FOAM CONTROL UTILIZING HYDRAULIC FORCES OF AN

ACCELERATED LIQUID SURFACE

and

CHARACTERIZATION OF DURABLE FOAMS BY

APPLICATION OF AN EXTERNAL FORCE

by

Darwin Fay Alt

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To the memory of

my mother

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V. INTRODUCTION

This thesis consists of two related but distinct studies. The first of these studies, described in Part I, was undertaken to evaluate a new method by which foaming of aerated cultures might be controlled by application of a mechanism involving hydraulic disruption and re-entrainment of the bubbles comprising foam. The second study, presented in Part II, was an attempt to develop an improved method of characterizing persistent type foams.

Foaming has frequently been a significant if not serious problem during and subsequent to treatment of domestic sewage. Foaming of aerated treatment units presents nuisance and potentially hazardous conditions for plant personnel as a result of foam accumulations soiling walls and sidewalks with slippery masses of grease. Also, anything more than the slightest breeze may carry foam considerable distances, possibly extending the nuisance to residential areas. In addition to the nuisance conditions, grease, and filth, foam is reported to have a high content of microorganisms of sewage origin and should therefore be considered as a potential health hazard due to the association of pathogenic microorganisms and sewage.

Foaming has been reported to cause interference with various processes during sewage treatment. For example,

activated sludge units are adversely affected by foaming due to interference with oxygen transfer as well as separation of substrate constituents from the active culture. Foaming has occurred in activated sludge units to such an extent that foam covered the entire aeration area to a depth of 10 feet spilling over walls onto surrounding areas for 30 feet (31).

Frequently at treatment plants where excessive foaming occurs, foams or effluents prone to foaming are discharged to receiving streams resulting in accumulations of foam below rapids or water falls. Such accumulations mar the aesthetic quality of natural watercourses and in some instances impair stream usage for recreational purposes. Accumulations of foam also interfere with oxygen transfer during the natural process of stream re-aeration.

Foaming is a serious problem in certain aerated industrial fermentations such as those employed in the pharmaceutical industry. Bungay et al (8) have reported that severe foaming during the fermentation of antibiotics may cause contamination or loss of material, either of which results in decreased yields of antibiotic. During the processing of synthetic rubber, foaming has been observed to fill up reactors, reducing volume for product and wasting material through overflow (1). Foaming of certain industrial processes can in some instances create serious safety hazards

such as in the handling of hot caustic soda solutions. Other industrial processes including dyeing of textiles, sizing of paper, and compounding of paints are examples where foaming causes interferences with processing operations (1).

Various methods have been employed to reduce or control the amount of foaming in aerated vessels. During waste treatment, water sprays and antifoam chemicals have been used with varying degrees of success either singularly or in combination. These methods have not been entirely satisfactory because of limited effectiveness or excessive cost. In addition, antifoam preparations may interfere with oxygen transfer and/or the activity of the culture and may constitute an undesirable constituent for discharge to natural water courses. Foaming of activated sludge units has been controlled at some plants by adjustment of mixed liquor culture concentration. The nature or strength of raw waste and plant design features limit the effectiveness of this procedure. Satisfactory results have been reported with mechanical methods of foam control in some industrial applications. These include such methods as beating foam with rotating paddles and centrifuging foam in revolving drums. A fairly recent method, which employs ultrasonic waves to break foam bubbles, is currently employed in detergent filling lines at two leading detergent manufacturers in the United States (2). The large majority

of troublesome foams in industrial applications are treated by antifoam agents. The problem has not been entirely resolved by these chemicals since the variety of industries with foaming problems have necessitated a vast number of antifoam agents. Finding the defoamer best suited for the specific application, optimum concentrations to use, and the most satisfactory method to control application remain as problems to be solved in many processes.

The initial experiments described in Part I of this thesis were conducted in an attempt to develop an improved method of controlling foaming in aerated cultures that would neither alter plant operation nor interfere with culture performance. The method of control was visualized to occur in two steps: 1) partial hydraulic disruption of foam at the liquid-foam interface by differential shearing forces between the two phases when motion was imparted to the liquid, and 2) re-entrainment of foam bubbles with subsequent collapse when returned to the bulk solution by means of a down-flow draft tube. The method appeared to be successful on a short term basis and prompted redesign and expansion of the experimental unit for larger scale, longer term experimentation. Further studies after redesigning the unit revealed development of resistant foam that defied control during extended periods of operation.

During the initial studies, an attempt was made to classify foams as to applicability for treatment by the process but existing foam classification procedures were inadequate to enable realization of the objective. Foam stability tests are usually conducted by noting the time of decay for a definite volume of foam. However, for durable foams such as those produced by proteins and many of the synthetic detergents, the period of decay is often too long to be practical. A new method of evaluating foam properties was conceived and the research effort shifted to the development of the method as a dissertation. The object of this phase of investigation was the development of an improved method by which characterization of durable foams could be realized.

VI. PART I – AN EXPERIMENTAL STUDY OF FOAM CONTROL

BY HYDRAULIC DISRUPTION AND RE-ENTRAINMENT

VII. SIGNIFICANCE OF AIR ENTRAINMENT TO THE STUDY OF PART I.

A search of available literature revealed a scarcity of
published material relating to re-entrainment of froth in
flowing streams. However, literature concerning the pheno-
menon of entrainment of air in flowing water was considered
pertinent to the proposed study. Gumensky (17) concluded
from studies of air entrained in water flowing down a spill-
way of a dam that the quantity of air entrained varied di-
rectly as the square of the Froude Number. Except for the
greater influence of shear force transmission through a foam-
liquid interface, re-entrainment of foam is considered es-
sentially analogous to the phenomenon of air entrainment.

Einstein and Sibul (14) considered the phenomenon of
air entrainment analogous to the transporting of sediment
in a turbulent flowing stream except that the buoyant force
exceeds the gravitational force. Air entrainment is visual-
ized as a result of water masses which "approach the surface
at velocities which enable them to break through the water
surface, overcoming gravity and surface tension, under the
influence of their own inertia. When they drop back into
the main water body, they are apt to entrap some air which
will form bubbles inside the water." It was believed that
forces effecting entrainment of air could effect re-entrain-
ment of foam by disruption of bubbles at the foam-liquid
interface.

The visualization of shear force transmission from liquid to foam is supported by Berkman and Egloff (4), who attributed the stability of foam to the creation of a surface having a lower surface tension and a higher viscosity than that of the body of the liquid. The implication that foam viscosity is equal to or greater than the liquid suggests that significant force can be transmitted through the liquid-foam interface, especially inasmuch as the design of the downdraft aerator incorporates a convergence of flow which serves to eliminate wall friction as a barrier to foam re-entrainment. The resulting increased stress on the foam was believed to be a factor in accelerating disruption of bubbles.

VIII. METHODS OF REMOVAL OF FOAMING CONSTITUENTS

Methods previously mentioned had as their immediate ob-
jective the reduction or prevention of foaming of aerated
cultures. Other methods which subsequently control or reduce
the amount of foaming have as their primary goal the removal
of foam producing constituents such as the alkyl benzene
sulfonate (ABS) synthetic detergents.

Although normal sewage treatment methods remove signi-
ficant quantities of ABS from domestic wastes, residual con-
centrations remain in effluents causing foaming in natural
watercourses and subsequently in municipal water treatment
plants. McGauhey and Klein (26) and Laverty et al (22) have
reported about 50 to 60 per cent reduction of influent ABS
by the activated sludge process and minor reductions by plain
sedimentation or by trickling filters. Evidence at present
does not support the conclusion that conventional type treat-
ment alone will be adequate to prevent objectionable accumu-
lations in receiving waters. Eckenfelder and Barnhart (13)
have reported partial success in removal of ABS in wastes
from laundermats and small laundries. This investigation was
directed toward the anionic detergents typical of ABS and
many other commercial compounds. Methods for removal em-
ployed adsorption of the synthetic detergents by activated
carbon with subsequent coagulation using alum. Results by

this method revealed that with proper control of adsorption
and chemical coagulation substantially all of the anionic
detergents (less than 1 to 2 ppm remaining in effluents)
might be removed from laundry wastes. Carbon requirements
were reported as 7 parts carbon to 1 part detergent for opti-
mum removal of ABS. In addition, alum dosages of 1710 ppm
were required to effect proper coagulation for the production
of completely clarified effluents. Inasmuch as this method
requires considerable quantities of carbon and alum and that
removal efficiencies would apparently be less for wastes of
lower ABS concentrations than for laundry wastes, further
studies appear to be warranted to effect removal of ABS
concentrations normally encountered in domestic sewage.

One of the more recent methods showing considerable
promise is that proposed by Klein and McGauhey (21). These
authors have investigated the use of an experimental unit
which utilizes forced air to induce detergent bearing foam
and by a process called "surface stripping" removes the foam
to a secondary compartment for foam destruction. Methods of
this process employ a narrow covered tank through which air
is diffused. The excess air issuing from the liquid surface
is made to flow the length of the tank owing to the tank cover
and in doing so forces the foam to a side port emptying into
the destruction compartment. The foam is then flamed with a
burning fuel resulting in its collapse and subsequent

evaporation of entrained water. These investigations revealed foam to contain ABS concentrations as high as 380 times that of the bulk liquid or 3800 mg/l of ABS in the foam for 10 mg/l of ABS in the bulk liquid. Final effluents usually contained a residual of 1.6 to 1.8 mg/l which amounted to a little more than 80 per cent removal for an initial concentration of 10 mg/l in the influent. This method appears to have considerable merit since it not only destroys foam but removes the foaming constituent as well. However, the method is proposed by the investigators as being most suited to tertiary treatment following an activated sludge unit and, while it will apparently reduce foaming problems subsequent to treatment by this process, the recommended procedure will not alleviate the foaming problem in the activated sludge unit.

IX. EXPERIMENTAL

A. Objective

The investigation reported in this section was undertaken in an effort to develop an improved method of controlling foam accumulations in aerated fermenters. The method involved application of some basic hydraulic principles to effect acceleration at the liquid surface and to provide sufficiently large shearing forces between the liquid-foam interface. Disruption of foam, owing to these differential shearing forces between the liquid-foam phases, and re-entrainment of foam, resulting from the collection and capture of foam in a converging down-flow, were visualized as the two mechanisms with which the objective might be realized. Although the primary objective was the evaluation of the potential of the process for foam control, it was surmised that a secondary objective might be realized from successful foam control inasmuch as separation of substrate from active culture might be minimized by re-entrainment of foam - thereby effecting a more complete and uniform metabolism of the substrate.

B. Apparatus and Methods

The experimental unit employed in the foam control study consisted of a cylindrical tank 4 feet in diameter and 6 feet tall fitted with an axially mounted draft tube as illustrated in Figure 1. Downflow in the draft tube was induced by a
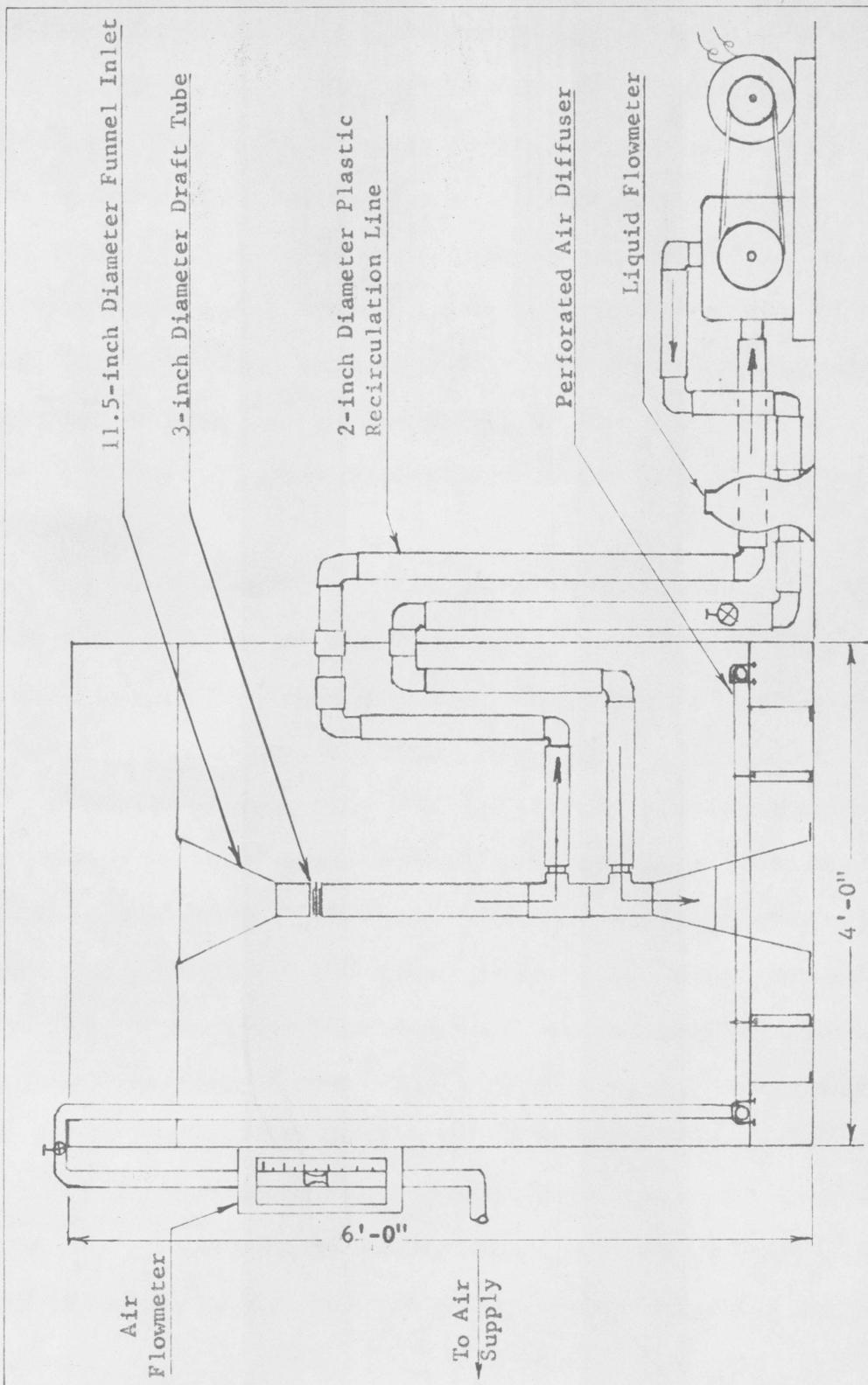
Figure 1: Sectional Sketch of Phase 1 Experimental Unit

11.5-inch Diameter Funnel Inlet

3-inch Diameter Draft Tube

2-inch Diameter Plastic Recirculation Line

Perforated Air Diffuser

Liquid Flowmeter

4'-0"

6.'-0"

Air Flowmeter

To Air Supply

variable flow rotary pump having a maximum capacity of 43
gallons per minute. The draft tube was fabricated to accom-
modate various inlet devices. The tank was fitted with a
ring sparger aeration system which was fabricated from 3/4
inch plastic pipe. The ring sparger was 3 feet in diameter
and was suspended 6 inches above the bottom of the tank.
Orifices, 1/16 inch in diameter, were bored alternately along
two rows located at the underside of the ring sparger. The
depth of liquid during typical operation was maintained at
4.5 feet.

The variables observed during experimentation included
draft tube flow rate, air flow rate, geometry of draft tube
inlets, hydraulic head on inlet, dosage of foaming agent,
solution foamability, and foam density.

Solution foamability was determined by measurement of
the height of foam formation in a lucite column having an
inside diameter of 3.75 inches. After aerating the tank con-
tents for periods of 1/2 hour, samples (2 liters each) were
transferred from the aeration tank to the lucite column. The
samples were then aerated for a period of 2.5 minutes at a
rate of 1.7 cfm. The height of foam formation was recorded
in addition to noting the physical appearance of foam with
regard to uniformity of bubble size, amount of separation
between bubbles, and the fragility characteristics of the
bubble.

Except for preliminary screening experiments, a standard alkyl benzene sulfonate compound (54.8% ABS) obtained from the Association of American Soap and Glycerine Producers, Incorporated, was employed as the foaming agent. The dosage of foaming agent employed in all experiments was 12 mg/l as ABS.

The foam control studies involved three phases. Experiments in Phase 1 employed a direct return from the recirculation pump to the tank as illustrated in Figure 1. Variables investigated during this phase include three recirculation rates, three aeration rates, and three hydraulic heads as given in the experimental outline presented as Table 1.

Experiments in Phase 2 employed gravity flow from the draft tube inlet to an open sump prior to recirculation through the pump and into the tank. This system is illustrated in the flow diagram of Figure 2. The experimental outline for Phase 2 is given in Table 2.

Experiments in Phase 3 employed recycling of the foam-liquid mixture within the tank. This was accomplished by revising the experimental unit and fitting the draft tube with a 7 inch diameter axially mounted mixing propeller. The revised unit is illustrated in the sketch of Figure 3. Four geometrically different inlet structures were employed during Phase 3 experiments. These inlets are shown on top of the operation platform of the revised unit in Figure 4.

Table 1: Phase 1 Experimental Outline
    Variables observed during Phase 1 experiments were
hydraulic head on inlets, recirculation rate, and aer-
ation rate as shown in the outline below.

Head On Inlet 1/2 inch		Head On Inlet 1/4 inch		Head On Inlet 1/8 inch	
Flow Rate	Aeration Rate	Flow Rate	Aeration Rate	Flow Rate	Aeration Rate
43 gpm	28 cfm. 21 cfm. 14 cfm.	43 gpm	28 cfm. 21 cfm. 14 cfm.	43 gpm	28 cfm. 21 cfm. 14 cfm.
30 gpm	28 cfm. 21 cfm. 14 cfm.	30 gpm	28 cfm. 21 cfm. 14 cfm.	30 gpm	28 cfm. 21 cfm. 14 cfm.
20 gpm	28 cfm. 21 cfm. 14 cfm.	20 gpm	28 cfm. 21 cfm. 14 cfm.	20 gpm	28 cfm. 21 cfm. 14 cfm.

Table 2: Phase 2 Experimental Outline
   Variables observed during Phase 2 experiments were
recirculation rate and hydraulic head on inlet as shown
in the outline below. The aeration rate was maintained
at 21 cfm. for all experiments.

Recirculation Rate	Aeration Rate	Head On Inlet
43 gpm.	21 cfm.	0.51 inch
30 gpm.	21 cfm.	0.42 inch
20 gpm.	21 cfm.	0.34 inch
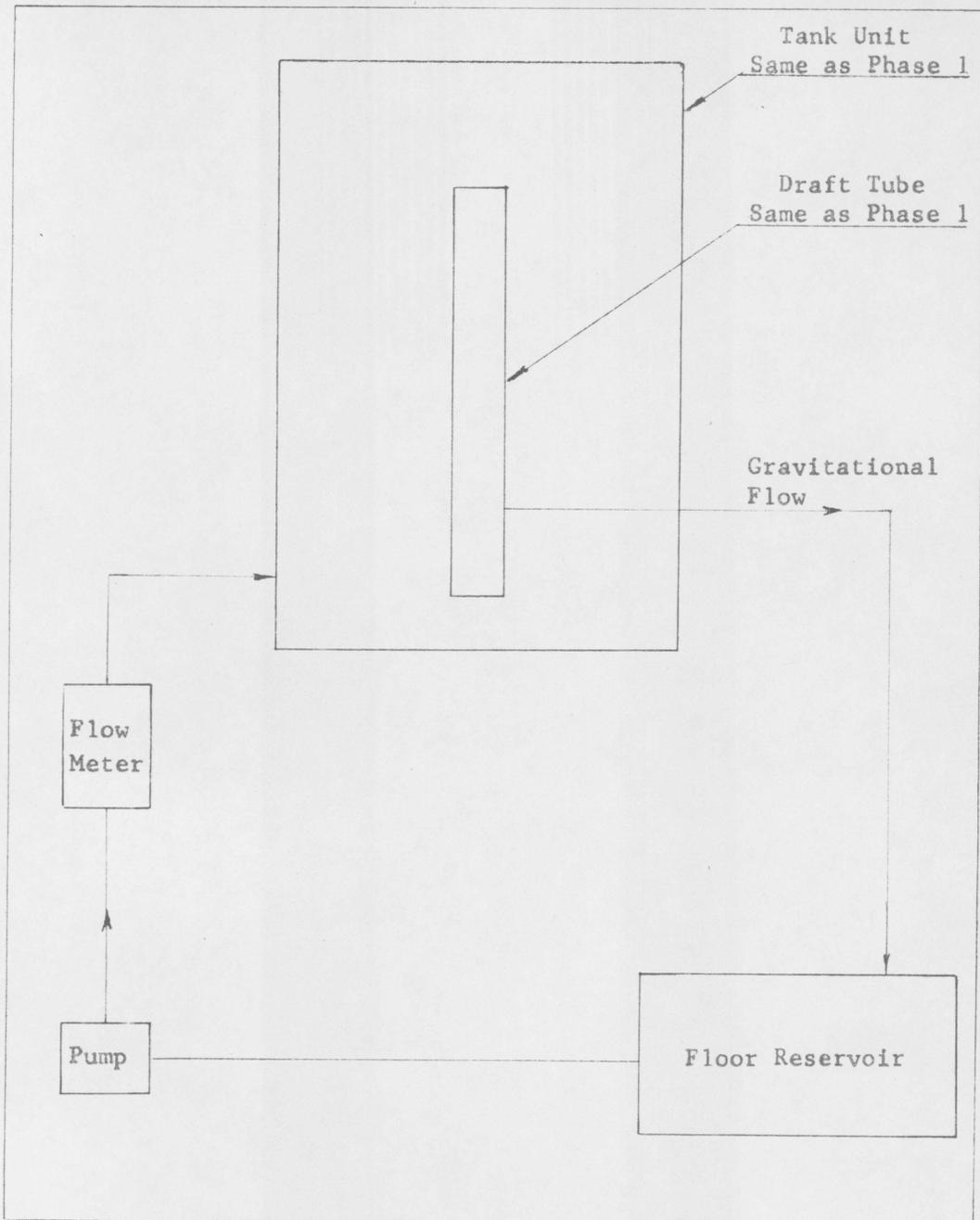
Figure 2: Flow Diagram Illustrating Phase 2 Experimental System
    Phase 2 system was identical to the system of Phase 1 ex-
cept that Phase 2 experiments employed gravitational flow to the
floor reservoir prior to recirculation into the tank unit.
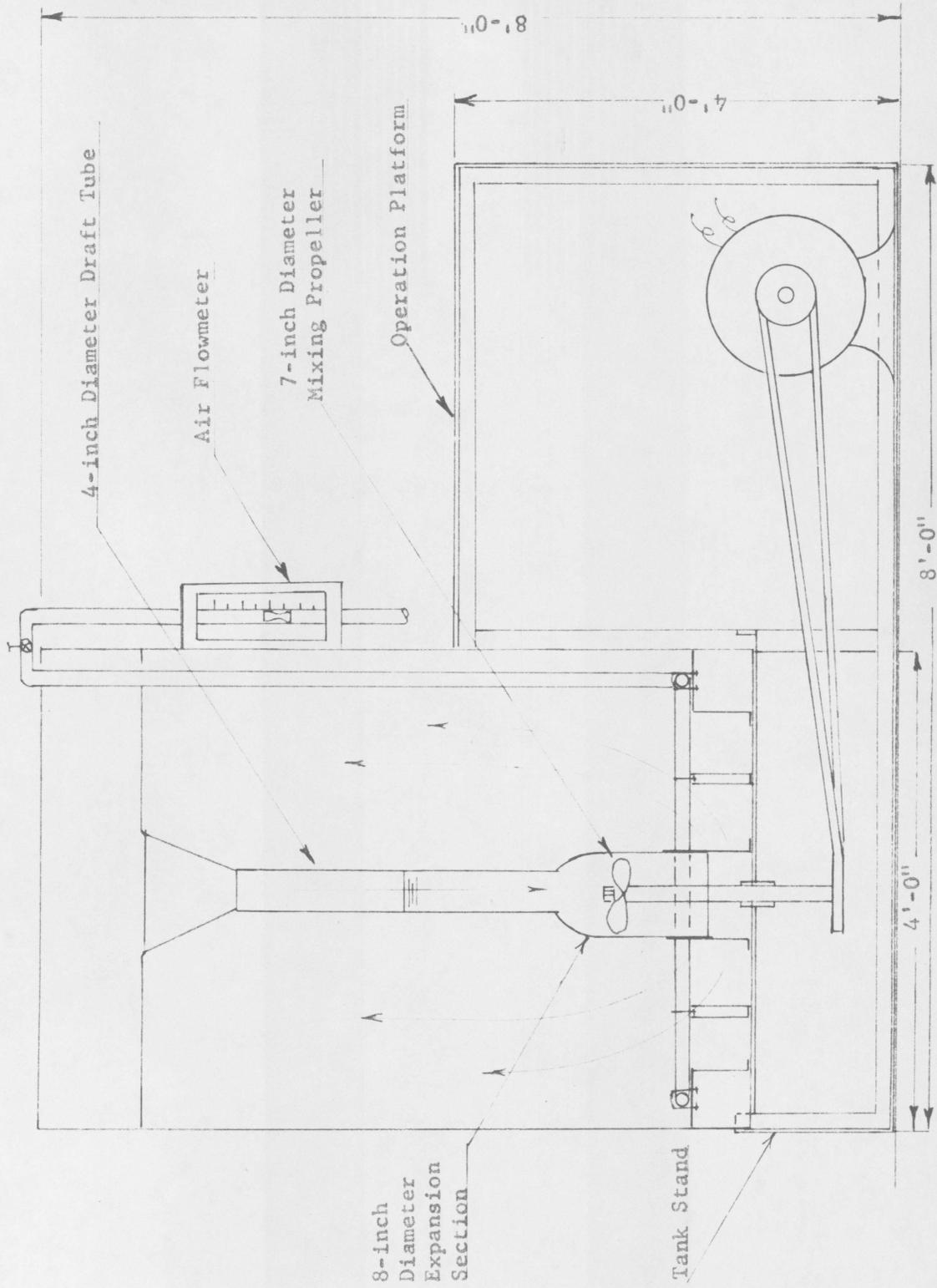
Figure 3: Sectional Sketch of Phase 3 Experimental Unit

4-inch Diameter Draft Tube

Air Flowmeter

7-inch Diameter Mixing Propeller

Operation Platform

8-inch Diameter Expansion Section

Tank Stand

8'-0"

4'-0"

4'-0"

8'-0"

Figure 4: Phase 3 Experimental Unit and Inlet Structures
     The inlet structures have a top diameter of 12 inches
and have depths of 24, 18, 12, and 6 inches respectively
from left to right.

The experimental outline, employing the four inlet structures, for Phase 3 is presented as Table 3.

Table 3:   Phase 3 Experimental Outline

Phase 3 experiments employed four geometrically different fun-
nel shaped inlet structures to investigate foam control performance
throughout the range of flows shown in the outline in terms of pro-
peller speed and hydraulic head on inlets. The aeration rate was
maintained at 21 cfm. for all experiments.

Propeller Speed (rpm)	Funnel 1 6" Depth	Funnel 2 12" Depth	Funnel 3 18" Depth	Funnel 4 24" Depth
	Head On Inlet	Head On Inlet	Head On Inlet	Head On Inlet
340	0.50 inch 0.75 1.00	0.50 inch 0.75 1.00	0.50 inch 0.75 1.00	0.50 inch 0.75 1.00
480	0.50 0.75 1.00	0.50 0.75 1.00	0.50 0.75 1.00	0.50 0.75 1.00
630	0.50 0.75 1.00	0.50 0.75 1.00	0.50 0.75 1.00	0.50 0.75 1.00

X. RESULTS

During exploratory runs using commercial laundering preparations as foaming agents, it was observed that the tendency of the solutions to foam diminished as the aeration period was extended. Experiments were made to screen various foaming agents for foam stability properties. Illustrative results of experiments comparing foamability with time of aeration are presented in Figure 5 for the proprietory compound "Wisk" and for the standardized alkyl benzene sulfonate compound. Because of superior stability characteristics the standardized compound was employed in all subsequent experiments.

A second series of experiments was undertaken to develop an index or end point suitable to describe the performance of the unit for control of foaming. According to Bikerman (5), previous investigators had successfully described foamability of solutions in terms of either the volume of foam produced in a given time under standard conditions or the time required to produce a given volume of foam. After some investigation with both methods, the latter was selected because of the inconvenience entailed in the measurement of an irregular mass of foam.

Additional experimentation developed a method which involved the covering of the tank with plywood sheeting and
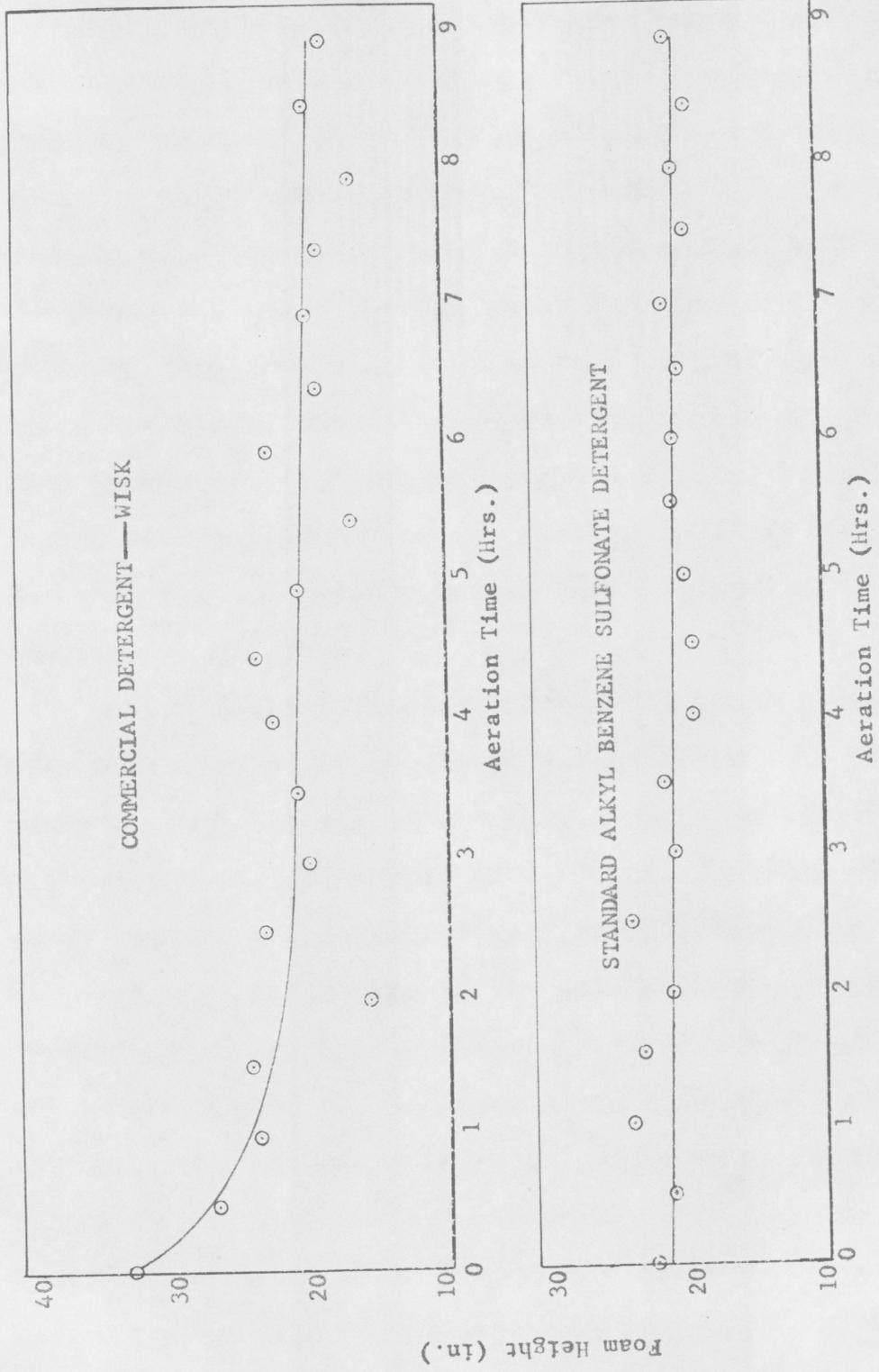
Figure 5: Results of Foamability Experiments

The results of the column foamability experiments illustrate height of foam formation after extended aeration periods for a commercial detergent-Wisk and a standard alkyl benzene sulfonate detergent.

recording the time for foam to emerge through a 1-inch dia-
meter aperture in the covering. Since the freeboard in the
tank was constant for a given series of experiments, the
observed times corresponded to comparable volumes of foam.
Results obtained from repeated determinations with the
developed end point for the three air flow rates are given in
Table 4. The time required for foam to fill the freeboard
space and emerge from the aperture decreased as the aeration
rate increased. As indicated by the figures beneath the
table, the coefficient of variability (CV) was about 7 to 8
per cent for any given aeration rate, indicating a reasonably
consistent end point.

During Phase 1 investigations, a series of experiments
were conducted to study the effect of draft tube inlet geo-
metry on foam control performance. Circular inlets (pipe
fittings) having diameters of 2, 3, and 4 inches were employ-
ed in screening experiments to compare relative performance.
Although the performance of the inlets improved with in-
creased diameter, the performance was adversely affected for
all inlets due to the tendency of foam to span or bridge the
opening. The larger diameter inlets, however, were less af-
fected by the spanning interference. Foam destruction ap-
peared to be greatest in situations where the flow at the
liquid surface was accelerated sufficiently to effect stretch-
ing of the foam laminae.

Table 4: Aeration Time for Repeated Determinations of
Three Aeration Rates

The values given in the table indicate the observed
periods of time required for foam to fill the freeboard
space and emerge through a 1-inch diameter aperture.

Aeration Rate		
14 cfm.	21 cfm.	28 cfm.
9.33 min.	4.21 min.	2.58 min.
9.74	3.46	2.41
9.25	3.56	2.16
8.89	3.99	2.54
10.56	4.13	2.30
10.44	4.09	2.61

$\bar{x} = 9.7$ $\quad\quad$ $\bar{x} = 3.91$ $\quad\quad$ $\bar{x} = 2.43$

$s = 0.68$ $\quad\quad$ $s = 0.32$ $\quad\quad$ $s = 0.17$

$CV = 7.01 \%$ $\quad\quad$ $CV = 8.18 \%$ $\quad\quad$ $CV = 7.0 \%$

where $\quad$ $\bar{x}$ = Arithmetic Mean

s = Standard Deviation

CV = Coefficient of Variation

$\quad\quad$ = $100(s)/\bar{x}$

With the objective of increasing the area of liquid ac-
celeration and to reduce the spanning effects, 18-inch diameter
flat circular flanges were affixed to the 2, 3, and 4-inch
diameter inlets previously investigated. These are shown
in Figure 6. The performance improved with increased dia-
meter but spanning of the inlets remained troublesome, parti-
cularly with the 2 and 3-inch diameter inlets.

A third series of experiments in the investigation of
the inlet geometry employed for the inlet a raked flange or
funnel 11.5 inches in diameter at the top, 3 inches in dia-
meter at the bottom, and 9 inches deep, also shown in Figure
6. Foam control performance with the inlet was observed
superior to all inlets previously tested and was therefore
employed throughout Phase 1 and Phase 2 investigations. The
performance of the inlet at maximum recirculation rate during
Phase 1 studies is illustrated in Figure 7.

Results for Phase 1 operating conditions are given in
Tables 5, 6, and 7 for the series of tests employing static
hydraulic heads of 1/8 inch, 1/4 inch, and 1/2 inch respec-
tively. Values of foam density and operative time periods
are given for experiments employing aeration alone and for
experiments employing aeration plus recirculation. The ex-
periments employing aeration alone serve as control experi-
ments in determining the time required for foam to fill the
freeboard space above the liquid due to plain aeration. The
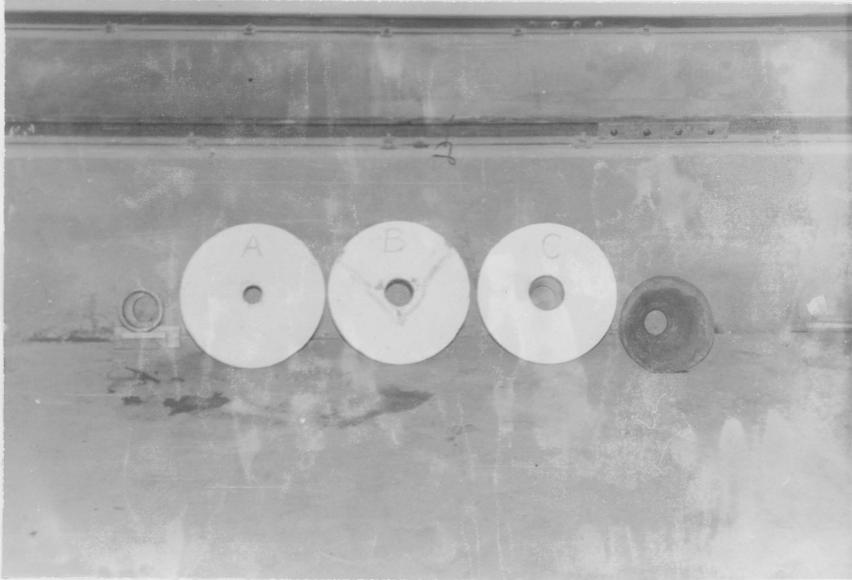
Figure 6: Inlet Structures Investigated During Phase 1
Experiments
    The photograph illustrates the five inlet struc-
tures employed in the investigation of the effects of
inlet geometry on foam control performance. The inlets
from left to right respectively are: 4-inch x 3-inch
diameter reducer, 3-inch x 2-inch diameter reducer with
18-inch diameter flange (A), 3-inch diameter coupling
with 18-inch diameter flange (B), 4-inch x 3-inch diam-
eter reducer with 18-inch diameter flange (C), and 11.5-
inch diameter funnel.

Figure 7: Foam Control Performance During Phase 1 Experiments

    The photograph illustrates foam removal for the funnel shaped inlet structure at maximum recirculation rate (43 gpm.) and intermediate aeration rate (21 cfm.) for Phase 1 experiments.

Table 5: Phase 1 Experimental Results for a Hydraulic Head of 1/8 inch
The values given in the table indicate time and foam density observed for each control experiment employing aeration alone and for each performance experiment employing both aeration and recirculation for a hydraulic head of 1/8 inch.

Flow Rate (gpm.)	Aeration Rate (cfm.)	Aeration Experiments (Control)		Recirculation Experiments (Performance)	
		Time (min.)	Density (gm/cc)	Time (min.)	Density (gm/cc)
43	14	8.39	0.00080	15.66	0.00210
		8.05	0.00055	13.54	0.00240
		7.46	0.00060	12.27	0.00225
		x̄ = 7.97	0.00065	x̄ = 13.82	0.00225
	21	3.73	0.00160	4.20	0.00370
		3.95	0.00130	3.91	0.00370
		4.58	0.00165	4.15	0.00365
		x̄ = 4.09	0.00152	x̄ = 4.09	0.00368
	28	3.69	0.00325	3.67	0.00350
		2.94	0.00235	3.55	0.00360
		2.82	0.00220	3.01	0.00350
		x̄ = 3.15	0.00260	x̄ = 3.41	0.00353
30	14	12.35	0.00015	16.84	0.00030
		10.61	0.00045	12.79	0.00045
		9.40	0.00025	11.84	0.00045
		x̄ =10.79	0.00028	x̄ = 13.82	0.00040
	21	6.50	0.00070	8.55	0.00125
		6.10	0.00120	6.72	0.00070
		5.95	0.00082	6.19	0.00097
		x̄ = 6.18	0.00091	x̄ = 7.15	0.00097
	28	5.11	0.00235	5.69	0.00240
		4.52	0.00200	4.70	0.00195
		4.04	0.00210	4.66	0.00180
		x̄ = 4.58	0.00215	x̄ = 5.02	0.00205
20	14	18.04	0.00010	19.36	0.00020
		21.16	0.00010	18.67	0.00010
		15.15	0.00020	20.85	0.00025
		x̄ =18.12	0.00013	x̄ = 19.63	0.00018
	21	8.06	0.00045	9.58	0.00070
		7.76	0.00040	9.58	0.00100
		7.38	0.00035	8.64	0.00120
		x̄ = 7.73	0.00040	x̄ = 9.27	0.00145
	28	6.40	0.00100	8.40	0.00205
		5.44	0.00155	6.78	0.00150
		5.00	0.00100	5.95	0.00120
		x̄ = 5.61	0.00115	x̄ = 7.04	0.00168

Table 6: Phase 1 Experimental Results for a Hydraulic Head of 1/4 inch
    The values given in the table indicate time and foam density observed for each control experiment employing aeration alone and for each performance experiment employing both aeration and recirculation for a hydraulic head of 1/4 inch.

Flow Rate (gpm.)	Aeration Rate (cfm.)	Aeration Experiments (Control)		Recirculation Experiments (Performance)	
		Time (min.)	Density (gm/cc)	Time (min.)	Density (gm/cc)
43	14	5.82	0.00060	9.08	0.00325
		5.29	0.00045	7.68	0.00205
		5.06	0.00040	7.88	0.00260
		x̄ = 5.39	0.00048	x̄ = 8.21	0.00263
	21	2.88	0.00215	4.12	0.00285
		2.95	0.00260	3.90	0.00370
		3.09	0.00215	3.33	0.00375
		x̄ = 2.97	0.00230	x̄ = 3.78	0.00343
	28	2.16	0.00225	2.20	0.00300
		2.23	0.00235	2.22	0.00175
		1.89	0.00300	2.20	0.00250
		x̄ = 2.09	0.00282	x̄ = 2.21	0.00242
30	14	13.53	0.00025	12.82	0.00045
		11.97	0.00035	13.14	0.00060
		12.43	0.00025	16.77	0.00025
		x̄ =12.64	0.00028	x̄ =14.24	0.00043
	21	6.08	0.00090	6.86	0.00130
		6.80	0.00125	7.26	0.00095
		5.80	0.00130	6.82	0.00110
		x̄ = 6.23	0.00115	x̄ = 6.98	0.00112
	28	3.63	0.00165	4.53	0.00180
		3.62	0.00130	4.16	0.00230
		3.57	0.00210	4.02	0.00255
		x̄ = 3.61	0.00168	x̄ = 4.24	0.00222
20	14	10.22	0.00020	12.32	0.00050
		9.08	0.00030	9.27	0.00040
		13.13	0.00030	11.87	0.00045
		x̄ =10.81	0.00023	x̄ =11.15	0.00045
	21	4.75	0.00105	5.81	0.00145
		5.15	0.00140	5.28	0.00145
		5.05	0.00125	6.10	0.00140
		x̄ = 4.98	0.00123	x̄ = 5.73	0.00143
	28	3.65	0.00140	4.24	0.00150
		3.15	0.00125	3.41	0.00210
		3.45	0.00185	3.41	0.00235
		x̄ = 3.42	0.00150	x̄ = 3.69	0.00189

Table 7: Phase 1 Experimental Results for a Hydraulic Head of 1/2 inch
The values given in the table indicate time and foam density observed for each control experiment employing aeration alone and for each performance experiment employing both aeration and recirculation for a hydraulic head of 1/2 inch.

Flow Rate (gpm.)	Aeration Rate (cfm.)	Aeration Experiments (Control)		Recirculation Experiments (Performance)	
		Time (min.)	Density (gm/cc)	Time (min.)	Density (gm/cc)
43	14	10.12	0.00045	17.07	0.00175
		12.54	0.00090	19.37	0.00190
		12.51	0.00055	21.68	0.00230
		$\bar{x}$ = 11.72	0.00063	$\bar{x}$ = 19.37	0.00198
	21	5.28	0.00130	6.75	0.00210
		5.19	0.00072	5.60	0.00225
		5.42	0.00110	5.97	0.00220
		$\bar{x}$ = 5.30	0.00104	$\bar{x}$ = 6.11	0.00218
	28	2.76	0.00220	3.07	0.00225
		2.68	0.00200	3.11	0.00185
		2.59	0.00220	2.94	0.00185
		$\bar{x}$ = 2.68	0.00213	$\bar{x}$ = 3.04	0.00198
30	14	9.33	0.00030	9.57	0.00045
		9.74	0.00025	9.18	0.00055
		9.25	0.00020	10.96	0.00055
		$\bar{x}$ = 9.44	0.00025	$\bar{x}$ = 9.90	0.00052
	21	4.21	0.00055	5.04	0.00065
		3.46	0.00090	4.02	0.00110
		3.56	0.00100	4.23	0.00096
		$\bar{x}$ = 3.74	0.00082	$\bar{x}$ = 4.43	0.00090
	28	2.58	0.00135	2.69	0.00135
		2.41	0.00230	2.88	0.00160
		2.16	0.00205	2.33	0.00155
		$\bar{x}$ = 2.37	0.00190	$\bar{x}$ = 2.63	0.00150
20	14	8.89	0.00065	9.49	0.00055
		10.56	0.00030	10.14	0.00030
		10.44	0.00025	10.44	0.00030
		$\bar{x}$ = 9.96	0.00040	$\bar{x}$ = 10.02	0.00038
	21	3.98	0.00070	4.12	0.00100
		4.13	0.00050	3.91	0.00105
		4.09	0.00070	4.61	0.00095
		$\bar{x}$ = 4.07	0.00063	$\bar{x}$ = 4.21	0.00100
	28	2.61	0.00195	2.90	0.00190
		2.54	0.00120	2.69	0.00180
		2.30	0.00140	2.35	0.00210
		$\bar{x}$ = 2.48	0.00152	$\bar{x}$ = 2.65	0.00190

experiments employing both aeration and recirculation indi-
cate the degree of foam control performance upon comparison
of the operative periods with those for plain aeration. A
significant increase in operational periods during recircula-
tion experiments suggests the degree of foam control effected
by the method.

Foam control performance for the data of Tables 5 through
7 is summarized in Table 8 as ratios of the recirculation
experimental periods to the aeration experimental periods.
These ratios were formed from the average values of time
given in Tables 5 through 7 for the conditions of hydraulic
head, aeration rate, and recirculation rates shown. The
data of Table 8 indicated that optimum foam control perfor-
mance occurred at the maximum recirculation rate of 43 gpm
and the minimum aeration rate of 14 cfm; i.e., the time re-
quired for foam to fill the freeboard space under optimum
conditions was about 1.76 times that of no recirculation
(aeration alone). For other aeration rates, the data were
inconsistent as to the effects of recirculation rate on foam
control performance. Similarly, the data exhibited incon-
sistent effects of hydraulic head on foam control performance
for recirculation rates of 30 and 43 gpm. For the recircu-
lation rate of 20 gpm, however, foam control performance
progressively declined with increased hydraulic head. During
the investigation, it was observed that the funnel inlet

Table 8: Degree of Foam Control Effected During Phase 1
Experiments

The values in the table are ratios of the average oper-
ational times of the experiments employing recirculation to
the average times for the experiments employing aeration
alone.

Recirculation Rate (gpm.)	Aeration Rate (cfm.)	Hydraulic Head		
		1/8 inch	1/4 inch	1/2 inch
43	14	1.76	1.52	1.65
	21	1.00	1.27	1.15
	28	1.08	1.06	1.13
30	14	1.28	1.13	1.05
	21	1.55	1.12	1.19
	28	1.09	1.17	1.11
20	14	1.08	1.03	1.01
	21	1.20	1.15	1.04
	28	1.25	1.08	1.07

became partially submerged during conditions of increased hydraulic head and decreased recirculation rate; hence, the declined performance for these conditions as shown in Table 8 was expected.

Foam density was measured after each control experiment employing aeration only and after each performance experiment employing both aeration and recirculation. Examination of Tables 5 through 7 indicates that for both types of experiments, foam density increased with aeration rate. However, comparison of the results for experiments employing recirculation with the experiments employing aeration alone usually indicated a significant increase in foam density during experiments employing recirculation. The increased density was especially noticeable during low hydraulic head conditions and high recirculation rates.

During the investigation, it was observed that the rotary pump used for recirculation tended to pump air in addition to foam when employing the higher flow rates and low hydraulic head conditions of operation. Hence, it was suspected that the pump may have contributed to the foaming. In an attempt to evaluate the assumption of pump induced foam, the experimental unit was operated at maximum recirculation rate and no aeration. The accumulation of a dense, shaving-lather type foam soon resulted at the liquid surface as illustrated by the milky appearing surface in Figure 8.
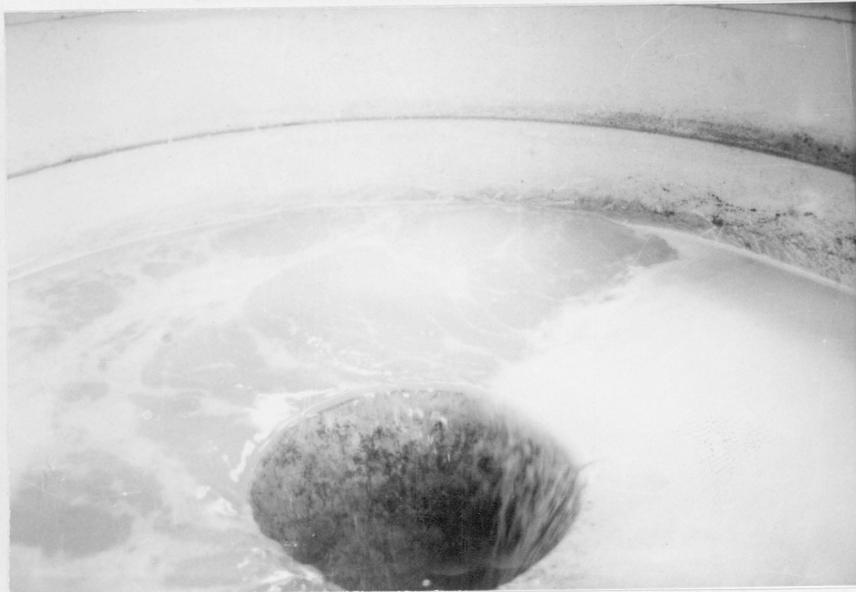
Figure 8: Pump Induced Foam During Phase 1 Experiments
    The photograph illustrates the appearance of pump
induced foam at maximum recirculation rate (43 gpm.) and
zero aeration during Phase 1 experiments.

In order to minimize pump induced foam in Phase 2 operations, the pipe arrangement was changed to allow the flow through the draft tube to discharge by gravity into a floor sump prior to recirculation into the tank by the pump. The results of the modified recirculation scheme are given in Table 9. These results indicate improved performance at all recirculation rates. The maximum degree of foam control at a flow rate of 20 gpm required up to 5.7 times the time of foam build-up recorded for the experiments employing aeration alone. For the 30 gpm and 43 gpm flow rates, the average operative periods were respectively 5.2 and 4.2 times those required for foam build-up by aeration alone. Increased recirculation rates above 20 gpm usually resulted in decreased foam control performance. However, it should be noted in reference to Table 9 that the hydraulic head, which is a function of the quantity of flow, increased as the recirculation rate increased; consequently the funnel inlet or weir structure became more submerged. Observations during earlier investigations revealed foam control performance to be hindered by submergence of the inlet structure.

The effect of Phase 2 operating conditions upon foam density may be observed from a comparison of the results presented in Table 9 for Phase 2 with those of Tables 5 through 7 for Phase 1. For an aeration rate of 21 cfm, Phase 1 generally exhibited foam densities during

Table 9:   Phase 2 Experimental Results
    The values given in the table indicate time and foam density ob-
served for each control experiment employing aeration alone and for
each performance experiment employing both aeration and recirculation.
The aeration rate was maintained at 21 cfm. for all experiments.

Flow Rate	Head On Inlet	Aeration Experiments (Control)		Recirculation Experiments (Performance)	
(gpm.)	(inch)	Time (min.)	Density (gm/cc)	Time (min.)	Density (gm/cc)
	0.52	9.63	0.00052	28.63	0.00025
43	0.48	7.28	0.00060	38.40	0.00010
	0.52	7.63	0.00035	36.71	0.00015
	$\bar{x}$ = 0.51	8.18	0.00049	34.58	0.00017
	0.41	6.87	0.00065	34.83	0.00020
30	0.43	7.93	0.00035	41.45	0.00010
	0.42	7.39	0.00050	39.60	0.00013
	$\bar{x}$ = 0.42	7.40	0.00050	38.63	0.00014
	0.31	12.02	0.00050	48.74	0.00010
20	0.35	7.98	0.00035	45.61	0.00010
	0.36	8.17	0.00030	46.39	0.00010
	$\bar{x}$ = 0.34	9.39	0.00038	46.91	0.00010

recirculation periods to be approximately equal to or considerably greater than the foam densities for plain aeration alone. For Phase 2, employing the same aeration rate, the foam densities during the recirculation periods were noticeably less than the plain aeration densities for all recirculation rates.

At least two factors were believed to cause the apparent improvement of foam control performance and lower densities in Phase 2 as compared to Phase 1. These factors are the elimination of pump induced foam and the transfer of foaming agent from the experimental unit to foam masses accumulated on the liquid surface of the floor sump. The absence of pump induced foam during Phase 2 studies may be realized from a comparison of Figure 9 with Figure 8. Both figures illustrate operation at the same recirculation rate and zero aeration. Figure 9, illustrating Phase 2 operation, shows the absence of the fine dense foam returning to the liquid surface as shown in Figure 8 for Phase 1 operation.

During Phase 2 operations, the air and foam entrapped in the liquid mixture discharging into the floor reservoir resulted in foam accumulations at the liquid surface. Inasmuch as foam has been reported to contain several hundred times the concentration of foaming agent as that in the bulk solution, it was reasonable to suspect that ABS was being transferred to the foam accumulations in the floor sump.
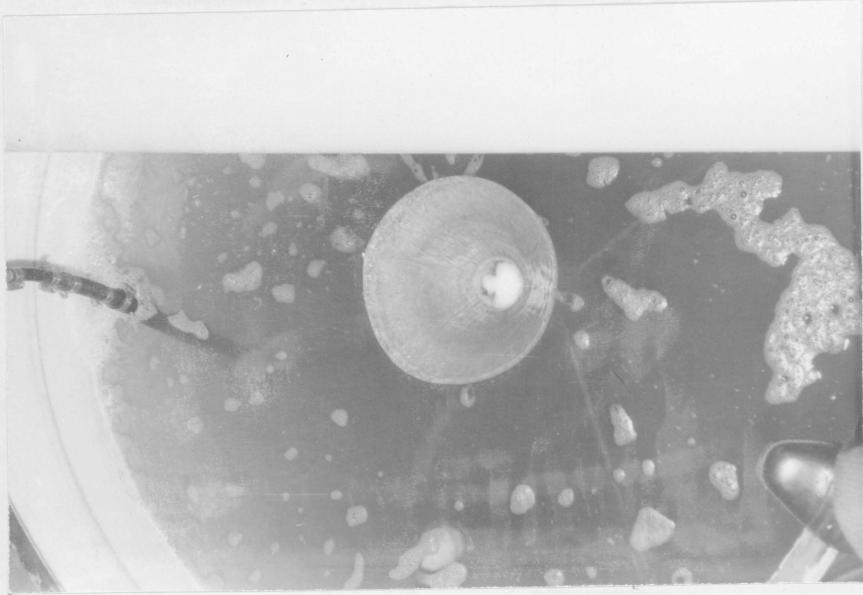
Figure 9: Elimination of Pump Induced Foam During
Phase 2 Experiments
        The photograph illustrates the absence of pump
induced foam at maximum recirculation rate (43 gpm.)
and zero aeration for Phase 2 experiments.

The data of Phase 1 and Phase 2 were inconsistent in regard to the effect of recirculation rate on foam control performance. However, it was suspected that greater acceleration due to increased recirculation rates would improve performance. The observation by Gumensky (17) that air entrainment in open channels is proportional to the square of the Froude Number added support to the recommendation of investigation of recirculation rates up to the practical limit.

In order to expand the range of flow rates, a 7-inch diameter mixing propeller was axially mounted in an 8-inch diameter expansion section which was welded to the lower end of a 4-inch diameter draft tube, illustrated in Figure 3. Four funnel inlets, each having a diameter of 12 inches at the top and a diameter of 4 inches at the bottom but having different depths, were constructed in an effort to minimize submergence of the inlets throughout the range of flows investigated. These inlets were shown in Figure 4.

Results for Phase 3 experiments are presented in Table 10. Flow rates are expressed in terms of propeller speed (rpm) and hydraulic head on the inlet. Actual flow rates were not determined since the results did not appear to justify continuation of the experiment and consequently the effort required to calibrate the inlets. The results in Table 10 indicate that the degree of foam control, expressed as the operation time required to accumulate a definite

Table 10: Phase 3 Experimental Results

The values given in the table indicate time and foam density observed for each control experiment employing aeration alone and for each performance experiment employing both aeration and recirculation. The aeration rate was maintained at 21 cfm. for all experiments.

Prop. Speed (rpm)	Type of Experiment	Head On Inlet (in.)	Funnel No. 1 (6 in. Depth) Time (min.)	Density (gm/cc)	Funnel No. 2 (12 in. Depth) Time (min.)	Density (gm/cc)	Funnel No. 3 (18 in. Depth) Time (min.)	Density (gm/cc)	Funnel No. 4 (24 in. Depth) Time (min.)	Density (gm/cc)
340	Aeration	0.50	11.5	0.00030	17.0	0.00025	12.8	0.00030	13.5	0.00030
		0.75	14.1	0.00030	10.2	0.00020	11.4	0.00035	11.5	0.00035
		1.00	11.7	0.00030	11.9	0.00025	9.8	0.00040	10.0	0.00040
	Recirculation plus Aeration	0.50	22.5	0.00045	20.0	0.00030	16.6	0.00035	20.0	0.00030
		0.75	16.7	0.00070	13.4	0.00040	14.9	0.00040	19.0	0.00040
		1.00	14.6	0.00045	12.3	0.00060	13.7	0.00050	18.6	0.00040
480	Aeration	0.50	11.7	0.00030	14.6	0.00025	12.3	0.00035	13.1	0.00040
		0.75	11.1	0.00050	10.5	0.00040	10.4	0.00035	11.6	0.00045
		1.00	12.1	0.00030	10.3	0.00030	9.9	0.00035	10.6	0.00040
	Recirculation plus Aeration	0.50	19.5	0.01320	19.4	0.00160	16.9	0.00320	22.1	0.00150
		0.75	22.6	0.00630	14.4	0.00680	17.4	0.00620	17.6	0.00550
		1.00	21.9	0.00670	16.2	0.00425	17.3	0.00350	17.7	0.00580
630	Aeration	0.50	13.2	0.00050	20.0	0.00030	15.5	0.00025	11.5	0.00050
		0.75	9.3	0.00065	13.0	0.00040	10.8	0.00035	10.9	0.00045
		1.00	10.3	0.00060	10.7	0.00055	10.4	0.00035	11.9	0.00035
	Recirculation plus Aeration	0.50	19.8	0.03400	19.5	0.01980	19.4	0.01740	32.3	0.01490
		0.75	18.1	0.02450	15.4	0.01920	17.2	0.01270	20.7	0.02660
		1.00	17.0	0.02770	16.4	0.01280	19.0	0.01660	20.4	0.01350

volume of foam, observed during Phase 3 experiments. These results indicate that the degree of foam control for experiments employing recirculation was no greater than about 2 to 3 times that for experiments employing aeration alone. For low head conditions of 1/2 inch, foam control performance for all inlets appeared to be inconsistent as to the effects of increased propeller speed. At the higher head conditions, optimum control for most inlets resulted throughout the range of 500 to 600 rpm. Although foam removal appeared to be greatest at these higher speeds, optimum performance for any given inlet appeared to result from a compromise between a head sufficiently low to minimize inlet submergence and a head large enough to provide the flow necessary to prevent emptying the draft tube for any set propeller speed.

During operation in this phase, it was observed that the foam captured in the converging down-flow reappeared at the liquid surface as minute air bubbles - a result of the propeller agitation upon the foam. The fine bubbles reappearing at the surface resulted in the accumulation of a dense foam having the consistency of shaving lather. This phenomenon may be readily observed from examination of the data in Table 9. As the rate of propeller rotation was increased, foam density increased remarkably, amounting to as much as 70 times that for plain aeration alone. This was particularly

evident at the lower head conditions. Phase 3 showed more
promise in the ability to remove large quantities of foam
at the liquid surface than Phases 1 and 2. However, the re-
turn of disintegrated foam masses to the liquid surface ulti-
mately resulted in an accumulation of very dense foam which
defied control by the method.

XI. DISCUSSION OF RESULTS

Although the investigation of foam control by hydraulic disruption and re-entrainment did not realize the objective over extended periods of operation, the method appeared to be successful on a short term basis. Optimum performance indicated operative periods were extended to about 6 times that of aeration alone. The inlet geometry and the tendency of foam to span the inlets were recognized as principal variables affecting the process. Large diameter inlets proved more effective in minimizing the tendencies for foam to span the inlets.

A limitation of the Phase 1 system was the tendency of the pump to draw air as well as the foam-liquid mixture. This phenomenon proved to be undesirable since the pump returned a fine bubble lather to the liquid surface effecting reduced operative periods. The Phase 3 system exhibited similar tendencies in the ability to produce a dense resistant foam as a result of disintegration of large foam masses by the propeller and subsequent return to the liquid surface.

Phase 2 performance indicated a greater degree of control than Phases 1 and 3. This improved performance, however, was attributed to the elimination of pump induced foam and to the transfer of foaming constituent from the experimental unit to foam accumulations resulting on the liquid surface of the floor sump.

The method of hydraulic disruption and re-entrainment did not prove successful as a singular solution to foaming problems. However, it is conceivable that the system of Phase 2 may be employed in conjunction with other methods to mutual advantage. The method would seem particularly adaptable to merger with methods employing water sprays, flaming, or surface stripping. The degree of mixing and enhancement of aeration, both required of most aerated fermenters, might conceivably justify the expenditure of energy for such a system.

XII. PART II – AN EXPERIMENTAL EVALUATION OF THE
RELATIVE STABILITY OF DURABLE FOAMS BY APPLICATION
OF AN EXTERNAL FORCE

XIII. FORMATION AND STRUCTURE OF FOAM

A. Introduction to Foam

Foams are agglomerations of microscopic and macroscopic gas bubbles separated from one another by thin liquid films. Because of the thinness of the films surrounding the gas bubbles and/or colloidal properties exhibited by the films, foams are considered as colloidal systems (4,34). Bikerman (5) reports that colloidal systems are usually prepared either by dispersion or condensation (agglomeration) methods. In the dispersion methods, the future disperse phase (i.e. gas phase) is initially present as a large separate phase and is later comminuted and spread throughout the dispersion medium or liquid phase. Foams produced by dispersion methods include injection of air into foaming solutions and entrainment of air by agitation methods such as whipping or beating. In condensation methods, the future disperse phase is initially present as solute dissolved in the dispersion medium. During the preparation of this colloidal system, the molecules or ions of solute combine to form larger aggregates or agglomerations. Examples of foam formation by condensation methods are foams produced on beer and on fermenter liquids. Since the foams employed in the investigations of this thesis were produced by injection of air into solutions, the discussion hereafter will be primarily of this method.

B. <u>Bubble Formation</u>

One of the most prevalent methods of dispersing gas in liquid consists of introducing gas bubbles into the liquid through rather fine capillaries or orifices. This method is frequently used in froth flotation and in the aeration of fermenters. Maier (25), van Krevelen and Hoftijzer (36) and Datta et al (12) report the mechanism of bubble formation for single orifices must be considered as two distinct cases: 1) bubbles are formed separately whereby the diameters are independent of the air flow rate, and 2) bubbles are formed in series (i.e. chain bubbling) whereby the diameters are dependent upon the air flow rate.

In the first case, the bubble is formed at such low air rates that buoyancy forces can be balanced against the surface tension forces tending to hold the bubble to the orifice. By equating these two forces, a simple relationship exists between the bubble size and orifice diameter, viz., the bubble diameter is directly proportional to the cube root of the product of the surface tension times the orifice diameter and inversely proportional to the cube root of the density difference between the gas and liquid.

In the second case, bubble frequency or air flow rate, viscosity, liquid momentum, gas impact, and frictional effects have been postulated as influencing the bubble size in addition to buoyancy and surface tension forces. Maier (25)

proposed two of these factors as being of principal importance. The principal factors, having similar magnitude to the buoyancy forces, were: 1) the liquid momentum effect or effect of liquid circulation produced by the rapidly rising stream of bubbles during appreciable gas flow rates, and 2) the viscosity effect. He thus postulated an equation for bubble size requiring bubble volume to pass through a maximum or minimum value with increasing air rate.

According to Maier, increased air flow rate produces greater agitation effecting the tearing away of the bubble from the orifice prior to reaching a size sufficient to release itself by buoyancy. Opposing this tendency to produce smaller bubbles during high aeration rates is the viscosity effect. The contraction of the bubble neck is the first stage in separation and it takes time. For liquids having higher viscosities, the time is longer and consequently larger bubbles are produced owing to more air being forced into the forming bubble. Overlapping of the momentum and viscosity effects may cause a maximum or minimum bubble size to occur at some particular air flow rate.

Datta et al (12) found that for orifices of diameters between 0.04 and 0.4 cm the bubble size diminished to a minimum value as air flow rate was increased; thereafter increased aeration produced progressively increased bubble size. Increasing both the diameter of the orifice and the surface

tension resulted in increased bubble size. Viscosity, according to these authors, played little part in determining bubble size.

Van Krevelen and Hoftijzer (36) reported that for chain bubbling, bubble diameters increased with increased gas flow rates. According to these authors, the distance between two successive bubbles is inversely proportional to the frequency of bubble formation. During an initial gradual increase in bubble formation, the bubble diameter remains constant and the distance between successive bubbles decreases. Since the distance can never be smaller than the bubble diameter, bubbles can not transport the increased quantity of gas above a certain flow rate without becoming larger.

The above discussion assumes the axis of the orifice to be vertical. Datta et al (12) reported bubble volumes for inclined orifices to be somewhat less than that for vertically oriented orifices. The observed effect was attributed to reduced effectiveness of surface tension forces for holding the bubbles to the orifice and the tendency of buoyancy forces to drag the bubbles upwards across the plane of the orifice. The premature release resulted in smaller size bubbles. Results with horizontally oriented orifices indicated bubble size to be about one-half that for vertically oriented orifices. As with vertically oriented orifices, increased

bubble sizes were observed when horizontally oriented orifices were operated at high rates of gas flow (6).

For several or more orifices placed near each other, as in a porous air diffuser, coalescence of bubbles occurs. The bubble radius will remain proportional to the radius of the orifice but the effect of orifice size on bubble size is less pronounced than with single orifices (6). Datta et al (12) state that when a liquid is highly aerated with small bubbles, coalescence may take place resulting in larger bubbles. The reverse may take place when large bubbles are rising in a liquid, since a large bubble may split into two or more smaller bubbles. The condition of coalescence apparently has not been investigated in detail and, as far as is known, this phenomenon has not been completely explained. Complete coalescence may occur under excessive aeration rates causing the gas to rise as a continuous column rather than as dis-crete bubbles.

In general, Bikerman (5) attributes small air bubbles to narrow orifices, small surface tension to liquid density ratios, and low gas flow rates.

C. Foam Formation

In liquids capable of foaming, a gas bubble reaching the surface does not break through but lifts up a liquid dome or film above the bubble (4, 5). In pure liquids (e.g., water

and glycerol) or aqueous solutions of salts (e.g., KNO_3, $CaCl_2$, Na_2CO_3), this film bursts at once or at most persists for such a short time that the construction of a foam system is very unlikely. Liquid mixtures (e.g., benzene plus carbon tetrachloride) of similar chemical type and surface tension also have limited foaming tendency according to Kitchener and Cooper (20).

In other liquids containing as little as an incomplete monolayer of insoluble surface film, a bubble lifting up this film may persist for seconds or as long as hours. When a second bubble rises and comes to be beneath the surface in the proximity of the first bubble, attractive forces - similar to the surface tension forces operative between two vertical parallel plates partly immersed in water - assist the second bubble to approach the first creating a tangential contact. Subsequent contact by many such bubbles results in the first layer of a foam being formed. As air bubbles continue to rise, repeated layers are formed and lifted continuously, effecting an increasing mass of foam.

D. Foam Structure

When bubbles come together on a liquid surface, they suffer deformations such that the resultant pressure on the septum between the bubbles is zero (5). The amount of the deformation is dependent upon relative bubble size. For

example, if two bubbles of equal size come together, the septum is plane. If a very large and a small bubble come together, the larger bubble will be deformed more than the small one. The curvature of the septum will not be greatly different from that of the small bubble. Contact between several or more bubbles in the same plane results in a liquid space being formed at the intersection of the septums, as illustrated in Figure 10. This liquid space was termed Plateau's Border, named after Plateau who visualized this space as being an essential part of a foam system. The liquid in the space is under a lower pressure than the liquid in the walls of the surrounding bubbles. This factor is of considerable importance in foam drainage which is discussed in a later section of this thesis.

The structure of foam for bubbles coming together in a common plane is essentially as shown in Figure 10. Three contiguous bubbles A, B, and C are shown separated by films 1, 2, and 3. Each film has two liquid-gas interfaces each having a surface tension σ. Hence, each film exerts a force of 2σ per centimeter on PB. Three identical forces can balance each other only if the three angles between them are equal. Consequently these forces 2σ are able to cancel each other only if the films are inclined to each other at 120°. This angle was observed to occur most commonly and appeared independent of the sizes of the three bubbles forming the PB.
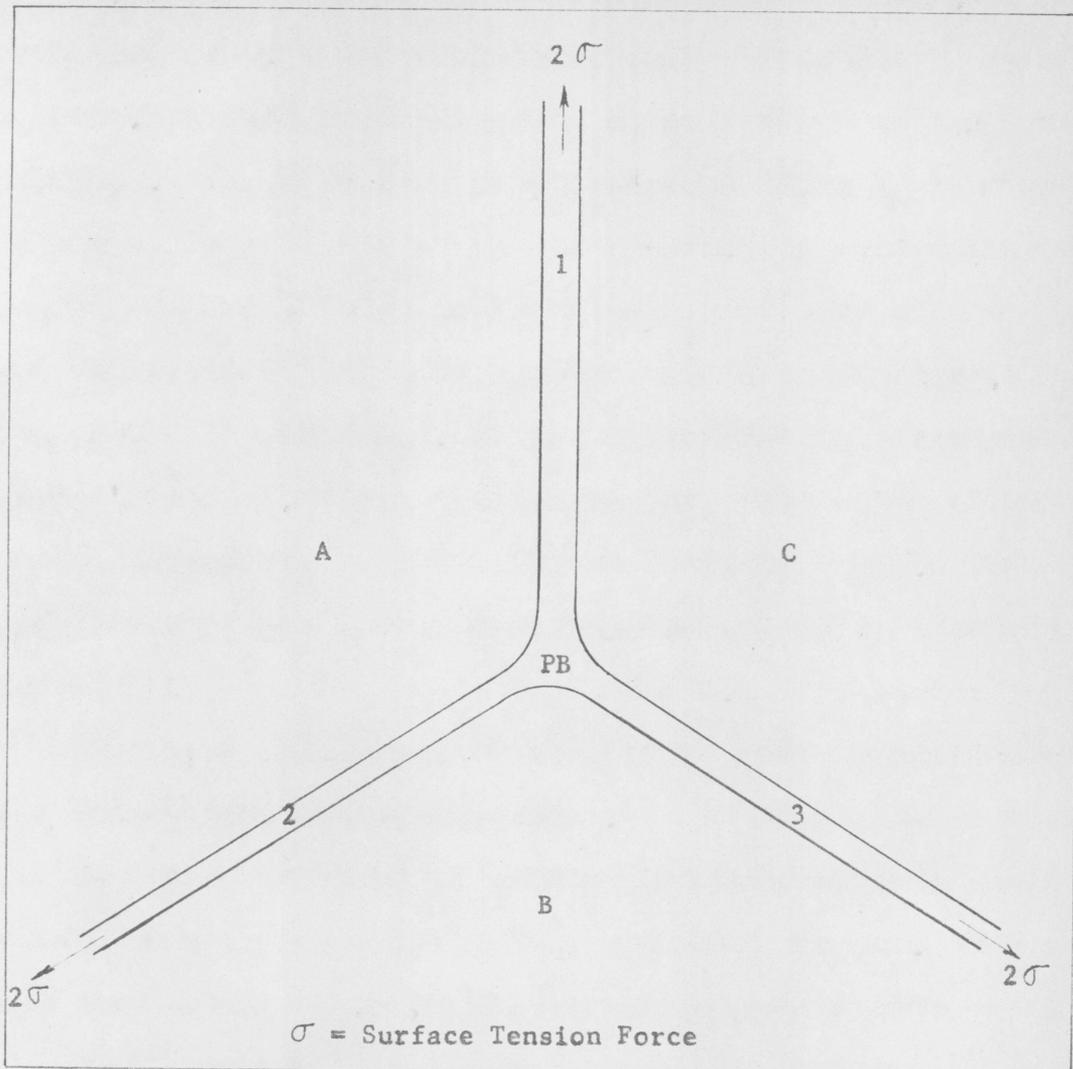
Figure 10: Plateau Border Resulting from Three Contiguous
Bubbles
     The sketch illustrates the union of three foam laminae
forming a Plateau Border (PB). The three identical forces
2σ, resulting from equal surface tension in the three con-
tiguous foam bubbles, are balanced only when the three lam-
inae form angles of 120 degrees with each other.

Frequently in the formation of foam, bubbles may come together in which more than three laminae radiate from PB in a common plane. This structure, however, is in a state of temporary equilibrium which in time will undergo sliding of laminae over one another until a true equilibrium of three laminae intersecting at a PB is established. When only three bubbles meet, pressure differences between bubbles will cause a shift of septums but will not cause an alteration to the number of bubbles adjacent to one Plateau Border. Therefore, three and only three laminae will usually be found to radiate from each line of contact in a foam structure contained in a single plane.

For three dimensional foams, four lines of contact may come together at one point. The foam bubbles will be arranged in a "tetrahedron like" structure with four lines of contact meeting at the center of the tetrahedron. Figures such as cubes having more than four lines of contact meeting at a point are unstable.

Bikerman (5) states that Plateau did not conclude from his studies the most probable crystal shape of a bubble in a foam. Desch, however, according to Bikerman, reported the pentagonal dodecahedron (figure bounded by twelve equilateral pentagons) was the most frequent approximate shape of foam bubbles. This figure is reportedly the only one whose repetition can fill the shape and in which all faces form angles of 120° with each other.

Foam bubbles and their agglomerations in the previous discussion were considered as equilibrium systems. In reality, few foams are in equilibrium owing to forces tending to destroy foam films. Bursting of foam films and film thinning due to drainage are two major processes affecting the lifetime of foams. These subjects are reviewed in the following sections.

XIV. FOAM PERSISTENCE

A. Theories Concerning Foamability and Lifetime of Foams

Plateau, as reported by Berkman and Egloff (4), visual-
ized surface viscosity considerably different from bulk vis-
cosity as being of prime importance in the formation and per-
sistence of foam laminae. His contention held that for a
liquid to be able to form bubbles, develop a large film, and
yet be persistent, the viscosity of the superficial layers
of the film must be sufficiently large for thinning to occur
slowly. Surface tension, however, must be sufficiently weak
so as not to overcome the opposing resistance of viscosity.
Liquids with high superficial viscosities and high surface
tensions at the same time do not form bubbles. Similarly,
liquids of low superficial viscosity do not form bubbles
owing to the films surrounding them becoming extremely thin
in a relatively short time - a condition favorable to break-
age by external factors. Weakly foamable alcohol solutions
having low surface viscosity and highly foamable soap and
detergent solutions having moderate to high surface viscosity
appear to support the concept of surface viscosity as being
a principal factor in foam development (4). Plateau's theory
also postulated increased foam persistence with increased
surface viscosity to surface tension ratio. Although surface
viscosity is generally agreed to be an important factor,

Bikerman (5) has reported contradictory evidence to the surface viscosity to surface tension ratio postulation.

Bikerman stated that the phenomenon now considered to be the main cause of foam stability is as postulated by Marangoni in his surface elastic theory. This theory maintains that two superficial tensions are operative in solutions having a surface composition different from the bulk. One superficial tension is a result of the surface layer or pellicle having a surface tension smaller than that of the bulk solution. Any force tending to rupture the pellicle encounters a resistance which is a function of the difference in surface tension between the pellicle and liquid. Hence a mechanism is present to promote healing or closing of ruptures in the surface. Similarly for foam laminae, as the surface layers of the films start to rupture, the exposed surface having greater surface tension contracts and tends to heal the fissure. When laminae become so thin that liquid between the surface layers no longer possesses properties (e.g., surface tension) of the bulk liquid, the healing effect becomes less pronounced and resilience of laminae is reduced. The Marangoni effect is more pronounced with aged solutions than with fresh solutions since the surface tension is greater in the superficial layers of a fresh solution than in an aged one.

Other theories may be found in the literature in an attempt to explain foam phenomena. Gibbs (16) presents a

somewhat different explanation of the surface elastic theory. Derjaguin, according to Kitchener and Cooper (20), puts forth the theory that very thin films owe their stability mainly to the electrical repulsions operative between the ionic double layers adsorbed in the two sides of the laminae. The theories presented are perhaps complementary rather than exclusive and are probably all operative but in different circumstances. No one theory has given a complete interpretation of the phenomenon of foam formation and persistence owing to the complexity of the many factors affecting foam systems.

B. Factors Affecting Foam Persistence

Factors which affect foam persistence other than viscosity and surface tension include manner of formation, concentration of solute, bubble size, temperature, presence of surface active agents, and presence of suspended solids (20). Studies on the effect of solute concentrations have generally indicated that foamability passes through a maximum at some intermediate concentration of foaming agent. In accord with the surface elastic theory, too dilute a solution results in a superficial layer not much different than that of the bulk solution. Consequently, the range of surface tension may be too small to be effective in maintaining stability. Conversely, too concentrated a solution contains a large reserve of solute which can diffuse to the surface and restore low surface tension during the thinning of laminae.

Increased solute concentrations have also been reported to result in smaller foam bubbles. According to Sinsheimer (32), bubbles tended to coalesce and became larger in dilute solutions while bubbles in solutions containing larger quantities of foaming agent remained small, maintaining their individual sizes of formation. The smaller bubbles at the increased concentrations were reportedly due to resistance to mixing or coalescence offered by the layers of solutions constituting the surfaces of the bubbles.

Bubble size may have a pronounced effect on foam persistence. Brady and Ross (7) indicate that the average lifetime of gas in foam is inversely proportional to the 0.86 power of the bubble diameter. The influence of bubble size may be illustrated by reducing the pressure on stable bubbles; the bubbles gradually stretch until they become unstable and break.

Temperature changes affect viscosity more than surface tension; however, local temperature changes have caused surface tension gradients which may cause thinning of laminae. Temperature effects have a marked influence upon foam drainage and will be discussed in the next section.

Mixtures of surface active agents may in some cases enhance foamability while others depress foamability. Mixtures in the first case tend to form a more viscous or "plastic"

film, thereby increasing superficial tension differentials. The second group of mixtures tend to separate into two phases, hence resulting in heterogeneity of film structure. The unbalanced local tension of such a structure results in unusually rapid disintegration.

Although foam density per se has not been found to be a reliable quantity in estimating foam stability (35), Brady and Ross (7) show that the average lifetime of a foam is greatly influenced by the ratio of final to initial amounts of liquid in foam ($\propto$). The ratio is influenced by the foam density when the films become unstable. During the collapse of foam, the foam density varies from top to bottom and also with time as drainage and film rupture occurs. At any given time the average relative density throughout the foam column is defined by the ratio of the liquid volume to the foam volume. The authors propose that the foam density be plotted against the volume of liquid in the foam throughout the foam collapse period. Extrapolation of this plot to zero liquid volume yields a value of density which the authors regard as the relative foam density at which films become unstable. The final density will therefore influence the ratio ($\propto$) since the volume of liquid corresponding to this density is included in the ratio.

Methods of foam formation may also influence the life-time of foams. Wet foams, for instance, may be formed when

insufficient gas has been injected in a solution capable of foaming readily. Incomplete agitation by beating devices may also produce wet foams (7). Dry foams, on the other hand, may result when excessive aeration or agitation has been employed, especially if the solution is too dilute or contains a fairly weak foaming agent. The ability of these foams to persist would depend upon the combined effects of factors previously mentioned in addition to the effects of drainage discussed in the following section.

XV. FOAM DRAINAGE

A. Mechanism of Drainage

Foam drainage is a phenomenon influencing the stability
of a foam system but is different from the factors already
mentioned; hence it is treated separately. During the life
of a foam, the interior of films are continuously subjected
to a diminution of thickness due to gravitation and suction
by Plateau's Borders (mentioned previously under the section
of foam structure). Although drainage may occur simultaneous-
ly with the destructive forces causing bursting of foam films,
drainage per se is regarded as thinning of laminae prior to
rupture.

Gravitational forces tend to reduce laminae thickness
as a result of molecules within foam films tending to slip
from top to bottom (4). Pressures within the laminae capil-
laries, on the other hand, modify gravitational effects to
a certain extent. Suction forces are likewise operative in
the lower pressure regions, referred to as Plateau's Borders,
and may cause a thinning of foam films. The relative impor-
tance of the gravitational and the suction forces is not
known definitely; however, Bikerman (5) suggests that the
latter is probably more significant when the smaller radius
of curvature of the Plateau's Border is less than $0.03/h$,
where h is the foam height in centimeters.

The combined effects of the two forces produce a thinning of foam films which finally become unstable at the thinned parts and vulnerable to destruction by external forces. For horizontal films, which would be a special case in a foam system, suction by Plateau's Border is the only driving force inducing drainage. Bikerman has presented an expression defining the thinning progress of such a system.

B. Factors Affecting Drainage of Films

The humidity of the ambient atmosphere may accelerate or decrease the thinning phenomenon depending upon the difference in vapor pressure between the foam film and the atmosphere. Berkman and Egloff (4) indicated that if soap and water films have a vapor pressure sufficiently different from that of the atmosphere, evaporation takes place in the upper region and condensation in the lower. These processes result in diffusion currents carrying moisture downward. The processes described would not be sufficiently rapid to be of importance when the vapor pressure of the atmosphere varied little from that of the film. For a dry atmosphere, the decrease in film thickness is accelerated; the reverse is true for a moist atmosphere. Volatility of a component in a film may enhance the effects of evaporation and condensation even if the mean vapor pressures for the component is the same as the surrounding atmosphere. Rupture is thus favored by increased volatility.

Increased viscosity causes molecular motion to decrease and thereby lessens the change in film thickness with time. Plateau's theory of surface viscosity to surface tension ratio attempts to explain the relationship of these factors and film rupture (4, 5). Temperature changes result in inverse changes in viscosity which in turn affect foam stability.

Other factors previously mentioned affecting foam persistence may likewise affect the foam drainage phenomenon. Bubble size, for example, may exert considerable influence on the rate of liquid drainage. Smaller bubbles would presumably require a greater degree of stretching and thinning prior to becoming unstable. Factors such as surface tension, viscosity, and atmospheric conditions combine to effect rupture of the resulting fragile films.

XVI. METHODS OF MEASURING FOAMABILITY AND COMPARATIVE STABILITY

The evaluation of foaming properties of a medium is an essential phase in industrial application of foams or in destabilization of undesirable foams. The ideal characterization would perhaps consist of reporting foaming capacity or foam persistence by a single number. This ideal, however, has not been realized since the volume and quality of foam produced by any method results from a complex variety of factors. The apparatus and procedure employed, nature and concentration of foaming constituent, and subsequent history of destructive forces to which the foam is subjected are all important considerations in evaluating foam properties (5, 30, 35).

Foam characterization measurements are generally classified as either dynamic or static methods (32). The dynamic method involves taking measurements such as rate of foam formation or ultimate volume of foam. Hence, measurements are usually taken during foam formation or immediately after formation. One of the more common procedures has been the production of foam by bubbling a gas through the foaming solution. Munro et al (27) employed a 16-mm diameter by 114-cm tall calibrated glass column to measure dynamic foams. Foam height was measured every 5 seconds for a period of 30

seconds during which time air was diffused into 50 ml of sample. Lynch and Sawyer (24) employed 4-inch diameter by 9-feet tall lucite columns as the experimental units. Aqueous solutions of commercial synthetic detergents were maintained at depths of 6.7 feet in the columns. Foam was produced by diffusing air into the detergent solutions through porous septums located at the bottom of the columns. Foam height was observed at regular time intervals during foam production. Christmann (10), Foulk and Miller (15), and Clark and Ross (11) have used similar apparatus for measuring dynamic foams; however, dimensions of apparatus, volume of sample, air flow rate, and experimental procedure often vary between experimenters. Consequently, results are not readily comparable owing to the lack of uniformity of procedures.

Some dynamic foams have been produced by shaking procedures such as reported by Sinsheimer (32). Shaking methods usually involve shaking a given quantity of sample in a stoppered flask for a specified time and observing the initial foam volume immediately after shaking. Shaking procedures, however, have the disadvantage of being too dependent on the individual analyst. Other dynamic methods employ mechanical beating and whipping of solutions to produce foam for foamability comparisons (3, 18, 29, 35).

Although the objective of most dynamic methods has been the determination of solution foaminess, some measure of foam

stability has been estimated from the pneumatic method of producing dynamic foams. Bikerman (5) reported that the foam height is proportional to the linear gas velocity for steady state foams (i.e., dynamic equilibrium between rates of formation of foam and rate of collapse in the top layers). Hence the ratio of the foam height to linear gas velocity, having the dimensions of time, has been proposed as the average lifetime of a bubble entrapped in the foam. Sinsheimer (32) and Ross and Miles (30) have similarly reported that a measure of instability could be obtained from unstable dynamic foams. These authors report that the difference between the volume of air introduced and the final volume of foam indicates the degree of instability for that foam. Foams possessing absolute stability would theoretically yield foam volumes approximately equal to the volume of air introduced. Hence, foams that are highly durable would result in unwieldy volumes of foam if the steady state were to be employed. The evaluation of foam stability by dynamic methods would therefore appear impractical for highly durable foams.

According to Ross and Miles (30), "various materials differ in the stability of their foams and not in their capacity to foam. Hence, any method of measuring foam formation is actually a method for measuring the stability of a foam towards that particular stress to which it is subjected."

These authors present a dynamic method of determining foam stability by measuring the effects of an arbitrary standard destructive mechanism acting upon foam produced under controlled conditions and protected from extraneous destructive forces. The method consisted of allowing a given volume of sample to fall through a distance of 90 cm in a "pour test apparatus" and measuring the volume of foam produced. Since the falling liquid must pass through foam already formed, breakdown stress is simultaneously applied during foam formation. Relative foam stability is reported in terms of the resultant volume of foam produced under these conditions.

Another method in which breakdown stresses were provided during foam production was proposed by Sisley and Loury, as translated by Wood (35). Their method employed a mixer type device to provide both the forces of formation and destruction. Mechanical agitation provided by rotating beaters caused foam rupture as well as foam formation. The resultant volume of foam after a given agitation period was reported as being representative of the stability of that particular foam.

The static method of foam characterization consists essentially of studying the behavior of foam after it has been produced (32). Measurements taken during the static method usually consist of recording the life of foam films, or decay rate, and the rate at which liquid drains from foam.

Procedures may employ any of the pneumatic, shaking, or agi-
tation devices for foam production; however, measurements do
not begin until after foam has been produced.

Collapse of foam films may begin immediately when bub-
bling, shaking, or agitation has been discontinued; hence
foam height or volume above the liquid is measured at once
and at subsequent regular intervals. The liquid level below
the foam may also be measured immediately upon completion of
foam production and at subsequent regular intervals to aid
in determining the relative importance of the effects of
foam density and/or drainage upon foam stability. The nature
of the foaming material may result in highly stable foams,
such as those produced from proteins and some detergents,
with total collapse time lasting for hours or days. Thus,
some end point other than the free liquid surface may be
desirable.

Relative foam stabilities may be determined by a com-
parison of the collapse rates for the different foams. Usu-
ally, however, the collapse rate is other than uniform and
graphical presentations with foam height plotted against
time are compared to determine relative stabilities.

Brady and Ross (7) have suggested that a direct compari-
son of foam stabilities may be made using the integral or
area of the foam volume vs time curve. This area, when
divided by the initial foam volume, yields a quantity L_f,

which the authors termed the average lifetime of foam. This expression is comprised of two separate integrals or areas: 1) the integral or area of the liquid volume-time curve and 2) the integral or area of the gas volume-time curve. Each of the latter integrals or areas is divided by its respective initial ordinate as was done for the foam volume-time expression. The two individual integrals provide more detailed information as to whether film rupture or foam drainage is a more pronounced factor in stability. For wet foams and usually freshly formed foams, drainage appears to be more significant than film rupture; hence liquid is removed from the foam at a rate faster than the liberation of gas. For foams in which film rupture or coalescence of bubbles at the exposed surface of the foam occurs prior to drainage, the rate of gas liberation is greater than the rate of drainage.

Realizing that different methods and procedures used in producing foams yielded results not apparently comparable, Brady and Ross divided the gas volume-time integral (L_g) by the product of kinematic viscosity and initial foam height. The authors found that by applying this conversion factor, a significant degree of correlation could be obtained between foams of similar character independent of such factors as: temperature, viscosity, quantity of sample, methods of foam

production, and dimensions of the apparatus. The authors also indicated that absolute values obtained for dynamic foams are not the same as for static foams owing to the non-uniform, heterogeneous character of most dynamic foams. However, by applying ratios of one dynamic foam to another and employing their respective conversion factors, a comparison might be made between dynamic and static foams.

Peter and Bell (29) employed a method of determining foam stability that was different from the usual static decay methods. This method consisted of producing a whip or volume of foam with a beater type device and allowing a penetrometer of given dimensions and weight to fall through the whip. The initial drop through the whip was indicative of the initial foam strength while the rate of descent through the foam was a measure of stability. Bikerman (5) reports a similar experiment whereby a vertical rod, placed on the bottom of a cylinderical vessel containing foam, is released and the time lapse is observed for the rod to tilt sufficiently to touch the wall of the container.

Static decay methods appear to be convenient in measuring foam persistence for the less stable foams. However, for durable and voluminous foams resulting from some soaps and synthetic detergents, the static decay time often becomes too great to be practical in routine stability measurements.

Consequently, some modification with the objective of reducing the time element required for completion of the static decay method seemed desirable.

XVII. EXPERIMENTAL

A. Objective

Static methods of determining foam stability often result in lengthy experiments which are inconvenient to perform for routine measurements. The collapse time of durable foams produced from materials such as proteins, soaps, and synthetic detergents may range from hours to days. It therefore appears that a substantial reduction in time would be desirable for repetitive sampling of foam stability.

A modification of the static decay method is presented in Part II of this thesis whereby an externally applied force is introduced in order to accelerate the destruction of static foams. It was observed that by application of a constant force to a column of foam, the time to complete a measurement could be reduced to minutes - a considerable reduction when compared to the natural decay periods of similar foams. Hence, an investigation was undertaken in an attempt to develop and evaluate a method by which the relative stability properties of persistent foams could be obtained by short-term experiments.

B. Apparatus and Methods

The apparatus for foam generation consisted of a lucite column having an inside diameter of 3.75 inches and a height of 4 feet. The column was fitted at the bottom with a porous

glass air diffuser through which air was forced into the solutions. Foam stability comparisons were obtained by loading the foam with a weighted glass disc and subsequently observing the rate of descent of the disc through the foam. The disc, having a diameter of 3.69 inches, was attached to a glass rod having a diameter of 1/4 inch and a length of 4.5 feet. The combination had a total weight of 112 grams. A circular plate, machined to fit the top of the foam column, was centrally bored to a diameter of 5/16 inch to provide a guide for maintaining vertical alignment of the glass disc assembly. A sketch of the apparatus is shown in Figure 11. Three similar foam generation columns, but without the disc assembly, were fabricated to enable observation of the natural decay of foam with time. These columns, in addition to the column employing the disc assembly, are shown in Figure 12.

The samples were aerated with compressed air that was passed through a glass-wool and cotton filter. The flow of air was controlled by a pressure reducing regulator and was metered by a Fisher Flowmeter having a capacity of 0.36 to 3.6 liter/min at 14.7 psi and 20°C. A mercury manometer was installed on the discharge side of the flowmeter to obtain pressures for subsequent conversions to standard conditions.

Variables observed during the investigation included liquid viscosity and surface tension, concentration of

1/4-inch Diameter Glass Rod

5/16-inch Diameter Guide Hole

4-inch Diameter Plastic
Guide Plate

Rubber Stopper Glued
To Glass Disc

3.69-inch Diameter
Glass Disc
(Petri Dish Bottom)

3.75-inch Inside
Diameter Lucite
Column
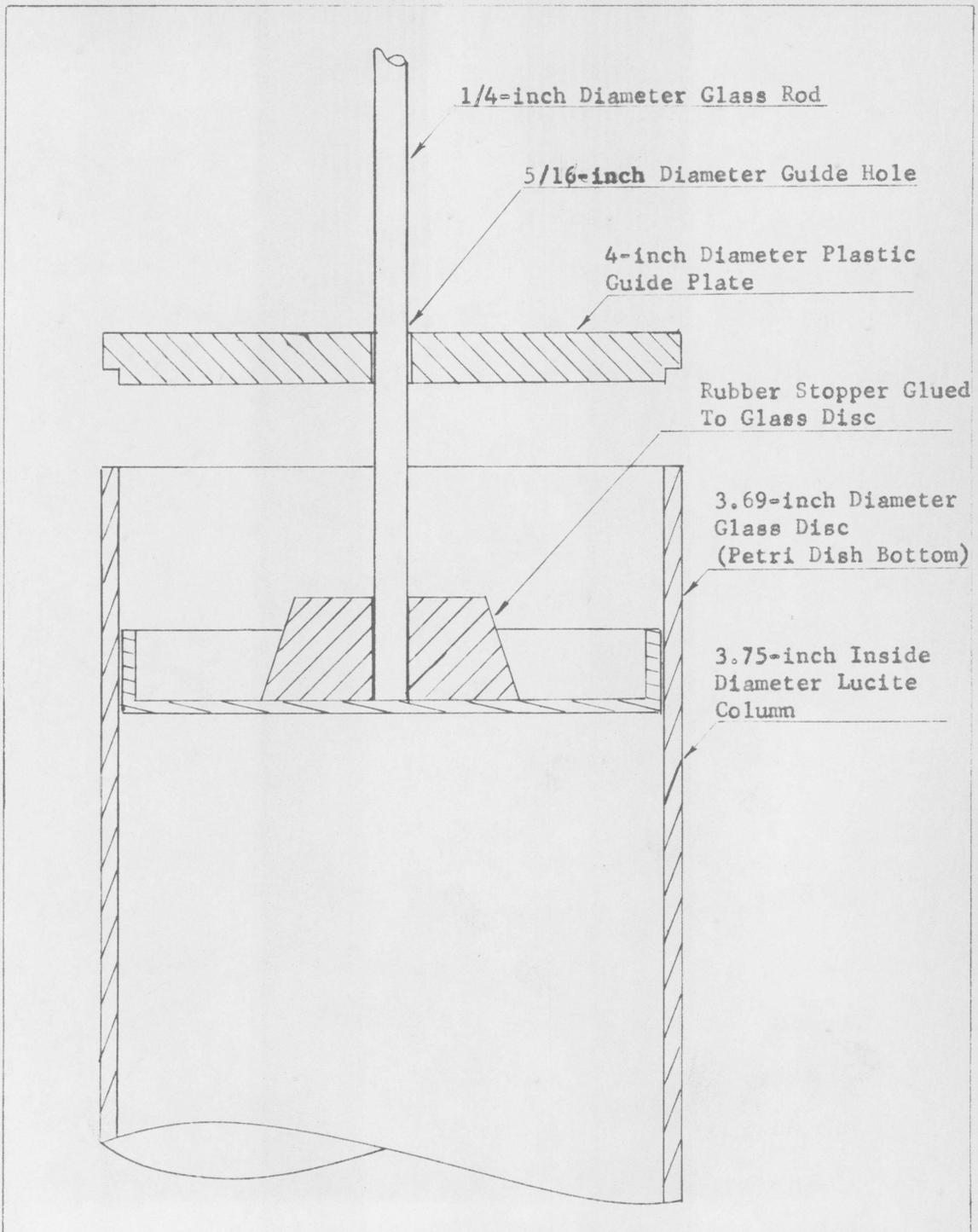
Figure 11:   Sectional Sketch of Weighted Disc Assembly

Figure 12: Foam Generation Columns
Three columns at left were employed for measurements of static decay of foams; column at right employed for characterization measurements with weighted disc assembly. Photograph illustrates comparable volumes of foam resulting from solutions containing 20 ppm ABS aerated at rates 0.75 l/min (A1), 1.5 l/min (A2), and 2.45 l/min (A3).

foaming agent, air flow rate, temperature, and dimensions
and weight of the disc assembly.

Previous to the foam stability tests, studies were con-
ducted to evaluate the effects of temperature and concentra-
tion of foaming agent upon liquid viscosity and surface ten-
sion. Solutions of the standard alkyl benzene sulfonate com-
pound were tested in the ranges of concentration and tempera-
tures shown in the outlines of Tables 11 and 12 for viscosity
and surface tension respectively. Viscosity measurements of
the 24 treatment combinations shown in Table 11 were performed
completely at random. Two successive measurements were made
on each of two samples for each treatment combination. For
surface tension measurements, three replicates of the basic
outline shown in Table 12 were performed; however, the 12
treatment combinations were selected randomly within the
replicate.

A Cannon-Fenske U-tube viscometer, as described in
references (9) and (33), was used to measure liquid viscosi-
ty. Principal variables included in the formulation for de-
termining viscosity by the viscometer were: 1) capillary
radius, 2) length of capillary, 3) volume of liquid, 4) ef-
fective head, 5) density of sample, and 6) time for liquid
volume to flow from capillary (33). These variables, except
time, may be included in a constant which is obtained by
calibration of the viscometer throughout a given range of

Table 11: Viscosity Experimental Outline

The variables observed during the viscosity experiments were ABS concentration and temperature as shown in the table. Two successive determinations were made on each of the two samples for each combination of ABS concentration and temperature.

ABS Concentration	Temperature			
	5°C	16°C	23°C	30°C
	Sample	Sample	Sample	Sample
20 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2
40 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2
60 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2
80 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2
100 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2
120 ppm	No. 1	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2	No. 2

Table 12: Surface Tension Experimental Outline
    The variables observed during the surface
tension experiments were ABS concentration and
temperature as shown in the table. Two succes-
sive samples were measured for each combination
of ABS concentration and temperature.

ABS Concentration	Temperature		
	16°C	23°C	30°C
	Sample	Sample	Sample
0 (soft water)	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2
40 ppm	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2
80 ppm	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2
120 ppm	No. 1	No. 1	No. 1
	No. 2	No. 2	No. 2

viscosities. Viscosities within the range of calibration
may then be determined by multiplying the calibration con-
stant by the time required for the sample volume to flow
from between two reference marks on one arm of the U-tube.

Surface tension values were obtained by the modified
drop weight method (23), employing a Traube stalagmometer to
observe falling drops. The Traube stalagmometer is essen-
tially a pipette with a broad flattened tip to permit large
drops of reproducible size to form slowly and finally drop.
The principle of the drop weight method is based on the
ratio of the weight of a drop of liquid to that of a drop
of a reference substance being equal to the ratios of their
surface tensions.

The modification of the drop weight method consists of
counting the drops formed when a definite volume of liquid
is allowed to flow slowly from a capillary orifice. The
weight of a single drop of liquid is equal to the product
of liquid volume times the liquid density divided by the
number of drops. This ratio may therefore be substituted
for weight in the above weight-surface tension relationship
for both sample and reference liquids. Calculation of sur-
face tension for the sample is therefore a function of the
relative drop numbers and densities for the sample and for a
reference liquid (e.g., water) of known surface tension.
The stalagmometer and viscometer are shown immersed in a

constant temperature water bath in Figure 13.

Softened water was used for all tests and was drawn into 20-liter carboys prior to each replicate to minimize possible changes of water characteristics which might have occurred between individual samples drawn separately. A stock solution containing 1000 mg/l as ABS was prepared prior to each replicate in order that each sample would be prepared from a common solution. The temperature in the water bath was maintained within ± 0.1°C of the reported temperature. Samples for both viscosity and surface tension were allowed to stand in the water bath for 10 minutes prior to each measurement.

The investigation of foam stability by the weighted disc method consisted of three separate phases. The experiments of Phase 1 employed a constant aeration period for foam generation. Samples, 2-liters each, were added to the column and aerated for a 2-minute period, after which the resultant foam level was recorded. The column of foam was then loaded with the disc assembly and the level to which the disc descended was recorded at 1-minute intervals until the disc reached the liquid surface. Simultaneously, the liquid level beneath the foam was recorded to obtain values indicative of foam density and foam drainage. The tests for Phase 1 were conducted under laboratory room conditions (approximately 23°C), employing three aeration rates and six
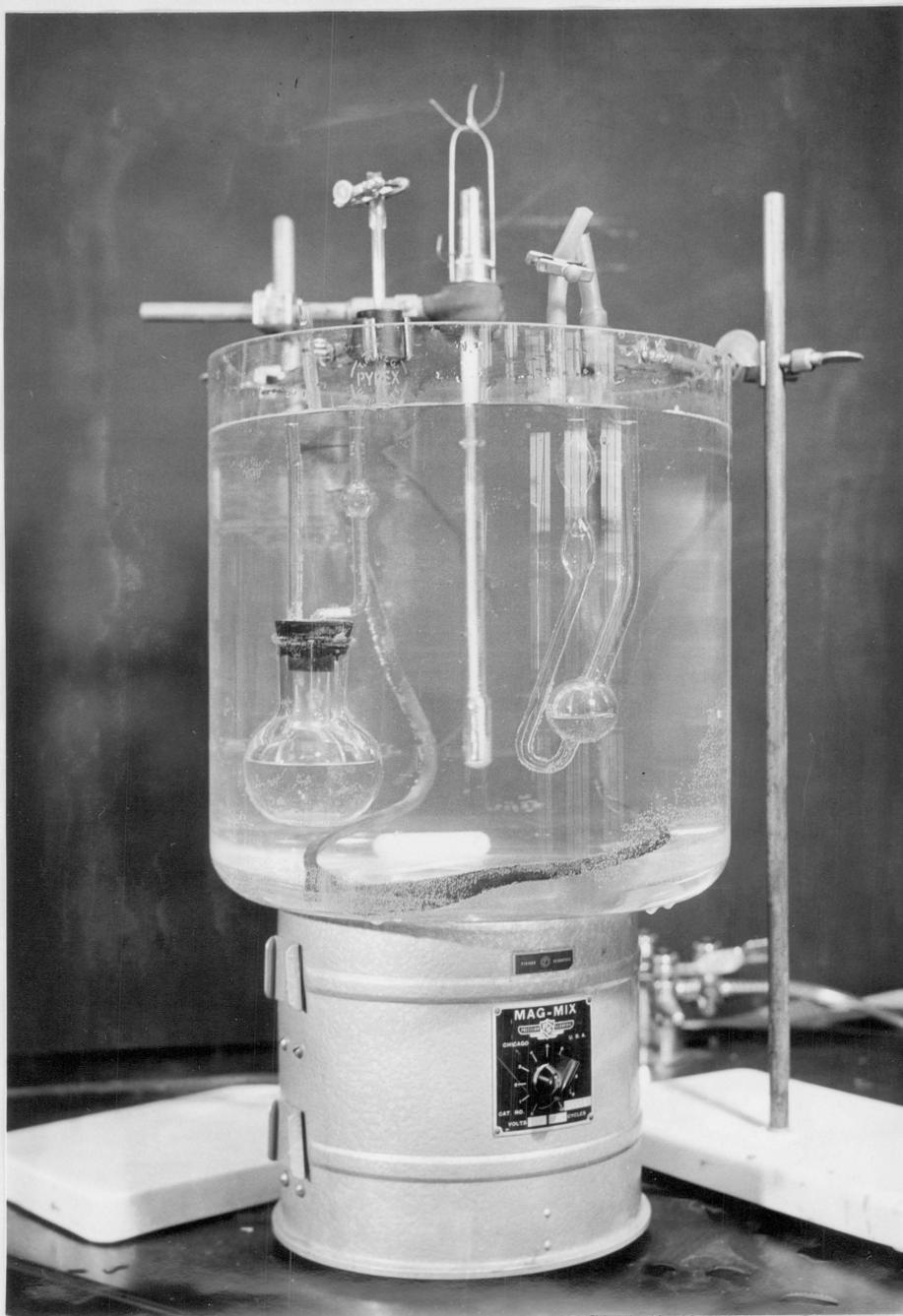
Figure 13: Stalagmometer and Viscometer Immersed in
a Constant Temperature Water Bath
    The Traube stalagmometer, employed for surface
tension measurements, is shown inserted in the stop-
pered flask at left in the water bath; the Cannon-
Fenske U-tube viscometer, employed for viscosity
measurements, is shown at right.

concentrations of the standard ABS solution. The basic test outline for Phase 1 is shown in Table 13. Temperature variations during the sampling within a replicate were about $\pm$ 1°C of the reported temperature.

The experiments of Phase 2 employed a constant head or volume of foam in the column prior to loading with the disc assembly. Each 2-liter sample, regardless of the aeration rate, was aerated until 28 cm of foam had been formed. The time required to generate this quantity of foam varied inversely with the aeration rate and was recorded upon completion of aeration. Observations of the disc descent through the foam were recorded as in Phase 1 measurements.

The experiments for Phase 2 were conducted under controlled conditions of temperature and relative humidity in a room specially designed to maintain constancy of these variables. Two temperatures were employed for the experiments. The basic experiment in Table 13 was conducted firstly at 20°C and secondly at 27°C. The relative humidity was maintained at about 67 - 68 per cent. Variables of aeration rate and concentration of ABS were identical to Phase 1.

The experiments of Phase 3 consisted of generating a constant volume of foam under controlled conditions of temperature and relative humidity; however, the foam was allowed to drain for 10-minutes prior to loading with the disc assembly. These tests were undertaken to observe how the

Table 13:   Outline of Experiments Employing the
              Weighted Disc
      The variables observed during the experi-
ments employing the weighted disc were ABS con-
centration and aeration rate as shown in the
table.

ABS Concentration	Aeration Rate		
20 ppm	0.75 l/min	1.5 l/min	2.45 l/min
40 ppm	0.75 l/min	1.5 l/min	2.45 l/min
60 ppm	0.75 l/min	1.5 l/min	2.45 l/min
80 ppm	0.75 l/min	1.5 l/min	2.45 l/min
100 ppm	0.75 l/min	1.5 l/min	2.45 l/min
120 ppm	0.75 l/min	1.5 l/min	2.45 l/min

quantity of liquid in the foam might influence foam stability as determined by the weighted disc method. The experiments were conducted at 20°C employing the variables of ABS concentration and aeration rate as shown in the outline of Table 13. Three replicates of the basic experimental outline of Table 13 were tested for all three phases employing the weighted disc. However, treatment combinations were selected at random within each replicate.

In the experimental procedure, softened water was employed for all tests and was drawn into 20-liter carboys and allowed to stand overnight in the test area so that temperature equilibrium between the softened water and the environment could be established. A stock solution, containing 1000 mg/l as ABS, was prepared prior to each replication and was used in preparing the individual sample concentrations throughout the replicate. The sampling was continued the same day it was initiated until all treatment combinations within a replicate had been completed.

Static collapse or decay experiments were conducted simultaneously with the experiments employing the weighted disc assembly. These static decay experiments consisted of two series of tests. The first series employed a two minute aeration period to generate volumes of foam comparable to those of Phase 1 employing the weighted disc. These tests,

were conducted under laboratory room conditions at a temperature of about 23°C. The static decay tests during this phase consisted of observing the natural collapse of foams generated from employing combinations of the three ABS concentrations and the three aeration rates shown in the outline of Table 14.

During Phase 1 studies, only one foam generation column was available for observation of the static decay of foam. A sample, consisting of 2-liters, was prepared from softened water and stock solution of ABS, and was added to the foam generation column at the beginning of each day of experimentation. After completion of aeration of the sample, the initial foam level was recorded as were subsequent foam levels at 1/2-hour intervals for a period of about eight hours. Because of the time involved in obtaining results, only one observation was obtained during Phase 1 studies for each combination of ABS concentration and aeration rate shown in Table 14.

The second series of static decay tests corresponded to Phase 2 experiments inasmuch as a constant volume of foam was generated for each sample prior to measuring its subsequent collapse. These static decay tests were conducted under controlled conditions of temperature (20°C) and relative humidity (67 - 68%) - identical to the first group of experiments of Phase 2. Three ABS concentrations and three aeration

Table 14: Outline of Static Decay Experiments
     The variables observed during the static
decay experiments were ABS concentration and
aeration rate as shown in the table.

ABS Concentration	Aeration Rate		
20 ppm	0.75 l/min	1.5 l/min	2.45 l/min
60 ppm	0.75 l/min	1.5 l/min	2.45 l/min
100 ppm	0.75 l/min	1.5 l/min	2.45 l/min

rates, as shown in Table 14, were employed to observe the natural collapse of foams during this phase.

Three foam generation columns were available during the second series of static decay tests. Hence, three samples, as described for Series 1 static decay tests, could be tested during an eight-hour period. Other than maintaining a constant volume of foam for all tests in Series 2, the method of foam production and measurement of foam collapse were identical to Series 1 tests. Three replicates of the basic outline of Table 14 were obtained for the static decay tests during Phase 2 as a result of the increased number of tests which could be completed during each period of experimentation.

XVIII. RESULTS

A. Viscosity and Surface Tension Experiments

Results of the viscosity measurements are summarized in Table 15 for the ranges of temperature and ABS concentration employed. The values of viscosity obtained are inversely related to temperature, as is the case with most liquids. The mean values for each temperature given in Table 15 are plotted in Figure 14 to illustrate temperature effects more clearly.

The effects of ABS concentration on viscosity are illustrated by the plots in Figure 15 which represent average values of viscosity for the ABS concentrations shown in Table 15. The plots reflect no appreciable change in viscosity throughout the range of ABS concentrations investigated.

Since the values of viscosity in Table 15 are viscosities of the bulk solutions, they are not indicative of superficial viscosities reported earlier as being important in foam stability. However, they are given to indicate viscosities which may occur in the bulk solution throughout the ABS concentrations and solution temperatures employed in subsequent experiments.

The results of the surface tension experiments are presented as Table 16. These data show the characteristic decrease in surface tension with increased quantities of ABS, a surface active agent. The values of surface tension in

Table 15: Kinematic Viscosities of ABS Solutions Evaluated
by the Cannon-Fenske U-Tube Viscometer.
The values in the table are given in centistokes and
represent the kinematic viscosity of the bulk solutions.

ABS Concentration (ppm)	Temp. OC	Kinematic Viscosity(centistokes) Observation				Mean
		No.1	No.2	No.3	No.4	
20	5	1.5151	1.5138	1.5210	1.5151	1.5162
	16	1.1158	1.1149	1.1094	1.1107	1.1127
	23	0.9275	0.9292	0.9232	0.9313	0.9278
	30	0.8005	0.8000	0.8000	0.8000	0.8001
40	5	1.5083	1.5087	1.5189	1.5227	1.5146
	16	1.1082	1.1052	1.1048	1.1052	1.1058
	23	0.0275	0.9292	0.0275	0.0275	0.0279
	30	0.8017	0.7992	0.7958	0.8009	0.7994
60	5	1.5108	1.5134	1.5040	1.5104	1.5096
	16	1.0992	1.1031	1.1031	1.1001	1.1014
	23	0.9270	0.9258	0.9287	0.9270	0.9271
	30	0.7950	0.7958	0.7966	0.7958	0.7958
80	5	1.5291	1.5312	1.5253	1.5185	1.5260
	16	1.0984	1.0997	1.1226	1.1056	1.1066
	23	0.9241	0.9249	0.9262	0.9283	0.9259
	30	0.7988	0.8000	0.7966	0.7966	0.7980
100	5	1.5261	1.5138	1.5159	1.5117	1.5169
	16	1.1014	1.0997	1.1022	1.1039	1.1018
	23	0.9241	0.9237	0.9279	0.9292	0.9262
	30	0.7958	0.7937	0.7958	0.7933	0.7946
120	5	1.5023	1.5096	1.5100	1.5032	1.5063
	16	1.1001	1.0997	1.0997	1.1005	1.1000
	23	0.9258	0.9287	0.9245	0.9232	0.9256
	30	0.7966	0.7958	0.7996	0.7966	0.7972
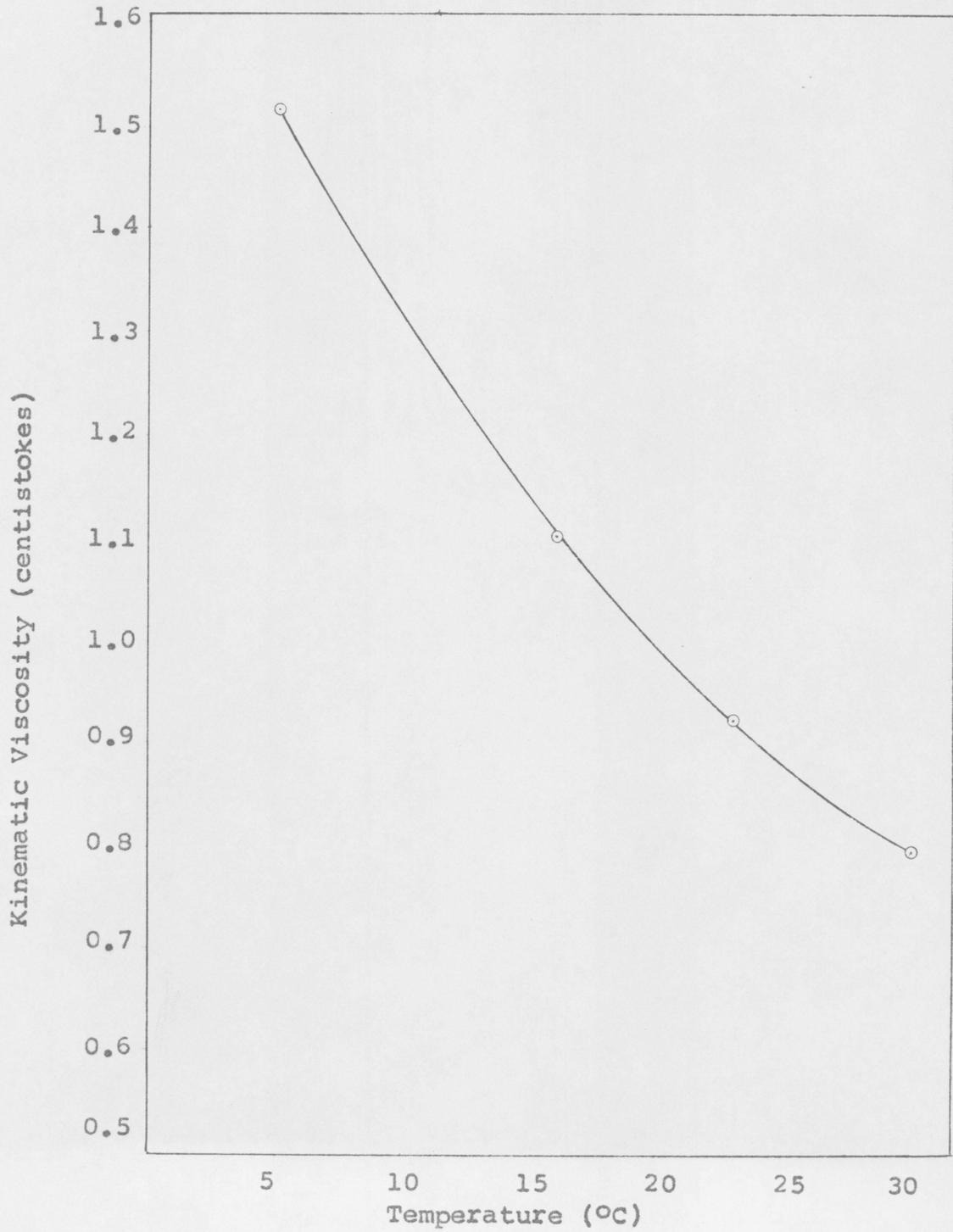
Figure 14: Effect of Temperature on Solution Viscosities
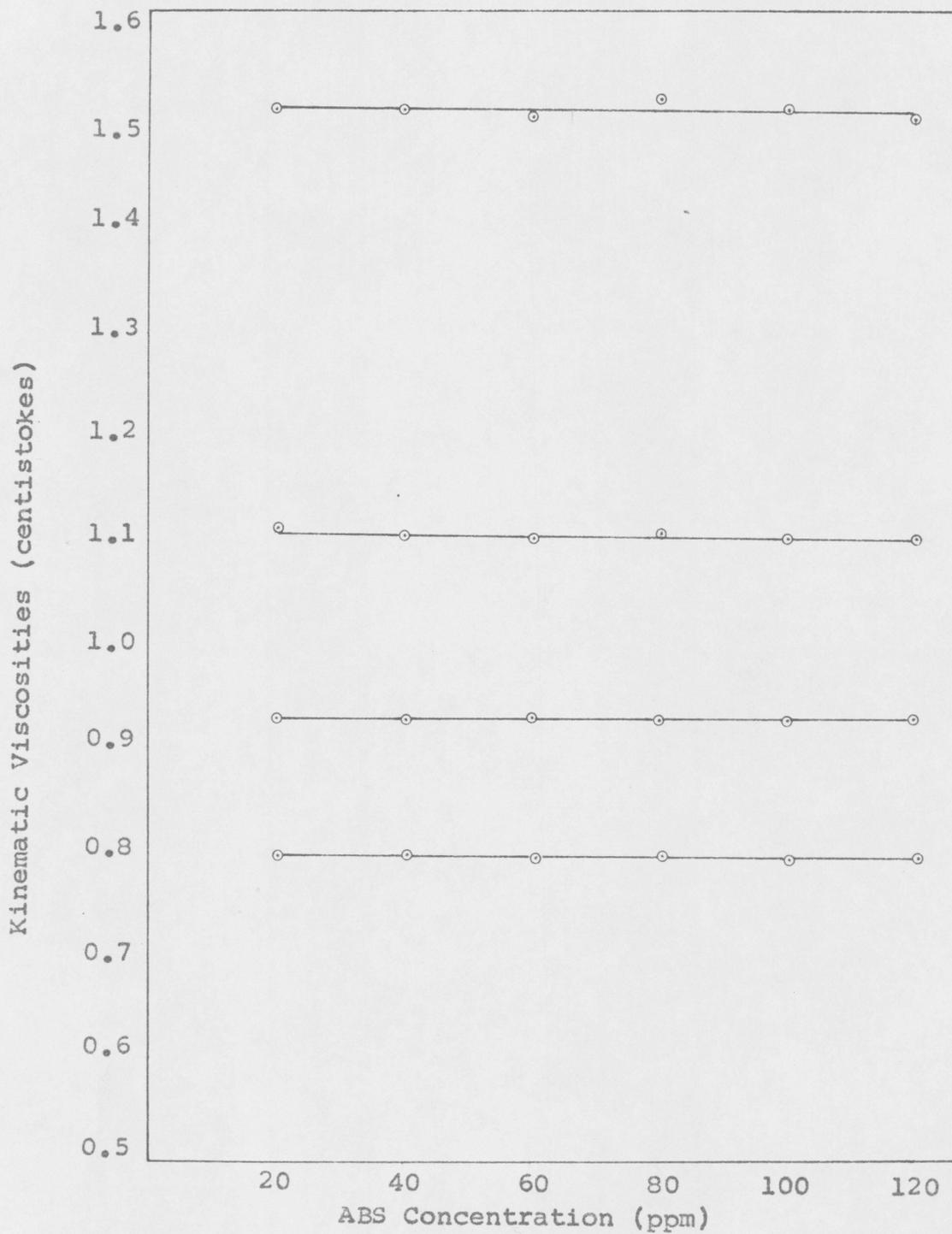
Figure 15: Effect of ABS Concentration on Solution
Viscosities.

Table 16: Surface Tension of ABS Solutions Evaluated by the Modified Drop Weight Method Employing a Traube Stalagmometer.
The values given in the table have units of dynes/cm.

ABS Concentration (ppm)	Temp. °C	Surface Tension Replicate			Mean
		No. 1	No. 2	No. 3	
0 (soft water)	16	65.68 71.33	71.33 74.54	72.50 75.82	71.87
	23	64.68 64.32	71.33 71.97	72.50 77.86	71.83
	30	71.56 69.33	75.60 76.46	71.94 77.80	73.78
40	16	62.88 66.01	69.10 68.75	69.10 72.50	68.06
	23	61.07 62.80	71.20 69.34	68.63 69.98	67.00
	30	65.92 61.95	70.80 70.06	69.33 69.69	67.96
80	16	60.58 62.00	60.58 61.14	62.00 61.43	61.29
	23	62.80 60.24	62.80 62.80	63.10 63.10	62.47
	30	60.55 60.82	61.38 60.82	63.72 63.42	61.78
120	16	52.65 53.07	55.75 56.22	58.97 57.19	55.64
	23	53.25 51.80	57.63 55.70	58.39 58.14	55.82
	30	52.47 50.11	55.75 54.84	51.86 55.99	53.50

Table 16 show no discernable effects due to temperature variations throughout the range of temperatures investigated. No apparent increase in surface tension was observed when the temperature was lowered from 30° to 16°C although the surface tension of water, obtained from the Handbook of Chemistry and Physics (19), increases approximately 2 dynes/cm for this temperature change. Examination of Table 16 revealed that variations of surface tension between samples for any given temperature and concentration were generally equal to or greater than 2 dynes/cm; thus, effects of temperature were apparently masked by lack of precision of the method.

Considerable effort was spent during the investigation to improve the ability to duplicate experimental results with the stalagmometer. The most evident causes for inconsistent measurements were: 1) failure to maintain vertical alignment of the stalagmometer, and 2) improper cleansing of the stalagmometer and tip between measurements. Failure to maintain the stalagmometer in a vertical position resulted in drops not forming completely and hence leaving the tip of the stalagmometer prematurely. Improper cleansing of the tip of the stalagmometer usually resulted in smaller drops being formed - the result of film accumulation over the glass surface. The results presented in Table 16 do not represent absolute values for the surface tension of solutions of ABS at various temperatures. However, the data does illustrate approximate

values of surface tension that could be expected in subsequent experiments employing identical conditions of temperature and ABS concentration.

B. **Foam Stability Experiments Employing Weighted Disc Method**

    1) **Preliminary Experiments**

        Initial investigations consisted of screening experiments to determine the dimensions and weight of the disc assembly for subsequent use in foam stability measurements. A glass rod-disc assembly, weighing 140 grams and having a disc diameter of 3.62 inches, was first investigated. Results, given in Table 17, indicated that the disc assembly fell too rapidly through the foam to reveal any appreciable differences for foams generated from solutions containing 20 to 120 ppm as ABS. The time required for the disc to fall through comparable volumes of foam for the different solutions varied only by fractions of a minute - a difference not considered significant owing to the variability previously experienced in foam for a particular set of conditions.

        A second disc assembly, having the same weight (140 grams) but having a larger diameter (3.69 inches), was employed to evaluate the effects that tolerance between the disc and column might have on the rate of descent. The results, shown in Table 17, indicated that slightly longer periods of descent were required for this disc; however, differences between consecutive ABS concentrations were still quite small.

Table 17:   Results of Preliminary Experiments with Three
                Weighted Disc Assemblies.
        The values in the table indicate the time required for
the different disc assemblies to descend through comparable
volumes of foam resulting from an aeration rate of 0.75
l/min and a 2-minute aeration period. The values given in
the table are in minutes.

Disc Assembly	ABS Concentration					
	20 ppm	40 ppm	60 ppm	80 ppm	100 ppm	120 ppm
No.1 3.62 in. dia. 140 gm.	1.95	2.22	1.80	2.22	2.37	1.93
No.2 3.69 in. dia. 140 gm.	3.42	3.78	3.90	3.60	3.70	3.58
No.3 3.69 in. dia. 112 gm.	11.73	15.98	19.88	25.92	26.18	29.12

With the objective of increasing the sensitivity of the method, a third disc assembly, having a disc diameter the same as the second disc (3.69 inches) but weighing 112 grams, was investigated. The results obtained from using the lighter disc are given in Table 17. Examination of these data revealed a substantial increase in the time for the disc to fall through the foam as the concentration of ABS was increased, indicating a possible increase of foam strength or durability with increased ABS concentration. In order to evaluate this effect more thoroughly, subsequent experiments, employing the 112 gram disc assembly, were undertaken.

2) Phase 1 Experiments

For Phase 1 experiments, each 2-liter sample was transferred to the foam generation column and aerated for two minutes prior to application of the 112-gram disc assembly. Measurements, which consisted of observing the foam-disc level, were recorded at one minute intervals until the disc reached the liquid surface.

Results, typical of Phase 1 measurements, are plotted in Figures 16 through 18 for one replicate of the basic experiment. The complete data for all three replicates of Phase 1 experiments are tabulated in Appendix A. Examination of the plots in Figures 16 through 18 revealed a greater descent rate of the disc as the aeration rate was increased. The increased
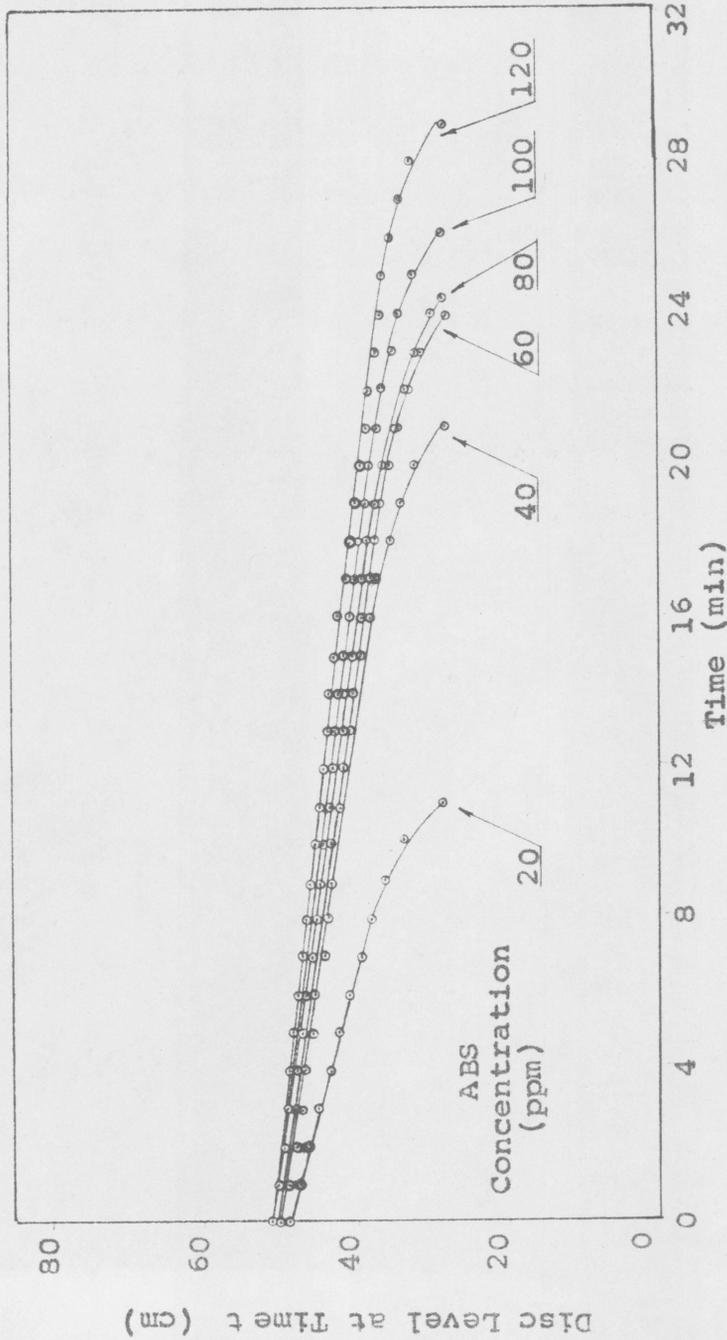
Figure 16: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 0.75 l/min for Phase 1 Experiments.
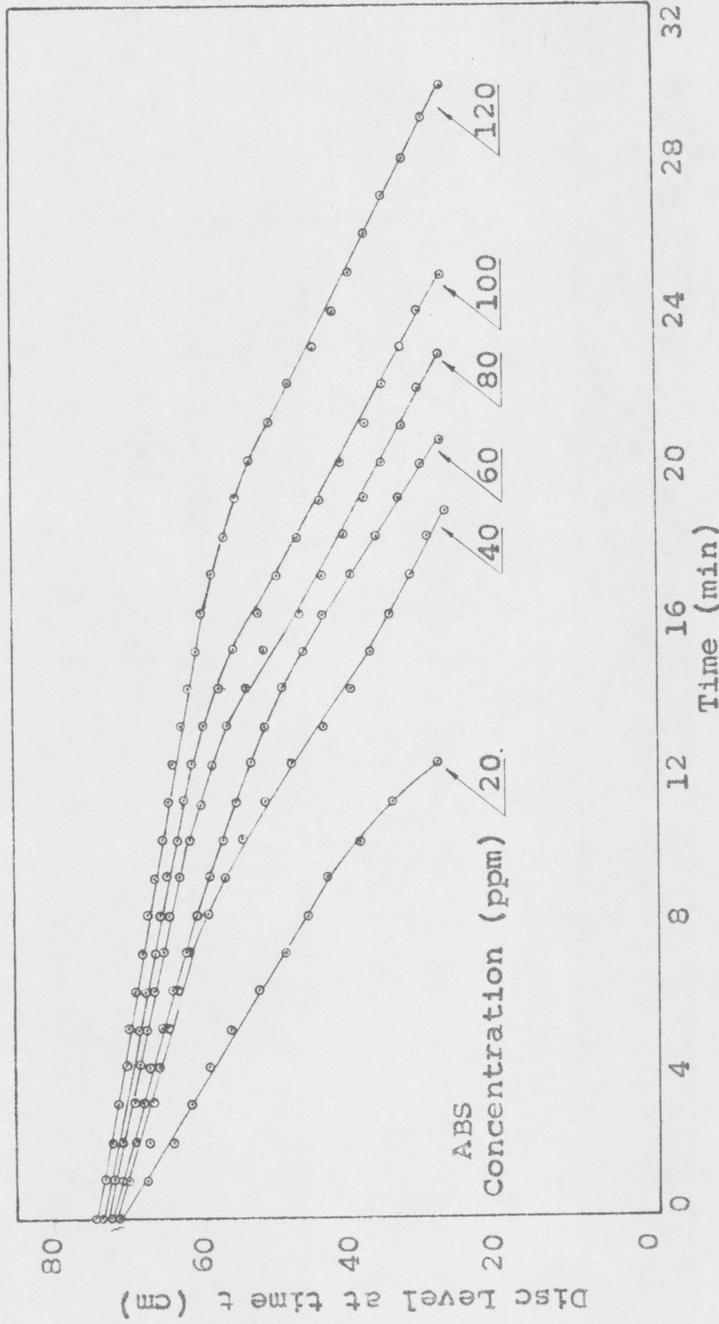
Figure 17: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 1.5 l/min for Phase 1 Experiments.
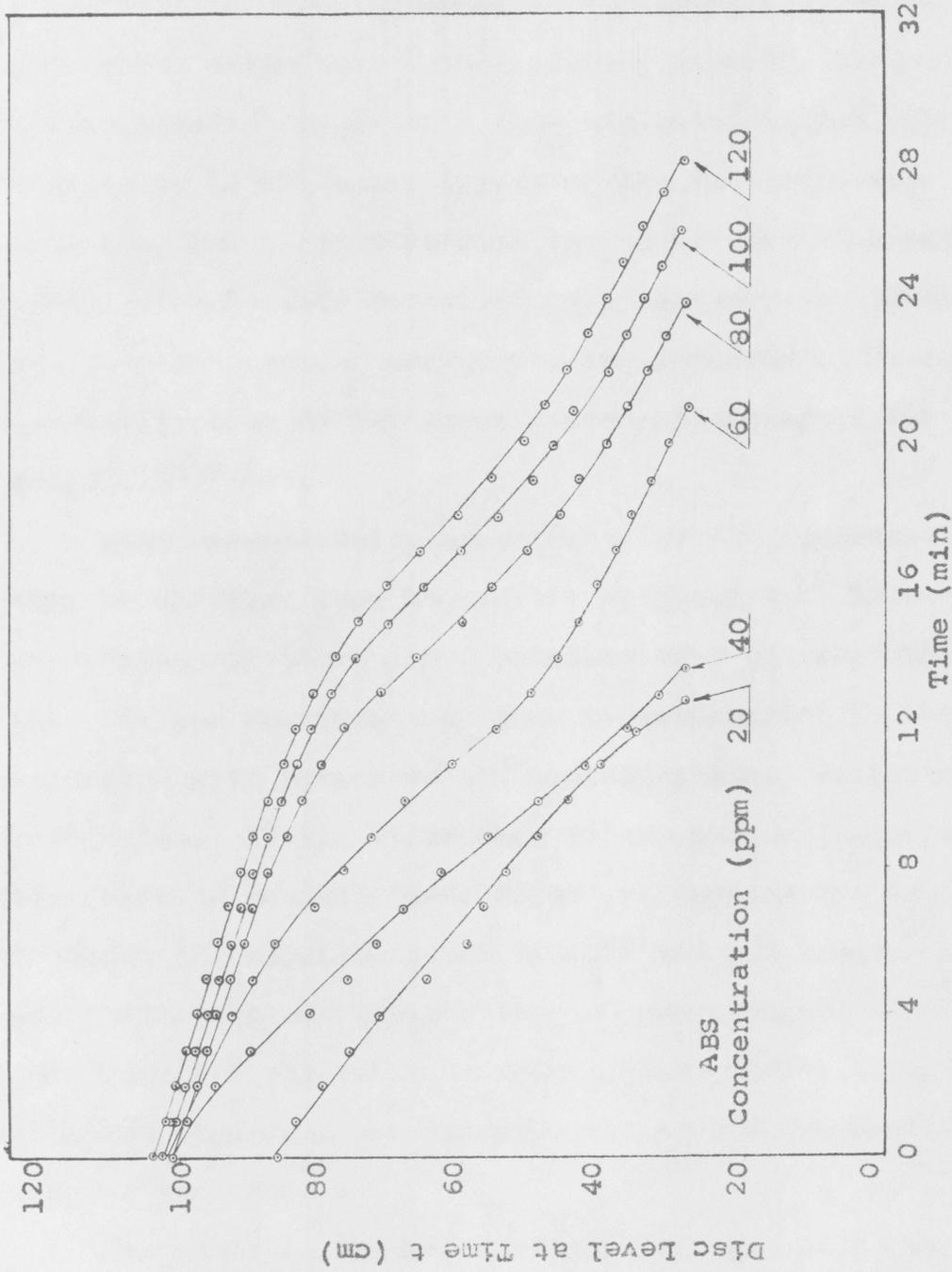
Figure 18: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 2.45 l/min for Phase 1 Experiments.

aeration rates resulted in foam formations which were observed
to be comprised of larger bubbles and thinner foam laminae.
Foams were observed to consist of different sizes at all aera-
tion rates during the investigation; however, foams at the
higher aeration rates as a rule exhibited larger bubbles,
especially in the upper layers of the foam structure. In
addition, the foams formed at the higher aeration rate (2.45
l/min) occasionally contained small air pockets of about
1 - 3 cm in diameter throughout the formation. This was
especially true of the foams formed at the lower ABS concen-
tration (20 ppm).

Disc descent rate, as affected by ABS concentration, may
also be observed from the curves in Figures 16 through 18.
Examination of these plots revealed that the strength of
foam, or the resistance of foam to destruction by the disc,
increased with increased ABS concentration. During the in-
vestigation, little difference in the physical appearance
was observed between foams formed at consecutive ABS concen-
trations for aeration rates of 0.75 and 1.5 l/min. However,
ABS concentrations greater than 20 ppm resulted in more uni-
form foam for the aeration rate of 2.45 l/min; i.e., the
pocketed type foam was not apparent at ABS concentrations
greater than 20 ppm.

The plots in Figures 16 through 18 exhibited increased
disc descent rates during the latter portion of the experi-
mental periods. The slopes representing the disc descent

rates during these latter periods may be observed to be essentially parallel indicating similar resistances to the disc assembly. However, during the initial experimental periods as shown in Figures 16 through 18, disc descent rates or slopes appeared to vary inversely with ABS concentration. In order to quantitatively compare the effects of aeration rate and ABS concentration on foam character, the results of all measurements of Phase 1 experiments are summarized in Table 18 in terms of the initial slopes of the curves as shown in Figures 16 through 18. Although slight curvature is exhibited in the initial portions of some curves in Figure 18, the slope of the line best fitting the points is given. The average values of the slopes given in Table 18 are plotted in Figure 19 to illustrate the effects of aeration rate and ABS concentration on disc descent rate.

The results of foam density for Phase 1 experiments are presented in Table 19. Examination of these data usually indicated increased foam densities with increased ABS concentration. The mean values of foam density in Table 19 are presented as Figure 20 to illustrate the effects of ABS concentration on foam density for each aeration rate. The rate at which density increased was observed to decline progressively as the ABS concentration was increased.

The mean values in Table 19 relative to aeration rate and foam density are presented as Figure 21 to illustrate the

Table 18: Effects of ABS Concentration and Aeration Rate on Disc Descent Rates for Phase 1 Experiments at 23°C.

The values given in the table are the initial slopes of the disc descent curves as shown in Figures 16 through 18. The units of the slopes are (cm/sec).

Aeration Rate (1/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0223	0.0107	0.0105	0.0092	0.0108	0.0097
	0.0153	0.0143	0.0126	0.0078	0.0113	0.0092
	0.0228	0.0109	0.0116	0.0104	0.0110	0.0087
	$\bar{x}$ = 0.0201	$\bar{x}$ = 0.0120	$\bar{x}$ = 0.0116	$\bar{x}$ = 0.0091	$\bar{x}$ = 0.0110	$\bar{x}$ = 0.0092
1.5	0.0503	0.0241	0.0319	0.0191	0.0145	0.0142
	0.0362	0.0294	0.0235	0.0217	0.0155	0.0188
	0.0518	0.0565	0.0213	0.0150	0.0181	0.0172
	$\bar{x}$ = 0.0464	$\bar{x}$ = 0.0367	$\bar{x}$ = 0.0256	$\bar{x}$ = 0.0186	$\bar{x}$ = 0.0160	$\bar{x}$ = 0.0167
2.45	0.0805	0.0914	0.0634	0.0320	0.0288	0.0282
	0.0951	0.0700	0.0660	0.0622	0.0266	0.0166
	0.0733	0.0672	0.0523	0.0227	0.0246	0.0246
	$\bar{x}$ = 0.0830	$\bar{x}$ = 0.0762	$\bar{x}$ = 0.0606	$\bar{x}$ = 0.0390	$\bar{x}$ = 0.0267	$\bar{x}$ = 0.0231
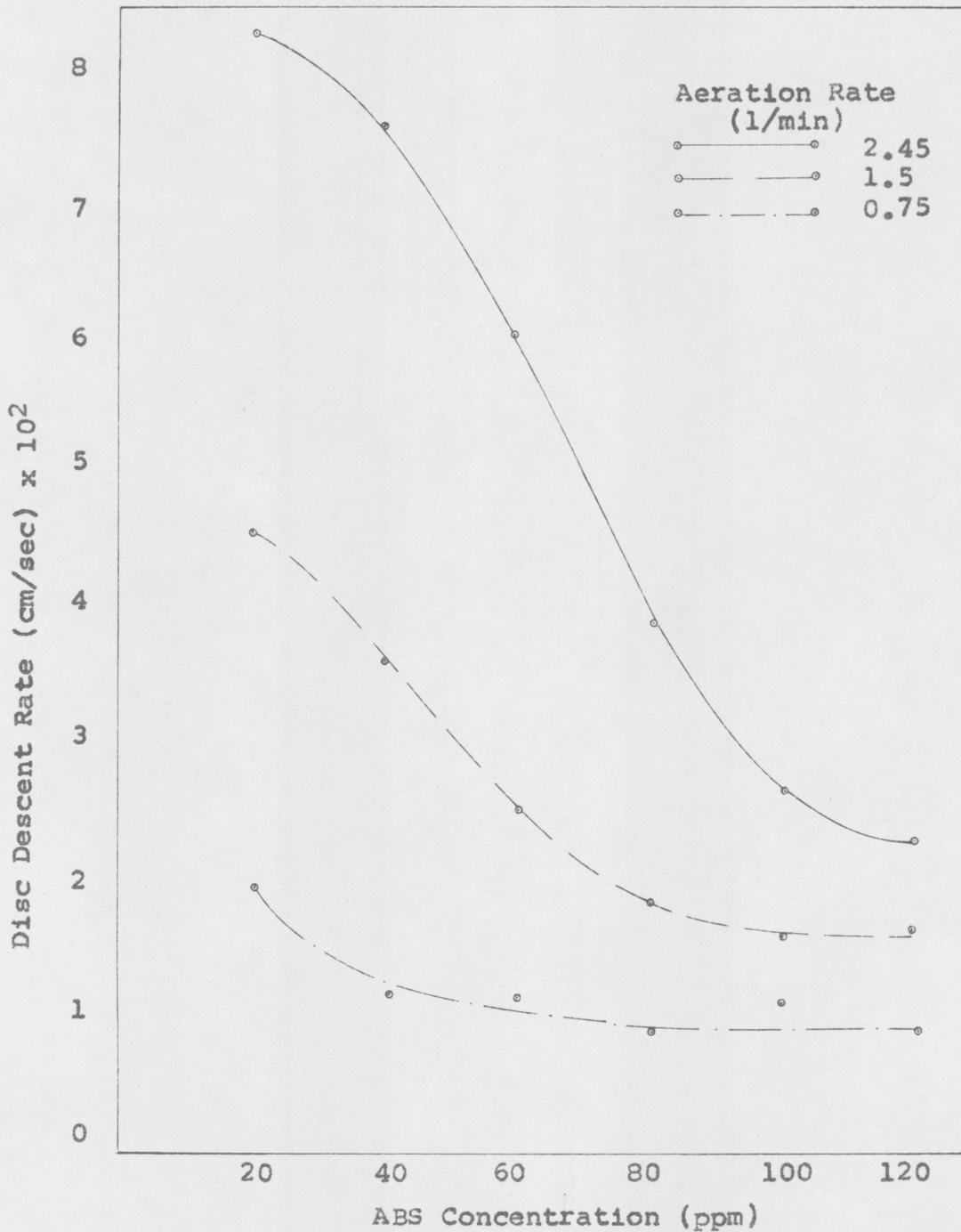
Figure 19:   Effects of ABS Concentration and Aeration
Rate on Disc Descent During Phase 1
Experiments.

Table 19: The Effect of ABS Concentration on the Density of Foam Formed by Aeration at Three Rates for Phase 1 Experiments.

The values given in the table have units of (gm/cc).

Aeration Rate (1/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0228	0.0429	0.0515	0.0560	0.0617	0.0579
	0.0197	0.0357	0.0452	0.0450	0.0557	0.0581
	0.0223	0.0407	0.0492	0.0540	0.0569	0.0546
	$\bar{x}$ = 0.0216	$\bar{x}$ = 0.0398	$\bar{x}$ = 0.0480	$\bar{x}$ = 0.0517	$\bar{x}$ = 0.0581	$\bar{x}$ = 0.0569
1.5	0.0159	0.0415	0.0531	0.0621	0.0718	0.0694
	0.0155	0.0334	0.0517	0.0632	0.0587	0.0679
	0.0153	0.0315	0.0464	0.0640	0.0696	0.0707
	$\bar{x}$ = 0.0156	$\bar{x}$ = 0.0355	$\bar{x}$ = 0.0504	$\bar{x}$ = 0.0631	$\bar{x}$ = 0.0667	$\bar{x}$ = 0.0693
2.45	0.0118	0.0250	0.0475	0.0554	0.0604	0.0635
	0.0760	0.0342	0.0457	0.0559	0.0488	0.0587
	0.0135	0.0306	0.0435	0.0557	0.0594	0.0674
	$\bar{x}$ = 0.0110	$\bar{x}$ = 0.0299	$\bar{x}$ = 0.0456	$\bar{x}$ = 0.0557	$\bar{x}$ = 0.0562	$\bar{x}$ = 0.0632
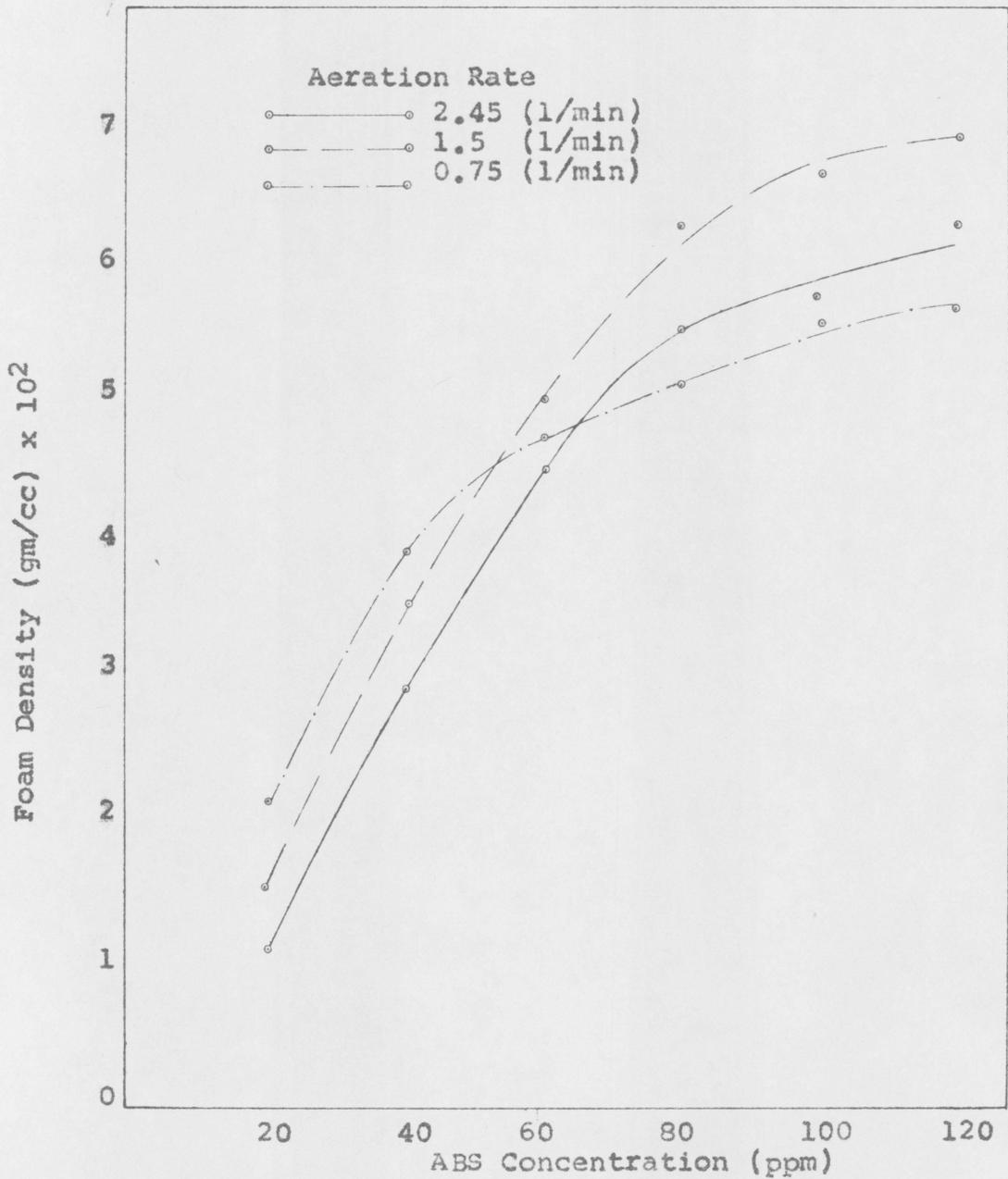
Figure 20: The Effect of ABS Concentration on Foam
            Density for Three Aeration Rates During
            Phase 1 Experiments.
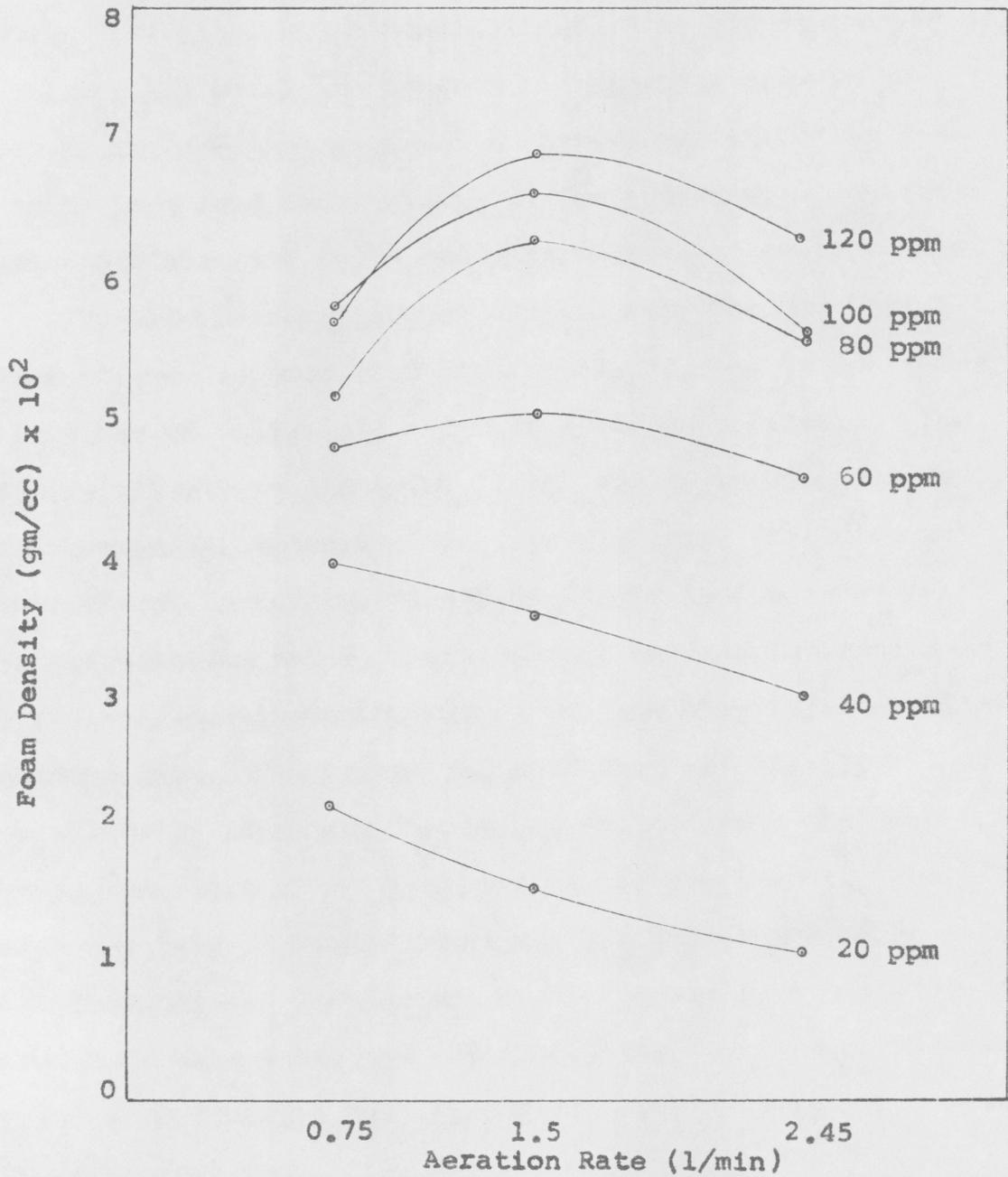
Figure 21:   The Effect of Aeration Rate on Foam Density
for Six ABS Concentrations During Phase 1
Experiments.

relationship between these variables. Examination of Figure 21 indicated that foam density varied inversely with aeration rate at the lower ABS concentrations. For ABS concentrations of 60 ppm and over, the inverse relationship between foam density and aeration rate was no longer evident. The foam density increased to a maximum at the intermediate aeration rate and thereafter decreased with increased aeration rate.

The rate at which liquid drained from freshly formed foams may be observed from Figures 22, 23, and 24 for aeration rates of 0.75, 1.5, and 2.45 l/min respectively. The figures illustrate the total liquid volume in foam during the experiments employing the disc assembly. Although the plots reveal increased volumes of liquid in foams for increased aeration rates, these volumes are not indicative of foam densities since the volumes of foam also increase with aeration rate. The curves indicate that practically all of the initially entrained liquid had drained from the foam during the first 10 - 13 minutes of the experiment. The small quantity of liquid remaining was that required to maintain foam films. Examination of the curves in Figures 22 through 24 also indicated a tendency for the rate of liquid drainage to increase with increased aeration rate for a given ABS concentration.

During Phase 1 experiments, it was observed that special precaution was needed to prevent film accumulations on the
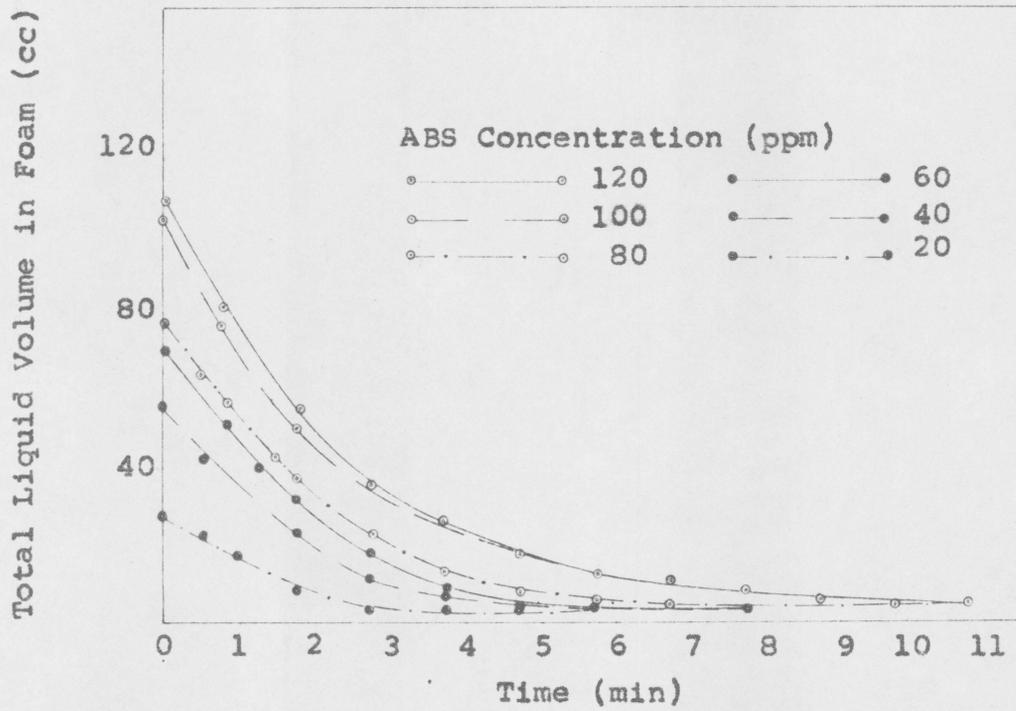
Figure 22: Total Liquid Volume in Foams Produced
from an Aeration Rate of 0.75 l/min
During Phase 1 Experiments.
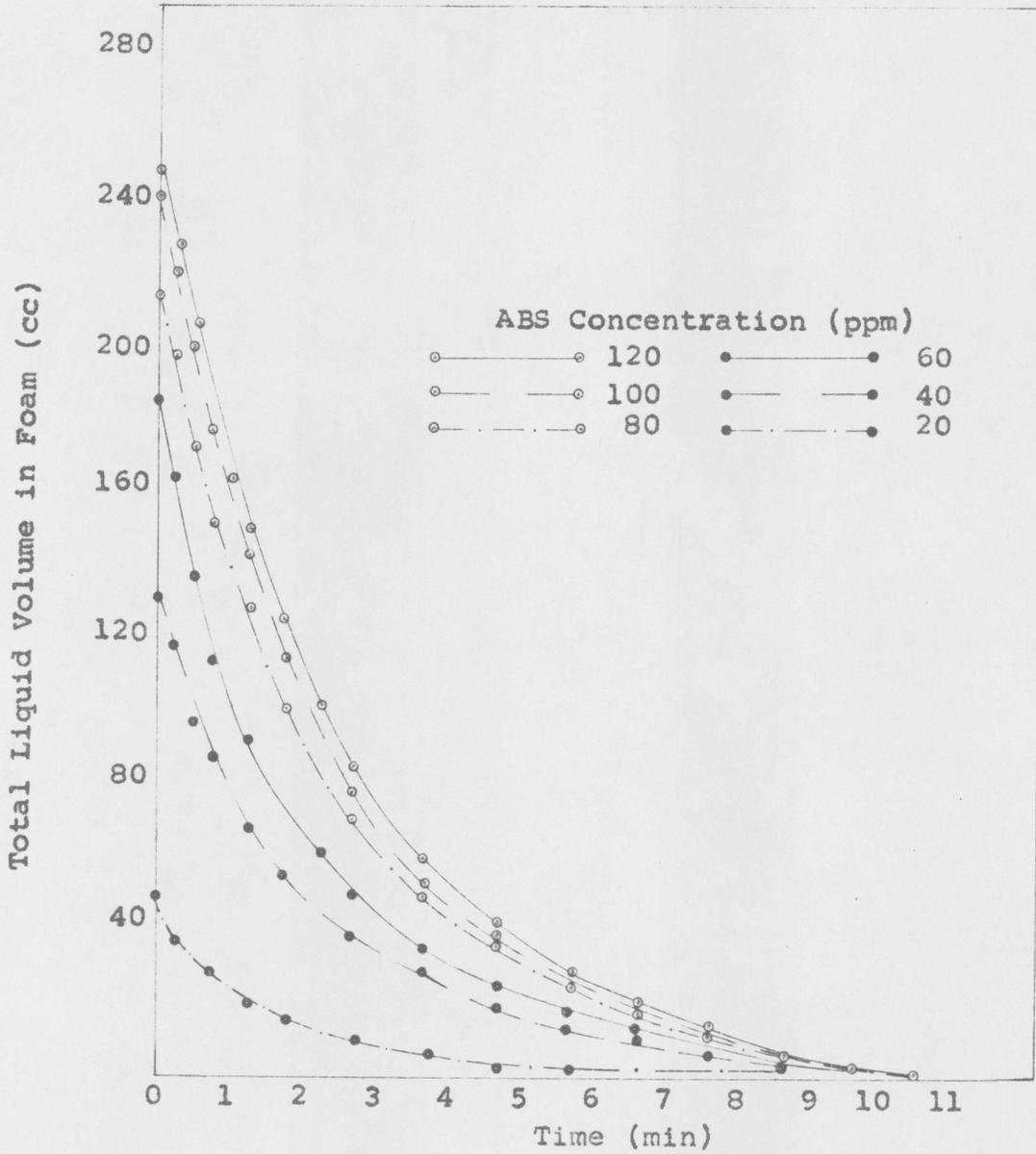
Figure 23: Total Liquid Volume in Foams Produced from an Aeration Rate of 1.5 l/min During Phase 1 Experiments.
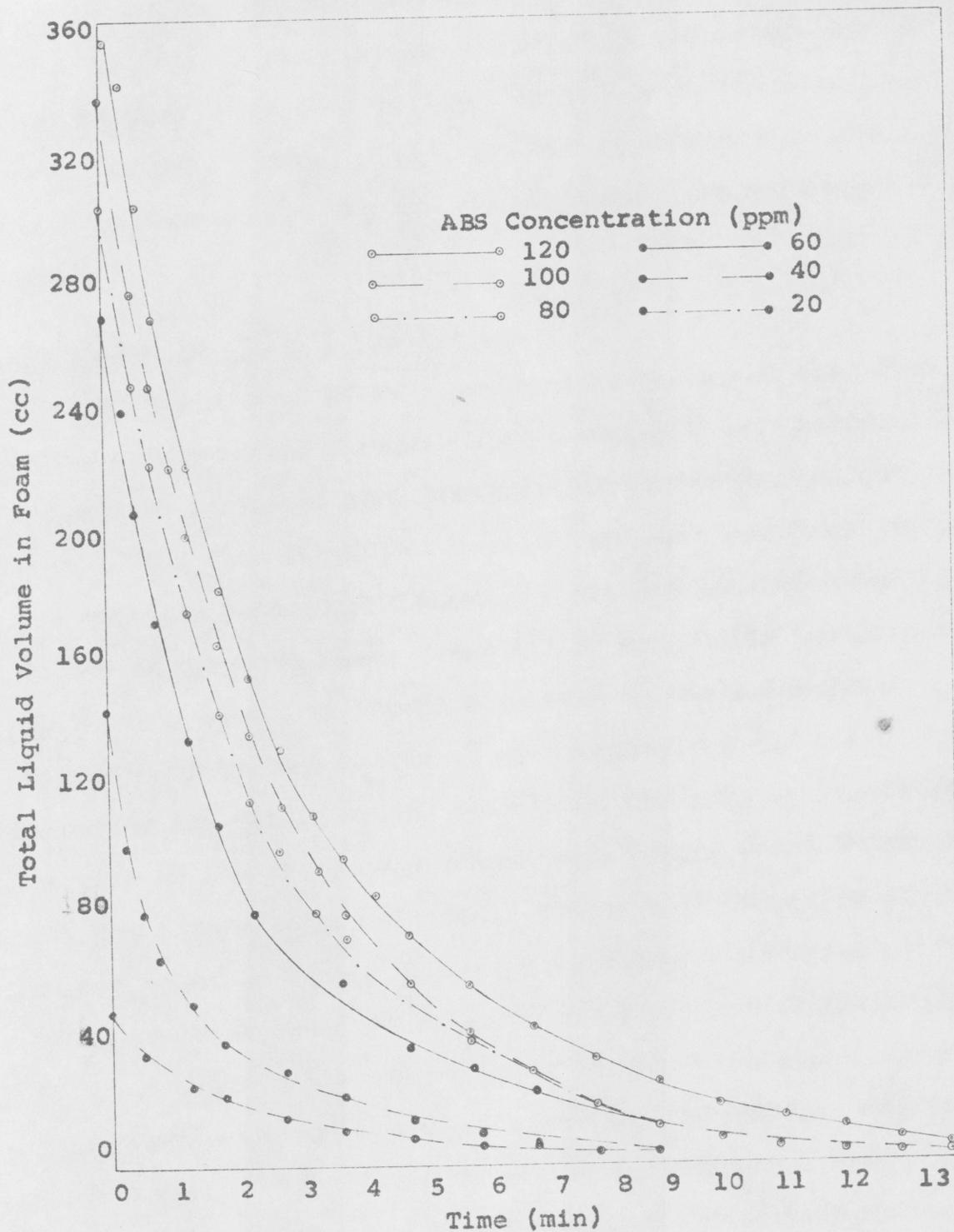
Figure 24: Total Liquid Volume in Foams Produced from
an Aeration Rate of 2.45 1/min During
Phase 1 Experiments.

disc assembly. Improper cleansing of the disc assembly between successive measurements resulted in increased rate of disc descent - a factor believed to be due to alkaline film accumulations. Hence, during the investigation care was taken to cleanse and dry the disc assembly between measurements.

Discussion of Phase 1 Results

The results of Phase 1 experiments indicated that disc descent rate varied directly with aeration rate. Figures 16 through 18 indicated that the greatest resistance to destruction by the disc assembly occurred for foams generated at the low aeration rate (0.75 l/min). Increased aerated rates resulted in foam structure comprised of noticeably larger bubbles which tended to increase in size in the upper foam layers. Since foam height is proportional to the linear gas velocity for fairly stable foams (7), the rate of formation or rise of the previously formed foam layers would be greater for the higher aeration rates. During foam formation at the higher aeration rates, a greater amount of stretching of foam films would be expected owing to the increased frictional effects exerted by the column wall. Since a two minute aeration period was employed for all experiments, regardless of aeration rate, the final foam height or distance over which the frictional effects were operative increased with increased

aeration rate. In view of the more fragile nature reported for foams comprised of larger bubbles (4, 7), the direct relationship of aeration rate and disc descent rate was expected.

The effects of ABS concentration on foam character were not obvious from the physical appearance of the foam. However, the increased resistance to destruction by the disc assembly indicated in Figures 16 through 18 for increased ABS concentrations suggested that differences in foam structure must have existed. The increased foam densities with increased ABS concentrations, shown in Table 19, further implied changes in foam structure had occurred. The changes in foam structure might be attributed to increased film formation at increased ABS concentrations. According to Sinsheimer (32) film formation increased owing to smaller bubbles being formed at increased concentrations of foaming agent. Hence, greater film surface per unit volume of foam would apparently not only result in increased densities but also offer more resistance to destruction owing to the greater degree of stretching and thinning of film laminae required to effect rupture.

The ability of foam to resist destruction by the disc assembly was observed to decrease during the latter portions of the experimental periods. As shown in Figures 16 through 18, practically all of the curves exhibited increased disc

descent rates after an initial period, the length of which appeared to vary directly with ABS concentration and inversely with aeration rate. The increased disc descent rates or slopes of the curves during the latter portion of the experiments were presumably the effects of drainage of solution from the foam. It was shown in Figures 22 through 24 that essentially all of the initially entrained moisture had drained from the foam within the first 10 to 13 minutes. It will be shown later that although no appreciable rupture had occurred due to an initial drainage period, subsequent breakage soon became evident after a total period of about 15 to 30 minutes, depending upon the character of foam. Since drainage effects the weakening of foam by stretching and thinning of foam laminae, foams of larger bubble size, as reported for the foams of Figure 18, would be expected to become susceptible to destruction sooner than the smaller bubble foam as reported for the foams of Figure 16 and 17.

The slopes of the initial portions of each curve of disc descent were given in Table 18 to characterize the foam for each measurement since the properties affecting the strength of foam appeared to be present primarily in freshly formed foams. Examination of the data of Table 18 exhibited some variability between slopes representing concentration effects. However, realizing that relatively dilute solutions, in the range of 0.002 to 0.012 per cent by weight were

employed, and that very small differences in foam structure
apparently resulted for consecutive ABS concentrations, some
variability could be expected. The data of Table 18 indi-
cated the trend of the slopes to vary directly with aeration
rate and inversely with ABS concentration as shown in Figure
19.

In order to examine the effects of ABS concentration
and aeration rate more thoroughly, a statistical analysis of
variance was performed for the data of Table 18 and is pre-
sented as Table 21. Computational details and discussion
of the analysis of variance have been presented by Ostle (28)
for randomized complete block experiments employing factorial
treatment combinations. However, a brief explanation of the
terminology employed in Table 21 was considered necessary
prior to examination of the results.

In previous sections of this thesis, the word treatment
(or treatment combination) was used with little or no ex-
planation as to the meaning of the term. To the statistician,
the word treatment implies the particular set of conditions
imposed on an experimental unit from which measurement is
made. The experiments in this thesis employed combinations
of the factors of aeration rate and ABS concentration as
treatments. Aqueous solutions were employed as the experi-
mental units in the investigation to determine how the char-
acter of foam resulting from these solutions might be

Table 20: Formulae for Expected Mean Squares and F-Ratios for a Two-Factor Factorial in a Randomized Complete Block Design (Fixed Model).

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	Expected Mean Squares	F-Ratios
Replicates	(r-1)	Ryy	R		
Treatments	(t-1)				
A (main effect)	(a-1)	Ayy	A	$\sigma^2 + rb\sum_{1}^{a}\frac{\alpha_i^2}{(a-1)}$	A/E
B (main effect)	(b-1)	Byy	B	$\sigma^2 + ra\sum_{k}^{b}\frac{\beta_k^2}{(b-1)}$	B/E
A x B (interaction)	(a-1)(b-1)	(AB)yy	AB	$\sigma^2 + r\sum_{j,k}^{a,b}\frac{(\alpha\theta)_{jk}}{(a-1)(b-1)}$	AB/E
Experimental Error	(r-1)(ab-1)	Eyy	E	σ^2	
Total	rab-1				

Table 21: Analysis of Variance of Disc Descent Rate Data of Table 18.

The values of sum of squares and mean squares have been multiplied by a factor of 105.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Ratio
Replicates	2	3.52	1.76	
Treatments	17			
Concentration (C)	5	834.87	166.97	22.56**
C(L)(Linear)	1	796.37	796.37	107.61**
C(Dev)(Higher Order)	4	38.47	9.61	1.30
Aeration Rate (AR)	2	1417.21	708.60	95.76**
AR(L)(Linear)	1	1385.59	1385.59	187.24**
AR(Q)(Quadratic)	1	31.62	31.62	4.27*
C x AR	10	398.91	39.89	5.39**
C(L)AR(L) (Linear)	1	357.02	357.02	48.24**
CAR(Dev) (Higher Order)	9	41.89	4.65	0.63
Experimental Error	34	251.64	7.40	
Total	53	2906.12		

* Denotes treatment differences declared significant at 5% probability level.
** Denotes treatment differences declared significant at 1% probability level.

affected by the various levels of ABS concentration and aeration rate.

The factors of both ABS concentration (C) and aeration rate (AR) are listed individually in Table 21 under treatments in the column entitled Source of Variation. Both (C) and (AR) represent the main effects for factors of ABS concentration and aeration rate respectively; i.e., each main effect is a measure of the change in foam character due to changes only in that particular factor when averaged over all of the levels of the other factor. The subscripted terms beneath each of the main effects represent the form of the response of foam character due to the various levels of the factors of ABS concentration and aeration rate; actually these terms indicate whether the response was linear, quadratic, etc.

The term (C x AR), also shown under the treatments in Table 21, represents the interaction between factorial combinations of ABS concentration and aeration rate. The interaction measures the differential response of one factor to stay constant when applied simultaneously with varying levels of another factor; i.e., interaction reflects the additional effect due to the combined influence of two (or more) factors. Hence, the interaction indicates the degree of interdependence between the two factors of ABS concentration and aeration as

given in Table 21. The subscripted terms beneath the inter-action, similar to the subscripted terms under the main ef-fects, indicate the form of the response which the factors of aeration rate and ABS concentration combined had on foam character.

The values under the column of mean squares in Table 21 result from dividing the sum of squares by the respective degrees of freedom for each of the sources of variation. Each mean square serves as an estimate of the parameters in-cluded in the expected mean squares as shown in Table 20.

The formulae of Table 20 are presented to illustrate the parameters comprising each of the mean squares. The ex-pected mean squares, as shown in Table 20, are derived from an assumed linear statistical model which describes an ob-servation in terms of a mean and other components such as treatment effects, environmental effects, and residual or error effects. A further assumption or choice regarding the linear model must be made according to whatever the research-er wishes to say about the treatment effects. The research-er's decision may be: 1) that only the t treatments present in the experiment are of primary concern, in which case the decision results in what is referred to as the fixed model, or 2) that the researcher is concerned with a population of treatments of which only a random sample is present in the experiment - hence the random model. For the fixed model,

inferences are drawn about the particular treatments investigated; for the random model, inferences are drawn about the population of treatments. Since the primary concern in the foam characterization studies of this thesis was to evaluate the method of the weighted disc, the treatments were fixed or selected in advance to ascertain if differential responses of foam character could be detected by the method throughout the range of the given variables. Once the foregoing assumption has been made, the expected mean squares may be obtained to reflect the researcher's decision as to the treatment effects. For the randomized complete block experiments employing the factors A and B, the expected mean squares for the fixed model are essentially as shown in Table 20.

The expected mean square or variance (σ^2) associated with the experimental error, as shown in Table 20, reflects the inability to duplicate measurements on experimental units treated alike. This variation is due either to differences in the experimental material and/or experimental techniques. Since the experimental error is assumed to be present in all observations, the error variance (σ^2) is included in each of the expected mean squares as shown in Table 20. In addition to the experimental error variance (σ^2) the expected mean squares for each of the treatments include a component which serves to estimate the variability resulting from the

respective treatment. Hence, the expected mean squares indicates the components of variation which are included in the calculated values of mean squares as shown in Table 21.

In order to evaluate the significance of the variability attributed to each of the main effects and interaction, the mean square for each must be compared to the mean square included from another source. The expected mean squares serve to indicate the proper procedure to follow in making these comparisons. The resulting F-ratios, shown in Table 20, illustrate the appropriate comparisons to be made and serve as the criterion in determining the significance as to the role of each of the main effects and interaction. The null hypothesis, corresponding to the previous decision concerning the treatment effects, assumes that there are no differences among treatment means; the alternative is that treatment differences exist. Hence, in performing the F- tests, calculated F-values sufficiently greater than one (1.0) may indicate that real treatment differences existed and in which case the null hypothesis is rejected.

Tabulated F-values are given in many statistics textbooks [e.g., Ostle (28)] for various probability levels and degrees of freedom to aid the analyst in evaluating results. When calculated values are greater than tabulated values for a given probability level (α per cent), the results are

declared significant at that probability level for the parti-
cular treatment effect being tested.

In addition to testing the significance of the effects
of a particular treatment effect, the variability associated
with this treatment effect may be desired. It was shown
previously that the expected mean squares in Table 20 includ-
ed both the error variance (σ^2) and the component estimating
the variability of the respective treatment effects; hence
the calculated mean squares are comprised of both sources of
variability. For estimation of the variability associated
with either the treatment main effects or interaction, the
mean square may be equated to the expected mean square and
solved for the component representing the respective treat-
ment effect. For example, the variability associated with
the main effect of factor A of Table 20 may be estimated as
follows:

$$\text{mean square (A)} = \sigma^2 + r\, b \sum_{j}^{a} \alpha_j^2/(a-1)$$

$$\text{or} \quad \sum_{j}^{a} \alpha_j^2/(a-1) = \frac{\text{mean square (A)} - \sigma^2}{rb}$$

where $\sum_{j}^{a} \alpha_j^2/(a-1)$ is an estimate of the variability of the
a levels of the main effects of factor A

mean square (A) is the calculated value of the mean
square similar to the mean square for
ABS concentration in Table 21

σ^2 is estimated by the error mean square (E) which

corresponds to the calculated value of error

mean square in Table 21

r is the number of replicates of which the factor A

is applied

b is the number of levels of factor B over which

the A main effects are averaged

The estimation of the variability of the main effects of factor B and the interaction may be performed in a similar manner.

The results of the analysis of variance in Table 21 revealed that the effects of both ABS concentration and aeration rate on foam character were significant at the one per cent probability level. Comparison of the relative magnitudes of the F-values seemingly suggested that aeration rate had a more pronounced effect on foam character than ABS concentration. The two factors, however, are not comparable on the basis of F-ratios alone since the terms (rb) and (ra), as shown in Table 20 for the corresponding expected mean squares, are unequal, being 9 and 18 for ABS concentration and aeration rate respectively. A comparison of the relative effects of ABS concentration and aeration rate may be made on the basis of the estimated variability associated with the treatment effects of each of these factors; hence, if the

factors of ABS concentration (C) and aeration rate (AR) in Table 21 are considered as factors A and B respectively, the same expressions as given in Table 20 for the expected mean squares may be used in the following estimation of the variability due to the main effects of these two factors.

For ABS concentration:

$$\sum_{j}^{a} \alpha_j^2/(a-1) = \frac{(166.97 - 7.40) \times 10^{-5}}{9} = 17.35 \times 10^{-5}$$

For aeration rate:

$$\sum_{k}^{b} \beta_k^2/(b-1) = \frac{708.60 - 7.40}{18} \times 10^{-5} = 38.96 \times 10^{-5}$$

These results indicated that the variability due to the effects of aeration rate was greater than or about 2.2 times that for ABS concentration. Therefore, the results suggested that aeration rate had a more pronounced effect on foam character than ABS concentration. This observation agreed with the results in Table 18 wherein differences in values of disc descent rate for consecutive aeration rates appeared to be greater than the differences in values for consecutive ABS concentrations.

The manner in which foam character responded to changes in either ABS concentration or aeration rate was not indicated by Table 18. Examination of Table 21, however, indicated that linear responses to the levels of each ABS concentration and aeration rate were significant at the one per

cent probability level. Quadratic and/or higher order re-
sponses to the levels of ABS concentration were not signifi-
cant; however, the effects of varying the levels of aeration
rate revealed a quadratic response significant at the five
per cent probability level.

The effects of interaction were also observed to be
significant at the one per cent probability level. The in-
teraction resulted primarily from linear responses to the
levels of the combined factors of ABS concentrations and
aeration rate. The accuracy of this statement may be veri-
fied by comparison of the F-values for the interaction in
Table 21.

The effects of ABS concentration and aeration rate on
foam density were illustrated in Table 19. Examination of
these data generally indicated a direct relationship between
foam density and ABS concentration for a given aeration rate.
As already indicated, this relationship was presumably due
to increased film formation owing to smaller bubbles being
formed at increased ABS concentrations.

Foam densities were observed to vary inversely with
aeration rate in Figure 21 for ABS concentrations of 20 and
40 ppm. The foam structure, resulting from the high aeration
rates at the lower ABS concentrations, tended to be thin,
fragile and occasionally pocketed. The density of such foam
would be expected to be low as indicated by the data. As

the ABS concentration was increased, the ability to foam appeared to be more compatible with the increased aeration rates than with lower concentration of ABS. Consequently, foams formed at the higher aeration rates and high ABS concentrations exhibited fewer and smaller air pockets and appeared more dense than foam formed under similar conditions from solutions of low ABS concentration.

Foam densities were apparently dependent upon other factors in addition to bubble size which presumably varied directly with aeration rate. Therefore, density per se would not be entirely indicative of the true bubble size nor, as Sisley and Loury - as translated by Wood (35) - indicated, would it be entirely reliable for estimation of the stability properties of foam.

3) Phase 2 Experiments

Phase 2 experiments differed from Phase 1 experiments insofar as a constant volume of foam was produced for each test solution regardless of aeration rate. In addition, Phase 2 experiments were performed under constant conditions of temperature and relative humidity rather than at room temperatures as in Phase 1. The experiments, as previously outlined in Table 13, were performed first at 20°C and later at 27°C to ascertain whether this temperature difference would reveal any appreciable changes in foam characteristics as determined by the weighted disc method.

Results typifying Phase 2 experiments are presented as
Figures 25 through 27 to illustrate disc descent through
foams for one replicate of the basic experiment. The data,
as presented in Figures 25 through 27, are tabulated in Appen-
dix A for all replicates of Phase 2 experiments. The slopes
of the linear portions of the disc descent curves, as illus-
trated in Figures 25 through 27, are summarized in Tables 22
and 23 for Phase 2 experiments employing temperatures of $20^{\circ}C$
and $27^{\circ}C$ respectively. The mean values of the slopes given
in Tables 22 and 23 are presented as Figure 28 to illustrate
the effects of ABS concentration on disc descent rates for the
three aeration rates and two temperatures.

An analysis of variance was performed on the data of
Tables 22 and 23 to evaluate the response of disc descent
rate to the levels of ABS concentration and aeration rate em-
ployed in the investigation. The results are presented as
Tables 24 and 25 for temperatures of $20^{\circ}C$ and $27^{\circ}C$ respective-
ly. The variability of the treatment main effects of the
factors of both ABS concentration and aeration rate were esti-
mated, in a similar manner as in Phase 1 experiments, and are
given as follows:

For the experiments at $20^{\circ}C$:

$$\sum_{i,j}^{a} \alpha_j^2 /(a-1) = 0.20 \times 10^{-5} \text{ (ABS concentration)}$$

$$\sum_{k}^{b} \beta_k^2 /(b-1) = 6.96 \times 10^{-5} \text{ (aeration rate)}$$
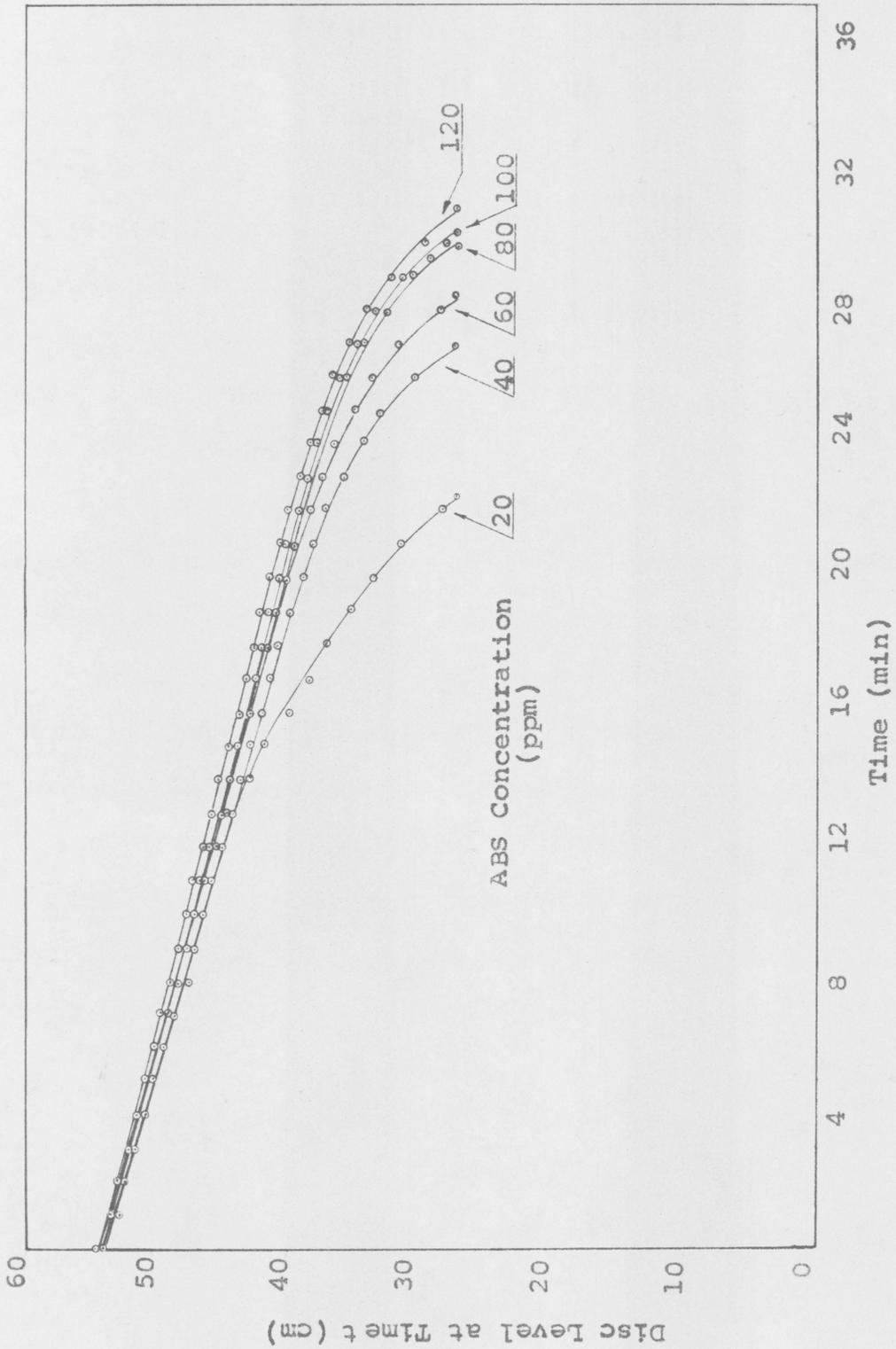
Figure 25: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 0.75 l/min During Phase 2 Experiments.
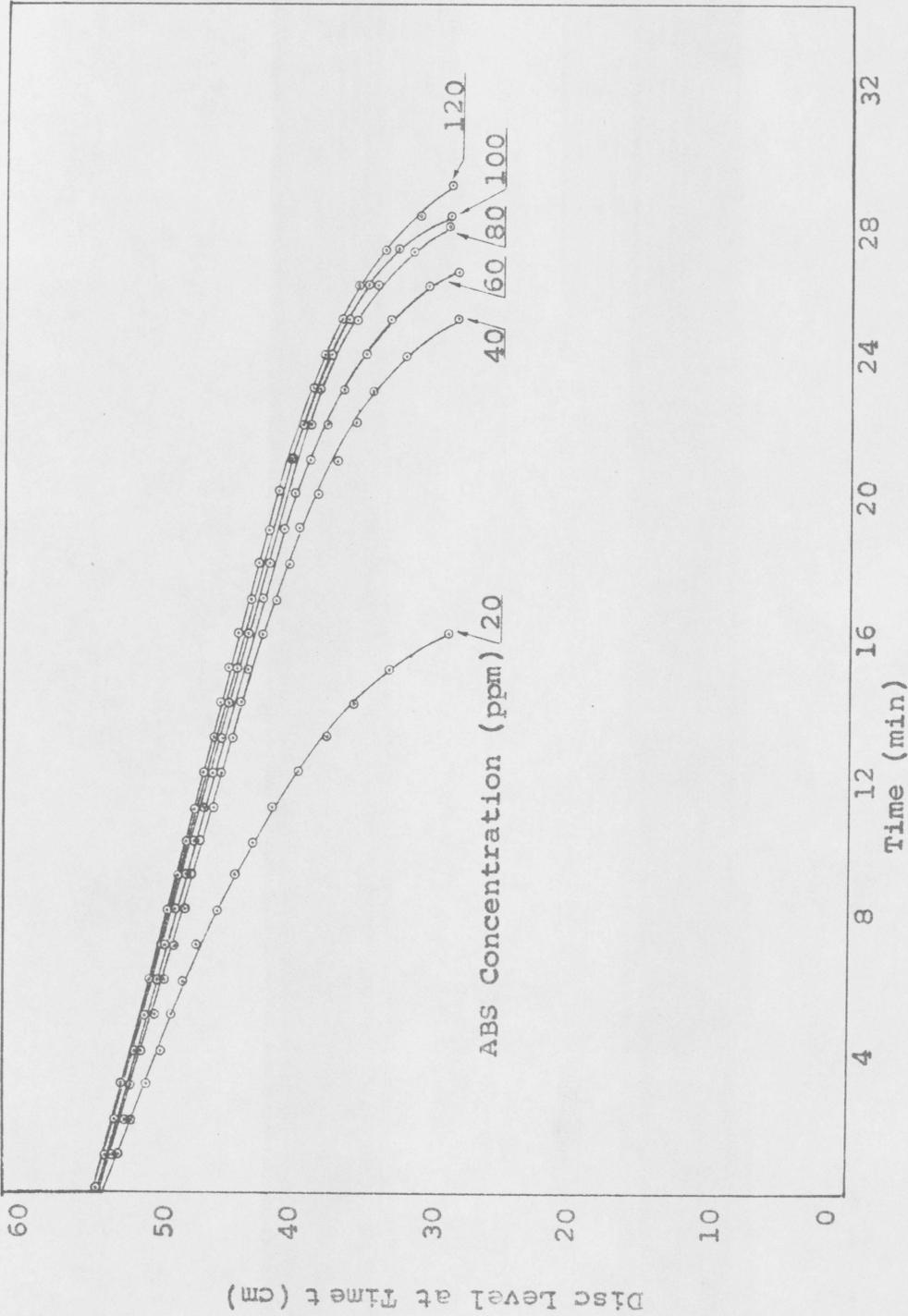
Figure 26: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 1.5 l/min During Phase 2 Experiments.
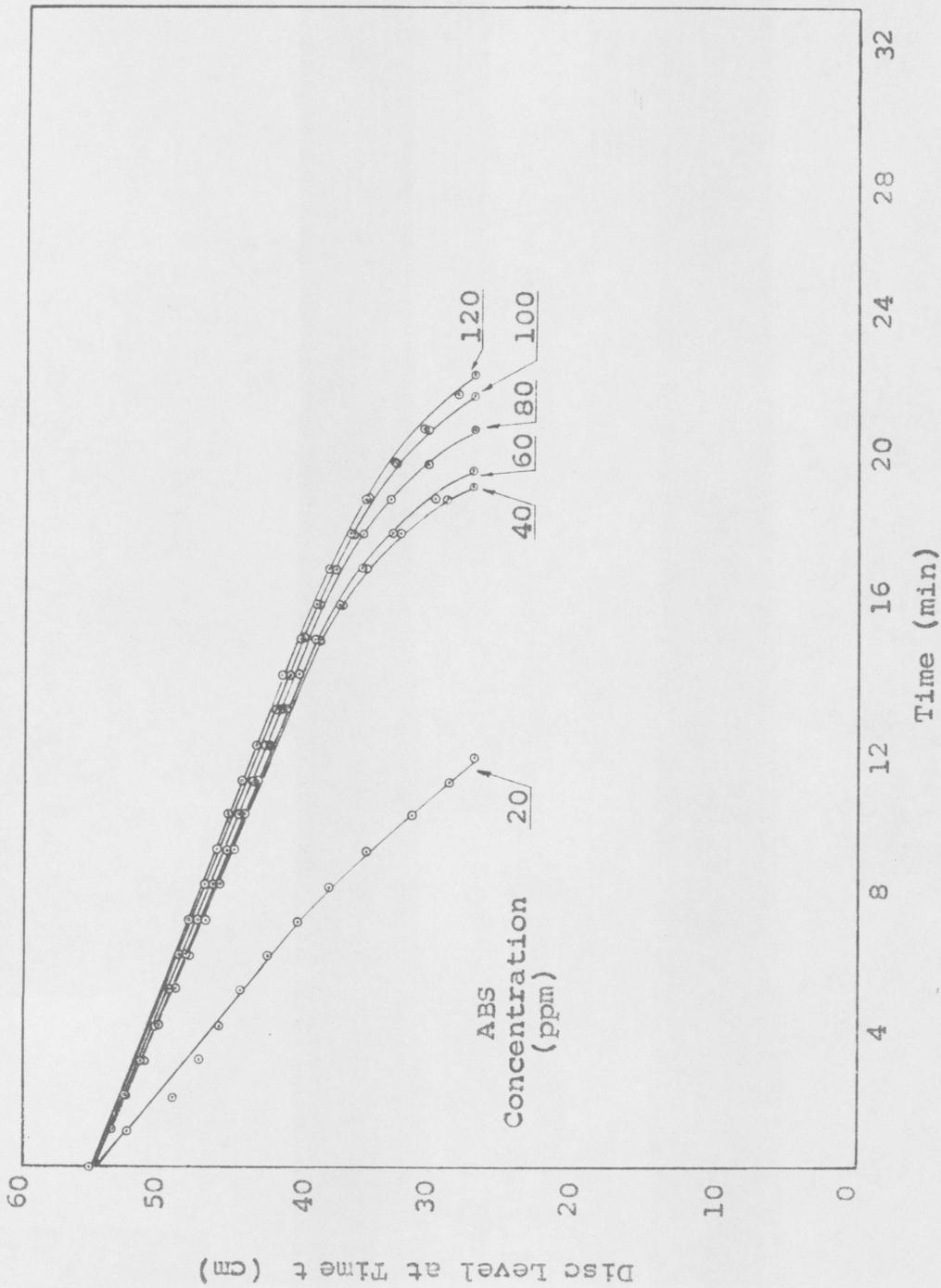
Figure 27: The Effect of ABS Concentration on Disc Descent Through Foams Produced by an Aeration Rate of 2.45 l/min During Phase 2 Experiments.

Table 22: Effects of ABS Concentration and Aeration Rate on Disc Descent Rates for Phase 2 Experiments at 20°C.

The values given in the table are the initial slopes of the disc descent curves as shown in Figures 25 through 27. The units of the slopes are (cm/sec).

Aeration Rate (l/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0120	0.0110	0.0105	0.0101	0.0101	0.0094
	0.0133	0.0111	0.0111	0.0107	0.0106	0.0097
	0.0148	0.0122	0.0112	0.0104	0.0108	0.0106
	$\bar{x}$ = 0.0134	$\bar{x}$ = 0.0114	$\bar{x}$ = 0.0109	$\bar{x}$ = 0.0104	$\bar{x}$ = 0.0105	$\bar{x}$ = 0.0099
1.5	0.0183	0.0172	0.0168	0.0164	0.0164	0.0160
	0.0184	0.0178	0.0178	0.0173	0.0163	0.0152
	0.0180	0.0174	0.0175	0.0159	0.0156	0.0157
	$\bar{x}$ = 0.0182	$\bar{x}$ = 0.0175	$\bar{x}$ = 0.0174	$\bar{x}$ = 0.0165	$\bar{x}$ = 0.0161	$\bar{x}$ = 0.0156
2.45	0.0267	0.0266	0.0260	0.0246	0.0231	0.0213
	0.0286	0.0280	0.0281	0.0250	0.0253	0.0246
	0.0376	0.0331	0.0316	0.0300	0.0284	0.0274
	$\bar{x}$ = 0.0310	$\bar{x}$ = 0.0292	$\bar{x}$ = 0.0286	$\bar{x}$ = 0.0265	$\bar{x}$ = 0.0256	$\bar{x}$ = 0.0244

Table 23: Effects of ABS Concentration and Aeration Rate on Disc Descent Rates for Phase 2 Experiments at 27°C.

The values given in the table are the initial slopes of the disc descent curves as shown in Figures 25 through 27. The units of the slopes are (cm/sec).

Aeration Rate (l/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0145	0.0130	0.0127	0.0125	0.0124	0.0126
	0.0145	0.0131	0.0129	0.0128	0.0135	0.0123
	0.0136	0.0122	0.0124	0.0125	0.0118	0.0117
	$\bar{x} = 0.0142$	$\bar{x} = 0.0128$	$\bar{x} = 0.0127$	$\bar{x} = 0.0126$	$\bar{x} = 0.0126$	$\bar{x} = 0.0122$
1.5	0.0240	0.0222	0.0214	0.0215	0.0206	0.0207
	0.0263	0.0230	0.0220	0.0200	0.0220	0.0212
	0.0277	0.0227	0.0205	0.0197	0.0190	0.0218
	$\bar{x} = 0.0260$	$\bar{x} = 0.0226$	$\bar{x} = 0.0213$	$\bar{x} = 0.0204$	$\bar{x} = 0.0205$	$\bar{x} = 0.0212$
2.45	0.0376	0.0384	0.0348	0.0321	0.0346	0.0343
	0.0360	0.0344	0.0371	0.0337	0.0322	0.0278
	0.0438	0.0369	0.0424	0.0414	0.0366	0.0276
	$\bar{x} = 0.0391$	$\bar{x} = 0.0366$	$\bar{x} = 0.0381$	$\bar{x} = 0.0357$	$\bar{x} = 0.0345$	$\bar{x} = 0.0299$
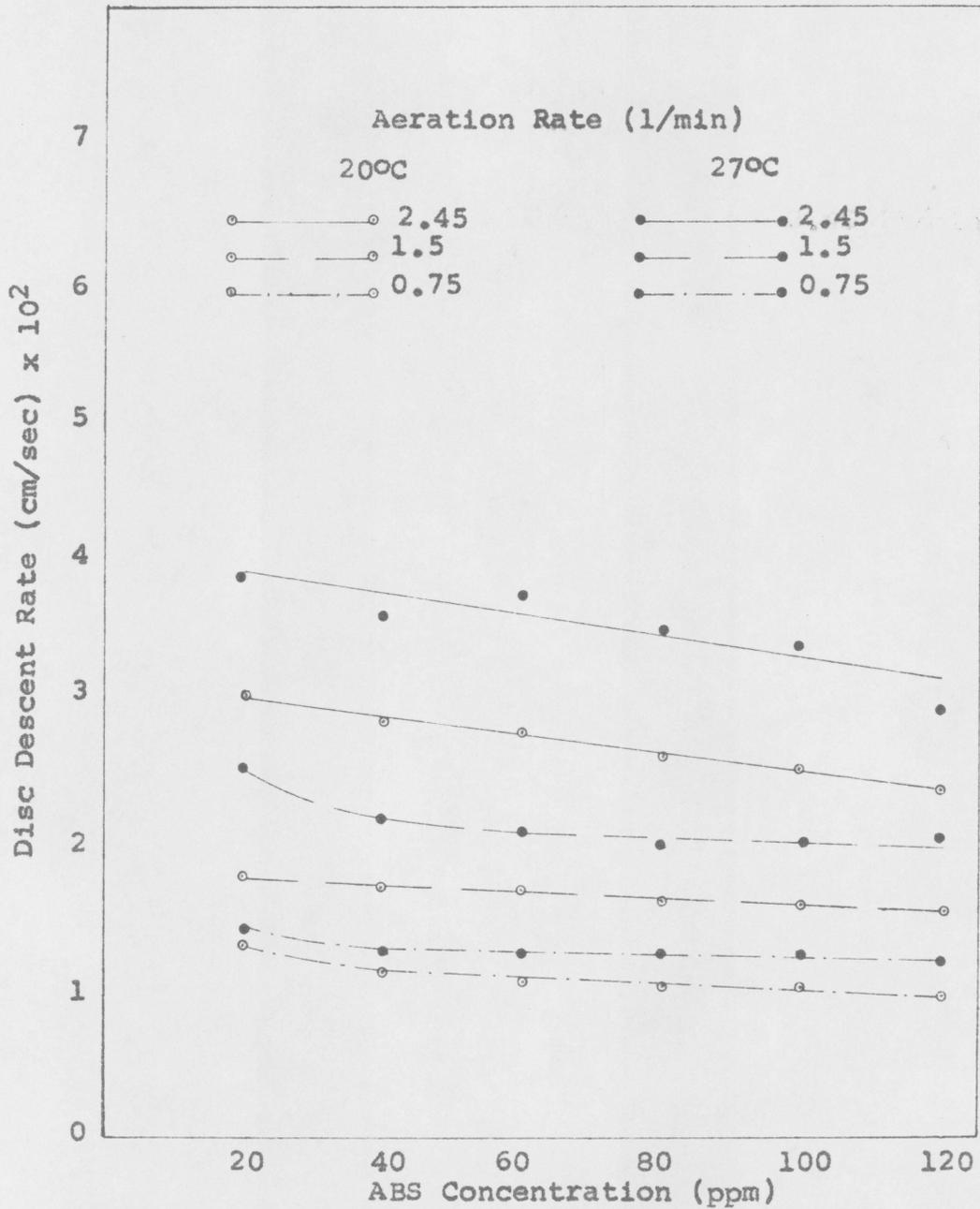
Figure 28: Effects of ABS Concentration on Disc Descent Rate During Phase 2 Experiments Employing Three Aeration Rates and Two Temperatures.

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Table 24: Analysis of Variance for the Disc Descent Rate Data of Table 22. The values of sum of squares and mean squares have been multiplied by a factor of 105.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Ratio
Replicates	2	5.96	2.98	
Treatments	17			
Concentration (C)	5	10.40	2.08	6.71**
C(L) (Linear)	1	10.13	10.13	32.68**
C(HO)(Higher order)	4	0.27	0.07	0.23
Aeration Rate (AR)		251.36	125.68	405.42**
AR(L) (Linear)		244.04	244.04	787.22**
AR(Q) (Quadratic)		7.32	7.32	23.61**
C x AR	10	2.22	0.22	0.71
Experimental Error	34	10.70	0.31	
Total	53	280.64		

** Denotes treatment differences declared significant at 1% probability level.

Table 25: Analysis of Variance for the Disc Descent Rate Data of Table 23.

The values of sum of squares and mean squares have been multiplied by a factor of 105.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Ratio
Replicates	2	1.13	0.56	
Treatments	17			
Concentration (C)	5	14.56	2.91	5.94**
C(L) (Linear)	1	13.31	13.31	27.16**
C(Dev) (Higher Order)	4	1.25	0.31	0.63
Aeration Rate (AR)	2	473.33	236.66	482.98**
AR(L) (Linear)	1	468.54	468.54	956.20**
AR(Q) (Quadratic)	1	4.79	4.79	9.78**
C x AR	10	8.78	0.88	1.80
Experimental Error	34	16.79	0.49	
Total	53	514.59		

** Denotes treatment differences declared significant at 1% probability level.

For the experiments at 27°C:

$$\sum_{j}^{a} \alpha_j^2 /(a-1) = 0.27 \times 10^{-5} \text{ (ABS concentration)}$$

$$\sum_{k}^{b} \beta_k^2 /(b-1) = 13.12 \times 10^{-5} \text{ (aeration rate)}$$

The foam densities for Phase 2 experiments are summarized in Tables 26 and 27 for the experiments at 20°C and 27°C respectively. The mean values of foam density relative to ABS concentration are presented in Figures 29 and 30 for the three aeration rates to illustrate the relationship of these variables.

Discussion of Phase 2 Experiments

The application of comparable foam volumes during Phase 2 measurements resulted in disc descent curves, as shown in Figures 25 through 27, having similar form for all three aeration rates with differences in slopes between consecutive aeration rates being less obvious than in Phase 1 experiments. The weakening of foam structure, owing to increased foam volumes or increased quantities of air supplied at the increased aeration rates as described in Phase 1 experiments, was minimized during the constant foam volume experiment of Phase 2. Hence, the results of Phase 2 measurements, as illustrated in Figures 25 through 27, appeared to be more representative of the effects of aeration rate on foam character than did Phase 1 measurements where the combined effects of aeration rate and greater aeration were operative.

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Table 26: The Effect of ABS Concentration on the Density of Foam Formed by Aeration at Three Rates During Phase 2 Experiments at 20°C.

The values given in the table have units of (gm/cc).

Aeration Rate (l/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0283	0.0383	0.0515	0.0652	0.0711	0.0794
	0.0249	0.0522	0.0520	0.0680	0.0748	0.0808
	0.0247	0.0418	0.0549	0.0680	0.0724	0.0833
	$\bar{x} = 0.0260$	$\bar{x} = 0.0441$	$\bar{x} = 0.0528$	$\bar{x} = 0.0671$	$\bar{x} = 0.0728$	$\bar{x} = 0.0812$
1.5	0.0315	0.0449	0.0584	0.0711	0.0716	0.0797
	0.0318	0.0454	0.0551	0.0641	0.0711	0.0833
	0.0283	0.0489	0.0584	0.0614	0.0745	0.0800
	$\bar{x} = 0.0305$	$\bar{x} = 0.0464$	$\bar{x} = 0.0573$	$\bar{x} = 0.0655$	$\bar{x} = 0.0724$	$\bar{x} = 0.0810$
2.45	0.0279	0.0416	0.0546	0.0584	0.0648	0.0000
	0.0246	0.0422	0.0482	0.0551	0.0616	0.0646
	0.0248	0.0419	0.0418	0.0519	0.0582	0.0513
	$\bar{x} = 0.0258$	$\bar{x} = 0.0419$	$\bar{x} = 0.0482$	$\bar{x} = 0.0551$	$\bar{x} = 0.0615$	$\bar{x} = 0.0591$

Table 27: The Effect of ABS Concentration on the Density of Foam Formed by Aeration at Three Rates During Phase 2 Experiments at 27°C.

The values given in the table have units of (gm/cc).

Aeration Rate (l/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	0.0249	0.0451	0.0513	0.0774	0.0833	0.0830
	0.0249	0.0419	0.0418	0.0580	0.0774	0.0830
	0.0318	0.0459	0.0578	0.0584	0.0740	0.0888
	$\bar{X}=0.0272$	$\bar{X}=0.0443$	$\bar{X}=0.0503$	$\bar{X}=0.0646$	$\bar{X}=0.0782$	$\bar{X}=0.0849$
1.5	0.0282	0.0452	0.0584	0.0614	0.0652	0.0779
	0.0214	0.0422	0.0517	0.0616	0.0745	0.0745
	0.0282	0.0419	0.0549	0.0652	0.0716	0.0753
	$\bar{X}=0.0259$	$\bar{X}=0.0431$	$\bar{X}=0.0550$	$\bar{X}=0.0627$	$\bar{X}=0.0704$	$\bar{X}=0.0759$
2.45	0.0282	0.0352	0.0486	0.0551	0.0584	0.0616
	0.0282	0.0384	0.0520	0.0515	0.0620	0.0709
	0.0246	0.0348	0.0452	0.0415	0.0549	0.0486
	$\bar{X}=0.0270$	$\bar{X}=0.0361$	$\bar{X}=0.0486$	$\bar{X}=0.0494$	$\bar{X}=0.0584$	$\bar{X}=0.0604$
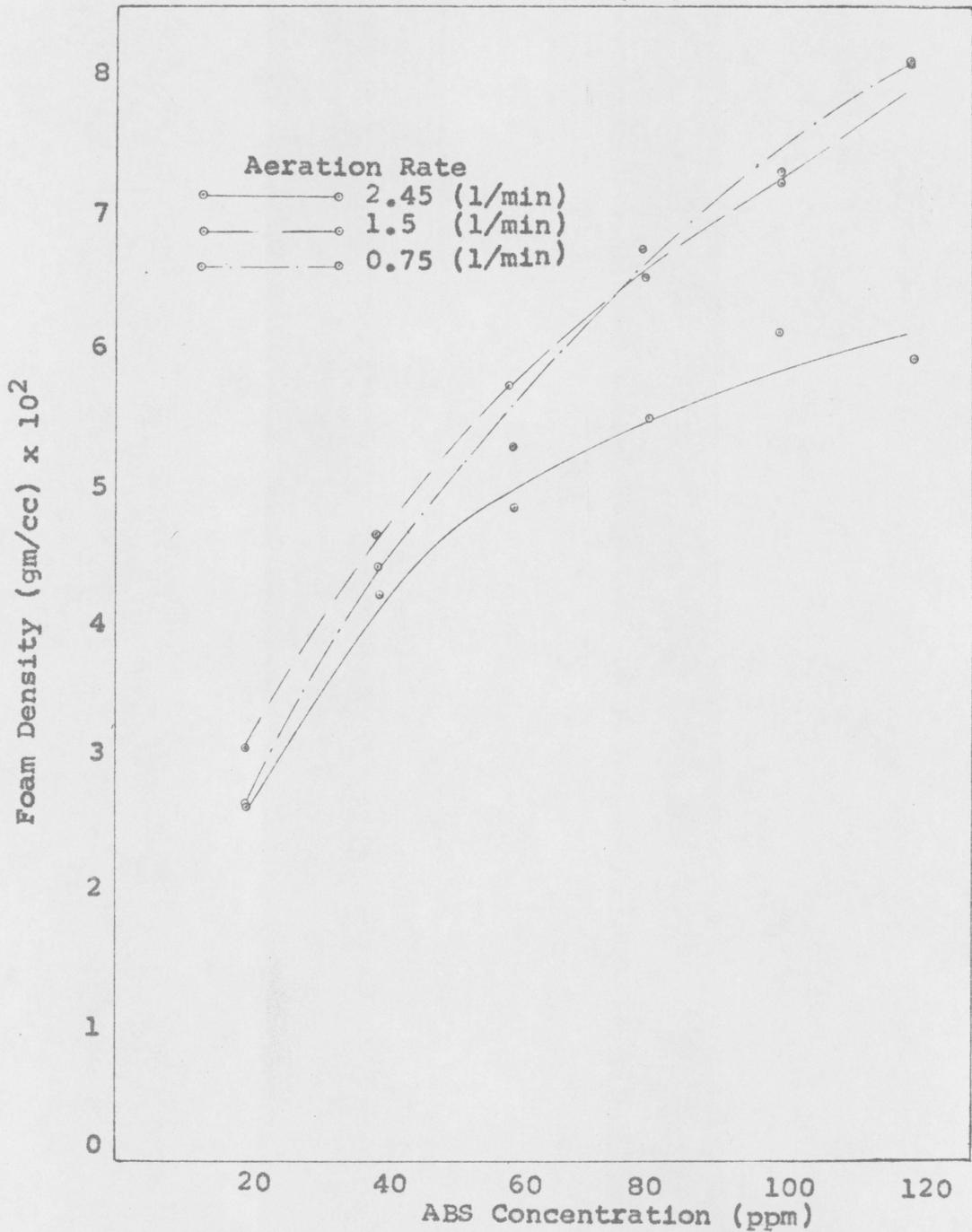
Figure 29: Effect of ABS Concentration on Foam
Density for Three Aeration Rates During
Phase 2 Experiments at 20°C.
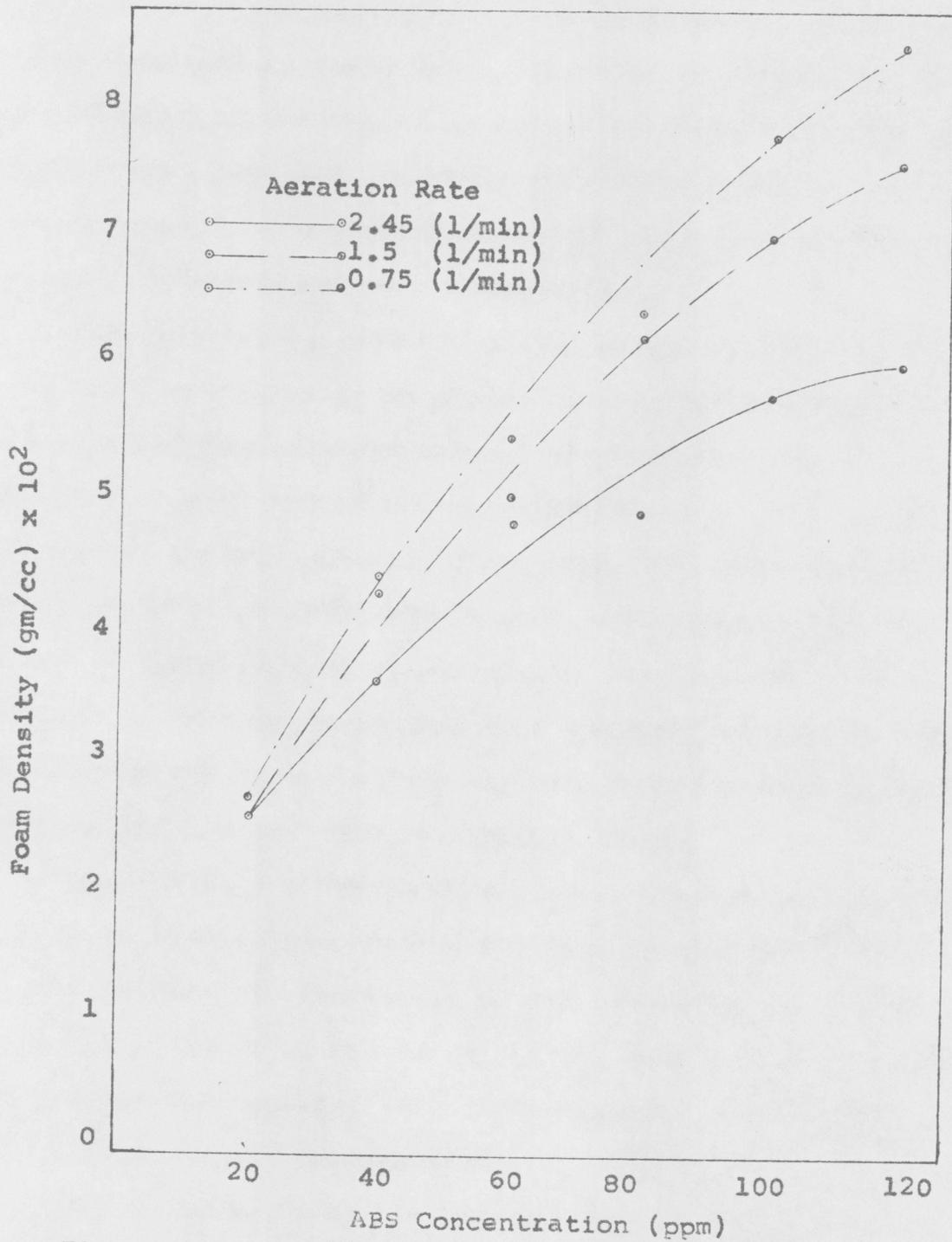
Figure 30: Effect of ABS Concentration on Foam
            Density for Three Aeration Rates During
            Phase 2 Experiments at 27°C.

Examination of the data in Tables 22 and 23 indicated that the slopes or disc descent rates increased substantially with increased aeration rate. The data also indicated that differences in the values of slopes for consecutive ABS concentrations were small in comparison with those for aeration rate; however, a gradual decrease in slope was generally observed with increased ABS concentration.

The relative importance of the effects of ABS concentration and aeration rate on slopes or disc descent rates may be observed from a comparison of the estimated variability due to the main effects of these two factors. The variability due to the main effects of aeration rate for the experiments at 20°C and 27°C were respectively about 35 and 49 times as large as ABS concentration. Examination of Tables 24 and 25, however, indicated that the main effects of both factors of ABS concentration and aeration rate were significant at the one per cent probability level.

Changes in the levels of ABS concentration resulted primarily in linear responses of the disc descent rate; only the linear response to the levels of ABS concentration was shown to be significant in Tables 24 and 25. The curves of Figure 28 reflect the apparent linear relationship between disc descent rate and ABS concentration.

The response to the levels of aeration rate indicated that both the linear and quadratic effects were significant

at the one per cent probability level. This response was essentially as reported for the effects of aeration rate for Phase 1 experiments.

The effects of temperature on foam character, as determined by the weighted disc method, may be observed from a comparison of the data in Table 22 with those in Table 23. Examination of the values reported in these tables indicated greater disc descent rates occurred at the higher temperature (27°C) as shown in Table 23. This observation was expected owing to the lower viscosities of the liquid comprising the films at the higher temperature. Since foam drainage is inversely related to viscosity (4), the degree of stretching and thinning of film laminae would be expected to be greater at the higher temperature. The drainage effects during the experiments at 27°C apparently resulted in the weakening of foam structure sufficiently to cause greater variations in the rates of disc descent for both ABS concentration and aeration rate. Comparison of the relative magnitude of the estimated variability for the main effects of each of these factors indicated increased values at the higher temperature (27°C).

The foam densities reported in Tables 26 and 27, for temperatures of 20°C and 27°C respectively, indicated a direct relationship with ABS concentration. Although foam densities in Table 27 appeared to be inversely related to

aeration rate, the foam densities reported in Table 26 indicated a maximum usually occurred for the intermediate aeration rate (1.5 l/min) for ABS concentrations of 60 ppm and below. Above 60 ppm, little difference occurred in the densities for foams formed at aeration rates of 0.75 l/min and 1.5 l/min. The different manner in which the foam densities were affected by the intermediate aeration rate at the two temperatures may be observed from a comparison of Figures 29 and 30. The reason for the differences in foam densities for the intermediate aeration rate was not apparent; however, it was suspected that the increased viscosity at the lower temperature influenced the quantity of liquid being carried into the foam by the bubble surfaces. It was shown in Phase 1 experiments at 23°C that the intermediate aeration rate exhibited a tendency for higher foam densities, with ABS concentrations above 40 ppm, than did the extreme aeration rates of 0.75 l/min and 2.45 l/min. Since larger bubbles reportedly comprise foam at increased aeration rates, increased foam density with increased aeration rate would presumably be indicative of the formation of wetter foams. Due to the apparent tendency of bubbles at the intermediate aeration rate to entrain greater quantities of moisture between foam films, the moisture carried into the foam would be expected to be greater at the lower temperature since drainage from bubble surfaces during foam formation would presumably vary inversely with viscosity or directly with temperature.

An alternate method of analysis of the disc descent data, other than disc descent rates, is the method proposed by Brady and Ross (7). According to this method, the area beneath the foam collapse curves when divided by the initial foam height results in a value which the authors termed "the average lifetime of foam"; hence,

$$L_f = \frac{1}{H_O} \int_0^T h \, dt$$

where L_f = average lifetime of foam

H_O = initial foam height

T = time for total foam collapse

h = foam height at time t.

The authors propose this method to analyze data of the static decay of foams since the collapse curves are usually other than uniform - thereby eliminating the possibility of collapse rates being employed.

Application of the method to the disc descent data would enable analysis of data exhibiting non-uniform disc descent rates. Since natural rupture does not occur during the weighted disc measurements, "the average time of foam destruction" (D_f) would perhaps be a more suitable term for the application to disc descent data.

Results of this analysis on the data for Phase 2 experiments at 20°C are given in Table 28. Examination of these data suggested the tendency for D_f to vary directly with ABS

Table 28: The Average Destruction Time of Foams (D_f) for Phase 2 Experiments at 20°C.

The values in the table result from dividing the area beneath the disc descent curves by the initial foam height. The values are given in minutes.

Aeration Rate (l/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
0.75	17.39	18.08	17.14	18.38	19.05	19.59
	16.37	16.45	17.18	18.02	18.71	19.32
	14.34	15.70	16.83	17.92	17.40	18.10
	$\bar{x}$ = 16.03	$\bar{x}$ = 16.74	$\bar{x}$ = 17.05	$\bar{x}$ = 18.11	$\bar{x}$ = 18.39	$\bar{x}$ = 19.00
1.5	12.05	11.74	11.68	11.74	11.97	13.16
	10.81	10.95	11.28	11.18	12.24	13.01
	10.82	11.37	11.65	12.54	12.40	12.33
	$\bar{x}$ = 11.23	$\bar{x}$ = 11.35	$\bar{x}$ = 11.54	$\bar{x}$ = 11.82	$\bar{x}$ = 12.20	$\bar{x}$ = 12.83
2.45	7.43	8.21	8.30	7.68	8.75	9.78
	7.49	8.19	7.59	7.62	8.17	8.83
	6.08	5.56	6.82	7.19	7.68	8.33
	$\bar{x}$ = 7.00	$\bar{x}$ = 7.32	$\bar{x}$ = 7.57	$\bar{x}$ = 7.50	$\bar{x}$ = 8.20	$\bar{x}$ = 8.98

concentration and inversely with aeration rate. This observation indicated the same relationship as previously shown for disc descent rates; however, agreement could be expected since the slopes influence the area beneath the disc descent curves. Similarly, the non-linear portions of the disc descent curves of Figures 25 through 27 exhibited tendencies of extended experimental periods with increased ABS concentration.

The statistical analysis of variance for the data of Table 28 is presented as Table 29. The analysis suggested that the effects of the factors of both ABS concentration and aeration rate were significant at the one per cent probability level. The response to the employed levels of ABS concentration was significant only for the linear response whereas both linear and quadratic responses were significant for the effects of aeration rate. The results of the analysis of variance for the data of Table 29 agreed with the results of Table 28 for the analysis of variance for the disc descent rate data. The variability for each of the treatment main effects was 0.59 and 24.18 respectively for ABS concentration and aeration rate - suggesting that the effects of aeration rate were considerably greater than ABS concentration as previously indicated.

The analysis of the disc descent data employing the disc descent rates involves less effort in analyzing the results

Table 29: Analysis of Variance for the Data of Table 28.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F- Ratio
Replicates	2	10.14	5.07	
Treatments	17			
Concentration (C)	5	28.55	5.71	15.86**
C(L) (Linear)	1	27.87	27.87	77.42**
C(Dev) (Higher Order)	4	0.68	0.17	0.47
Aeration Rate (AR)	2	871.21	435.61	1210.00**
AR(L) (Linear)	1	863.09	863.09	2397.47**
AR(Q) (Quadratic)	1	8.12	8.12	22.56**
C x AR	10	3.56	0.36	1.00
Experimental Error	34	12.35	0.36	
Total	53	925.81		

** Denotes treatment differences declared significant at 1% probability level.

since the slope may be easily determined for curves exhibiting a linear relationship. In addition, the slopes as determined are direct indications of the rates at which the disc descended through the foam. The average time of destruction (D_f), however, has the advantage of being applicable for non-uniform disc descent rates. For the foams encountered in the investigation of this thesis, disc descent rate was employed as the parameter to characterize foam. It would seem that for foams sufficiently different from those encountered in the investigation, the method of analysis would be influenced by the resulting data.

4) Phase 3 Experiments

The investigation of Phase 3 employed for each measurement a constant volume of foam which was produced under controlled conditions of temperature (20°C) and relative humidity (67-68 per cent), as in Phase 2 experiments. The objective of Phase 3 experiments differed from both Phase 1 and 2 experiments since the effects of an initial drainage' period on foam character were to be studied. Hence, after generation of foam, the foam was allowed to drain for 10 minutes prior to application of the disc assembly.

The disc descent curves for Phase 3 experiments were identical in form to those of Phase 2 experiments and are not given. The disc descent data are tabulated in Appendix A for

all three replicates of the basic experiment which was presented as Table 13.

The results of Phase 3 experiments are given in Table 30 in terms of the initial slopes of the disc descent vs time curves. These slopes represent the disc descent rates through foams formed from the given ABS concentrations and aeration rates. The mean values of the slopes shown in Table 30 are presented as Figure 31 to illustrate the effects of ABS concentration and aeration rate on disc descent rates.

The statistical analysis of the data presented in Table 30 is presented as Table 31. The variability estimated for each of the main effects of ABS concentration and aeration rate is respectively:

$$\sum_{j}^{a} \alpha_j^2 /(a-1) = 3.12 \times 10^{-5}$$

$$\sum_{k}^{b} \beta_k^2 /(b-1) = 16.71 \times 10^{-5}$$

Discussion of Phase 3 Experimental Results

The data of both Table 30 and Figure 31 indicated that the values of slope or disc descent rate for each aeration rate decreased appreciably as the ABS concentration ranged from 20 to 40 ppm. Above 40 ppm the foams formed at consecutive ABS concentrations for a given aeration rate exhibited similar resistance to the destructive action of the disc assembly. Although small differences were observed in Table 30

Table 30: The Effects of ABS Concentration and Aeration Rate on Disc Descent Rates for Phase 3 Experiments at 20C.

The values given in the table are the initial slopes of the disc descent curves. The units of the slopes are (cm/sec).

Aeration Rate (1/min)	ABS Concentration (ppm)					
	20	40	60	80	100	120
1.75	0.0210 0.0167 0.0184 $\bar{x}$ = 0.0187	0.0113 0.0122 0.0123 $\bar{x}$ = 0.0119	0.0121 0.0112 0.0114 $\bar{x}$ = 0.0116	0.0120 0.0108 0.0109 $\bar{x}$ = 0.0112	0.0101 0.0123 0.0117 $\bar{x}$ = 0.0114	0.0102 0.0121 0.0121 $\bar{x}$ = 0.0115
1.5	0.0335 0.0386 0.0240 $\bar{x}$ = 0.0320	0.0201 0.0178 0.0191 $\bar{x}$ = 0.0190	0.0194 0.0183 0.0181 $\bar{x}$ = 0.0181	0.0196 0.0200 0.0175 $\bar{x}$ = 0.0190	0.0201 0.0195 0.0167 $\bar{x}$ = 0.0188	0.0182 0.0193 0.0171 $\bar{x}$ = 0.0182
2.45	0.0600 0.0515 0.0550 $\bar{x}$ = 0.0555	0.0354 0.0307 0.0372 $\bar{x}$ = 0.0344	0.0345 0.0327 0.0347 $\bar{x}$ = 0.0340	0.0369 0.0314 0.0393 $\bar{x}$ = 0.0359	0.0347 0.0398 0.0322 $\bar{x}$ = 0.0356	0.0306 0.0342 0.0346 $\bar{x}$ = 0.0331

Figure 31:   Effects of ABS Concentration on Disc
              Descent Rate During Phase 3 Experiments
              Employing Three Aeration Rates.

Table 31: Analysis of Variance for the Disc Descent Rate Data of Table 30.

The values of sum of squares and mean squares have been multiplied by a factor of 105.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Ratio
Replicates	2	1.02	0.51	
Treatments	17			
Concentration (C)	5	144.19	28.84	36.05**
C(L) (Linear)	1	65.22	65.22	81.52**
C(Q) (Quadratic)	1	45.28	45.28	56.60**
C(Dev) (Higher Order)	3	33.69	11.23	14.04**
Aeration Rate (AR)	2	603.08	301.54	376.92**
AR(L)(Linear)	1	579.12	579.12	723.90**
AR(Q)(Quadratic)	1	23.96	23.96	29.95**
C x AR	10	24.36	2.44	3.05**
C(L)AR(L)	1	10.07	10.07	12.59**
C(Q)AR(L)	1	5.90	5.90	7.35**
C(c)AR(L)	1	8.06	8.06	10.07**
Experimental Error	34	27.10	0.80	
Total	53	799.75		

** Denotes treatment differences declared significant at 1 per cent probability level.

to occur between disc descent rates for successive ABS concentrations above 40 ppm, little consistency was evident as to the direction of the changes or differences.

The initial drainage period seemingly had a more pronounced effect on the foams generated from solutions containing 20 ppm of ABS. This effect, however, was expected owing to the more fragile nature exhibited by the freshly formed foams in Phases 1 and 2. Foams for both phases exhibited the most pronounced decrease in disc descent rate between ABS concentrations of 20 and 40 ppm. Apparently, the foam structure resulting at 20 ppm was comprised of bubbles sufficiently larger than the foam structure at successively higher ABS concentrations. According to Sinsheimer (32), larger bubbles are formed at the lower concentrations of foaming agent as a result of bubble coalescence. Since the properties of viscosity and surface tension in bubble films would presumably not differ greatly from the bulk solution, at ABS concentrations of 20 ppm, these properties would be less operative in detering the effects of drainage as previously described by the viscosity to surface tension postulation (4). Hence the foams formed at ABS concentrations of 20 ppm would be expected to become susceptible to destruction by the disc assembly sooner than foams at higher ABS concentrations whereupon higher viscosities and lower surface tensions would presumably be more effective in detering the effects of drainage.

The increased disc descent rates during Phase 3 experiments, as compared to those for Phase 2 experiments at the same temperature ($20^{\circ}C$), may be observed upon comparison of Tables 22 and 30 for Phases 2 and 3 respectively. Although no apparent rupture of foam films occurred during the 10-minute drainage period of Phase 3, the foams were observed to consist of larger and thinner films than when freshly formed. As a result of the stretching and thinning owing to the initial drainage period, the foams apparently offered less resistance to the action of the disc assembly than the freshly formed foams of Phase 2 measurements.

The drained foams of Phase 3 experiments indicated the direct relationship between disc descent rates and aeration rate that was shown earlier for Phases 1 and 2. However, the initial drainage period resulted in larger differences in disc descent rates for successive aeration rates than occurred in Phase 2 experiments at the same temperature ($20^{\circ}C$). Comparison of the variability due to the main effects of aeration rate, (6.96×10^{-5} vs 16.71×10^{-5}) for the experiments of Phase 2 and 3 respectively, suggested that differences in foam structure were greater for Phase 3 experiments for consecutive aeration rates. The appreciable increase in disc descent rate with increased aeration rate may be observed from Figure 31.

Similarly, comparison of the variability due to the main effects of ABS concentration, $(0.20 \times 10^{-5}$ vs $3.12 \times 10^{-5})$ for Phases 2 and 3 experiments at 20°C respectively, indicated a considerable increase for Phase 3 experiments. However, considering the appreciably large differences in disc descent rate between the foams resulting from ABS solutions of 20 to 40 ppm as shown in Figure 31, a larger variation due to the effects of ABS concentration could be expected for Phase 3 experiments. For foams resulting from ABS concentrations greater than 40 ppm, differences in disc descent rates were not appreciably different from those of Phase 2 experiments except that the differences were less consistent as to the direction of the changes of disc descent rates for consecutive ABS concentrations during Phase 3 experiments.

The analysis of variance presented as Table 31 indicated that, for the main effects of both ABS concentration and aeration rate, differences in the respective treatments were of such magnitude to be declared significant at the one per cent probability level. However, unlike Phase 1 and 2, which primarily indicated the responses to the levels of ABS concentration were linear, the results of Phase 3 experiments revealed that the quadratic and higher order responses were significant. The non-linear response to the levels of ABS concentration may be observed from the curves in Figure 31. The responses to the employed levels of aeration rate were

significant for both the linear and quadratic effects as previously indicated for Phases 1 and 2.

The initial drainage period of Phase 3 resulted in a significant interaction as indicated in Table 31. The form of the interaction revealed that the response was primarily linear with respect to aeration rate; the response with respect to ABS concentration indicated that the linear, quadratic, and cubic effects were significant. The interaction apparently resulted from the inconsistent response of the disc through the drained foams for ABS concentrations above 40 ppm as shown in Table 30.

From the previous results, it appeared that varying the levels of aeration rate resulted in changes in foam character which were sufficiently large to be detected rather easily by the weighted disc method. For concentration effects, differences in foam character appeared to be more pronounced for freshly formed foams than for drained foams. Small differences in foam character which seemed to exist during Phases 1 and 2 between freshly formed foams at consecutive ABS concentrations above 40 ppm were not so apparent after the initial drainage period employed in Phase 3 had occurred.

If foams at successive ABS concentrations, as employed in the investigation, have different stability characteristics or lifetimes, it would appear that the initial differences

between freshly formed foams would tend to influence rupture of the foam films by natural causes. In order to observe the effects which ABS concentration may have upon the natural rupture or decay of foams, static decay experiments were undertaken and are reported in the following section.

C. Foam Stability Experiments Employing Static Decay Methods

1) Series 1 Experiments

Series 1 experiments were conducted simultaneously with those of Phase 1 employing the weighted disc. Volumes of foam, comparable to the foams of Phase 1 experiments, were allowed to collapse at a natural rate during a period of 8 hours under laboratory room conditions. The results of the static decay experiments are illustrated by the curves in Figures 32 and 33 for Series 1 experiments. These curves represent the uppermost foam levels observed at one-half hour intervals throughout the experiments.

2) Series 2 Experiments

Series 2 experiments were conducted simultaneously with those at 20°C of Phase 2 employing the weighted disc. A constant volume of foam, comparable to Phase 2, was generated for each test prior to observing the natural collapse during a period of 8 hours under controlled conditions of temperature and relative humidity. The results for the three replicates of Series 2 experiments are presented as Figures
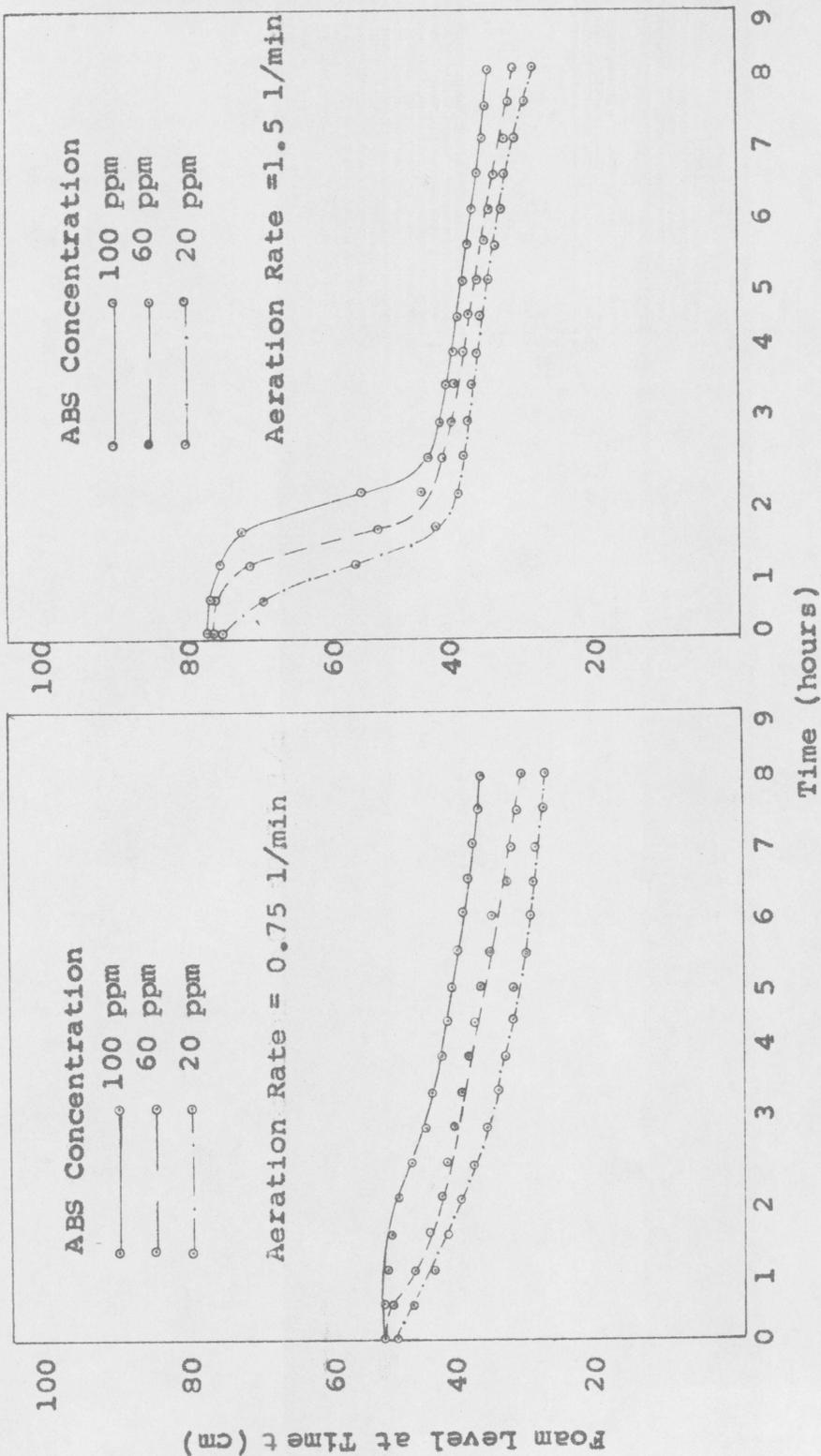
Figure 32: The Effect of ABS Concentration on the Natural Decay of Foams Produced by Aeration Rates of 0.75 l/min and 1.5 l/min for Series 1 Experiments.
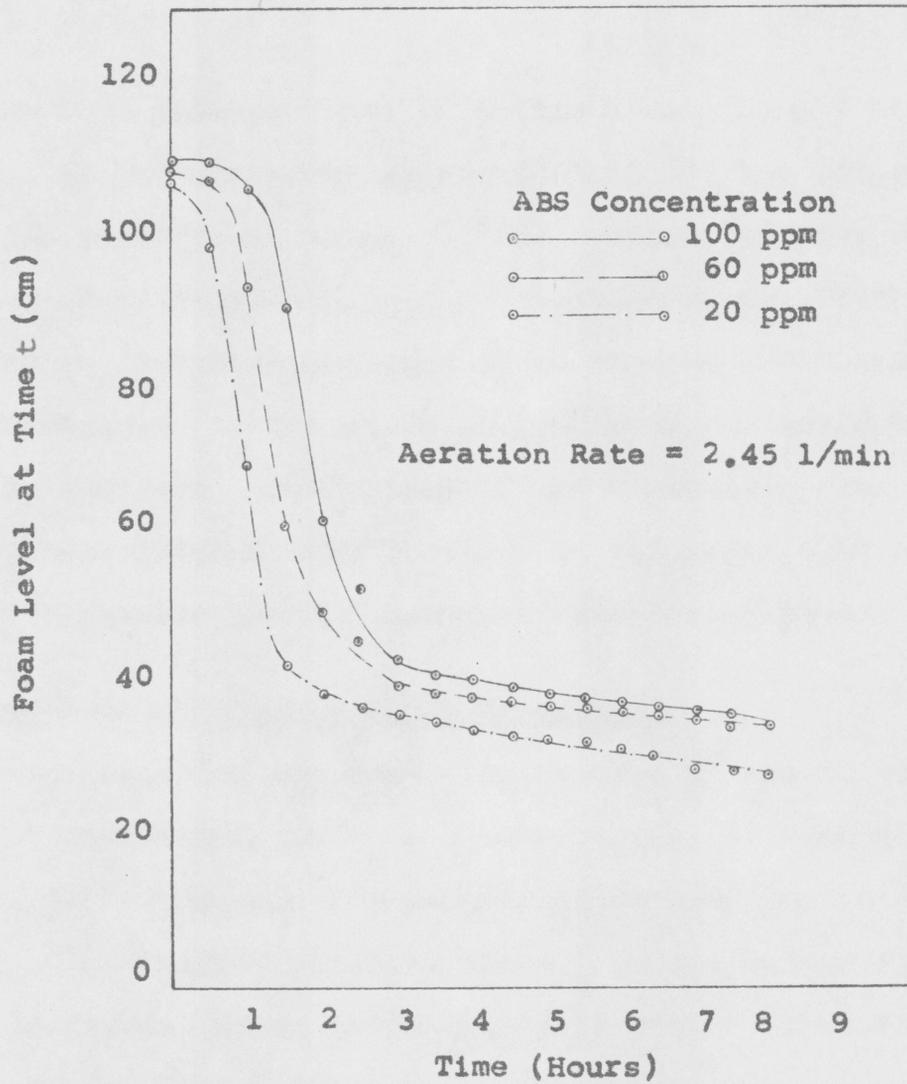
Figure 33: The Effect of ABS Concentration on the
Natural Decay of Foams Produced by an
Aeration Rate of 2.45 l/min for Series 1
Experiments.

34 through 36. The curves in these figures represent the foam levels observed at one-half hour intervals throughout the experimental periods. Data for the foam decay curves for both Series 1 and 2 experiments are tabulated in Appendix B.

The foam collapse data of Series 2 experiments were analyzed by the method of Brady and Ross (7) and are presented as Table 32 in terms of "the average lifetime of foams," (L_f). A statistical analysis of variance of the data in Table 32 is presented as Table 33 to examine the response of foam persistence to the employed levels of ABS concentration and aeration rate. Estimation of the variability for each of treatment main effects resulted in values of 0.17 and 0.39 for ABS concentration and aeration rate respectively.

Discussion of the Static Decay Experiments

Examination of the curves in Figures 32 and 33 for Series 1 experiments indicated that rupture of foam was greater during the early experimental periods for foams generated at the higher aeration rates. Following an initial drainage period, foams at the higher aeration rates collapsed rather rapidly throughout the upper foam strata. However, as the foam levels near the liquid surface were approached, as shown in Figures 32 and 33, a progressively declining collapse rate may be observed. Foam layers at the liquid surface
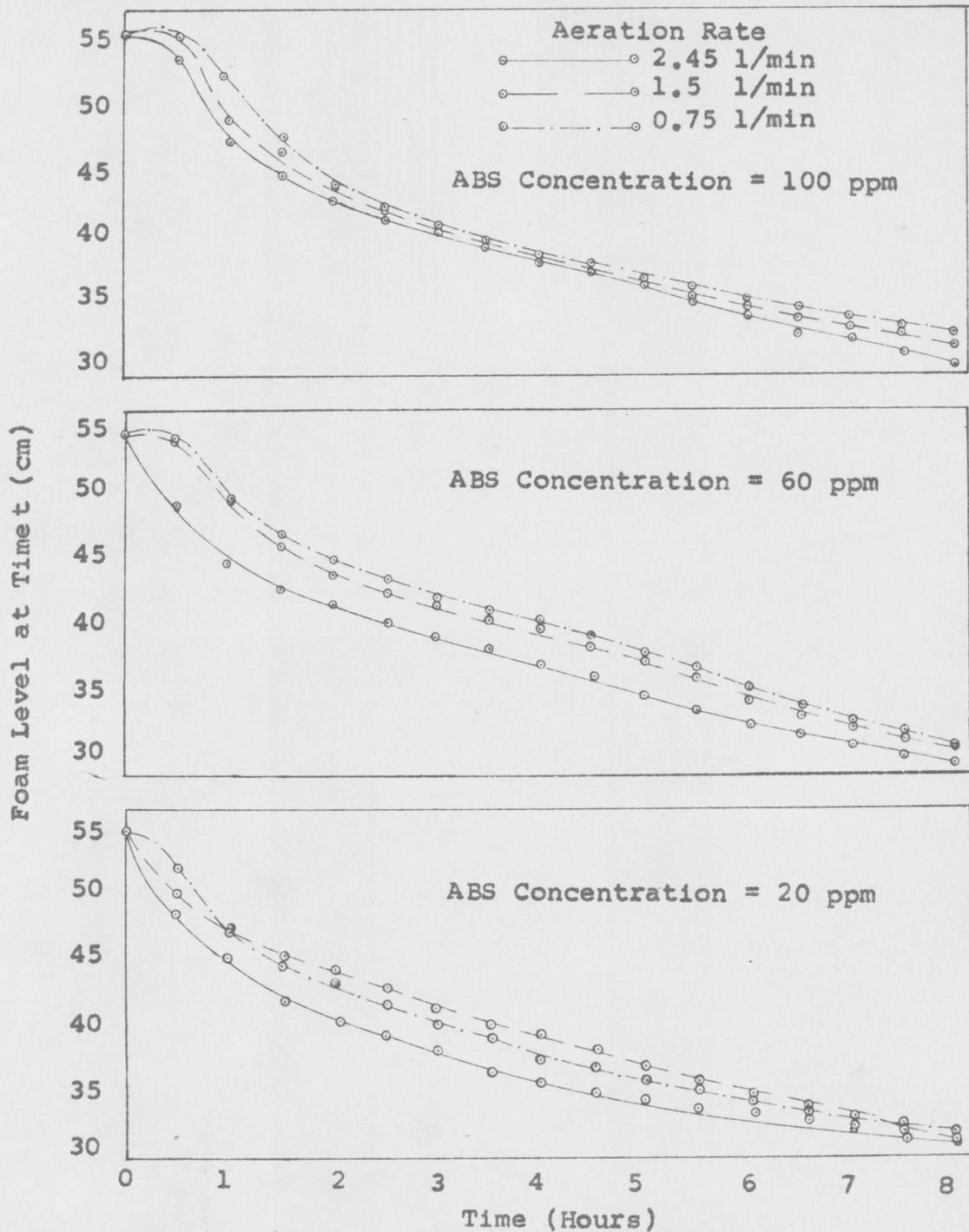
Figure 34: Effects of ABS Concentration and Aeration
Rate on the Natural Decay of Foams for
Replicate 1 of Series 2 Experiments.
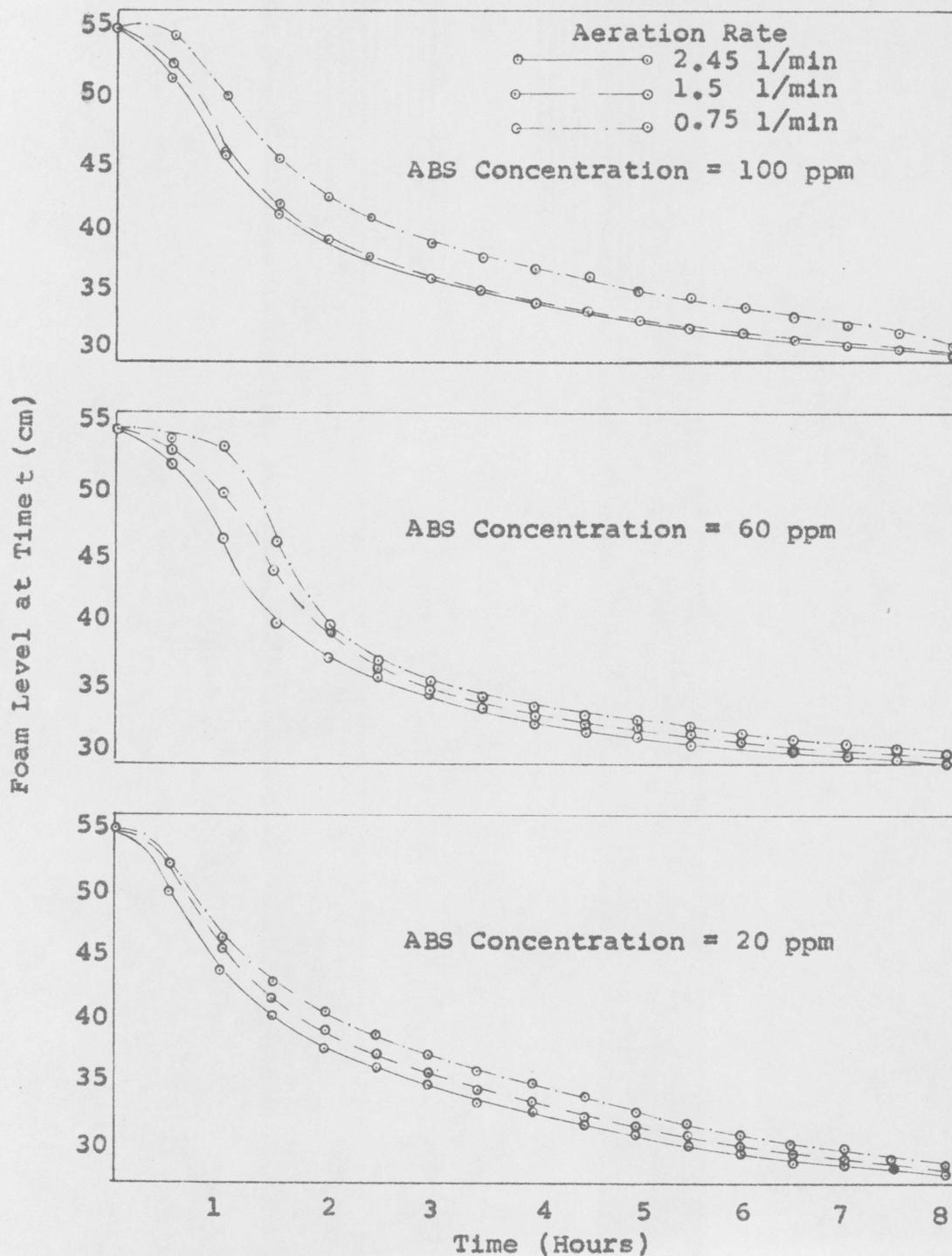
Figure 35: Effects of ABS Concentration and Aeration
Rate on the Natural Decay of Foams for
Replicate 2 of Series 2 Experiments.
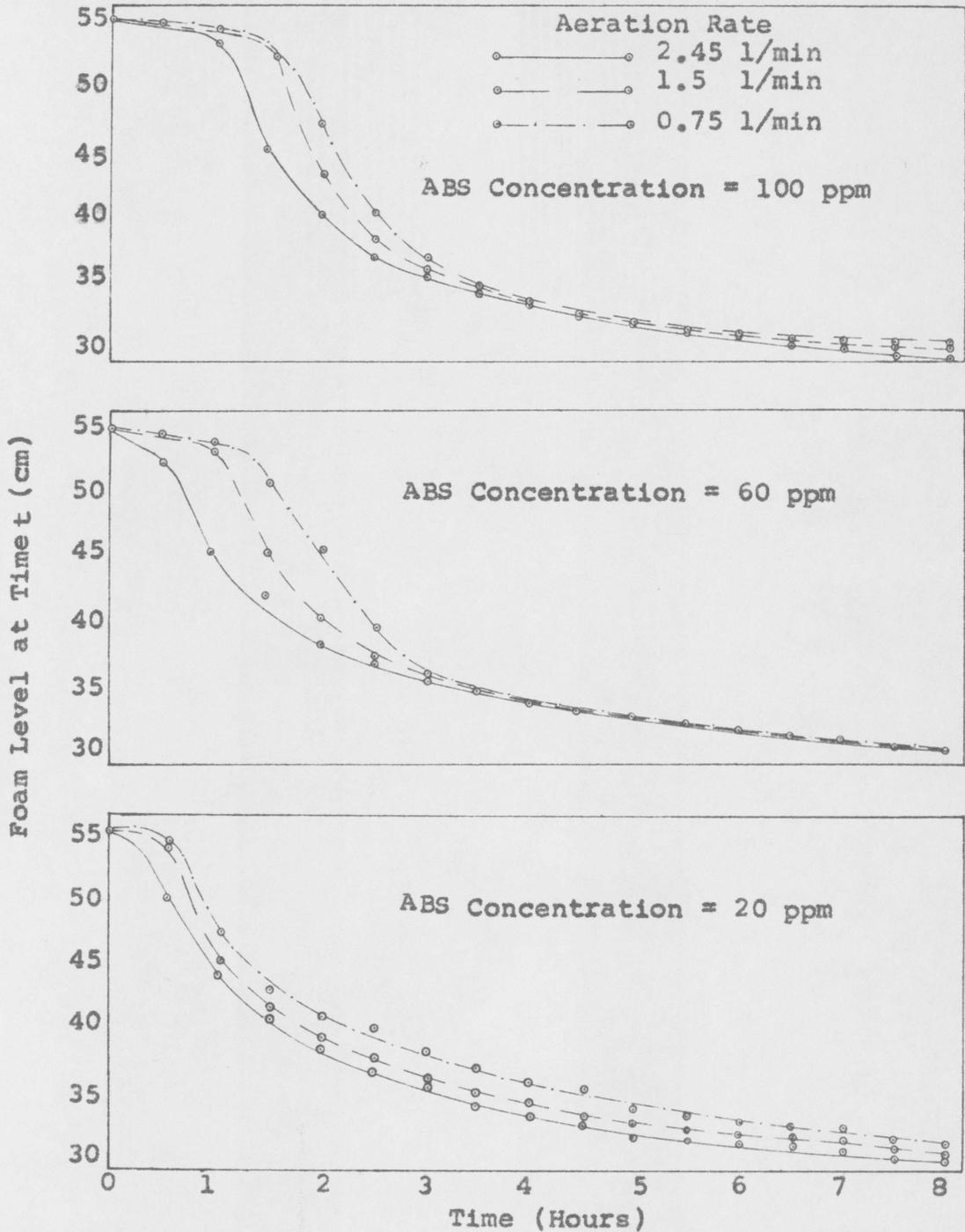
Figure 36: Effects of ABS Concentration and Aeration Rate on the Natural Decay of Foams for Replicate 3 of Series 2 Experiments.

Table 32: The Average Lifetime of Foams (L_f) for Series 2
           Static Decay Experiments.

The values in the table result from dividing the area
beneath the foam collapse curves by the initial foam height.
The values are given in hours.

Aeration Rate (1/min)	ABS Concentration (ppm)		
	20	60	100
0.75	7.90 6.59 7.34 $\bar{x}$ = 7.28	8.51 7.18 7.46 $\bar{x}$ = 7.72	8.79 7.96 7.96 $\bar{x}$ = 8.24
1.5	8.12 5.89 6.57 $\bar{x}$ = 6.86	8.55 6.01 7.14 $\bar{x}$ = 7.23	8.41 6.39 7.50 $\bar{x}$ = 7.43
2.45	6.49 5.24 6.05 $\bar{x}$ = 5.93	6.85 6.17 6.49 $\bar{x}$ = 6.50	7.86 6.19 6.90 $\bar{x}$ = 6.98

Table 33: Analysis of Variance for the Data of Table 32

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F-Ratio
Replicates	2	12.19	6.06	
Treatments	8			
Concentration (C)	2	3.35	1.68	14.00**
C$_{(L)}$ (Linear)	1	3.35	3.35	27.92**
Aeration Rate (AR)	2	7.30	3.65	30.42**
AR$_{(L)}$ (Linear)	1	7.28	7.28	60.67**
C x AR	4	0.22	0.05	0.42
Experimental Error	16	1.88	0.12	
Total	26	24.95		

** Denotes treatment differences declared significant at 1% probability level.

exhibited a remarkable degree of persistence, frequently lasting more than 24 hours. The effects of drainage were presumably less operative in these layers of foam owing to moisture being retained in the thin capillaries of foam films at the liquid surface.

It was mentioned in the results of Phase 3 experiments that no apparent rupture occurred during the initial 10 minute drainage period. Similarly, for Series 1 experiments foam films were observed to exhibit no appreciable rupture until after an initial period ranging from about 10 to 30 minutes depending upon ABS concentration and aeration rate as indicated by the curves in Figures 32 and 33. Film rupture was delayed to the greatest extent in foams resulting from solutions containing greater quantities of ABS.

The delay in foam rupture with increased ABS concentration was accompanied by a delay in drainage. In addition, the level at which foam appeared to be more persistent usually occurred earlier for the higher ABS concentrations. For the portion of the curves exhibiting the rapid collapse rates, little difference appeared to occur between these rates for foams formed from consecutive ABS concentration at aeration rates of 1.5 and 2.5 l/min.

Examination of the curves in Figures 34 through 36, for the constant volume experiments of Series 2, suggested that differences in the durability characteristics occurred

primarily during the early experimental periods. Comparison of these curves indicated that foam rupture, with the exception of the foams at the low concentration (20 ppm), had not occurred to any appreciable extent for the low aeration rate (0.75 1/min) until after a period of 30 minutes or more. Foams for the high aeration rate (2.45 1/min) usually indicated that foam rupture was more pronounced during the initial 30 minutes. Initiation of foam rupture for the intermediate aeration rate (1.5 1/min) usually occurred somewhere between the times of rupture for the other two aeration rates.

Comparison of the curves representing concentration effects for a given aeration rate indicated that the initial resistance to foam rupture generally increased with increased ABS concentration. Foam rupture for a given aeration rate may be observed to occur appreciably during the first 15 minutes at the low ABS concentration (20 ppm) or may be delayed as much as 30 to 60 minutes at the high ABS concentration (100 ppm). The combination of low aeration rate and high ABS concentration appeared to effect the greatest initial resistance to foam rupture.

The initial relative foam persistence is presumably the result of the time required for drainage, the rate of which is influenced by the combined effects of aeration rate and ABS concentration. After the initial drainage period, the

foams appeared to collapse at about the same rate which progressively declined throughout the foam levels near the liquid surface - similar to Series 1 experiments.

The results of the L_f (half life) values in Table 32 for Series 2 experiments indicated the direct relationship of foam persistence with ABS concentration that was previously suggested from the foam collapse curves. Similarly, an inverse relationship of foam persistence and aeration rate may be observed. The results in Table 32 merely serve to compare quantitatively the differences in relative foam persistence expressed for the entire period of the measurements. The property of the initial resistance to foam rupture must be observed from the foam collapse curves.

The analysis of variance in Table 33, on the basis of the F-values, indicated that the factors of both ABS concentration and aeration rate appeared to have appreciably influenced foam persistence. Comparison of the F-values with tabulated values indicated that the effects of both factors were significant at the one per cent probability level. Comparison of the variability due to each of the main effects of aeration rate and ABS concentration (0.39 vs 0.17 respectively) suggested that aeration rate had a more pronounced effect on foam persistence. Both ABS concentration and aeration rate in Table 33 were observed to result in significant linear responses to the employed levels of these factors.

The results of the static decay experiments of Series 2 agreed with the comparable volume weighted disc experiments of Phase 2 inasmuch as foam character was enhanced by increased ABS concentration and low aeration rate. Increased resistance to destruction, either by an applied force or by natural causes, was observed to be effected primarily by linear responses to the levels of ABS concentration. Both the static decay experiments and weighted disc experiments indicated significant linear responses to the levels of aeration rate; however, the weighted disc experiments revealed a significant quadratic response which was not experienced for the static decay experiments.

XIX. GENERAL DISCUSSION

The evaluation of foam properties by the weighted disc method indicated that aeration rate and concentration of ABS were principal factors affecting foam character. The results of the experiments of both Phases 1 and 2 indicated that appreciable differences in resistance to the action of the disc assembly were detected between foams for consecutive aeration rates as employed in the investigation. Reduction of air flow rate resulted in increased foam strength which presumably was indicative of smaller bubble foam produced from the low aeration rates as described in the discussion of Phase 1 experiments.

The effect of ABS concentration on foam properties was not obvious from observations of the foams formed from the range of ABS concentrations employed in the investigation. However, the disc descent curves of Figures 16 through 18 and Figures 25 through 27, for Phases 1 and 2 experiments respectively, suggested increased foam strength with increased ABS concentration. Similarly, the increased foam densities with increased ABS concentration provided further support to the probable changes in foam character occurring with increased ABS concentrations. The changes in foam character with ABS concentration presumably resulted from increased film formation owing to smaller bubbles being formed as reported by Sinsheimer (32).

The disc descent rate data for both Phases 1 and 2 indicated that differences in resistance properties for consecutive ABS concentrations were small relative to those exhibited for consecutive aeration rates. Similarly, the variability estimated for each of the main effects of aeration rate and ABS concentration suggested that aeration rate had a more pronounced effect on foam character than ABS concentration. The range of ABS concentration (0.002 to 0.012 per cent) employed in the investigation effected considerably less changes in foam properties than that effected by the range of aeration rates.

Foams formed at the higher aeration rates (1.5 and 2.45 l/min) during Phase 1 experiments exhibited larger differences in resistance characteristics between successive ABS concentrations than were observed for the experiments of Phase 2. However, as described in the discussion of Phase 1 experiments, the effects of unequal volumes of foam produced as a result of application of unequal volumes of air resulted in increased variability of foam properties. Also since longer periods of aeration were employed for Phase 1 experiments, the effects of drainage throughout the upper foam strata during foam formation would presumably have been greater than for Phase 2 experiments for similar conditions of ABS concentration and aeration rate. Hence, differences in the resistance characteristics of the foams for Phases 1

and 2 apparently reflected the difference in methods of foam production for the two phases.

The attenuation of foam structure as effected by drainage was illustrated by a comparison of Phase 3 experiments with the experiments of Phase 2 at the same temperature (20^oC). The drained foams of Phase 3 exhibited less resistance to action of the disc assembly than was indicated for the foams of Phase 2 at 20^oC. The effects of drainage of foams were seemingly present for the foams generated from aeration rates of 1.5 and 2.45 l/min during Phase 1 experiments. The disc descent curves of Figures 17 and 18 for these aeration rates respectively exhibited a pronounced decrease in resistance to the disc assembly during the latter part of the experimental periods. The stretching and thinning action attributable to drainage resulted in foam structures weakened to the extent that little difference in the resistance properties existed between foams for successive ABS concentrations.

The statistical analyses performed on the disc descent rate data suggested that the effects of both ABS concentration and aeration rate were significant at the one per cent probability level for Phases 1, 2, and 3. For Phases 1 and 2, the response of foam character, as determined by the disc descent rates, was linear with respect to ABS concentration; however, both the linear and quadratic responses to the levels of aeration rate were significant. The experiments

of Phase 3 indicated a significant quadratic response to the levels of ABS concentration in addition to the linear response. Apparently the greater effect of drainage on the foams at 20 ppm than at successively higher ABS concentrations was the primary contribution to the quadratic response as shown by the non-linear relationship of disc descent rate and ABS concentration in Figure 31.

Both Phases 1 and 3 indicated a significant interaction at the one per cent probability level. The interaction for Phase 1 experiments was due primarily to the combined linear responses of ABS concentration and aeration rate. The fact that this interaction did not result for Phase 2 experiments, which were conducted under controlled conditions of temperature and relative humidity, suggested that these uncontrolled variables in Phase 1 experiments may have caused the interaction. For Phase 3 experiments, the erratic values of disc descent rate resulting from the employed initial drainage period indicated an interaction comprised of linear, quadratic, and cubic responses with respect to ABS concentration; the interaction with respect to aeration rate was linear.

The results of the static decay experiments agreed with those of the weighted disc experiments inasmuch as foam persistence was enhanced by increased ABS concentration and low aeration rate. For both Series 1 and 2 experiments, differences in foam persistence were observed to occur mainly

during the early hours of the investigation. Initiation of foam rupture did not occur until the foams had weakened sufficiently as the result of stretching and thinning of foam films which have been reported to occur during drainage (4, 5). Film rupture was observed to occur earlier in foams formed from low ABS concentrations and high aeration rates. The observations agreed with those reported in the Literature Review with regard to the effects of aeration rate and concentration of foaming agent upon bubble size and subsequent influence on foam persistence.

Once film rupture had begun, little difference in rates of collapse were observed between foams formed from the different aeration rates or ABS concentrations. The experiments, however, examined foams resulting from a single foaming agent and at relatively dilute solutions. Apparently the concentrations of ABS were not significantly different to cause appreciable differences in foam structure except for the initially entrained liquid.

The initial period of the static decay experiments therefore appeared to be indicative of foam persistence for the conditions of ABS concentration and aeration rate employed. The experiments of Phases 1 and 2, employing the weighted disc, reflected a similar phenomenon inasmuch as differences in resistance to destruction by the disc assembly were measured in the foams immediately after being formed. Both

methods indicated that the resistance to destruction was enhanced by increased ABS concentration and decreased aeration rate. The static decay method measured the resistance to foam destruction by natural forces whereas the weighted disc method measured the resistance to destruction by an applied external force. Both methods, however, are indicative of the strength or durability characteristics of foam.

The results from application of the method of Brady and Ross (7) to the disc descent data of Phase 2 and the static decay data of Series 2 agreed insofar as "the average destruction time" (D_f) and "the average lifetime" (L_f) of foams appeared to vary directly with ABS concentration and inversely with aeration rate. The statistical analysis for each set of data suggested a significant linear response to the factors of both ABS concentration and aeration rate. Although the analysis indicated a significant quadratic response to the employed levels of aeration rate for the weighted disc experiments of Phase 2, the quadratic response was not evident from the analysis of the static decay data.

Although the static decay method is commonly employed in evaluating the durability properties of foams, the method often results in lengthy experiments when characterizing persistent type foams. The time required to conduct static decay experiments may range from minutes to hours with the longer times being required for the more durable foams.

Some indication of foam persistence for durable foams may be obtained during the earlier minutes of the experiments as illustrated by the initial periods of Series 2 static decay tests. However, as previously indicated, these experiments were performed at relatively dilute concentrations of ABS. If the concentrations of ABS were increased to 0.1 to 0.8 per cent, as reported by Bikerman for experiments employing different synthetic detergent solutions, the initial period required to obtain relative stability measurements may be too long to be practical. Other foaming media such as protein solutions may yield foams of longer duration. Berkman and Egloff (4), for instance, reported albumin solutions may last for hours or as much as several days.

The initial periods of the static decay tests may not always be indicative of the stability properties of foams when characterizing foams of different foaming media. Unlike the foams of Series 2 experiments which exhibited decay curves of similar form for various ABS dosages, foams originating from different media may result in curves of various shapes. Brady and Ross (7), for example, presented decay curves for a lubricating oil and a two per cent solution of "Aerosol OT" from which the lubricating oil appeared to be more durable on the basis of the initial collapse periods. However, the decay curve for the lubricating oil was linear and terminated after about 54 minutes. The decay curve for

the solution of "Aerosol OT", on the other hand, showed a progressively declined collapse rate after about 50 minutes with total collapse time amounting to about 265 minutes.

In addition to static decay experiments often being time consuming, determination of the upper foam level depends somewhat on the individual owing to the irregular manner in which rupture occurs. The upper foam level may be taken as the uppermost bubble remaining or as an estimated average of the irregular foam surface. The weighted disc method eliminates the estimation of the upper foam level since the bottom of the disc assembly conveniently indicates the foam level at any particular moment.

The main disadvantage of the weighted disc method is the special need for cleanliness of the disc assembly. Both methods require frequent cleansing of the foam generation column to prevent accumulations of films of surface active agent. However, the disc assembly should be rinsed and dried between consecutive measurements to prevent film accumulations. This film may serve as a lubricant which tends to accelerate the rate of disc descent.

The weighted disc method has the principal advantage of rapidity of the measurements. The experiments reported in this thesis indicated that periods of about 10 to 25 minutes were required for completion of the measurements. Some flexibility is offered by the method since discs of different

weights and/or dimensions can be employed to extend application to foams sufficiently different from those investigated in this thesis. The length of the experiments and sensitivity to detect small differences in foam character can therefore be controlled somewhat by the individual owing to the desired changes in disc weight and dimensions relative to the durability of the foams encountered. For foams of similar strength characteristics as employed in the investigation, the disc assembly as previously described appeared to be satisfactory for routine characterization studies.

The generation of a constant volume of foam, as employed in Phase 2 studies, for each measurement is considered preferable in order to minimize changes in foam characteristics owing to unequal aeration as in Phase 1. Although the higher aeration rate (2.45 l/in) resulted in occasional air pockets at the low ABS concentrations (20 ppm) during Phase 1 experiments, this phenomenon was not apparent when employing the smaller volumes of foam in Phase 2; all three aeration rates appeared compatible with the foaming tendencies of the solutions at the employed ABS concentrations. The methods as outlined in this thesis appear to be readily applicable to the evaluation of relative durability properties of foams; however, modifications to the given procedures may be advantageous for specific situations.

The weighted disc method offers a simple and convenient means of evaluating relative strength of foams. The time saved in performing experiments by this method, in comparison with static decay experiments, serves to make this method suitable for repeated foam measurements. Hence, the method is offered as a practical means of evaluating durable foam characteristics during routine investigations.

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XXIII. APPENDIX A

Data for the Experiments Employing the Weighted Disc Method

The information given in Appendix A includes the experimental data obtained from the weighted disc experiments of Phases 1, 2, and 3. The headings of each set of data indicate the ABS concentration, aeration rate, foam volume, aeration time to generate the given foam volume, foam density, and the time required for completion of the indicated measurement.

The data given beneath the headings indicate the disc level (cm) observed at one minute intervals reading from left to right. The first value given is the initial foam height after discontinuation of aeration which corresponds to time equal to zero.

PHASE 1 WEIGHTED DISC EXPERIMENTAL DATA (23 C)

REPLICATE   1

```
ABS CONCENTRATION  =  20 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     1559  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0228 GM/CC       EXPERIMENT TIME = 11.2   MIN

   49.4   48.4   47.1   45.8   44.5   43.0   41.3   39.8   38.1   36.2
   33.6   29.8   28.0


ABS CONCENTRATION  =  20 PPM        AERATION RATE =  1.48 L/MIN
FOAM VOLUME    =     3133  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0159 GM/CC       EXPERIMENT TIME = 12.1   MIN

   71.3   68.0   64.7   62.0   59.4   56.5   52.3   48.8   46.0   43.3
   39.0   35.0   28.7   28.0


ABS CONCENTRATION  =  20 PPM        AERATION RATE =  2.52 L/MIN
FOAM VOLUME    =     4216  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0118 GM/CC       EXPERIMENT TIME = 12.8   MIN

   86.5   84.1   80.2   76.6   72.0   65.7   59.9   57.1   54.4   49.8
   45.3   40.5   35.2   28.0


ABS CONCENTRATION  =  40 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     1659  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0429 GM/CC       EXPERIMENT TIME = 20.8   MIN

   50.3   49.6   49.0   48.5   48.0   47.3   46.7   46.0   45.2   44.5
   43.8   42.9   42.1   41.4   40.6   39.6   38.7   37.4   36.0   34.2
   32.0   28.0


ABS CONCENTRATION  =  40 PPM        AERATION RATE =  1.48 L/MIN
FOAM VOLUME    =     3482  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0415 GM/CC       EXPERIMENT TIME = 18.3   MIN

   74.4   72.4   70.7   69.2   67.4   65.5   63.7   61.6   59.2   57.0
   54.6   51.8   48.3   44.5   40.6   37.9   35.4   32.8   30.2   28.1


ABS CONCENTRATION  =  40 PPM        AERATION RATE =  2.52 L/MIN
FOAM VOLUME    =     5391  CC        AERATION TIME = 2.00    MIN
FOAM DENSITY =     .0250 GM/CC       EXPERIMENT TIME = 13.4   MIN
```

```
101.7  98.7  95.1  90.1  82.1  76.9  72.8  68.9  63.0  56.7
 49.5  42.8  36.8  31.5  27.9
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME     =    1659  CC       AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0515 GM/CC    EXPERIMENT TIME = 24.3   MIN
```

```
 50.0  49.0  48.4  47.6  47.0  46.4  45.8  45.2  44.5  43.9
 43.3  42.7  42.0  41.4  40.7  40.0  39.3  38.5  37.8  37.0
 36.0  34.9  33.7  32.0  29.7  27.9
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =  1.48 L/MIN
FOAM VOLUME     =    3254  CC       AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0531 GM/CC    EXPERIMENT TIME = 20.4   MIN
```

```
 72.0  70.4  69.2  68.0  66.5  65.2  63.8  62.4  60.6  59.1
 57.3  55.7  53.8  51.8  49.4  46.9  44.1  40.4  37.3  34.2
 30.9  28.2
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =  2.52 L/MIN
FOAM VOLUME     =    5690  CC       AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0475 GM/CC    EXPERIMENT TIME = 20.6   MIN
```

```
104.0 101.8  99.7  96.6  93.2  90.2  87.2  81.2  77.0  73.0
 68.0  61.4  55.4  50.4  46.7  43.4  40.8  38.2  35.6  33.1
 30.6  27.9
```

```
ABS CONCENTRATION =  80 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME     =    1652  CC       AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0560 GM/CC    EXPERIMENT TIME = 23.9   MIN
```

```
 49.8  49.1  48.5  47.9  47.3  46.7  46.2  45.7  45.1  44.6
 44.1  43.5  42.9  42.3  41.7  40.9  40.2  39.4  38.4  37.3
 36.2  35.0  33.5  31.6  27.9
```

```
ABS CONCENTRATION =  80 PPM        AERATION RATE =  1.48 L/MIN
FOAM VOLUME     =    3439  CC       AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0621 GM/CC    EXPERIMENT TIME = 22.9   MIN
```

```
 73.4  72.2  71.0  70.0  69.0  68.0  66.9  65.8  64.6  63.2
 61.9  60.5  58.9  56.9  54.5  51.8  47.5  44.2  41.0  38.4
 35.9  33.5  31.3  28.1
```

ABS CONCENTRATION = 80 PPM　　　　AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   5519 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0554 GM/CC　EXPERIMENT TIME = 23.6 MIN

```
101.3  99.5  98.3  96.8  95.4  93.8  91.9  90.1  88.0  85.4
 83.0  80.0  76.6  71.9  66.7  60.0  55.3  50.7  46.4  43.1
 39.5  36.5  33.9  31.2  28.1
```

ABS CONCENTRATION = 100 PPM　　　 AERATION RATE = .75 L/MIN
FOAM VOLUME   =   1844 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0617 GM/CC　EXPERIMENT TIME = 26.2 MIN

```
 52.3  50.9  50.0  49.4  48.8  48.0  47.4  46.7  46.1  45.5
 44.8  44.2  43.6  43.0  42.3  41.7  41.1  40.4  39.7  38.9
 38.1  37.2  36.1  34.9  33.7  32.1  29.6  27.8
```

ABS CONCENTRATION = 100 PPM　　　 AERATION RATE = 1.48 L/MIN
FOAM VOLUME   =   3468 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0718 GM/CC　EXPERIMENT TIME = 25.0 MIN

```
 73.3  71.5  70.5  69.6  68.8  67.8  67.0  66.2  65.4  64.6
 63.8  62.8  61.4  60.0  58.1  55.9  52.8  50.3  47.8  44.3
 41.6  38.8  36.3  34.0  31.8  28.1
```

ABS CONCENTRATION = 100 PPM　　　 AERATION RATE = 2.51 L/MIN
FOAM VOLUME   =   5718 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0604 GM/CC　EXPERIMENT TIME = 25.8 MIN

```
103.3 101.3  99.8  98.2  96.7  95.2  93.5  91.7  90.2  88.6
 86.8  84.6  82.2  79.1  75.2  71.4  65.5  59.8  55.5  51.1
 47.2  44.1  39.1  36.9  34.2  31.4  28.1
```

ABS CONCENTRATION = 120 PPM　　　 AERATION RATE = .75 L/MIN
FOAM VOLUME   =   1844 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0579 GM/CC　EXPERIMENT TIME = 28.7 MIN

```
 52.4  51.1  50.5  50.0  49.6  49.1  48.5  47.9  47.3  46.7
 46.0  45.4  44.7  44.2  43.6  43.0  42.5  41.7  41.0  40.4
 39.6  38.9  38.1  37.5  36.8  36.2  35.2  34.0  32.3  28.0
```

ABS CONCENTRATION = 120 PPM　　　 AERATION RATE = 1.48 L/MIN
FOAM VOLUME   =   3589 CC　　AERATION TIME = 2.00 MIN
FOAM DENSITY =   .0694 GM/CC　EXPERIMENT TIME = 29.6 MIN

```
74.9  73.6  72.7  71.7  70.8  70.0  69.1  68.3  67.5  66.7
65.8  65.0  64.1  63.3  62.3  61.3  60.3  59.2  57.5  55.9
53.8  51.1  48.7  45.7  42.9  40.5  38.3  36.0  33.6  30.8
28.0
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   2.52 L/MIN
FOAM VOLUME =   5768 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY =   .0635 GM/CC   EXPERIMENT TIME = 27.7 MIN

```
104.1 102.3 101.1  99.8  98.3  96.9  95.3  93.7  92.0  90.2
 87.8  85.7  83.7  81.7  78.2  75.0  70.9  65.8  60.7  55.9
 51.4  48.8  45.0  42.4  39.7  36.9  34.0  31.2  28.0
```

REPLICATE 2

ABS CONCENTRATION = 20 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME =   1445 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0197 GM/CC   EXPERIMENT TIME = 11.7 MIN

```
47.8  46.4  45.3  44.5  43.7  42.6  41.2  39.8  38.5  36.8
35.1  32.1  27.9
```

ABS CONCENTRATION = 20 PPM   AERATION RATE =   1.48 L/MIN
FOAM VOLUME =   3204 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0155 GM/CC   EXPERIMENT TIME = 12.5 MIN

```
72.0  62.8  60.0  57.8  55.8  53.8  51.7  49.6  47.3  44.6
40.2  36.9  31.9  27.7
```

ABS CONCENTRATION = 20 PPM   AERATION RATE =   2.53 L/MIN
FOAM VOLUME =   4672 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0076 GM/CC   EXPERIMENT TIME = 11.3 MIN

```
93.0  90.3  88.4  84.0  72.7  69.6  66.5  63.2  47.1  41.6
36.9  31.0  27.9
```

ABS CONCENTRATION = 40 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME =   1595 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0357 GM/CC   EXPERIMENT TIME = 16.0 MIN

```
49.5  48.5  47.6  46.8  46.0  45.1  44.2  43.3  42.3  41.3
40.2  39.3  37.8  36.6  34.9  32.7  27.9
```

ABS CONCENTRATION = 40 PPM   AERATION RATE = 1.48 L/MIN
FOAM VOLUME   =   3411 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0334 GM/CC   EXPERIMENT TIME = 17.9 MIN

   74.0 72.3 70.9 69.6 68.2 66.2 64.3 62.2 59.9 57.6
   55.0 52.7 50.2 46.5 43.4 39.4 36.0 32.4 27.7

ABS CONCENTRATION = 40 PPM   AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   4985 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0342 GM/CC   EXPERIMENT TIME = 15.1 MIN

   95.4 90.5 86.7 83.3 78.7 74.9 68.8 66.0 59.5 54.3
   49.2 43.9 39.6 35.6 32.8 29.5 27.8

ABS CONCENTRATION = 60 PPM   AERATION RATE = .76 L/MIN
FOAM VOLUME   =   1730 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0452 GM/CC   EXPERIMENT TIME = 19.5 MIN

   51.3 49.7 48.8 47.9 47.2 46.5 45.7 45.0 44.3 43.5
   42.7 42.0 41.1 40.0 39.0 37.7 36.5 35.0 33.0 30.5
   27.7

ABS CONCENTRATION = 60 PPM   AERATION RATE = 1.47 L/MIN
FOAM VOLUME   =   3439 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0517 GM/CC   EXPERIMENT TIME = 17.4 MIN

   73.6 71.9 70.5 69.5 68.1 66.7 65.2 63.5 62.0 59.6
   57.1 53.8 50.0 45.4 40.8 36.8 33.2 30.2 27.8

ABS CONCENTRATION = 60 PPM   AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   5448 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0457 GM/CC   EXPERIMENT TIME = 19.1 MIN

  100.8 99.0 96.9 94.8 89.3 85.5 82.5 76.9 72.7 68.4
   63.8 57.5 51.3 45.7 42.4 39.7 36.9 34.7 32.1 29.2
   27.8

ABS CONCENTRATION = 80 PPM   AERATION RATE = .76 L/MIN
FOAM VOLUME   =   1737 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY   =   .0450 GM/CC   EXPERIMENT TIME = 28.8 MIN

   51.2 50.4 50.0 49.6 49.0 48.6 48.0 47.5 47.0 46.6

```
46.2   45.7   45.3   44.8   44.3   43.8   43.3   42.7   42.2   41.6
41.0   40.4   39.6   38.8   37.8   36.7   35.5   34.0   31.8   27.9
```

```
ABS CONCENTRATION =  80 PPM        AERATION RATE  =   1.48 L/MIN
FOAM VOLUME      =    3489  CC      AERATION TIME  =   2.00    MIN
FOAM DENSITY     =    .0632 GM/CC   EXPERIMENT TIME = 24.0    MIN.
```

```
74.0   72.7   71.5   70.2   68.9   67.5   66.3   65.1   63.8   62.5
61.1   59.5   57.8   56.0   54.2   51.8   49.3   46.2   43.1   40.3
37.9   35.7   33.5   31.6   28.1
```

```
ABS CONCENTRATION =  80 PPM        AERATION RATE  =   2.52 L/MIN
FOAM VOLUME      =    5597  CC      AERATION TIME  =   2.00    MIN
FOAM DENSITY     =    .0559 GM/CC   EXPERIMENT TIME = 16.6    MIN
```

```
102.2   99.8   97.4   95.1   93.2   90.4   85.5   79.2   72.5   64.6
 58.2   52.2   47.3   42.6   37.7   33.8   30.5   28.0
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE  =    .76 L/MIN
FOAM VOLUME      =    2044  CC      AERATION TIME  =   2.00    MIN
FOAM DENSITY     =    .0557 GM/CC   EXPERIMENT TIME = 29.8    MIN
```

```
55.0   53.2   52.5   52.0   51.4   50.8   50.1   49.5   48.6   47.9
47.2   46.5   45.8   45.1   44.5   43.8   43.2   42.5   41.9   41.2
40.5   39.8   39.1   38.3   37.4   36.5   35.5   34.3   32.8   30.9
27.9
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE  =   1.48 L/MIN
FOAM VOLUME      =    3397  CC      AERATION TIME  =   2.00    MIN
FOAM DENSITY     =    .0587 GM/CC   EXPERIMENT TIME = 32.6    MIN
```

```
72.5   71.0   69.7   68.7   67.8   66.8   65.6   64.9   64.0   63.0
62.1   61.3   60.4   59.5   58.5   57.5   56.8   55.8   54.7   53.6
52.5   51.4   50.2   48.5   47.0   45.3   43.4   41.5   39.4   37.3
35.2   32.9   30.7   27.6
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE  =   2.53 L/MIN
FOAM VOLUME      =    5683  CC      AERATION TIME  =   2.00    MIN
FOAM DENSITY     =    .0488 GM/CC   EXPERIMENT TIME = 27.3    MIN
```

```
104.0  102.6  101.3  100.1   99.2   98.0   96.7   95.2   93.6   91.8
 89.8   87.7   85.6   82.8   79.9   76.3   72.1   66.1   59.8   53.0
 48.6   45.7   43.0   40.6   37.9   35.5   33.0   30.3   28.1
```

```
ABS CONCENTRATION = 120 PPM          AERATION RATE =    .76 L/MIN
FOAM VOLUME    =      1837  CC        AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0581 GM/CC      EXPERIMENT TIME = 29.1  MIN

   52.4   51.2   50.7   50.2   49.8   49.2   48.5   48.0   47.4   46.9
   46.4   45.7   45.2   44.6   44.0   43.4   42.8   42.2   41.5   40.9
   40.1   39.4   38.7   37.9   37.0   36.0   35.0   33.8   32.1   29.7
   28.1
```

```
ABS CONCENTRATION = 120 PPM          AERATION RATE =   1.47 L/MIN
FOAM VOLUME    =      3461  CC        AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0679 GM/CC      EXPERIMENT TIME = 29.8  MIN

   73.0   70.8   69.2   67.7   66.1   64.8   63.6   62.6   61.6   60.6
   59.6   58.6   57.6   56.6   55.6   54.6   53.5   52.5   51.3   50.0
   48.8   47.6   46.2   44.8   43.4   41.8   40.2   38.3   36.0   33.1
   27.8
```

```
ABS CONCENTRATION = 120 PPM          AERATION RATE =   2.53 L/MIN
FOAM VOLUME    =      5697  CC        AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0587 GM/CC      EXPERIMENT TIME = 37.0  MIN

  103.2  102.4  101.9  101.3  100.5   99.8   99.1   98.4   97.5   96.6
   95.5   94.1   93.0   91.9   90.3   89.6   88.5   87.0   85.4   83.6
   81.8   78.5   77.4   74.5   70.8   66.1   60.9   55.5   51.4   48.0
   46.0   43.9   41.3   39.0   36.8   34.5   31.8   27.9
```

REPLICATE 3

```
ABS CONCENTRATION =  20 PPM          AERATION RATE =    .76 L/MIN
FOAM VOLUME    =      1595  CC        AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0223 GM/CC      EXPERIMENT TIME =  9.3  MIN

   49.9   49.0   47.9   46.5   44.9   43.0   40.7   38.5   35.5   31.7
   28.0
```

```
ABS CONCENTRATION =  20 PPM          AERATION RATE =   1.47 L/MIN
FOAM VOLUME    =      3254  CC        AERATION TIME =  2.00   MIN
FOAM DENSITY =       .0153 GM/CC      EXPERIMENT TIME = 12.3  MIN

   73.0   70.6   68.3   64.5   62.4   59.5   54.1   50.0   47.6   44.3
   40.8   36.7   31.0   28.0
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   2.53 L/MIN
FOAM VOLUME    =      4728  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0135 GM/CC   EXPERIMENT TIME = 14.5  MIN


   93.4   91.8   88.0   76.0   73.7   71.4   68.9   65.0   62.0   58.8
   54.8   50.5   43.4   38.6   33.0   27.9



ABS CONCENTRATION =  40 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =      1573  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0407 GM/CC   EXPERIMENT TIME = 20.9  MIN


   49.2   48.5   47.9   47.4   46.8   46.1   45.7   44.7   44.0   43.3
   42.7   41.9   41.2   40.4   39.5   38.8   37.7   36.7   35.6   34.0
   31.9   28.0



ABS CONCENTRATION =  40 PPM        AERATION RATE =   1.48 L/MIN
FOAM VOLUME    =      3382  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0315 GM/CC   EXPERIMENT TIME = 13.1  MIN


   74.0   71.8   69.4   66.2   61.8   58.8   55.3   52.2   48.2   44.3
   41.1   37.4   33.2   29.3   28.0



ABS CONCENTRATION =  40 PPM        AERATION RATE =   2.53 L/MIN
FOAM VOLUME    =      5348  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0306 GM/CC   EXPERIMENT TIME = 15.8  MIN


  100.8   98.4   96.3   90.5   86.2   82.5   78.5   75.3   68.0   63.8
   59.0   52.0   45.8   41.0   36.5   32.5   28.0



ABS CONCENTRATION =  60 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME    =      1659  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0472 GM/CC   EXPERIMENT TIME = 19.9  MIN


   50.2   49.3   48.6   47.9   47.2   46.6   45.8   45.1   44.4   43.7
   43.0   42.2   41.3   40.5   39.6   38.5   37.4   36.0   34.5   32.6
   28.0



ABS CONCENTRATION =  60 PPM        AERATION RATE =   1.47 L/MIN
FOAM VOLUME    =      3375  CC      AERATION TIME =  2.00   MIN
FOAM DENSITY =        .0464 GM/CC   EXPERIMENT TIME = 23.1  MIN


   73.0   71.4   70.2   68.9   67.6   66.4   65.3   64.0   62.7   61.3
   59.9   58.4   56.9   55.3   53.4   51.6   49.3   47.1   44.4   41.8
   38.9   36.0   32.7   29.3   27.8
```

ABS CONCENTRATION = 60 PPM   AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   5391 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0435 GM/CC   EXPERIMENT TIME = 18.4 MIN

  100.2 98.0 95.5 93.3 90.8 88.0 85.7 82.0 77.1 71.6
   65.4 57.4 49.3 43.8 40.3 37.8 35.2 32.7 30.1 27.8

ABS CONCENTRATION = 80 PPM   AERATION RATE = .76 L/MIN
FOAM VOLUME   =   1844 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0540 GM/CC   EXPERIMENT TIME = 29.1 MIN

   52.5 50.5 50.0 49.4 48.7 48.0 47.3 46.8 46.2 45.6
   44.9 44.3 43.6 43.0 42.4 41.8 41.3 40.7 40.1 39.5
   38.9 38.2 37.5 36.7 35.9 35.0 34.0 32.9 31.4 29.0
   28.0

ABS CONCENTRATION = 80 PPM   AERATION RATE = 1.48 L/MIN
FOAM VOLUME   =   3447 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0640 GM/CC   EXPERIMENT TIME = 25.5 MIN

   73.4 72.1 71.1 70.2 69.4 68.5 67.6 66.8 66.0 65.0
   64.0 63.1 61.8 60.3 58.6 56.8 55.1 53.0 49.9 46.8
   43.7 40.4 37.8 35.3 32.8 30.3 28.1

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   5747 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0557 GM/CC   EXPERIMENT TIME = 31.9 MIN

  104.0 101.8 100.2 99.0 97.6 96.2 94.9 93.7 92.5 91.2
   90.0 88.6 87.2 85.7 83.8 81.7 79.0 76.0 72.4 68.5
   64.4 59.8 55.7 52.1 49.1 46.7 44.7 42.3 39.8 37.3
   34.7 31.5 27.8

ABS CONCENTRATION = 100 PPM   AERATION RATE = .76 L/MIN
FOAM VOLUME   =   2001 CC   AERATION TIME = 2.00   MIN
FOAM DENSITY =   .0569 GM/CC   EXPERIMENT TIME = 26.7 MIN

   54.6 53.5 52.7 52.0 51.4 50.7 50.1 49.4 48.8 48.2
   47.5 46.8 46.1 45.4 44.7 43.9 43.1 42.3 41.5 40.6
   39.7 38.7 37.7 36.6 35.3 33.7 31.7 28.1

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.47 L/MIN

FOAM VOLUME   =   3375 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY   =   .0696 GM/CC   EXPERIMENT TIME = 27.0   MIN

```
 72.0  70.4  69.1  67.8  66.8  65.8  64.7  63.7  62.5  61.5
 60.4  59.3  58.3  57.1  56.0  54.8  53.4  52.2  50.8  49.3
 47.0  46.2  44.5  42.5  40.3  38.0  34.7  27.8
```

ABS CONCENTRATION = 100 PPM   AERATION RATE =   2.53 L/MIN
FOAM VOLUME   =   5633 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY   =   .0594 GM/CC   EXPERIMENT TIME = 31.7   MIN

```
102.2 101.0 100.0  98.9  97.9  97.0  95.8  94.5  93.1  91.5
 90.0  88.0  86.2  84.3  82.3  80.0  77.5  74.8  71.3  67.5
 62.7  57.8  53.4  49.9  47.3  45.1  42.7  40.5  38.0  35.7
 33.3  30.7  27.8
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   1823 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY   =   .0546 GM/CC   EXPERIMENT TIME = 31.1   MIN

```
 52.5  51.3  50.7  50.2  49.7  49.2  48.6  48.0  47.6  46.9
 46.5  46.0  45.5  45.0  44.5  43.9  43.3  42.8  42.2  41.6
 41.0  40.5  39.8  39.2  38.4  37.7  36.9  36.0  35.0  33.7
 32.3  29.7  28.3
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   1.48 L/MIN
FOAM VOLUME   =   3625 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY   =   .0707 GM/CC   EXPERIMENT TIME = 32.3   MIN

```
 75.2  73.7  72.7  71.7  70.7  69.7  68.8  67.8  66.8  65.8
 64.8  63.8  62.8  61.6  60.4  59.3  57.9  56.5  55.1  53.6
 51.9  50.3  48.7  46.9  45.0  43.3  41.6  40.0  38.2  36.5
 34.6  32.3  29.7  27.9
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   2.51 L/MIN
FOAM VOLUME   =   5597 CC   AERATION TIME =   2.00   MIN
FOAM DENSITY   =   .0674 GM/CC   EXPERIMENT TIME = 28.0   MIN

```
101.2  99.4  97.8  96.3  94.8  93.5  92.3  91.0  89.5  88.0
 86.6  84.9  83.0  80.9  78.7  75.2  72.0  67.8  63.0  57.5
 52.9  49.5  47.0  43.4  41.0  37.7  35.0  32.2  27.9
```

PHASE 2 WEIGHTED DISC EXPERIMENTAL DATA (20 C)

REPLICATE   1

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME   =     2008   CC       AERATION TIME =  2.40    MIN
FOAM DENSITY =      .0283 GM/CC     EXPERIMENT TIME = 27.5   MIN

   55.0   54.1   53.5   53.0   52.4   51.8   51.3   50.7   50.0   49.3
   48.7   48.0   47.4   46.8   46.0   45.3   44.5   43.5   42.6   41.7
   40.5   39.5   38.4   37.0   35.7   34.2   32.5   30.2   27.6
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   1.52 L/MIN
FOAM VOLUME   =     2029   CC       AERATION TIME =  1.19    MIN
FOAM DENSITY =      .0315 GM/CC     EXPERIMENT TIME = 19.5   MIN

   55.0   54.0   53.2   52.4   51.5   50.6   49.8   48.7   47.5   46.3
   45.2   44.1   42.8   41.5   40.0   38.4   36.7   34.8   32.7   29.8
   27.4
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   2.63 L/MIN
FOAM VOLUME   =     2036   CC       AERATION TIME =    .68    MIN
FOAM DENSITY =      .0279 GM/CC     EXPERIMENT TIME = 13.1   MIN

   55.0   52.4   50.5   48.8   47.5   46.5   45.2   43.7   41.7   39.6
   36.8   34.3   31.3   28.3   27.2
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME   =     2044   CC       AERATION TIME =  2.42    MIN
FOAM DENSITY =      .0383 GM/CC     EXPERIMENT TIME = 29.3   MIN

   55.0   53.9   53.2   52.5   52.0   51.2   50.7   50.0   49.5   48.8
   48.2   47.5   47.0   46.3   45.7   45.0   44.2   44.7   43.0   42.2
   41.3   40.5   39.7   38.6   37.7   36.5   35.3   33.8   32.1   29.3
   27.4
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =   1.52 L/MIN
FOAM VOLUME   =     2058   CC       AERATION TIME =  1.20    MIN
FOAM DENSITY =      .0449 GM/CC     EXPERIMENT TIME = 19.8   MIN

   55.0   53.6   52.5   51.3   50.2   49.2   48.2   47.3   46.2   45.3
   44.3   43.3   42.2   41.1   40.0   38.7   37.2   35.6   33.7   31.2
   27.4
```

ABS CONCENTRATION = 40 PPM   AERATION RATE = 2.62 L/MIN
FOAM VOLUME   =   2051 CC   AERATION TIME =   .65   MIN
FOAM DENSITY =   .0416 GM/CC   EXPERIMENT TIME = 14.8 MIN

    55.0   52.5   51.2   49.8   48.0   46.3   45.1   43.8   42.4   41.0
    39.3   37.5   35.8   33.4   30.7   27.4

ABS CONCENTRATION = 60 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME = 2.30   MIN
FOAM DENSITY =   .0515 GM/CC   EXPERIMENT TIME = 29.8 MIN

    55.0   53.2   52.2   51.2   50.2   49.6   49.0   48.2   47.7   47.1
    46.5   46.0   45.4   44.8   44.3   43.7   43.1   42.5   41.9   41.3
    40.7   39.8   39.2   38.3   37.6   36.6   35.6   34.5   33.1   31.1
    27.4

ABS CONCENTRATION = 60 PPM   AERATION RATE = 1.53 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME = 1.55   MIN
FOAM DENSITY =   .0584 GM/CC   EXPERIMENT TIME = 19.8 MIN

    55.0   53.6   52.4   51.1   50.0   49.0   48.0   47.1   46.3   45.3
    44.3   43.4   42.3   41.3   40.1   38.8   37.4   35.8   33.7   31.2
    27.6

ABS CONCENTRATION = 60 PPM   AERATION RATE = 2.63 L/MIN
FOAM VOLUME   =   2086 CC   AERATION TIME =   .65   MIN
FOAM DENSITY =   .0546 GM/CC   EXPERIMENT TIME = 15.0 MIN

    55.0   53.0   51.5   50.1   48.5   46.8   45.0   43.3   42.0   40.6
    39.1   37.6   35.9   33.8   31.2   27.3

ABS CONCENTRATION = 80 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME = 2.26   MIN
FOAM DENSITY =   .0652 GM/CC   EXPERIMENT TIME = 30.7 MIN

    55.0   53.6   52.8   52.0   51.3   50.7   50.0   49.5   48.8   48.1
    47.5   47.1   46.5   46.0   45.4   44.9   44.2   43.8   43.1   42.5
    41.8   41.2   40.5   39.8   39.0   38.1   37.1   36.0   34.7   33.3
    31.3   27.8

ABS CONCENTRATION = 80 PPM   AERATION RATE = 1.53 L/MIN
FOAM VOLUME   =   2100 CC   AERATION TIME = 1.13   MIN
FOAM DENSITY =   .0711 GM/CC   EXPERIMENT TIME = 20.7 MIN

.

```
55.0   53.2   52.0   50.8   49.6   48.5   47.7   46.8   45.2   44.9
44.0   43.0   42.0   41.1   40.0   39.0   37.8   36.3   34.8   33.0
30.6   27.6
```

```
ABS CONCENTRATION =   80  PPM       AERATION RATE  =    2.63 L/MIN
FOAM VOLUME    =       2072  CC      AERATION TIME  =    .68   MIN
FOAM DENSITY   =       .0584 GM/CC   EXPERIMENT TIME = 15.0   MIN
```

```
55.0   52.7   50.8   48.8   46.7   45.1   43.7   42.3   40.9   39.4
38.0   36.3   34.7   33.0   30.9   27.6
```

```
ABS CONCENTRATION = 100  PPM        AERATION RATE  =    .87 L/MIN
FOAM VOLUME    =       2100  CC      AERATION TIME  =   2.33   MIN
FOAM DENSITY   =       .0711 GM/CC   EXPERIMENT TIME = 32.0   MIN
```

```
55.0   53.7   53.0   52.3   51.6   50.8   50.1   49.6   49.0   48.3
47.8   47.2   46.6   46.1   45.5   45.0   44.5   43.9   43.3   42.7
42.1   41.4   40.8   40.0   39.3   38.6   37.8   37.0   35.8   34.7
33.3   31.6   27.6
```

```
ABS CONCENTRATION = 100  PPM        AERATION RATE  =   1.52 L/MIN
FOAM VOLUME    =       2086  CC      AERATION TIME  =   1.10   MIN
FOAM DENSITY   =       .0716 GM/CC   EXPERIMENT TIME = 21.1   MIN
```

```
55.0   53.1   52.1   51.0   50.0   49.0   48.0   47.0   46.1   45.1
44.2   43.3   42.3   41.3   40.3   39.2   38.0   36.8   35.4   33.7
31.7   28.7   27.8
```

```
ABS CONCENTRATION = 100  PPM        AERATION RATE  =   2.63 L/MIN
FOAM VOLUME    =       2086  CC      AERATION TIME  =    .64   MIN
FOAM DENSITY   =       .0648 GM/CC   EXPERIMENT TIME = 16.7   MIN
```

```
55.0   52.8   51.2   49.5   48.2   46.4   44.8   43.6   42.5   41.2
39.9   38.5   37.3   35.8   34.1   32.3   30.0   27.6
```

```
ABS CONCENTRATION = 120  PPM        AERATION RATE  =    .78 L/MIN
FOAM VOLUME    =       2150  CC      AERATION TIME  =   2.20   MIN
FOAM DENSITY   =       .0794 GM/CC   EXPERIMENT TIME = 33.6   MIN
```

```
55.0   53.2   52.3   51.7   51.1   50.5   49.9   49.2   48.6   48.0
47.5   46.9   46.3   45.9   45.4   44.8   44.3   43.7   43.2   42.7
42.1   41.6   41.0   40.4   39.8   39.1   38.4   37.7   36.8   35.9
34.8   33.7   32.3   30.2   27.2
```

```
ABS CONCENTRATION = 120 PPM        AERATION RATE =   1.54 L/MIN
FOAM VOLUME     =      2143  CC     AERATION TIME =   1.18   MIN
FOAM DENSITY =         .0797 GM/CC  EXPERIMENT TIME = 22.9   MIN

   55.0   53.7   52.7   51.6   50.7   49.8   48.8   47.9   46.8   46.0
   45.1   44.1   43.2   42.3   41.3   40.3   39.2   38.2   37.0   35.7
   34.2   32.5   30.1   27.3
```

```
ABS CONCENTRATION = 120 PPM        AERATION RATE =   2.63 L/MIN
FOAM VOLUME     =      2086  CC     AERATION TIME =    .67   MIN
FOAM DENSITY =         .0614 GM/CC  EXPERIMENT TIME = 17.6   MIN

   55.0   52.9   51.8   50.6   49.3   48.0   46.9   45.7   44.3   43.1
   41.8   40.3   38.8   37.5   36.0   34.3   32.3   29.8   27.5
```

REPLICATE 2

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME     =      2001  CC     AERATION TIME =   2.41   MIN
FOAM DENSITY =         .0249 GM/CC  EXPERIMENT TIME = 25.9   MIN

   55.0   54.3   53.8   53.1   52.5   51.8   51.1   50.5   49.8   49.1
   48.4   47.8   46.9   46.1   45.3   44.3   43.4   42.4   41.4   40.3
   39.1   37.9   36.4   35.0   33.2   31.1   27.6
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   1.53 L/MIN
FOAM VOLUME     =      2015  CC     AERATION TIME =   1.20   MIN
FOAM DENSITY =         .0318 GM/CC  EXPERIMENT TIME = 17.8   MIN

   55.0   53.3   52.0   51.1   50.2   49.5   48.2   47.7   46.5   45.5
   44.3   42.8   41.5   39.8   38.2   36.1   34.0   31.1   27.6
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   2.63 L/MIN
FOAM VOLUME     =      2022  CC     AERATION TIME =    .68   MIN
FOAM DENSITY =         .0246 GM/CC  EXPERIMENT TIME = 12.9   MIN

   55.0   53.1   50.1   49.3   48.3   47.2   45.3   43.8   42.0   40.1
   37.0   33.8   31.0   27.3
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME     =      2044  CC     AERATION TIME =   2.33   MIN
FOAM DENSITY =         .0522 GM/CC  EXPERIMENT TIME = 28.5   MIN
```

```
55.0   53.3   52.3   51.3   50.5   49.8   49.1   48.4   47.7   47.1
46.5   45.9   45.4   44.7   44.1   43.5   42.9   42.3   41.6   40.8
40.1   39.3   38.5   37.5   36.5   35.5   34.2   32.6   30.3   27.7
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE  =   1.53 L/MIN
FOAM VOLUME     =     2036  CC     AERATION TIME  =   1.12   MIN
FOAM DENSITY    =    .0454 GM/CC   EXPERIMENT TIME = 18.8   MIN
```

```
55.0   53.3   52.1   51.0   49.8   48.5   47.5   46.6   45.6   44.6
43.6   42.5   41.4   40.3   39.0   37.5   35.8   33.8   31.2   27.7
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE  =   2.65 L/MIN
FOAM VOLUME     =     2022  CC     AERATION TIME  =    .66   MIN
FOAM DENSITY    =    .0422 GM/CC   EXPERIMENT TIME = 13.8   MIN
```

```
55.0   53.7   52.5   51.3   50.0   48.7   46.8   44.8   43.0   41.0
38.3   36.0   33.5   31.0   27.8
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =    .78 L/MIN
FOAM VOLUME     =     2051  CC     AERATION TIME  =   2.43   MIN
FOAM DENSITY    =    .0520 GM/CC   EXPERIMENT TIME = 28.1   MIN
```

```
55.0   53.5   52.8   52.2   51.5   50.9   50.2   49.8   49.0   48.3
47.7   47.1   46.5   45.9   45.2   44.5   43.8   43.1   42.4   41.6
40.8   39.9   38.9   38.0   37.0   35.5   34.0   32.3   29.0   27.7
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =   1.54 L/MIN
FOAM VOLUME     =     2065  CC     AERATION TIME  =   1.13   MIN
FOAM DENSITY    =    .0551 GM/CC   EXPERIMENT TIME = 19.3   MIN
```

```
55.0   53.2   52.2   51.1   50.1   49.0   48.0   47.0   46.0   44.8
43.8   42.6   41.6   40.5   39.3   38.0   36.5   34.8   32.7   29.4
27.6
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =   2.65 L/MIN
FOAM VOLUME     =     2065  CC     AERATION TIME  =    .67   MIN
FOAM DENSITY    =    .0482 GM/CC   EXPERIMENT TIME = 13.6   MIN
```

```
55.0   53.0   51.1   49.4   48.1   46.7   45.2   43.4   41.5   39.4
37.3   35.0   32.3   29.9   27.4
```

```
ABS CONCENTRATION =  80 PPM        AERATION RATE  =    .78 L/MIN
FOAM VOLUME     =     2093  CC     AERATION TIME  =   2.30   MIN
```

FOAM DENSITY =   .0680 GM/CC   EXPERIMENT TIME = 30.2 MIN

```
55.0  53.7  52.8  52.1  51.5  50.8  50.0  49.4  48.8  48.2
47.5  47.0  46.4  45.8  45.3  44.6  44.0  43.4  42.8  42.1
41.3  40.8  39.8  39.0  38.2  37.3  36.1  35.1  33.6  32.0
29.0  27.6
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 1.52 L/MIN
FOAM VOLUME   =   2108 CC   AERATION TIME = 1.12   MIN
FOAM DENSITY =   .0641 GM/CC   EXPERIMENT TIME = 19.4 MIN

```
55.0  53.0  51.6  50.5  49.5  48.5  47.4  46.4  45.5  44.5
43.5  42.5  41.5  40.4  39.2  37.8  36.3  34.7  32.7  29.7
27.3
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.65 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0551 GM/CC   EXPERIMENT TIME = 14.0 MIN

```
55.0  52.8  51.3  49.8  48.3  46.5  44.8  43.0  41.2  39.2
37.4  35.4  33.3  31.0  27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2093 CC   AERATION TIME = 2.33   MIN
FOAM DENSITY =   .0748 GM/CC   EXPERIMENT TIME = 30.2 MIN

```
55.0  54.2  53.5  52.8  52.2  51.5  51.0  50.2  49.8  49.0
48.4  47.8  47.2  46.8  46.1  45.5  44.9  44.2  43.5  43.0
42.2  41.5  40.6  39.8  38.8  37.8  36.6  35.4  34.0  32.2
29.0  27.8
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.54 L/MIN
FOAM VOLUME   =   2100 CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0711 GM/CC   EXPERIMENT TIME = 20.9 MIN

```
55.0  53.3  52.3  51.3  50.4  49.4  48.5  47.4  46.6  45.7
44.8  43.8  42.8  41.6  40.6  39.5  38.3  36.9  35.4  33.8
31.5  27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.63 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME =   .65   MIN
FOAM DENSITY =   .0616 GM/CC   EXPERIMENT TIME = 14.9 MIN

```
55.0  53.0  51.2  49.5  48.0  46.7  45.3  43.8  42.3  40.7
```

39.1   37.3   35.5   33.4   31.0   27.6

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2115   CC   AERATION TIME = 2.27   MIN
FOAM DENSITY =   .0808 GM/CC   EXPERIMENT TIME = 31.2   MIN

    55.0   53.6   53.0   52.3   51.7   51.2   50.5   50.0   49.4   48.8
    48.4   47.6   47.1   46.6   46.1   45.5   45.0   44.5   43.8   43.2
    42.6   42.0   41.3   40.6   39.8   38.9   38.1   37.1   36.0   34.8
    33.3   31.2   27.7

ABS CONCENTRATION = 120 PPM   AERATION RATE =   1.52 L/MIN
FOAM VOLUME   =   2136   CC   AERATION TIME =   1.22   MIN
FOAM DENSITY =   .0833 GM/CC   EXPERIMENT TIME = 22.8   MIN

    55.0   53.3   52.3   51.3   50.2   49.3   48.3   47.5   46.5   45.6
    44.8   44.0   43.2   42.3   41.4   40.4   39.4   38.4   37.2   36.0
    34.5   32.9   30.4   27.5

ABS CONCENTRATION = 120 PPM   AERATION RATE =   2.62 L/MIN
FOAM VOLUME   =   2093   CC   AERATION TIME =   .65   MIN
FOAM DENSITY =   .0646 GM/CC   EXPERIMENT TIME = 15.8   MIN

    55.0   53.3   51.8   50.4   49.0   47.5   46.1   44.8   43.2   41.7
    40.2   38.5   36.8   35.0   33.0   30.5   27.5

REPLICATE   3

ABS CONCENTRATION = 20 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2015   CC   AERATION TIME = 2.43   MIN
FOAM DENSITY =   .0247 GM/CC   EXPERIMENT TIME = 23.1   MIN

    55.0   54.0   53.1   52.4   51.8   51.1   50.3   49.5   48.8   48.0
    47.0   46.1   45.2   44.2   43.2   42.1   41.0   39.8   38.5   37.0
    35.5   33.8   31.6   28.4   27.4

ABS CONCENTRATION = 20 PPM   AERATION RATE =   1.54 L/MIN
FOAM VOLUME   =   2008   CC   AERATION TIME = 1.25   MIN
FOAM DENSITY =   .0283 GM/CC   EXPERIMENT TIME = 18.1   MIN

    55.0   53.2   52.2   51.0   49.8   48.9   48.0   47.2   46.4   45.3
    44.2   42.9   41.5   40.0   38.3   36.3   34.4   31.9   28.5   27.6

```
ABS CONCENTRATION =  20 PPM       AERATION RATE =  2.65 L/MIN
FOAM VOLUME    =     2008  CC      AERATION TIME =   .70   MIN
FOAM DENSITY =       .0248 GM/CC   EXPERIMENT TIME = 11.4  MIN

   55.0  52.3  49.2  47.3  45.8  44.3  42.4  40.3  38.2  35.2
   32.1  29.5  27.5


ABS CONCENTRATION =  40 PPM       AERATION RATE =   .78 L/MIN
FOAM VOLUME    =     2044  CC      AERATION TIME =  2.40   MIN
FOAM DENSITY =       .0418 GM/CC   EXPERIMENT TIME = 26.9  MIN

   55.0  53.4  52.7  51.8  50.9  50.1  49.4  48.4  47.6  46.9
   46.3  45.7  45.1  44.5  43.9  43.2  42.4  41.7  40.8  40.0
   39.1  38.1  37.1  35.8  34.4  33.0  30.8  27.5


ABS CONCENTRATION =  40 PPM       AERATION RATE =  1.54 L/MIN
FOAM VOLUME    =     2036  CC      AERATION TIME =  1.19   MIN
FOAM DENSITY =       .0489 GM/CC   EXPERIMENT TIME = 19.3  MIN

   55.0  53.4  52.3  51.3  50.2  48.9  47.8  46.9  46.1  45.2
   41.2  43.3  42.2  41.1  39.9  38.6  37.2  35.3  33.0  29.6
   27.8


ABS CONCENTRATION =  40 PPM       AERATION RATE =  2.65 L/MIN
FOAM VOLUME    =     2036  CC      AERATION TIME =   .66   MIN
FOAM DENSITY =       .0419 GM/CC   EXPERIMENT TIME = 11.2  MIN

   55.0  52.3  49.3  46.5  44.3  42.5  40.8  38.5  35.6  33.3
   31.0  28.7  27.6


ABS CONCENTRATION =  60 PPM       AERATION RATE =   .78 L/MIN
FOAM VOLUME    =     2072  CC      AERATION TIME =  2.36   MIN
FOAM DENSITY =       .0549 GM/CC   EXPERIMENT TIME = 28.1  MIN

   55.0  53.6  52.8  51.8  51.0  50.2  49.7  49.0  48.3  47.7
   47.1  46.6  46.0  45.3  44.8  44.0  43.3  42.7  42.0  41.2
   40.4  39.5  38.5  37.7  36.5  35.2  33.8  32.0  28.7  27.5


ABS CONCENTRATION =  60 PPM       AERATION RATE =  1.54 L/MIN
FOAM VOLUME    =     2072  CC      AERATION TIME =  1.21   MIN
FOAM DENSITY =       .0584 GM/CC   EXPERIMENT TIME = 19.9  MIN

   55.0  53.5  52.5  51.5  50.5  49.4  48.4  47.4  46.3  45.3
   44.3  43.3  42.2  41.0  39.8  38.6  37.2  35.3  33.3  30.2
```

27.6

```
ABS CONCENTRATION =   60 PPM        AERATION RATE =   2.65 L/MIN
FOAM VOLUME    =      2044  CC       AERATION TIME =    .67   MIN
FOAM DENSITY =        .0418 GM/CC    EXPERIMENT TIME = 12.6   MIN

   55.0   52.8   51.0   49.2   47.4   45.5   43.3   40.8   39.0   37.2
   35.2   32.8   30.1   27.5


ABS CONCENTRATION =   80 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME    =      2093  CC       AERATION TIME =  2.33   MIN
FOAM DENSITY =        .0680 GM/CC    EXPERIMENT TIME = 30.0   MIN

   55.0   53.5   52.6   51.8   51.2   50.6   49.9   49.3   48.7   48.1
   47.5   46.9   46.3   45.8   45.2   44.7   44.0   43.4   42.8   42.1
   41.4   40.8   40.0   39.1   38.2   37.2   36.2   34.9   33.5   31.6
   27.6


ABS CONCENTRATION =   80 PPM        AERATION RATE =   1.54 L/MIN
FOAM VOLUME    =      2086  CC       AERATION TIME =  1.19   MIN
FOAM DENSITY =        .0614 GM/CC    EXPERIMENT TIME = 20.8   MIN

   55.0   53.7   52.6   51.7   50.7   49.8   48.7   48.0   47.0   46.1
   45.3   44.3   43.4   42.4   41.3   40.1   38.7   37.3   35.5   33.6
   31.1   27.5


ABS CONCENTRATION =   80 PPM        AERATION RATE =   2.62 L/MIN
FOAM VOLUME    =      2058  CC       AERATION TIME =    .65   MIN
FOAM DENSITY =        .0519 GM/CC    EXPERIMENT TIME = 13.3   MIN

   55.0   53.0   50.5   49.0   47.4   45.8   44.1   42.1   40.2   38.3
   36.3   34.3   32.0   29.5   27.6


ABS CONCENTRATION =  100 PPM        AERATION RATE =    .78 L/MIN
FOAM VOLUME    =      2065  CC       AERATION TIME =  2.28   MIN
FOAM DENSITY =        .0724 GM/CC    EXPERIMENT TIME = 29.5   MIN

   55.0   53.5   52.8   52.0   51.2   50.5   49.8   49.2   48.5   47.8
   47.2   46.7   46.1   45.5   45.0   44.4   43.7   43.5   42.5   41.8
   41.1   40.4   39.1   38.8   37.9   37.0   35.8   34.5   33.0   30.6
   28.1
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.54 L/MIN
FOAM VOLUME   =   2100   CC   AERATION TIME = 1.18   MIN
FOAM DENSITY =   .0745 GM/CC   EXPERIMENT TIME = 21.9 MIN

```
 55.0   53.5   52.3   51.1   50.0   48.9   47.9   46.8   45.8   45.0
 44.2   43.5   42.7   41.8   40.9   40.0   38.9   37.8   36.4   35.0
 33.2   31.1   27.7
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.65 L/MIN
FOAM VOLUME   =   2079   CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0582 GM/CC   EXPERIMENT TIME = 14.4 MIN

```
 55.0   52.9   51.1   49.4   47.9   46.2   44.7   42.8   41.1   39.3
 37.5   35.5   33.7   31.7   29.5   27.5
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   2136   CC   AERATION TIME = 2.29   MIN
FOAM DENSITY =   .0833 GM/CC   EXPERIMENT TIME = 30.4 MIN

```
 55.0   53.8   52.8   52.0   51.4   50.8   50.0   49.4   48.8   48.0
 47.5   47.0   46.2   45.6   45.0   44.4   43.8   43.3   42.6   42.0
 41.5   40.7   40.0   39.2   38.3   37.5   36.5   35.3   34.0   32.3
 29.8   27.5
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.54 L/MIN
FOAM VOLUME   =   2136   CC   AERATION TIME = 1.12   MIN
FOAM DENSITY =   .0800 GM/CC   EXPERIMENT TIME = 22.1 MIN

```
 55.0   53.3   52.0   50.9   49.8   48.6   47.5   46.4   45.6   44.8
 44.0   43.2   42.3   41.5   40.6   39.6   38.5   37.5   36.2   34.8
 33.1   31.1   28.5   27.4
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 2.65 L/MIN
FOAM VOLUME   =   2079   CC   AERATION TIME =   .70   MIN
FOAM DENSITY =   .0513 GM/CC   EXPERIMENT TIME = 15.0 MIN

```
 55.0   53.3   52.0   50.5   49.0   47.2   45.5   44.0   42.3   40.6
 38.8   36.9   35.0   33.0   31.0   27.3
```

PHASE 2 WEIGHTED DISC EXPERIMENTAL DATA (27 C)

REPLICATE   1

ABS CONCENTRATION = 20 PPM   AERATION RATE =   .76 L/MIN
FOAM VOLUME   =   2001 CC   AERATION TIME = 2.37   MIN
FOAM DENSITY =   .0249 GM/CC EXPERIMENT TIME = 22.3 MIN

```
55.0  53.4  52.6  51.9  51.1  50.3  49.5  48.8  48.0  47.2
46.4  45.5  44.6  43.7  42.6  41.5  40.3  39.0  37.7  36.2
34.5  32.7  30.0  27.6
```

ABS CONCENTRATION = 20 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME = 1.21   MIN
FOAM DENSITY =   .0282 GM/CC EXPERIMENT TIME = 13.2 MIN

```
55.0  52.0  50.3  49.2  48.0  46.9  45.4  43.6  42.1  40.5
38.7  36.3  33.5  29.4  27.5
```

ABS CONCENTRATION = 20 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME =   .72   MIN
FOAM DENSITY =   .0282 GM/CC EXPERIMENT TIME = 9.5 MIN

```
55.0  50.9  47.7  46.2  43.9  41.5  39.6  36.8  34.0  30.1
27.5
```

ABS CONCENTRATION = 40 PPM   AERATION RATE =   .76 L/MIN
FOAM VOLUME   =   2051 CC   AERATION TIME = 2.38   MIN
FOAM DENSITY =   .0451 GM/CC EXPERIMENT TIME = 24.4 MIN

```
55.0  53.5  52.6  51.8  51.1  50.2  49.6  48.8  48.0  47.3
46.6  45.9  45.2  44.4  43.6  42.7  41.8  40.9  39.9  38.8
39.7  36.3  34.8  33.0  30.3  27.5
```

ABS CONCENTRATION = 40 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2044 CC   AERATION TIME = 1.17   MIN
FOAM DENSITY =   .0452 GM/CC EXPERIMENT TIME = 15.3 MIN

```
55.0  53.0  51.3  49.9  48.5  47.3  46.0  44.8  43.5  42.2
40.9  39.4  37.8  36.0  33.3  29.5  27.6
```

ABS CONCENTRATION = 40 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2022 CC   AERATION TIME =   .66   MIN
FOAM DENSITY =   .0352 GM/CC EXPERIMENT TIME = 9.8 MIN

```
55.0   51.9   49.5   47.0   45.2   43.1   40.6   37.6   34.6   31.3
27.6
```

ABS CONCENTRATION = 60 PPM   AERATION RATE =   .76 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME = 2.21   MIN
FOAM DENSITY =   .0513 GM/CC   EXPERIMENT TIME = 25.4 MIN

```
55.0   53.3   52.3   51.5   50.7   49.9   49.2   48.4   47.7   47.0
46.3   45.6   44.9   44.1   43.3   42.6   41.8   41.0   40.0   39.1
38.2   37.0   35.8   34.3   32.7   30.0   27.3
```

ABS CONCENTRATION = 60 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0584 GM/CC   EXPERIMENT TIME = 16.0 MIN

```
55.0   53.0   51.2   49.8   48.5   47.3   46.1   45.0   43.8   42.3
41.1   39.7   38.3   36.6   34.7   32.3   27.6
```

ABS CONCENTRATION = 60 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2051 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0486 GM/CC   EXPERIMENT TIME = 11.2 MIN

```
55.0   52.6   50.8   48.7   46.9   44.8   42.5   40.3   38.0   35.3
32.5   29.0   27.6
```

ABS CONCENTRATION = 80 PPM   AERATION RATE =   .76 L/MIN
FOAM VOLUME   =   2115 CC   AERATION TIME = 2.35   MIN
FOAM DENSITY =   .0774 GM/CC   EXPERIMENT TIME = 25.9 MIN

```
55.0   53.3   52.5   51.8   50.9   50.1   49.4   48.6   48.0   47.2
46.5   45.8   45.0   44.4   43.6   43.0   42.2   41.4   40.5   39.8
38.8   37.7   36.5   35.3   33.8   31.8   27.6
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2086 CC   AERATION TIME = 1.15   MIN
FOAM DENSITY =   .0614 GM/CC   EXPERIMENT TIME = 16.1 MIN

```
55.0   52.8   51.5   50.2   48.9   47.7   46.3   45.1   43.8   42.5
41.2   39.8   38.5   36.8   34.9   32.5   28.7   27.5
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME =   .66   MIN

FOAM DENSITY = .0551 GM/CC   EXPERIMENT TIME = 11.6 MIN

```
55.0  52.1  50.4  48.6  46.3  44.8  43.0  40.8  38.5  36.2
33.6  30.6  27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = .77 L/MIN
FOAM VOLUME = 2136 CC   AERATION TIME = 2.30 MIN
FOAM DENSITY = .0833 GM/CC   EXPERIMENT TIME = 26.1 MIN

```
55.0  53.2  52.3  51.5  50.7  49.8  49.0  48.3  47.7  46.8
46.2  45.5  44.8  44.1  43.4  42.7  42.0  41.2  40.4  39.6
38.7  37.7  36.6  35.4  34.0  32.2  28.8  27.5
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME = 2072 CC   AERATION TIME = 1.12 MIN
FOAM DENSITY = .0652 GM/CC   EXPERIMENT TIME = 16.3 MIN

```
55.0  52.8  51.3  49.3  48.3  47.2  46.0  44.8  43.6  42.5
41.3  40.0  38.6  37.0  35.3  33.2  29.8  27.8
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME = 2072 CC   AERATION TIME = .66 MIN
FOAM DENSITY = .0584 GM/CC   EXPERIMENT TIME = 11.7 MIN

```
55.0  52.8  51.0  49.0  46.8  44.8  42.6  40.5  38.4  36.0
33.5  30.8  27.6
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = .76 L/MIN
FOAM VOLUME = 2143 CC   AERATION TIME = 2.17 MIN
FOAM DENSITY = .0830 GM/CC   EXPERIMENT TIME = 25.8 MIN

```
55.6  53.3  52.1  50.9  50.1  49.3  48.5  47.7  47.0  46.3
45.6  44.9  44.2  43.5  42.8  42.1  41.3  40.6  39.8  39.0
38.0  37.0  36.0  34.7  33.3  31.3  27.4
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME = 2100 CC   AERATION TIME = 1.13 MIN
FOAM DENSITY = .0779 GM/CC   EXPERIMENT TIME = 17.1 MIN

```
55.0  53.3  52.0  50.7  49.4  48.1  47.0  45.9  44.7  43.4
42.1  40.8  39.5  38.1  36.4  34.5  32.2  29.8  27.8
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 2.59 L/MIN

```
FOAM VOLUME    =       2079  CC        AERATION TIME =      .63    MIN
FOAM DENSITY   =      .0616 GM/CC       EXPERIMENT TIME = 11.8    MIN


    55.0   52.4   49.8   47.7   45.8   43.8   41.8   39.8   37.7   35.5
    33.0   30.5   27.6
```

REPLICATE 2

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =     .77 L/MIN
FOAM VOLUME    =      2001  CC        AERATION TIME = 2.50    MIN
FOAM DENSITY   =      .0249 GM/CC       EXPERIMENT TIME = 23.0    MIN


    55.0   53.9   53.0   52.2   51.5   50.7   50.0   49.2   48.3   47.7
    46.8   46.0   45.1   44.2   43.2   42.1   41.0   39.7   38.5   37.2
    35.6   34.0   31.8   27.6
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =  1.51 L/MIN
FOAM VOLUME    =      1994  CC        AERATION TIME = 1.20    MIN
FOAM DENSITY   =      .0214 GM/CC       EXPERIMENT TIME = 13.1    MIN


    55.0   52.5   51.2   49.9   48.6   47.1   45.8   44.0   42.2   40.2
    38.0   35.7   32.8   28.5   27.6
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =  2.60 L/MIN
FOAM VOLUME    =      2015  CC        AERATION TIME =     .71    MIN
FOAM DENSITY   =      .0282 GM/CC       EXPERIMENT TIME =  9.3    MIN


    55.0   51.5   49.8   48.1   46.0   43.6   40.5   36.8   33.2   29.4
    27.5
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =     .77 L/MIN
FOAM VOLUME    =      2036  CC        AERATION TIME = 2.43    MIN
FOAM DENSITY   =      .0419 GM/CC       EXPERIMENT TIME = 24.6    MIN


    55.0   53.9   53.0   52.2   51.5   50.8   49.9   49.2   48.4   47.7
    47.0   46.3   45.5   44.7   44.0   43.1   42.2   41.2   40.2   39.1
    38.0   36.6   35.3   33.5   31.3   27.6
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =  1.51 L/MIN
FOAM VOLUME    =      2022  CC        AERATION TIME = 1.16    MIN
FOAM DENSITY   =      .0422 GM/CC       EXPERIMENT TIME = 14.8    MIN


    55.0   53.1   52.0   50.9   49.5   48.0   46.6   45.3   43.8   42.5
    41.0   39.4   37.6   35.3   32.3   27.8
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =   2.60 L/MIN
FOAM VOLUME    =     2036  CC       AERATION TIME =    .66   MIN
FOAM DENSITY =      .0384 GM/CC     EXPERIMENT TIME = 10.5   MIN

    55.0  51.8  49.8  48.0  46.2  44.3  41.8  39.1  36.0  33.3
    30.0  27.5


ABS CONCENTRATION =  60 PPM        AERATION RATE =    .77 L/MIN
FOAM VOLUME    =     2044  CC       AERATION TIME =  2.28   MIN
FOAM DENSITY =      .0418 GM/CC     EXPERIMENT TIME = 24.7   MIN

    55.0  53.5  52.5  51.8  50.8  50.1  49.4  48.5  47.7  47.1
    46.4  45.7  45.0  44.2  43.4  42.6  41.8  40.8  39.9  38.9
    37.8  36.6  35.2  33.6  31.4  27.5


ABS CONCENTRATION =  60 PPM        AERATION RATE =   1.51 L/MIN
FOAM VOLUME    =     2065  CC       AERATION TIME =  1.18   MIN
FOAM DENSITY =      .0517 GM/CC     EXPERIMENT TIME = 15.5   MIN

    55.0  53.1  51.5  50.0  48.8  47.5  46.2  45.0  43.7  42.5
    41.2  39.7  38.0  36.0  33.8  30.6  27.5


ABS CONCENTRATION =  60 PPM        AERATION RATE =   2.60 L/MIN
FOAM VOLUME    =     2051  CC       AERATION TIME =    .66   MIN
FOAM DENSITY =      .0520 GM/CC     EXPERIMENT TIME = 10.9   MIN

    55.0  52.0  50.0  47.7  45.7  43.5  41.3  38.8  36.3  34.0
    31.3  27.7


ABS CONCENTRATION =  80 PPM        AERATION RATE =    .77 L/MIN
FOAM VOLUME    =     2086  CC       AERATION TIME =  2.30   MIN
FOAM DENSITY =      .0580 GM/CC     EXPERIMENT TIME = 25.2   MIN

    55.0  53.1  52.2  51.4  50.5  49.8  49.0  48.1  47.5  46.8
    46.1  45.4  44.7  43.9  43.2  42.4  41.5  40.7  39.8  38.8
    37.9  36.8  35.5  34.0  32.3  29.0  27.4


ABS CONCENTRATION =  80 PPM        AERATION RATE =   1.51 L/MIN
FOAM VOLUME    =     2079  CC       AERATION TIME =  1.17   MIN
FOAM DENSITY =      .0616 GM/CC     EXPERIMENT TIME = 17.1   MIN

    55.0  53.4  52.1  50.8  49.5  48.3  47.3  46.2  45.0  43.8
```

42.6   41.5   40.0   38.6   37.0   35.0   32.6   29.0   27.6

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0515 GM/CC   EXPERIMENT TIME = 11.9 MIN

   55.0   52.5   50.8   49.1   47.3   45.4   43.4   41.0   38.6   36.3
   34.0   31.2   27.4

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .76 L/MIN
FOAM VOLUME   =   2115 CC   AERATION TIME = 2.34   MIN
FOAM DENSITY =   .0774 GM/CC   EXPERIMENT TIME = 24.1 MIN

   55.0   53.3   52.3   51.5   50.6   49.6   48.8   48.1   47.2   46.5
   45.7   45.0   44.2   43.4   42.7   41.8   41.0   40.1   39.2   38.1
   36.9   35.7   34.3   32.4   29.2   27.6

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2100 CC   AERATION TIME = 1.20   MIN
FOAM DENSITY =   .0745 GM/CC   EXPERIMENT TIME = 16.0 MIN

   55.0   52.7   51.4   50.0   48.7   47.3   46.1   44.8   43.5   42.2
   40.8   39.5   38.0   36.4   34.3   31.8   27.7

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0620 GM/CC   EXPERIMENT TIME = 12.0 MIN

   55.0   52.2   50.3   48.5   46.8   44.8   42.8   41.0   38.9   36.5
   34.4   31.8   27.8

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .77 L/MIN
FOAM VOLUME   =   2143 CC   AERATION TIME = 2.36   MIN
FOAM DENSITY =   .0830 GM/CC   EXPERIMENT TIME = 26.6 MIN

   55.0   53.5   52.5   51.7   50.8   49.8   49.1   48.2   47.5   46.8
   46.2   45.5   44.8   44.1   43.5   42.8   42.1   41.3   40.6   39.8
   38.9   38.0   37.0   35.8   34.6   33.0   30.8   27.4

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2100 CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0745 GM/CC   EXPERIMENT TIME = 16.3 MIN

```
55.0  52.6  50.8  49.4  48.0  46.9  45.7  44.5  43.3  42.0
40.8  39.4  38.1  36.5  34.6  32.5  29.5  27.7
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   2108 CC   AERATION TIME =   .67 MIN
FOAM DENSITY   =   .0709 GM/CC EXPERIMENT TIME = 13.7 MIN

```
55.0  52.7  51.1  49.5  47.9  46.4  44.8  43.0  41.3  39.4
37.5  35.4  33.1  30.3  27.5
```

REPLICATE   3

ABS CONCENTRATION = 20 PPM   AERATION RATE =   .77 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME = 2.45 MIN
FOAM DENSITY   =   .0318 GM/CC EXPERIMENT TIME = 24.3 MIN

```
55.0  53.8  53.0  52.3  51.7  51.0  50.2  49.6  48.8  47.8
47.1  46.3  45.6  44.8  43.9  43.0  42.0  40.9  39.8  38.6
37.3  36.0  34.4  32.6  30.0  27.6
```

ABS CONCENTRATION = 20 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME = 1.20 MIN
FOAM DENSITY   =   .0282 GM/CC EXPERIMENT TIME = 13.1 MIN

```
55.0  53.0  51.6  50.0  48.5  47.0  45.5  43.8  42.0  39.8
37.8  35.2  32.5  28.4  27.5
```

ABS CONCENTRATION = 20 PPM   AERATION RATE = 2.58 L/MIN
FOAM VOLUME   =   2022 CC   AERATION TIME =   .70 MIN
FOAM DENSITY   =   .0246 GM/CC EXPERIMENT TIME = 9.7 MIN

```
55.0  51.8  48.8  46.0  43.4  41.0  38.5  35.8  33.2  30.5
27.3
```

ABS CONCENTRATION = 40 PPM   AERATION RATE =   .77 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME = 2.37 MIN
FOAM DENSITY   =   .0459 GM/CC EXPERIMENT TIME = 25.4 MIN

```
55.0  53.8  52.8  52.0  51.1  50.4  49.6  49.0  48.3  47.7
47.0  46.3  45.7  45.0  44.2  43.5  42.7  41.8  41.0  40.0
39.0  38.0  36.8  35.5  34.0  32.0  28.0
```

ABS CONCENTRATION = 40 PPM   AERATION RATE = 1.51 L/MIN

```
FOAM VOLUME    =       2036  CC        AERATION TIME = 1.14   MIN
FOAM DENSITY   =       .0419 GM/CC     EXPERIMENT TIME = 15.0 MIN

   55.0  53.3  52.2  51.0  49.8  48.3  47.0  45.8  44.2  42.9
   41.3  39.6  37.9  35.8  33.0  27.6


ABS CONCENTRATION = 40 PPM        AERATION RATE = 2.59 L/MIN
FOAM VOLUME    =       2044  CC        AERATION TIME = .68   MIN
FOAM DENSITY   =       .0348 GM/CC     EXPERIMENT TIME = 10.4 MIN

   55.0  53.2  51.4  49.2  46.9  44.8  42.4  40.0  37.1  33.6
   29.3  27.3


ABS CONCENTRATION = 60 PPM        AERATION RATE = .76 L/MIN
FOAM VOLUME    =       2093  CC        AERATION TIME = 2.25  MIN
FOAM DENSITY   =       .0578 GM/CC     EXPERIMENT TIME = 26.2 MIN

   55.0  53.6  52.8  52.0  51.2  50.5  49.8  49.0  48.3  47.7
   47.0  46.3  45.6  45.0  44.2  43.4  42.6  41.8  41.0  40.1
   39.1  38.1  36.9  35.6  34.2  32.3  29.3  27.3


ABS CONCENTRATION = 60 PPM        AERATION RATE = 1.52 L/MIN
FOAM VOLUME    =       2072  CC        AERATION TIME = 1.13  MIN
FOAM DENSITY   =       .0549 GM/CC     EXPERIMENT TIME = 16.4 MIN

   55.0  52.8  51.6  50.3  49.1  47.8  46.6  45.4  44.3  43.1
   41.8  40.5  39.1  37.6  35.7  33.4  30.0  27.5


ABS CONCENTRATION = 60 PPM        AERATION RATE = 2.59 L/MIN
FOAM VOLUME    =       2044  CC        AERATION TIME = .67   MIN
FOAM DENSITY   =       .0452 GM/CC     EXPERIMENT TIME = 10.2 MIN

   55.0  52.9  50.8  48.8  46.4  43.6  40.4  37.8  34.8  32.8
   29.0  27.6


ABS CONCENTRATION = 80 PPM        AERATION RATE = .76 L/MIN
FOAM VOLUME    =       2072  CC        AERATION TIME = 2.32  MIN
FOAM DENSITY   =       .0584 GM/CC     EXPERIMENT TIME = 25.5 MIN

   55.0  53.5  52.5  51.7  51.0  50.2  49.4  48.6  48.0  47.3
   46.6  45.9  45.2  44.5  43.8  43.0  42.1  41.3  40.5  39.5
   38.5  37.3  36.1  34.8  33.1  30.5  27.6
```

```
ABS CONCENTRATION =  80 PPM          AERATION RATE =   1.51 L/MIN
FOAM VOLUME    =      2072  CC        AERATION TIME =   1.14   MIN
FOAM DENSITY =       .0652 GM/CC      EXPERIMENT TIME = 17.0   MIN

    55.0  53.2  51.8  50.5  49.3  48.1  47.1  46.0  44.9  43.7
    42.5  41.3  40.0  38.5  36.7  34.7  32.3  27.8


ABS CONCENTRATION =  80 PPM          AERATION RATE =   2.59 L/MIN
FOAM VOLUME    =      2058  CC        AERATION TIME =    .66   MIN
FOAM DENSITY =       .0415 GM/CC      EXPERIMENT TIME = 10.6   MIN

    55.0  52.5  50.1  47.5  45.1  42.8  40.0  37.5  35.2  33.0
    30.3  27.3


ABS CONCENTRATION = 100 PPM          AERATION RATE =    .76 L/MIN
FOAM VOLUME    =      2115  CC        AERATION TIME =  2.31   MIN
FOAM DENSITY =       .0740 GM/CC      EXPERIMENT TIME = 27.6   MIN

    55.0  53.3  52.5  51.7  51.0  50.2  49.6  48.8  48.1  47.5
    46.8  46.2  45.5  45.0  44.2  43.5  42.8  42.1  41.3  40.5
    39.6  38.7  37.7  36.7  35.4  34.0  32.3  29.5  27.5


ABS CONCENTRATION = 100 PPM          AERATION RATE =   1.51 L/MIN
FOAM VOLUME    =      2086  CC        AERATION TIME =   1.11   MIN
FOAM DENSITY =       .0716 GM/CC      EXPERIMENT TIME = 17.9   MIN

    55.0  53.3  51.9  50.8  49.3  48.2  47.2  46.2  45.1  44.0
    43.0  41.8  40.6  39.3  37.8  36.1  34.2  31.7  27.8


ABS CONCENTRATION = 100 PPM          AERATION RATE =   2.59 L/MIN
FOAM VOLUME    =      2072  CC        AERATION TIME =    .68   MIN
FOAM DENSITY =       .0549 GM/CC      EXPERIMENT TIME = 11.4   MIN

    55.0  52.4  50.2  48.0  46.0  43.8  41.5  39.2  37.0  34.6
    32.3  29.7  27.5


ABS CONCENTRATION = 120 PPM          AERATION RATE =    .76 L/MIN
FOAM VOLUME    =      2165  CC        AERATION TIME =  2.38   MIN
FOAM DENSITY =       .0888 GM/CC      EXPERIMENT TIME = 29.3   MIN

    55.0  53.7  52.8  52.1  51.3  54.6  50.0  49.3  48.6  48.0
    47.3  46.6  46.0  45.4  44.7  44.1  43.4  42.7  42.1  41.3
    40.7  39.9  39.1  38.2  37.3  36.3  35.1  33.8  32.1  29.2
    27.3
```

```
ABS CONCENTRATION = 120 PPM      AERATION RATE =   1.51 L/MIN
FOAM VOLUME   =       2079  CC    AERATION TIME =   1.15   MIN
FOAM DENSITY =        .0753 GM/CC  EXPERIMENT TIME = 16.5   MIN

   55.0   53.3   51.8   50.6   49.2   47.9   46.6   45.3   44.1   42.9
   41.5   40.2   38.8   37.2   35.4   33.3   30.5   28.0


ABS CONCENTRATION = 120 PPM      AERATION RATE =   2.59 L/MIN
FOAM VOLUME   =       2051  CC    AERATION TIME =    .67   MIN
FOAM DENSITY =        .0486 GM/CC  EXPERIMENT TIME = 12.3   MIN

   55.0   53.1   51.8   50.5   49.0   47.5   46.1   44.2   41.9   39.5
   36.7   32.9   29.2   27.6
```

PHASE 3 WEIGHTED DISC EXPERIMENTAL DATA (20 C)

REPLICATE   1

ABS CONCENTRATION = 20 PPM   AERATION RATE =   .74 L/MIN
FOAM VOLUME   =   1958 CC   AERATION TIME = 2.33   MIN
FOAM DENSITY =   .0145 GM/CC   EXPERIMENT TIME = 13.6 MIN

   55.0 52.7 51.8 50.9 49.7 48.5 47.2 46.0 44.7 43.1
   41.1 38.8 36.2 32.4 27.9

ABS CONCENTRATION = 20 PPM   AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =   1994 CC   AERATION TIME = 1.21   MIN
FOAM DENSITY =   .0178 GM/CC   EXPERIMENT TIME = 8.9   MIN

   55.0 51.4 49.5 47.7 45.9 43.6 41.2 38.4 34.8 27.5

ABS CONCENTRATION = 20 PPM   AERATION RATE = 2.49 L/MIN
FOAM VOLUME   =   1994 CC   AERATION TIME =   .66   MIN
FOAM DENSITY =   .0178 GM/CC   EXPERIMENT TIME = 5.5   MIN

   55.0 50.2 47.1 43.0 39.1 33.1 27.5

ABS CONCENTRATION = 40 PPM   AERATION RATE =   .74 L/MIN
FOAM VOLUME   =   2001 CC   AERATION TIME = 2.28   MIN
FOAM DENSITY =   .0249 GM/CC   EXPERIMENT TIME = 25.7 MIN

   55.0 53.4 52.6 52.0 51.3 50.6 50.0 49.3 48.7 48.1
   47.6 46.9 46.3 45.7 45.1 44.3 43.6 42.7 41.8 40.8
   39.8 38.6 37.4 36.0 34.3 32.0 27.6

ABS CONCENTRATION = 40 PPM   AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =   2008 CC   AERATION TIME = 1.17   MIN
FOAM DENSITY =   .0283 GM/CC   EXPERIMENT TIME = 15.5 MIN

   55.0 53.1 51.8 50.5 49.5 48.4 47.3 46.1 45.0 43.6
   42.3 41.0 39.4 37.6 35.4 32.0 27.6

ABS CONCENTRATION = 40 PPM   AERATION RATE = 2.49 L/MIN
FOAM VOLUME   =   1987 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0215 GM/CC   EXPERIMENT TIME = 9.6   MIN

   55.0 53.1 51.2 49.3 47.5 45.2 42.8 40.2 37.0 33.0
   27.7

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =    .74 L/MIN
FOAM VOLUME   =      2072  CC       AERATION TIME = 2.36   MIN
FOAM DENSITY =        .0274 GM/CC   EXPERIMENT TIME = 26.6  MIN

    55.0  53.5  52.7  52.0  51.3  50.6  50.0  49.2  48.5  47.8
    47.2  46.6  46.0  45.0  44.3  43.6  42.9  42.1  41.2  40.4
    39.5  38.5  37.5  36.4  35.1  33.5  31.3  26.7


ABS CONCENTRATION =  60 PPM        AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =      2029  CC       AERATION TIME = 1.15   MIN
FOAM DENSITY =        .0385 GM/CC   EXPERIMENT TIME = 17.4  MIN

    55.0  53.8  52.8  51.6  50.7  49.5  48.4  47.3  46.1  45.0
    43.7  42.4  41.0  39.7  38.1  36.4  34.3  31.2  27.6


ABS CONCENTRATION =  60 PPM        AERATION RATE = 2.49 L/MIN
FOAM VOLUME   =      1987  CC       AERATION TIME =   .65   MIN
FOAM DENSITY =        .0250 GM/CC   EXPERIMENT TIME = 10.0  MIN

    55.0  53.5  51.8  50.1  48.0  46.0  43.6  41.0  38.3  34.8
    27.8


ABS CONCENTRATION =  80 PPM        AERATION RATE =    .74 L/MIN
FOAM VOLUME   =      2008  CC       AERATION TIME = 2.32   MIN
FOAM DENSITY =        .0354 GM/CC   EXPERIMENT TIME = 27.0  MIN

    55.0  53.8  52.8  52.0  51.2  50.6  49.8  49.1  48.4  47.6
    47.0  46.3  45.7  45.0  44.3  43.5  42.8  42.0  41.3  40.5
    39.6  38.7  37.7  36.7  35.5  34.2  32.3  27.8


ABS CONCENTRATION =  80 PPM        AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =      2072  CC       AERATION TIME = 1.17   MIN
FOAM DENSITY =        .0549 GM/CC   EXPERIMENT TIME = 17.4  MIN

    55.0  53.4  52.0  50.8  49.5  48.3  47.2  46.2  45.0  43.8
    42.5  41.5  40.2  39.0  37.7  36.0  34.0  30.7  27.5


ABS CONCENTRATION =  80 PPM        AERATION RATE = 2.49 L/MIN
FOAM VOLUME   =      2065  CC       AERATION TIME =   .67   MIN
FOAM DENSITY =        .0517 GM/CC   EXPERIMENT TIME = 9.6   MIN

    55.0  53.4  51.8  49.8  47.6  45.3  42.8  40.2  36.4  32.6
```

27.5

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2029 CC   AERATION TIME = 2.24   MIN
FOAM DENSITY   =   .0385 GM/CC   EXPERIMENT TIME = 31.4   MIN

    55.0 53.7 53.1 52.5 51.9 51.5 50.9 50.3 49.7 49.1
    48.6 48.0 47.6 47.0 46.4 45.8 45.3 44.8 44.0 43.3
    42.5 41.8 41.0 40.2 39.3 38.5 37.6 36.6 35.4 34.2
    32.7 30.3 27.6

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME =   1.13   MIN
FOAM DENSITY   =   .0584 GM/CC   EXPERIMENT TIME = 16.4   MIN

    55.0 53.5 52.5 51.3 50.2 49.0 47.9 46.6 45.4 44.2
    42.9 41.6 40.1 38.5 36.7 34.5 31.3 27.6

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.49 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME =   .65   MIN
FOAM DENSITY   =   .0551 GM/CC   EXPERIMENT TIME = 9.9   MIN

    55.0 53.7 52.0 50.2 48.3 46.1 43.5 41.3 38.0 34.4
    27.6

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME = 2.35   MIN
FOAM DENSITY   =   .0482 GM/CC   EXPERIMENT TIME = 31.9   MIN

    55.0 53.7 53.1 52.5 51.8 51.3 50.8 50.2 49.5 49.0
    48.4 47.9 47.3 46.8 46.3 45.7 45.2 44.6 44.0 43.3
    42.5 41.8 41.0 40.3 39.5 38.7 37.7 36.8 35.8 34.7
    33.1 31.3 27.4

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =   2093 CC   AERATION TIME =   1.18   MIN
FOAM DENSITY   =   .0612 GM/CC   EXPERIMENT TIME = 19.5   MIN

    55.0 53.7 52.6 51.7 50.6 49.8 48.5 47.4 46.5 45.4
    44.3 43.2 42.0 40.8 39.5 38.2 36.7 35.0 33.0 28.8
    27.4

ABS CONCENTRATION = 120 PPM   AERATION RATE =   2.49 L/MIN

```
FOAM VOLUME    =      2079  CC       AERATION TIME =    .67   MIN
FOAM DENSITY   =      .0616 GM/CC    EXPERIMENT TIME = 11.9   MIN

    55.0  53.1  51.4  49.7  47.8  46.0  44.2  42.3  40.3  38.4
    36.1  33.1  27.6
```

REPLICATE 2

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME    =      2001  CC       AERATION TIME = 2.36   MIN
FOAM DENSITY   =      .0177 GM/CC    EXPERIMENT TIME = 16.0   MIN

    55.0  53.3  52.5  51.8  51.0  50.2  49.2  48.4  47.3  46.3
    45.0  43.5  41.8  40.0  37.8  34.8  27.4
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =  1.46 L/MIN
FOAM VOLUME    =      1979  CC       AERATION TIME =  1.17   MIN
FOAM DENSITY   =      .0179 GM/CC    EXPERIMENT TIME =  8.8   MIN

    55.0  52.8  50.7  48.3  46.1  43.7  41.2  38.6  34.6  27.7
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =  2.51 L/MIN
FOAM VOLUME    =      1987  CC       AERATION TIME =    .68   MIN
FOAM DENSITY   =      .0179 GM/CC    EXPERIMENT TIME =  6.1   MIN

    55.0  50.9  47.8  44.8  41.6  37.0  29.4  27.6
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME    =      2022  CC       AERATION TIME = 2.34   MIN
FOAM DENSITY   =      .0246 GM/CC    EXPERIMENT TIME = 24.9   MIN

    55.0  52.9  52.0  51.3  50.7  50.0  49.4  48.7  48.0  47.4
    46.8  46.2  45.4  44.7  43.9  43.0  42.2  41.3  40.4  39.5
    38.4  37.2  36.0  34.5  32.3  27.3
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =  1.46 L/MIN
FOAM VOLUME    =      2022  CC       AERATION TIME =  1.16   MIN
FOAM DENSITY   =      .0316 GM/CC    EXPERIMENT TIME = 18.2   MIN

    55.0  53.4  52.4  51.5  50.4  49.3  48.3  47.4  46.3  45.3
    44.3  43.0  41.8  40.6  39.3  37.9  36.2  34.0  30.0  27.5
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =  2.51 L/MIN
```

```
FOAM VOLUME    =      2015  CC      AERATION TIME =     .69   MIN
FOAM DENSITY   =    .0247 GM/CC     EXPERIMENT TIME = 10.5   MIN

  55.0  53.1  51.2  49.2  47.5  45.7  43.8  42.0  39.3  36.3
  31.9  27.4
```

```
ABS CONCENTRATION =  60 PPM      AERATION RATE  =    .75 L/MIN
FOAM VOLUME    =      2044  CC    AERATION TIME = 2.23   MIN
FOAM DENSITY   =    .0313 GM/CC   EXPERIMENT TIME = 28.3   MIN

  55.0  53.2  52.4  51.8  51.1  50.6  49.8  49.2  48.6  48.0
  47.5  46.8  46.2  45.6  45.0  44.3  43.5  42.9  42.0  41.3
  40.4  39.7  38.7  37.9  37.0  35.8  34.5  32.8  30.1  27.2
```

```
ABS CONCENTRATION =  60 PPM      AERATION RATE  = 1.46 L/MIN
FOAM VOLUME    =      2029  CC    AERATION TIME = 1.16   MIN
FOAM DENSITY   =    .0350 GM/CC   EXPERIMENT TIME = 18.4   MIN

  55.0  53.0  51.9  51.0  49.9  48.8  47.8  46.8  45.5  44.4
  43.3  42.3  41.1  39.8  38.6  37.1  35.5  33.5  30.3  27.5
```

```
ABS CONCENTRATION =  60 PPM      AERATION RATE  = 2.51 L/MIN
FOAM VOLUME    =      1994  CC    AERATION TIME =    .61   MIN
FOAM DENSITY   =    .0285 GM/CC   EXPERIMENT TIME = 10.7   MIN

  55.0  53.1  51.7  49.6  48.0  45.9  43.7  41.7  39.5  36.8
  33.1  27.8
```

```
ABS CONCENTRATION =  80 PPM      AERATION RATE  =    .75 L/MIN
FOAM VOLUME    =      2029  CC    AERATION TIME = 2.24   MIN
FOAM DENSITY   =    .0350 GM/CC   EXPERIMENT TIME = 29.3   MIN

  55.0  53.6  52.9  52.2  51.6  51.0  50.4  49.7  49.1  48.5
  48.0  47.3  46.6  46.1  45.5  44.9  44.2  43.4  42.8  42.0
  41.3  40.5  39.7  38.8  38.0  37.0  36.0  34.6  33.0  30.3
  27.5
```

```
ABS CONCENTRATION =  80 PPM      AERATION RATE  = 1.48 L/MIN
FOAM VOLUME    =      2072  CC    AERATION TIME = 1.16   MIN
FOAM DENSITY   =    .0584 GM/CC   EXPERIMENT TIME = 17.3   MIN

  55.0  53.5  52.4  51.2  50.0  49.0  47.8  46.8  45.6  44.4
  43.0  41.6  40.3  38.9  37.3  35.4  33.5  30.0  27.6
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.51 L/MIN
FOAM VOLUME   =   2008 CC   AERATION TIME =   .66   MIN
FOAM DENSITY =   .0354 GM/CC   EXPERIMENT TIME = 10.4 MIN

    55.0 53.3 51.6 49.7 48.3 46.5 44.2 41.7 39.1 35.8
    31.5 27.5

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME = 2.23   MIN
FOAM DENSITY =   .0582 GM/CC   EXPERIMENT TIME = 26.2 MIN

    55.0 53.4 52.8 51.9 51.3 50.6 49.9 49.2 48.5 48.0
    47.3 46.7 46.0 45.2 44.5 43.6 42.8 41.9 41.0 40.1
    39.2 38.2 37.1 35.8 34.5 32.7 29.2 27.5

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.46 L/MIN
FOAM VOLUME   =   2086 CC   AERATION TIME = 1.27   MIN
FOAM DENSITY =   .0580 GM/CC   EXPERIMENT TIME = 18.6 MIN

    55.0 53.1 52.1 51.2 50.0 48.8 47.6 46.4 45.3 44.1
    43.0 41.8 40.5 39.2 37.9 36.4 34.8 32.8 30.1 27.4

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.53 L/MIN
FOAM VOLUME   =   2022 CC   AERATION TIME =   .66   MIN
FOAM DENSITY =   .0352 GM/CC   EXPERIMENT TIME = 10.6 MIN

    55.0 53.1 51.3 49.5 47.1 45.0 42.4 39.2 36.4 33.8
    30.8 27.6

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME = 2.21   MIN
FOAM DENSITY =   .0616 GM/CC   EXPERIMENT TIME = 26.4 MIN

    55.0 53.1 52.4 51.7 51.1 50.5 49.8 49.8 48.5 47.8
    47.1 46.4 45.7 45.1 44.3 43.5 42.7 41.9 41.0 40.2
    39.2 38.3 37.2 36.1 34.8 33.3 30.8 27.6

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.48 L/MIN
FOAM VOLUME   =   2086 CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0648 GM/CC   EXPERIMENT TIME = 17.6 MIN

    55.0 52.9 51.6 50.4 49.1 47.8 46.8 45.7 44.5 43.5
    42.4 41.3 40.0 38.6 37.2 35.5 33.8 31.1 27.7

```
ABS CONCENTRATION = 120 PPM        AERATION RATE =   2.51 L/MIN
FOAM VOLUME     =     2079  CC      AERATION TIME =    .62   MIN
FOAM DENSITY =        .0616 GM/CC   EXPERIMENT TIME =  9.9   MIN

   55.0  53.3  51.8  50.1  48.3  46.3  43.8  40.7  37.1  33.3
   27.6
```

REPLICATE 3

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME     =     1994  CC      AERATION TIME =  2.32   MIN
FOAM DENSITY =        .0178 GM/CC   EXPERIMENT TIME = 15.2   MIN

   55.0  53.6  52.7  51.8  50.9  49.8  48.7  47.7  46.5  45.3
   44.0  42.3  40.4  38.3  35.5  30.6  27.5
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   1.46 L/MIN
FOAM VOLUME     =     2036  CC      AERATION TIME =  1.17   MIN
FOAM DENSITY =        .0314 GM/CC   EXPERIMENT TIME = 12.0   MIN

   55.0  52.0  51.0  49.4  48.3  47.2  45.8  44.3  42.3  40.1
   37.5  33.8  27.3
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   2.51 L/MIN
FOAM VOLUME     =     1994  CC      AERATION TIME =    .68   MIN
FOAM DENSITY =        .0178 GM/CC   EXPERIMENT TIME =  5.6   MIN

   55.0  51.0  47.4  44.4  40.1  34.3  27.5
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =    .75 L/MIN
FOAM VOLUME     =     2015  CC      AERATION TIME =  2.22   MIN
FOAM DENSITY =        .0282 GM/CC   EXPERIMENT TIME = 24.5   MIN

   55.0  53.5  52.5  51.6  50.8  50.0  49.4  48.7  48.1  47.5
   46.8  46.2  45.5  44.8  44.0  43.1  42.2  41.3  40.4  39.4
   38.3  37.1  35.7  34.1  31.5  27.5
```

```
ABS CONCENTRATION =  40 PPM        AERATION RATE =   1.47 L/MIN
FOAM VOLUME     =     2051  CC      AERATION TIME =  1.22   MIN
FOAM DENSITY =        .0451 GM/CC   EXPERIMENT TIME = 16.1   MIN

   55.0  53.2  52.0  51.0  50.0  49.0  48.0  46.9  45.7  44.4
```

43.2   41.7   40.2   38.3   36.3   33.6   28.3   27.5

ABS CONCENTRATION = 40 PPM   AERATION RATE = 2.51 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME =   .68 MIN
FOAM DENSITY =   .0247 GM/CC   EXPERIMENT TIME = 9.1 MIN

   55.0   52.6   50.0   48.0   45.9   43.6   41.2   38.6   35.0   29.1
   27.4

ABS CONCENTRATION = 60 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2036 CC   AERATION TIME = 2.30 MIN
FOAM DENSITY =   .0314 GM/CC   EXPERIMENT TIME = 27.6 MIN

   55.0   53.7   53.0   52.3   51.6   51.1   50.3   49.8   49.1   48.4
   48.0   47.2   46.6   46.0   45.3   44.6   43.8   43.0   42.3   41.5
   40.5   39.6   38.8   37.7   36.5   35.2   33.6   31.3   27.3

ABS CONCENTRATION = 60 PPM   AERATION RATE = 1.47 L/MIN
FOAM VOLUME   =   2086 CC   AERATION TIME = 1.19 MIN
FOAM DENSITY =   .0580 GM/CC   EXPERIMENT TIME = 18.9 MIN

   55.0   53.7   52.8   51.9   51.0   50.2   49.3   48.3   47.3   46.4
   45.3   44.2   43.1   42.0   40.8   39.3   37.6   35.6   32.7   27.4

ABS CONCENTRATION = 60 PPM   AERATION RATE = 2.51 L/MIN
FOAM VOLUME   =   1987 CC   AERATION TIME =   .68 MIN
FOAM DENSITY =   .0250 GM/CC   EXPERIMENT TIME = 9.6 MIN

   55.0   53.0   51.0   48.8   46.8   44.7   42.8   40.4   37.0   32.4
   27.8

ABS CONCENTRATION = 80 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2036 CC   AERATION TIME = 2.25 MIN
FOAM DENSITY =   .0349 GM/CC   EXPERIMENT TIME = 29.8 MIN

   55.0   53.9   53.2   52.5   51.9   51.2   50.6   50.0   49.3   48.7
   48.3   47.6   47.0   46.5   45.8   45.1   44.4   43.8   43.1   42.4
   41.6   40.8   40.0   39.1   38.3   37.3   36.3   35.1   33.7   31.8
   27.4

ABS CONCENTRATION = 80 PPM   AERATION RATE = 1.47 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME = 1.19 MIN
FOAM DENSITY =   .0616 GM/CC   EXPERIMENT TIME = 18.9 MIN

```
55.0   53.7   52.7   51.7   50.6   49.8   48.7   47.7   46.7   45.7
44.7   43.7   42.5   41.3   40.0   38.6   37.0   35.2   32.7   27.6
```

ABS CONCENTRATION = 80 PPM   AERATION RATE = 2.52 L/MIN
FOAM VOLUME   =   2015 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0318 GM/CC   EXPERIMENT TIME = 10.6   MIN

```
55.0   52.9   51.1   49.1   47.0   44.8   42.1   39.2   36.4   33.8
30.8   27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2072 CC   AERATION TIME = 2.21   MIN
FOAM DENSITY =   .0584 GM/CC   EXPERIMENT TIME = 27.0   MIN

```
55.0   53.7   53.0   52.3   51.6   51.0   50.3   49.7   49.1   48.4
47.9   47.2   46.5   45.8   45.1   44.3   43.5   42.7   41.8   41.0
40.1   39.2   38.2   37.1   35.8   34.4   32.6   27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.47 L/MIN
FOAM VOLUME   =   2093 CC   AERATION TIME = 1.19   MIN
FOAM DENSITY =   .0680 GM/CC   EXPERIMENT TIME = 19.3   MIN

```
55.0   53.8   52.7   51.8   51.0   50.2   49.3   48.3   47.5   46.5
45.4   44.3   43.2   42.0   40.7   39.3   37.7   35.8   33.6   30.0
27.6
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.51 L/MIN
FOAM VOLUME   =   2065 CC   AERATION TIME =   .67   MIN
FOAM DENSITY =   .0551 GM/CC   EXPERIMENT TIME = 10.8   MIN

```
55.0   53.4   51.9   50.1   48.0   46.4   44.5   42.3   39.7   36.9
33.3   27.6
```

ABS CONCENTRATION = 120 PPM   AERATION RATE =   .75 L/MIN
FOAM VOLUME   =   2079 CC   AERATION TIME = 2.18   MIN
FOAM DENSITY =   .0650 GM/CC   EXPERIMENT TIME = 26.5   MIN

```
55.0   53.7   52.9   52.2   51.5   51.0   50.3   49.6   48.9   48.3
47.6   47.0   46.2   45.5   44.7   44.0   43.2   42.3   41.5   40.6
39.7   38.8   37.7   36.4   35.1   33.5   31.1   27.7
```

ABS CONCENTRATION = 120 PPM   AERATION RATE = 1.47 L/MIN

```
FOAM VOLUME    =       2108  CC      AERATION TIME = 1.20   MIN
FOAM DENSITY   =      .0709 GM/CC    EXPERIMENT TIME = 18.6  MIN

  55.0  53.8  52.7  51.8  51.0  50.1  49.2  48.3  47.2  46.2
  45.1  44.0  42.8  41.5  40.0  38.5  36.7  34.5  31.3  27.5


ABS CONCENTRATION = 120 PPM    AERATION RATE = 2.51 L/MIN
FOAM VOLUME    =       2086  CC      AERATION TIME =  .66   MIN
FOAM DENSITY   =      .0546 GM/CC    EXPERIMENT TIME =  9.9  MIN

  55.0  53.3  51.4  49.5  47.6  45.5  43.5  40.5  37.2  33.4
  27.3
```

XXIV. APPENDIX B

<u>Data</u> <u>for</u> <u>the</u> <u>Experiments</u> <u>Employing</u> <u>the</u> <u>Static</u> <u>Decay</u> <u>Method</u>

The information given in Appendix B includes the experimental data for both Series 1 and 2 static decay experiments. The headings of each set of data indicate the ABS concentration, aeration rate, foam volume, aeration time to generate the given foam volume, foam density, and the time (8-hours) employed for each static decay measurement.

The data given beneath the headings indicate the foam level (cm) observed at one-half hour intervals reading from left to right. The initial value corresponds to the foam height at time equal to zero.

SERIES 1 STATIC DECAY EXPERIMENTAL DATA (23 C)

```
ABS CONCENTRATION =  20 PPM        AERATION RATE  =   .76 L/MIN
FOAM VOLUME     =     1623  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0394 GM/CC    EXPERIMENT TIME =  8.0   HR

    50.0   47.5   45.0   43.0   41.0   38.7   37.0   35.3   34.0   33.2
    33.0   31.5   30.7   30.0   29.5   28.6   28.1
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE  =  1.51 L/MIN
FOAM VOLUME     =     3390  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0357 GM/CC    EXPERIMENT TIME =  8.0   HR

    74.0   67.8   55.3   43.5   40.9   39.8   39.0   38.7   37.8   37.0
    35.5   34.5   34.0   33.5   31.5   30.3   29.3
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE  =  2.59 L/MIN
FOAM VOLUME     =     5740  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0198 GM/CC    EXPERIMENT TIME =  8.0   HR

   107.4   98.0   69.5   42.8   39.0   37.3   36.0   35.0   34.0   33.0
    32.5   32.0   31.5   30.5   28.4   28.4   28.4
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =   .77 L/MIN
FOAM VOLUME     =     1816  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0627 GM/CC    EXPERIMENT TIME =  8.0   HR

    52.0   51.0   47.2   44.5   43.5   42.7   42.0   40.7   39.5   38.8
    38.0   36.7   35.0   34.0   33.0   32.2   31.3
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =  1.51 L/MIN
FOAM VOLUME     =     3511  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0405 GM/CC    EXPERIMENT TIME =  8.0   HR

    75.5   75.0   70.0   51.7   45.7   42.7   41.7   40.5   39.8   38.1
    37.2   36.0   34.7   34.3   33.0   32.4   31.5
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE  =  2.59 L/MIN
FOAM VOLUME     =     6039  CC      AERATION TIME  =  2.00   MIN
FOAM DENSITY    =    .0507 GM/CC    EXPERIMENT TIME =  8.0   HR

   108.5  107.0   92.8   62.0   49.7   45.6   43.3   41.6   40.5   39.7
    38.7   38.0   37.3   35.8   35.3   34.7   34.3
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =       1830  CC     AERATION TIME = 2.00   MIN
FOAM DENSITY =         .0622 GM/CC  EXPERIMENT TIME = 8.0   HR

   52.0  51.9  51.5  50.7  49.5  47.8  45.5  44.8  43.5  42.5
   42.0  41.0  40.0  39.0  38.7  38.0  37.6


ABS CONCENTRATION = 100 PPM        AERATION RATE =   1.51 L/MIN
FOAM VOLUME    =       3717  CC     AERATION TIME = 2.00   MIN
FOAM DENSITY =         .0842 GM/CC  EXPERIMENT TIME = 8.0   HR

   76.0  75.4  73.8  71.0  54.5  44.3  42.0  41.3  40.5  39.8
   39.2  38.7  37.8  37.0  36.4  35.8  35.2


ABS CONCENTRATION = 100 PPM        AERATION RATE =   2.59 L/MIN
FOAM VOLUME    =       6075  CC     AERATION TIME = 2.00   MIN
FOAM DENSITY =         .0515 GM/CC  EXPERIMENT TIME = 8.0   HR

  109.3 108.0 105.8  90.0  62.0  53.0  40.0  38.9  38.3  37.8
   37.3  36.8  36.2  35.6  35.0  34.4  33.8
```

SERIES 2 STATIC DECAY EXPERIMENTAL DATA (20 C)

REPLICATE   1

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     1972  CC       AERATION TIME = 2.23   MIN
FOAM DENSITY   =      .0216 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   52.0   47.2   44.8   43.3   41.8   40.2   38.8   37.5   37.0
   35.7   35.0   34.0   33.5   32.9   32.3   31.7
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   1.50 L/MIN
FOAM VOLUME    =     1951  CC       AERATION TIME =   1.19   MIN
FOAM DENSITY   =      .0291 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   50.0   47.0   45.5   44.0   43.0   41.5   40.0   39.0   37.8
   36.7   35.6   34.5   33.5   32.6   31.7   31.0
```

```
ABS CONCENTRATION =  20 PPM        AERATION RATE =   2.59 L/MIN
FOAM VOLUME    =     2001  CC       AERATION TIME =    .69   MIN
FOAM DENSITY   =      .0462 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   48.5   45.0   42.0   40.5   39.0   38.0   36.5   35.5   34.5
   34.0   33.5   33.0   32.5   32.0   31.0   31.0
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     2029  CC       AERATION TIME = 2.22   MIN
FOAM DENSITY   =      .0631 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   54.5   49.7   47.2   45.2   43.7   42.5   42.0   40.5   39.2
   37.8   36.3   35.0   33.5   32.5   31.5   30.7
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =   1.50 L/MIN
FOAM VOLUME    =     2022  CC       AERATION TIME =   1.12   MIN
FOAM DENSITY   =      .0598 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   54.5   49.5   46.5   44.0   43.0   42.0   41.2   40.0   38.5
   37.2   35.8   34.5   33.1   32.0   31.0   30.5
```

```
ABS CONCENTRATION =  60 PPM        AERATION RATE =   2.59 L/MIN
FOAM VOLUME    =     1979  CC       AERATION TIME =    .67   MIN
FOAM DENSITY   =      .0323 GM/CC   EXPERIMENT TIME =  8.0   HR

   55.0   49.5   45.0   43.0   41.8   40.5   39.3   38.2   37.0   36.1
```

34.4   33.3   32.2   31.2   30.3   29.6   29.3

```
ABS CONCENTRATION = 100 PPM        AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     2051  CC       AERATION TIME = 2.22   MIN
FOAM DENSITY =        .0763 GM/CC   EXPERIMENT TIME = 8.0   HR
```

  55.0   54.9   52.0   47.3   43.6   41.5   40.0   38.7   37.7   37.0
  36.2   35.5   34.8   34.3   33.8   33.3   32.8

```
ABS CONCENTRATION = 100 PPM        AERATION RATE = 1.50 L/MIN
FOAM VOLUME    =     2044  CC       AERATION TIME = 1.08   MIN
FOAM DENSITY =        .0662 GM/CC   EXPERIMENT TIME = 8.0   HR
```

  55.0   54.8   48.5   46.0   43.5   42.0   40.6   39.5   38.5   37.6
  36.5   36.0   35.0   33.5   33.0   32.5   31.5

```
ABS CONCENTRATION = 100 PPM        AERATION RATE = 2.59 L/MIN
FOAM VOLUME    =     2036  CC       AERATION TIME =   .62   MIN
FOAM DENSITY =        .0594 GM/CC   EXPERIMENT TIME = 8.0   HR
```

  55.0   53.5   47.0   44.5   42.5   41.5   40.5   39.0   38.0   37.0
  36.0   35.0   34.0   32.5   32.2   31.0   30.0

REPLICATE 2

```
ABS CONCENTRATION = 20 PPM         AERATION RATE =    .76 L/MIN
FOAM VOLUME    =     1965  CC       AERATION TIME = 2.24   MIN
FOAM DENSITY =        .0144 GM/CC   EXPERIMENT TIME = 8.0   HR
```

  55.0   52.0   46.3   43.2   40.8   39.2   37.8   36.7   35.7   34.7
  33.7   32.8   32.0   31.2   30.5   29.8   29.6

```
ABS CONCENTRATION = 20 PPM         AERATION RATE = 1.50 L/MIN
FOAM VOLUME    =     1979  CC       AERATION TIME = 1.14   MIN
FOAM DENSITY =        .0287 GM/CC   EXPERIMENT TIME = 8.0   HR
```

  55.0   52.0   45.8   41.8   39.5   37.5   36.2   35.0   34.0   33.2
  32.3   31.5   30.8   30.0   29.6   29.5   29.0

```
ABS CONCENTRATION = 20 PPM         AERATION RATE = 2.59 L/MIN
FOAM VOLUME    =     1987  CC       AERATION TIME =   .67   MIN
FOAM DENSITY =        .0358 GM/CC   EXPERIMENT TIME = 8.0   HR
```

```
55.0   50.0   44.0   40.5   38.2   36.6   35.3   34.3   33.3   32.6
31.8   31.2   30.3   29.7   29.5   29.3   29.0
```

```
ABS CONCENTRATION =   60 PPM        AERATION RATE =     .76 L/MIN
FOAM VOLUME     =      1979  CC     AERATION TIME =   1.19    MIN
FOAM DENSITY  =        .0395 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   54.5   54.2   47.0   40.5   37.7   36.2   35.1   34.4   33.7
33.2   32.7   32.3   31.9   31.5   31.2   30.8
```

```
ABS CONCENTRATION =   60 PPM        AERATION RATE =   1.49 L/MIN
FOAM VOLUME     =      1958  CC     AERATION TIME =   1.15    MIN
FOAM DENSITY  =        .0290 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   52.5   47.0   40.3   38.0   36.4   35.1   34.2   33.5   32.8
32.7   32.3   32.0   31.3   31.0   30.8   30.7
```

```
ABS CONCENTRATION =   60 PPM        AERATION RATE =   2.55 L/MIN
FOAM VOLUME     =      1972  CC     AERATION TIME =     .70    MIN
FOAM DENSITY  =        .0252 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   53.5   50.5   44.5   39.7   37.0   35.3   34.1   33.2   32.5
32.0   31.6   31.2   31.0   30.5   30.2   30.0
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE =     .77 L/MIN
FOAM VOLUME     =      1987  CC     AERATION TIME =   2.23    MIN
FOAM DENSITY  =        .0394 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   54.9   50.0   45.5   42.5   40.5   39.0   38.0   37.0   36.5
35.5   35.0   34.5   33.5   33.0   32.5   31.5
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE =   1.51 L/MIN
FOAM VOLUME     =      1994  CC     AERATION TIME =   1.21    MIN
FOAM DENSITY  =        .0571 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   52.5   45.7   41.2   39.2   37.6   36.3   35.3   34.5   33.8
33.3   32.8   32.3   31.8   31.4   31.0   30.5
```

```
ABS CONCENTRATION = 100 PPM        AERATION RATE =   2.59 L/MIN
FOAM VOLUME     =      1987  CC     AERATION TIME =     .72    MIN
FOAM DENSITY  =        .0322 GM/CC  EXPERIMENT TIME =   8.0    HR
```

```
55.0   51.5   45.7   41.2   39.2   37.6   36.3   35.3   34.5   33.8
```

33.3   32.8   32.3   31.8   31.4   31.0   30.5

REPLICATE   3

ABS CONCENTRATION =   20 PPM   AERATION RATE =   .78 L/MIN
FOAM VOLUME   =   1958   CC   AERATION TIME = 2.23   MIN
FOAM DENSITY =   .0218 GM/CC   EXPERIMENT TIME = 8.0   HR

   55.0   54.2   47.0   43.0   41.0   40.3   38.5   37.5   36.5   35.6
   34.7   34.0   33.8   33.6   33.5   32.2   32.0

ABS CONCENTRATION =   20 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   1972   CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0288 GM/CC   EXPERIMENT TIME = 8.0   HR

   55.0   53.5   45.0   41.1   39.0   38.0   36.5   35.5   35.0   34.0
   33.5   33.0   32.8   32.6   32.5   32.4   32.3

ABS CONCENTRATION =   20 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   1965   CC   AERATION TIME = .70   MIN
FOAM DENSITY =   .0289 GM/CC   EXPERIMENT TIME = 8.0   HR

   55.0   50.0   44.5   41.5   39.0   38.0   36.0   34.9   34.0   33.5
   32.7   32.5   32.2   32.0   31.9   31.8   31.7

ABS CONCENTRATION =   60 PPM   AERATION RATE =   .77 L/MIN
FOAM VOLUME   =   1987   CC   AERATION TIME = 2.23   MIN
FOAM DENSITY =   .0394 GM/CC   EXPERIMENT TIME = 8.0   HR

   55.0   54.5   53.8   51.0   41.5   37.7   36.3   35.5   34.7   34.2
   33.7   33.2   32.7   32.3   32.0   31.7   31.3

ABS CONCENTRATION =   60 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   1951   CC   AERATION TIME = 1.16   MIN
FOAM DENSITY =   .0255 GM/CC   EXPERIMENT TIME = 8.0   HR

   55.0   54.5   53.5   45.5   40.5   37.6   36.3   35.5   34.7   34.2
   33.7   33.2   32.7   32.3   32.0   31.7   31.3

ABS CONCENTRATION =   60 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   1994   CC   AERATION TIME = .73   MIN
FOAM DENSITY =   .0357 GM/CC   EXPERIMENT TIME = 8.0   HR

```
55.0   52.4   45.7   42.5   39.1   37.5   36.3   35.5   34.7   34.2
33.7   33.2   32.7   32.3   32.0   31.7   31.3
```

ABS CONCENTRATION = 100 PPM   AERATION RATE =   .77 L/MIN
FOAM VOLUME   =   1987 CC   AERATION TIME = 2.18   MIN
FOAM DENSITY =   .0358 GM/CC   EXPERIMENT TIME = 8.0   HR

```
55.0   55.0   54.7   53.3   47.0   41.2   37.8   35.6   34.5   33.6
32.8   32.4   32.0   31.8   31.5   31.4   31.3
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 1.51 L/MIN
FOAM VOLUME   =   1922 CC   AERATION TIME = 1.06   MIN
FOAM DENSITY =   .0259 GM/CC   EXPERIMENT TIME = 8.0   HR

```
55.0   55.0   54.6   53.0   44.0   38.8   36.8   35.4   34.2   33.4
32.8   32.4   32.0   31.7   31.4   31.2   30.9
```

ABS CONCENTRATION = 100 PPM   AERATION RATE = 2.59 L/MIN
FOAM VOLUME   =   1987 CC   AERATION TIME =   .66   MIN
FOAM DENSITY =   .0286 GM/CC   EXPERIMENT TIME = 8.0   HR

```
55.0   54.8   54.3   46.0   40.0   38.0   36.5   35.3   34.5   33.7
33.0   32.3   31.8   31.3   31.0   30.5   30.0
```

Abstract

FOAM CONTROL UTILIZING HYDRAULIC FORCES OF AN ACCELERATED LIQUID SURFACE AND CHARACTERIZATION OF DURABLE FOAMS BY APPLICATION OF AN EXTERNAL FORCE

by

Darwin Fay Alt

Major Professor: Dr. William A. Parsons

The dissertation presents two distinct but related studies of foam. The initial investigation involves the evaluation of a method of controlling foaming in aerated fermenters; the second involves the evaluation of a method of characterization of durable foams.

Since foaming has frequently been a problem of considerable magnitude in aerated waste treatment and various other aerated cultures, a method was conceived which involved the disruption of foam at the liquid-foam interface during carriage as a result of an accelerated converging flow through a down flow draft tube. The principles of the method were based on the creation of differential shearing forces at the foam-liquid interface to cause disruption of foam at the interface and subsequent re-entrainment during the convergence of flow through the down flow draft tube.

The geometry of the inlet to the draft tube, recirculation rate, and hydraulic head over the inlet were principal variables affecting the degree of foam control. Foam control performance increased with increased diameter of the inlets as a result of the reduced tendencies of foams to span or

bridge inlets of larger size. Increased recirculation rate and low hydraulic head over the inlet offered the greatest potential relative to foam re-entrainment; however, the conditions of increased recirculation rate and low hydraulic head resulted in air being drawn into the draft tube in addition to the foam-liquid mixture. The foam subsequently reappearing at the liquid surface possessed a dense, fine bubble structure which was resistant to control.

The method proved successful on a short-term basis inasmuch as operational times were extended to about six times those required to generate comparable volumes of foam while employing aeration only. For extended operational periods, the method resulted in resistant foams which defied control by the process.

During the course of the foam control investigation a method was sought which could practically be employed to evaluate the durability properties of foams for routine characterization measurements. The natural collapse periods for foams resulting from the employed alkyl benzene sulfonate (ABS) solutions were of such duration to be impractical for repetitive measurements. A method was conceived whereby the destruction of foams could be accelerated by application of an external force. The method involved application of a weighted disc assembly to a definite volume of foam confined in a 3.75-inch inside diameter foam generation column. The principle of the method was based on the hypothesis that a

measure of the durability properties of foams could be obtained relative to the rate of collapse under applied stress.

The method was evaluated on foams generated from solutions containing ABS concentrations ranging from 20 to 120 ppm employing aeration rates of 0.75, 1.5, and 2.45 1/min. Measurements consisted of recording the level of disc descent at one-minute intervals until the disc reached the liquid surface. The results were presented as disc descent rates or slopes of the disc descent curves for each measurement.

Experiments employing static decay methods were performed to observe the behavior of foams subjected to destruction due to natural causes. Measurements consisted of observing the remaining foam level at one-half hour intervals for a total period of eight hours. The results were presented graphically as foam collapse vs time curves and quantitatively in terms of the average lifetime of the foams.

The results of the experiments employing the weighted disc and the experiments employing static decay methods agreed insofar as the durability properties of foam were enhanced by increased ABS concentration and low aeration rate. The results of both methods indicated that, on a comparative basis of the data and by a statistical analysis of the data, aeration rate had a more pronounced effect on foam character than ABS concentration for the ranges of the variables employed in the investigation.

The periods required for completion of the measurements of the weighted disc experiments ranged from about 10 to 25 minutes which represent a considerable saving in time in comparison to the length of experiments employing static decay procedures. The rapidity and simplicity of the method employing the weighted disc appear to make this method applicable for routine characterization measurements of durable foams.