FE-3162-T1
Distribution Category UC-90d

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EVALUATION OF COAL/OIL/WATER SLURRY (COWS) EMULSIONS PRODUCED BY AN ON-LINE CAVITATING EMULSIFICATION PROCESS

TECHNICAL REPORT

Submitted to:

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October 1979

DAI Technical Report No. 7807-001-DT

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1.0 INTRODUCTION

1.1 Purpose of Program

There is a growing requirement for reducing the national dependence on foreign oil by converting presently operated oil-fired furnaces to coal without involving large capital investments by the utility industry. One approach which is currently being technically evaluated in order to achieve this goal utilizes emulsified coal in oil as the fuel. The success of the approach would substantially extend the oil supplies through the substitution of coal in the coal/oil slurry emulsion. Combustion tests have demonstrated emulsions can be burned in oil-fired furnaces. For example, General Motors Corp. (1)* demonstrated that a mixture of pulverized coal (50 percent) by weight and No. 6 bunker C fuel oil could be burned under variable load conditions. Based on these test results, New England Power Service, Co. (2) demonstrated the overall feasibility of coal/oil mixture combustion in an 80 MW electric utility boiler. No significant ash deposition or slagging was experienced during the tests. Moreover, fine-sized particulate emissions were obtained.

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* Numbers in parenthesis refer to references at the end of this technical report.

The particulates from the coal-in-oil slurry were dry and fully combusted--characteristics similar to the ash product for pulverized coal boilers.

The technical requirements for this approach necessitate that a stable slurry be prepared and maintained under economically feasible conditions. Furthermore, large quantities of the fuel (coal/oil slurry) are needed in order to meet the full scale requirements of major utility boilers. The results of these technical needs have identified the fact that improved methods and equipment are therefore needed to provide the quantities of stable coal/oil slurries that are necessary in order to meet full scale boiler applications.

1.2 Background

In order to provide the slurry, it is necessary to emulsify the coal/oil mixture. The current available emulsification techniques utilize chemical additives in order to stabilize the slurry. The costs of these additives has become a significant portion of the overall economics related to the emulsification approach for reducing oil usage (3). This program addresses the use of an on-line emulsification process that utilizes the phenomenon of cavitation. Cavitating emulsifiers provide several technical advances over conventional state-of-technology emulsification systems (4). Included among these advances are: improved emulsification efficiency;

extended demulsification times; reduced fuel consumption; and reduced exhaust emissions. The improved emulsification efficiency and the extended demulsification times are the result of the cavitation process. Whereas, the reduced exhaust emissions are the result of emulsion combustion tests. These technical advantages are obtained from cavitating emulsifiers without the need or use of surface reducing agents (surfactants).

Initial research efforts into cavitation research for emulsification evaluated the feasibility of creating a stable emulsion for a mixture of 50 percent water and 50 percent No. 2 fuel oil. Figure 1 illustrates photomicrographs of the emulsification taken as the emulsion leaves the cavitation device and after 30 minutes. The range of water droplet size in the emulsion increased from a maximum of 1.0μ to 1.8μ. Figure 2 is an elapsed time photograph of the emulsification coefficient for the 50/50 fuel oil/water emulsion at two specific cavitation parameters. In addition to the photographic data, experiments were conducted in order to compare the demulsification times of various water percentage emulsions with state-of-technology emulsifiers. Figure 3 illustrates the demulsification time for three different water percentage emulsions created by cavitation and the associated emulsification coefficients with respect to the demulsification time for state-of-technology emulsifiers (5).

Addressing the feasibility that water-in-oil emulsions could be created using cavitation as a motivating factor, additional research was undertaken to obtain verification of the performance characteristics of emulsified fuels. Emulsions were subsequently tested as the fuel supply for a single cylinder diesel engine. As the test engine was operated, data was generated regarding engine performance and exhaust emissions. Several water percentage emulsions were evaluated at three different engine speeds. Figure 4 illustrates the statistical variance in the data obtained with respect to fuel consumption for one of the test conditions. The bars indicate a 90 percent confidence interval for the data obtained. At all values of indicated mean effective pressure, the indicated specific fuel consumption values were reduced using emulsified fuels. With respect to the exhaust emissions testing, four tests were conducted. Carbon monoxide, unburned hydrocarbons, oxides of nitrogen and particulates levels were measured. Particulates were measured in terms of Bosch smoke numbers. Figure 5 is an example of the emissions data gathered. In this instance, the NO_x levels decreased over the entire range of indicated mean effective pressures (6).

Because of these test results, emulsification work progressed with No. 6 bunker C fuel oil and water. In this regard, on-line cavitating emulsification systems have been placed on 100,000 lbs/hr steam boilers. To date, the test results indicate that the stack temperature has been reduced 40° F; the excess air has been reduced up to 60 percent; the sulfur plume has been eliminated and the fire side walls of the boiler are free of scale (7).

The results of the previous research efforts coupled with the fact that the cavitation process has no fluid flow rate or power limitation have led to the impetuous for the current program. This program addresses the development and evaluation of coal/oil/water slurry (COWS) emulsions produced by a cavitating on-line emulsification process.

1.3 Program Objectives

The major objective of this research effort was to evaluate the feasibility of producing a stable COWS emulsion utilizing cavitating emulsification technology. In order to meet this objective, the research program concentrated on the following areas of investigation:

1. The operational parameters of velocity, pressure, orifice size, intensity of cavitation, water droplet size, and percentage water added in order to produce a stable COWS emulsion were determined.
2. The experiments necessary to establish the emulsification parameters with respect to

system power requirements were performed.

3. The research effort was limited to a 30 percent by weight coal emulsion.

In addition to the original areas of concentration, the particle size distribution of the coal within the emulsion was also evaluated. While evaluating the distribution, an attempt was made to establish the size reduction of the coal particle as a result of exposure to the cavitating slurry. The data generated from the test results for evaluating these parameters can be used as design criteria for a prototype COWS emulsifier. COWS emulsions of 10 and 20 percent water were evaluated for particle size reduction.

1.4 Program Scope

In order to complete the established objectives, several specific evaluation experiments were conducted. Initial program activities were related to assembly of the emulsion production apparatus. A tank for making large test batch samples were constructed. The apparatus instrumentation was assembled and installed and the orifice plate sizes were determined. With this information, the five orifice plates to be evaluated were constructed.

Following the equipment construction, the emulsification characteristics were determined. The test samples were produced and cavitation parameters established for each test condition. For each test sample taken, an evaluation slide was produced and photomicrographs were taken. These photomicrographs were analyzed, and with the aid of a computer, histogram type particle distributions were established. Moreover, particle distribution data was correlated with the cavitation parameters to establish the degree of particle size reduction obtained.

This report discusses in detail the test procedure utilized to gather the data. Also addressed are the results of the data analysis and the salient findings of the research program. The last portion of this report addresses the conclusions which can be made from the data obtained and the recommendations which result from those conclusions.

2.0 DESCRIPTION OF EXPERIMENTAL EQUIPMENT AND TECHNIQUES

2.1 Laboratory Equipment

The COWS emulsification test apparatus was designed to determine the associated parameters for producing a stable emulsion from premixed coal and oil with water. The cavitation process used to create these emulsions and discussions of emulsion in general are detailed in Appendices A and B respectively of this report. To meet the established 30 percent by weight coal ratio for each batch tested, the amount of coal per batch size was established. Table 1 lists the coal quantities required.

The test apparatus consists of the process equipment and the emulsification equipment. Figure 6 is the flow diagram of the laboratory system which illustrates the equipment components. The COWS laboratory emulsification apparatus consists of four main sections: the mixture preparation, water injection, cavitation section, waste disposal. The coal/oil mixture was prepared in the mixture tank and agitated during operation to maintain coal particle suspension. This mixture was fed to the pump and water metered into the mixture at the appropriate amount. This slurry passed through the pump into the orifice flange assemble. At this point, the slurry was cavitated to emulsify the slurry and produce the COWS emulsion. The emulsion was then pumped to the slurry dump tank. Figure 7 is a flow schematic identifying the system components. The letter/number designations for each component shown in Figure 7 will be used as identification reference throughout this report. A front view and an isometric top view of the laboratory apparatus is photographically illustrated in Figures 8 and 9. Figure 8 is the front view of the equipment and shows the control panel, slurry bypass valves, pressure gauge and mixing tank. Figure 9 is a top view of the equipment in which the pump, motor, belt drive, and orifice flange are shown.

Referring to the flow schematic of Figure 7, premixed coal and oil was pumped from the 55 gallon thermostatically controlled mixing tank (T1) through a two inch diameter line to the pump inlet. The remainder of the system piping was one inch in diameter. A gate valve (V1) was used to isolate the mix tank when the system was not operating. A temperature indicator monitored the temperature of the mixture in order to maintain 180°±5°F. A 30 inch mercury vacuum gauge was installed at the pump inlet to insure pump inlet pressures between three and five inches of mercury during operation.

The pump used for the program was a screw type positive displacement pump. The specifications for this unit as supplied by the manufacturer are given in Figure 10. The pump was powered by a 3,600 rpm, 3 hp, 3ϕ, TEFC electric motor. A belt and pulley arrangement with a 4:1 speed ratio connected the pump and motor. At the pump outlet, a pressure switch and relief valve assured automatic system shutdown and overpressure protection. Discharge from the relief valve was connected to the mixing tank.

Flow proceeded downstream to a cross where, through a combination of valves (V2, V3, and V7), the slurry could be diverted back to the mixing tank, (T1), to the holding tank (T2), or through the orifice plate assembly. A one inch gate valve, (V4), was used to isolate the mixing tank from the emulsification system return line when the system was idle. The orifice plate assembly consisted of Class 600 1 1/2 inch ring joint orifice flange, sealing ring, and orifice plate. Differential pressure across the orifice plate assembly was controlled by varying the needle valve, (V6), downstream of the orifice plate assembly. A plug valve, (V5), installed in a tee between the orifice plate assembly and the needle valve, (V6), allowed samples of the COWS emulsions to be taken. Bourdon tube pressure gauges were installed on each side of the orifice plate assembly to monitor the operating pressure. A one inch globe valve, (V), was installed downstream of the needle valve, (V6), to isolate the orifice plate assembly from mixing tank to avoid siphoning while the orifice plates were being changed. A flow indicator was installed to indicate flow during system operation. The COWS emulsion was then discharged into the slurry holding tank, (T2). All fluid lines were capable of being heated to facilitate system start-up.

The water injection system consisted of three flow control valves, (V8, V9, and V10), a check valve, flowmeter and pressure gauge arranged in a flow divider circuit. The system operated off of tap pressure and injected water into the inlet side of the emulsification system pump. The amount of water was metered through the two needle valves, (V8, and V9), with the three way valve,(V10), in the position shown in Figure 7. After setting the desired flowrate, the three way valve, (V10), was shifted allowing water to flow to the emulsification system. The water injection pressure was kept low to prevent contamination of the mixing tank.

2.2 Experimental Techniques

2.2.1 Sample Preparation

Bituminous coal supplied by the Pittsburgh Energy Technology Center (PETC) was used for this program. The coal was prepulverized to an 80 percent No. 200 mesh screen size. The fuel used for the program was No. 6 bunker C fuel oil and was supplied by a local vendor. The coal and oil were mixed in batches in a heated, thermostatically controlled 55 gallon mixing tank. Typical batch sizes ranged from 42 to 50 gallons. This program was limited to investigations of 30 percent by weight coal/oil mixtures. Table 1 shows the weights and volumes used to obtain a 30 percent by weight coal/oil mixture. For a given amount of coal/oil mixture, a known volume of No. 6 bunker C fuel oil was metered into the mixing tank. The necessary amount of coal, determined from Table 1, was then weighed and added to the tank. The emulsification system inlet and discharge gate valves were closed for this operation to prevent the unmixed coal from settling. As the coal was weighed into the mix tank, a constant speed propeller type mixer was used to disperse the coal. After the proper amount of coal was added, the coal/oil mixture was mixed for a minimum of two hours. This assured that a homogenous mixture would be delivered to the COWS emulsification system (8).

2.2.2 System Operation

Operation of the COWS emulsification system was standardized to conserve the supply of coal and to minimize testing errors. Following the preparation of the batch of coal/oil mixture, a small (approximately 75 ml.) sample was collected from the mixing tank by surface skimming with a clean glass jar. The contents of the jar were transferred to a 25 mm x 250 mm culture tube, labeled, and capped. The electrical heaters to the COWS emulsification system were turned on.

The gate valves isolating the mixing tank from the emulsification system were opened. The globe valves V3 and V7 were closed and V2 was opened. The pump was turned on and a sample of the coal/oil mixture was collected in another culture tube, labeled, and capped. The globe valve V7 and needle valve V6 were then opened and globe valve V2 was then closed. This allowed the coal/oil mixture to flow through the orifice plate assembly. At this time, the pump flow rate was determined by timing the discharged flow into a graduated container. A third sample was collected in a culture tube by bleeding off through plug valve V5. For a given orifice plate and flow rate, the cavitation parameters were determined measuring the differential pressure across the orifice plate assembly. The pressure across the orifice plate assembly was varied by adjustment of the needle valve V6. Typically four to seven samples were collected in this manner.

The range of cavitation parameters investigated represent a series of cavitating jets from the supercavitating region to inception of cavitation. The test procedure was repeated with the addition of 10 percent and 20 percent water. The water was metered in by adjustment of valves V8, V9, and V10. With valve V10 in the "bypass" position as shown in Figure 7, needle valves V8 and V9 were adjusted so that an amount of water equal to either 10 percent or 20 percent of the coal/oil mixture flow rate was flowing through the water flowmeter. After the flow stabilized, valve V10 was shifted to the "inject" position. Samples of the coal/oil/water mixture were then collected by bleeding from plug valve V5 into culture tubes.

2.2.3 Photomicrographic Technique

The following procedure was used in the analysis of each culture tube sample. Two glass microscope slides were cleaned. A small spatula was inserted into the top of the culture tube and a drop of the sample placed on the surface of one slide (9). One to three drops of 100 percent No. 6 bunker C fuel oil were added to the slide to dilute the sample. This dilusion was necessary in order to obtain photomicrographs in which the coal appeared as distinct particles. Crowding of the coal particles resulted in the image analysis apparatus reading several small, close coal particles as a single large feature.

A second slide was placed over the first and allowed to settle for one to three minutes. This allowed a translucent layer of the mixture to form when the slides were separated. The slide was placed on the microscope and focused with a magnification of 100x at the eyepiece (75x at the focal plane). This allowed approximately 500 particles per field of view. Photomicrographs were taken of the slide sample and were analyzed using an image analyzer. Data from the image analyzer was input to the computer which determined the coal particle size distribution. The results were printed out in the form of a histogram with the number percent of particles as a function of coal particle length in microns.

2.3 Experimental Test Matrix

Three nozzle orifice diameters were selected for evaluation. The orifice diameters ranged from 0.662 to 0.077 inches. For each nozzle plate, three main experimental sequences were conducted and each sequence consisted of a minimum of four test runs. The test sequences were conducted to establish nozzle operational parameters and evaluate the addition of two different percentages of water. The individual test runs were used to evaluate nozzle performance with respect to cavitation parameter. The evaluated cavitation parameter range was 2.0×10^3 to 16.0×10^3.

As each nozzle plate experimental process was initiated, the system was operated without the addition of water. This sequence was utilized to define upstream and downstream pressures required to obtain the cavitation parameter range and to define the cavitation inception parameter for that nozzle. Once the upstream pressure was established, the downstream pressure was varied between 0 and 100 psi and the cavitation parameter established. In addition, flow rate measurements were made and the nozzle velocity and loss coefficient were calculated. This procedure was repeated two more times. The second sequence was utilized to make the same measurements as a 10 percent COWS emulsion was produced. The third sequence evaluated these parameters with respect to production of a 20 percent COWS emulsion. This complete procedure was carried out for each of the three nozzle plates used in the experimental evaluation. Table 2 summarizes the data collection process. The test numbers are repeated for each test run which was reproduced as a result of any requirement to verify the test information.

3.0 DISCUSSION OF EXPERIMENTAL RESULTS

3.1 Nozzle Selection

In order to relate COWS emulsions to previous emulsification efforts, the nozzles to be evaluated had to be determined. The nozzle diameter range of interest was based on research tests conducted with No. 6 bunker C fuel oil. Figure 11 illustrates the range of nozzle orifice diameters of interest. The nozzle pressure differential is plotted as a function of the nozzle diameter for different flow rates. The pressure differential is the difference between the upstream pressure (UPS) and the downstream pressure (DPS). From this information, three orifice diameters were determined which would operate within the specific cavitation. These orifice diameters were 0.0624, 0.0695, and 0.0765 inches respectively. The three orifice plates were constructed of AISI 86 L 20 case hardened chomium-nickerl-molybdenum steel. This steel was selected on the basis of: ability to develop a hard, wear resistant case; low distortion during heat treatment; ease to machine; and general availability of the material.

3.2 Experimental Data Analysis

3.2.1 Parameter Analysis and Observations

With the nozzles constructed, tests were conducted in accordance with the procedure previously discussed in Section

2. Table 2 summarizes the data obtained from the experiments with these three orifice plates. The nozzle number, slurry and water flow rates, upstream and downstream pressures, associated cavitation parameter and associate loss coefficient were recorded. For each test condition, two factors remained constant. The percentage of coal in the slurry was maintained at 30 percent, and the operating temperature of the system was kept at a constant $180^0 \pm 5^0$ F.

For the three nozzles evaluated, upstream pressures ranged from 300 to 425 psi depending upon the orifice being tested. Control of the downstream pressure established the cavitation parameters for each test sequence. Downstream pressures ranged from 0 to 100 psi for all nozzles. This established values of the cavitation parameter (σ) ranging from 2.0×10^3 to 16.0×10^3 for each nozzle tested.

The slurry flow was established at approximately 2 gpm and varied slightly depending upon the nozzle orifice diameter. The water flow rate varied with each test and with each nozzle and was dependent upon the desired percentage of water emulsion being evaluated for the specific test. Water flow ranged from a low of 0.18 gpm for nozzle number 4 to a high of 0.49 gpm for nozzle number 3.

The final characteristic analyzed and recorded in Table 2 was the loss coefficient. Loss coefficient (C_V) is a measure of the nozzle efficiency as expressed in terms of nozzle velocity. For each velocity that was established, there was an associated ideal velocity. The ratio of measured velocity to ideal velocity is defined as loss coefficient. For the three nozzles evaluated the loss coefficient range from 0.85 maximum obtained for nozzle number 3 to 0.73 minimum obtained for nozzle number 5.

The major purpose for conducting these tests was to evaluate the effect of the cavitation on coal particle size in the emulsions. In order to accomplish this task, test samples were extracted from different locations in the test loop. These samples were utilized to produce slide samples which, in turn, were used in the microscopic analysis. However, with samples from single pass cavitation exposure, subjective evaluation of the emulsion stability was performed. The COWS emulsions were observed to remain completely stable for periods of up to five minutes at 180^0 F. After five minutes globules of water were observed suspended in the samples. The water droplet sizes that were obtained range from one to ten micrometers.

3.2.2 Coal Particle Size Analysis

In order to relate the cavitation parameter to reduction of coal particle size, a series of samples which had undergone various degrees of cavitation were collected. These samples were used to produce microscope slides from which photomicrographs were taken. The photomicrographs were analyzed and the coal particle size distributions were established. Table 3 lists the photomicrographs utilized in the analysis process to determine the particle size distribution. For each nozzle, samples were obtained from various points in the experimental apparatus loop. The samples taken from the mixing tank and the pump outlet were used as input particle size control samples. The samples marked as having been taken at other conditions represent the samples from the system which had been exposed to various degrees of cavitation.

Figures 12, 13, and 14 are representative examples of the photomicrographs taken for each nozzle evaluation. On each figure, there appears three photomicrographs. The first two are the control samples and the third shows the particles after exposure to cavitating slurry. Subjective analysis of the photomicrographs on any of these figures indicated that a particle size reduction has occurred as a result of exposure to the cavitation. A total of 23 of these photomicrographs were taken and utilized in the analysis process.

An image analyzer with output coupled to a computer was utilized to establish distinct particle size distribution information. Table 4 summarizes the particle distribution data with respect to the cavitation parameter associated with each test sample. Included in this table was the operating conditions, cavitation parameter, degree of cavitation and coal particle size. The two terms which appear in the coal particle size column are the mean particle size (μ_c) and the particle size standard deviation (σ_c). An example of the actual histogram data from the image analyzer is shown in Figure 15. This example was obtained from the photomicrograph sample taken from test runs with nozzle plate number three. The test was conducted at a cavitation parameter of 6.6×10^3. This histogram was a good example of all the information obtained from the image analyzer. The remaining histogram data is included in Appendix C of this report.

In order to better visualize the histogram information in Figure 15, the data was plotted in standard statistical frequency distribution form. This plot is shown in Figure 16. From an examination of Figure 16, it was noted that the particle sizes ranged from 1μ to 60μ. The largest number of particles were approximately 5μ in diameter. The statistical calculations from this data indicated the mean particle size (μ_c) to be 9.2μ. The standard deviation (σ_c) for this particle size distribution was 6.7μ.

The obtained distribution exhibited positive skewness rather than taking the form of a theoretically normal, bell shaped, distribution curve. Similar distributions can be obtained from the additional histograms for future comparison.

A thorough evaluation of all of the histogram information illustrated that in all cases a degree of particle size reduction was obtained for an associated cavitation number. For nozzle number 3 operating at a degree of cavitation of 5.9×10^3 an approximate 2μ reduction was obtained. With nozzle number 5 an approximate 3μ reduction was obtained from operations at a 2.3×10^3 degree of cavitation. For nozzle number 4 at a condition of 2.5×10^3 for the degree of cavitation, an approximate 2μ size reduction was indicated. The standard deviation in the case of nozzle number 4 did not show the same degree of reduction as the size distribution. For this reason no clearly established size reduction was established. However, with nozzles 3 and 5 not only was the size reduced but also the standard deviation was reduced by the appropriate degree. For these nozzles and cavitation numbers, the data did indicate that a size reduction was obtained.

3.3 Equipment Limitations Analysis

3.3.1 Orifice Limitations

The experimental procedures have characterized that the operation of a COWS system has certain nozzle orifice limitations. The system as designed was apparently orifice size limited. The operations with nozzle number 4 illustrated this limitation. Nozzle number 4 clogged during operation in its original configuration. However, modifying the nozzle orifice diameter by 0.001 inches was enough to allow the test data to be generated.

Operations with the next larger orifice resulted in only minor clogging of the nozzle. This nozzle was not affected by the slurry as much as the addition of the water into the slurry eliminated the problem.

The largest orifice diameter nozzle plate was not influenced by the clogging problem. As a result of these activities, the limitation of the orifice was size related. In order to insure that size was the limiting factor, additional equipment modifications were made and tests conducted.

The system pump speed was adjusted and the driver pulley of the system was reduced. This change decreased the speed ratio. The ratio was decreased to 3.6:1 which increases the pump flowrate by 12 percent. However, these pump and motor modifications resulted in no significant reduction of the fouling problem in the smaller orifice diameter nozzle plates. Section 3.3.3 discusses the design modifications that can be made to the system in order to circumvent the nozzle fouling from the coal particles.

3.3.2 Component Limitations

Due to the abrasive nature of the COWS slurry, certain components such as the close tolerance pump experienced an abnormal amount of wear. Another component which showed sizes of significant wear was the flow control valves. The wear which occurred was the result of the high velocity of the slurry within the narrow passages of these components. This wear results in a loss of efficiency in the components in question.

Although the nozzle did not see the exposure time that the permanant components did, there was no apparent wear on any of the nozzle plates tested. These plates were constructed with the fact that cavitation erosion would be present and therefore were constructed of a wear-resistant material. Similar pump component specifications should be considered as a method of overcoming this limitation.

3.3.3 Equipment System Design Modifications to Eliminate Orifice Restriction

With the several test experiences as motivation, a design modification of the COWS emulsification system was considered as a method for elimination of the above discussed technical restriction. The major problem, both from the abnormal wear and nozzle clogging standpoint, was the necessity to pump a coal/oil mixture. If the coal can be added downstream of the orifice assembly, this would eliminate both the wear problem and the clogging problem.

Emulsions of water and oil have been created with this principle for some time and no previous wear or clogging problems had been encountered. If the mixture of oil and water entered the orifice then the pump, control valves and orifice would not see the abrasive coal slurry as they were affected during this research effort. However, to establish the stable COWS emulsion the coal must be added into the influence of the cavitation envelope. This technical problem became the objective of the design modification.

Cavitation creates a localized low pressure region which approaches low vacuum pressures. The modification was based on this cavitation condition as a method of adding the coal. The coal can be added immediately downstream of the orifice into the low pressure area and would then be exposed to the bubble collapse to create the stable emulsion. Figure 17 illustrates the system modification in a modified flow diagram. The incorporation of this design change should allow a stable COWS emulsion to be produced.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the data obtained during these research efforts. In addition to the laboratory data, subjective observations and deductions made during the data gathering have contributed to these conclusions and recommendations.

4.1 Conclusions

1. The cavitating emulsification system was able to create coal/oil/water slurry (COWS) emulsions which remain stable for up to five minutes with an emulsification coefficient (K_e) equal to 1.0.
2. The COWS emulsion contained water droplets ranging in size from one to ten microrons (μ).
3. The cavitation present in the cavitating emulsifier was sufficient to cause reductions in coal particle size.
4. From the data obtained, the nozzle which produced the COWS emulsion with the best results as well as an apparent reduction in coal particle size was the 0.077 inch diameter orifice. The particular conditions for which this occurred were:

   Upstream Pressure (UPS) = 300 psi

Downstream Pressure (DPS)	=	30 psi
Loss Coefficient (C_v)	=	0.85
Cavitation Parameter (σ)	=	6.6×10^3
Degree of Cavitation ($\sigma i - \sigma$)	=	5.9×10^3

5. The coal particle size reduction was obtained with two of the nozzles operating with a degree of cavitation of approximately 3.0×10^3.
6. Abrasive wear in the system components can be eliminated by correct component selection and system design. The nozzle plate material was selected for its erosion resistance in order to protect it from cavitation damage. The nozzle plates showed no signs of wear at the conclusion of the testing. This protection as well as the elimination of the nozzle clogging problem can be concluded if the design modifications discussed in Section 3.3.3 are incorporated.

4.2 Recommendations

1. It is recommended that experiments be conducted with the coal dust added to the emulsion immediately downstream of the nozzle. This modification will eliminate the wear characteristics of pumping the slurry while maintaining exposure to the cavitation. This design modification would also provide

several other advantages. The nozzle clogging would no longer be a problem because the coal would be added beyond the nozzle orifice. Moreover, this modification would allow the system to function at higher pressure differentials because the pump efficiency would not be reduced and the coal would not block the nozzle. The higher pressures would permit high intensities of cavitation to be obtained. Furthermore, if concluded, the design modification would also allow the potential for greater percentages of coal to be added into the COWS emulsion.

2. It is recommended that the principle of cavitation erosion technique be considered as a method of coal pulverization. This method of coal pulverization could be incorporated into a supply line and coal pulverized as it is being transported. The method indicates that very little energy is required for large pulverized coal output. The concept to be examined is including cavitating nozzles in a section of the supply pipe wall which would then pulverize the coal in anticipation of producing the 200 mesh size required for boiler feed.
3. It is recommended that the COWS emulsification efforts be pursued. Continued experimentation into

the modified system can move this effort rapidly into the design of a prototype COWS emulsifier for industrial size boiler operation.

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Gallons of Mixture	Gallons of Oil Necessary	Lbs. of Coal Necessary	Gallons of Mixture	Gallons of Oil Necessary	Lbs. of Coal Necessary
9	7	22	33	26	85
10	8	27	34	27	89
12	9	31	36	28	93
14	11	36	38	30	98
15	12	40	39	31	102
17	14	45	41	32	107
19	15	49	43	34	111
21	16	53	45	35	116
22	18	58	46	37	120
24	19	62	48	38	125
26	20	67	50	39	129
27	22	71	51	41	134
29	23	76	53	42	138
31	24	80	55	43	142

TABLE 1 AMOUNT OF COAL NECESSARY TO OBTAIN A 30% BY WEIGHT COAL/OIL MIXTURE FOR VARIOUS AMOUNTS OF MIXTURE.

TABLE 2 SUMMARY CHART OF DATA COLLECTED WITH THE THREE NOZZLE ORIFICE PLATES

USP = Upstream Pressure
DSP = Downstream Pressure
C_v = Loss Coefficient
σ = Cavitation Parameter

Coal: 30% by weight
Temperature: 180 ± 5° F

Test No.	Time	Slurry Flow (GPM)	Orifice Number	Orifice Dia. (in.)	USP (PSIG)	DSP (PSIG)	Water Flow (GPM)	$\sigma \times 10^3$	C_v
1	467.4	2.5	3	0.0765	Mix Tank				
2	467.4	2.5	3	0.0765	Pump Outlet				
3	467.4	2.5	3	0.0765	280	0		2.2	0.85
4	467.4	2.5	3	0.0765	to	20		5.1	0.85
5	467.4	2.5	3	0.0765		30		6.6	0.85
6	467.4	2.5	3	0.0765	300	50		9.6	0.85
7	472.1	2.5	3	0.0765	psi	70 = σ_i		12.5	0.85
1	472.1	2.5	3	0.0765	300	0	0.245	2.2	0.84
2	472.1	2.5	3	0.0765	300	20	0.245	5.1	0.84
3	472.1	2.5	3	0.0765	300	30	0.245	6.6	0.84
4	472.1	2.5	3	0.0765	300	50	0.245	9.6	0.84
5	476.7	2.5	3	0.0765	300	70 = σ_i	0.245	12.5	0.84
6	476.7	2.5	3	0.0765	300	0	0.49	2.2	0.83
7	476.7	2.5	3	0.0765	300	20	0.49	5.2	0.83
8	476.7	2.5	3	0.0765	300	30	0.49	6.6	0.83
9	476.7	2.5	3	0.0765	300	50	0.49	9.6	0.83
10	487.6	2.5	3	0.0765	300	70 = σ_i	0.49	12.6	0.83
1	487.6	1.9	4	0.062	Mix Tank				
2	490.1	1.9	4	0.062	Pump Outlet				
No sample from cavitator outlet due to intermittent clogging of the orifice plate					525	0			
3	490.1	2.0	5	0.0685	390	0		2.2	0.73

TABLE 2 CONTINUED SUMMARY CHART OF DATA COLLECTED WITH THE THREE NOZZLE ORIFICE PLATES

Coal: 30% by weight
Temperature: 180 ± 5° F

Test No.	Time	Slurry Flow (GPM)	Orifice Number	Orifice Dia. (in.)	USP (PSIG)	DSP (PSIG)	Water Flow (GPM)	$\sigma \times 10^3$	C_v
4	490.1	2.0	5	0.0685	390	20		5.2	0.73
5*	No sample due to pressure fluctuations				390	30			
6*	No sample due to pressure fluctuations				390	50			
7*	No sample due to pressure fluctuations				390	85 = σ_i			
8	490.1	2.0	5	0.0685	390	60		11.2	0.73
9	490.1	2.0	5	0.0685	390	75		13.4	0.73
10	490.1	2.0	5	0.0685	390	90 = σ_i		15.7	0.73
11	490.1	2.0	5	0.0685	390	0	0.2	2.2	0.74
12	490.1	2.0	5	0.0685	390	20	0.2	5.2	0.74
13	490.1	2.0	5	0.0685	390	30	0.2	6.7	0.74
14	490.1	2.0	5	0.0685	390	40 - 50	0.2	8.9	0.74
15	490.1	2.0	5	0.0685	390	75	0.2	13.4	0.74
16	490.1	2.0	5	0.0685	375	75 [90 = σ_i]	0.2	15.7	0.74
17**	490.1	2.0	5	0.0685	375	0	0.4	2.2	0.74
18**	490.1	2.0	5	0.0685	375	20	0.4	5.2	0.74
19**	490.1	2.0	5	0.0685	375	30	0.4	6.7	0.74
20**	490.1	2.0	5	0.0685	375	40 - 50	0.4	9.0	0.74
21**	506.7	2.0	5	0.0685	375	$100<\sigma_i<120$	0.4	18.7	0.74
1	522.5	1.8	4	0.062	Mix Tank				
2	522.5	1.8	4	0.062	Pump Outlet				
3	522.5	1.8	4	0.062	425	0		1.8	0.77
4	522.5	1.8	4	0.062	425	20		4.3	0.77

* Indicates pressure pulses > 5 psig
** Addition of water increases σ_i .

TABLE 2 CONTINUED SUMMARY CHART OF DATA COLLECTED WITH THE THREE NOZZLE ORIFICE PLATES

Coal: 30% by weight
Temperature: 180 ± 5° F

Test No.	Time	Slurry Flow (GPM)	Orifice Number	Orifice Dia. (in.)	USP (PSIG)	DSP (PSIG)	Water Flow (GPM)	$\sigma \times 10^3$	C_v
5	522.5	1.8	4	0.062	425	30		5.5	0.77
6	522.5	1.8	4	0.062	425	50		7.9	0.77
7	522.5	1.8	4	0.062	425	60		9.2	0.77
8	522.5	1.8	4	0.062	425	75		11.0	0.77
9	522.5	1.8	4	0.062	425	95 = σ_i		13.5	0.77
10	531.6	1.8	4	0.062	425	0	0.18	1.8	0.77
11	531.6	1.8	4	0.062	425	20	0.18	4.3	0.77
12	534.1	1.8	4	0.062	425	35	0.18	6.1	0.77
13	534.1	1.8	4a****	0.063	420	75	0.18	11.9	0.75
14	534.1	1.8	4a****	0.063	420	95 = σ_i	0.18	14.5	0.75
15	534.1	1.8	4a****	0.063	420	0	0.36	2.0	0.74
16	534.1	1.8	4a****	0.063	420	25	0.36	5.3	0.74
17	534.1	1.8	4a****	0.063	420	35	0.36	6.6	0.74
18	534.1	1.8	4a****	0.063	420	50	0.36	8.6	0.74
19***	540.0	1.8	4a****	0.063	420	75	0.36	11.9	0.74

*** Orifice clogs intermittently so testing was discontinued at this point.
**** Orifice clogs. Rebored to 0.063" and tests continued.

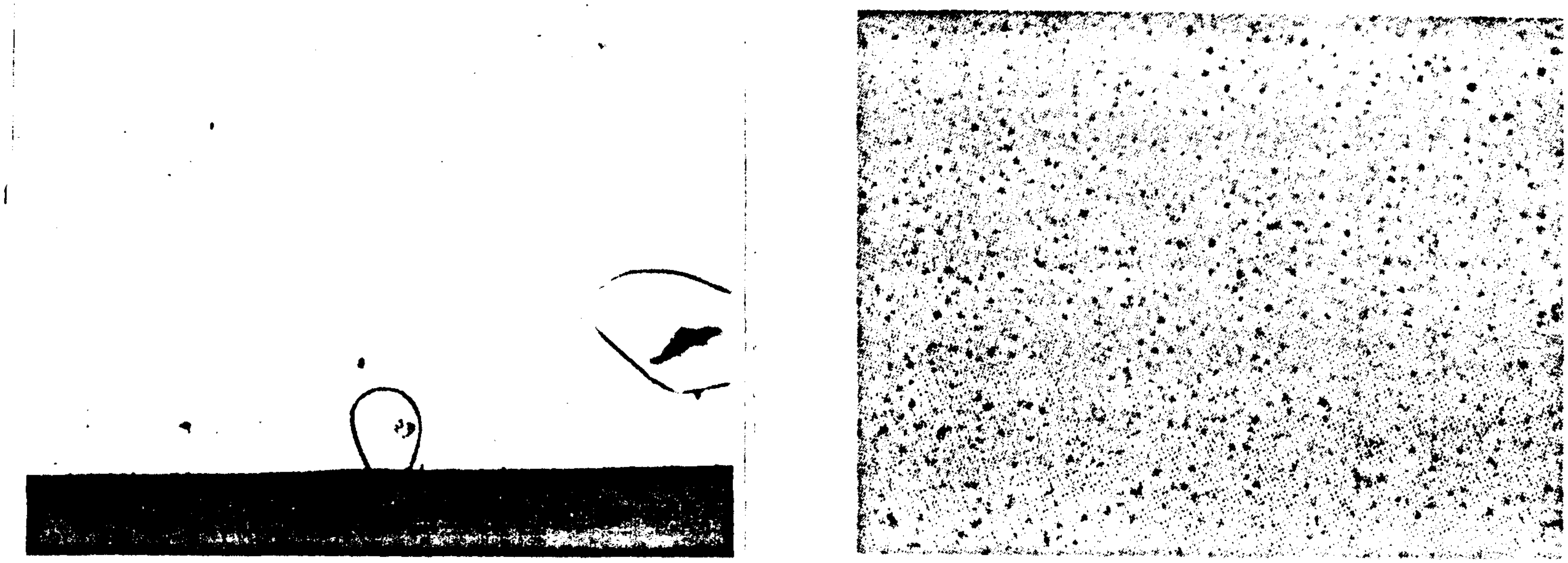
USP = Upstream Pressure
DSP = Downstream Pressu

Photo No.	Code No.	Sample Conditions (USP/DSP)-Orifice No.	Magnification
1	5/14/79 1	Mix Tank	75 X
2	5/14/79 2	Pump Outlet	75 X
3	5/14/79 3	300/0 -3	75 X
4	5/14/79 4	300/20 -3	75 X
5	5/14/79 5	300/30 -3	75 X
6	5/14/17 6	300/50 -3	75 X
7	5/14/79 7	300/70 -3	75 X
8	5/16/79 1	Mix Tank	75 X
9	5/16/79 2	Pump Outlet	75 X
10	5/16/79 3	390/0 -5	75 X
11	5/16/79 4	390/20 -5	75 X
12	5/16/79 8	390/60 -5	75 X
13	5/16/79 9	300/75 -5	75 X
14	5/16/79 10	390/90 -5	75 X
15	5/17/79 1	Mix Tank	75 X
16	5/17/79 2	Pump Outlet	75 X
17	5/17/79 3	425/0 -4	75 X
18	5/17/79 4	425/20 -4	75 X
19	5/17/79 5	425/30 -4	75 X
20	5/17/79 6	425/50 -4	75 X
21	5/17/79 7	425/60 -4	75 X
22	5/17/79 8	425/75 -4	75 X
23	5/17/79 9	425/95 -4	75 X

TABLE 3 LIST OF PHOTOMICROGRAPHS ANALYZED FOR COAL PARTICLE SIZE DISTRIBUTION

TABLE 4 REDUCED DATA SUMMARIZING THE RELATION BETWEEN CAVITATION PARAMETER (σ), DESIGN OF CAVITATION ($\sigma - \sigma_i$), COAL PARTICLE SIZE (μ_c, σ_c)

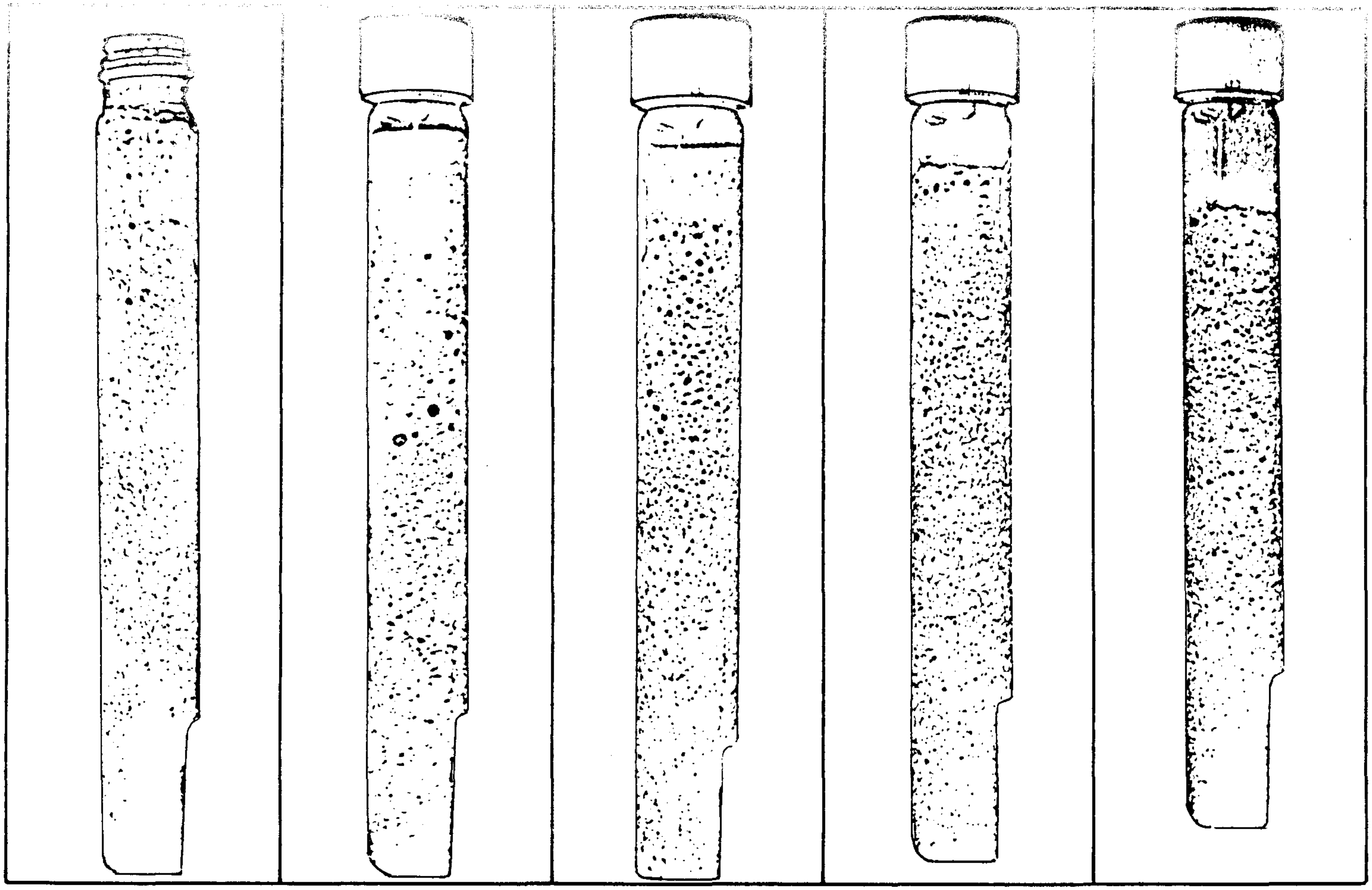
Photo No.	Code No.	Sample Conditions USP/DSP - Orifice No.	Orifice Diameter (inches)	Loss Coefficient (C_v)	Cavitation Parameter ($\sigma \times 10^3$)	Degree of Cavitation ($\sigma_i - \sigma$) $\times 10^3$	Coal Particle Size (μ_c, σ_c) Micrometers	
1	5/14/79-1	Mix Tank					11.4	9.2
2	5/14/79-2	Pump Outlet					11.2	8.1
3	5/14/79-3	300/0 - 3	0.077	0.85	2.2	10.3	9.0	5.5
4	5/14/79-4	300/20 - 3	0.077	0.85	5.1	7.4	12.0	8.9
5	5/14/79-5	300/30 - 3	0.077	0.85	6.6	5.9	9.2	6.7
6	5/14/79-6	300/50 - 3	0.077	0.85	9.6	2.9	11.5	10.6
7	5/14/79-7	300/70 - 3	0.077	0.85	12.5 = σ_i	0.0	10.8	7.3
8	5/16/79-1	Mix Tank					12.5	8.6
9	5/16/79-2	Pump Outlet					12.6	9.1
10	5/16/79-3	390/0 - 5	0.069	0.73	2.2	13.5	11.2	7.0
11	5/16/79-4	390/20 - 5	0.069	0.73	5.2	10.5	11.4	8.0
12	5/16/79-8	390/60 - 5	0.069	0.73	11.2	4.5	11.8	7.7
13	5/16/79-9	390/75 - 5	0.069	0.73	13.4	2.3	8.5	4.7
14	5/16/79-10	390/90 - 5	0.069	0.73	15.7 = σ_i	0.0	13.9	11.1
15	5/17/79-1	Mix Tank					15.9	17.3
16	5/17/79-2	Pump Outlet					14.9	17.4
17	5/17/79-3	425/0 - 4	0.062	0.77	1.8	11.7	15.3	10.3
18	5/17/79-4	425/20 - 4	0.062	0.77	4.3	9.2	13.5	10.7
19	5/17/79-5	425/30 - 4	0.062	0.77	5.5	8.0	14.3	10.8
20	5/17/79-6	425/50 - 4	0.062	0.77	7.9	5.6	13.8	10.0
21	5/17/79-7	425/60 - 4	0.062	0.77	9.2	4.3	14.5	8.9
22	5/17/79-8	425/75 - 4	0.062	0.77	11.0	2.5	12.3	10.7
23	5/17/79-9	425/95 - 4	0.062	0.77	13.5 = σ_i	0.0	13.0	8.3



- 50/50 OIL IN WATER EMULSION AT TIME = 0 MIN.
- 0.3µ TO 1.0µ DROPLET SIZE

- 50/50 OIL IN WATER EMULSION AFTER 30 MIN.
- 0.7µ TO 1.8µ DROPLET SIZE

FIGURE 1 PHOTOMICROGRAPHS SHOWING REPRESENTATIVE DROPLET SIZES PRODUCED BY THE DAEDALEAN EMULSIFICATION EQUIPMENT (DIESEL FUEL AND WATER)



20 MINUTES
K_e = 0.982
200 MINUTES

50 MINUTES
K_e = 0.965
500 MINUTES

100 MINUTES
K_e = 0.956
1000 MINUTES

200 MINUTES
K_e = 0.912
2000 MINUTES

500 MINUTES
K_e = 0.860
5000 MINUTES

FIGURE 2 ELAPSED TIME PHOTOGRAPHS OF 50/50 FUEL/WATER EMULSION FROM THE DAI EMULSIFICATION FACILITY WITH A 0.030 INCH DIAMETER EMULSIFIER ORIFICE AND A 0.033 VALUE FOR THE CAVITATION PARAMETER.

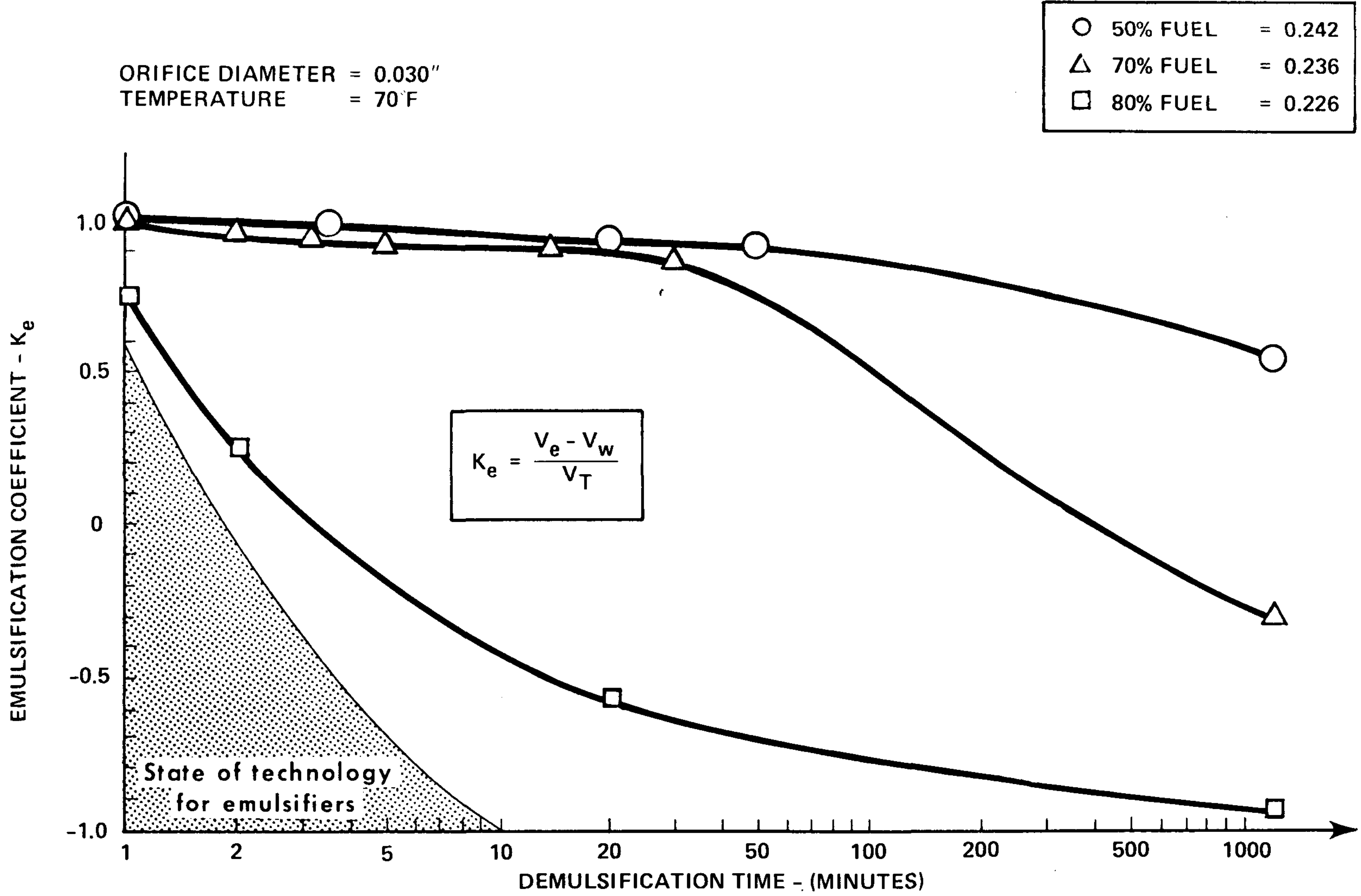


FIGURE 3 RELATIONSHIP OF EMULSIBILITY COEFFICIENT TO DEMULSIFICATION TIME WITH RESPECT TO FUEL/WATER CONCENTRATION FOR A 0.030 INCH DIAMETER EMULSIFIER ORIFICE AND A 0.23 MEAN VALUE FOR THE CAVITATION PARAMETER (σ).

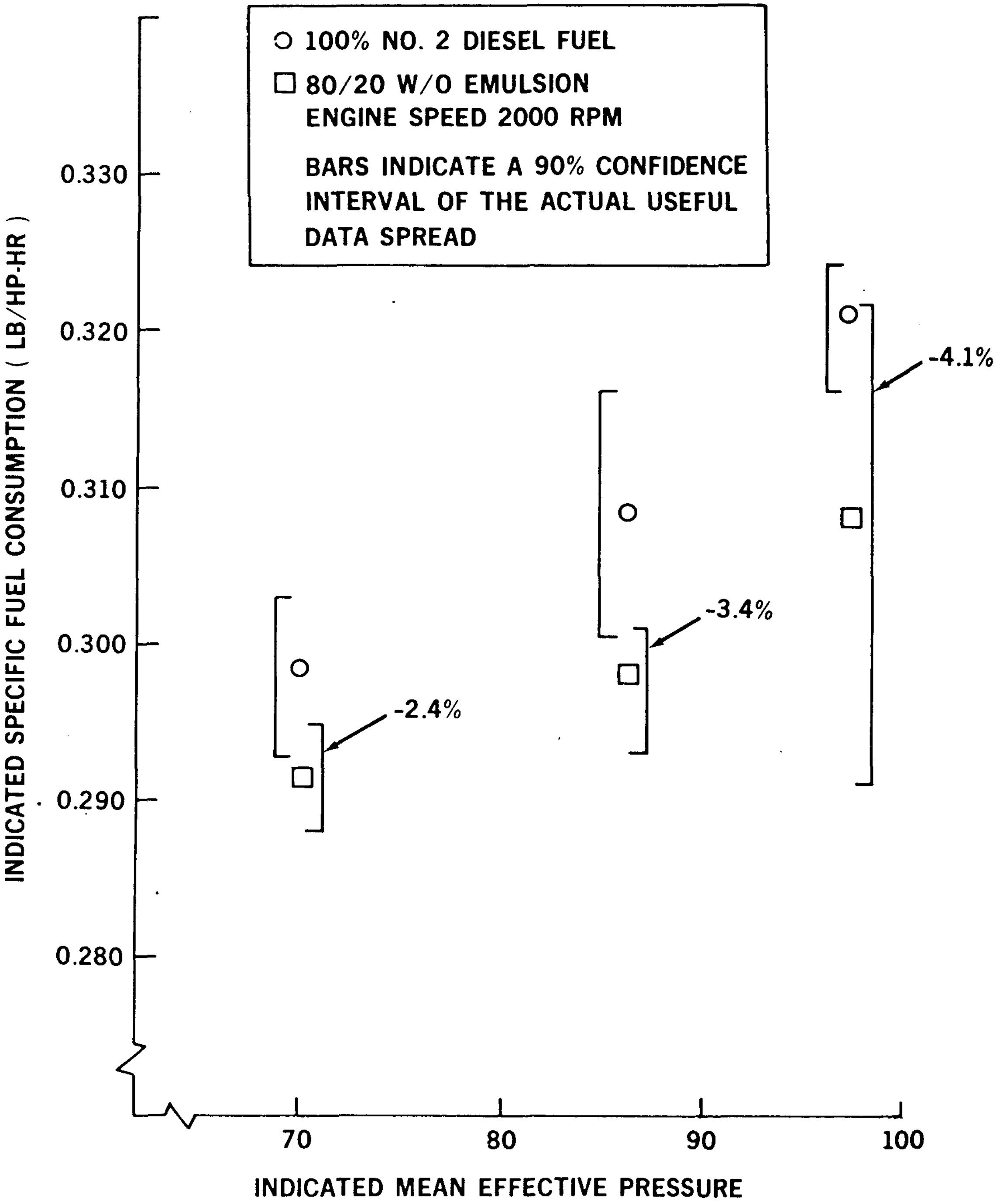


FIGURE 4 PERFORMANCE DATA OF A SINGLE CYLINDER DIESEL ENGINE SHOWING IMPROVEMENTS IN FUEL ECONOMY THROUGH A REDUCTION IN INDICATED SPECIFIC FUEL CONSUMPTION WHEN UTILIZING THE DAI ON-LINE EMULSIFICATION DEVICE (PRELIMINARY RESULTS)

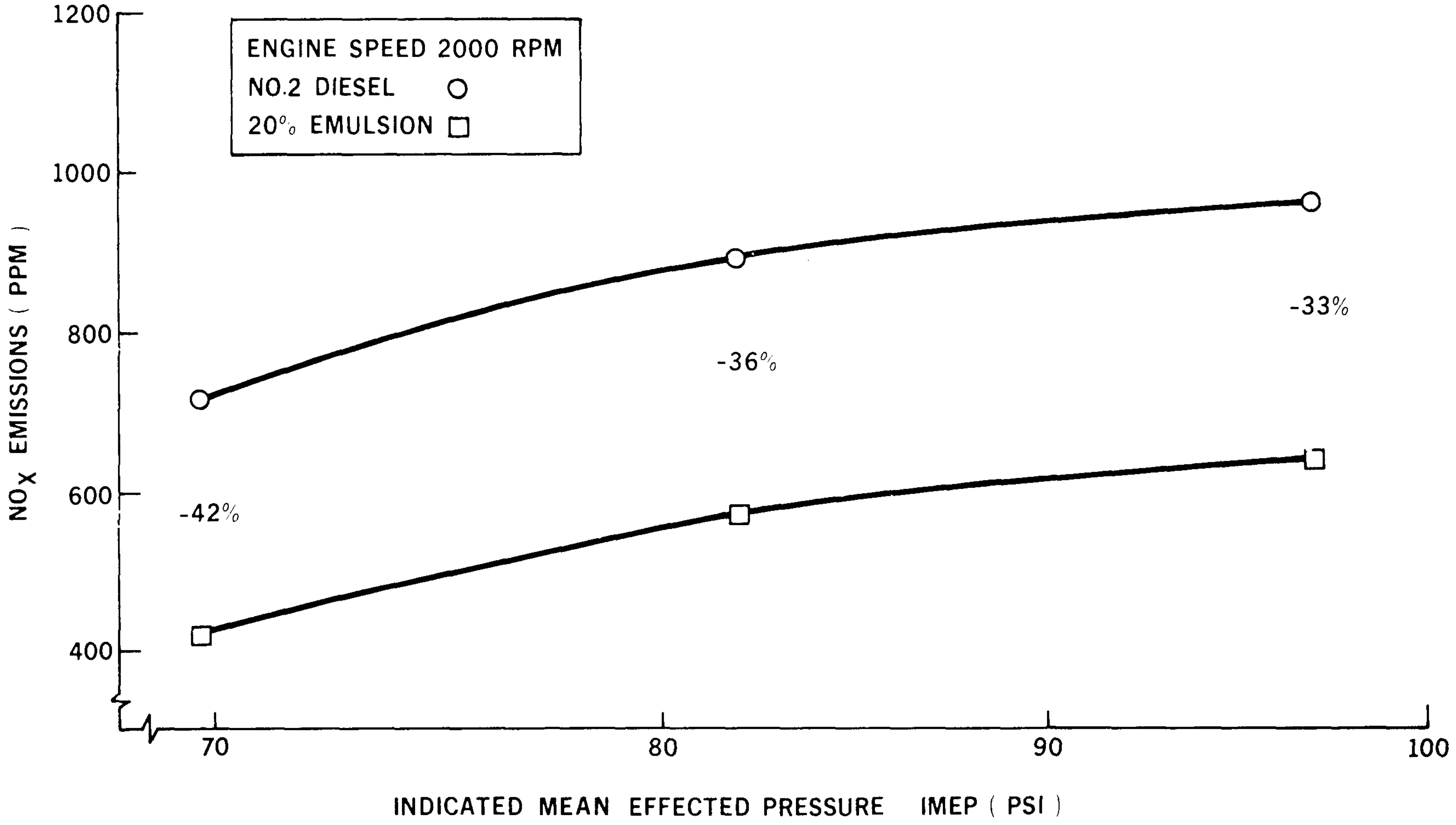


FIGURE 5 NITROGEN OXIDE COMPOUND EMISSIONS TEST DATA AS TAKEN DURING OPERATION OF A SINGLE CYLINDER DIESEL ENGINE

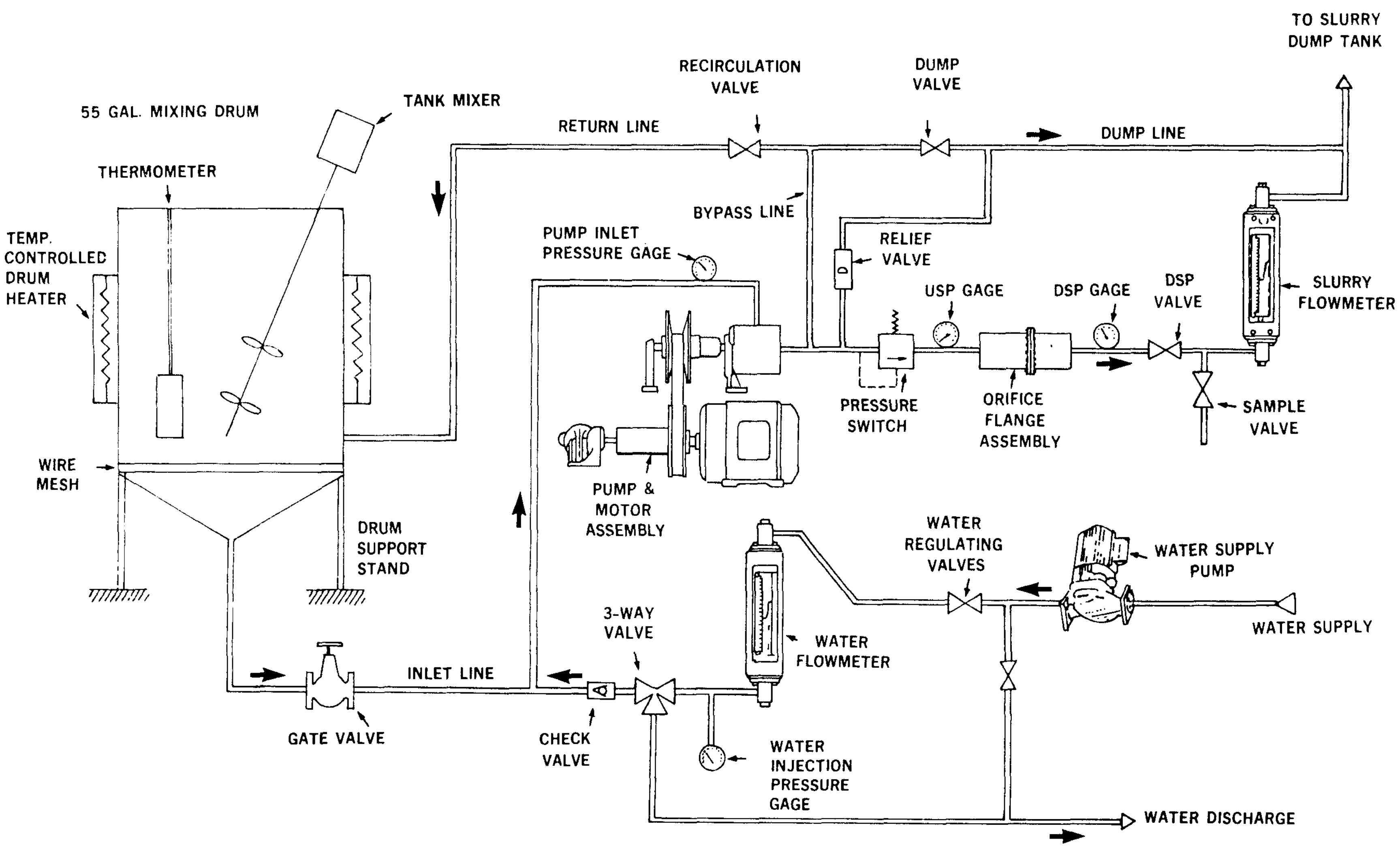


FIGURE 6 FLOW DIAGRAM OF COWS LABORATORY EMULSIFICATION SYSTEM

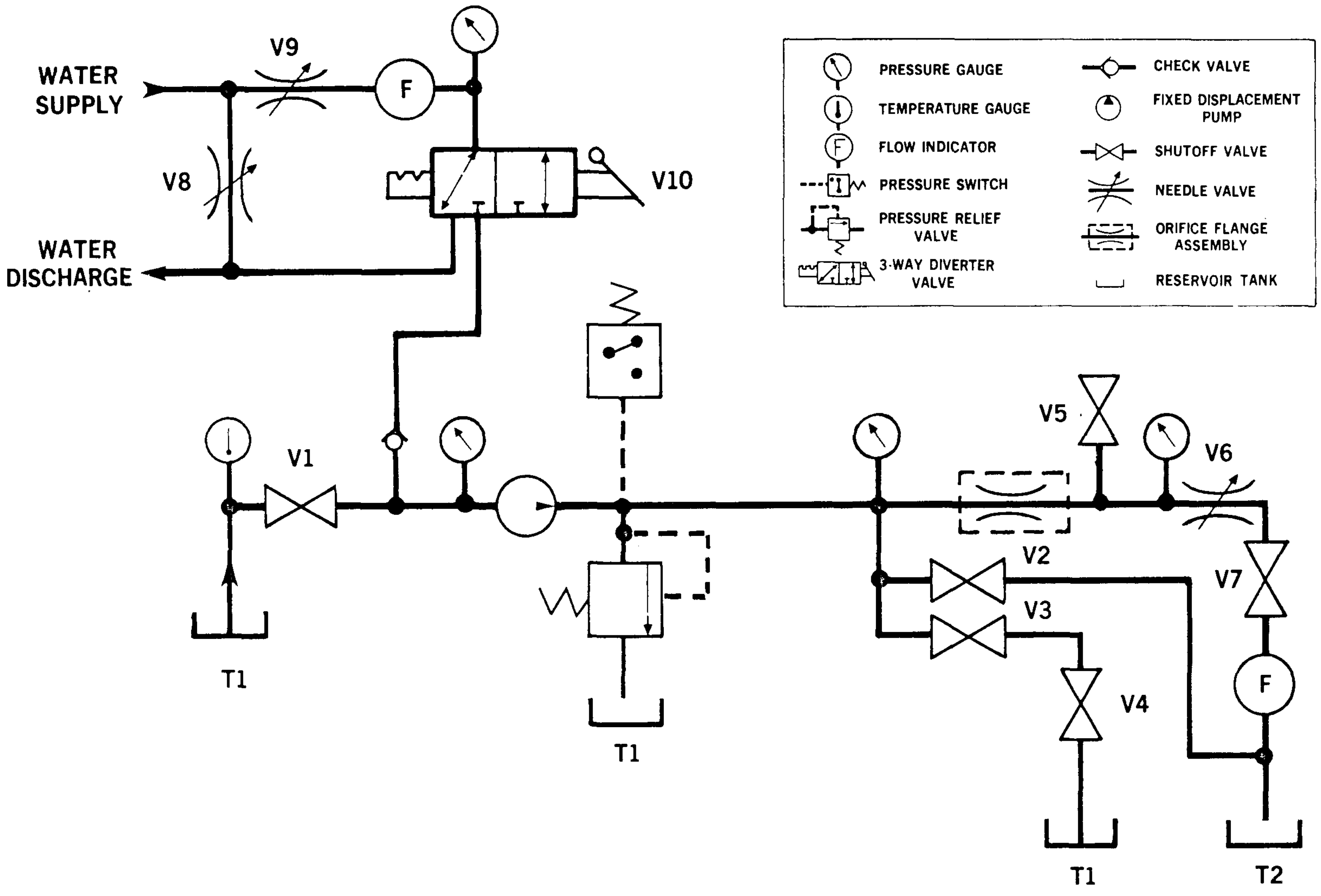


FIGURE 7 FLOW SCHEMATIC OF COWS EMULSIFICATION SYSTEM

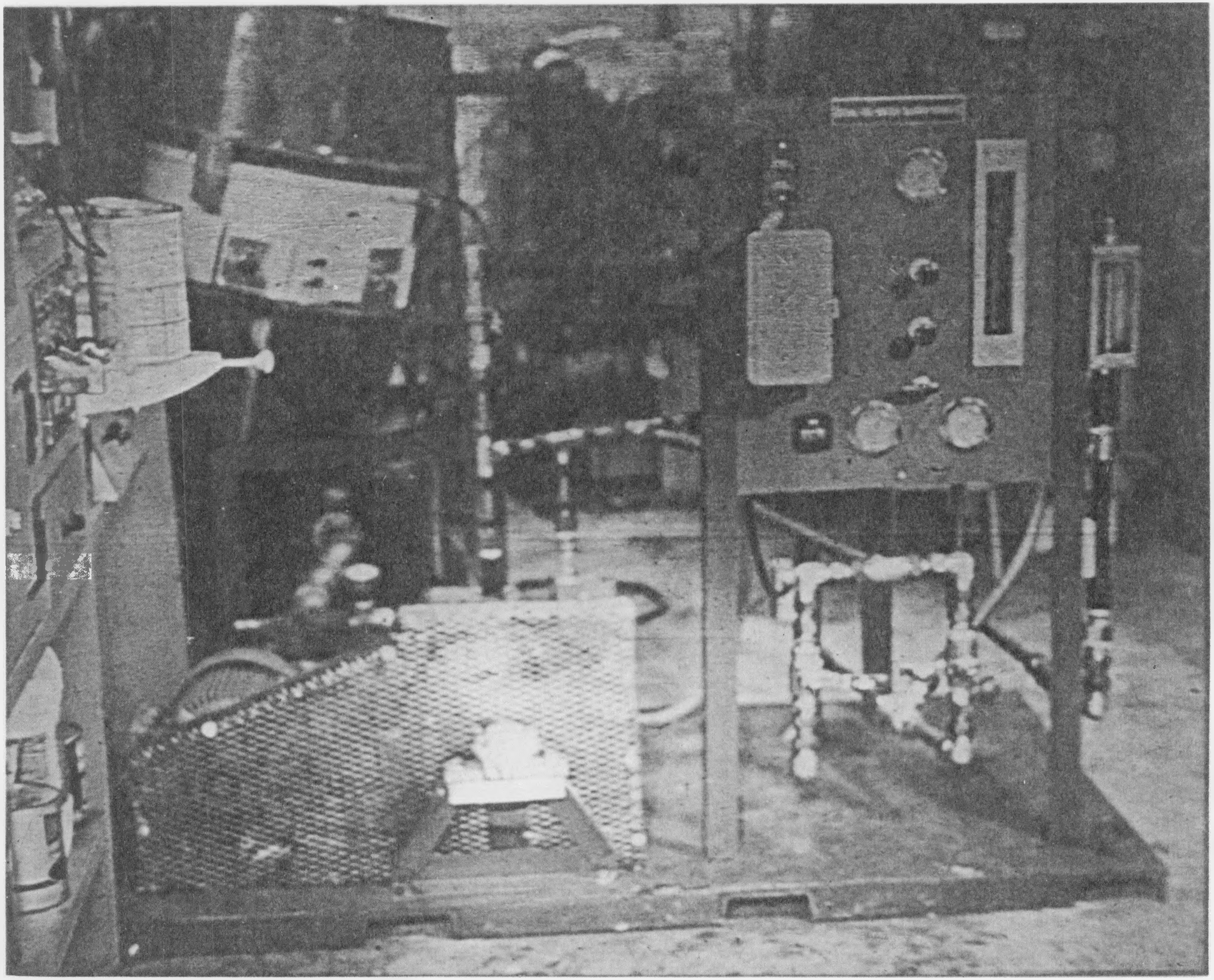


FIGURE 8 FRONT VIEW OF COWS EMULSIFICATION SYSTEM

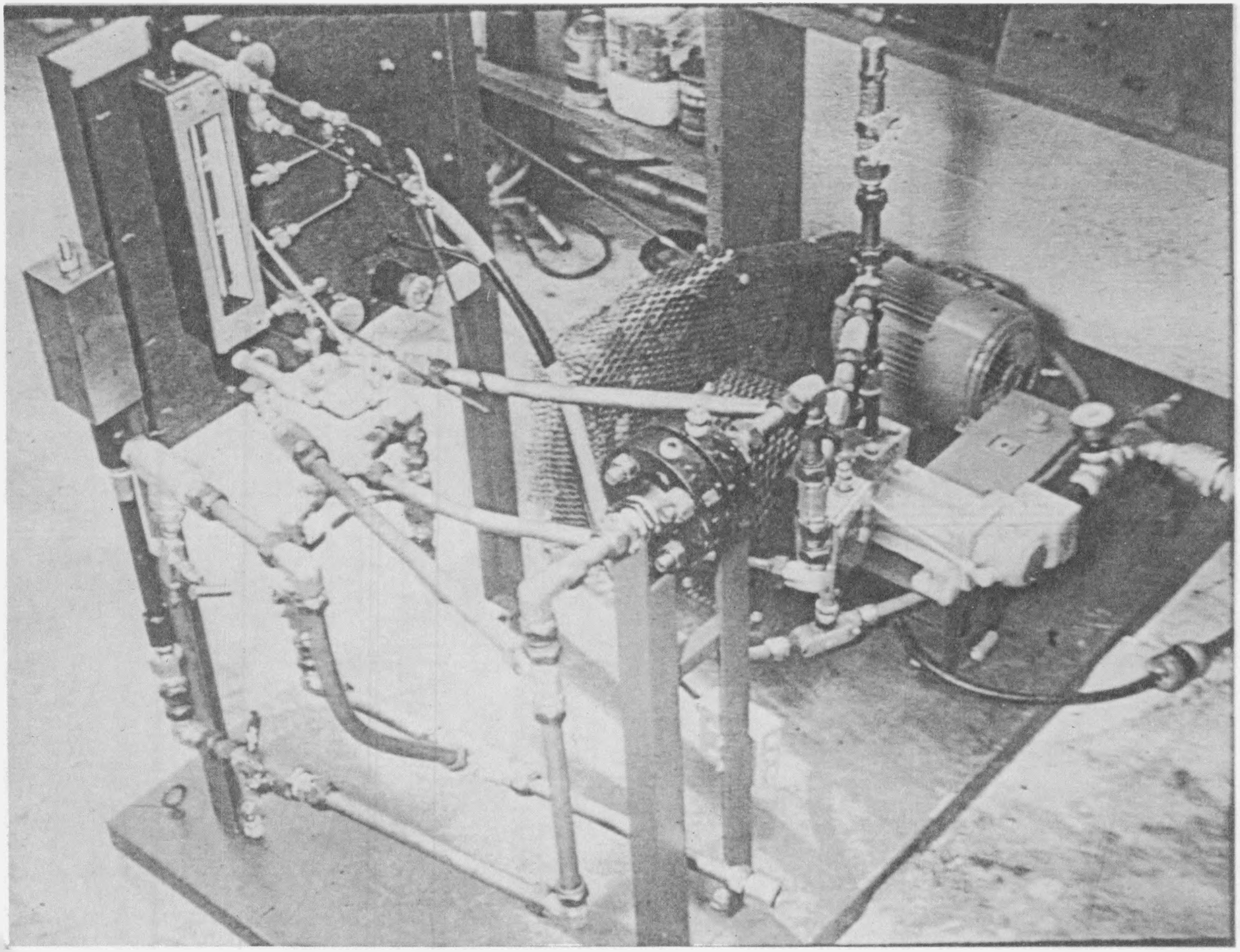


FIGURE 9 REAR VIEW OF COWS EMULSIFICATION SYSTEM

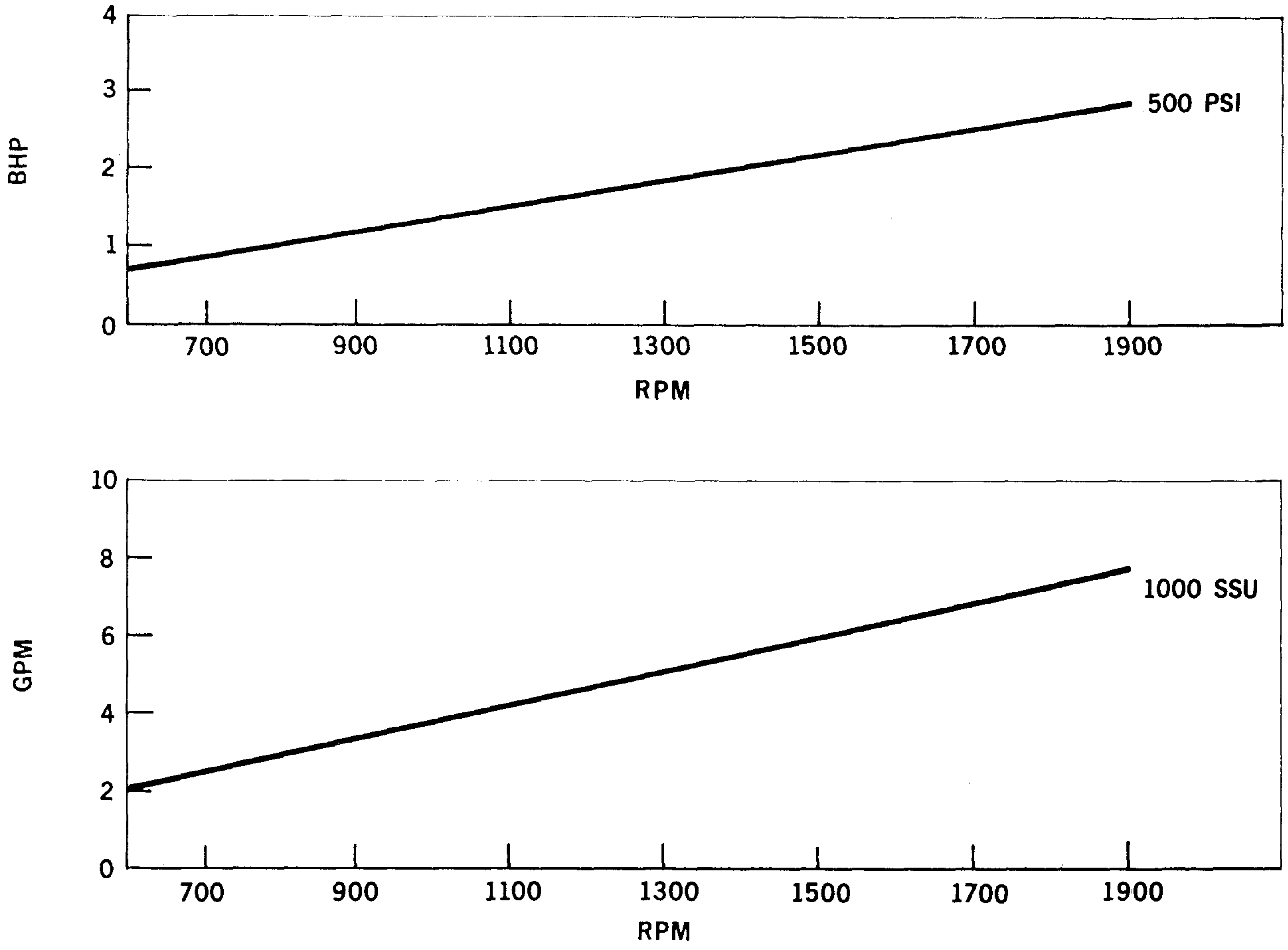


FIGURE 10 BRAKE HORSEPOWER AND FLOWRATE (GPM) AS A FUNCTION OF PUMP SPEED FOR THE COWS EMULSIFICATION SYSTEM PUMPING UNIT.

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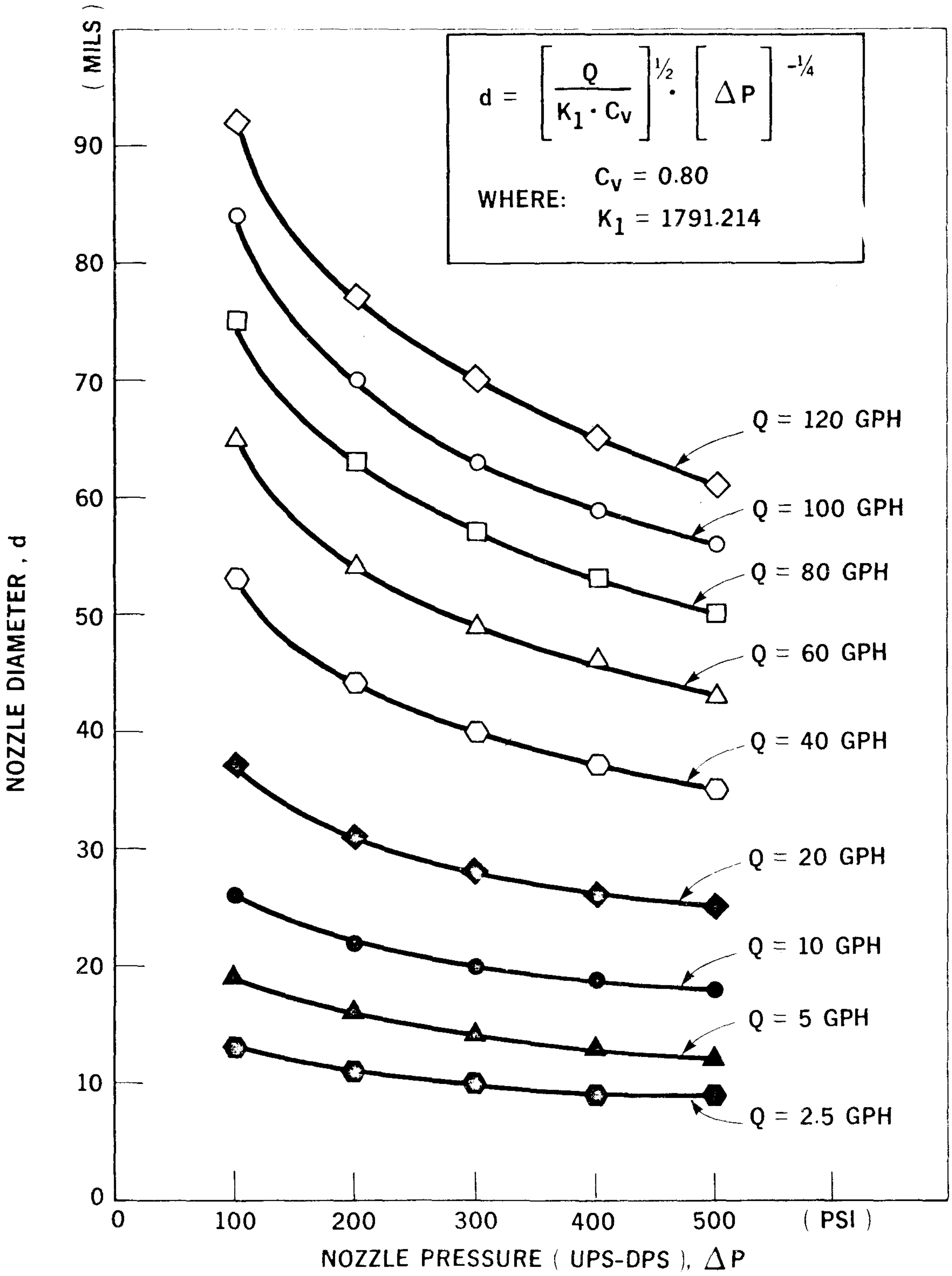
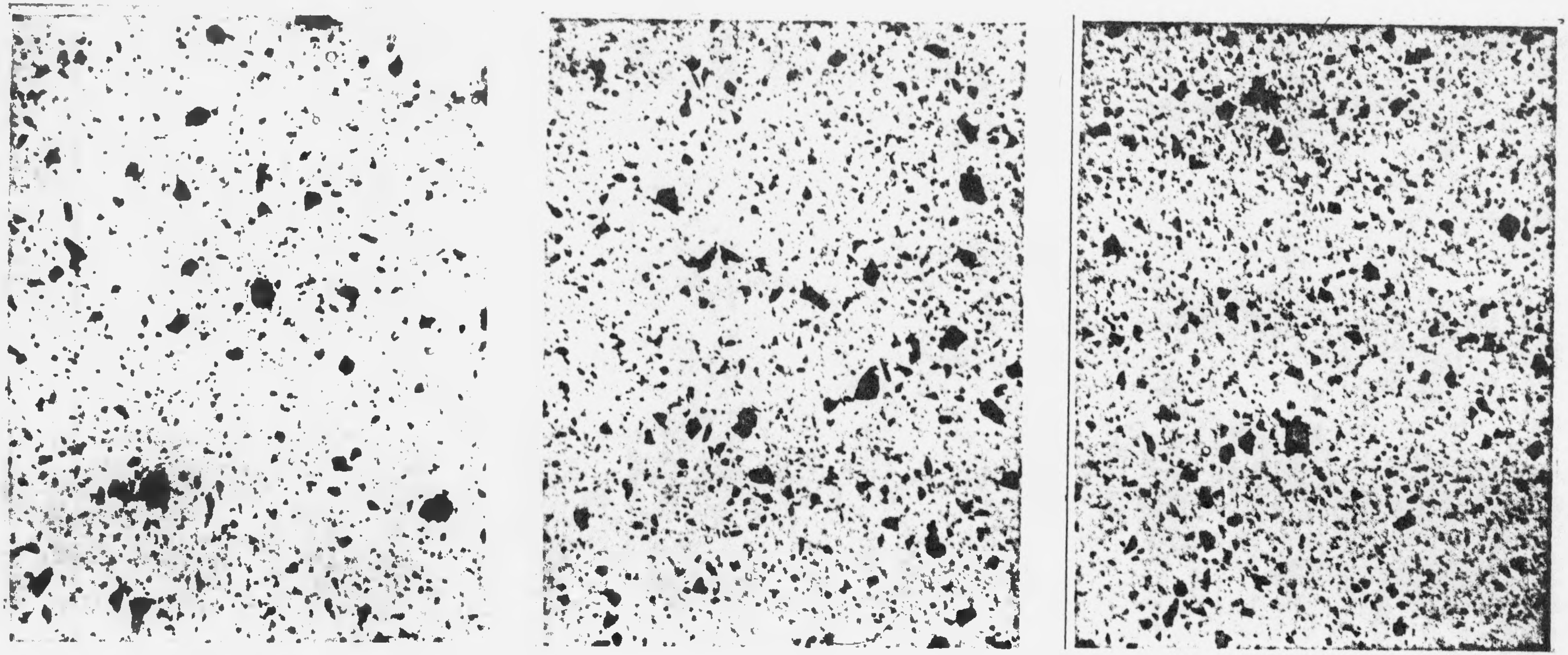


$$d = \left[\frac{Q}{K_1 \cdot C_V}\right]^{1/2} \cdot \left[\Delta P\right]^{-1/4}$$

WHERE: $C_V = 0.80$

$K_1 = 1791.214$

FIGURE 11 RANGE OF NOZZLE DIAMETERS OF INTEREST AS A FUNCTION OF NOZZLE PRESSURE BASED ON NO. 6 FUEL OIL TESTS

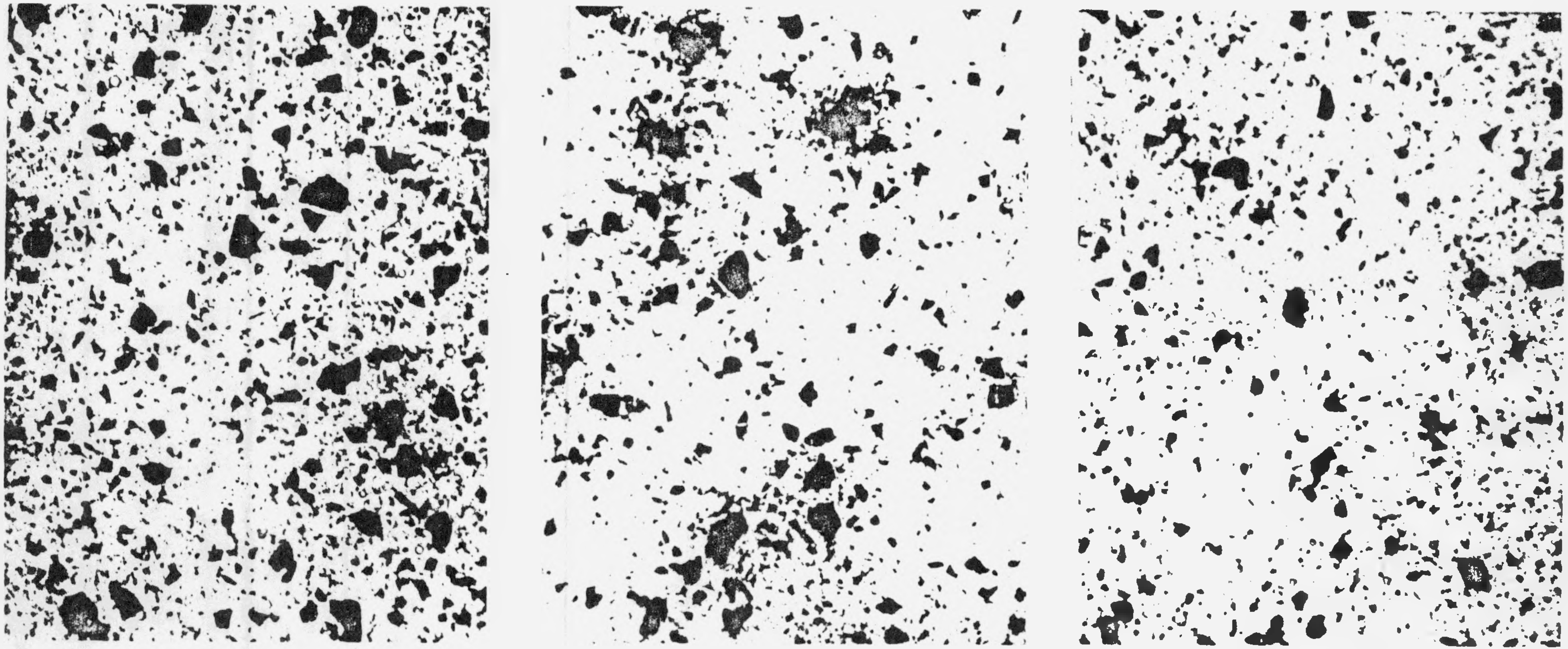


MIX TANK

PUMP

ORIFICE PLATE 3

FIGURE 12 PHOTOMICROGRAPHS OF COAL-OIL MIX TANK SAMPLE, PUMP SAMPLE, AND AFTER PASSING THROUGH ORIFICE PLATE NO. 3.

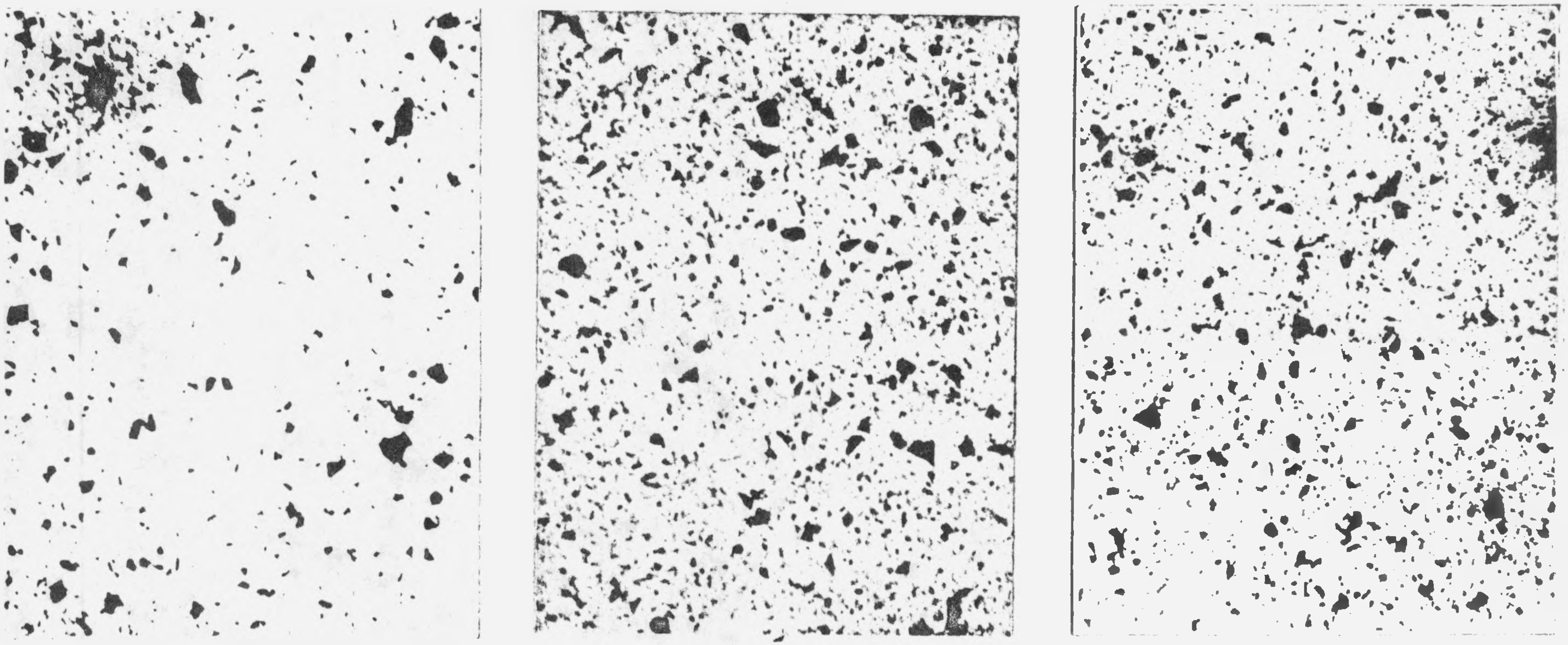


MIX TANK

PUMP

ORIFICE PLATE 4

FIGURE 13 PHOTOMICROGRAPHS OF COAL-OIL MIX TANK SAMPLE, PUMP SAMPLE , AND AFTER PASSING THROUGH ORIFICE PLATE NO. 4.



MIX TANK

PUMP

ORIFICE PLATE 5

FIGURE 14 - PHOTOMICROGRAPHS OF COAL-OIL MIX TANK SAMPLE, PUMP SAMPLE, AND AFTER PASSING THROUGH ORIFICE PLATE NO. 5.

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                         FREQUENCY DISTRIBUTION

      MICROMETERS              NUMBER OF PARTICLES

       0        TO 2           8      **
       2        TO 4           23     ******
       4        TO 6           145    ************************************
       6        TO 8           87     **********************
       8        TO 10          96     ************************
       10       TO 12          42     ***********
       12       TO 14          13     ***
       14       TO 16          21     *****
       16       TO 18          8      **
       18       TO 20          20     *****
       20       TO 22          6      **
       22       TO 24          5      *
       24       TO 26          4      *
       26       TO 28          3      *
       28       TO 30          0
       30       TO 32          1
       32       TO 34          0
       34       TO 36          0
       36       TO 38          1
       38       TO 40          0
       40       TO 42          0
       42       TO 44          1
       44       TO 46          1
       46       TO 48          1
       48       TO 50          1
       50       TO 52          0
       52       TO 54          2      *
       54       TO 56          0
       56       TO 58          0
       58       TO 60          0
       60       TO 62          0
       62       TO 64          0
       64       TO 66          0
       66       TO 68          0
       68       TO 70          0
       70       TO 72          0
       72       TO 74          0
       74       TO 76          0
       76       TO 78          0
       78       TO 80          0
       80       TO 82          0
       82       TO 84          0
       84       TO 86          0
       86       TO 88          0
       88       TO 90          0
```

FIGURE 15 COAL PARTICLE SIZE DISTRIBUTION
5/14/79 #5 300/30 ORIFICE PLATE 3

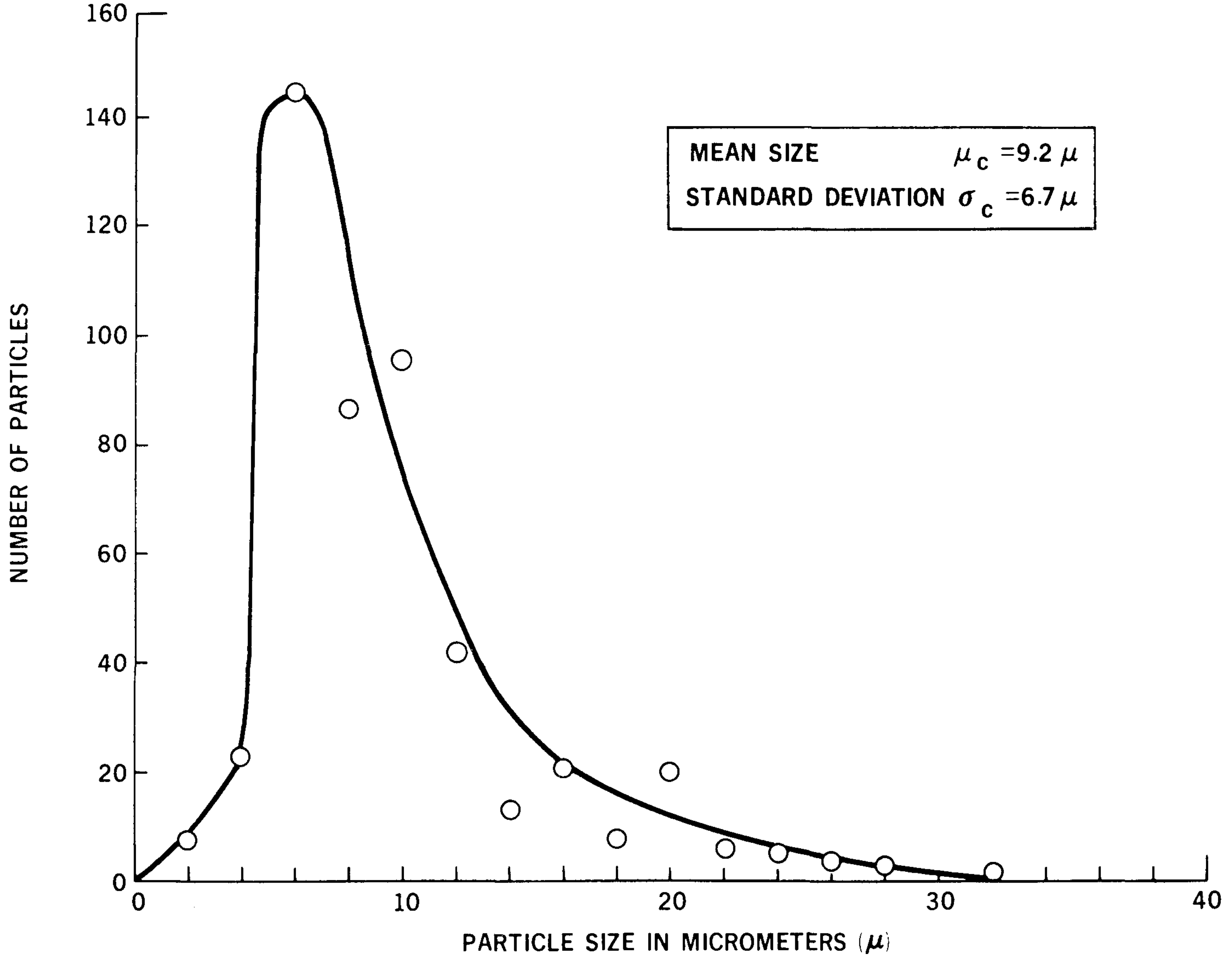

FIGURE 16 THE PARTICLE DISTRIBUTION AS A FUNCTION OF PARTICLE SIZE FORM THE IMAGE ANALYSIS DATA - 5/14/79 #5 - 300/30

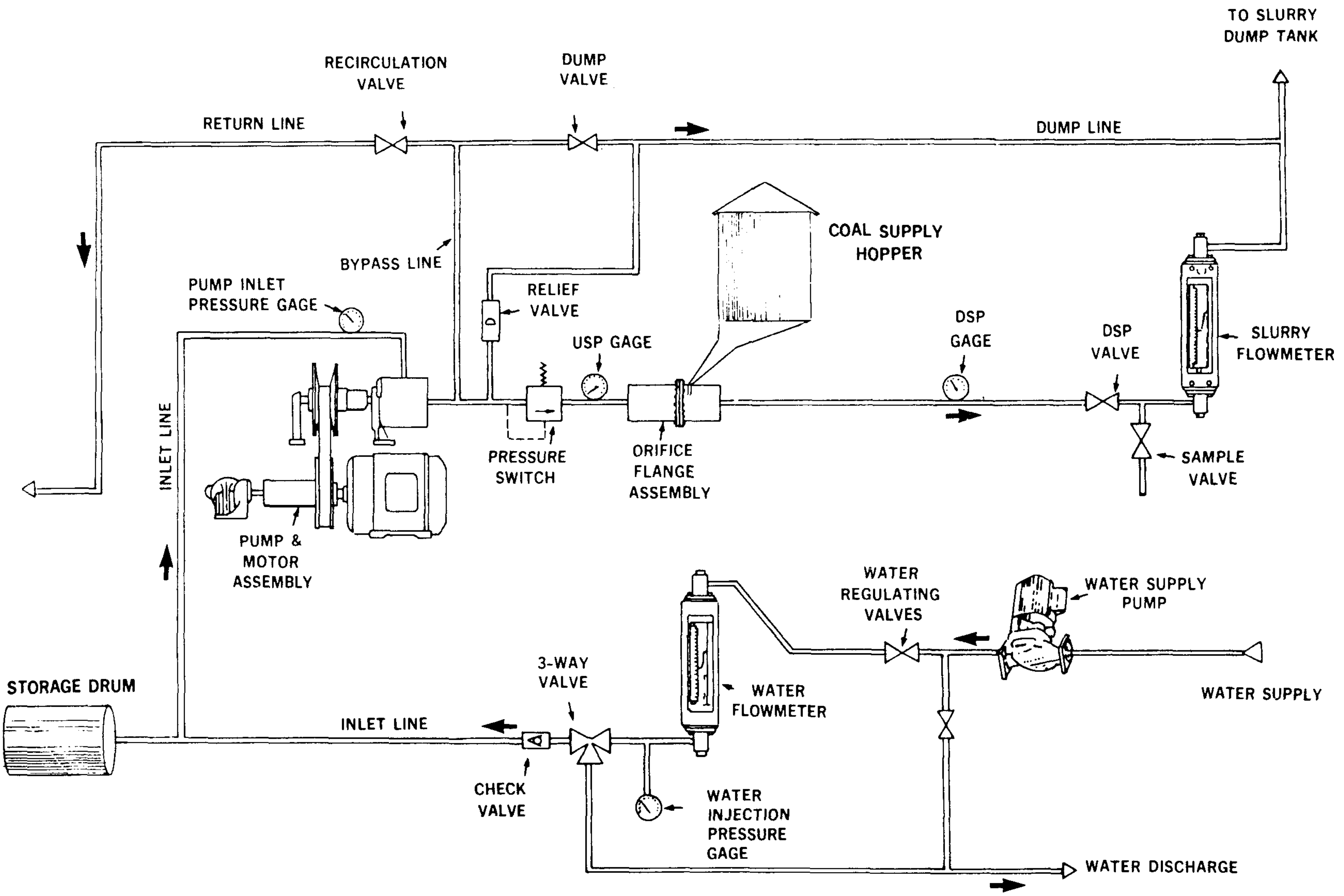

FIGURE 17 FLOW DIAGRAM OF COWS LABORATORY EMULSIFICATION SYSTEM WITH DESIGN MODIFICATIONS TO SOLVE SLURRY PUMPING LIMITATION

APPENDIX A

DESCRIPTION OF CAVITATION PHENOMENON

In engineering contexts, cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. In general, a liquid is said to cavitate when vapor bubbles are observed to form and grow as a consequence of pressure reduction. When the phase transition is a result of pressure changed by hydrodynamic means, a two-phase flow composed of a liquid and its vapor is called a cavitating flow.

While these definitions imply a distinction between phase transitions associated with reduction of pressure and those associated with the addition of heat (i.e. boiling), heat-transfer effects may play an important role in many cases of cavitating liquids. Such effects are especially of importance in liquids near their boiling points. From a purely physical-chemical point of view, no distinction need be made between boiling and cavitation, at least insofar as the question of inception is concerned, and many of the basic physical ideas regarding inception, vapor mass transfer, and condensation apply equally (1)*.

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* Numbers in parenthesis refer to references at the end of this appendix.

As cavitation just begins, tiny vapor bubbles form in rapid succession at the point of lowest pressure and are carried downstream by the flow into a zone of higher pressure, where they immediately collapse as the vapor within them condenses. The process of formation and collapse is so nearly instantaneous that with the naked eye only a continuous opaque blur can be distinguished. Figure A-1 illustrates the cavitation bubble formation, growth and collapse. However, as each of the countless individual bubbles collapse, the resulting impact of opposing masses of liquid produces an extremely great local pressure which is transmitted radially outward with the speed of sound, followed by a negative pressure wave which may lead to one or more repetitions of the vaporization-condensation cycle. Boundary materials in the immediate vicinity are, therefore, subject to rapidly repeated stress reversals and may eventually fail through fatigue. This failure of the material is cavitation erosion (2).

An increase in the velocity of flow beyond that required for incipient cavitation can produce no further reduction in pressure at the point of cavitation, but merely an elongation of the zone over which the vapor limit prevails. At the same time the size of the vapor bubbles increases, until at advanced stages a more or less stable vapor pocket is formed, which is very similar in shape to the zone of separation next to an unstreamlined boundary. Figure A-2 is photographic evidence of the cavity which forms as the cavitation zone elongates. Since the formation of such a pocket must result in a change of the surrounding flow pattern, it is to be expected that the pressure distribution will change accordingly, the pressure necessarily remaining at its vapor limit throughout the length of the cavitation pocket.

For the purposes of research, the phenomenon of cavitation is the formation, growth, and collapse of the vapor cavities formed from nuclei. The energy released from these collapsing cavities may be utilized in many different ways to accomplish beneficial results. The actual mechanism of the energy transfer is not as important as an understanding that regardless of mechanism the energy from both hypothesis is the same. Figure A-3 illustrates the two hypothetical transfer mechanisms and the related energy equations. Figure A-4 relates the parameters which govern the cavitation process.

CAVITATION INCEPTION PARAMETER

A useful index for the cavitation phenomenon is formulated by introducing for the symbol P in the pressure parameter its minimum value P_v, the result being called the cavitation number.

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho \ V_o^2} \qquad [1]$$

where: P_o = free stream pressure

P_v = vapor pressure of liquid

V_o = free stream velocity

ρ = density of liquid

So long as σ has an appreciably greater numerical value than the minimum ordinate on the dimensionless pressure-distribution curve for a body of given form, the occurrence of cavitation is not be be expected at any point on the boundary. Once σ becomes approximately equal in absolute magnitude to the minimum ordinate, on the other hand, conditions of incipient cavitation should prevail, and at values of σ below this critical limit σ_i a marked effect upon the pressure distribution is to be expected (3).

In the case of body forms which result in separation, it is to be noted that cavitation will generally begin within the fine-scaled eddies formed at the separation surface long before the boundary pressure attains its vapor limit. As a result, it is then not possible to predict the magnitude of σ_i either by analytical means or by actual measurement of the pressure distribution in flow without cavitation. On the other hand, not only are boundary forms which properly guide the flow most subject to analytical determination, but they are also those least subject to cavitation. The process of streamlining, in other words, simultaneously lowers the magnitude of σ_i (i.e., the tendency toward cavitation) and makes it more accurately predictable by analytical means.

The cavitation inception parameter is to be experimentally determined in order to evaluate the optimum operating parameters and the efficiency of the cavitation technique being evaluated.

CONTROLLED CAVITATION EROSION TECHNIQUE

Cavitation erosion is caused by the collapse of bubbles at or near the solid boundaries guiding high speed flow. Since the early cavitation experiences were encountered on ship propellers in a corrosive medium (seawater), there were some controversies as to whether the mechanism was corrosion or mechanical removal. However, it is now generally accepted that the high pressures caused by the collapse of bubbles produce mechanical removal of material. During the process of cavitation a certain volume of material is removed from the surface as a result of the work done by the bubble collapse forces. Figure A-5 illustrates the controlled cavitation erosion technique. The energy absorbed by the material is given by:

$$E = \Delta V \bullet S \qquad [2]$$

where: E = energy absorbed by the material removed

ΔV = volume of material removed

S = scale strength which represents the energy absorbing capacity of the material per unit volume under the action of the forces.

The intensity of cavitation is then defined as the power absorbed by the material per unit area and given by:

$$I = \frac{\Delta V \bullet S}{A \bullet \Delta t} \qquad [3]$$

or

$$I = \frac{\Delta y}{\Delta t} S \qquad [4]$$

where: A = area of erosion

Δy = mean depth of erosion = $\frac{\Delta V}{A}$

Δt = exposure time

S = erosion strength of the material

This is the output intensity of erosion as seen by the material; similarly one can derive an expression for the bubble collapse intensity which is the input to the process.

$$\left(\frac{\Delta y}{\Delta t}\right) \cdot \left(S\right)^q \quad \alpha \quad (P_i) \cdot (R) \cdot (n) \qquad [5]$$

where: P_i = impact pressure

R = size of the bubble in the jet

n = number of impacts per unit time

These ideas have been incorporated into a master chart for cavitation erosion as shown in Figure A-6 (4). In this chart, the intensity of erosion is plotted against the rate of mean depth or erosion for various materials ranging from soft lead to very highly resistant stellites. The range of intensities typical of practical machines varies from 10^3-10^4- in.-lb/year-in.^{2}. The screening tests such as the vibratory test and rotating disk test operate at intensity levels on the order of 10^5 in.-lb/year-in.^{2} (1 watt/meter^2). The depth of erosion is generally in the range of a fraction of an inch per year. Chemical corrosion rates on steels are in the range of 10^{-3} - 10^{-2} in. per year (ipy). Erosion rates on the order of 1 ipy represent serious erosion which may warrant operational limitation or redesign.

The level of threshold intensities for various metals are on the order of 10^{-1} w/m^2 at the most. Elimination of cavitation by the substitution of one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selected coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 w/m^2. However, if the intensity levels are higher than these values, then the foregoing protection methods may not work. In such cases, hydrodynamic redesign, air injection, and specifying limits for operation are the alternate remedial possibilities.

Another tool for the benefit of designers and operators is a multipurpose nomogram as shown in Figure A-7. It provides a visual idea of the range of intensities encountered in actual practice within the range of the depth of cavitation material used and time of operation. It also provides a quick and easy method of estimating the intensity of cavitation for a given field installation. Lastly, the selection of better materials, if available, is easily made.

From such tools as the master chart and the nomogram, it is possible to estimate the intensity of cavitation required to erode any given sample material most efficiently at the optimum rate of erosion without unwarranted damage occurring. The intensity of erosion can be adjusted to the required level to meet any specific task.

APPENDIX A REFERENCES

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2. Thiruvengadam, A. P. "Prevention and Cure of Cavitation Erosion," *Naval Research Reviews*, May 1972.

3. Thiruvengadam, A. P. "Cavitation Inception and Damage," M. Sc. Thesis, Department of Power Engineering, Indian Institute of Science, Bangalore, India, 1959.

4. Thiruvengadam, A. P. "Scaling Laws for Cavitation Erosion," Proc, Syns on Flow of Water at High Speed, International Union of Theoretical and Applied Mechanics, Leningrad, 1971.

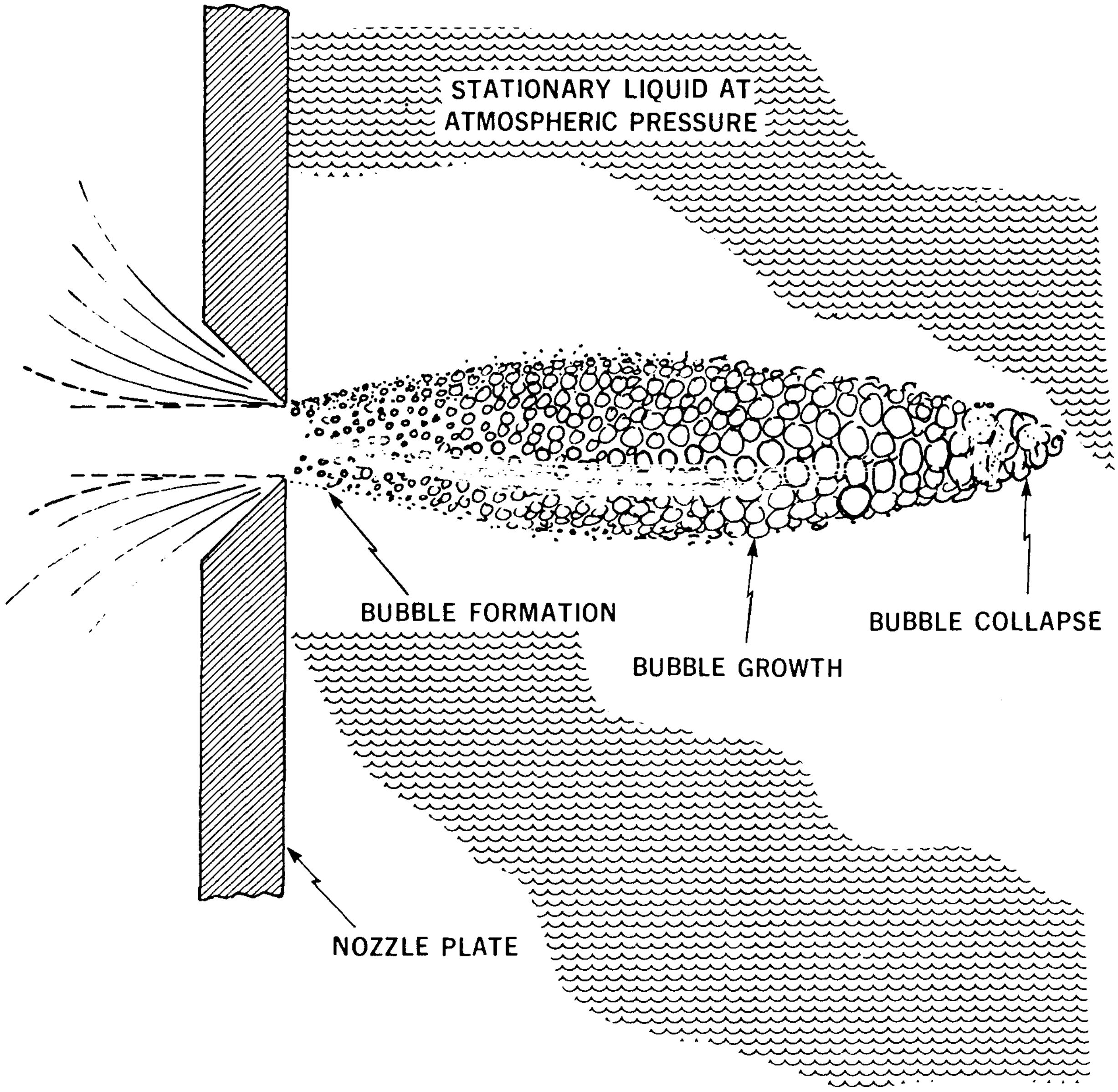


FIGURE A-1 DEFINITION SKETCH FOR THE CAVITATION TECHNIQUE ILLUSTRATING BUBBLE FORMATION, GROWTH AND COLLAPSE

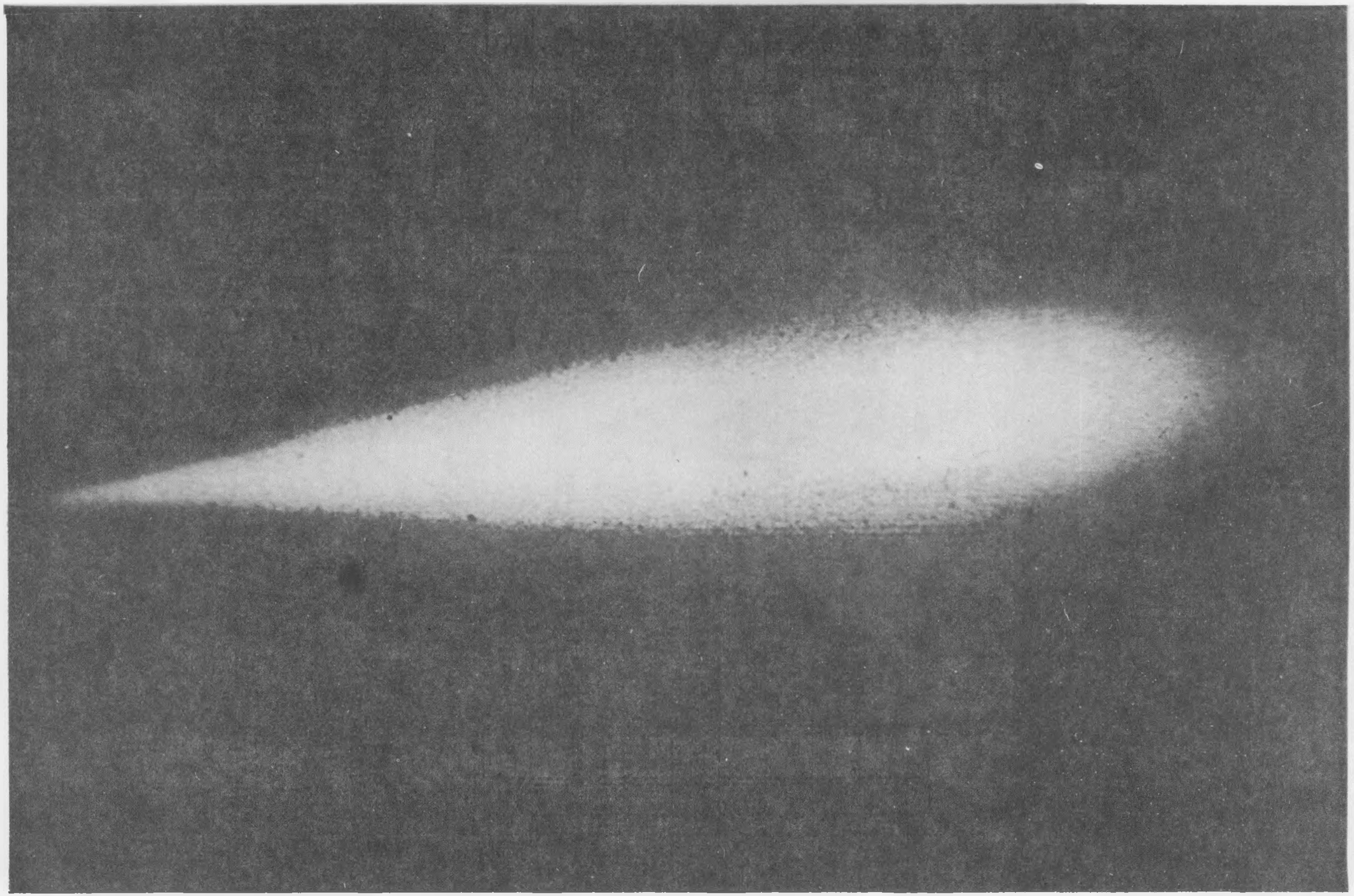
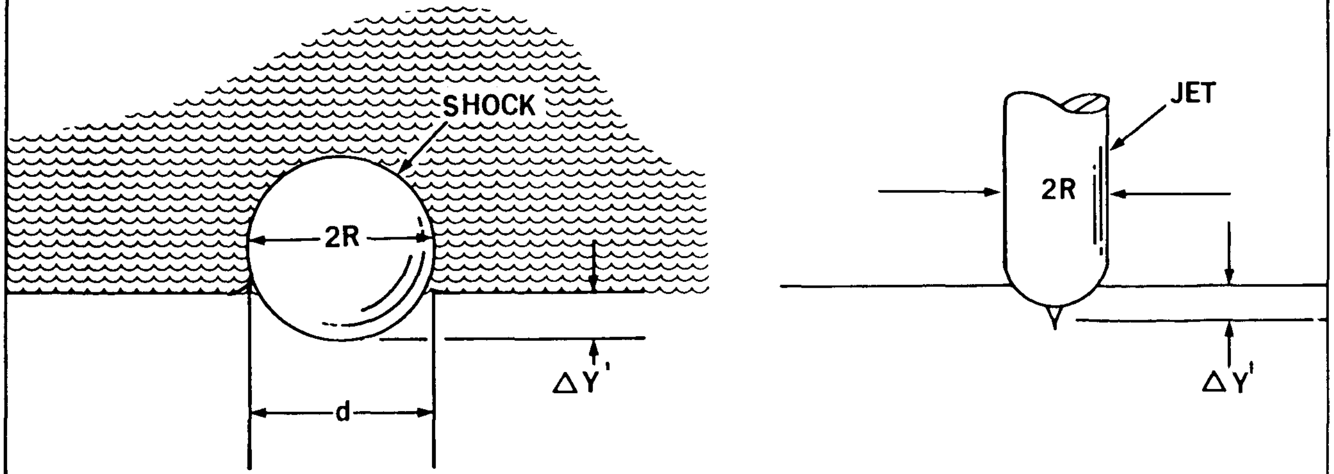


FIGURE A-2 PHOTOGRAPHIC REPRESENTATION OF THE CAVITATING ENVELOPE DURING WHICH TIME THE BUBBLES FORM A NUCLEI, GROW TO CRITICAL SIZE AND COLLAPSE IN THE CONTINUOUS CAVITATION PROCESS

PARAMETERS GOVERNING INDENTATION AND RATE OF EROSION

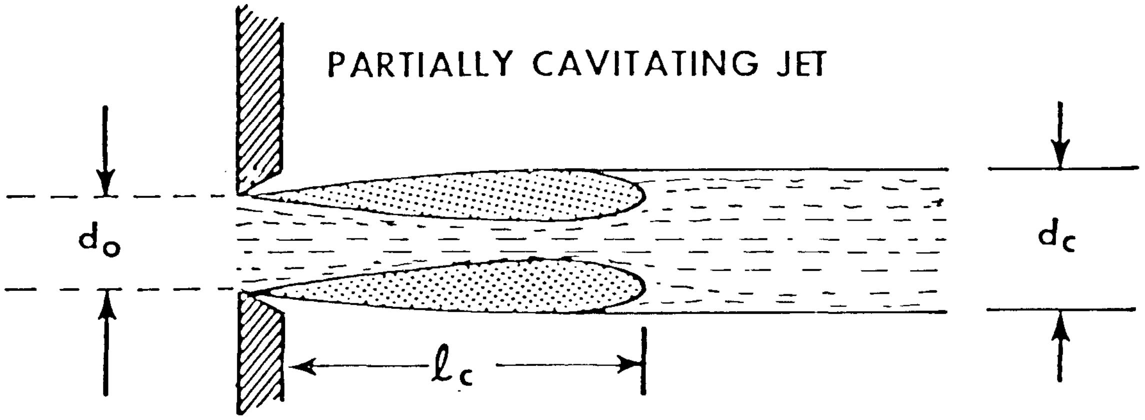


SINGLE IMPACT $\Delta Y' \cdot S_e \, \alpha \, P_i \cdot R$

MULTIPLE IMPACT $\frac{\Delta Y}{\Delta t} \cdot S_e \, \alpha \, P_i \cdot R \cdot f$

SPHERICAL COLLAPSE	STAGNATION PRESSURE (MACROJET)	WATER-HAMMER PRESSURE (MICROJET)
$P_i \, \alpha \, P_o \, (R_o / R_c)^2$	$P_i \, \alpha \, \frac{1}{2} \, p \, V_j^2$	$P_i \, \alpha \, p \, C V_j$
FOR EXAMPLE:	$P_i \, \alpha \, \frac{1}{2} \, p \cdot P_o / p$	$P_i \, \alpha \, p \, C \, (P_o / p)^{1/2}$
$R_o / R_c \, \alpha \, \exp \, (P_o / Q_o)$	$P_i \, \alpha \, P_o$	$P_i \, \alpha \, C \, (p P_o)^{1/2}$

FIGURE A-3 PARAMETERS GOVERNING BUBBLE COLLAPSE AND INTENSITY OF EROSION



$$\textcircled{H} = \frac{\sigma}{\delta}\left(\sigma - \sigma_i\right)^{1/2} \ \text{EXP}\left[\frac{-2.67}{W(\Delta\sigma)}\right]$$

$$\textcircled{H} = \frac{\frac{\Delta y}{\Delta t} \ S_e}{\frac{1}{2} P V_o^3}$$: EROSION NUMBER

$$\sigma = \frac{P_o - P_v}{\frac{1}{2} P V_o^2}$$:CAVITATION NUMBER

σ_i =CAVITATION INCEPTION NUMBER

$$W = \frac{\frac{1}{2} \rho V_o \ \bar{d}}{\gamma}$$: WEBER NUMBER

$\Delta\sigma = (\sigma_i - \sigma)$: DEGREE OF CAVITATION

$\delta = \frac{\bar{d}}{\ell_c}$: RELATIVE NUCLEI SIZE $\qquad \log \frac{\textcircled{H}\,\delta}{\sigma\,(\Delta\sigma)^{1/2}}$

FIGURE A-4 PARAMETERS GOVERNING CAVITATION

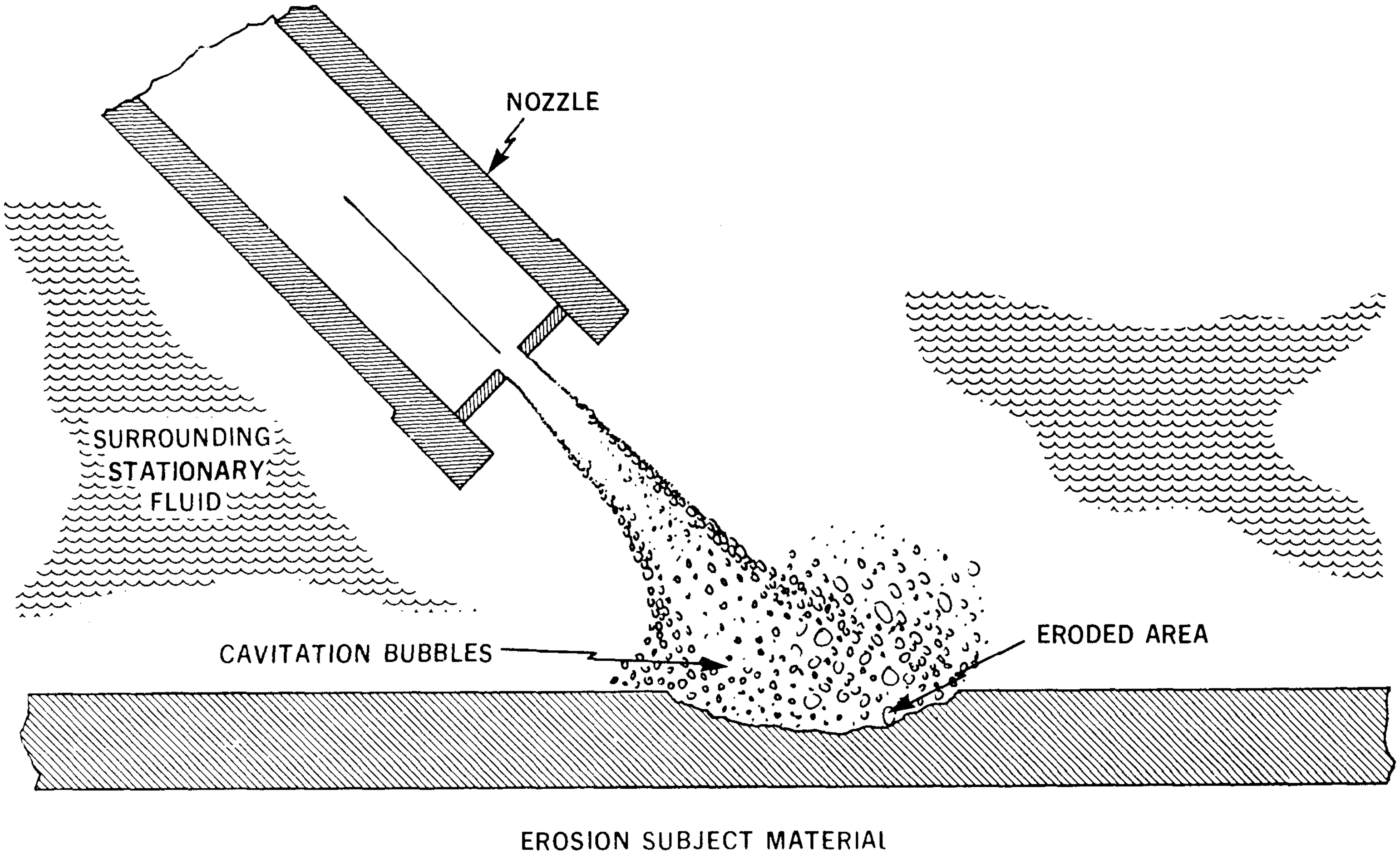


FIGURE A-5 PRINCIPLE OF CONTROLLED CAVITATION EROSION TECHNIQUE AS APPLIED TO MATERIAL EROSION APPLICATIONS

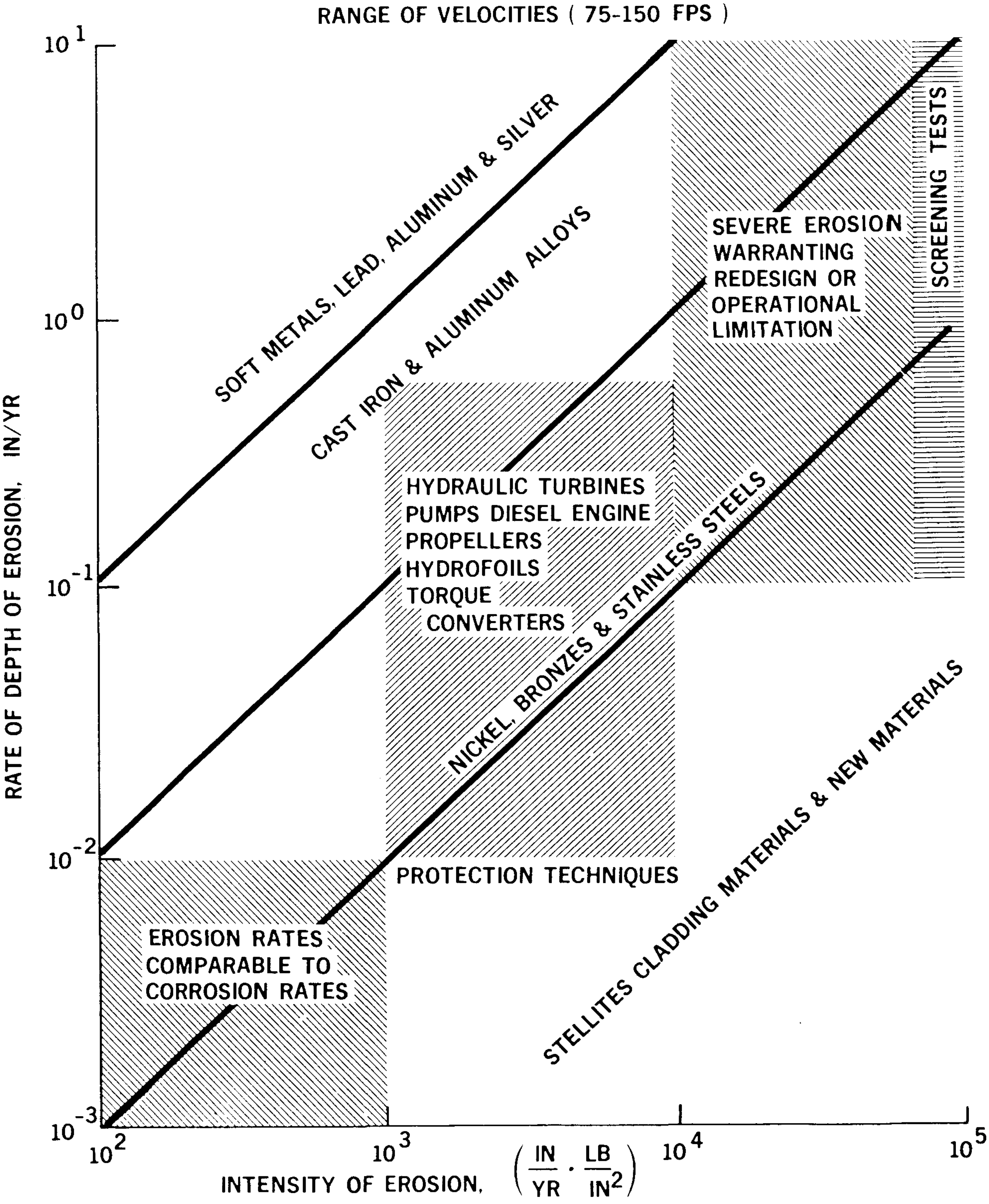
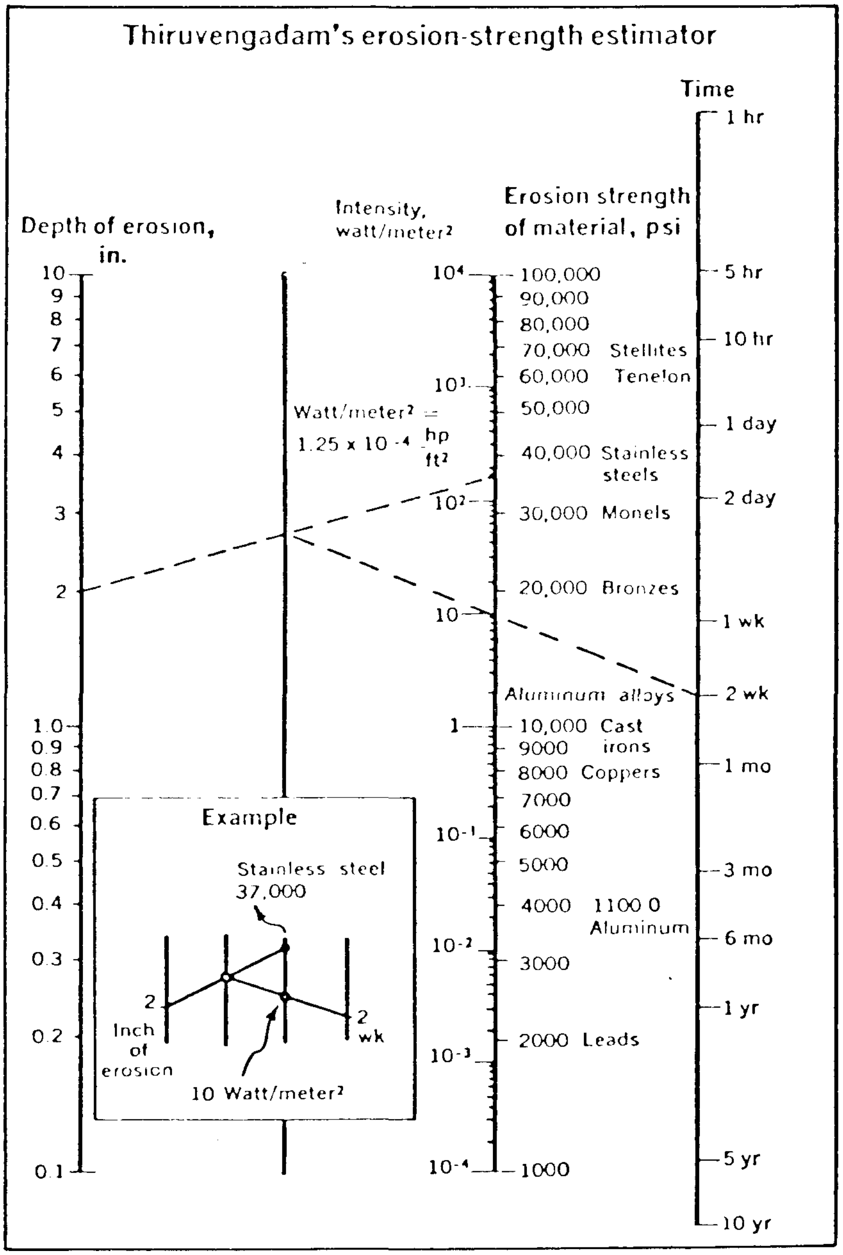


FIGURE A-6 MASTER CHART FOR CAVITATION EROSION



Thiruvengadam's erosion-strength estimator

FIGURE A-7 EROSION INTENSITY ESTIMATOR

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APPENDIX B

DESCRIPTION OF EMULSIFICATION PHENOMENON

A typical and one of the simplest liquid-liquid dispersion systems known is that of oil in water. It is evident that in such a system, known as an emulsion, the oil globules are separated from one another, while the dispersion medium (water) is the continuous phase. Water globules may also be dispersed as droplets in oil. The disperse phase in this case is water and the dispersion medium, oil. Figure B-1 is a photomicrograph of a finely dispersed water in oil emulsion. Both the dispersion medium and the disperse phase have a boundary surface; that of the former is concave, while that of the latter is convex. In the chemistry of dispersoids, the distinction between molecular and coarse systems depends upon the particle size of the phase distributed in the medium, that is, whether it is composed of molecules or aggregates of molecules, or of particles which can be readily seen under a microscope. The latter are called coarse systems. Between these two types of disperse systems (molecular and coarse) are the colloidal systems.

No demarcation can be made between the classes of dispersoids, as some intermediate transition systems are always present. But there is a twilight zone between coarse colloids and fine emulsions which cannot be defined according to observations, such as Brownian movement, cataphoresis, gel formation, and other phenomenon occurring in emulsions. Generally speaking, it seems that it is the predominant size of the particles or globules of the disperse phase which determines the system to which an emulsion may belong. Emulsions, according to their properties, approach either coarse dispersions or colloidal systems. Many properties of emulsions which have number distribution curves with a maximum for small globules asymptotically approach those of colloidal systems, the stable state of emulsions being indicated, among other factors, by the presence of small globules. Gelatinization, so often observed in crude-oil emulsions, is a process of alteration caused by changes in emulsions concentration; it is also attributed to the presence of electrolytes or by-products in a colloidal state so well known in colloidal systems. The molecular portion of soaps in solution favors the rapid diffusion of a low molecular substance, whereas the colloidal portion causes gel formation (1)*. The division of natural emulsions into two groups of different properties, hydrophilic and hydrophobic, also supports the assumption that, even though characteristic differences exist between certain emulsions and colloids, they are systems of the same order. A great many investigators have

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* Numbers in parenthesis refer to references at the end of this appendix.

studied the nature of emulsions, their properties, formation (emulsification), destruction (demulsification), and stability; but usually only a single system has been studied at a time, and that with respect to one or two significant factors or characteristics.

Many working hypotheses have been proposed, but only one or two of them seem to attain, even approximately, the value of a theory which might give a complete picture of, and an explanation for, emulsion behavior. Nevertheless, a knowledge of the hypothesis offered by different investigators in the field of emulsions is of importance and practical value.

CAVITATION EMULSIFICATION TECHNIQUE

Cavitating jet devices utilize the phenomenon of cavitation in the emulsification process. Cavitation involves the formation, critical growth and collapse of vapor cavities formed in the liquid. These cavities are filled with vapor or with the dissolved gases in the liquid. During the implosion, the instantaneous velocities reach supersonic speeds and high intensity microshock waves are produced. The original line pressure is amplified by microshock waves to several thousand atmospheres (2). It is the pressure amplification that is used to disperse the liquids into the finely divided particles of emulsion. Figure B-2 is a schematic diagram of the cavitation emulsification technique. As the liquids flow through the nozzle, the vapor cavities are formed downstream of the nozzle. The collapse of the bubbles within the vapor cavity produce the dispersed emulsion. The energy utilized in this high-shear dispersion given as the cavitating jet technique input intensity (equation 5 of Appendix A). In this equation the number of impacts is redefined as the number of implosions per unit time. These implosions are the amplification energy used to create the high-shear turbulance.

This emulsification process has been designed for low intensity of cavitation erosion in order to prevent any erosion of the materials used to construct the emulsifier. From research on the dynamics of cavitation bubble collapse, it is well known that the intensity of the bubble collapse is a function of the cavitation parameters at a given velocity. For example, if the cavitation number is greater than the cavitation inception number, then there will be no cavitation and hence no emulsification. However, if the cavitation number is very small compared with the cavitation inception number, then the flow becomes supercavitating (3,4). In a supercavitating flow the bubbles do not cavitate as efficiently because the bubble collapse is greatly reduced by the reduction in the surrounding pressures. Between these two extremes, there is an optimum value of the cavitation parameters which produces the most efficient bubble collapse intensity and therefore the most efficient emulsification.

APPENDIX B REFERENCES

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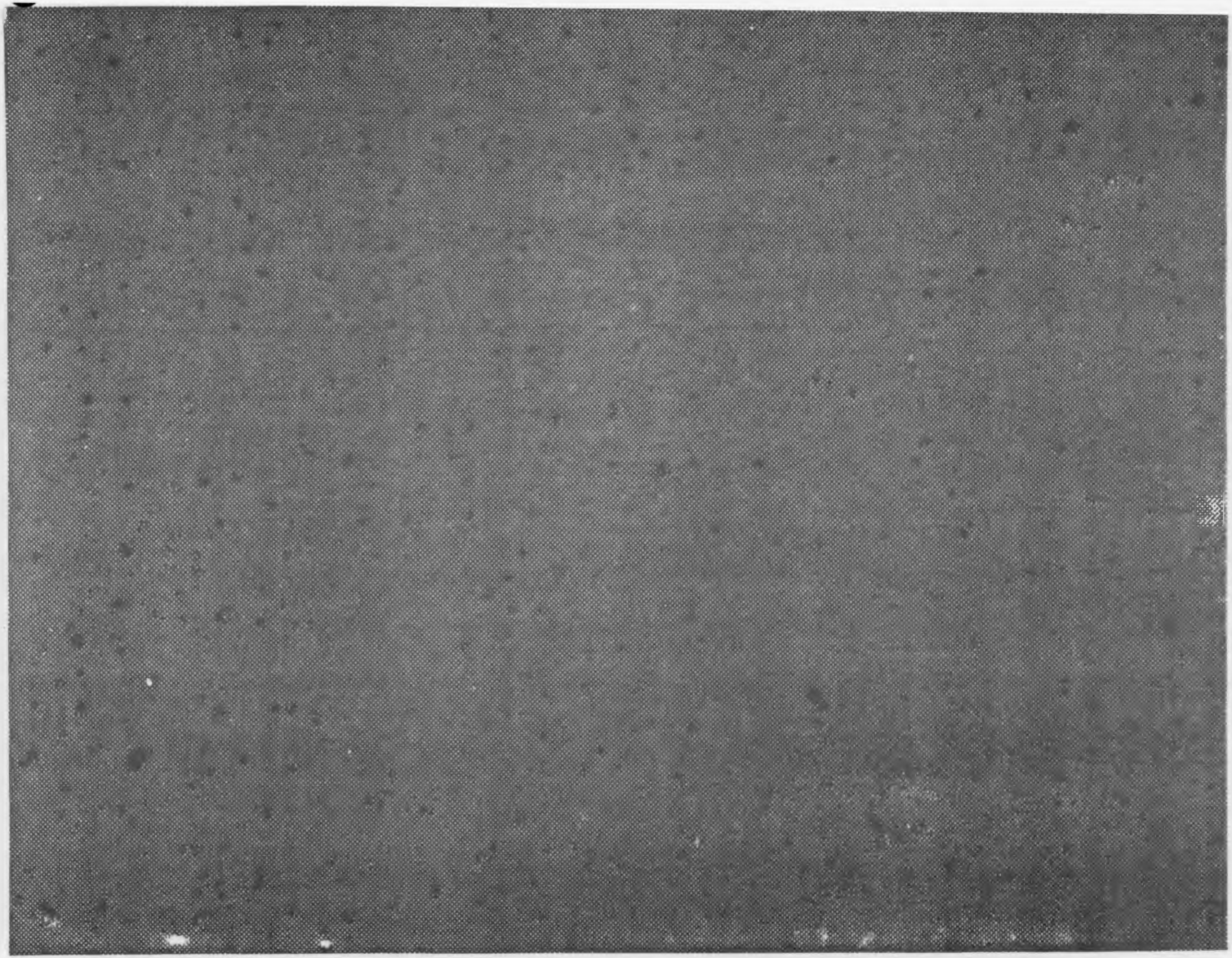

FIGURE B-1 PHOTOMICROGRAPH OF A FINELY DISPERSED WATER IN OIL EMULSION

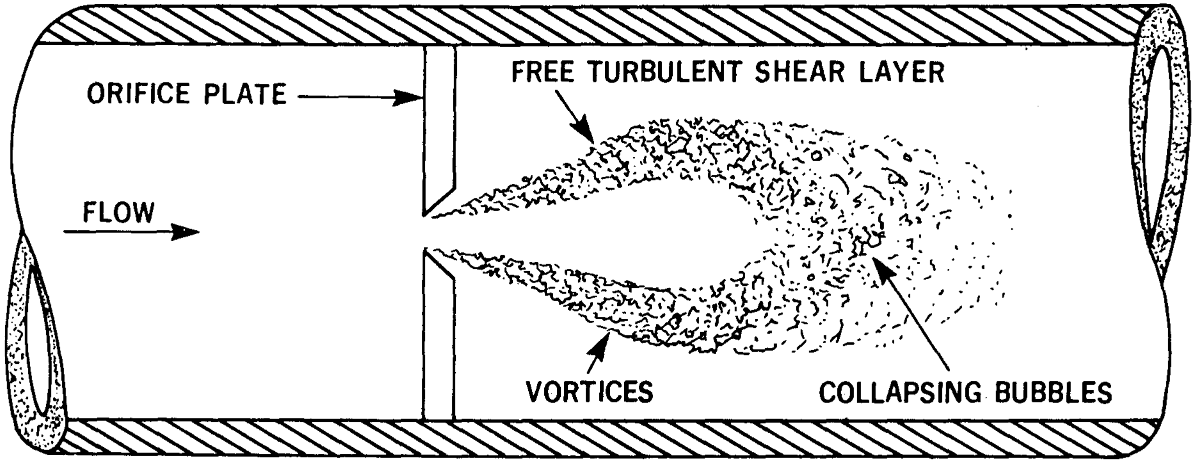

FIGURE B-2 PRINCIPLE OF THE CAVITATION TECHNIQUE AS APPLIED TO EMULSIFICATION APPLICATIONS

APPENDIX C

ADDITIONAL FREQUENCY HISTOGRAMS

The contents of this Appendix is the other histogram data obtained from the image analyzer evaluation of the photomicrographs. The coded number at the bottom of each histogram refers to the specific test condition for which the specimen sample was taken. To establish specific test conditions, use this code information and refer to Table 3 of this report.

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 22     TO 24        14    *****
 24     TO 26        15    *****
 26     TO 28        11    ****
 28     TO 30        4     *
 30     TO 32        3     *
 32     TO 34        2     *
 34     TO 36        2     *
 36     TO 38        5     **
 38     TO 40        7     **
 40     TO 42        0
 42     TO 44        1
 44     TO 46        2     *
 46     TO 48        1
 48     TO 50        1
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 52     TO 54        1
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COAL PARTICLE SIZE DISTRIBUTION
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 50    TO 52        2     *
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 54    TO 56        0
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COAL PARTICLE FREQUENCY DISTRIBUTION
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     56       TO 58           0
     58       TO 60           1     *
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     62       TO 64           0
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     66       TO 68           0
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COAL PARTICLE SIZE DISTRIBUTION
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COAL PARTICLE SIZE DISTRIBUTION
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COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #7 425/60 ORIFICE PLATE 4

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COAL PARTICLE SIZE DISTRIBUTION

5/17/79 #5 425 /30 ORIFICE PLATE 4

DAEDALEAN ASSOCIATES, Inc.

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       62        TO  64            0
       64        TO  66            1      *
       66        TO  68            0
       68        TO  70            1      *
       70        TO  72            0
       72        TO  74            1      *
       74        TO  76            1      *
       76        TO  78            0
       78        TO  80            0
       80        TO  82            0
       82        TO  84            0
       84        TO  86            0
       86        TO  88            0
       88        TO  90            0
```

COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #2 PUMP OUTLET

DAEDALEAN ASSOCIATES, Inc.

```
                    FREQUENCY DISTRIBUTION

   MICROMETERS          NUMBER OF PARTICLES

    0       TO 2        13   ****
    2       TO 4        3    *
    4       TO 6        59   ********************
    6       TO 8        119  ****************************************
    8       TO 10       84   ****************************
    10      TO 12       91   ******************************
    12      TO 14       43   ****************
    14      TO 16       35   ************
    16      TO 18       36   ************
    18      TO 20       23   ********
    20      TO 22       7    **
    22      TO 24       16   *****
    24      TO 26       31   **********
    26      TO 28       0
    28      TO 30       13   ****
    30      TO 32       9    ***
    32      TO 34       9    ***
    34      TO 36       6    **
    36      TO 38       4    *
    38      TO 40       5    **
    40      TO 42       3    *
    42      TO 44       2    *
    44      TO 46       0
    46      TO 48       0
    48      TO 50       1
    50      TO 52       2    *
    52      TO 54       2    *
    54      TO 56       0
    56      TO 58       0
    58      TO 60       0
    60      TO 62       0
    62      TO 64       1
    64      TO 66       0
    66      TO 68       1
    68      TO 70       0
    70      TO 72       0
    72      TO 74       0
    74      TO 76       1
    76      TO 78       1
    78      TO 80       0
    80      TO 82       0
    82      TO 84       0
    84      TO 86       0
    86      TO 88       0
    88      TO 90       0
```

COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #6 425/50 ORIFICE PLATE 4

DAEDALEAN ASSOCIATES, Inc.

```
                         FREQUENCY  DISTRIBUTION

        MICROMETERS             NUMBER OF PARTICLES

          0       TO  2          3     *
          2       TO  4          0
          4       TO  6          2     *
          6       TO  8         91     ******************************
          8       TO 10         44     ***************
         10       TO 12         44     ***************
         12       TO 14         38     *************
         14       TO 16         13     ****
         16       TO 18         25     ********
         18       TO 20         17     ******
         20       TO 22         18     ******
         22       TO 24         10     ***
         24       TO 26          6     **
         26       TO 28          4     *
         28       TO 30          8     ***
         30       TO 32          0
         32       TO 34          7     **
         34       TO 36          6     **
         36       TO 38          4     *
         38       TO 40          2     *
         40       TO 42          7     **
         42       TO 44          1
         44       TO 46          0
         46       TO 48          1
         48       TO 50          0
         50       TO 52          2     *
         52       TO 54          1
         54       TO 56          1
         56       TO 58          0
         58       TO 60          1
         60       TO 62          0
         62       TO 64          0
         64       TO 66          0
         66       TO 68          1
         68       TO 70          0
         70       TO 72          0
         72       TO 74          0
         74       TO 76          0
         76       TO 78          0
         78       TO 80          0
         80       TO 82          0
         82       TO 84          0
         84       TO 86          0
         86       TO 88          0
         88       TO 90          0
```

COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #3 425/0 ORIFICE PLATE 4

```
                         FREQUENCY DISTRIBUTION

MICROMETERS              NUMBER OF PARTICLES

 0      TO  2      8    ***
 2      TO  4      3    *
 4      TO  6     62    *********************
 6      TO  8     88    *****************************
 8      TO 10     54    ******************
10      TO 12     63    *********************
12      TO 14     55    ******************
14      TO 16     28    *********
16      TO 18     33    ***********
18      TO 20     16    *****
20      TO 22     18    ******
22      TO 24      8    ***
24      TO 26      6    **
26      TO 28      9    ***
28      TO 30     10    ***
30      TO 32      6    **
32      TO 34      0
34      TO 36      1
36      TO 38      1
38      TO 40      1
40      TO 42      3    *
42      TO 44      1
44      TO 46      4    *
46      TO 48      2    *
48      TO 50      0
50      TO 52      0
52      TO 54      2    *
54      TO 56      1
56      TO 58      1
58      TO 60      0
60      TO 62      0
62      TO 64      1
64      TO 66      0
66      TO 68      1
68      TO 70      0
70      TO 72      0
72      TO 74      0
74      TO 76      0
76      TO 78      0
78      TO 80      0
80      TO 82      0
82      TO 84      0
84      TO 86      0
86      TO 88      0
88      TO 90      0
```

COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #4 425/20 ORIFICE PLATE 4

```
                    FREQUENCY DISTRIBUTION

MICROMETERS             NUMBER OF PARTICLES

 0      TO 2       1
 2      TO 4       0
 4      TO 6       102  **********************************
 6      TO 8       79   **************************
 8      TO 10      87   *****************************
 10     TO 12      72   ************************
 12     TO 14      23   ********
 14     TO 16      19   ******
 16     TO 18      5    **
 18     TO 20      16   *****
 20     TO 22      7    **
 22     TO 24      4    *
 24     TO 26      3    *
 26     TO 28      5    **
 28     TO 30      7    **
 30     TO 32      0
 32     TO 34      4    *
 34     TO 36      2    *
 36     TO 38      3    *
 38     TO 40      2    *
 40     TO 42      1
 42     TO 44      1
 44     TO 46      2    *
 46     TO 48      0
 48     TO 50      0
 50     TO 52      0
 52     TO 54      0
 54     TO 56      0
 56     TO 58      1
 58     TO 60      0
 60     TO 62      0
 62     TO 64      0
 64     TO 66      1
 66     TO 68      0
 68     TO 70      0
 70     TO 72      0
 72     TO 74      0
 74     TO 76      1
 76     TO 78      0
 78     TO 80      0
 80     TO 82      0
 82     TO 84      0
 84     TO 86      1
 86     TO 88      0
 88     TO 90      0
```

COAL PARTICLE FREQUENCY DISTRIBUTION
5/14/79 #1 MIX TANK

```
                         FREQUENCY DISTRIBUTION

    MICROMETERS              NUMBER OF PARTICLES

      0       TO 2      1
      2       TO 4      20    ****
      4       TO 6      180   ************************************
      6       TO 8      171   **********************************
      8       TO 10     114   ***********************
      10      TO 12     65    *************
      12      TO 14     56    ***********
      14      TO 16     17    ***
      16      TO 18     15    ***
      18      TO 20     10    **
      20      TO 22     4     *
      22      TO 24     8     **
      24      TO 26     4     *
      26      TO 28     2
      28      TO 30     3     *
      30      TO 32     0
      32      TO 34     0
      34      TO 36     0
      36      TO 38     0
      38      TO 40     0
      40      TO 42     1
      42      TO 44     1
      44      TO 46     1
      46      TO 48     0
      48      TO 50     0
      50      TO 52     1
      52      TO 54     1
      54      TO 56     0
      56      TO 58     0
      58      TO 60     0
      60      TO 62     0
      62      TO 64     0
      64      TO 66     0
      66      TO 68     0
      68      TO 70     0
      70      TO 72     0
      72      TO 74     0
      74      TO 76     0
      76      TO 78     0
      78      TO 80     0
      80      TO 82     0
      82      TO 84     0
      84      TO 86     0
      86      TO 88     0
      88      TO 90     0
```

COAL PARTICLE FREQUENCY DISTRIBUTION
5/14/79 # 3 300/0 ORIFICE PLATE 3

```
                        FREQUENCY DISTRIBUTION

    MICROMETERS             NUMBER OF PARTICLES

     0      TO 2           1     *
     2      TO 4           0
     4      TO 6           32    ****************
     6      TO 8           33    *****************
     8      TO 10          50    *************************
     10     TO 12          24    ************
     12     TO 14          12    ******
     14     TO 16          11    ******
     16     TO 18          1     *
     18     TO 20          8     ****
     20     TO 22          11    ******
     22     TO 24          0
     24     TO 26          5     ***
     26     TO 28          2     *
     28     TO 30          2     *
     30     TO 32          0
     32     TO 34          1     *
     34     TO 36          0
     36     TO 38          0
     38     TO 40          0
     40     TO 42          1     *
     42     TO 44          0
     44     TO 46          2     *
     46     TO 48          0
     48     TO 50          0
     50     TO 52          1     *
     52     TO 54          0
     54     TO 56          0
     56     TO 58          1     *
     58     TO 60          0
     60     TO 62          1     *
     62     TO 64          0
     64     TO 66          0
     66     TO 68          0
     68     TO 70          0
     70     TO 72          0
     72     TO 74          0
     74     TO 76          0
     76     TO 78          0
     78     TO 80          0
     80     TO 82          0
     82     TO 84          0
     84     TO 86          0
     86     TO 88          0
     88     TO 90          0
```

COAL PARTICLE SIZE DISTRIBUTION
5/14/79 #4 300/20 ORIFICE PLATE 3

```
                    FREQUENCY DISTRIBUTION

   MICROMETERS           NUMBER OF PARTICLES

    0      TO 2          6    *
    2      TO 4          11   **
    4      TO 6          197  ***************************************
    6      TO 8          105  *********************
    8      TO 10         90   ******************
    10     TO 12         46   *********
    12     TO 14         74   ***************
    14     TO 16         31   ******
    16     TO 18         26   *****
    18     TO 20         13   ***
    20     TO 22         14   ***
    22     TO 24         10   **
    24     TO 26         6    *
    26     TO 28         7    *
    28     TO 30         0
    30     TO 32         3    *
    32     TO 34         4    *
    34     TO 36         2
    36     TO 38         3    *
    38     TO 40         3    *
    40     TO 42         3    *
    42     TO 44         1
    44     TO 46         1
    46     TO 48         3    *
    48     TO 50         1
    50     TO 52         2
    52     TO 54         2
    54     TO 56         1
    56     TO 58         0
    58     TO 60         2
    60     TO 62         0
    62     TO 64         0
    64     TO 66         0
    66     TO 68         0
    68     TO 70         0
    70     TO 72         0
    72     TO 74         0
    74     TO 76         0
    76     TO 78         1
    78     TO 80         1
    80     TO 82         0
    82     TO 84         0
    84     TO 86         0
    86     TO 88         0
    88     TO 90         0
```

COAL PARTICLE SIZE DISTRIBUTION
5/14/79 #6 300/50 ORIFICE PLATE 3

DAEDALEAN ASSOCIATES, Inc.

```
                    FREQUENCY  DISTRIBUTION

    MICROMETERS              NUMBER OF PARTICLES

     0        TO 2           6     **
     2        TO 4           0
     4        TO 6           36    ************
     6        TO 8           98    *********************************
     8        TO 10          86    *****************************
     10       TO 12          39    *************
     12       TO 14          26    *********
     14       TO 16          16    *****
     16       TO 18          5     **
     18       TO 20          10    ***
     20       TO 22          5     **
     22       TO 24          8     ***
     24       TO 26          1
     26       TO 28          4     *
     28       TO 30          2     *
     30       TO 32          2     *
     32       TO 34          1
     34       TO 36          2     *
     36       TO 38          0
     38       TO 40          2     *
     40       TO 42          1
     42       TO 44          0
     44       TO 46          0
     46       TO 48          1
     48       TO 50          0
     50       TO 52          0
     52       TO 54          0
     54       TO 56          0
     56       TO 58          0
     58       TO 60          0
     60       TO 62          0
     62       TO 64          0
     64       TO 66          0
     66       TO 68          0
     68       TO 70          0
     70       TO 72          0
     72       TO 74          0
     74       TO 76          0
     76       TO 78          1
     78       TO 80          0
```

COAL PARTICLE SIZE DISTRIBUTION
5/14/79 #7 300/70 ORIFICE PLATE 3

DAEDALEAN ASSOCIATES, Inc.

```
                    FREQUENCY DISTRIBUTION

   MICROMETERS           NUMBER OF PARTICLES

    0       TO  2         6     **
    2       TO  4         1
    4       TO  6         31    **********
    6       TO  8         98    *********************************
    8       TO  10        108   ************************************
    10      TO  12        58    *******************
    12      TO  14        45    ***************
    14      TO  16        19    ******
    16      TO  18        25    ********
    18      TO  20        19    ******
    20      TO  22        9     ***
    22      TO  24        5     **
    24      TO  26        9     ***
    26      TO  28        7     **
    28      TO  30        0
    30      TO  32        7     **
    32      TO  34        0
    34      TO  36        3     *
    36      TO  38        1
    38      TO  40        2     *
    40      TO  42        1
    42      TO  44        0
    44      TO  46        1
    46      TO  48        1
    48      TO  50        1
    50      TO  52        2     *
    52      TO  54        1
    54      TO  56        1
    56      TO  58        0
    58      TO  60        2     *
    60      TO  62        0
    62      TO  64        0
    64      TO  66        0
    66      TO  68        0
    68      TO  70        0
    70      TO  72        0
    72      TO  74        0
    74      TO  76        0
    76      TO  78        0
    78      TO  80        0
    80      TO  82        0
    82      TO  84        1
    84      TO  86        0
    86      TO  88        0
    88      TO  90        0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #2 PUMP OUTLET

```
                         FREQUENCY DISTRIBUTION

MICROMETERS                  NUMBER OF PARTICLES

 0      TO  2            2     *
 2      TO  4            0
 4      TO  6            24    ********
 6      TO  8            88    *****************************
 8      TO 10            58    *******************
10      TO 12            67    **********************
12      TO 14            26    *********
14      TO 16            21    *******
16      TO 18            10    ***
18      TO 20            8     ***
20      TO 22            9     ***
22      TO 24            4     *
24      TO 26            10    ***
26      TO 28            3     *
28      TO 30            3     *
30      TO 32            1
32      TO 34            3     *
34      TO 36            3     *
36      TO 38            2     *
38      TO 40            1
40      TO 42            1
42      TO 44            1
44      TO 46            0
46      TO 48            2     *
48      TO 50            0
50      TO 52            1
52      TO 54            0
54      TO 56            0
56      TO 58            0
58      TO 60            0
60      TO 62            1
62      TO 64            0
64      TO 66            0
66      TO 68            0
68      TO 70            1
70      TO 72            0
72      TO 74            0
74      TO 76            0
76      TO 78            0
78      TO 80            0
80      TO 82            0
82      TO 84            0
84      TO 86            0
86      TO 88            0
88      TO 90            0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #1 MIX TANK

DAEDALEAN ASSOCIATES, Inc.

```
                         FREQUENCY DISTRIBUTION

   MICROMETERS              NUMBER OF PARTICLES

    0        TO  2         1
    2        TO  4         5     *
    4        TO  6         90    ***********************
    6        TO  8         128   ********************************
    8        TO  10        96    ************************
    10       TO  12        54    **************
    12       TO  14        36    *********
    14       TO  16        23    ******
    16       TO  18        14    ****
    18       TO  20        18    *****
    20       TO  22        12    ***
    22       TO  24        4     *
    24       TO  26        5     *
    26       TO  28        7     **
    28       TO  30        6     **
    30       TO  32        8     **
    32       TO  34        2     *
    34       TO  36        3     *
    36       TO  38        5     *
    38       TO  40        1
    40       TO  42        0
    42       TO  44        0
    44       TO  46        2     *
    46       TO  48        0
    48       TO  50        0
    50       TO  52        2     *
    52       TO  54        0
    54       TO  56        0
    56       TO  58        0
    58       TO  60        0
    60       TO  62        0
    62       TO  64        0
    64       TO  66        0
    66       TO  68        0
    68       TO  70        0
    70       TO  72        1
    72       TO  74        0
    74       TO  76        0
    76       TO  78        0
    78       TO  80        0
    80       TO  82        0
    82       TO  84        0
    84       TO  86        0
    86       TO  88        0
    88       TO  90        0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #4 390/25 ORIFICE PLATE 5

```
                    FREQUENCY DISTRIBUTION

MICROMETERS               NUMBER OF PARTICLES

 0        TO  2         6    *
 2        TO  4        24    *****
 4        TO  6       141    ****************************
 6        TO  8       172    **********************************
 8        TO 10        71    **************
 10       TO 12        53    ***********
 12       TO 14        24    *****
 14       TO 16        18    ****
 16       TO 18        13    ***
 18       TO 20         7    *
 20       TO 22         2
 22       TO 24         5    *
 24       TO 26         4    *
 26       TO 28         4    *
 28       TO 30         1
 30       TO 32         3    *
 32       TO 34         0
 34       TO 36         0
 36       TO 38         0
 38       TO 40         0
 40       TO 42         0
 42       TO 44         0
 44       TO 46         0
 46       TO 48         0
 48       TO 50         0
 50       TO 52         0
 52       TO 54         0
 54       TO 56         0
 56       TO 58         0
 58       TO 60         0
 60       TO 62         0
 62       TO 64         0
 64       TO 66         0
 66       TO 68         0
 68       TO 70         0
 70       TO 72         0
 72       TO 74         0
 74       TO 76         0
 76       TO 78         0
 78       TO 80         0
 80       TO 82         0
 82       TO 84         0
 84       TO 86         0
 86       TO 88         0
 88       TO 90         0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #9 390/75 ORIFICE PLATE 5

```
                    FREQUENCY DISTRIBUTION

MICROMETERS             NUMBER OF PARTICLES

 0        TO 2          0
 2        TO 4          5      **
 4        TO 6          73     ************************
 6        TO 8          81     ***************************
 8        TO 10         79     **************************
 10       TO 12         52     *****************
 12       TO 14         38     *************
 14       TO 16         24     ********
 16       TO 18         11     ****
 18       TO 20         15     *****
 20       TO 22         12     ****
 22       TO 24         4      *
 24       TO 26         7      **
 26       TO 28         5      **
 28       TO 30         0
 30       TO 32         5      **
 32       TO 34         0
 34       TO 36         1
 36       TO 38         2      *
 38       TO 40         0
 40       TO 42         0
 42       TO 44         1
 44       TO 46         1
 46       TO 48         0
 48       TO 50         0
 50       TO 52         1
 52       TO 54         0
 54       TO 56         1
 56       TO 58         0
 58       TO 60         0
 60       TO 62         0
 62       TO 64         0
 64       TO 66         0
 66       TO 68         0
 68       TO 70         0
 70       TO 72         0
 72       TO 74         0
 74       TO 76         0
 76       TO 78         0
 78       TO 80         0
 80       TO 82         0
 82       TO 84         0
 84       TO 86         0
 86       TO 88         0
 88       TO 90         0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #3 390/0 ORIFICE PLATE 5

DAEDALEAN ASSOCIATES, Inc.

```
                         FREQUENCY DISTRIBUTION

   MICROMETERS               NUMBER OF PARTICLES

    0         TO  2          0
    2         TO  4          1
    4         TO  6          31    **********
    6         TO  8          102   **********************************
    8         TO  10         85    ****************************
    10        TO  12         52    *****************
    12        TO  14         38    *************
    14        TO  16         16    *****
    16        TO  18         21    *******
    18        TO  20         10    ***
    20        TO  22         7     **
    22        TO  24         4     *
    24        TO  26         2     *
    26        TO  28         4     *
    28        TO  30         6     **
    30        TO  32         0
    32        TO  34         3     *
    34        TO  36         2     *
    36        TO  38         1
    38        TO  40         4     *
    40        TO  42         0
    42        TO  44         1
    44        TO  46         1
    46        TO  48         2     *
    48        TO  50         0
    50        TO  52         0
    52        TO  54         0
    54        TO  56         0
    56        TO  58         0
    58        TO  60         0
    60        TO  62         1
    62        TO  64         0
    64        TO  66         0
    66        TO  68         0
    68        TO  70         0
    70        TO  72         0
    72        TO  74         0
    74        TO  76         0
    76        TO  78         0
    78        TO  80         0
    80        TO  82         0
    82        TO  84         0
    84        TO  86         0
    86        TO  88         0
    88        TO  90         0
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #8 390/60 ORIFICE PLATE 5

```
                    FREQUENCY DISTRIBUTION

MICROMETERS                NUMBER OF PARTICLES

 0       TO 2              2     *
 2       TO 4              0
 4       TO 6              33    ***********
 6       TO 8              82    ***************************
 8       TO 10             65    **********************
 10      TO 12             56    *******************
 12      TO 14             28    *********
 14      TO 16             31    **********
 16      TO 18             16    *****
 18      TO 20             4     *
 20      TO 22             11    ****
 22      TO 24             4     *
 24      TO 26             6     **
 26      TO 28             13    ****
 28      TO 30             2     *
 30      TO 32             3     *
 32      TO 34             3     *
 34      TO 36             2     *
 36      TO 38             2     *
 38      TO 40             2     *
 40      TO 42             3     *
 42      TO 44             0
 44      TO 46             3     *
 46      TO 48             4     *
 48      TO 50             0
 50      TO 52             0
 52      TO 54             0
 54      TO 56             2     *
 56      TO 58             1
 58      TO 60             1
 60      TO 62             0
 62      TO 64             1
 64      TO 66             0
 66      TO 68             0
 68      TO 70             0
 70      TO 72             0
 72      TO 74             0
 74      TO 76             1
 76      TO 78             0
 78      TO 80             0
 80      TO 82             0
 82      TO 84             0
 84      TO 86             0
 86      TO 88             0
 88      TO 90             1
```

COAL PARTICLE SIZE DISTRIBUTION
5/16/79 #10 390/90 ORIFICE PLATE 5

DAEDALEAN ASSOCIATES, Inc.

```
                        FREQUENCY DISTRIBUTION

      MICROMETERS              NUMBER OF PARTICLES

       0       TO 2          7     *
       2       TO 4          9     **
       4       TO 6          121   ********************
       6       TO 8          212   ***********************************
       8       TO 10         132   **********************
       10      TO 12         84    **************
       12      TO 14         59    **********
       14      TO 16         25    ****
       16      TO 18         24    ****
       18      TO 20         26    ****
       20      TO 22         12    **
       22      TO 24         20    ***
       24      TO 26         11    **
       26      TO 28         8     *
       28      TO 30         8     *
       30      TO 32         2
       32      TO 34         3     *
       34      TO 36         11    **
       36      TO 38         1
       38      TO 40         3     *
       40      TO 42         1
       42      TO 44         0
       44      TO 46         0
       46      TO 48         10    **
       48      TO 50         1
       50      TO 52         1
       52      TO 54         1
       54      TO 56         0
       56      TO 58         1
       58      TO 60         1
       60      TO 62         0
       62      TO 64         2
       64      TO 66         1
       66      TO 68         2
       68      TO 70         2
       70      TO 72         0
       72      TO 74         1
       74      TO 76         0
       76      TO 78         1
       78      TO 80         1
       80      TO 82         0
       82      TO 84         0
       84      TO 86         0
       86      TO 88         0
       88      TO 90         0
```

COAL PARTICLE SIZE DISTRIBUTION
5/17/79 #8 425/75 ORIFICE PLATE 4