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INFORMAL REPORT

FEASIBILITY STUDY TO EVALUATE THE
EFFECTS OF CAVITATION MIXING UPON THE
PUMPABILITY AND STRENGTH CHARACTERISTICS
OF CEMENTS FOR GEOTHERMAL APPLICATIONS

FINAL REPORT

MAY 1982

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FLUID SYSTEMS DIVISION
SPRINGLAKE RESEARCH CENTER
DAEDALEAN ASSOCIATES, INCORPORATED

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ABSTRACT

Two on-line emulsification techniques were evaluated as potential systems for preparation of geothermal cement. The objective of the program was met through the demonstrated feasibility and enhanced material properties by cavitation emulsification of geothermal cements.

A standard mixing technique for preparing two types of geothermal cements, a lightweight and a heavyweight, was supplemented in a laboratory environment using either of two cavitation mixing techniques. The density and viscosity of the respective slurries and the compressive strength of the corresponding set cements, which were cured at elevated temperature and pressure, were measured to compare the effects of the supplemental techniques with that produced by the established method alone.

The test results indicated an enhanced improvement in the compressive strength of the lightweight emulsified cement. The lightweight emulsified cement also showed an increase in the room temperature density. The room temperature viscosity of the emulsified lightweight cement was initially improved. The emulsification of the heavyweight cement had little effect on the material properties.

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EXECUTIVE SUMMARY

Cavitation emulsification 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. It is the pressure amplification that is used to dispense the liquids into the finely divided particles of emulsions.

Two types of equipment, an orifice type laboratory cavitation mixer and a vibratory apparatus were used to induce the cavitation bubble collapse mechanism into premixed slurries of a lightweight and a heavyweight cement, which are candidates for completing geothermal wells. The purpose of this program was to see if cavitation mixing could:

1. increase the mechanical strength through a better dispersion of water and cement additives, and
2. improve pumpability through a finer control of the size distribution of cement particles in the slurry and through more homogeneous mixing of the additives.

Joint testing was performed at the National Bureau of Standards (NBS) to evaluate the effects of cavitation mixing

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on the two cements. DAEDALEAN ASSOCIATES, Inc. (DAI) transported, assembled and operated the two mixers at NBS. NBS prepared the cements, and after mixing, measured the property changes.

Emulsification of the lightweight cement, using the vibratory apparatus, made the compressive strength 22 percent stronger than the control sample. The room temperature density was increased by six percent. The room temperature viscosity was 13 percent less viscous than the control sample after 2.5 hours. After 21.5 hours, this difference decreased to 5 percent. Emulsification of the heavyweight cement using the vibratory apparatus had a negligible effect on the properties measured.

Attempts at using the orifice type cavitation mixer were unsuccessful. This equipment was designed for a bench top laboratory environment and was too small to allow the free flow of the cement particles through the orifice.

I. INTRODUCTION

The environment within a geothermal well is different from that of an oil or normal water well. Those differences result from the temperature, pressure and saline condition of the geothermal brine fluid. As a result of those differences, studies

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have been undertaken to develop specialized cements for geothermal well applications.

Certain general characteristics are required if the candidate cements are to be suitable for geothermal applications. These characteristics include: compressive strength, permeability, placement ability, compatibility with drilling fluids and noncorrosive to the steel well casing. Of these factors, the two which are primary from a working standpoint are placement ability or pumpability and stability. Because geothermal wells are approaching depths of 10,000 feet, the ability of the cement to be pumped becomes a primary concern. The time requirement to place the grout in a well of that depth can exceed two hours.¹ The pumpability of the cement must be maintained over that period at well temperatures if the cement is to be installed in the well. Stability on the other hand is the property of the cement to show no reduction in strength or increase in permeability after prolonged exposure to the downhole environment.

DAI has been involved in evaluation and determination of beneficial uses of the phenomenon of cavitation for the past seven years. One application in which this phenomenon has been used successfully is emulsification. The cavitation bubble collapse energy has proven to be a very efficient mixing mechanism. A basic discussion of the phenomenon of cavitation is included in Appendix A. A discussion of emulsification and cavitating

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emulsification is included in Appendix B. To date, stable emulsions of varied grades of heavy fuel oil and light fuel oil have been emulsified with water. These emulsions have been used as fuels in industrial boilers. The emulsification technology appears directly applicable to the preparation of geothermal well cements.

A. Technical Background

Research programs evaluating the beneficial uses of cavitation have been addressed by DAI for the past seven years. DAI has been directly involved in the geothermal energy area in the development of equipment to use cavitation water jets as an on-line descaling technique for geothermal plant piping.² In another geothermal application, a self-rotating cleaning tool was designed, fabricated and tested by DAI which removes geothermal scale buildup from a geothermal well in Niland, California.³ The application of cavitation which appeared directly related to geothermal cement preparation is the emulsification of water-in-oil. In five years of research and development, DAI has perfected a technique which uses the phenomenon of cavitation as an on-line emulsification mechanism for water and fuel oil.⁴ Another related research activity was the use of emulsification technology to produce stable coal/oil/water emulsions.⁵

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B. Program Approach

Based on the above results, a technical program was initiated with Brookhaven National Laboratory in order to perform a feasibility study evaluating the effects of cavitation mixing upon the pumpability and strength characteristics of cements for geothermal applications.

Under the auspices of this program, DAI evaluated two methods of inducing the cavitation bubble collapse mechanism into premixed cement slurries. A small Laboratory Cavitation Mixer was designed and built to be used in a bench top laboratory environment. Emphasis was placed on keeping the equipment small, and to use minimum amount of cement slurry for the experiments. The second set of equipment used was the DAI vibratory apparatus.

C. Technical Purpose

Geothermal well cementing is basically the process of mixing a slurry of cement and water and pumping it down through steel casing and up into the annulus between the casing and the formation. The principal functions of the cementing process are to restrict fluid movement between formations, to bond and support the casing, and to prevent corrosion of the casing.

Well cementing encompasses a wide depth and temperature range. These extreme differences have resulted in the development of specialized cements for geothermal applications. To allow a cement slurry to maintain working properties, cement

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additives have been developed which alter the chemical or physical behavior of the slurry.

1. Accelerators are added to reduce the time necessary for the cement to set and harden.
2. Retarders are used to prolong the set time of cement, and are presently in virtually all cement slurries where the temperature in the well exceeds about 60°C (140°F).
3. Extenders are added to the cement to reduce the slurry density.
4. Weighting Agents increase the density of cement slurries.
5. Dispersants are utilized to reduce the viscosity of a cement slurry.
6. Fluid Loss Additives prevent the loss of slurry water to highly porous formations.
7. Lost Circulation Control Agents prevent loss of the entire cement slurry to highly fractured or weak formations.
8. Expansion Inducing Additives cause the hardened cement to expand slightly.¹

Due to the extensive line of additives available, it is apparent that the mixing of the slurry's component parts, prior to placement downwell, is of extreme importance. Presently, high pressure water flows through a nozzle contained in a pipe which exists directly below a hopper of dry cement. The dry

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cement is combined with the water and pumped downwell. The addition of an on-line emulsification process after this initial mixing could improve the pumpability through a finer control of the size distribution of cement particles in the slurry and through a more homogeneous mixing of the additives. Increased mechanical strength through a better dispersion of water and cement additives could also be realized.

D. Technical Objective

The objective of this program is to demonstrate the feasibility and advantage of cavitation mixing/emulsification of geothermal cements. An established laboratory method of preparing slurries of a lightweight cement and of a heavyweight cement was supplemented by either of two cavitation emulsification techniques. The density and viscosity of the respective slurries and the compressive strength of the corresponding set cements, which were cured at elevated temperature and pressure, were measured to compare the effects of the supplemental techniques with that produced by the established method alone.

The National Bureau of Standards (NBS) provided DAI with two batches of powdered cement. A lightweight cement and a heavyweight cement, which are candidates for use in completing geothermal wells, were mixed from their component parts.

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Joint testing was performed at NBS to evaluate the effects of cavitation mixing on the two cements. DAI transported, assembled and operated the two mixers at the National Bureau of Standards. NBS prepared the cements, and after mixing, measured the property changes in the cements produced by inducing the cavitation bubble collapse mechanism into the cement slurries. Room temperature density, room temperature viscosity, relative rate of hydration, and compressive strength were measured.

II. EXPERIMENTAL APPARATUS, TECHNIQUES AND PROCEDURES

A. Cementing Materials

A standard mixing technique for preparing two types of geothermal cements was supplemented in a laboratory environment. Two methods of inducing the cavitation bubble collapse energy into premixed slurries were tested; a small laboratory cavitation mixer shown in Figure 1 and the DAI vibratory apparatus shown in Figure 2. The tests were designed in order to determine if the stability, pumpability and strength of the cement could be improved through cavitation mixing.

Lightweight Dowell-7 cement and heavyweight Halliburton-2 cement were used for developing the cavitation mixing techniques.^{6,7} Figure 3 is a description of these two cements.

FIGURE 1 LABORATORY CAVITATION MIXER

FIGURE 2 DAI VIBRATORY APPARATUS

TYPE OF CEMENT	PARTS BY WEIGHT	INGREDIENTS	REFERENCE
LIGHTWEIGHT DOWELL-7	100	API CLASS G CEMENT	(7)
	35	SILICA FLOUR	
	10	DIATOMACEOUS EARTH	
	1	RETARDER	
	91	DISTILLED WATER	
HEAVYWEIGHT HALLIBURTON-2	100	API CLASS G CEMENT	(8)
	100	SILICA SAND (SSA-2)	
	0.3	RETARDER (HR-12)	
	44.5	DISTILLED WATER	

FIGURE 3 DESCRIPTION OF CEMENTING MATERIALS USED IN CAVITATION EMULSIFICATION TESTS

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B. Slurry Preparation

Enough of the premixed lightweight Dowell-7 cement and the heavyweight Halliburton-2 cement powder were received from NBS to prepare three 600 ml batches of slurry for each of the two cements.

For the Dowell-7 cement, 387 grams of water were placed in a mechanical blender. The blender was started at low speed. Within 15 seconds, 620 grams of the powdered cement were added to the water. A large spatula was used to enhance the addition of the powder to the water. Once all of the powder was in the water, the blender speed was increased to high and the slurry was allowed to mix for 35 more seconds.

For the heavyweight Halliburton-2 cement, 222 grams of water were placed in a mechanical blender. The blender was started at low speed. Within 15 seconds, 1,000 grams of the powdered cement were added to the water. A large spatula was used to enhance the addition of the powder to the water. Once all of the powder was in the water, the blender speed was increased to high and the cement was allowed to mix for 35 more seconds.

C. Description of Experimental Apparatus

1. Laboratory Cavitation Mixer. Figure 1 is a picture of the laboratory cavitation mixer which consists of a variable displacement diaphragm type metering pump and motor combination,

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a suction reservoir, a discharge reservoir, and a test section where the cavitation bubbles are induced into the flow.

The metering pump is capable of pumping very abrasive slurries to a maximum pressure of 3.45 MPa (500 psi), with a maximum flow of 410 ml/min. It is powered by a 1/4 hp electric motor. An adjustment knob on the pump permits continuous variation of the discharge flow as desired between zero and the maximum value. A suction reservoir is mounted above the pump head. This ensures that the head will be in a flooded condition at all times during operation.

Figure 4 is a picture of the test section where the orifice plate is held. The orifice plate is sandwiched between male and female halves of a high pressure coupling creating a metal to metal seal. Figure 5 is a picture of the three orifice plates which were evaluated at DAI; 0.051 cm (0.020 in), 0.076 cm (0.030 in), and 0.102 cm (0.040 in) diameter orifices were tested. After the cement passed through the orifice it was collected in the discharge reservoir.

2. Vibratory Apparatus. Figure 2 is a photograph of the DAI vibratory apparatus utilized to emulsify the two types of geothermal cements. This equipment consists of a commercially available piezoelectric transducer, velocity transformer, power supply and voltmeter. The vibratory equipment drives a test specimen through a small amplitude, high frequency, axial

FIGURE 4 TEST SECTION ORIFICE ARRANGEMENT SHOWING MALE AND FEMALE COMPONENTS

FIGURE 5 ORIFICE PLATES OF 0.020", 0.040" DIAMETER RESPECTIVELY FOR PUMP SLURRY TESTS

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oscillation. The oscillation produces alternating pressure fields causing cavitation bubbles to grow and collapse on the specimen's surface. In order to produce the cavitation bubbles, the face of the specimen must be submerged within a fluid media. The two types of geothermal cements are the fluid medias used in these experiments. The specimen tip chosen was 316SS. This material takes hours to be eroded by the cavitation bubbles; therefore, the tip can easily be used for the short duration tests needed to transfer the cavitation bubbles into the various cements being emulsified. The frequency of vibration was fixed at 20 KHz. The peak to peak displacement amplitude was 5×10^{-3} cm (2×10^{-3} in).

D. Techniques and Procedures Utilized to Emulsify Cements

1. Laboratory Cavitation Mixer Experiments. Initial tests were performed using water as the cavitation medium. Water was placed in the feed reservoir and the pump head was flooded. The pump motor was started with the flow adjustment knob set at zero. This knob was slowly adjusted until 3.45 MPa (500 psi) was achieved. The orifice utilized was 0.051 cm (0.020 in) in diameter. The measured flow rate at 3.45 MPa (500 psi) pressure was 350 ml/min. The pump performed within its quoted specifications.

Lightweight Dowell-7 cement was the first cement to be run

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through the system. The cement was blender mixed first using the procedure described in Section II-B of this report. The cement mixture was then placed in the feed reservoir. The pump motor was started with the flow adjustment knob set at zero. The cement pumped through a 0.051 cm (0.020 in) diameter orifice very well at zero pressure. The pressure was slowly increased from 0 MPa (0 psi) to 0.34 MPa (50 psi) where there was a sudden pressure pulse in the system which reached 4.83 MPa (700 psi). The system was immediately shut down. The pulse was the result of the orifice plate and the entire pumping system before the orifice plate being packed solid with cement particles.

A 0.076 cm (0.030 in) diameter orifice plate was then tried with the Dowell-7 cement. The pressure again pulsed from approximately 0.34 MPa (50 psi) to 4.83 MPa (700 psi), the result of the cement particles packing the entire system before the orifice plate with cement particles.

A 0.102 cm (0.040 in) diameter orifice plate was then tried with the Dowell-7 cement. The orifice was too large to produce any pressure at all. The cement just flowed through the orifice without generating any pressure.

The heavyweight Halliburton-2 cement was then tried. A 0.076 cm (0.030 in) diameter orifice was placed in the test

section. The cement was blender mixed using the procedure described in Section II-B of this report. The cement mixture was then placed in the feed reservoir. The cement was so thick and paste-like that it was impossible to flood the pump head to start pumping the cement. The 1/2 inch diameter supply line would not allow this heavyweight cement to free flow. This realization left doubt as to whether the cavitation mixer could ever successfully pump this heavyweight cement. These experiments were then abandoned to concentrate on the ASTM Vibratory Apparatus experiments.

2. Vibratory Apparatus Experiments. Initial tests, using water as the fluid medium, were used to determine if the DAI vibratory apparatus was working properly. Three hundred milliliters of water were placed in a 500 ml beaker. The vibratory apparatus was turned on and the sonifer tip slowly lowered into the water. The output wattage was adjusted to 100 watts power. A stopwatch was used to time this process for one minute. Visual observation showed that everything was performing properly. The blur of the cavitation bubbles could be seen on the surface of the specimen tip and directly below the tip. At the end of one minute, the apparatus was turned off. The beaker felt warm to the touch which is a sign that the cavitation bubbles were growing and collapsing in the water, transferring their energy (in the form of heat) to the water.

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The lightweight Dowell-7 cement was emulsified using the DAI vibratory apparatus. The cement was blender mixed using the procedure described in Section II-B of this report. Three hundred milliliters of slurry was placed in a 500 ml beaker. The vibratory apparatus was turned on and the sonifer tip slowly lowered into the cement slurry. The output wattage was adjusted to 100 watts power. A stopwatch was used to time the process for one minute. During the one minute time period the beaker was slowly moved from side to side up and down to expose the entire sample to the cavitation bubbles. At the end of one minute, the vibratory apparatus was turned off. A second experiment was performed on another 300 ml batch of the cement using the same procedure except the time the cavitation was exposed to the sample was lengthened to three minutes. Visual observations were made during these experiments to see if there was any visual physical change to the cement slurry.

While the first sample was being emulsified for one minute, entrapped air and water could be seen rising from the surface of the cement. The observations of the second sample which was emulsified for three minutes showed that after the first minute there was little additional air or water rising to the surface. In a 300 ml sample a time of one minute seemed sufficient to emulsify the cement.

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The heavyweight Halliburton-2 cement was emulsified using the DAI vibratory apparatus. The cement was blender mixed using the procedure described in Section II-B of the report. Three hundred milliliters of slurry was placed in a 500 ml beaker. The vibratory apparatus was turned on and the sonifer tip slowly lowered into the cement slurry. The output wattage was adjusted to 100 watts power. A stopwatch was used to time the process for one minute. During the one minute time period, the beaker was slowly moved from side to side and up and down to expose the entire sample to the cavitation bubbles. At the end of one minute, the vibratory apparatus was turned off. A second experiment was performed on another 300 ml batch of the same cement using the same procedure except the time the cavitation was exposed to the samples was lengthened to five minutes.

Observations made while emulsifying the heavyweight cement for one minute showed a slight amount of air and water rising to the surface but compared to the lightweight cement, this was negligible. The five minute emulsification showed no difference in the amount of air or water which surfaced.

E. Slurry Preparation at NBS

The slurries were prepared following the API Recommended Practice 10B (December 1979).⁶ Weighed dry ingredients of a given cement were hand blended and their mix was added during

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a period of about 15 seconds to the weighted portion of water in a two speed propeller blender, operating at the lower speed; the slurry was then blended for a period of 35 seconds at the higher speed.

F. Techniques and Procedures Utilized at NBS to Emulsify Cements.

1. Laboratory Cavitation Mixer Experiments. Four hundred milliliters of the Dowell-7 cement slurry were placed in the feed reservoir of the cavitation mixer. The pump head was flooded and the pump was turned on with the flow adjustment knob set at zero pressure. The pressure was slowly increased from zero to approximately 0.21 MPa (30 psi) when the system clogged and pulsed up to 4.14 MPa (600 psi). Several attempts using both 0.051 cm (0.020 in) diameter and 0.076 cm (0.030 in) diameter orifices were made with no success. It was hoped that the preparation of the slurry at NBS would be better than the preparation at DAI, and that this difference would allow the cement to flow through the orifice at the desired operating pressure of 3.45 MPa (500 psi). This was not the case. The orifice diameter needed to achieve the desired operating pressure to induce the cavitation bubble collapse mechanism into the slurry flow, for this small laboratory cavitation mixer, was too small to allow for the passage of the cement

particles. The problem DAI encountered was the use of full scale cement particles in a scaled down cavitation emulsification unit. It is anticipated that further tests using a full scale cavitation emulsification system, on the lightweight cement, would allow the slurry to flow under desired operating conditions. Previous experience with the heavyweight Halliburton-2 cement at DAI showed that the present configuration of the Laboratory Cavitation Mixer, pumping this cement was impossible. The Laboratory Cavitation Mixer was abandoned to concentrate on the DAI vibratory apparatus.

2. Vibratory Apparatus Experiments. A 1,000 ml batch of the lightweight Dowell-7 slurry was prepared and divided into three portions. Four hundred milliliters was used for the cavitation mixer experiments detailed in Section II-F.1 of this report. Three hundred milliliters was used for control samples. The remaining 300 ml was used in the ASTM vibratory apparatus.

The three hundred milliliters of slurry was placed in a 500 ml beaker. The vibratory apparatus was turned on and the sonifer tip slowly lowered into the cement slurry. The output wattage was adjusted to 100 watts power. A stopwatch was used to time the process for one minute. During the one minute time period the beaker was slowly moved from side to side and up and

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down to expose the entire sample to the cavitation bubbles. At the end of one minute, the vibratory apparatus was turned off. Samples of the emulsified cement were taken to be used in evaluating its properties after emulsification.

A 600 ml batch of the Halliburton-2 slurry was prepared and divided into two portions. Three hundred milliliters was used for control samples. The remaining 300 ml was used in the vibratory apparatus.

The 300 ml of slurry was poured into a 500 ml beaker. The vibratory apparatus was turned on and the sonifer tip lowered into the cement slurry. The output wattage was adjusted to 100 watts power. A stopwatch was used to time the process for one minute. During the one minute time period the beaker was slowly moved from side to side and up and down to expose the entire sample to the cavitation bubbles. At the end of one minute, the vibratory apparatus was turned off. Samples of the emulsified cement were taken to be used in evaluating its properties after emulsification.

G. Property Measurements at NBS

The control sample and the cavitation sample for each of the two cements were treated the same for the determination of slurry density, slurry viscosity, relative rate of cement hydration, and compressive strength of the set cement.

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Room temperature density (ρ) was determined by comparing the weight of a given slurry in a 25 ml pycnometer to that of the same volume of water of known density.

Room temperature viscosity (μ) was determined by the Thomas-Stormer method in which the time to rotate a 25 mm diameter rod 100 revolutions in a 50 ml cup of slurry is compared to that of water of known viscosity.⁶

The rate of hydration of the emulsified sample relative to that of the control sample was examined by monitoring their temperatures during one day at room temperature.

The compressive strength of set cement specimens was measured following their cure for one day in molds immersed in water and heated to 200°C under 17 MPa (2,400 psi) nitrogen pressure. A given slurry sample of a cement was poured into two glass tube molds (25 mm (1 in) o.d., 150 mm (6 in) long) which were lightly coated inside with silicone grease. The slurries were puddled to remove air bubbles. The eight filled tubes of all the cement samples were capped with Teflon stoppers, having 1 mm holes (.03937 in), and held together in a basket within a stirred autoclave for the curing. The heating and cooling rates of the autoclave were about 2.5°C/minute (1.4°F/min). Upon completion of the cure the glass tubes were carefully broken away, and each rod of set cement was diamond sawed cross sectionally into two

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specimens of length twice the diameter. A gear driven loading machine was used at a cross head displacement rate of 0.5 mm/min (0.020 in/min) to cause failure of the specimens.

III. DISCUSSION OF EXPERIMENTAL RESULTS

All of the property measurements made on the two cements were performed at NBS. The following results are based on the analysis performed by Mr. Ralph Krause, Fracture and Deformation Division, National Bureau of Standards.⁶

A. Room Temperature Density

Figure 6 gives the results of the Room Temperature Density (ρ) measurements. Column one gives the type of cement and whether it was the control or emulsified sample. Column two gives the density in grams/milliliter (g/ml) of the cements. Column three gives the range of two control measurements for each cement. Column four gives the percent difference between the emulsified and control values.

The control sample of the Lightweight Dowell-7 cement slurry had a density of 1.496 g/ml with a range of 0.4 percent for the two control samples measured. The emulsified sample had a density of 1.586 g/ml. A comparison between the control and emulsified samples show that the emulsified sample is 6.0 percent denser.

TYPE OF CEMENT		DENSITY g/MI	RANGE	PERCENT DIFFERENCE
LIGHTWEIGHT DOWELL-7	CONTROL	1.496	0.4%	
	EMULSIFIED	1.586		6.0%
HEAVYWEIGHT HALLIBUTION-2	CONTROL	2.158	0.5%	
	EMULSIFIED	2.176		0.8%

FIGURE 6 ROOM TEMPERATURE DENSITY MEASUREMENTS FOR CEMENT SLURRIES IN BOTH CONTROLLED AND EMULSIFIED CONDITIONS

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The control sample of the Heavyweight Halliburton-2 cement slurry had a density of 2.158 g/ml with a range of 0.5 percent for the two control samples measured. The emulsified sample had a density of 2.176 g/ml. A comparison between the control and emulsified samples shows that the emulsified sample is 0.8 percent denser.

B. Room Temperature Viscosity

Figure 7 gives the results of the room temperature viscosity (μ) measurements on the Lightweight Dowell-7 cement slurry. The Heavyweight Halliburton-2 cement was too paste-like to be measured by the method used. Column one lists whether the sample was the control or emulsified. Column two gives the slurry age (t) in hours. Column three gives the viscosity (μ) in milli Pascal $\cdot$ Seconds (mPa $\cdot$ S). Column four gives the percent standard deviation.

The viscosity of three runs for each sample were averaged. After 2.5 hours, the control sample's viscosity was 2.80 mPa $\cdot$ S with a standard deviation of $\pm$ 2.7 percent. After 2.5 hours the emulsified sample's viscosity was 2.44 mPa $\cdot$ S with a standard deviation of $\pm$ 2.2 percent. At this age the emulsified sample was about 13 percent less viscous than the control sample.

After 21.5 hours the control sample's viscosity was 3.49 mPa $\cdot$ S with a standard deviation of $\pm$ 1.9 percent. After 21.5

SAMPLE	SLURRY AGE (HOURS)	VISCOSITY (mPa·S)	PERCENT STANDARD DEVIATION
CONTROL	2.5	2.80	±2.7
	21.5	3.49	±1.9
EMULSIFIED	2.5	2.44	±2.2
	21.5	3.32	±1.5

FIGURE 7 ROOM TEMPERATURE VISCOSITY MEASUREMENTS FOR LIGHTWEIGHT DOWELL-7 CEMENT SLURRIES IN BOTH CONTROLLED AND EMULSIFIED CONDITION

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hours the emulsified sample's viscosity was $3.32 \text{ mPa} \cdot \text{S}$ with a standard deviation of ± 1.5 percent. At this age, the emulsified sample was about 5 percent less viscous than the control sample.

As the sample's viscosity increased with extent of hydration, being slow at room temperature, the difference in viscosity between the emulsified and control samples decreased.

C. Relative Rate of Hydration

The relative rate of hydration between the emulsified and control samples, for the pair of cements, was examined by monitoring their temperatures during one day at room temperature. This rate appeared as unity within 0.5 percent. The rate of hydration had been suppressed by the presence of a retarder and was negligibly perceived by this method.

D. Compressive Strength

Figure 8 shows the results of the compressive strength (σ) measurements. Column one gives the type of cement and whether it was the control or emulsified sample. Column two gives the average compressive strength (σ) in Mega Pascals (MPa). Column three gives the standard deviation.

The compressive strengths of four specimens of each sample were averaged. The control sample of the lightweight Dowell-7 cement had a compressive strength of $41.8 \text{ MPa} \pm 2.5$. The emulsified sample had a compressive strength of $50.9 \text{ MPa} \pm 5.1$. The

TYPE OF CEMENT		COMPRESSIVE STRENGTH (MPa)	STANDARD DEVIATION
LIGHTWEIGHT DOWELL-7	CONTROL	41.8	±2.5
	EMULSIFIED	50.9	±5.1
HEAVYWEIGHT HALLIBUTON-2	CONTROL	114.4	±7.1
	EMULSIFIED	106.6	±6.4

FIGURE 8 COMPRESSIVE STRENGTH MEASUREMENTS FOR CEMENTS IN BOTH
CONTROLLED AND EMULSIFIED CONDITIONS

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emulsified sample of the lightweight Dowell-7 cement appeared about 22 percent stronger than the control sample.

The control sample of the heavyweight Halliburton-2 cement had a compressive strength of $114.4 \text{ MPa} \pm 7.1$. The emulsified sample had a compressive strength of $106.6 \text{ MPa} \pm 6.4$. The compressive strength of the heavyweight Halliburton-2 cement samples showed a negligible difference in strength within the precision of measurements.

IV. CONCLUSIONS AND RECOMMENDATIONS

The completion of the tasks of this program have yielded sufficient engineering data to justify the following conclusions and recommendations.

A. Conclusions

1. The emulsification of the lightweight Dowell-7 cement, using the vibratory apparatus, made the compressive strength of the cement 22 percent stronger than the control sample. This increase in compressive strength could be the result of the removal of the air bubbles from the slurry creating a more uniform and stronger concrete sample through a better bonding of the particles.

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2. The emulsification of the lightweight Dowell-7 cement, using the DAI vibratory apparatus, increased the room temperature density by about six percent. When this cement was mixed in the blender air bubbles were entrained in the slurry. All of the samples which were taken for both control and emulsification purposes were hand puddled to aid in the removal of the air bubbles. The measured increase in density difference between the control and emulsified samples may indicate that the air was further removed from the emulsified sample. Increases in slurry density may be bad since higher placement pressures are needed, thereby increasing the possibility of loss circulation problems.
3. The emulsification of the lightweight Dowell-7 cement, using the DAI vibratory apparatus, made the room temperature viscosity of the emulsified sample about 13 percent less viscous than the control sample after 2.5 hours. After 21.5 hours, this difference decreased to about five percent. The viscosity of the slurries increases

as the cement hydrates. The lightweight cement has a retarder added to reduce the rate of hydration. A possible explanation for the emulsified sample being 13 percent less viscous than the control sample after 2.5 hours would be that the emulsification of the cement slurry created better surface contact between the cement particles and the retarder. This could cause the emulsified sample's rate of hydration to be slower than the control sample. This difference could account for lower viscosity of the emulsified sample.

4. The emulsification of the heavyweight Halliburton-2 cement, using the DAI Vibratory Apparatus, had little effect on the slurry. The effect on the density and compressive strength were negligible within the precision of measurements. The viscosity of this cement was not measured because of the limitations of the viscometer used. The cement was too paste-like.
5. The rate of hydration of the emulsified sample relative to that of the control sample was examined by monitoring their temperatures during

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one day curing at room temperature. While the pair of slurry samples for either cement were held in twin insulated chambers, the relative rate of hydration appeared as unity within 0.5 percent. The rate of hydration had been suppressed by the presence of a retarder and was negligibly perceived by this method.

6. The orifice diameters used in the Laboratory Cavitation Mixer did not allow for free flow of the cement particles at a pressure great enough to emulsify the lightweight cement slurry. It was impossible for this apparatus to pump the heavyweight cement slurry. In a full scale application it is possible that an orifice-type emulsification unit would work. The problem experienced in this program was the use of a scale model laboratory emulsification unit.

B. Recommendations

1. Further investigations into emulsifying lightweight cements should be performed. Emulsifying of the cements in conditions simulating the

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field should lead to a better understanding of the effects on the cement. The density, viscosity and hydration measurements made during this program were all performed at room temperature. These property measurements should be made at elevated temperatures to achieve any type of significant data on the effects of emulsifying the cements. A high temperature, high pressure consistometer could be used to compare the differences in hydration between emulsified and nonemulsified cements.

2. Companies who perform the field operation of cementing geothermal wells should be contacted so that a better understanding of how this type of emulsification system could best be incorporated into the existing cementing equipment. An analysis of the cost of modifying existing equipment compared to the benefits of emulsifying cements should be performed. The information collected should lead to an understanding as to whether this type of technology should be pursued.

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3. Larger scale equipment using an orifice-type emulsifier should be constructed. Larger flow rates should be used to better simulate field conditions. Existing emulsification units have the capacity of 227 l/min (60 gpm) at temperatures to 93°C (200°F). These units could be modified to pump the cements and see if an orifice-type emulsifier would work.

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APPENDIX A

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)*.

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

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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 fatigue 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

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

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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 and the pressure necessarily remains 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. The energy released from these collapsing cavities may be utilized in many different ways to accomplish beneficial results provided an understanding and control of the collapse is achieved. 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.

PARAMETERS GOVERNING INDENTATION AND RATE OF EROSION

SINGLE IMPACT

MULTIPLE IMPACT

$$\Delta Y' \cdot S_e \propto P_i \cdot R$$

$$\frac{\Delta Y}{\Delta t} \cdot S_e \propto P_i \cdot R \cdot f$$

SPHERICAL COLLAPSE

$$P_i \propto P_o (R_o/R_c)^2$$

STAGNATION
PRESSURE
(MACROJET)

$$P_i \propto \frac{1}{2} \rho V_j^2$$

WATER-HAMMER
PRESSURE
(MICROJET)

$$P_i \propto \rho C V_j$$

FOR EXAMPLE:

$$P_i \propto \frac{1}{2} \rho \cdot P_o / \rho$$

$$P_i \propto \rho C (P_o / \rho)^{1/2}$$

$$R_o/R_c \propto \exp (P_o / Q_o)$$

$$P_i \propto P_o$$

$$P_i \propto C (\rho P_o)^{1/2}$$

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

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

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

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

σ_i = CAVITATION INCEPTION NUMBER

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

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

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

FIGURE A-4 PARAMETERS GOVERNING CAVITATION

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 (σ).

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

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 to 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

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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:

$$E = \Delta V \cdot S_e \quad [2]$$

Where:

E = energy absorbed by the material removed

ΔV = volume of material removed

S_e = scale strength which represents the energy absorbing capability 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:

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

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$$I_e = \frac{\Delta V \cdot S_e}{A \cdot \Delta t} \quad [3]$$

or:

$$I_e = \frac{\Delta y}{\Delta t} S_e \quad [4]$$

Where:

A = area of erosion

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

Δt = exposure time

S_e = 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.

$$\left(\frac{\Delta y}{\Delta t} \right) \cdot (S_e) q \propto (P_i) \cdot (R) \cdot (n) \quad [5]$$

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

FIGURE A-6 MASTER CHART FOR CAVITATION EROSION

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of practical machines varies from 10^3 - 10^4 - in.-lb/year-in². The screening tests such as the vibratory test and rotating disc test operate at intensity levels on the order of 10^5 in.-lb/year-in². The screening tests such as the vibratory test and rotating disc test operate at intensity levels on the order of 10^5 in.-lb/year-in² (1 watt/meter²). 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} inch 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/m² 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/m². 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.

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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.

THIRUVENGADAM'S EROSION-STRENGTH ESTIMATOR

FIGURE A-7 EROSION INTENSITY ESTIMATOR

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APPENDIX B

APPENDIX B

DESCRIPTION OF EMULSIFICATION PHENOMENON

A typical and one of the simplest liquid-liquid dispersion system 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. This 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

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

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FIGURE B-1 PHOTOMICROGRAPH OF A FINELY DISPERSED WATER IN OIL EMULSION
AT MAGNIFICATION OF 400x

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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 determined 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 studied the nature of emulsions,

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

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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 hypothesis 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 cavities produce the dispersed emulsion. The energy utilized in this high-shear dispersion is 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 turbulence.

The number of implosion in time is proportional to the number of bubbles formed. Beyond the critical value of cavitation number (σ_i), the bubble formation is a function of the

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

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changes in velocity of the free stream. As a result, the intensity of cavitation used in emulsification can be expressed as a function of the velocity of the fluid.

$$I = \frac{1}{2} \rho V_o^3 \cdot C \quad [1]$$

Where:

I = intensity of cavitation (w/m²)

ρ = the density of the fluid (slugs/ft³)

V_o = the free stream velocity (ft/sec)

C = unit conversion factor

This equation is utilized to define the energy of the cavitation used in emulsification per unit area. The degree of cavitation which is used in a specific emulsification system is defined by the cavitation number as defined in equation [1] of Appendix A.

One other major factor must be determined with respect to the emulsion produced by a cavitating system. That parameter, which is of major importance with respect to on-line production and effective utilization, is the stability of the emulsion. The stability of an emulsion is a measure of the dispersed phase to remain dispersed within the dispersion medium. A familiar example of an extremely stable emulsion is homogenized milk. The cream is dispersed throughout the milk in a manner that the separation of the two constituents will not occur for several months. The following equation defines

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the coefficient of emulsification which is a nondimensional coefficient related to the stability of any emulsion.

$$K_e = \frac{V_e - V_w}{V_t} \quad [2]$$

Where:

K_e = the coefficient of emulsification (emulsibility)

V_e = volume of emulsion

V_w = volume of separated liquids after some specific time interval (In our case the volume of water)

V_t = the total volume of fluids used to produce the tested emulsion sample.

The emulsification process has been designed for low intensity of cavitation 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

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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.

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