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Evaluation of Aqueous-Foam Surfactants for Geothermal Drilling Fluids

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EVALUATION OF AQUEOUS-FOAM SURFACTANTS
FOR GEOTHERMAL DRILLING FLUIDS*

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ABSTRACT

Aqueous foams are potentially useful drilling and cleanout fluids for geothermal applications. Successful use of foams requires surfactants (foaming agents) that can survive in the high-temperature geothermal environment. In this study, solutions of aqueous-foam-forming surfactants have been exposed to 260°C (500°F) and 310°C (590°F) in various chemical environments to determine if they can survive and make foams after exposure. Comparison of foams before and after exposure and the change in solution pH were used to evaluate their performance. Controlled liquid-volume-fraction foams, made in a packed-bed foam generator, were used for all tests. These tests have shown that many commercially available surfactants can survive short high-temperature cycles in mild acids, mild bases, and salt solutions as evidenced by their ability to make foams after exposure to high temperatures.

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TABLE OF CONTENTS

	<u>Page</u>
Introduction	2
Experimental	4
Results and Discussion	6
Conclusions	10
References	11

LIST OF ILLUSTRATIONS

<u>Figures</u>	<u>Page</u>
1. Aqueous Foam Generator	25
2. Foam Drainage Test	26

Tables

I Effect of 260°C - Deionized Water-Air Aging Environment on Aqueous Foams and Solutions	12
II Effect of 260°C - Deionized Water-Nitrogen Aging Environment on Aqueous Foams and Solutions	14
III Effect of 260°C-1.0M Sodium Chloride-Air Aging Environment on Aqueous Foams and Solutions	15
IV Effect of 260°C-10% Sodium Chloride 2% Calcium Chloride Brine-Air Aging Environment on Aqueous Foams and Solutions	16
V Effect of 260°C-0.1M Hydrochloric Acid-Air Aging Environment on Aqueous Foams	17
VI Effect of 260°C-0.1M Sodium Hydroxide-Air Aging Environment on Aqueous Foams	18
VII Effect of 310°C-Deionized Water-Air Aging Environ- ment on Aqueous Foams and Solutions	19
VIII Effect of 310°C-Deionized Water-Nitrogen Aging Environment on Aqueous Foams and Solutions	20
IX Effect of 310°C-Salt Solutions-Air Aging Environ- ments on Aqueous Foams and Solutions	21
X Effect of 310°C-Acidic and Basic Solutions-Air Aging Environments on Aqueous Foams	22
XI Surfactant Performance Ratings After 260°C Aging in Various Chemical Environments	23
XII Surfactant Performance Ratings After 310°C Aging in Various Chemical Environments	24

INTRODUCTION

Aqueous foam is a potentially useful drilling fluid for under-pressured geothermal reservoirs and workover fluid in many geothermal wells.^{1,2,3} Use of aqueous foams in these high temperature environments will require foaming agents or surfactants that are chemically stable and that will form stable foams at high temperatures. Some surfactants have been evaluated at high temperatures;^{4,5} however, a broad survey has not been conducted. Our interest in aqueous foams for geothermal drilling fluids led to an evaluation of more than fifty surfactants to determine their ability to withstand the combination of high temperatures and various chemical environments. Evaluation of foams made before and after the surfactant solution was exposed to high temperature was the primary tool used to evaluate their resistance to these environments. Although the test procedures and chemical environments developed for this study were selected to simulate the geothermal environment, the results are useful for other high temperature aqueous foam applications such as steam foam workover fluids for well cleanout and steam foam drives for oil recovery.⁶

The geothermal drilling environment was simulated by exposing the surfactant solutions to a seven hour cycle with a two hour hold at the maximum temperature. Maximum temperatures of 260°C (500°F) and 310°C (590°F) were used. Promising surfactants in preliminary tests were exposed to mild acids, mild bases, and salt solutions at high temperatures to simulate reservoir conditions. Foams, made with the surfactant solution before and after the solution was exposed to the high temperature cycle,

were used to determine the effects of the high temperature exposure. The foams were made in a packed column foam generator which provided small celled foams with controlled liquid volume fractions. Liquid drainage from the foams and a visual evaluation of the cell structure were used to rate the foams.³ Solution pH was also measured before and after high temperature exposure. These relatively simple tests allowed a large number of surfactants to be evaluated in various chemical environments before and after exposure to 260°C and 310°C.

Experimental

A wide variety of commercially available surfactants were evaluated including amphoteric, anionic, cationic, and nonionic types. Most surfactants were evaluated as 0.5 weight percent active solutions. A few nonionic and other ethoxylated surfactants were evaluated as 1.0 weight percent active solutions because of their poor foaming performance at the 0.5 percent level. The surfactant solutions were contained in stainless steel mud aging vessels during the high temperature cycles. 0.25 liter of solution was placed in the 0.5 liter vessels for all tests. The seven hour temperature cycle used for all tests was as follows: a) ambient to test temperature, two hours, b) hold at test temperature, two hours and c) test temperature to ambient, three hours. All cycles were programmed with linear ramps up to temperature and down to ambient. Maximum temperatures of 260°C and 310°C were used. All fifty-six of the surfactants evaluated were tested after exposure to 260°C in deionized water. If successful in the environment, they were exposed to various chemical environments at 260°C. The chemical environments included 1.0 molar sodium chloride, a 10.0 wt/% sodium chloride -2.0 wt/% calcium chloride brine, 0.1 molar hydrochloric acid, and 0.1 molar sodium hydroxide. Deionized water surfactant solutions were also evaluated with a nitrogen blanket to evaluate the effect of an oxygen free environment. Surfactants that proved successful in these tests were then evaluated at 310°C in the same environments.

Foams for evaluation were made using a packed bed foam generator. The generator was made by filling a 10 cm section of a 12 cm long 46 mm I.D. stainless tube with a coarse stainless wool packed to a density of 1.0 gm/cc. The solution and gas flow rates were controlled with fine metering valves fitted with micrometer heads. (Figure 1) This technique provided small-celled foams with controlled liquid volume fractions for evaluation. The liquid volume fraction was controlled to 0.045 ± 0.05 for all tests.

Foam drainage time, a measure of the short term or density stability of aqueous foams, was the primary quantitative test used to measure the effect of the high temperature cycles on the surfactant solutions. (Figure 2) The time to fifty percent drainage or weight loss was measured. The liquid volume fraction was determined for all foams evaluated by measuring the foam's weight and volume. The solution pH was measured before and after exposure with a Beckman Model 4500 pH meter. All data presented are the average from three tests. A qualitative visual examination of the foam cell structure after exposure also proved to be an important measure of the surfactant's usability. Ratings of good, fair, or poor cell structure were given. The ratings are defined as follows: good--small uniform cells; fair--nonuniform cell structure; poor--nonuniform cell structure with large cells.

Results and Discussion

Organic surfactants exposed to either 260°C (500°F) or 310°C (590°F) will degrade chemically. The objective of this study was not to measure chemical degradation but to determine the effect of the degradation on foams made with the surfactant solution after exposure to these high temperatures. At a given temperature exposure time is the most important factor. Our seven hour exposure cycle, with a two hour hold at the maximum temperature was selected to simulate the worst case for a foam drilling fluid in a geothermal well. If these surfactants were exposed for long times at these temperatures they would all fail. It is important to realize that only the surfactant solutions were exposed to the high temperature environment in this study. The foams were evaluated at room temperature.

One interesting result of this study was the discovery that the high temperature exposure would in some cases improve the foam properties rather than degrade them. The surfactant degradation products in these cases were profoamers which would cause longer drainage times. As might be expected many surfactants would not make foam at all after exposure, either because the surfactant was destroyed or the degradation products acted as antifoams. In a few cases we observed evidence of both pro and antifoamers from one surfactant. The evidence for this was provided by solutions that would not make fine uniform celled foams but would still give longer drainage times. This leads to an important point. As some degradation of the surfactant will occur at high temperatures the effect of the degradation products on the foams

can be more important than the amount of surfactant degraded. For this reason surfactants with similar chemical stabilities can give very different results because of the effect of the degradation products on the foam.

The effects of exposing surfactant solutions to either 260°C or 310°C in various chemical environments are presented in Tables I-X. A summary of these data are presented in Tables XI and XII for 260°C and 310°C respectively using a performance rating system. The data on the surfactant includes the chemical type, trade name, and the weight-percent activity of the solution tested. The properties before exposure, liquid drainage time and solution pH are listed next. In Tables III-VI the percent change in drainage time caused by the various chemical environments is also given. These data compare the drainage time in deionized water to the drainage time in the specified environment before exposure. The effects of the high temperature exposure are shown by the percentage change in drain time, a cell structure rating, and the change in solution pH.

A review of the data in Table I shows that more than half of the surfactants tested survived the 260°C exposure in the deionized water-air environment and were able to make good foams after exposure. Only small improvements were made by putting nitrogen over the surfactant solution--Table II. In the one molar sodium chloride solution, only one-third of the surfactants tested made good foams after the 260°C exposure--Table III. Six of the surfactants would not make foams in the sodium chloride solution before the high temperature exposure. The toughest environment

was the sodium chloride/calcium chloride brine as shown by the data in Table IV. Most of the anionic surfactants would not make foams because of the insolubility of their calcium salts. Only three surfactants made good foams after the 260°C exposure in this brine. The 0.1 molar hydrochloric acid environment also proved destructive to many surfactants as shown in Table V. Only six surfactants would make good foams after the 260°C exposure in the acid. The 260°C-0.1 molar sodium hydroxide data, Table VII, reveal a number of surfactants that would make good foams after exposure. These data are important for foam drilling applications as a high pH is usually required for corrosion control.

The effects of a 310°C exposure in the various chemical environments are presented in Tables VII-X. Only surfactants that showed promise in the 260°C tests were evaluated. As shown in Tables VII and VIII only two surfactants failed to make foam after exposure to 310°C in deionized water. The adverse effect of dissolved salts is again shown by the data on surfactants exposed to 310°C in the sodium chloride and sodium chloride-calcium chloride brines--Table IX. Only three surfactants made good foams after exposure to the sodium chloride and only one in the calcium chloride-sodium chloride brine. The effects of the acidic and basic environments at 310°C are given in Table X. Only one surfactant survived in the acid; however, six of nine made good foams after exposure in the 0.1 molar sodium hydroxide.

A summary of all testing is presented in Tables XI and XII for 260°C and 310°C using performance ratings. The ratings

are defined as follows: E-excellent, less than 20.0% decrease in drainage time with good cell structure after exposure; G-good, more than 20.0% decrease in drainage time with good cell structure; P-poor, poor cell structure; U-unsatisfactory, no foam measurements possible after exposure. The ratings show that several classes of surfactants may be suitable for high temperature applications. These include the alpha olefin sulfonates, quaternary aluminum chlorides, coco betaines, alkyl ethoxylates, alkyl aryl sulfonates, and several proprietary surfactants. Although no single surfactant was suitable for all environments, surfactants with excellent ratings in all environments tested at both 260°C and 310°C are available.

Conclusions

These tests have shown that commercially available surfactants have sufficient chemical stability in high temperature aqueous environments to be useful for geothermal drilling and cleanout fluids. Because of their relatively low cost and good performance in these tests the alpha olefin sulfonates, as a class, appear to be the best surfactants available for these applications. The alpha olefin sulfonates performed well in all environments except the sodium chloride/calcium chloride brine, and the 310°C, 0.1 M hydrochloric acid. Other surfactants including the quarternary ammonium chlorids, coco betaines, alkyl aryl sulfonates, alkyl ethoxylates and several proprietary surfactants have also shown promise in these tests. Surfactant selection for a given application will depend on cost, anticipated chemical environment, compatibility with corrosion inhibitors, and the stability of aqueous foams made with the surfactant solution in high temperature environments.

As noted earlier in this report these high temperature exposure tests can only be used to evaluate the chemical stability or survivability of the surfactant in these aqueous environments. All foam evaluation was done at room temperature. Given surfactants with sufficient chemical stability the next step is to evaluate the structural stability of aqueous foams made with these surfactants at high temperatures and pressures in a suitable autoclave. These tests are under way.

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TABLE I

EFFECT OF 260°C - DEIONIZED WATER - AIR AGING ENVIRONMENT ON AQUEOUS
FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		CHANGE IN DRAIN (%)	AFTER AGING	
			DRAINAGE TIME (MIN)	pH		CELL STRUCTURE	CHANGE IN pH
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	9.13	11.1	+ 14.9	GOOD	+ 0.01
ALPHA OLEFIN SULFONATE	SULFOTEX AOS	0.5	7.61	8.65	+ 23.9	GOOD	- 4.30
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	8.44	8.05	+ 9.1	GOOD	- 0.61
PROPRIETARY ANIONIC	THERMOPHOAM BWD	0.5	7.32	10.3	+ 21.3	GOOD	- 1.42
ALKYL ARYL SULFONATE	SUNTECK XIV	0.5	7.26	6.45	+ 19.3	GOOD	- 2.98
ANIONIC FLUORO-CHEMICAL	FC-99	0.5	7.30	6.13	+ 12.1	GOOD	- 3.00
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	7.45	6.70	+ 8.6	GOOD	- 2.49
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	8.06	5.88	- 0.6	GOOD	- 2.03
QUAT. AMMONIUM CHLORIDE	ADGEN 461	0.5	7.66	7.23	- 0.3	GOOD	- 3.17
AMPHOTERIC FLUORO-CHEMICAL	1-4357	0.5	11.30	9.49	- 34.6	GOOD	- 1.31
ALKYL ARYL SULFONATE	UDET-950	0.5	7.23	9.51	- 0.7	GOOD	- 2.48
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	7.10	6.17	- 1.3	GOOD	- 1.50
COCO BETAINE	VELVETEX BC	0.5	6.68	5.03	+ 3.3	GOOD	+ 0.73
ANIONIC FLUORO-CHEMICAL	L-4587	0.5	9.92	9.34	- 31.7	GOOD	- 6.68
ETHER SULFONATE	80-69067	0.5	6.22	5.24	+ 4.3	GOOD	- 2.22
QUAT. AMMONIUM CHLORIDE	ARQUAD C-50	0.5	6.65	6.71	- 4.4	GOOD	- 1.64
PROPRIETARY ANIONIC	S-1100	0.5	6.14	8.53	+ 3.2	GOOD	- 4.41
ETHER SULFONATE	80-69068	0.5	6.11	5.78	- 6.2	GOOD	- 2.88
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	5.34	6.85	+ 5.6	GOOD	- 3.10
PROPRIETARY	MA-943	0.5	8.29	7.24	- 32.6	FAIR	+ 1.69
ALKYL ARYL SULFONATE	NINEX N-300	0.5	10.20	6.76	- 45.3	GOOD	- 2.48
ALKYL ARYL SULFONATE	PETRO BAF	0.5	6.00	8.81	- 13.2	GOOD	- 4.01
PROPRIETARY NONIONIC	PEN-5E	1.0	3.10	5.72	+ 59.0	GOOD	- 0.27
ALKYL AMIDE SULFONATE	IGEPON TC-42	0.5	5.33	7.64	- 8.4	FAIR	- 0.25
IMIDAZOLINE AMPHOTERIC	AMPHOTERGE NEX	0.5	8.23	7.22	- 41.3	POOR	- 0.50
ALKYL ARYL SULFONATE	PETRO P	0.5	4.92	9.77	- 9.3	GOOD	- 4.28
PROPRIETARY QUATERNARY	M-QUAT 155-104	0.5	6.36	9.17	- 31.9	FAIR	- 2.49

TABLE I continued

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		CHANGE IN DRAIN (%)	AFTER AGING	
			DRAINAGE TIME (MIN)	DH		CELL STRUCTURE	CHANGE IN DH
PETROLEUM SULFONATE	SUNTECK VII	0.5	4.67	11.48	- 7.5	GOOD	- 0.07
ETHER SULFONATE	79-69005	0.5	4.43	3.64	- 3.2	GOOD	- 0.25
ETHOXYLATED QUAT. AMMONIUM	ETHOQUAD 18/25	1.0	3.59	3.87	+ 17.5	FAIR	- 0.03
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	5.52	7.20	- 26.4	GOOD	- 2.21
ETHOXYLATED AMINE	MAZEEN C-15	0.5	2.63	9.70	+ 53.6	FAIR	- 2.10
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	3.44	6.52	+ 10.7	FAIR	- 2.71
PROPRIETARY ETHOXYLATED ALCOHOL	MPD-5421	1.0	3.89	4.35	- 9.4	GOOD	- 0.72
PROPRIETARY NONIONIC	MAZAWET 77	1.0	2.86	6.77	+ 30.0	GOOD	- 3.22
PROPRIETARY AMPHOTERIC	HC-2	0.5	6.17	5.29	- 41.6	POOR	+ 3.33
PROPRIETARY ETHOXYLATED ALCOHOL	MPD-5420	1.0	4.39	5.15	- 20.7	GOOD	- 0.33
ETHOXYLATED AMINE	VARONIC K215 LC	1.0	2.83	9.62	+ 21.9	FAIR	- 2.85
PETROLEUM SULFONATE	PETROSTEP 450	0.5	3.70	7.69	- 11.6	POOR	- 1.99
PETROLEUM SULFONATE	PETROSTEP 420	0.5	4.42	10.41	- 26.7	FAIR	- 6.12
PROPRIETARY ANIONIC	HOWCO SUDS	0.5	6.70	8.46	- 52.8	FAIR	- 5.99
ETHER SULFATE	TD-1	0.5	6.38	8.42	- 55.0	FAIR	- 6.02
PROPRIETARY	MAGCOFOAMER 77	0.5	5.34	6.64	- 47.5	FAIR	- 3.00
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	2.65	5.62	+ 1.5	GOOD	- 2.05
ALKYL ETHOXYLATE	TRICOL IAL-23	1.0	3.18	6.58	- 19.2	GOOD	- 2.78
PROPRIETARY	ADOFOAM BF-1	0.5	4.31	8.43	- 43.8	GOOD	- 5.91
PROPRIETARY	MA-945	0.5	5.09	6.87	- 53.4	POOR	- 4.29
IMIDAZOLINE AMPHOTERIC	MONATERIC CA-35	0.5	6.81	7.44	————— NO FOAM —————		+ 1.12
PROPRIETARY AMPHOTERIC	AMPHO B11-34	0.5	8.48	6.18	————— NO FOAM —————		- 1.07
AMPHOTERIC FLUORO-CHEMICAL	ZONYL FSB	0.5	12.40	4.18	————— NO FOAM —————		- 0.02
IMIDAZOLINE AMPHOTERIC	AMPHOTERGE K2	0.5	10.69	9.70	————— NO FOAM —————		- 1.57
IMIDAZOLINE AMPHOTERIC	MONATERIC 1000	0.5	5.01	8.92	————— NO FOAM —————		- 1.88
ALKYL ESTER SULFONATE	LANTHANOL IAL	0.5	6.43	6.35	————— NO FOAM —————		- 2.39
ALKYL SULFONATE	ALKANOL 189S	0.5	4.37	5.97	————— NO FOAM —————		- 2.72
CATIONIC FLUORO-CHEMICAL	FC-135	0.5	————— VISCIOUS SOLUTION - COULD NOT MAKE FOAM —————				
ANIONIC FLUORO-CHEMICAL	FC-95	0.5	————— COULD NOT MAKE DESIRED LIQUID VOLUME FRACTION FOAM —————				

NOTES: 1. $0.045 \pm .005$ LIQUID VOLUME FRACTION USED FOR ALL FOAMS EVALUATED

TABLE II
EFFECT OF 260°C - DEIONIZED WATER -
NITROGEN AGING ENVIRONMENT ON AQUEOUS
FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		AFTER AGING		
			DRAINAGE TIME (MIN)	pH	CHANGE IN DRAIN %	CELL STRUCTURE	CHANGE IN pH
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	7.45	6.70	+38.2	GOOD	-1.36
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	9.13	11.12	+ 7.4	GOOD	-3.33
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	8.44	8.05	- 3.5	GOOD	-0.10
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	7.32	10.30	+ 9.7	GOOD	+0.03
ALKYL ARYL SULFONATE	UDET-950	0.5	7.23	9.51	+ 6.8	GOOD	-1.92
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	8.06	5.88	- 7.8	GOOD	-0.66
PROPRIETARY ANIONIC	S-1100	0.5	6.14	8.53	+18.4	GOOD	-3.37
ALKYL ARYL SULFONATE	NINEX N-300	0.5	10.20	6.76	-29.9	GOOD	+0.62
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	7.10	6.17	- 3.5	GOOD	-1.58
QUAT. AMMONIUM CHLORIDE	ADAGEN 461	0.5	7.66	7.23	-18.5	GOOD	-2.42
COCO BETAINE	VELVETEX BC	0.5	6.68	5.03	-13.6	GOOD	+1.91
ETHER SULFONATE	80-69068	0.5	6.11	5.78	- 6.2	GOOD	-2.51
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	5.34	6.85	+ 5.8	GOOD	-2.85
ETHER SULFONATE	79-69005	0.5	4.43	3.64	+ 9.2	GOOD	+0.82
ALKYL AMIDE SULFONATE	IGEPON TC-42	0.5	5.33	7.74	-12.2	GOOD	+1.98
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	5.52	7.20	-25.2	GOOD	+3.16
PROPRIETARY NONIONIC	PEN-5 E	1.0	3.10	5.72	+25.2	GOOD	-0.80
AMINE ETHOXYLATE	VARONIC K215 LC	1.0	3.00	9.59	+11.7	GOOD	-1.08
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	3.44	6.52	- 9.3	GOOD	+1.41
PROPRIETARY NONIONIC	MARAWET 77	1.0	2.85	5.77	+ 5.6	GOOD	-3.27
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	2.65	5.62	+10.9	GOOD	+3.80
ALKYL ETHOXYLATE	TRICOL LAL-23	1.0	3.18	6.58	+13.5	GOOD	+3.10
PROPRIETARY ANIONIC	ADOFOAM EF-1	0.5	4.31	8.43	-40.6	FAIR	-5.76
ALKYL ESTER SULFONATE	LANTHANOL LAL	0.5	6.43	6.35	—NO FOAM—		-

TABLE III
EFFECT OF 260°C - 1.0M SODIUM CHLORIDE -
AIR AGING ENVIRONMENT ON AQUEOUS
FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL			AFTER AGING		
			DRAINAGE TIME (MIN)	CHANGE IN DRAIN (%)	pH	CHANGE IN DRAIN (%)	CELL STRUCTURE	CHANGE IN pH
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	8.53	+12.1	5.13	+49.4	FAIR	-2.39
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	10.77	+18.0	11.01	- 3.2	GOOD	-4.54
PROPRIETARY ANIONIC	S-1100	0.5	6.95	+13.1	7.93	-46.6	FAIR	-3.14
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	11.32	+54.6	9.45	-18.6	GOOD	-0.24
ALPHA OLEFIN SULFONATE	LAKWAY 301-10	0.5	7.49	-11.2	7.54	+13.1	GOOD	+1.60
COCO BETAINE	VELVETEX-BC	0.5	5.89	-11.8	5.13	+14.4	GOOD	+1.79
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	6.72	+25.8	7.10	- 4.5	GOOD	-1.55
ETHER SULFONATE	80-69068	0.5	6.85	+12.1	4.68	-23.9	GOOD	+0.41
ETHER SULFONATE	79-69005	0.5	4.64	+ 4.7	3.35	+ 2.1	FAIR	+1.97
QUAT. AMMONIUM CHLORIDE	ADGEN 461	0.5	4.37	-42.9	7.89	+ 7.1	GOOD	-2.30
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	4.53	-36.2	6.67	+ 1.5	GOOD	-0.08
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	4.33	+25.8	6.53	-13.6	FAIR	-2.21
PROPRIETARY NONIONIC	PEN-5 E	1.0	3.71	+19.7	5.88	-11.0	FAIR	-0.66
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	3.18	+20.0	5.56	+ 3.8	GOOD	-1.52
PROPRIETARY NONIONIC	MARAWET-77	1.0	3.26	+14.0	6.16	+14.0	GOOD	-1.52
ALKYL ETHOXYLATE	TRICOL LAL-23	1.0	3.13	- 1.6	6.58	- 3.2	GOOD	-2.77
AMINE ETHOXYLATE	VARONIC K215 LC	1.0	2.70	-10.0	9.73	+ 9.6	FAIR	-1.68
PROPRIETARY ANIONIC	ADOFOAM BF-1	0.5	3.92	- 9.0	8.62	-38.8	POOR	4.96
ALKYL ARYL SULFONATE	NINEX N-300	0.5					NO FOAM	
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5					NO FOAM	
ALKYL ARYL SULFONATE	UDET-950	0.5					NO FOAM	
ALKYL ESTER SULFONATE	LAVIHANOL LAL	0.5					NO FOAM	
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5					NO FOAM	
ALKY L AMIDE SULFONATE	IGEPON TC-42	0.5					NO FOAM	

TABLE IV

EFFECT OF 260°C-10%/2.0% SODIUM CHLORIDE/CALCIUM CHLORIDE BRINE
- AIR AGING ENVIRONMENT ON AQUEOUS FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	DRAINAGE TIME (MIN)	ORIGINAL	pH	CHANGE IN DRAIN (%)	AFTER AGING	
				CHANGE IN DRAIN (%)			CELL STRUCTURE	CHANGE IN pH
COCO BETAINE	VELVETEX BC	0.5	7.91	+ 18.4	6.75	- 21.6	FAIR	+ 0.04
QUAT. AMMONIUM CHLORIDE	ADAGEN 461	0.5	4.64	- 39.4	9.92	+ 31.2	GOOD	- 4.09
SULFONATED QUAT. AMMONIUM	EMS-121	0.5	6.89	+ 29.0	7.67	- 13.9	GOOD	- 1.69
ETHER SULFONATE	80-69068	0.5	5.90	- 3.9	5.21	- 8.6	GOOD	- 0.60
ETHER SULFONATE	79-69005	0.5	5.24	+ 18.2	5.17	- 6.9	FAIR	- 1.83
ALKYL ETHOXYLATE	TRICOL LAL-23	1.0	3.37	+ 6.0	6.04	+ 40.6	FAIR	- 1.07
PROPRIETARY NONIONIC	MAXAWET 77	1.0	3.94	+ 37.8	9.80	+ 11.7	POOR	- 4.22
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	4.76	+ 81.7	9.62	- 9.2	FAIR	- 4.58
AMINE ETHOXYLATE	VARONIC K215LC	1.0	4.24	+ 49.8	10.21	- 0.5	POOR	- 2.72
PROPRIETARY ANIONIC	ADOFOAM BF-1	0.5	6.98	+ 61.9	8.68	- 52.3	POOR	- 3.55
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	6.17	- 13.1	9.70	NO FOAM		- 3.28
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	VERY POOR FOAM - NO MEASUREMENTS POSSIBLE					
PROPRIETARY NONIONIC	PEN-5E	1.0	VERY POOR FOAM - NO MEASUREMENTS POSSIBLE					
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	SURFACTANT SALTED OUT					
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	SURFACTANT SALTED OUT					
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	SURFACTANT SALTED OUT					
PROPRIETARY ANIONIC	THERMOPHOAM EW-D	0.5	SURFACTANT SALTED OUT					
PROPRIETARY ANIONIC	S-1100	0.5	SURFACTANT SALTED OUT					
ALKYL ARYL SULFONATE	UDFD-950	0.5	SURFACTANT SALTED OUT					
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	SURFACTANT SALTED OUT					
ALKYL ARYL SULFONATE	NINEX N-800	0.5	SURFACTANT SALTED OUT					
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	SURFACTANT SALTED OUT					
ALKYL AMIDE SULFONATE	IGEPON TC-42	0.5	SURFACTANT SALTED OUT					
ALKYL ESTER SULFONATE	LANTHANOL LAL	0.5	SURFACTANT SALTED OUT					

TABLE V

EFFECT OF 260°C - 0.1 M HYDROCHLORIC ACID - AIR AGING
ENVIRONMENT ON AQUEOUS FOAMS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		AFTER AGING	
			DRAINAGE TIME (MIN)	CHANGE IN DRAIN (%)	CHANGE IN DRAIN (%)	CELL STRUCTURE
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	4.79	- 43.2	+ 28.8	GOOD
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	4.18	- 43.9	+ 30.1	GOOD
QUAT. AMMONIUM CHLORIDE	ADGEN-461	0.5	4.69	- 38.8	+ 13.6	GOOD
COCO BETAINE	VELVETEX BX	0.5	5.32	- 20.4	- 13.3	GOOD
AMINE ETHOXYLATE	VARONIC K215LC	1.0	3.03	+ 1.0	+ 32.0	GOOD
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	4.34	- 52.5	- 8.3	GOOD
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	5.78	- 18.6	- 35.4	FAIR
PROPRIETARY ANIONIC	THERMOPHOM BW-D	0.5	3.56	- 51.4	- 3.6	HIGH DENSITY
PROPRIETARY ANIONIC	S-1100	0.5	3.83	- 37.6	- 11.0	FAIR
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	3.40	- 1.2	- 9.4	FAIR
ALKYL ETHOXYLATE	TRICOL LAL-23	1.0	2.93	- 7.9	- 11.3	POOR
ETHER SULFONATE	79-69005	0.5	5.24	+ 18.2	NO FOAM	
ALKYL ARYL SULFONATE	UDET-950	0.5	5.14	- 29.8	NO FOAM	
ETHER SULFONATE	80-69068	0.5	5.03	- 17.7	NO FOAM	
ALKYL ARYL SULFONATE	NINEX N-300	0.5	4.32	- 57.6	NO FOAM	
ALKYL AMIDE SULFONATE	IGEPON IC-42	0.5	3.92	- 26.5	NO FOAM	
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	3.91	- 51.5	NO FOAM	
PROPRIETARY NONIONIC	PEN-5E	1.0	3.68	+ 18.7	NO FOAM	
PROPRIETARY ANIONIC	ADOFOAM BF-1	0.5	3.58	- 16.9	NO FOAM	
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	2.87	- 48.0	NO FOAM	
PROPRIETARY NONIONIC	MAZAMET 77	1.0	2.81	- 1.7	NO FOAM	
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	2.77	+ 4.6	NO FOAM	
SULFONATED QUAT. AMMONIUM	EWS-121	0.5			NO FOAM	
ALKYL ESTER SULFONATE	LANTHANOL LAL	0.5			NO FOAM	

TABLE VI

EFFECT OF 260°C - 0.1 M SODIUM HYDROXIDE - AIR AGING ENVIRONMENT
ON AQUEOUS FOAMS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		AFTER AGING	
			DRAIN TIME (MIN)	CHANGE IN DRAIN (%)	CHANGE IN DRAIN (%)	CELL STRUCTURE
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	8.31	+ 11.5	+ 15.4	GOOD
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	8.45	- 7.5	+ 0.3	GOOD
ALKYL AMIDE SULFONATE	IGEPON TC-42	0.5	5.98	+ 12.2	+ 31.1	GOOD
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	7.99	- 5.3	- 7.4	GOOD
PROPRIETARY ANIONIC	S-1100	0.5	5.70	- 7.2	+ 25.3	GOOD
ALKYL ARYL SULFONATE	UDET-950	0.5	6.26	- 13.4	+ 8.1	GOOD
ALKYL ARYL SULFONATE	NINEX N-300	0.5	5.67	- 44.4	+ 4.9	GOOD
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	6.10	- 16.6	- 2.9	GOOD
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	5.25	- 34.9	- 5.9	GOOD
COCO BETAINE	VELVETEX BC	0.5	3.94	- 41.0	+ 21.8	FAIR
ETHER SULFONATE	79-69005	0.5	5.03	+ 13.5	- 16.5	FAIR
ALKYL ETHOXYLATE	WITCONOL SN-90	1.0	3.35	+ 26.4	- 2.7	GOOD
PROPRIETARY NONIONIC	MAZAWET-77	1.0	3.08	+ 7.7	+ 5.2	GOOD
ETHER SULFONATE	80-69068	0.5	6.09	- 0.3	- 51.4	FAIR
AMINE ETHOXYLATE	VARONIC K-215 LC	1.0	2.83	- 5.7	0.0	GOOD
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	3.21	- 6.7	- 11.8	FAIR
PROPRIETARY NONIONIC	PEN-5E	1.0	4.00	+ 29.0	- 30.0	GOOD
ALKYL ETHOXYLATE	TRICOL IAL-23	1.0	2.79	- 12.3	- 1.8	GOOD
PROPRIETARY ANIONIC	ADOFOAM BF-1	0.5	4.17	- 3.2	- 35.0	FAIR
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	5.78	- 18.6	— NO FOAM —	
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	5.24	- 1.9	— NO FOAM —	
QUAT. AMMONIUM CHLORIDE	ADGEN 461	0.5	5.10	- 33.4	— NO FOAM —	
ALKYL ESTER SULFONATE	LANTHANOL LAL	0.5	4.19	- 34.8	— NO FOAM —	
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	3.13	- 43.3	— NO FOAM —	

TABLE VII
EFFECT OF 310°C - DEIONIZED WATER - AIR AGING ENVIRONMENT
ON AQUEOUS FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	ORIGINAL		CHANGE IN DRAIN (%)	AFTER AGING CELL STRUCTURE	CHANGE IN pH
			DRAINAGE TIME (MIN)	pH			
QUAT. AMMONIUM CHLORIDE	ADAGEN 461	0.5	7.66	7.23	+ 19.8	GOOD	- 1.47
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	9.13	11.12	- 7.0	GOOD	- 5.56
ALKYL ARYL SULFONATE	SUNTECK XIV	0.5	7.26	6.95	+ 12.7	GOOD	- 3.05
PROPRIETARY ANIONIC	S-1100	0.5	6.14	8.53	+ 32.1	GOOD	- 4.48
ALKYL ARYL SULFONATE	UDET-950	0.5	7.23	9.51	+ 1.8	GOOD	- 6.21
ALPHA OLEFIN SULFONATE	SULFOTEX AOS	0.5	7.61	8.65	- 5.5	GOOD	- 5.34
ANIONIC FLUORO-CHEMICAL	FC-99	0.5	7.30	6.13	- 4.4	GOOD	- 2.03
ANIONIC FLUORO-CHEMICAL	L-4587	0.5	9.92	4.34	- 32.0	GOOD	- 6.49
ALKYL ARYL SULFONATE	RICHONATE 60B	0.5	8.06	5.88	- 19.3	GOOD	- 2.48
ETHER SULFONATE	80-69067	0.5	6.22	5.24	+ 2.6	GOOD	- 2.74
ETHER SULFONATE	80-69068	0.5	6.11	5.78	+ 4.1	GOOD	- 2.74
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	7.32	10.30	- 10.5	GOOD	- 1.23
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	7.95	6.70	- 24.6	GOOD	- 0.75
ALKYL ARYL SULFONATE	PETRO BAF	0.5	6.00	8.81	- 9.3	GOOD	- 1.35
ETHER SULFONATE	79-69005	0.5	4.43	3.64	+ 15.3	GOOD	+ 0.98
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	8.44	8.05	- 40.9	GOOD	- 3.10
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	5.34	6.85	- 22.3	HIGH DENSITY	- 1.80
ALKYL ARYL SULFONATE	PETRO P	0.5	4.92	9.77	- 18.1	FAIR	- 5.09
PROPRIETARY NONIONIC	PEN-5 E	1.0	3.10	5.72	+ 29.5	GOOD	- 0.71
PROPRIETARY NONIONIC	MAZAWET 77	1.0	2.86	6.77	+ 33.5	GOOD	- 2.74
ETHOXYLATED ALCOHOL	WITCONOL SN-90	1.0	2.65	5.62	+ 30.2	GOOD	+ 0.62
ETHOXYLATED ALCOHOL	TRICOL LAL-23	1.0	3.18	6.58	- 3.1	FAIR	- 2.35
COCO BETAINE	VELVETEX EX	0.5	6.68	5.03	NO FOAM		+ 2.27
AMPHOTERIC FLUORO-CHEMICAL	L-4357	0.5	11.30	9.49	NO FOAM		- 5.05

TABLE VIII

EFFECT OF 310°C - DEIONIZED WATER - NITROGEN AGING ENVIRONMENT
ON AQUEOUS FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	ORIGINAL			AFTER AGING		
		WT - % ACTIVE	DRAINAGE TIME (MIN)	pH	CHANGE IN DRAIN (%)	CFLL STRUCTURE	CHANGE IN pH
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	7.32	10.30	+ 35.2	GOOD	- 1.10
PROPRIETARY ANIONIC	S-1100	0.5	6.14	8.53	+ 41.4	GOOD	- 3.92
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	8.44	8.05	+ 2.1	GOOD	- 1.77
ALKYL ARYL SULFONATE	UDET-950	0.5	7.23	9.51	- 5.0	GOOD	- 5.16
QUAT. AMMONIUM CHLORIDE	ADAGEN 461	0.5	7.66	7.23	- 20.4	GOOD	- 1.62
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	9.13	11.12	- 33.9	GOOD	- 5.20
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	7.45	6.70	- 23.7	GOOD	- 2.89
ETHOXYLATED ALCOHOL	WITCONOL SN-90	1.0	2.65	5.62	+ 98.1	GOOD	+ 0.57
ETHER SULFONATE	80-69068	0.5	6.11	5.78	+ 14.2	GOOD	- 2.52

TABLE IX

EFFECT OF 310°C - SALT SOLUTIONS - AIR AGING ENVIRONMENT
ON AQUEOUS FOAMS AND SOLUTIONS

CHEMICAL TYPE	TRADE NAME	ORIGINAL		AFTER AGING		CHANGE IN pH
		DRAINAGE TIME (MIN)	pH	CHANGE IN DRAIN (%)	CELL STRUCTURE	
IN 1.0 M SODIUM CHLORIDE						
ALPHA OLEFIN SULFONATE	SURFLOW S-398	10.77	11.01	+ 32.2	FAIR	- 3.99
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	7.49	7.54	+ 84.6	GOOD	- 1.78
PROPRIETARY ANIONIC	S-1100	6.95	7.93	+ 93.8	FAIR	- 2.25
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	11.32	9.45	- 15.7	HIGH DENSITY	- 1.10
ETHER SULFONATE	80-69068	6.85	4.68	- 2.2	GOOD	- 0.50
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	8.53	6.91	- 40.6	POOR	- 1.56
QUAT. AMMONIUM CHLORIDE	ADGEN 461	4.37	7.89	+ 5.7	GOOD	- 1.91
ETHOXYLATED ALCOHOL	WITCONOL SN-90	3.18	5.56	NO FOAM		-
IN 10% SODIUM CHLORIDE / 2.0% CALCIUM CHLORIDE BRINE						
QUAT. AMMONIUM CHLORIDE	ADGEN 461	4.64	9.92	+ 23.7	GOOD	- 0.91
ETHOXYLATED ALCOHOL	WITCONOL SN-90	4.76	8.06	+ 3.1	POOR	- 2.71
ETHER SULFONATE	80-69068	5.90	5.21	NO FOAM		- 0.37

TABLE X
EFFECT OF 310°C - ACIDIC AND BASIC SOLUTIONS - AIR AGING ENVIRONMENTS
ON AQUEOUS FOAMS

CHEMICAL TYPE	TRADE NAME	ORIGINAL	AFTER AGING	
		DRAINAGE TIME (MIN)	CHANGE IN DRAIN (%)	CELL STRUCTURE
<u>IN 0.1 M HYDROCHLORIC ACID</u>				
QUAT. AMMONIUM CHLORIDE	ADGEN 461	4.69	+ 6.8	GOOD
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	4.18	+ 2.6	FAIR
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	3.56	+ 2.2	FAIR
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	4.79	- 39.4	FAIR
ETHER SULFONATE	80-69068	5.90	———— NO FOAM ————	
ALKYL ARYL SULFONATE	UDET-950	5.14	———— NO FOAM ————	
ALPHA OLEFIN SULFONATE	SURFLOW S-398	4.34	———— NO FOAM ————	
PROPRIETARY ANIONIC	S-1100	3.83	———— NO FOAM ————	
ETHOXYLATED ALCOHOL	WITCONOL SN-90	2.77	———— NO FOAM ————	
<u>IN 0.1 M SODIUM HYDROXIDE</u>				
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	6.10	+ 18.8	GOOD
PROPRIETARY ANIONIC	S-1100	5.10	+ 26.0	GOOD
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	7.99	- 11.6	GOOD
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	8.31	- 15.3	GOOD
ALPHA OLEFIN SULFONATE	SURFLOW S-398	8.45	- 26.1	GOOD
ALKYL ARYL SULFONATE	UDET-950	6.26	- 8.3	GOOD
ETHER SULFONATE	80-69068	6.09	- 47.3	FAIR
ETHOXYLATED ALCOHOL	WITCONOL SN-90	3.35	- 5.7	FAIR
QUAT. AMMONIUM CHLORIDE	ADGEN 461	5.10	———— NO FOAM ————	

TABLE XI
SURFACTANT PERFORMANCE RATINGS AFTER 260°C AGING IN
VARIOUS CHEMICAL ENVIRONMENTS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	WATER AIR	WATER NITROGEN	1.0 M NaCl	10/2 BRINE	0.1 M HCl	0.1 M NaOH
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	E	E	E	U	E	E
QUAT. AMMONIUM CHLORIDE	ADAGEN 461	0.5	E	E	E	E	E	U
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	E	E	E	U	E	E
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	E	E	G	U	E	E
COCO BETAINE	VELVETEX BC	0.5	E	E	E	P	E	P
PROPRIETARY ANIONIC	THERMOPHOM BW-D	0.5	E	E	E	U	P	E
ALKYL ETHOXYLATE	WITCONOL SN-90	0.5	E	E	E	P	U	E
SULFONATED QUAT. AMMONIUM	EWS-121	0.5	E	E	E	E	U	U
ETHER SULFONATE	80-69068	0.5	E	E	G	E	U	P
PROPRIETARY ANIONIC	S-1100	0.5	E	E	P	U	P	E
PROPRIETARY NONIONIC	MAZAWET-77	1.0	E	E	P	P	U	E
QUAT. AMMONIUM CHLORIDE	ARQUAD S-50	0.5	E	E	E	U	P	U
ALKYL ETHOXYLATE	TRICOL LAL-23	1.0	G	E	E	P	U	P
AMINE ETHOXYLATE	VARONIC K2151C	1.0	P	P	P	P	E	E
ALKYL ARYL SULFONATE	UDET-950	0.5	E	E	U	U	U	E
ALKYL ARYL SULFONATE	RICHONATE 60 B	0.5	E	E	U	U	U	E
PROPRIETARY NONIONIC	PEN-5E	1.0	E	E	P	U	U	G
ETHER SULFONATE	79-69005	0.5	E	E	P	P	U	P
ALKYL ARYL SULFONATE	NINEX N-300	0.5	G	G	U	U	U	E
ALKYL ARYL ETHOXYLATE	WITCONOL NP-120	1.0	P	E	P	U	P	P
PROPRIETARY ANIONIC	ADOFOAM BF-1	0.5	G	P	P	P	U	P
ALKYL AMIDE SULFONATE	IGEPON TC-42	0.5	P	E	U	U	U	P
ALKYL ARYL ETHER SULFONATE	TRITON X-200	0.5	G	G	U	U	U	U
ALKYL ESTER SULFONATE	LANTHANOL LAL	0.5	U	U	U	U	U	U

TABLE XII
SURFACTANT PERFORMANCE RATINGS AFTER 310°C AGING
IN VARIOUS CHEMICAL ENVIRONMENTS

CHEMICAL TYPE	TRADE NAME	WT - % ACTIVE	WATER AIR	WATER NITROGEN	1.0 M NaCl	10/2 BRINE	0.1 M HCl	0.1 M NaOH
QUAT. AMMONIUM CHLORIDE	ADOGEN 461	0.5	E	G	E	E	E	U
ALPHA OLEFIN SULFONATE	LAKEWAY 301-10	0.5	G	E	E	U	P	E
PROPRIETARY ANIONIC	THERMOPHOAM BW-D	0.5	E	F	P	U	P	E
PROPRIETARY ANIONIC	S-1100	0.5	F	F	P	U	U	E
ALKYL ARYL SULFONATE	UDET-950	0.5	E	F	U	U	U	E
ETHOXYLATED ALCOHOL	WITCONOL SN-90	1.0	F	F	U	P	U	P
ALPHA OLEFIN SULFONATE	SULFRAMIN 14/16 AOS	0.5	G	G	P	U	P	E
ALPHA OLEFIN SULFONATE	SURFLOW S-398	0.5	F	G	P	U	U	G
ETHER SULFONATE	80-69068	0.5	F	F	U	U	U	P

AQUEOUS FOAM GENERATOR

FIGURE 1

FOAM DRAINAGE TEST

FIGURE 2

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