co-injection of gas and brine until steady state was obtained.

The water saturation at that steady state was calculated by material balance and the relative permeability to each fluid measured.

3.4 Effective Additive on Gas Mobility

Following the brine characterization the model was flooded with the same brine containing 0.5% wt. Plurafoam NO-2N. This additive was selected as one of the best candidate foaming agents based on the static tests. Several volumes of brine containing the surfactant were injected at constant pressure using a pressure flow cell so that the experiment could run 24 hours a day. As the surfactant containing brine was injected, an immediate effect on the irreducible gas saturation was noted. Whereas the irreducible gas saturation had been averaging 10% in the presence of brine, it increased to 25% due to the surfactant. At this point k_{wrg} was only 65 md compared to 290 md for the pure brine but at a higher S_w . At the same S_w , 75%, k_w is about the same for brine and surfactant fluids.

Nitrogen was then injected to displace the water to its irreducible saturation which turned out to be 38% as compared to 62% when no surfactant was present.

The presence of the Plurafoam in the brine produced a dramatic lowering of the gas mobility. The permeability of gas, k_{gcw} was only 0.9 millidarcys as compared to 350 millidarcys when no additive was present. The complete relative permeability curves are shown in Figure 3.4. It can be seen that the permeability to water was affected mostly by shifts in irreducible saturations. This is very encouraging because, when oil is present, this shift in saturation will result largely in the production of oil, not water.

Figure 3.4 Gas-Liquid permeabilities of linear sand pack. Water phase contains 0.5% Plurafoam NO-2N (BASF Wyandotte) $\Delta P = 5$ psi/ft.

The effect of pressure on gas mobility is shown in Figure 3.5. It appears that the reduction in gas mobility may be a function of flow velocity in the pores. In experiments conducted at a pressure gradient of 5 psi per foot, gas permeability was reduced to 0.9 millidarcys at at irreducible water saturation. In the same experiment conducted at a 1 psi per foot gradient the mobility was reduced only to 3.0 millidarcys

and the irreducible water saturation was higher, approximately 45%.

Measurements of surface tension have not been made for lack of a tensiometer. One would expect the tension to be above 20 dynes/cm and it is surprising to see a pressure effect at such high interfacial tensions. Additional experiments are planned to further define the effect of pressure gradient on gas mobility.

Figure 3.5 Preliminary experiments suggest pressure drop affects gas mobility in foam system

SECTION FOUR

RHEOLOGICAL STUDIES

A study of the rheology of foams was initiated in mid-year. The foams studied were selected from the group shown to be stable in the previously described static foam tests.

Initial rheological work was done with a Brookfield viscometer. The work was then expanded through the construction and use of a capillary viscometer. The Brookfield studies showed the foams to be non-Newtonian in nature. Also, the apparent viscosity at given shear conditions was found to be significantly affected by foam density. The viscosity of the foams was shown to be orders of magnitude higher than the viscosity of the liquid solution from which the foam was produced.

Flow data for foams in the capillary viscometer have also been obtained. These data support the results of the initial study. Again the viscosity of the foam is much higher than the viscosity of the unfoamed solution. Capillary flow tests were also made for nitrogen and for water to evaluate the performance of the instrument. The results show the instrument to be accurate with an expected error of less than 4% in measured viscosities.

4.1 Brookfield Viscometer Studies

The Brookfield viscosity tests were conducted with a Motel LTV Viscometer. A 600 ml beaker was used for the samples being tested. The viscometer was operated at various speeds (shear rates) as shown in Table 4.1.

System: Brine (3% NaCl, 100 PPM Ca^{++}) with 0.5% Aromox DMC and 0.1% xanthan Polymer.

Unfoamed Solution: pH 7.0
 2.20 ± .20cp 2.74 ± .13 cp

<u>Spindle Speed, RPM</u>	<u>Drain Time, min.</u>	<u>Viscosity, cp</u>	
		<u>pH 7.0</u>	<u>pH 3.6</u>
6	30	1620 $\pm$ 40	1410 $\pm$ 30
	100	2150 $\pm$ 100	1850 $\pm$ 100
12	30	1280 $\pm$ 20	1080 $\pm$ 20
30	31	720 $\pm$ 10	
60	31	480 $\pm$ 30	

The foam was produced by blending 400 ml of solution for 20 seconds in a Waring blender. The viscosity of the foam was then measured repeatedly for a one-hour period. As time increased, the foam gradually drained so that the foam became drier - that is the foam specific gravity decreased. The viscosity was found to be a function of the specific gravity.

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It showed the characteristics of a pseudoplastic fluid having a finite yield stress.

The results showed a much higher apparent viscosity of the foam as compared to the unfoamed solution. The foam is about 800 times more viscous than the liquid phase. This comparison is made with the foam viscosity measured at the lowest shear rate, a limiting value most meaningful for non-Newtonian fluids. The flow rate and, therefore, the shear rate would be very low in an oil reservoir.

4.2 Capillary Viscometer Studies

Equipment and Procedure. The capillary viscometer is constructed so that it can be run in several different modes. It can be run with either gas or liquid. It can also be used to measure the viscosity of foams. The foam can be prepared and placed in the viscometer or it can be generated in the equipment. A sketch of the equipment is shown as Figure 4.1.

During operation the sample of either liquid or foam is placed in its respective chamber. The chamber is then pressurized and then fluid is allowed to flow through the capillary tube. Liquid is metered through a calibrated rotameter, but the foam must be collected and weighed to get its mass flow rate.

Gases can also be used if desired by passing the gas, such as CO_2 , through the gas rotameter and then through the equipment.

In each case the pressure required for flow through the capillary tube is measured with either the manometer or the calibrated pressure gauge, depending on its magnitude.

Figure 4.1 Capillary viscometer apparatus

Gas-liquid mixtures may also be used. The liquid, usually brine containing a surfactant, would be metered through the liquid rotameter and then passed into the small, packed bed where it mixes with the gas. The packed bed acts as a mixing chamber to produce foam. The foam then passes through the capillary tube, where the pressure drop is measured.

A critical variable in the analysis is the diameter of the capillary tube. The diameter was determined by filling the tube with mercury and then weighing the mercury. The diameter of the tube was then calculated knowing the density and tube length.

Results. The results of tests with water and nitrogen show that the viscometer is accurate for the determination of viscosity. The deviation in a typical run is shown in Table 4.2.

Several sizes of capillary tubes were used ranging in diameter from 0.69 to 4.23 mm inside. The tube length was also varied to check for end effects (entrance and exit losses). These effects were found to be negligible for the tubes used.

When liquid-gas mixtures were used in the viscometer, a problem was encountered. In the larger size tubes flow separation occurred which varied depending on the flow rate and the distance down the tube. The flow separation produced the following observed modes:

annular flow	intermittent flow
wavy flow	bubble flow
slug flow	

The use of a smaller tube-diameter prevented the separation into the different flow regimes when surfactant solutions were tested. In each case uniform bubble flow was observed for the flow rates tested.

TABLE 4.2

Capillary Viscometer

Calibration Test.

Tube diameter	0.6876 mm., I.d.	Fluid: Water (purified)
Tube length	110.3 cm.	Temperature: 25° C

Viscosity 0.890 centipoise

Flow Rate g/sec	Measured Viscosity cp	% Errors
0.080	0.852	-4.36
0.124	0.861	-3.31
0.160	0.876	-1.60
0.229	0.826	-7.21
0.233	0.869	-2.36
0.259	0.876	-1.60
0.289	0.885	-0.66
0.326	0.879	-1.3
0.359	0.886	-0.54
0.396	0.904	1.51
0.446	0.886	-0.54
		Aver. -2.00
		S = 2.32
		a = 2.21

4.3 Foam Viscosities

The results of the Brookfield studies on a brine solution of 0.5% Aromox DMC with 0.1% xanthan polymer served as a basis for a series of tests with the same solution in the capillary viscometer.

The foam tested was generated in the blender in a manner similar to that used in the Brookfield tests. The foam was then placed in the foam chamber and extruded through the capillary tube. The pressure drop and flow rates were measured, and then the apparent viscosity was calculated as follows:

Hagen-Poiseuille Equation
$$-\Delta P = \frac{32\mu L \bar{v}}{D^2}$$

Where

$$\bar{v} = \frac{Q}{A} = \frac{Q}{\pi D^2/4}$$

and therefore:
$$\mu = \frac{-\Delta P \pi D^4}{128 L Q}$$

ΔP = Pressure drop (dynes/cm²)

D = Capillary diameter (cm)

L = Capillary length (cm)

Q = Volumetric Flow Rate (cm³/sec)

μ = Viscosity (poise)

As was predicted by the Brookfield viscometer tests, the viscosity was found to increase with time. The increase was found to be due to drainage of liquid from the foam, causing the foam density to decrease with time. A relationship between foam density and apparent viscosity was developed and presented in Figure 4.2.

Note the sharp rise in apparent viscosity as the foam density decreases. This effect is important because it suggests that as gas saturations in an oil reservoir increase, CO₂ mobility may actually be reduced. The strong tendency of CO₂ to channel creates regions of high gas saturation, and optimum foam generation in these areas would produce higher viscosity which would greatly inhibit further channeling.

Figure 4.2 Foam viscosity decreases as liquid content increases

The curve will be extended in future work to the region of extremely low foam density since in the limit, as the liquid content approaches zero, the viscosity should approach that of the gas alone, which is about 0.02 centipoise. Consequently, in the low-density region the viscosity must go through a maximum and then drop sharply to that of the gas. This work is underway at present.

Figure 4.3 shows the change in foam flow-rate as a function of time. This plot should be compared with Figure 4.4 which is the mass flow-rate of the foam as a function of time. The mass flow-rate decreases with time much more rapidly than the volumetric flow-rate, due to the appreciable decrease in foam density. This latter effect is shown in Figure 4.5. The data for these plots were taken at essentially constant pressure drop.

Some difficulty was encountered in measuring the foam density since it varies as it leaves the flow tube. It was calculated from foam volume measurements and foam mass values obtained by graphical integration of the mass flow-rate vs. time curve. During the tests there was some stratification of the flow stream at the higher foam densities. This stratification would affect the lower viscosity readings somewhat, but the effect would be at least an order of magnitude less than the density effect. The equipment is being modified at present so that smaller tubes and larger ΔP 's can be used to further minimize stratification errors.

Figure 4.3 Foam volumetric flow rate decreases with time in constant ΔP capillary viscometer

FOAM MASS-FLOW RATE vs. TIME

Figure 4.4 Liquid drainage increases foam viscosity and reduces foam flow rate in constant ΔP capillary viscometer

Figure 4.5 Liquid drainage is reflected in decrease in foam density with time

An alternate method of generating foam for viscosity measurement has been tested. In this method the foam is generated from liquid and gas which are passed through a bed of fine beads. It was found that a consistent foam can be obtained in this manner. The effect of the bead size on the rheology of the foam generated is now being studied.

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APPENDIX A

Surfactant Chemical Structures

<u>Surfactant</u>	<u>Chemical composition</u>	<u>Code</u>
<u>AMOCO</u>		
Cosurfactant 120	6-mole adduct of ethoxylated hexyl alcohol + distribution of higher and lower adducts	1:3
Cosurfactant 122	6-mole adduct of ethoxylated amyl alcohol + distribution of higher and lower adducts	1:4
Sulfonate 151	Sodium salt of a polybutene sulfonate with a broad equivalent wt. distribution with an average of 400-420	1:1
Sulfonate 152	Sulfonated specially treated vacuum-gas oil with a broad equivalent wt. distribution of 400-420 average	1:2
<u>Armak</u>		
Aromox C/12	bis (2-hydroxyethyl) cocoamine oxide and aqueous isopropanol	2:2
Aromox T/12	bis (2-hydroxyethyl) tallowamine oxide and aqueous isopropanol	2:1
Aromox DM16	dimethylhexadecylamine oxide and aqueous isopropanol	2:3
Aromox DMC	dimethylcocoamine oxide and aqueous isopropanol	2:4
Armeen Z	N-coco-betaaminobutyric acid	2:7
Ethomeen 18/25	$R-N \begin{matrix} \diagup (CH_2CH_2O)_x H \\ \diagdown (CH_2CH_2O)_y H \end{matrix} \quad \text{where } x+y=15$ and $R = CH_3(CH_2)_{16}-C \begin{matrix} O \\ \diagup \\ OH \end{matrix}$	2:5
Ethomeen 18/60	The same ethoxylate as above where $x+y=50$ and $R = CH_3(CH_2)_{16}-C \begin{matrix} O \\ \diagup \\ OH \end{matrix}$	2:6
<u>BASF Wyandotte</u>		
ES-179	unknown	3:23
Klearfac AA 270	phosphate ester	3:14
Klearfac AA 420	phosphate ester	3:15
Pluronic F68	$HO(CH_2CH_2O)_a \underset{\substack{ \\ CH_3}}{(CH_2CH_2O)_b} (CH_2CH_2O)_c H$ Molecular wt. = 8,350 80% poly(oxyethylene)	3:1

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<u>Surfactant</u>	<u>Chemical composition</u>	<u>Code</u>
<u>BASF Wyandotte</u>		
Pluronic F87	$\text{HO}(\text{CH}_2\text{CH}_2\text{O})_a(\text{CH}_2\text{CH}_2\text{O})_b(\text{CH}_2\text{CH}_2\text{O})_c\text{H}$ CH_3	3:2
	Molecular wt. = 7,700	
	70% poly(oxyethylene)	
Pluronic F108	" , 14,000, 80%	3:3
Pluronic L62	" , 2,500, 20%	3:4
Pluronic L64	" , 2,900, 40%	3:5
Pluronic P85	" , 4,600, 50%	3:6
Pluronic P103	" , 4,950, 30%	3:7
Pluronic P104	" , 5,850, 40%	3:8
Pluronic P105	" , 6,500, 50%	3:9
Pluronic 25R2	" , 3,120, 20%	3:10
Pluronic 25R4	" , 3,800, 40%	3:11
Pluronic 25R5	" , 4,500, 50%	3:12
Pluronic 25R8	" , 9,000, 80%	3:13
Tetronic 904	$\text{H}(\text{C}_2\text{H}_4\text{O})_y(\text{C}_3\text{H}_6\text{O})_x\text{N}(\text{C}_3\text{H}_6\text{O})_x(\text{C}_2\text{H}_4\text{O})_y\text{H}$ $\text{H}(\text{C}_2\text{H}_4\text{O})_y(\text{C}_3\text{H}_6\text{O})_x\text{N}(\text{C}_3\text{H}_6\text{O})_x(\text{C}_2\text{H}_4\text{O})_y\text{H}$	3:18
	Molecular wt. = 7,500	
	40% poly(oxyethylene)	
Tetronic 908	" , 27,000, 80%	3:19
Tetronic 1501	" , 7,900, 10%	3:20
Tetronic 1504	" , 12,500, 40%	3:21
Tetronic 1508	" , 27,000, 80%	3:22
Tetronic 50R4	$\text{H}(\text{C}_3\text{H}_6\text{O})_y(\text{C}_2\text{H}_4\text{O})_x\text{N}(\text{C}_2\text{H}_4\text{O})_x(\text{C}_3\text{H}_6\text{O})_y\text{H}$ $\text{H}(\text{C}_3\text{H}_6\text{O})_y(\text{C}_2\text{H}_4\text{O})_x\text{N}(\text{C}_2\text{H}_4\text{O})_x(\text{C}_3\text{H}_6\text{O})_y\text{H}$	3:16
	Molecular wt. = 50,000	
	40% poly(oxyethylene)	
Tetronic 150R4	" , 150,000, 40%	3:17
<u>Conoco</u>		
Alfonic 610-50	$\text{CH}_3(\text{CH}_2)_x\text{CH}_2(\text{OCH}_2\text{CH}_2)_n\text{OH}$	5:1
	where $x=4-8$, $n=3$	
Alfonic 1012-40	" , $x=8-10$, $n=2.5$	5:2
Alfonic 1012-60	" , $x=8-10$, $n=5.7$	5:3
Alfonic 1216-22	" , $x=10-14$, $n=1.2$	5:4
Alfonic 1412-40	" , $x=10-12$, $n=3$	5:5
Alfonic 1412-60	" , $x=10-12$, $n=7$	5:6
Alfonic 1218-70	" , $x=10-16$, $n=10.7$	5:7

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<u>Surfactant</u>	<u>Chemical composition</u>	<u>Code</u>
<u>Dow</u>		
Dowfax 2A1	sodium dodecyl diphenyl ether disulfonate and sodium didodecyl diphenyl ether disulfonate	6:1
Dowfax 3B2	sodium decyl diphenyl ether disulfonate and sodium didecyl diphenyl ether disulfonate	6:2
XD-8390	sodium hexadecyl diphenyl ether disulfonate	6:3
<u>Exxon</u>		
Corexit 8534	inorganic salt of oxyalkylated sulfated alcohol	7:1
<u>GAF</u>		
Alipal CD-128	nonadecyldiethoxy ammonium sulfate	8:1
Alipal CO-436	nonylphenoxypolyethoxyethanol	8:2
<u>Mona, Ind.</u>		
Monamid 150AD	$ \begin{array}{c} \text{O} \quad \text{H} \\ \parallel \quad \diagup \\ \text{R}_2 - \text{C} - \text{N} - \text{CH}_2\text{CHOH} \\ \quad \quad \quad \diagdown \\ \quad \quad \quad \text{R}_1 \end{array} \quad \& \quad \begin{array}{c} \text{O} \quad \text{CH}_2\text{CH}_2\text{OH} \\ \parallel \quad \diagup \\ \text{R}_2 - \text{C} - \text{N} - \text{CH}_2\text{CH}_2\text{OH} \\ \quad \quad \quad \diagdown \\ \quad \quad \quad \text{CH}_2\text{CH}_2\text{OH} \end{array} $	9:1
	where $\text{R}_1 = \text{H}$ or CH_3 , $\text{R}_2 =$ coconut fatty acid	
<u>Nalco</u>		
Adofoam BF-1	alcohol ether sulfate ammonium salt	10:1
Visco 1111	ethylene oxide adducts of alkylated phenols, alcohols and fatty acids	10:2
Visco 1152	3-alkoxy-2-hydroxy-N-propyl trimethyl ammonium chloride	10:3
<u>Petrochem</u>		
Morwet IP Powder	2,5-diisopropyl-8-methyl naphthalene sodium sulfonate	11:1
Petro BAF Powder	2-dodecyl-8-methyl naphthalene sodium sulfonate (25%), and 8-methyl naphthalene sodium sulfonate (75%)	11:3
Petro BAF Liquid	Same as Petro BAF Powder except in 50% aqueous solution	11:2
Petro P Powder	2-nonyl-8-methyl naphthalene sodium sulfonate (30%), and 8-methyl naphthalene sodium sulfonate (70%)	11:5
Petro P Liquid	Same as Petro P Powder except in 50% aqueous solution	11:4
Udet 950	2-dodecyl-8-methyl naphthalene sodium sulfonate (50%), and 8-methyl naphthalene sodium sulfonate (50%)	11:6

<u>Surfactant</u>	<u>Chemical composition</u>	<u>Code</u>
<u>Proctor & Gamble</u>		
Amide #27	coconut monoethanolamide	12:1
CO-1214N	fatty alcohol; 67% C ₁₂ , 6% C ₁₆	12:2
Equex AEM	ammonium lauryl ether sulfate (38%), alkanolamide (9%)	12:3
<u>Rohm & Haas</u>		
Triton X-100	octylphenyl nonylethoxy ethanol	13:1
Triton X-165	octylphenyl hexadecylethoxy ethanol	13:2
Triton X-200	sodium alkylaryl polyether sulfonate	13:3
Triton X-301	sodium alkylaryl ether sulfate	13:4
Triton X-405	octylphenyl tetracontylethoxy ethanol	13:5
<u>Shell</u>		
Neodol 23-3	C ₁₂ -C ₁₃ linear, primary alcohol propylethoxylate	14:1
Neodol 25-7	C ₁₂ -C ₁₅ linear, primary alcohol heptylethoxylate	14:2
Neodol 25-12	C ₁₂ -C ₁₅ linear, primary alcohol dodecylethoxylate	14:3
Neodol 91-2.5	C ₉ -C ₁₁ linear, primary alcohol diethoxylate	14:4
Neodol 91-8	C ₉ -C ₁₁ linear, primary alcohol octylethoxylate	14:5
<u>Union Carbide</u>		
Tergitol TMN-6	trimethyl nonyl polyethylene glycol ether	4:1
Tergitol 15-S-40	polyethylene glycol ether of linear alcohol	4:2
<u>Witco</u>		
Emcol CC37-18	unknown	15:1
Emcol CMCD	amphoteric derived from coconut oil	15:2
Sulframin AOS	alpha olefin sulfonate consisting primarily of 14-16 carbon chain dist- ribution	15:3
Sulframin 1250	linear alkylaryl sodium sulfonate	15:4
TRS X-107,203	petroleum sodium sulfonates	15:5, 15:6
301,401		15:7, 15:8
501,601		15:9, 15:10
Witcamide 5195	lauric diethanolamide	15:11
Witcolate 1247-H	unknown	15:12
Witcolate 1259	unknown	15:13
Witcolate 1276	alcohol ether sulfate	15:14

APPENDIX A

<u>Surfactant</u>	<u>Chemical Composition</u>	<u>Code</u>
<u>GAF</u>		
Alipal CO-433	nonylphenoxypoly (ethyleneoxy) ethanol sodium sulfate	8:3
Antaron FC-34	monocarboxyl coco imidazoline	8:4
Antaron PC-37	sulfated polyoxyethylene quaternary nitrogen compound	8:5
Igepal CA-420	polyethyleneoxy derivative	8:6
Igepal CA-620	polyethyleneoxy derivative	8:7
Igepal CA-720	alkylphenoxypolyoxyethylene ethanol	8:8
Igepal CO-530	nonylphenoxypolyoxyethylene ethanol	8:9
Igepal CO-720	polyethyleneoxy derivative	8:10
Igepal CO-88/	nonylphenoxypoly (ethyleneoxy) ethanol	8:11
Igepal RC-630	polyethyleneoxy derivative	8:12
<u>Conoco</u>		
Alfonic 1412A	ammonium ether sulfate	5:8
Alfonic 1412S	Sodium ether sulfate $\text{CH}_3(\text{CH}_2)_x\text{CH}_2(\text{OCH}_2\text{CH}_2)_N\text{O}_3\text{SO}_3^- \text{M}^+$ $x=10-12, N=3, M=\text{Na}^+ \text{ or } \text{NH}_4^+$	5:9
Tested, but not in Appendix A		
<u>BASF</u>		
Plurafoam DT5	ether sulfate ester	3:24
Plurafoam NO-2N	ether sulfate ester	3:25
Plurafoam N2	ether sulfate ester	3:26
Plurafac C-17	ether sulfate ester	3:27
<u>Petrochem</u>		
Petrodispersant 425		11:7
Petro Ag Special		11:8
<u>Chemical Oil Recovery Company (Corco)</u>		
COR - 188		16:1
COR - 288		16:2
COR - 305		16:3

Appendix B

Blender Foam Test

Objective:

The objective of the foam test is to measure the foamability of surfactant solutions and the stability of the resultant foams in a manner which yields accurate and reproducible results. Foamability is the initial height of the foam after generating it with a blender, and stability is the resistance of the foam to decay.

Apparatus:

The foam is generated in a Pulsmatic 10 Osterizer blender. A three inch O. D. Plexiglass tube, at least 24 inches long, is fitted to the base of the blender and used as the container for both the blending and the measurement of foam height. The surfactant concentration is usually 0.5%, but it may be specified otherwise for particular tests.

Procedure:

1. All data including surfactant name, concentration, pH, volume used, blending speed, blending time, and foam height vs. time will be recorded in one of the EOR lab data books.
2. The surfactant solutions are prepared by weighing 1.0 g of surfactant in a bottle of approximately 110 ml volume. 100 ml of brine is then added to the bottle, and the surfactant is allowed time to dissolve before it is tested. If the solution must be agitated, time must be allowed for any foam generated from the agitation to settle before the surfactant solution can be tested.

3. Before subjecting any surfactant to the blender test, the pH of the solution is adjusted to 2.5 - 2.7. Pour the 100 ml of solution from the bottle into a beaker, add 100 ml of brine, and measure the pH of the solution. Use a magnetic stirrer to maintain a well mixed system, but keep the stirring rate low to prevent foaming. Add hydrochloric acid dropwise until the pH is within the proper range.
4. Pour the pH-adjusted solution into a blender cylinder. Allow it to run down the wall rather than falling to the bottom to prevent foam generation due to pouring.
5. Prepare a table for recording foam heights such as the one below:

TIME	TOP	BOTTOM	VOLUME
(min)	(cm)	(cm)	(ml)

The time will start at 0 and end at 20 minutes.

6. Blend at puree speed for 15 seconds. Puree speed is approximately 10,000 RPM.
7. At time = 0, when the blender blades have stopped rotating, record the heights at the foam surface and the foam liquid interface. If the interface can't be seen, record it as zero initially, but do not record any value for it again until it can be seen clearly.
8. Measure the heights of the foam surface and the foam liquid interface at two-minute intervals for a period of 20 minutes.
9. After the test, rinse the cylinder well with tap water. The absence of any foam indicates the surfactant has been rinsed out. Give the column a final rinse with R. O. water and allow to drain well.

10. To calculate the foam volume, use the following information:

A column height of 1.3 cm is equivalent to a 50 ml volume.

Since the base of the cylinder is not uniform to the rest, the 3.5 cm mark is equivalent to 100 ml. The foam volume is then calculated by the formula:

$$\text{Vol} = ((\text{Top} - \text{Bottom}) \times 50) / 1.3$$

Vol is foam volume in ml

Top is height of foam surface in cm

Bottom is height of foam liquid interface in cm

In those cases where the foam liquid interface can't be seen for the initial reading (time = 0), use 3.5 as the bottom value and add 100 ml to the foam volume calculated from the above equation.

APPENDIX C

STATIC FOAM TEST DATA

0.5 wt% surfactant in brine, pH 2.5, room temperature

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN.</u>
			<u>h_0</u>	<u>$-c$</u>	
AMOCO					
Sulfonate 152	20	0.000			
Cosurfactant 120	160	0.219	127.9	0.172	4.0
Cosurfactant 122	160	0.013	91.9	0.451	1.5
ARMAK					
Aromox T/12	170	0.412	146.1	0.119	5.8
Aromox C/12	370	0.608	359.3	0.065	10.7
Aromox DM16	150	0.267	114.5	0.185	3.7
Aromox DMC	300	0.633	291.9	0.070	9.9
Ethomeen 18/25	300	0.233	291.9	0.176	3.9
Ethomeen 18/60	300	0.203	267.9	0.202	3.4
Armeen Z	190	0.158	152.3	0.251	2.8
BASF WYANDOTTE					
Pluronic F68	240	0.583	231.4	0.086	8.1
Pluronic F87	260	0.231	233.4	0.158	4.4
Pluronic F108	240	0.421	204.4	0.102	6.8
Pluronic L62	100	0.000			
Pluronic L64	200	0.000	137.2	0.471	1.5
Pluronic P85	180	0.222	154.2	0.159	4.4
Pluronic P103	190	0.316	171.2	0.128	5.4
Pluronic P104	250	0.396	216.3	0.115	6.0
Pluronic P105	250	0.380	233.9	0.110	6.3
Pluronic 25R2	130	0.000			
Pluronic 25R4	0	0.000			
Pluronic 25R5	190	0.000			
Pluronic 25R8	160	0.000			
Klearfac AA270	350	0.257	352.5	0.161	4.3
Klearfac AA420	330	0.197	284.7	0.172	4.0

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>$-c$</u>	
BASF WYANDOTTE					
Tetronic 50R4	120	0.375	107.4	0.111	6.2
Tetronic 904	250	0.220	213.1	0.162	4.3
Tetronic 908	250	0.540	241.9	0.072	9.6
Tetronic 1501	40	0.500	38.2	0.124	5.6
Tetronic 1504	220	0.318	193.5	0.106	6.5
Tetronic 1508	230	0.587	216.4	0.079	8.8
ES 179	120	0.083	56.9	0.373	1.9
CONOCO					
Alfonic 610-50	170	0.294	139.5	0.151	4.6
Alfonic 1012-40	180	0.278	152.9	0.145	4.8
Alfonic 1012-60	320	0.313	331.6	0.127	5.5
Alfonic 1216-22	170	0.471	143.0	0.116	6.0
Alfonic 1412-40	40	0.750	42.5	0.015	46.2
Alfonic 1412-60	250	0.540	275.9	0.102	6.8
Alfonic 1218-70	250	0.480	224.9	0.105	6.6
DOW					
Dowfax 2A1	290	0.483	270.4	0.088	7.9
Dowfax 3B2	290	0.328	270.6	0.149	4.7
XD-8390	310	0.323	285.9	0.142	4.9
EXXON					
Corexit 8534	380	0.539	394.6	0.090	7.7
GAF					
Alipal CD-128	450	0.356	458.5	0.057	12.2
Alipal CO-436	270	0.519	257.0	0.079	8.8
MONA					
Monamid 150AD	160	0.281	112.9	0.174	4.0
NALCO					
Adofoam BF-1	400	0.475	411.6	0.091	7.6
Visco 1111	240	0.417	219.3	0.109	6.4
Visco 1152	290	0.586	276.1	0.082	8.5

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	-c	
PETROCHEM					
Morwet IP Powder	380	0.316	365.2	0.064	10.8
Petro BAF Liquid	300	0.567	285.1	0.090	7.7
Petro BAF Powder	380	0.684	361.1	0.046	15.1
Petro P Liquid	230	0.413	197.0	0.108	6.4
Petro P Powder	270	0.463	240.7	0.088	7.9
Udet 950	350	0.714	335.1	0.049	14.1
PROCTOR & GAMBLE					
Equex AEM	300	0.500	289.0	0.080	8.7
ROHM & HAAS					
Triton X-100	330	0.303	312.1	0.156	4.4
Triton X-165	300	0.367	285.4	0.126	5.5
Triton X-200	170	0.324	133.0	0.123	5.6
Triton X-301	50	0.600	52.4	0.036	19.3
Triton X-405	270	0.426	256.4	0.098	7.1
SHELL					
Neodol 23-3	160	0.344	128.8	0.147	4.7
Neodol 25-7	260	0.462	240.0	0.096	7.2
Neodol 25-12	290	0.397	268.6	0.112	6.2
Neodol 91-2.5	170	0.294	148.6	0.169	4.1
Neodol 91-8	320	0.328	322.9	0.159	4.4
UNION CARBIDE					
Tergitol TMN-6	300	0.300	292.8	0.164	4.2
Tergitol 15-S-40	320	0.328	308.0	0.126	5.5
WITCO					
Emcol CC37-18	330	0.545	314.5	0.093	7.5
Emcol CMCD	290	0.586	269.5	0.075	9.2
Sulframin AOS	310	0.468	288.6	0.100	6.9
Sulframin 1250	200	0.700	185.4	0.055	12.6
TRS X-107	60	0.083	50.0	0.219	3.2
TRS X-203	80	0.000	62.1	0.228	3.0
TRS X-301	20	0.000			

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>$-c$</u>	
WITCO					
TRS X-401	40	0.000	40.0	0.347	2.0
TRS X-501	90	0.278	68.8	0.172	4.0
TRS X-601	50	0.000	44.5	0.287	2.4
Witcolate 1247-H	410	0.610	419.9	0.054	12.8
Witcolate 1259	500	0.380	520.9	0.066	10.5
Witcolate 1276	410	0.573	399.7	0.080	8.7

APPENDIX C

STATIC FOAM TEST DATA

0.5 wt% surfactant in brine, neutral pH, room temperature

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	-c	
Sulfonate 151	140	0.071	99.5	0.344	2.0
Sulfonate 152	60	0.250	52.8	0.148	4.7
Cosurfactant 120	250	0.040	124.1	0.422	1.6
Cosurfactant 122	220	0.046	123.1	0.464	1.5
ARMAK					
Aromox T/12	130	0.154	104.9	0.281	2.5
Aromox C/12	330	0.576	316.7	0.074	9.4
Aromox DM16	270	0.593	250.7	0.063	11.0
Aromox DMC	450	0.467	403.3	0.115	6.0
Ethomeen 18/25	210	0.143	172.2	0.191	3.6
Ethomeen 18/60	250	0.160	194.6	0.227	3.1
Armeen Z	270	0.407	241.2	0.128	5.4
BASF WYANDOTTE					
Pluronic F68	270	0.333	241.4	0.123	5.6
Pluronic F87	270	0.259	241.8	0.160	4.3
Pluronic F108	240	0.500	222.2	0.087	8.0
Pluronic L62	120	0.000			
Pluronic L64	190	0.026	136.8	0.511	1.4
Pluronic P85	270	0.296	231.9	0.177	3.9
Pluronic P103	240	0.292	217.2	0.143	4.8
Pluronic P104	280	0.321	264.7	0.133	5.2
Pluronic P105	270	0.296	241.5	0.138	5.0
Pluronic 25R2	110	0.000			
Pluronic 25R4	120	0.000			
Pluronic 25R5	180	0.000			
Pluronic 25R8	130	0.015	91.3	0.523	1.3
Klearfac AA270	310	0.194	309.3	0.164	4.2
Klearfac AA420	210	0.262	194.2	0.160	4.3

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>$-c$</u>	
BASF WYANDOTTE					
Tetronic 50R4	70	0.000			
Tetronic 150R4	170	0.000	104.8	0.471	1.5
Tetronic 904	280	0.161	254.1	0.206	3.4
Tetronic 908	260	0.462	246.1	0.087	8.0
Tetronic 1501	40	0.500	43.9	0.071	9.8
Tetronic 1504	210	0.429	186.5	0.101	6.9
Tetronic 1508	240	0.542	227.2	0.081	8.6
ES 179	120	0.417	56.9	0.373	1.9
CONOCO					
Alfonic 610-50	210	0.286	170.8	0.144	4.8
Alfonic 1012-40	180	0.250	146.4	0.175	4.0
Alfonic 1012-60	270	0.389	238.2	0.115	6.0
Alfonic 1216-22	170	0.471	141.3	0.107	6.5
Alfonic 1412-40	140	0.357	102.8	0.154	4.5
Alfonic 1412-60	240	0.542	217.2	0.074	9.4
Alfonic 1218-70	240	0.500	219.4	0.097	7.1
DOW					
Dowfax 2A1	310	0.548	298.6	0.074	9.4
Dowfax 3B2	340	0.324	269.2	0.177	3.9
XD-8390	310	0.355	274.9	0.169	4.1
EXXON					
Corexit 8534	350	0.600	348.7	0.068	10.2
GAF					
Alipal CD-128	530	0.321	552.2	0.067	10.3
Alipal CO-436	230	0.478	212.2	0.092	7.5
MONA					
Monamid 150AD	160	0.031	125.3	0.274	2.5
NALCO					
Adofoam BF-1	380	0.487	379.7	0.047	14.7
Visco 1111	210	0.476	184.9	0.105	6.6
Visco 1152	260	0.519	237.1	0.092	7.5

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE</u>
			<u>h_0</u>	<u>-c</u>	
PETROCHEM					
Morwet IP Powder	400	0.638	383.1	0.054	12.8
Petro BAF Liquid	300	0.667	277.3	0.063	11.0
Petro BAF Powder	440	0.682	417.1	0.057	12.2
Petro P Liquid	170	0.529	161.0	0.093	7.5
Petro P Powder	240	0.542	219.1	0.077	9.0
Udet 950	470	0.745	450.5	0.048	14.4
PROCTOR & GAMBLE					
CO-1214N	150	0.067	100.4	0.302	2.3
Equex AEM	250	0.480	235.4	0.093	7.5
ROHM & HAAS					
Triton X-100	290	0.328	271.3	0.101	6.9
Triton X-165	280	0.393	273.0	0.106	6.5
Triton X-200	80	0.750	80.7	0.019	36.5
Triton X-301	55	0.727	56.4	0.019	36.5
Triton X-405	250	0.420	224.9	0.105	6.6
SHELL					
Neodol 23-3	130	0.231	96.7	0.220	3.2
Neodol 25-7	270	0.444	239.0	0.113	6.1
Neodol 25-12	240	0.417	215.0	0.099	7.0
Neodol 91-2.5	160	0.250	135.0	0.225	3.1
Neodol 91-8	310	0.387	296.1	0.124	5.6
UNION CARBIDE					
Tergitol TMN-6	310	0.194	312.6	0.180	3.9
Tergitol 15-S-40	320	0.531	291.7	0.083	8.4
WITCO					
Emcol CC37-18	310	0.581	282.4	0.071	9.8
Emcol CMCD	330	0.606	313.8	0.067	10.3
Sulframin AOS	370	0.595	374.7	0.076	9.1
Sulframin 1250	220	0.455	193.5	0.106	6.5
TRS X-107	150	0.100	105.8	0.292	2.4
TRS X-301	130	0.077	76.3	0.338	2.1

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h₀</u>	<u>-c</u>	
WITCO					
TRS X-501	160	0.281	135.4	0.194	3.6
TRS X-601	130	0.077	85.2	0.385	1.8
Witcamide 5195	190	0.421	158.4	0.117	5.9
Witcolate 1247-H	540	0.370	599.3	0.077	9.0
Witcolate 1259	570	0.263	678.9	0.104	6.7
Witcolate 1276	400	0.550	389.2	0.075	9.2

APPENDIX C

STATIC FOAM TEST DATA

0.1 wt% surfactant in brine, neutral pH, room temperature

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	$-c$	
Sulfonate 151	15	0.000	14.1	0.432	1.6
Sulfonate 152	20	0.050	17.4	0.243	2.9
Cosurfactant 120	100	0.050	83.4	0.366	1.9
Cosurfactant 122	110	0.000	57.4	0.498	1.4
ARMAK					
Aromox T/12	20	0.500	16.2	0.104	6.7
Aromox C/12	250	0.320	215.2	0.135	5.1
Aromox DM16	190	0.421	166.3	0.117	5.9
Aromox DMC	240	0.458	220.1	0.095	7.3
Ethomeen 18/25	210	0.167	164.3	0.195	3.6
Ethomeen 18/60	180	0.278	137.7	0.172	4.0
Armeen Z	160	0.313	119.2	0.147	4.7
BASF WYANDOTTE					
Pluronic F68	160	0.000	171.3	0.816	0.8
Pluronic F87	180	0.278	153.1	0.140	5.0
Pluronic F108	210	0.238	179.7	0.206	3.4
Pluronic L62	130	0.000			
Pluronic L64	130	0.000	95.4	0.730	0.9
Pluronic P85	200	0.350	160.3	0.156	4.4
Pluronic P103	190	0.263	150.8	0.168	4.1
Pluronic P104	200	0.250	154.0	0.164	4.2
Pluronic P105	190	0.316	157.0	0.138	5.0
Pluronic 25R5	130	0.000			
Pluronic 25R8	140	0.000	51.5	0.500	1.4
Klearfac AA270	220	0.250	187.7	0.159	4.4
Klearfac AA420	160	0.250	112.9	0.174	4.0
Tetronic 50R4	50	0.000			
Tetronic 150R4	150	0.000	71.3	0.545	1.3

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>-c</u>	
BASF WYANDOTTE					
Tetronic 904	200	0.300	175.5	0.150	4.6
Tetronic 908	220	0.409	190.2	0.118	5.9
Tetronic 1501	30	0.333	24.4	0.104	6.7
Tetronic 1504	200	0.400	175.6	0.145	4.8
Tetronic 1508	220	0.409	189.8	0.146	4.7
ES 179	140	0.007	55.8	0.588	1.2
CONOCO					
Alfonic 610-50	50	0.700	51.7	0.039	17.8
Alfonic 1012-40	150	0.167	105.8	0.204	3.4
Alfonic 1012-60	220	0.364	185.4	0.120	5.8
Alfonic 1216-22	140	0.286	100.8	0.194	3.6
Alfonic 1412-40	30	0.833	28.4	0.027	25.7
Alfonic 1412-60	200	0.450	171.8	0.099	7.0
Alfonic 1218-70	190	0.421	160.2	0.126	5.5
DOW					
Dowfax 2A1	210	0.429	186.7	0.124	5.6
Dowfax 3B2	230	0.391	198.8	0.115	6.0
XD-8390	230	0.391	194.5	0.129	5.4
EXXON					
Corexit 8534	220	0.318	198.1	0.154	4.5
GAF					
Alipal CD-128	270	0.481	248.7	0.084	8.3
Alipal CO-436	230	0.348	183.0	0.141	4.9
MONA					
Monamid 150AD	140	0.000	95.3	0.421	1.6
NALCO					
Adofoam BF-1	260	0.423	225.4	0.117	5.9
Visco 1111	180	0.333	151.9	0.148	4.7
Visco 1152	170	0.353	135.6	0.113	6.1

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	-c	
PETROCHEM					
Morwet IP Powder	200	0.250	163.6	0.163	4.3
Petro BAF Liquid	90	0.556	79.7	0.061	11.4
Petro BAF Powder	100	0.600	91.2	0.084	8.3
Petro P Liquid	80	0.500	69.5	0.071	9.8
Petro P Powder	190	0.316	140.8	0.150	4.6
Udet 950	210	0.476	180.7	0.097	7.1
PROCTOR & GAMBLE					
CO-1214N	20	0.500	24.1	0.052	13.3
Equex AEM	180	0.444	146.2	0.104	6.7
ROHM & HAAS					
Triton X-100	240	0.354	211.2	0.148	4.7
Triton X-165	230	0.391	207.8	0.135	5.1
Triton X-200	80	0.563	71.5	0.056	12.4
Triton X-301	90	0.278	73.8	0.171	4.1
Triton X-405	220	0.273	173.7	0.181	3.8
SHELL					
Neodol 23-3	40	0.750	41.2	0.058	12.0
Neodol 25-7	240	0.375	198.5	0.140	5.0
Neodol 25-12	240	0.375	193.3	0.119	5.8
Neodol 91-2.5	130	0.231	91.3	0.177	3.9
Neodol 91-8	250	0.400	223.1	0.141	4.9
UNION CARBIDE					
Tergitol TMN-6	200	0.300	179.3	0.168	4.1
Tergitol 15-S-40	160	0.313	129.1	0.191	3.6
WITCO					
Emcol CC37-18	230	0.391	190.9	0.115	6.0
Emcol CMCD	220	0.409	198.5	0.112	6.2
Sulframin AOS	250	0.400	213.3	0.118	5.9
Sulframin 1250	110	0.636	106.2	0.080	8.7
TRS X-301	10	0.000	10.6	0.371	1.9

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h₀</u>	<u>-c</u>	
WITCO					
TRS X-501	30	0.500	28.1	0.104	6.7
TRS X-601	10	0.000			
Witcamide 5195	70	0.571	63.3	0.050	13.9
Witcolate 1247-H	270	0.481	245.1	0.094	7.4
Witcolate 1259	330	0.364	285.9	0.135	5.1
Witcolate 1276	250	0.560	230.7	0.086	8.1

APPENDIX C

STATIC FOAM TEST DATA
0.5 wt% surfactant in brine, neutral pH, 120°F

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	-c	
AMOCO					
Sulfonate 151	10	0.000			
Sulfonate 152	70	0.000	61.5	0.205	3.4
Cosurfactant 120	10	0.000			
ARMAK					
Aromox T/12	160	0.281	121.3	0.160	4.3
Aromox C/12	350	0.571	337.5	0.078	8.9
Aromox DML6	350	0.543	332.4	0.054	12.8
Aromox DMC	420	0.524	410.8	0.067	10.3
Ethomeen 18/25	230	0.130	195.5	0.254	2.7
Ethomeen 18/60	220	0.046	190.0	0.276	2.5
Armeen Z	190	0.605	182.9	0.052	13.3
BASF WYANDOTTE					
Pluronic F68	260	0.327	231.2	0.111	6.2
Pluronic F87	230	0.261	209.1	0.145	4.8
Pluronic F108	250	0.560	224.2	0.078	8.9
Pluronic L62	60	0.167	58.5	0.225	3.1
Pluronic L64	220	0.227	174.9	0.178	3.9
Pluronic P85	210	0.286	181.7	0.152	4.6
Pluronic P104	200	0.300	172.6	0.163	4.3
Pluronic P105	210	0.357	184.7	0.136	5.1
Pluronic 25R4	70	0.429	64.7	0.095	7.3
Pluronic 25R5	80	0.438	78.1	0.113	6.1
Pluronic 25R8	50	0.400	45.6	0.084	8.3
Klearfac AA270	240	0.000	222.8	0.413	1.7
Klearfac AA420	10	0.000			
Tetronic 150R4	140	0.071	99.9	0.309	2.2

SURFACTANT	INITIAL FOAM, ML	INITIAL ÷ FINAL	EXPONENTIAL FIT		FOAM HALF-LIFE, MIN
			h_0	-c	
BASF WYANDOTTE					
Tetronic 904	220	0.227	193.3	0.166	4.2
Tetronic 908	250	0.400	227.8	0.095	7.3
Tetronic 1504	190	0.184	152.8	0.161	4.3
Tetronic 1508	210	0.405	182.7	0.128	5.4
ES 179	150	0.067	105.8	0.292	2.3
CONOCO					
Alfonic 610-50	130	0.000	112.3	0.750	0.9
Alfonic 1012-40	150	0.100	114.6	0.281	2.5
Alfonic 1012-60	230	0.174	166.3	0.222	3.1
Alfonic 1216-22	40	0.250	35.5	0.115	6.0
Alfonic 1412-40	60	0.333	58.2	0.117	5.9
Alfonic 1412-60	230	0.239	190.2	0.159	4.4
Alfonic 1218-70	260	0.288	214.7	0.126	5.5
DOW					
Dowfax 2A1	310	0.145	284.6	0.158	4.4
Dowfax 3B2	290	0.052	263.3	0.239	2.9
XD-8390	260	0.019	237.7	0.331	2.1
EXXON					
Corexit 8534	410	0.171	424.7	0.156	4.4
GAF					
Alipal CD-128	580	0.172	650.7	0.130	5.3
Alipal CO-436	270	0.426	245.1	0.094	7.4
MONA					
Monamid 150AD	210	0.000	174.3	0.440	1.6
NALCO					
Adofoam BF-1	450	0.200	462.8	0.134	5.2
Visco 1111	110	0.455	113.0	0.076	9.1
Visco 1152	280	0.589	257.3	0.083	8.4
PETROCHEM					
Morwet IP Powder	380	0.013	420.6	0.436	1.6
Petro BAF Liquid	290	0.310	259.0	0.077	9.0

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>-c</u>	
PETROCHEM					
Petro BAF Powder	465	0.237	451.0	0.050	13.9
Petro P Liquid	200	0.175	184.1	0.159	4.4
Petro P Powder	240	0.208	226.0	0.124	5.6
Udet 950	570	0.246	618.2	0.095	7.3
PROCTOR & GAMBLE					
Amide No. 27	180	0.278	161.6	0.155	4.5
Equex AEM	280	0.607	257.2	0.069	10.0
ROHM & HAAS					
Triton X-100	250	0.140	223.5	0.240	2.9
Triton X-165	280	0.214	243.0	0.196	3.5
Triton X-200	120	0.167	113.4	0.185	3.7
Triton X-301	100	0.100	84.8	0.256	2.7
Triton X-405	230	0.196	203.6	0.196	3.5
SHELL					
Neodol 23-3	130	0.077	81.0	0.291	2.4
Neodol 25-7	220	0.182	165.2	0.209	3.3
Neodol 25-12	300	0.250	266.6	0.168	4.1
Neodol 91-2.5	130	0.000	78.5	0.324	2.1
Neodol 91-8	350	0.143	309.7	0.208	3.3
UNION CARBIDE					
Tergitol TMN-6	220	0.136	181.7	0.243	2.9
Tergitol 15-S-40	260	0.269	233.5	0.194	3.6
WITCO					
Emcol CC37-18	330	0.273	288.3	0.149	4.7
Emcol CMCD	330	0.576	313.9	0.078	8.9
Sulframin AOS	350	0.657	325.2	0.056	12.4
Sulframin 1250	330	0.303	315.1	0.053	13.1
TRS X-107	10	0.000			
TRS X-301	70	0.143	69.1	0.320	2.2
TRS X-501	15	0.000	28.0	0.180	3.9

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN[*]</u>
			<u>h_0</u>	<u>$-c$</u>	
WITCO					
Witcamide 5195	200	0.300	166.1	0.149	4.7
Witcolate 1247-H	600	0.117	734.4	0.232	3.0
Witcolate 1259	610	0.098	666.3	0.148	4.7
Witcolate 1276	590	0.127	639.9	0.152	4.6

APPENDIX _

STATIC FOAM TEST DATA

0.1 wt% surfactant in brine, neutral pH, 120°F

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>-c</u>	
AMOCO					
Sulfonate 152	10	0.000			
Cosurfactant 120	40	0.000			
Cosurfactant 122	30	0.000			
ARMAK					
Aromox T/12	10	0.000			
Aromox C/12	235	0.468	211.1	0.098	7.1
Aromox DM16	210	0.476	178.6	0.116	6.0
Aromox DMC	270	0.519	250.4	0.097	7.1
Ethomeen 18/25	235	0.043	200.1	0.254	2.7
Ethomeen 18/60	200	0.125	151.0	0.225	3.1
Armeen Z	60	0.667	58.1	0.072	9.6
BASF WYANDOTTE					
Pluronic F68	210	0.286	168.4	0.153	4.5
Pluronic F87	200	0.250	152.3	0.172	4.0
Pluronic F108	200	0.300	168.1	0.143	4.8
Pluronic L62	40	0.375	35.5	0.115	6.0
Pluronic L64	60	0.333	58.0	0.043	16.1
Pluronic P85	200	0.250	166.5	0.193	3.6
Pluronic P104	190	0.316	156.6	0.142	4.9
Pluronic P105	200	0.300	158.8	0.164	4.2
Pluronic 25R4	40	0.625	39.7	0.087	8.0
Pluronic 25R5	50	0.400	44.5	0.104	6.7
Pluronic 25R8	40	0.375	40.5	0.078	8.9
Klearfac AA270	230	0.043	194.5	0.244	2.8
Klearfac AA420	180	0.139	134.6	0.217	3.2

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>$-c$</u>	
BASF WYANDOTTE					
Tetronic 150R4	20	0.000	19.3	0.319	2.2
Tetronic 904	190	0.263	143.0	0.181	3.8
Tetronic 908	200	0.300	162.7	0.146	4.7
Tetronic 1504	165	0.242	115.3	0.179	3.9
Tetronic 1508	170	0.324	137.4	0.140	5.0
ES 179	30	0.000	24.4	0.104	6.7
CONOCO					
Alfonic 610-50	30	0.000	29.1	0.289	2.4
Alfonic 1012-40	15	0.000	14.2	0.199	3.5
Alfonic 1012-60	70	0.357	61.9	0.134	5.2
Alfonic 1216-22	10	0.000			
Alfonic 1412-40	15	0.000	15.3	0.165	4.2
Alfonic 1412-60	190	0.263	146.9	0.164	4.2
Alfonic 1218-70	200	0.300	176.0	0.192	3.6
DOW					
Dowfax 2A1	225	0.156	192.5	0.191	3.6
Dowfax 3B2	235	0.170	187.1	0.190	3.6
XD-8390	240	0.208	197.3	0.178	3.9
EXXON					
Corexit 8534	205	0.220	169.4	0.197	3.5
GAF					
Alipal CD-128	320	0.422	292.6	0.119	5.8
Alipal CO-436	230	0.370	197.7	0.131	5.3
MONA					
Monamid 150AD	160	0.000	113.6	0.383	1.8
NALCO					
Adofoam BF-1	230	0.304	198.7	0.145	4.8
Visco 1111	180	0.194	136.1	0.205	3.4
Visco 1152	220	0.364	183.3	0.141	4.9

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h₀</u>	<u>-c</u>	
PETROCHEM					
Morwet IP Powder	80	0.000	66.5	0.367	1.9
Petro BAF Liquid	150	0.400	131.9	0.110	6.3
Petro BAF Powder	210	0.381	192.2	0.105	6.6
Petro P Liquid	100	0.300	88.2	0.142	4.9
Petro P Powder	140	0.179	119.8	0.162	4.3
Udet 950	250	0.360	223.2	0.099	7.0
PROCTOR & GAMBLE					
Amide No. 27	70	0.000	69.1	0.320	2.2
Equex AEM	210	0.405	179.5	0.114	6.1
ROHM & HAAS					
Triton X-100	200	0.250	160.4	0.204	3.4
Triton X-165	220	0.250	174.9	0.177	3.9
Triton X-200	70	0.429	64.7	0.095	7.3
Triton X-301	45	0.222	40.9	0.176	3.9
Triton X-405	200	0.250	162.7	0.190	3.6
SHELL					
Neodol 23-3	10	0.000	14.8	0.380	1.8
Neodol 25-7	160	0.125	115.7	0.264	2.6
Neodol 25-12	210	0.238	160.1	0.191	3.6
Neodol 91-2.5	10	0.000			
Neodol 91-8	260	0.154	204.6	0.192	3.6
UNION CARBIDE					
Tergitol TMN-6	170	0.147	113.1	0.237	2.9
Tergitol 15-S-40	210	0.286	174.1	0.166	4.2
WITCO					
Emcol CC37-18	80	0.500	76.3	0.095	7.3
Emcol CMCD	220	0.477	183.4	0.091	7.6
Sulframin AOS	260	0.538	233.3	0.094	7.4
Sulframin 1250	220	0.386	201.3	0.090	7.7
TRS X-301	10	0.000			

<u>SURFACTANT</u>	<u>INITIAL FOAM, ML</u>	<u>INITIAL ÷ FINAL</u>	<u>EXPONENTIAL FIT</u>		<u>FOAM HALF-LIFE, MIN</u>
			<u>h_0</u>	<u>$-c$</u>	
WITCO					
TRS X-501	30	0.000	21.6	0.165	4.2
Witcamide 5195	110	0.364	94.3	0.123	5.6
Witcolate 1247-H	180	0.139	127.0	0.263	2.6
Witcolate 1259	200	0.150	174.5	0.271	2.6
Witcolate 1276	190	0.263	150.3	0.173	4.0

Appendix D

Surfactant	con., %	Additive	conc., %	foam height, cm	
				initial	after (time)
Adofoam BF1	0.5	None	0.05	23.7	16.8(10)
"	0.45	Dowfax 3B2	0.05	23.3	16.3(10)
"	0.45	Monomid 15AD	0.05	20.5	13.5(20)
"	0.45	Aromox DM16	0.05	17.1	12.1(20)
"	0.45	CO1214N	0.05	8.9	2.9(20)
Alipal CD 128	0.5	None		23.9	17.2(10)
"	0.45	Dowfax 3B2	0.05	24.1	17.6(10)
"	0.45	Monomid 150AD	0.05	23.9	23.9(10)
"	0.45	Aromox DM16	0.05	23.0	16.6(10)
"	0.45	CO 1214 N	0.45	10.8	4.6(10)
Corexit 8635	0.05	None		20.0	8.0(20)
"	0.45	CO 1214 N	0.05	9.4	3.4(20)
"	0.45	Dowfax 3B2	0.05	19.5	9.0(20)
"	0.45	Aromox DM16	0.05	13.6	7.5(20)
"	0.45	Monomid 150AD		15.0	9.0(20)
Dispersant 425	0.05	None		10.3	0(8)
ES 179	0.45	Aromox DM 16	0.05	0	
"	0.45	Monomid 150AD	0.05	6.7	0.4(10)
"	0.45	Dowfax 3B2	0.05	8.3	0.8(16)
"	0.45	Dispersant 425	0.05	1.3	0.6(20)

Surfactant	con.,%	Additive	conc.,%	foam height, cm	
				initial	after (time)
Klearfac AA270	0.05	None		10.0	2.7(20)
"	0.45	Monomid 150AD	0.05	10.4	4.5(20)
"	0.40	Monomid 150AD	0.10	10.7	4.8(20)
"	0.35	Monomid 150AD	0.15	10.5	4.7(20)
Petrochem BAF Pdr	0.5	None		18.8	13.0(16)
"	0.45	Aromox DM 16	0.05	11.3	2.2(16)
"	0.45	Aromox DM C	0.05	13.4	7.0(16)
"	0.45	Aromox T/12	0.05	13.4	7.1(16)
"	0.45	Aromox C/12	0.05	15.5	9.1(16)
"	0.45	Monomid 150AD	0.05	11.0	4.8(10)
"	0.45	Dowfax 3B2	0.05	18.5	12.5(10)
Plurafac C-17	0.5	None		10.2	2.5(20)
"	0.45	Monomid 150AD	0.05	10.4	4.4(20)
"	0.40	Monomid 150AD	0.10	10.3	4.4(20)
"	0.35	Monomid 150AD	0.15	9.8	3.9(20)
Plurafoam N2	0.5	None		20.0	3.3(20)
"	0.45	Monomid 150AD	0.05	22.9	10.8(20)
Plurafoam NO-2N	0.5	None		23.8	17.4(20)
"	0.45	Monomid 150AD	0.05	24.0	16.7(20)
Plurafoam DT5	0.5	None		23.4	8.0(20)
"	0.45	Monomid 150AD	0.05	23.2	15.9(20)
Pluronic L64	0.45	Monomid 150AD	0.05	8.0	2.2(10)
"	0.45	Dowfax 3B2	0.05	9.3	1.1(20)
"	0.45	Dispersant 425	0.05	8.9	2.7(20)

Surfactant	con., %	Additive	conc., %	foam height, cm	
				initial	after (time)
Pluronic F68	0.45	Aromox DM16	0.05	10.5	4.6(20)
"	0.45	Monomid 150AD	0.05	9.0	2.4(10)
"	0.45	Dowfax 3B2	0.05	9.8	2.9(20)
"	0.45	Petro Ag Special	0.05	9.7	3.5(20)
"	0.45	Dispersant 425	0.05	10.0	2.6(20)
Pluronic F108	0.45	Aromox DM16	0.05	10.0	3.6(20)
"	0.45	Monomid 150AD	0.05	9.2	3.0(20)
"	0.45	Dowfax 3B2	0.05	9.5	3.4(20)
"	0.45	Petro Ag Special	0.05	8.9	3.2(20)
"	0.45	Dispersant 425	0.05	9.4	3.4(20)
Pluronic F87	0.45	Aromox DM16	0.05	9.9	3.7(20)
"	0.45	Monomid 150AD	0.05	9.4	3.2(10)
"	0.45	Dowfax 3B2	0.05	9.8	1.1(20)
"	0.45	Petro Ag Special	0.05	8.8	2.1(20)
"	0.45	Dispersant 425	0.05	9.0	2.6(20)
Sulfonate 152	0.5	None		0.05	0(2)
"	0.45	Monomid 150AD	0.05	1.3	0.8(20)
"	0.45	Aromox DM15	0.05	0.4	9.2(20)
"	0.45	Dowfax 3B2	0.05	1.5	0.8(20)
"	0.45	CO 1214N	0.05	0.5	0.5(20)
Tergitol T15-S-40	0.5	None		10.1	3.6(20)
"	0.45	Dowfax 3B2	0.05	10.3	4.3(20)
"	0.45	Monomid 150AD	0.05	10.3	4.3(20)
"	0.45	CO1214N	0.05	8.3	2.3(20)
"	0.45	Aromox DM16	0.05	10.9	4.9(20)

Surfactant	con.,%	Additive	conc.,%	foam height, cm	
				initial	after (time)
Tetronic 904	0.45	Aromox DM16	0.05	9.8	3.7(10)
"	0.45	Monomid 150AD	0.05	9.6	3.1(10)
"	0.45	Dowfax 3B2	0.05	9.5	2.7(16)
"	0.45	Dispersant 425	0.05	9.5	2.5(20)
Tetronic 908	0.45	Aromox DM16	0.05	10.8	4.9(20)
"	0.45	Monomid 150AD	0.05	8.5	1.9(10)
"	0.45	Dowfax 3B2	0.05	10.0	4.1(16)
"	0.45	Dispersant 425	0.05	10.9	4.6(20)
Mdet 950	0.5	None		20.9	14.9(20)
"	0.45	CO 1214N	0.05	7.2	1.0(20)
"	0.45	Dowfax 3B2	0.05	21.1	15.1(20)
"	0.45	Aromox DM16	0.05	11.5	5.5(20)
"	0.45	Monomid 150AD	0.05	11.4	5.5(20)
"	0.45	Petro Ag Special	0.05	21.4	15.5(20)
"	0.45	Dispersant 425	0.05	20.2	13.8(20)
Witcolate 1259	0.5	ONONE	0.05	23.8	17.7(16)
"	0.45	Monomid 150AD	0.05	23.7	17.5(10)
"	0.45	Dowfax 3B2	0.05	24.0	17.8(10)
"	0.45	CO 1214N	0.05	12.9	6.9(10)
Witcolate 1247H	0.5	None		23.9	12.9(16)
"	0.45	Aromox DM16	0.05	23.9	17.7(16)

Surfactant	con.,%	Additive	conc.,%	foam height, cm	
				initial	after(time)
Witcolate 1247H	0.5	None		23.9	12.9(16)
"	0.45	Aromox DM16	0.05	23.9	17.7(16)
Witcolate 1276	0.5	None		21.5	14.5(20)
"	0.45	Aromox DM16	0.05	21.5	11.8(16)
Witcolate Sulframin	0.5	None		11.6	5.49(16)
AOS	0.45	Aromox DM16	0.05	12.0	6.0(16)