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I am submitting herewith a thesis written by Larry Willis Perkins entitled "Oil/Water/Solids Separations Using a Hydroclone." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

Robert M. Counce

Robert M. Counce, Major Professor

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Interim Vice Provost and
Dean of The Graduate School

OIL/WATER/SOLIDS SEPARATIONS USING A HYDROCLONE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Larry W. Perkins

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Dedication

This thesis is dedicated to my fiancée, Christy Adams,
and our future together.

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Abstract

Existing oil wells generate a substantial amount of water in the production stream. To make production more efficient, the Oak Ridge National Laboratory is developing a centrifugal separator unit to separate the oil and water in these streams. Although the unit effectively separates the oil and water, it cannot tolerate solids, such as sand. Therefore, this research employs a hydroclone to remove these solids from the production stream, thus, protecting the centrifugal separator from mechanical failure.

Feeds that ranged from 90% oil to 10% oil, with the remainder water, were used in this research. Solids were also added to the feed in an amount equal to 3% by mass. The two streams exiting the hydroclone were analyzed for oil content, water content, and solids content. The goal of the research is to remove all of the sand in the underflow (flow out of the bottom of the hydroclone) with a limited amount of water. All of the oil and most of the water are desired to be in the overflow (flow out of the top of the hydroclone). This is a specific operating condition that is needed to use the hydroclone in series with a centrifugal separator in the downhole environment of an oil well.

The data obtained from this research indicates that the solids can be almost completely removed at all feed conditions. Operating conditions did not affect the solids separation to any great degree. The separation of the oil and water was more difficult. In the predominately water feeds, nearly all of the oil could be removed. In feeds that were predominately oil, there was significant carryover of oil into the water stream. This was shown to be a function of the operating conditions (the flow rates of streams exiting the

hydroclone). It appears that the desired liquid and solid separation can be obtained at high water contents in the feed, but that the desired liquid separation is not obtained at high oil concentrations.

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Nomenclature

Bp	bypass	-
C(d)	corrected partition number	-
Cy_{50}	cyclone number	-
D_c	cyclone diameter	[m]
D_i	inlet diameter	[m]
D_o	overflow diameter	[m]
d_c	critical drop diameter	[m]
D_n	hydroclone nominal section diameter	[m]
d_{cut}	cut size	[m]
d_{50}	cut size (50% in each stream)	[m]
E_{HP}	liquid separation efficiency (heavy phase)	-
E_{LP}	liquid separation efficiency (light phase)	-
E_S	solids separation efficiency	-
E_u	Euler number (pressure loss factor)	-
F	mass flow rate of solids in feed	[kg/s]
f(d)	weight fraction of particle size in feed	-
g	gravitational constant	-
G'	grade efficiency curve	-
H	pressure drop	[m/liq]

k's	hydroclone constants	-
C_c	oil concentration by volume on clean stream	-
C_i	oil concentration by volume on inlet stream	-
C_o	oil concentration by volume on overflow stream	-
C_U	oil concentration by volume on underflow stream	-
ℓ or l	length of vortex finder	[m]
L	length of hydroclone	[m]
n	vortex velocity profile constant	-
P(d)	partition number	-
Q	flow rate	[m^3/s]
Re	Reynold's Number	-
R_f	underflow/feed	-
Stkc	droplet critical Stokes Number	-
Stk_{50}	Stokes Number	-
U	mass flow rate of solids in underflow	[kg/s]
u(d)	weight fraction of particle size in underflow	-
y	oil fraction in the stream	-
Y	mass ratio of solids to liquids in stream	-

Greek Symbols:

α	velocity @ wall/inlet velocity	-
ε	oil separation efficiency	-
ϕ_{LP}	the hypothetical fraction of the underflow stream at its feed composition	-
ϕ_{HP}	the hypothetical fraction of the overflow stream at its feed composition	-
γ	interfacial tension	[N/m]
η	viscosity	[Pa-s]
μ	viscosity	[kg/m-s]
θ	included angle at cone apex	[rads]
$\Delta\rho$	density difference	[kg/m^3]

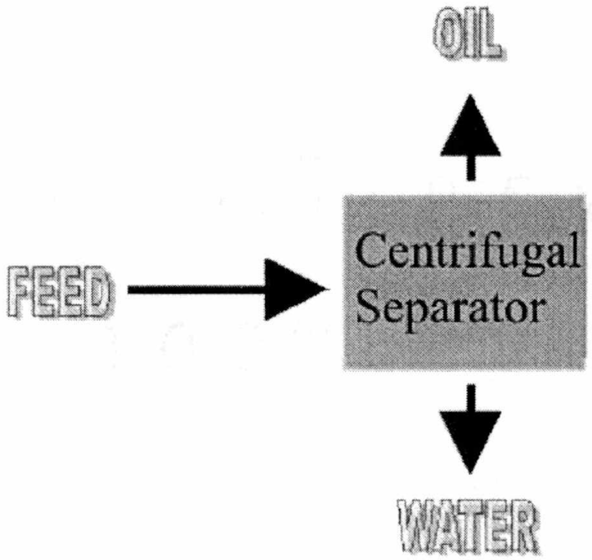
Subscripts:

U	underflow
O	overflow
F	feed
i	inlet

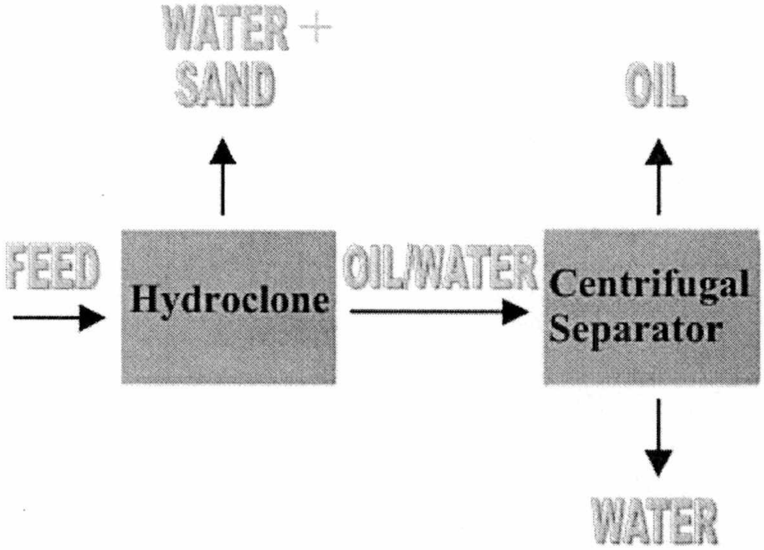
1. INTRODUCTION AND BACKGROUND

1.1 Introduction

This research activity focuses on the removal of solid particulate from oil-water mixtures. This activity is a part of the development of advanced oil-water separator equipment for downhole oil well applications. The oil-water separation in this program utilizes an ORNL (Oak Ridge National Laboratory) centrifugal separator, which requires an essentially solids free feed. This need for a feed that is of low solids content is the motivation for the current study. The fluid entering the bore of an oil well may contain oil, water, and solid particulates. The removal of some water from the fluids entering the well bore will also be accompanied with the removal of solid particulate. Water containing particulates may not be reinjected in some applications, thus requiring the separated phases to be (1) solids with some water, (2) water for reinjection and (3) oil. If solids particulate removal is not necessary, then a 1-step process as indicated in Figure 1(a) is useful, but if solids removal is a concern then the 2-step process of Figure 1(b) is appropriate. While extensive research has been performed on hydroclones to separate solid particulates, this research looks at a specific application of the hydroclone. The concept of utilizing the hydroclone downhole in conjunction with a centrifugal separator sets the goals of the research. The goal of this research is to remove solids from the three-phase feed, while removing as little water as possible with the sand. The objective is to send all of the oil, most of the water, and no sand to the centrifugal separator for separation.



(a) – With No Solids Present



(b) - With Solids Present

Figure 1 - Downhole Separation System

The motivation for this study is to reduce the energy demands of pumping produced fluids that may contain large water-oil ratios and also to reduce the costs associated with the treatment and disposal of the wastewater. By separating oil-water in the well, the additional energy, primarily associated with bringing water to the surface, as well as costs associated with the treatment of that water, may be reduced. The application of the results of this study is for the design and operations simulation of a solids separation unit, to function upstream of an oil-water separation unit. Both of these units are expected to function in an integrated process to separate oil and water in the oil-bearing well of the oil field, commonly referred to as downhole separation.

This activity focuses on oil-water-solid separation from simulated oil well fluids using a small-scale, commercial hydroclone. The simulated oil well fluids (produced fluids) will contain oil-water ratios from 9:1 to 1:9 (by volume) to simulate conditions over the lifetime of an oil well. This thesis provides relevant background information, develops theoretical concepts for data reduction, describes the experimental setup and operation, and provides results, conclusions, and recommendations. In the following paper, the terms cyclone, hydrocyclone, and hydroclone are used interchangeably to refer to the cyclone units.

1.2 Typical Wells

Oil-well characteristics may vary drastically from one field to another. Some of the major concerns for typical oil wells include composition of the fluids (oil, water, sand) and the method of bringing the fluids to the surface. This section briefly discusses the composition encountered in oil wells (including the importance of water reinjection), typical lifting methods for the fluids, and separation techniques for segregating the production and disposal zones of an oil well. The different requirements for onshore versus offshore oil wells are also addressed. This discussion will give a brief insight into the range of conditions encountered in oil production.

An important aspect of oil wells is that the oil and water exist as separate phases in the formation and are emulsified by pumping.[1] Brine is generally the aqueous phase in oil wells. This aqueous phase becomes the major part of the produced fluid flow (fluid reaching the surface) toward the end of the well's life.[2] The brine is typically separated at the wellhead (where the produced fluids come above ground), but costs of transporting the brine to disposal sites are an economical limitation, as is equipment corrosion due to the brine. In fact, the cost of water handling, disposal, and treatment are the main factors in closing a well to oil production.[2] Such wells are called "Orphan wells."[3] The American Petroleum Institute estimated 20.9 billion barrels of wastewater from oil production was disposed of in 1985 in The United Sates.[4] Shutting down oil wells, due to water production, leaves behind oil reserves that could be processed.[3]

Approximately 90% of the time, oil wells require some type of lifting system (e.g. pumps); otherwise, the oil will not flow to the surface. Several factors are evaluated in determining which type of lifting device will be used. The factors include depth of the well (a typical well may be 2 miles deep or more), nature of the oil-bearing medium, gas-oil ratio, presence of solids, and viscosity of the crude oil. The lifting systems consist of surface or subsurface equipment. Surface lifting methods include surface pumps, such as rod pumps, which account for approximately 80% of the oil lifting systems. Subsurface lifting equipment includes the common submergible centrifugal pumps and hydraulic pumps.[1] In general, the ORNL oil-water separation system appears to be compatible with only continuous flow pumps, such as centrifugal pumps or hydraulic pumps.

In the past, above-ground liquid-liquid separation equipment has had residence times of 5-20 minutes, usually requiring a large-volume separator. On offshore platforms, this type of equipment is hard to accommodate due to space limitations. Hydroclones are an option, particularly as part of an offshore system, due to their advantages of low residence time, compactness, and separation efficiency.[5] Hydroclones have been used for oil/water separations since the mid-1980's.[6] Liquid-liquid hydrocyclones have shown promise in offshore oil wells but generally have not been economically feasible for land-based applications.[7]

An oil well, utilizing a DOWS system, is typically viewed as having two regions downhole. The disposal zone is the area where the water is reinjected into the well, while the production zone is the area where the produced fluids are obtained. The injection (disposal) zone must be isolated from the production zone for the oil well to operate properly.[8] One common solution is the use of a packer. A packer is placed in the well to isolate the injection and production zones. Packers prevent the injected water from contaminating the production zone.[3] Using a disposal zone below the production zone in oil wells has been the typical concept used to date.[4] New packers have been developed to allow a disposal zone above the production zone, but this is not the typical installation.[9] The type of packer used is another important consideration. Some packers cannot operate in shallow wells, while others can. A good understanding is needed to properly use a packer in an oil well.[9] Figure 2 illustrates a typical oil production well. The packer would typically be in the area of the oil/water contact to separate the production and injection zones.

1.3 Current DOWS Technology

This next section will look at some of the technology currently used in downhole oil-water separation (DOWS) systems. This discussion will include the current techniques used in DOWS systems, as well as the current lifting systems utilized. The current use of DOWS units in onshore versus offshore oil wells will be compared and the problems and areas of concern in current downhole technology will be explored. This discussion will lead to a better understanding of the current use and limitations of DOWS technology. The discussion will also aid in an understanding of the importance and relevance of the current study.

Currently, there are two major techniques for oil/water separation in downhole applications. These techniques are liquid-liquid hydroclones and gravity separations.[10] This discussion is limited to the use of liquid-liquid hydroclones due to the relevance of this technology in the current research. Hydroclone based DOWS systems are usually operated in wells with water-to-oil ratios of 5-100 and usually result in a production stream that has a 1-2 water-to-oil ratio. These DOWS hydroclones for liquid-liquid

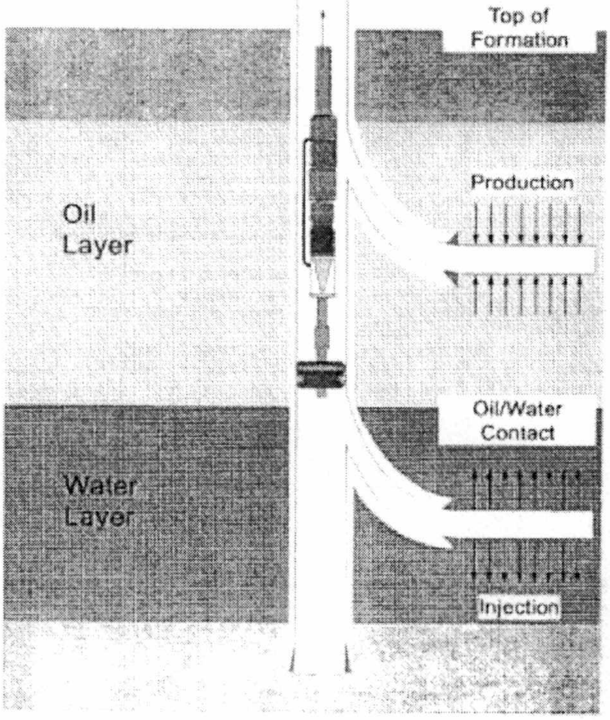


Figure 2 – Typical Oil-Water Layers Downhole

(Source: "Downhole application of liquid-liquid hydrocyclones"
by: B. Bowers, D.D. Lloyd, P. Schrenkel, C. Matthews,
HYDROCLONES '96 editors: D. Claxton, L. Svarovsky, M. Thew)

separations tend to be narrow and long. A typical liquid-liquid hydroclone system may be only 50-mm in diameter but 1-2 meters long.[4] Liquid-liquid hydrocyclones also require large centrifugal forces for separation, which can be greater than 2000 g's.[7] Liquid/liquid hydroclones have been used to separate water for disposal above ground (and downhole in some cases).[10] These liquid/liquid units are used to produce one clean stream, not two concurrent pure streams. Reports indicate that if a liquid-liquid unit is used to produce a nearly pure water stream, then some water will be present in the oil stream and vice versa. Generally, there is no underflow (flow from the bottom of the hydroclone) control mechanism for a hydroclone used downhole,[8] but some of the liquid is routed to cool the pump motor. If a DOWS system is operating effectively, a common total concentration is 10-200 ppm of oil in the discharge stream.[3]

Current lifting techniques in oil production involve the use of various types of pumps. This discussion focuses on two of the more common types of pumps used in DOWS units, rod pumps and progressing cavity pumps. A rod pump uses sucker rods to lift the oil, and the rod has a piston pump at the bottom. As the rod goes up (the piston moves up), a one-way valve opens, and fluid enters the pumping chamber. As the piston goes down, the fluid is forced through another valve to a point above the piston and to the surface.[1] Rod pumps have been used, but they are not feasible offshore due to cost and well conditions.[10] Rod pumps can tolerate sand and debris, but they cannot tolerate dissolved gas.[1] Another type of pump used is a progressing cavity pump, which can tolerate solids; this type of pump is used for mixtures that emulsify easily, but is only capable of maintaining low flow rates of produced fluids.[10] Many other pumps have also been used. Subsurface pumps include a submersible centrifugal pumping, hydraulic pumping, and gas-lift pumping systems. Hydraulic pumps cannot tolerate sand or dissolved gases. While submergible pumps can tolerate sand, this tolerance comes at the expense of increased wear. Airlift systems can operate in the presence of dissolved gas and sand.[1] Electric submergible pumps, rod pumps, and progressing cavity pumps have all been used to provide the pressure difference necessary to operate a hydroclone.[4] The pump feeds the hydroclone, and the water stream (underflow) is routed to the injection zone, while the oil stream (overflow) is routed to the surface. The pump provides the pressure for the separation and injection and connects directly to the separator.[10]

Offshore oil wells have different economic aspects than onshore wells and must be considered separately. Offshore oil-producing platforms have high disposal costs, that may be reduced by a DOWS system.[3] In the past, large separation tanks have been used to perform the oil-water separation, but this process can be expensive, due to the vessel size required to obtain the desired residence time for the separation. The space needed for these separation vessels is generally not available on offshore oil wells.[2]

In The United States, large volumes of water are commonly produced in oil production. These large water volumes add costs in the form of increased production power, disposal, water handling, and chemical treatment costs.[8] Reducing the water brought topside (above ground) reduces chemical and space requirements for surface treatment. For example, the cost of corrosion inhibitors (used to protect equipment) depends on the volume of water to be treated.[3]

Currently, down-hole separation systems are only economically feasible for on-shore applications where high transportation and treating costs for water are considerations, or where high water production limits oil production. Offshore applications require high reliability, due to the high cost of installation and high maintenance costs downhole. The current downhole separation systems have not shown the reliability needed to incorporate them extensively offshore.[1] Offshore platforms have used equipment (e.g. above ground liquid-liquid hydroclones or in limited situations separation tanks) in the past to clean up the water streams so that oil is not discharged to the sea.[5]

The primary problem with the use of the ORNL centrifugal separator for oil/water separations is protecting the unit from solids. In centrifugal separators, the dense particles sink and collect in the separator, which reduces the effective capacity of the separator and eventually makes the separator inoperative.[11] The difficulty of processing solids in a centrifugal separator provides the motivation for this research.

Even in the midst of the uncertainty and expense of using DOWS systems, there are potential benefits. The costs versus possible benefits must be considered. Most DOWS systems have been tested in wells that have favorable conditions, such as high formation temperature (>100°F), high water content (>95%), and high crude gravity (>30°API). Mechanical failures such as plumbing (due to tube damage at installation), seal failures, pump failures (inadequate thrust bearings), and solids production are all realistic concerns.[10] Upgraded materials may be used for the DOWS system to decrease wear. Small hydrocyclones give better separation, but at limited capacity, and groups of hydrocyclones are not thought to be practical downhole.[10]

Major advantages of DOWS systems include reduced operating expenses, reduced capital expenses, improved oil recoverability, and reduced risk of environmental damage.[3] DOWS systems may prove to be more beneficial and increase in use as the price of oil rises, thus making the economic advantages even larger.[4] Some DOWS units are in use today, but the threat of early failure has limited their extensive use.

2. LITERATURE STUDY

2.1 General Literature Introduction

There are many different types of cyclones, including hydraulic cyclones (hydroclones) that are used with liquids. A cyclone is an apparatus that uses centrifugal force and specific gravity differences to perform the separation of the two components.[12] The main types of cyclones considered in this paper are liquid-solid hydroclones and liquid-liquid hydroclones. A liquid-liquid system is designed to separate two immiscible liquids. A solid-liquid apparatus is designed to remove particles or solids from the feed stream. The liquid-liquid units have a typical length-to-diameter ratio of 20 to 40 while solid-liquid units have a typical length-to-diameter ratio of 5 to 8.[1]

The following sections introduce each of these types of hydroclones and then a discussion of the types of calculations needed to understand each is presented. Advantages, disadvantages, and uses of these hydroclones are also discussed. This discussion leads to a better understanding of the mathematics involved in designing a system for use with a hydroclone.

2.2 Hydroclone Operation

A hydroclone consists of two main sections, a cylindrical section and a conical section. The geometry of a hydroclone consists a cylinder sitting on top of a cone. The unit has three ports. These three ports consist of one feed port and two exit ports. The feed port is located in the side of the cylinder portion of the hydroclone. One exit port is located in the center of the bottom of the cone. The other exit port is located in the center of the top of the cylinder, with a small portion of the port protruding down into the apparatus. Figure 3 gives a representation of the flow inside a hydroclone and shows the geometry of the hydroclone. The next thing to consider is the flow inside the hydroclone. In a hydroclone, the feed stream enters the apparatus on a tangent at the point of largest diameter.[13] The largest diameter (diameter of the cylindrical section) is used to classify hydroclones by size.[14] The feed enters at a high velocity, resulting in a centrifugal field,[14] which generates a vortex.[13] The flow pattern in a hydroclone commonly has an air core that may wobble and cause the pattern to be more complex, but some hydroclones do operate without this air core.[6] The velocity at the wall increases as the radius decreases in the conical section. In the lower sections of the cone, the radial velocity decreases toward the center of the unit.[15] As the process fluids separate in the apparatus, they form an interface that is reported to take on a sinusoidal shape.[6] The hydroclone walls taper down to the exit underflow port in a cone shape.[14] Small diameter hydroclones are typically used to separate very small particles because the high centrifugal forces needed to obtain the separation are more easily obtained in these smaller units. These small units do experience turbulence fluctuations though, which can present a problem.[16]

The cylindrical tube, through which the overflow from the hydroclone exits, protrudes down into the hydroclone some distance. This tube is called the vortex finder.[17] See Figure 4 for a sketch of a hydroclone including the vortex finder. A pump typically provides the pressure drop across the hydroclone, providing the energy needed

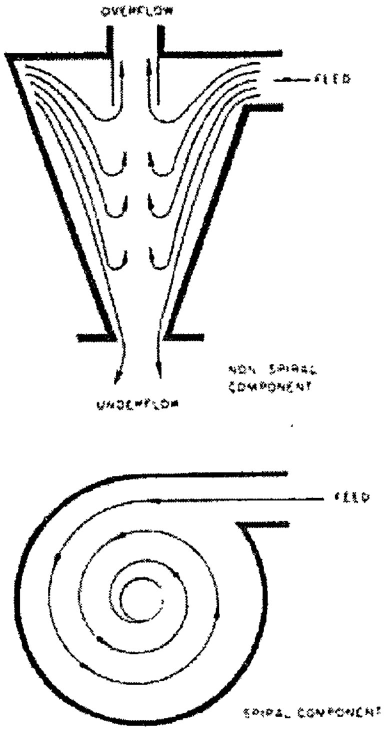


Figure 3 – Top View of a Hydroclone

(Source: Haas et al., Midget Hydroclones Remove Micron Particles, Union Carbide Nuclear Company Unit Operations Section, Chemical Technology Division (1957))

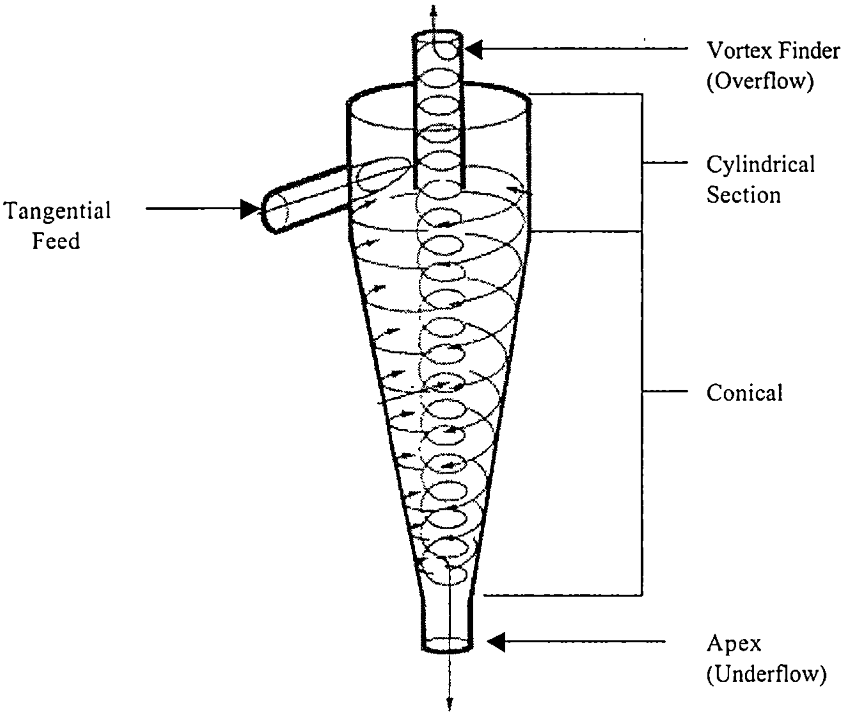


Figure 4 – Flow Pattern of a Hydroclone

(Source: Day, R.W., The Hydroclone In Process and Pollution Control, *Chemical Engineering Progress*, 69, No. 9, pp. 68, (September 1973)) for the separation.[14] The ratio of overflow to underflow streams is called the "split" and is usually adjusted by control valves on the underflow stream. The split does not have to be the same as the feed ratio of the substances to be separated.[18] The feed ratio, as used in this report, is defined as the volume of oil per volume of water in the feed stream. Control of the flow rate through the hydroclone is obtained by controlling the pressure drop across the device.

2.3 Typical Solid-Liquid Hydroclone Design

Feeds to a hydroclone can be rectangular or circular but are typically rectangular, with the circular inlet easier to manufacture, but the rectangular inlet giving better results. The inlet is at the top of the hydroclone to prevent any short-circuiting (both components exiting the top of the hydroclone without separation), due to an inactive zone at the top of the hydroclone.[13] The vortex motion (necessary for hydroclone use) is obtained from the fluid itself. The tangential injection of the feed into the hydroclone produces a strong swirling motion. The vortex finder is the route for the flow, which exits from the top of the apparatus.[17]

The diameter of the unit is the main way to classify hydroclones. Table 1 gives a summary of some typical dimensions for a hydroclone unit, as obtained by various researchers. General reports indicate that the optimum inlet diameter ranges from $D_C/4$ to $D_C/7$ for separations. All other dimensions of a hydroclone are generally related to the cyclone diameter (D_C), which serves as the main design variable.[13]

Table 1 – Summary of Some Known Hydrocyclone Designs
(Source: *Solid-Liquid Separation* by:L. Svarovsky pg. 162-188 (1981))

	Geometrical proportions				
Cyclone type and size of hydrocyclone	D_i/D_c	D_o/D_c	l/D_c	L/D_c	*Angle θ, degrees*
Rietema's design[18] (optimum separation), $D_c = 0.075$ m	0.28	0.34	0.4	5	20
Bradley's design[19], $D_c = 0.038$ m	0.133 (1/7.5)	0.20 (1/5)	0.33 (1/3)	6.85	9
Mozley cyclone[20], $D_c = 0.022$ m	0.154 (1/6.5)	0.214 (3/14)	0.57 (4/7)	7.43	6
Mozley cyclone[21], $D_c = 0.044$ m	0.160 (1/6.25)	0.25 (1/4)	0.57 (4/7)	7.71	6
Mozley cyclone[22], $D_c = 0.044$ m	0.197 (1/5)	0.32 (1/3)	0.57 (4/7)	7.71	6
Warman 3" Model R[23], $D_c = 0.076$ m	0.29 (1/3.5)	0.20 (1/5)	0.31	4.0	15
RW 2515 (AKW)[24], $D_c = 0.125$	0.20 (1/5)	0.32 (1/3)	0.8	6.24	15

2.4 Solid-Liquid Hydroclones

In order for the particles to be removed from the fluid, they must be at a velocity that is so high that the particle moves away from the center of the hydroclone where there is upward flow.[14] Centrifugal and drag forces are the only forces considered acting on a particle because the gravitational forces are so small they are considered negligible. If the centrifugal force is greater than the drag force, then the particle moves outwards toward the wall of the hydroclone. If the centrifugal force is less than the drag force, then the particle moves toward the center of the hydroclone.[13] The result of this centrifugal field is that the heavy phase (particles) accumulates at the wall of the unit. The substances at the wall of the hydroclone can then be removed through the underflow steam exiting the bottom of the separator.[14]

Solid-liquid hydroclones can typically produce forces up to about 1,000 g's or more and have residence times of seconds or less.[12] Feed concentration, liquid viscosity, particle size, and cyclone geometry are some factors that affect cyclone performance.[19] Particles that are separated by hydroclones are generally in the range of 40-400 μm, but can range from 5-1000 μm in special applications.[20] A typical density of these particles is 1.5 to 2.0 g/mL.

2.4.1 Operation

As previously discussed, the level of forces created, residence times, and turbulence created are all factors used to characterize the hydroclone. According to Stokes Law, which is used to characterize gravity-force machines, "…separability is directly proportional to the particle diameter squared times the specific gravity differential between the solid and liquid phases, and it is inversely proportional to the viscosity of the suspending fluid."[12] Other variables, not included in Stokes Law, that influence the performance of the hydroclone, include flow rate and apparatus dimensions (e.g. length, diameter, etc.).[12] The optimum operating point for the apparatus is found by plotting overflow concentration versus underflow concentration. The sharp break in the curve is the point of optimum operating conditions.[21]

Some parameters that affect the separation efficiency of the solid-liquid hydroclone should also be discussed. Separation efficiency decreases with feed concentration of solids, but efficiency predictions are not readily available.[22] Generally, the area of the inlet nozzle is a rectangle and is approximately 0.05 times the cyclone diameter squared. The vortex finder serves two purposes. One is to aid the separation, and the other is to control the flow exiting the overflow of the hydroclone. Smaller vortex finders tend to give finer separations, and vice versa. The cylindrical section of the hydroclone serves to make the hydroclone longer and to provide a longer retention time. An increasing retention time provides a finer separation, within limits. However, the retention time is only a minor factor in separation efficiency. The cone angle and cylinder section may also be used to change the retention time. Related to this, there is an assumption made, as stated by Arterburn[20], that some solids go to the underflow based on the split only and not based on a separation.[20] Particles that enter the upward flow may be recirculated near the bottom of the vortex finder and separated again. The larger particles are closer to the wall of the hydrocyclone, but the maximum in concentration is not at the wall.[23]

Napier-Munn[24] performed research on solid/liquid separations in a 30-mm hydroclone. Napier-Munn found that increased viscosity related to a poorer separation quality. He also noted that "It is known that the d_{50} will increase with viscosity, diverting more medium solids to the overflow and thus increasing the density of the overflow medium [overflow stream] at the expense of the underflow medium [underflow stream]."[24]

Another area of concern is that two clean streams cannot be produced. "The dilemma is that a thick underflow and a high solids recovery cannot be achieved at the same time and one has to be sacrificed for the other. For maximum solids recoveries, the solids concentration in the underflow should be below a certain limit because above that limit some solids will start going into the overflow." [22]

2.4.2 Design

The 'grade efficiency curve' is the best way to demonstrate the efficiency of a hydroclone separation. This type of curve shows the probability that certain particle sizes will be separated into the overflow or underflow. This method is often complicated and time consuming, so a single number called the cut size (previously mentioned) can be used. The cut size is a correlation with using a screen such that "... the cut size is the aperture size of a hypothetical and ideal screen which would achieve the same separation as the hydrocyclone."[25] For example, d_{50} correlates to 50% on the grade efficiency curve and thus a particle of this size has the same possibility of going to the overflow as going to the underflow.[25] Hydroclone efficiencies are classified by the cut size they produce. However, due to incidents such as short-circuiting, the particle sizes removed in the underflow may range in removal efficiency from zero to 100%. Here are some empirical equations for determining the pressure drop (H) and the cut size (d_{cut}) of a hydroclone:

0.4 - 7.5-mm diameter cyclones[14]:

$$H = \frac{21.04Q^{2.27}}{D_C^{0.8} D_i^{1.3} D_O^{2.0}} \tag{1}$$

7.5 and 15-cm diameter cyclones[26]:

$$H = \frac{44.0Q^{2}}{gD_C^{0.9} D_i^{1.2} D_O^{1.9}} \tag{2}$$

The cut size, d_{cut}, characterizes the separation efficiency of the hydroclone. Particles larger than the cut size exit in the underflow and particles smaller than the cut size exit in the overflow. Haas[14] gives the cut size as

$$d_{cut} = \frac{0.0765 D_C^{0.5} \mu^{0.5}}{H^{0.25} \Delta\rho^{0.5}} \tag{3}$$

Bradley[13,27] developed the following equations to estimate the cut size

$$\frac{d_{50} D_C}{D_i^2} = \frac{3(0.38)^n}{\alpha} \left[\frac{\mu D_C (1 - R_f) \tan(\Theta/2)}{Q \Delta\rho} \right] \tag{4}$$

$$d_{50} = \frac{3(0.38)^n D_i^2}{\alpha} \left(\frac{\tan(\Theta/2) \mu (1 - R_f)}{D_C Q \Delta\rho} \right)^{0.5} \tag{5}$$

Another method for estimating the cut size of the hydroclone was developed by Rietema.[13] Rietema assumes, for example "...that [d_{50}] is the diameter of particle which, if injected precisely in the centre of the inlet, just succeeds in reaching the cyclone wall at the apex."[13] A similar equation is available for the cut size and is given as:

$$\frac{d_{50}}{D_C} = 0.239\,\mathrm{Re}^{-0.1874}\left(\frac{D_C\mu}{Q\Delta\rho}\right)^{0.5} \tag{6}$$

A direct analogy with gravity settling by Trawinski[13] gives:

$$\frac{d_{50}}{D_C} = 0.02283\left(\frac{\mu D_C}{Q\Delta\rho}\right)^{0.5} \tag{7}$$

Using 5-cm and 12-cm hydroclones, an equation is proposed, by Svarovsky[22], to estimate the cut size for high solids concentrations in the feed and is given as[22]

$$\frac{d_{50}}{D_C} = k_1\left(\frac{\mu D_C}{Q\Delta\rho}\right)^{0.5} e^{k_2 c} \tag{8}$$

In general, d_{50} increases with increasing viscosity and hydroclone diameter. The feed flow rate and density difference of the two phases is inversely proportional to d_{50} in each of the equations given above. Although the value of the constants differs in value, the main variable have the same effect in each prediction. These equations indicate that regardless of the theory used, the cut size estimation is approximately the same. If R_f (underflow/feed ratio) is higher than 1% or 2%, then the above predictions overestimate the cut size.[13] Reliable techniques are not generally available to determine what particular hydroclone design is best for a given situation. Empirical tests are best for achieving a reliable separation for a given separation problem, but the above equations provide a good starting point for this determination.[12]

The efficiency of hydroclones is usually predicted using semi-empirical methods.[13] An efficiency curve is often represented as a partition curve. This curve gives the fraction of a certain size particle that goes to the underflow of the hydrocyclone. A partition number can be calculated from: [17]

$$P(d) = \frac{Uu(d)}{Ff(d)} \tag{9}$$

where U and F are mass flow rates of solids and u(d) and f(d) are weight fractions of the particle size of interest in the underflow and feed respectively. The partition number does not always approach zero for small particles in a hydroclone, but goes to a bypass number (the small particles are split in proportion to the liquid split[17]).

2.4.3 Advantages/Disadvantages

There are many advantages and disadvantages in utilizing hydroclones. Some of these advantages include the materials that can be used to manufacture the units. Materials for hydroclones range from stainless steel to titanium depending on the fluids and solids to be separated. Stainless steel units have critical velocities that separate high and low corrosion regions. Stainless steel systems are undependable for use in certain operations though due to wear.[14] Cyclones can be made of mild steel, fiberglass, and even elastomers.[28] Most hydroclones have replaceable liners.[28] Various materials are used to prevent abrasive wear on the system walls and include steel, nylon, ceramics, rubber liners, etc.[13] Liners are usually temperature resistant elastomers such as chlorobutyl.[28]

Advantages of using a solid-liquid apparatus for non-oil producing separations include the low residence time and low cost. The low cost results from the low residence time, which results in smaller equipment and inventory.[18] Some additional advantages of solid-liquid systems are low operating expense, benefit to other process equipment, and improving operability of separators that may be downstream.[12] Hydroclones also generally provide higher throughput, higher efficiency, more flexibility, higher underflow densities, and better product quality than operation without a hydroclone.[19]

Some problems do exist with the use of hydroclones. These units may need to be replaced due to corrosion, plugging, or varying operating parameters, such as capacity, underflow ratio, or efficiency changes. A problem that is also found in solid-liquid systems is the plugging of ports. Using screens to remove very large particles that may plug an opening can reduce plugging.[14]

2.4.4 Non-Oil Producing Uses

Some uses of the hydroclones include the removal of insoluble corrosion products, in various reactor systems, to protect the equipment.[14] Hydroclones are also used in the pharmaceutical industry. Extraction of some antibiotics is performed in hydroclones because the conditions result in deterioration (rapidly) of the product and demand a small residence time.[18] Hydroclones can be very useful in process and pollution control situations and even used to separate polymers from slurries. Cyclones are used in gas cleaning and powder classification.[13] Mineral product separation, and drilling mud regeneration are also currently utilizing hydroclones.[13] Other uses of hydrocyclones are sand washing and cooling tower water clean up.[29] These devices are used to remove particles as small as one micrometer from the feed fluids.[14]

2.4.5 Discussion

As previously stated, the flow is very complex inside a hydrocyclone. Some research on hydroclones indicates that particles are moving with "...the same tangential and vertical velocities as the water,..." [15] Some experiments have shown that a volume of concentrated particles moves down the wall, turns sharply at the bottom, and exits in the overflow.[15] Theory and simulations are the main emphasis of solid particle velocity studies. Current studies are underway using a laser Doppler equipment to better understand the movement of the solids and liquids, but for now, the best way to utilize solid-liquid hydroclones is to perform empirical testing in each new situation.[23]

2.5 Liquid-Liquid Hydroclones

Liquid-liquid hydroclones separate two immiscible liquids. In this current research, the liquids are oil and water. One example of a liquid/liquid hydroclone has a 30-mm diameter, 16-mm apex (underflow exit), L/D ratio (length/diameter ratio) ~ 15, and two inlet ports.[2] Another liquid/liquid hydrocyclone has the dimensions $D_C = 35$ mm and $L = 1.337$ m.[30] The vortex finder length is about 1.1 times the hydroclone diameter ($\ell/D_C=1.1$), which is higher than the 0.2 to 0.5 ratio used in solid/liquid hydrocyclones.[2] These values indicate that the liquid-liquid hydroclones are much longer than the comparable solid-liquid hydroclones, but with similar sizes for the ports and unit diameter. This increases length allows for a longer residence time to aide in the liquid-liquid separation.

The pressure drop required for the separation generally ranges from 1-5 bar.[5] As the fluids go through the unit, the lighter fluid moves toward the center of the hydroclone. At a point in the apparatus, the velocity in the vertical direction reverses and forms a flow (spiral path) back up. The heavier phase is at the wall of the separation unit and exits out of the bottom of the hydroclone. The flow in the center of the hydroclone exits in the overflow out the top.[14]

In previous work, the main concept is to concentrate the dispersed component and provide a clean (mostly pure) stream with minimum concentration of the dispersed component. Even though the amount of flow in the secondary stream "... has been kept as small as possible, this has not been the major objective."[31] While literature related to liquid-liquid cyclones is not abundant, some limited research studies are available. For example, Tepe and Woods report poor separation of isobutanol and water in conventional 1-inch and 2-inch hydroclones. This investigation evaluates different feed rates, feed compositions, and different splits to demonstrate the possible operating range of the hydroclones. Based on the mentioned study, the optimum split (maximum separation efficiency) approaches the phase ratio at low flow rates and approaches unity at high flow rates. Other limited research (Simkin and Olney) uses oil-water volume ratios (for the feed) of 1:3 to 9:1 with flows up to 24 gallons per minute.[32]

2.5.1 Operation

The concept to improve efficiency in liquid-liquid separators is to separate the phases without breaking up the oil droplets. The result is a different geometry than for solid-liquid separators, even though the basic design or concept of the hydroclone does not change.[5] Increasing the pressure drop across the hydroclone reduces the efficiency, while maintaining the split. Increasing the volume of the hydroclone increases the residence time and decreases the separation efficiency, for a given pressure drop. These results have been interpreted to indicate that drop breakup controls the separation.[32] Enlarging overflow tube diameters reduces the maximum efficiency without disturbing the optimum split. The determination is made that hydroclone geometry has little effect on separation, but the separation depends primarily on the split and feed rate.[32] Shorter vortex finders decrease performance due to short-circuiting. A decrease in performance is reported at a $\ell/D_C > 2$ (ℓ is the length of the vortex finder), due to the surface of the vortex finder being in contact with the vortex core. The drop-off in efficiency at high flow rates is probably due to drop breakup, while the drop-off in efficiency at low flow rates is probably due to a reduced acceleration field. When the water composition increases, the pressure difference between the feed and the underflow reportedly drops. This indicates "… that the rise in average density … has a much smaller effect than the decrease in viscosity."[2]

Oil is less dense than water, thus the oil phase moves toward the center of the hydroclone, while the water moves toward the walls. The heavier phase reaches the wall and is held there, but the lighter phase (in the center) does not have a wall available, and thus relies entirely on the flow regimes in the hydroclone.[5] For oil/water separations, where oil is the primary ingredient in the feed, it is desirable that most of the flow goes out the overflow. Conversely, if water is the primary ingredient in the feed, then it is desirable that most of the flow goes out the underflow.[2]

2.5.2 Design

The overall flow rate determines the vortex strength, and thus how the oil drops will behave inside the hydroclone.[5] Liquid/liquid separation is characterized by the overall efficiency (η) and individual separation efficiencies (ε_U and ε_O) which are given by: [2]

$$\eta = \frac{Q_U}{Q_i}\left|\left(\frac{100-C_U}{100-C_i}\right)-\frac{C_U}{C_i}\right| \qquad (10)$$

$$\varepsilon_U = 1 - \frac{C_U}{C_i} \tag{11}$$

$$\varepsilon_O = 1 - \left(\frac{1 - C_O}{1 - C_i} \right) \tag{12}$$

Oil drop size is an important concern in separating oil and water in a hydroclone. Increasing the feed flow rate increases separation efficiency, if increased drop breakup does not occur.[5] It is desirable to avoid shear in upstream piping, because it contributes to drop breakup and makes the separation more difficult. However, high shear can occur in the hydroclone itself. Mixtures that are predominately water are easier to separate due to the lower viscosity. Viscous emulsions that are difficult to separate can form from high oil ratios and shear rates.[10] In general, larger inlet droplet sizes give a better separation up to a critical diameter, beyond which the separation does not improve.[33] The critical drop diameter is estimated by: [34]

$$d_C = \left[Stkc \frac{D_n{}^3 \mu_i}{Q_i \Delta\rho_i} \right]^{\frac{1}{2}} \tag{13}$$

2.5.3 Advantages/Disadvantages

Liquid-liquid hydroclones have several advantages for use in industry. These advantages include high efficiency, (some tests show 98% efficiency of liquid-liquid units in oil-water separations.[7]) small size, high capacity, (hydroclones can have high capacities of as much as 400 gpm per square foot of area.[15]) and simplicity. The hydroclones can also be made to withstand high-temperature and high-pressure fluids, and generally require little maintenance because of the lack of moving parts or mechanical seals.[14] Hydroclones have low holdup and are completely sealed. The longer liquid-liquid units have longer residence times than the solid-liquid units but the relative residence time is still small.[12]

Liquid-liquid units do have limitations, for example, they cannot handle mixtures of gas, oil, and water when used as the primary separating device. The apparatus also cannot operate well in the oil-rich regions, but are usually limited to feeds containing 65+% water, if the system solely relies on the hydroclone separation.[1] Another problem with these liquid/liquid systems is that they commonly experience break up, due to the high forces, thus reducing separation efficiency.[13] Since the separation depends on the drop size, the performance is impaired. Efficiency increases with flow rate unless the resultant forces begin to cause the oil droplets to break up; a problem that is not present in solid/liquid separations.[5] Higher viscosity corresponds to increased drop breakup.[2] At high overflow/underflow ratios, drop breakup is increased.[33]

Droplet size, oil slugging ("Globs of viscous liquid"[7]), interfacial tension, and chemical treatment all affect the performance of a liquid-liquid hydrocyclone. Oil droplets less than 10 μm are hard to separate, but higher temperatures may improve the performance of liquid-liquid units. Oil slugging and solids can be detrimental to the performance of the hydroclone unit.[7]

2.5.4 Uses

Many different uses for liquid-liquid hydroclones exist. Cyclones can help keep mechanical seals in operation by removing contaminants and producing a clean liquid to use on the seal.[12] Cleaning of solvents is another application for hydroclones, as well as clean up of cooling oil.[13] Mass transfer applications are also under study for liquid-liquid hydroclones.[32] As more uses become apparent for liquid-liquid hydroclones, more and more industries will begin to utilize them and fund future research in their use.

2.5.5 Discussion

Liquid-liquid hydroclones are more difficult to understand than solid-liquid units. The problem of drop breakup only adds to the already complex flow regime. The dimension alterations, as well as the lack of research on the liquid-liquid units, also make the understanding more difficult. Even though research is limited on the liquid-liquid hydroclones, the use of these units, particularly in oil/water separation, appears to be very promising.

3. THEORY

3.1 Predictions

There are many equations that are used to perform calculations involving the use of hydroclones. In this chapter, derivations of equations for predicting the maximum theoretical separation efficiency for liquid separation and solid separation are given and example calculations preformed.

3.2 Efficiency Development

The equations used to predict the liquid and solid separation efficiencies are derived below. Note that the calculations of efficiency using the light phase (E_{LP}) versus using the heavy phase (E_{HP}) give the same value for the efficiency (see Appendix A). Figure 5 is used to develop the following equations. The feed, overflow, and underflow streams are each labeled on this figure and the same symbols are used in the following derivations. The first efficiency derived is the light phase (oil) efficiency. Then we look at the derivation of the efficiency for the heavy phase (water) and finally for the solids separation.

3.2.1 Light Phase (Oil)

In order to develop an efficiency for the liquid separation, consider the overflow stream only. Assume that the overflow exiting the hydroclone consists of a portion that is the same composition as the feed stream. Define this fraction of the overflow as ϕ_{LP}. The remainder of the overflow ($1-\phi_{LP}$) is assumed to be pure oil. An equation for the oil in the overflow can then be written as:

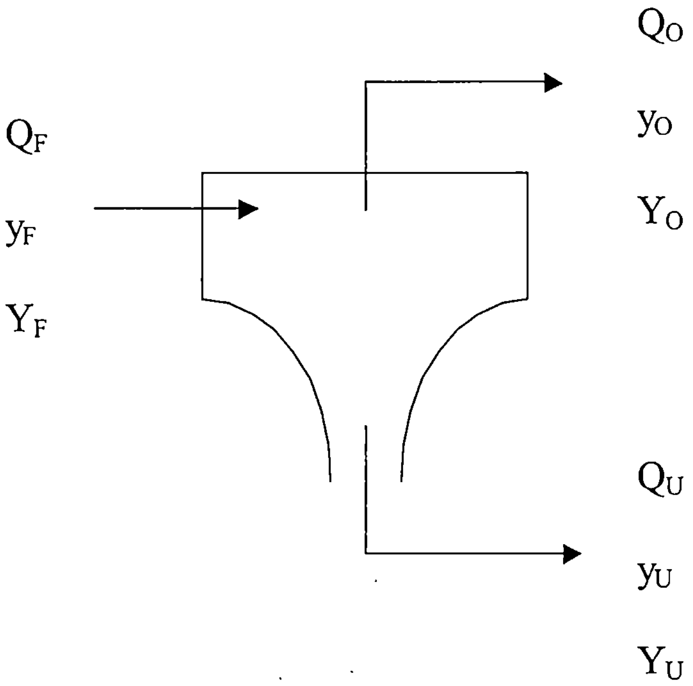


Figure 5 – Figure for Material Balance Around Hydroclone

$$Q_O y_O = \phi_{LP} Q_O y_F + (1-\phi_{LP}) Q_O \tag{14}$$

Solving Equation 14 for the fraction of the overflow stream that is at the feed composition (ϕ_{LP}) gives:

$$\phi_{LP} = \frac{1-y_O}{1-y_F} \tag{15}$$

Now substituting the expression for ϕ_{LP} into Equation 14 gives:

$$Q_O y_O = \left(\frac{1-y_O}{1-y_F}\right) Q_O y_F + \left[1-\left(\frac{1-y_O}{1-y_F}\right)\right] Q_O \tag{16}$$

Simplifying the right hand side of the equation yields:

$$Q_O y_O = \underbrace{Q_O(1-y_O)\left(\frac{y_F}{1-y_F}\right)}_{\text{original feed composition}} + \underbrace{\left(\frac{y_O-y_F}{1-y_F}\right) Q_O}_{\text{pure oil}} \tag{17}$$

The following equation is used as the definition for the efficiency of the separation.

$$E_{LP} = \frac{\textit{hypothetical pure liquid light phase in the overflow}}{\textit{light phase in feed liquid}} \tag{18}$$

Substituting the appropriate expressions into this definition gives:

$$E_{LP} = \frac{Q_O\left(\frac{y_O-y_F}{1-y_F}\right)}{Q_F y_F} \tag{19}$$

which may be rearranged to obtain the more simple expression of:

$$E_{LP} = \frac{Q_O(y_O-y_F)}{Q_F y_F(1-y_F)} \tag{20}$$

3.2.2 Heavy Phase (Water)

In order to develop an efficiency for the liquid separation based on the heavy phase, consider the underflow stream only. Assume that the underflow exiting the hydroclone consists of a portion that is the same composition as the feed stream. Define this fraction of the underflow as ϕ_{HP}. The remainder of the underflow (1-ϕ_{HP}) is assumed to be pure water. An equation for the water in the underflow can then be written as:

$$Q_U(1-y_U)=\phi_{HP}Q_U(1-y_F)+(1-\phi_{HP})Q_U \tag{21}$$

Solving Equation 21 for the fraction of the underflow stream that is at the feed composition (ϕ_{HP}) gives:

$$\phi_{HP}=\frac{y_U}{y_F} \tag{22}$$

Now substituting the expression for ϕ_{HP} into Equation 21 gives:

$$Q_U(1-y_U)=\underbrace{\left(\frac{y_U}{y_F}\right)Q_U(1-y_F)}_{\text{original feed composition}}+\underbrace{\left(1-\frac{y_U}{y_F}\right)Q_U}_{\text{pure water}} \tag{23}$$

The following equation as the definition for the efficiency of the separation.

$$E_{LP}=\frac{\textit{hypothetical pure liquid heavy phase in the underflow}}{\textit{heavy phase in feed liquid}} \tag{24}$$

Substituting the appropriate expressions into this definition gives:

$$E_{HP}=\frac{Q_U\left(1-\frac{y_U}{y_F}\right)}{Q_F(1-y_F)}. \tag{25}$$

which may be rearranged to obtain the more simple expression of:

$$E_{HP} = \frac{Q_U (y_F - y_U)}{Q_F y_F (1 - y_F)} \tag{26}$$

3.2.3 Solids

From a material balance on the solid phase in the above system we obtain the following equation:

$$Q_F Y_F = Q_O Y_O + Q_U Y_U \tag{27}$$

The solids efficiency is given by the mass of solids in the underflow divided by the mass of solids in the feed stream.

$$E_S = \frac{Q_U Y_U}{Q_F Y_F} \tag{28}$$

3.3 Solid-Liquid Separation Efficiency Estimation

In order to conduct calculations of this solids removal system, Equation 4 is used. This equation predicts the cut size and also accounts for the change in the split. As discussed in the previous chapter, the split does not have a tremendous affect on the solids removal efficiency. The cut size predicted for this system is calculated using a viscosity and density of pure oil and then the viscosity and density of pure water at varying splits; Table 2 shows the resulting cut size estimations. As Table 2 shows, the cut size prediction ranges from 2.64 μm for an overflow/underflow ratio of 1, to 4.39 μm for an overflow/underflow ratio of 5 for a pure oil feed. With a pure water feed, a

Table 2 – Cut size Predictions

Overflow/Underflow Ratio	Oil Feed (μm)	Water Feed (μm)
1	3.02	0.86
2	4.02	1.15
3	4.53	1.29
4	4.83	1.38
5	5.03	1.44

cut size of 0.34 μm for an overflow/underflow ratio of 1 and 0.57 μm for an overflow/underflow ratio of 5 is predicted. Due to the fact that the solids used in this research have a much larger particle size than the cut size predicted, we assume approximately 100% solids removal.

3.4 Liquid-Liquid Separation Efficiency Estimation

Predicting the liquid separation efficiency is also addressed in this research. There is a maximum efficiency that can be reached in the unit based simply on material balances. One of the equations used to calculate the liquid separation efficiency is Equation 26. As an example of how to calculate the maximum efficiency of the hydroclone, first assume that the maximum efficiency occurs when the underflow is pure water ($y_u = 0$). The equation for the efficiency thus becomes:

$$E_{HP} = \frac{Q_U(y_F - 0)}{Q_F y_F (1 - y_F)} \tag{29}$$

A hypothetical feed is used as a simple example, and then the same method is used to calculate the theoretical efficiency curve (as a function of split) for each of the experimental runs in this research. For the example, it is assumed that 500 grams of oil and 500 grams of water are fed into the unit per minute. (Note that this separation efficiency of the liquid phase does not take into account any solids present. The assumption is made that the solids do not affect the liquid separation to any significant degree.) The overflow/underflow ratio is assumed to be 2.0 for the example calculation.

Example:

$$\frac{Q_U}{Q_F} = \frac{1}{3}$$

$$y_F = 0.5$$

$$y_U = 0$$

$$E_{HP} = \frac{1}{3}\frac{(0.5-0)}{0.5(1-0.5)}$$

$$E_{HP} = 0.67$$

This equation predicts the maximum possible efficiency that can be achieved in the liquid phase separation (under these conditions) is 67%. These values for liquid separation are plotted as a maximum efficiency curve (see Chapter 5) that is compared to the actual efficiencies obtained from the experimental data.

4. OPERATION

4.1 Equipment

A schematic of the experimental setup is illustrated in Figure 6. (Pictures of the actual equipment setup used in this research may be found in Appendix B.) The equipment used to perform this research includes two 55-gallon stainless steel drums for feed and recovery tanks, a 10-mm inside diameter stainless steel hydroclone (Dorr-Oliver Inc. of Milford, CT - model no. Doxie A), two one-half hp mixers (Leeson Electric Corp. of Graftom, WS – model no. C6C17FB1E), a variable pressure, two hp, feed pump (Hays Pumps of Redding, CA - model no. Quantum VS 7A200), a one-third hp transfer pump (Ebara International Corp. of Rock Hill, SC - model no. 327707U 6.3S), a pressure gauge on the feed line (0-150 psig made by 3D Instruments Inc. of Huntington Beach, CA - model no. DD504-24), two flow meters (Kent Meters Inc. of Ocala, FL - model no. KMJ Bronze), one Whitey needle valve (Swaglok Corp. of Solou, OH - model no. SS-18RS8), one Whitey semi-needle valve (Swaglok Corp. of Solou, OH - model no. SS1RS8), and four on/off valves (NUPRO Co. of Willoughby, Ohio - model no. SS8P6T). The transfer lines were one-half inch stainless steel tubing.

The most important piece of equipment, however, is the 10-mm hydroclone (inside diameter). The hydroclone removes the solids, which is the main point of this research. The hydroclone used here is stainless steel and is designed to remove solids from the liquid phase. This 10-millimeter (inside diameter) hydroclone has a natural split of 60/40 (overflow-to-underflow). A control valve can be used to throttle the underflow

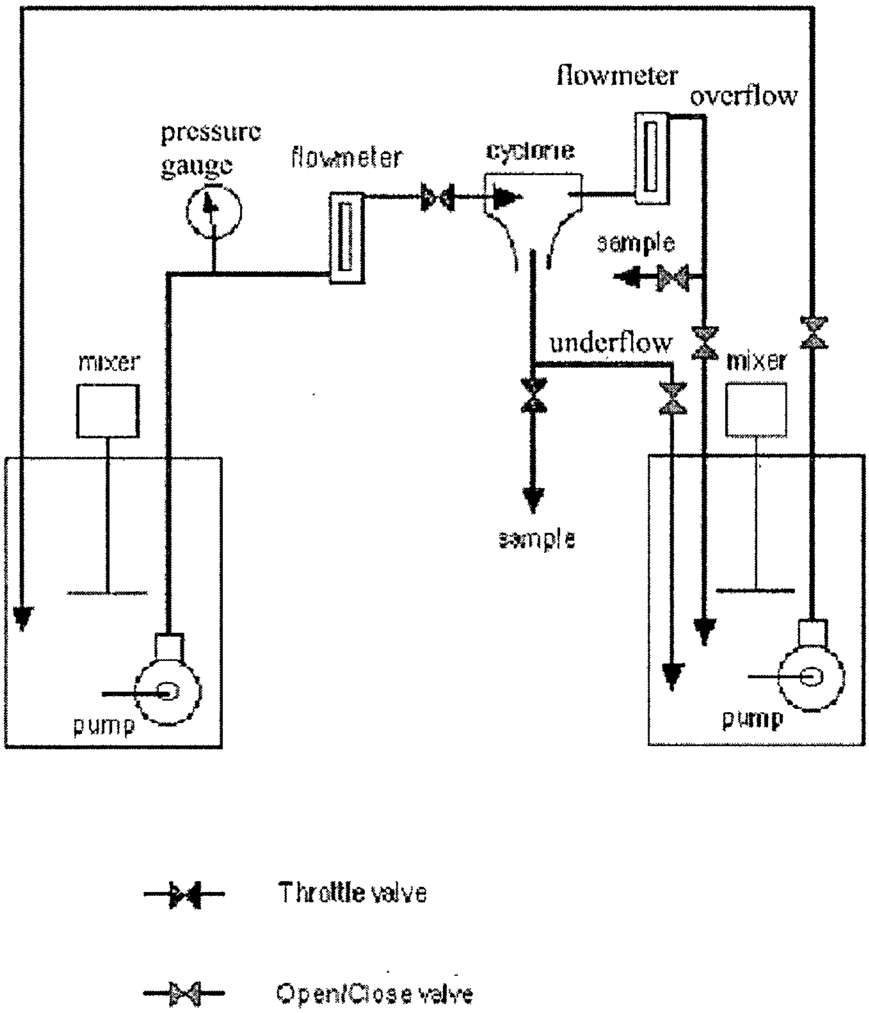


Figure 6 – Experimental Design of Research Apparatus

and change the split; Dorr Oliver Inc. recommends not exceeding a split of 10:1.[21] The hydroclone is mounted upright to aid in cleaning and draining of the unit. The recommended pressure differential across the hydroclone is about 40 psig and should be kept at or above this value. This unit will handle about 0.9 gallons per minute at 60 psig. A picture of the hydroclone is shown in Figure 7. Tests were performed at different oil-water ratios and different feed pressures with at least three different splits for each set of operating conditions. Choking off the underflow valve increases the backpressure on the underflow. This research used a needle valve for split control, but rubber tubing and pinch clips were also used in preliminary testing of the equipment. The procedure used in this research is to start with the underflow valve fully open, and throttle it back.

4.2 Materials

Kendall 10-W non-detergent motor oil is used to give an organic layer as close to crude oil as possible, but with known characteristics. The density of the oil was measured to be 0.869 g/mL and the viscosity was given as 5 cSt. The sand used to simulate solid particles in the produced fluids is white quartz sand (–50+70 mesh) and is supplied by Aldrich Chemical Inc. of Milwaukee, Wisconsin. A plot of the particle size distribution of the sand, as determined by the use of sieves, is presented in Figure 8. The density of the sand was determined to be 1.539 g/mLThe additional materials needed are to make the substitute seawater according to ASTM D1141-90 standard. These materials include potassium chloride (KCl), sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4) all supplied by Fisher Chemical Co. of Fair Lawn,

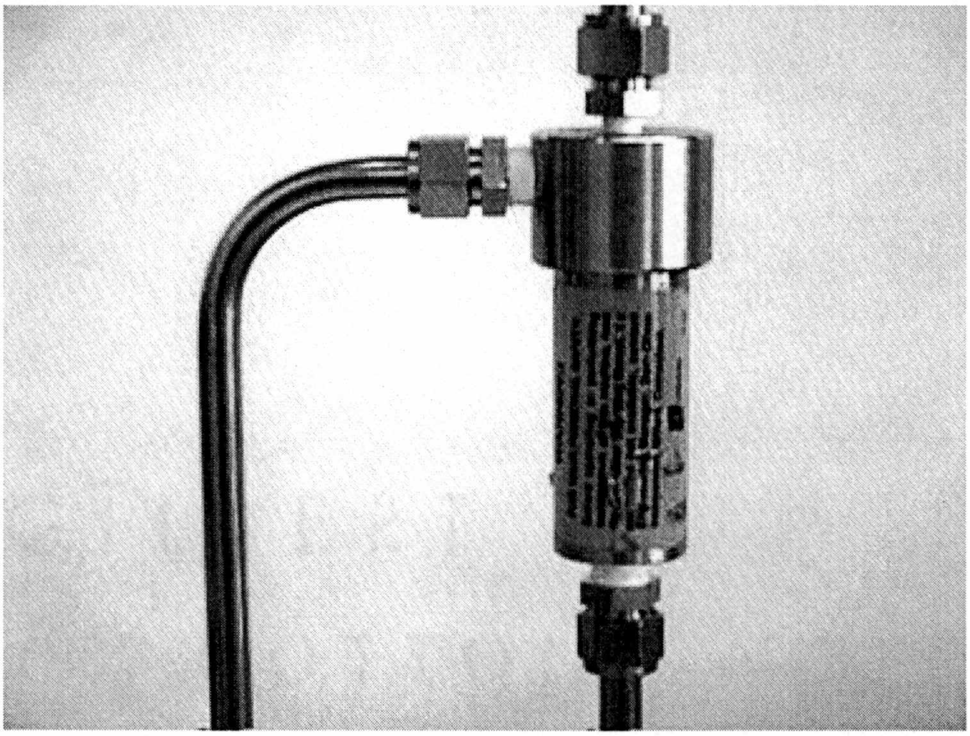


Figure 7 – Dorrclone Model Doxie 5 – 10-mm Hydroclone

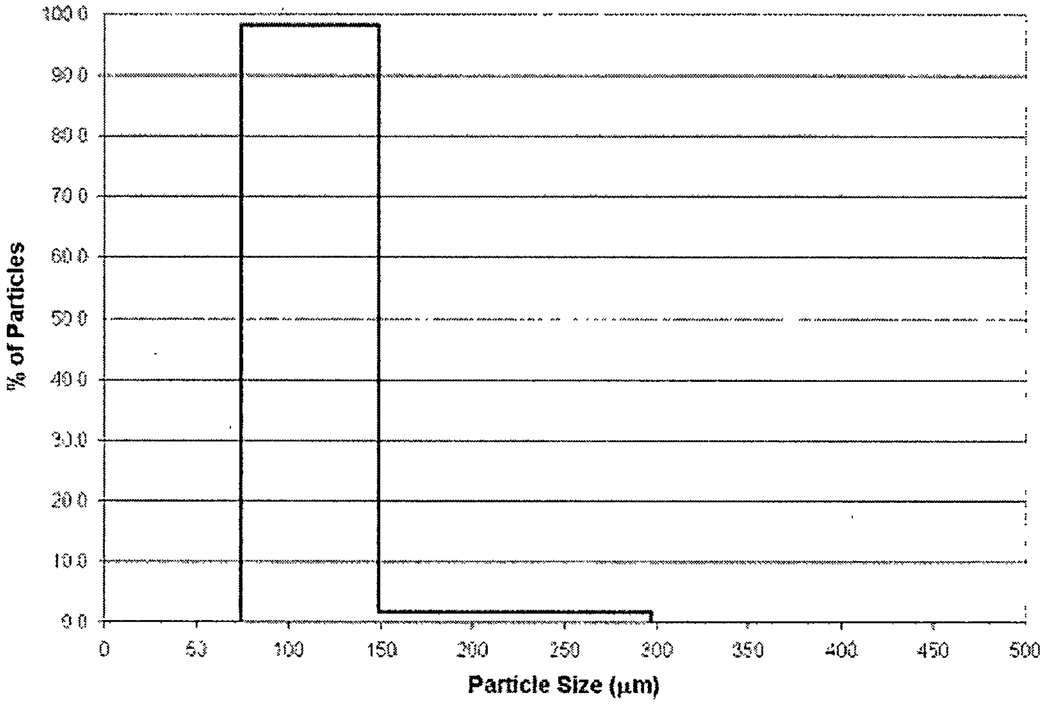


Figure 8 – Particle Size Distribution of Sand Used in the Experiments

New Jersey. Other materials needed are potassium bromide (KBr), boric acid (H_3BO_3), and sodium bromide (NaBr), which were supplied by Aldrich Chemical Inc. of Milwaukee, Wisconsin. Sodium hydroxide (0.1 N NaOH) is also needed and is supplied by Mallinckrodt Chemical Inc. of Paris, Kentucky.

4.3 Procedures

Initially, the substitute seawater was prepared according to ASTM D1141-90 standard (see Appendix C). The feed mixture for the first set of experiments is selected and prepared by adding the appropriate amounts of oil and water to the feed drum. Three percent sand is added to the drum to supply the solids. Both mixers are placed in the first drum to ensure homogeneity of the feed. If the second mixer is not used, the solids will have a tendency to get under the submergible variable speed pump and not be well mixed. The variable speed pump is set to a feed pressure of 40 psig, and the valves from the top and bottom of the hydroclone set fully open. The feed mixture is placed in the feed drum and the mixers turned on. The mixers are left running for five minutes to ensure that good mixing of the feed occurred. The feed pump is then turned on and the system allowed to reach steady state at the specified pressure. The feed pressure determines the flow rate through the hydroclone according to manufacturer specifications.

Once steady state is reached in the system, the samples are collected from the overflow and underflow streams from the hydroclone. The samples are collected simultaneously in 600-mL beakers. The dry beakers are weighed and recorded prior to taking the samples. The feed concentration is determined by the combination of the two flows. The samples are collected for 5 seconds, which was timed on a stopwatch. Three samples of each flow are collected for consistency. Prior to placing parafilm on the beakers, the beakers are then weighed to get a total sample weight. The beakers were covered with parafilm to avoid evaporation. The samples are then allowed to set overnight to assure a good separation of the oil and water components of the samples.

Additional beakers are then weighed for collection of the oil when it is removed from the samples. In order to analyze the samples, the equipment needed includes a 100-mL pipette, a pipette bulb, filter paper, a fritted disk filter, a filtration flask, and hexane. After the samples have set overnight, they are analyzed by first removing the oil. To the extent possible, the oil is removed from the beaker by a pipette. The oil is removed carefully so as not to remove any water or solids. Once all of the oil that can be removed has been removed physically, 30 milliliters of hexane is added to the beaker, and the beaker swirled to dissolve the remaining oil. The hexane is then removed and added to the previously removed oil in the same manner. This left water and solids in the sample beaker. The oil removed was then placed in a hot water bath for 30 to 60 minutes, until the hexane has evaporated from the oil. Another alternative is to let the sample sit open overnight and allow the hexane to evaporate at room temperature in a fume hood. The evaporation is considered complete when the smell of hexane in the sample was no longer present. Once the smell of hexane is gone from the beaker, the oil weight is measured.

After adding an additional 10-milliliters of hexane to the sample, the water and solids are then vacuum filtered through the fretted disk. The sample is filtered down until only hexane and solids remain in the filter. The solids are then allowed to soak in the hexane for about five minutes to remove any trace amounts of oil that may be trapped in the solids and alter its correct mass. The hexane is then filtered off of the solids, and the solids washed into a beaker. The fretted disk funnel is washed between samples to prevent contamination. The solids are then filtered through previously weighed filter paper in the fretted disk funnel. The filter paper and solids are allowed to dry overnight and then weighed to get the mass of the solids in the sample. By subtracting the mass of the oil and solids from the total mass of the sample, the mass of the water can then be determined.

Densities are determined for the solids, oil, and substitute seawater so that volumes could then be calculated. The total volume of the sample collected is also recorded so that a flow rate for the system could be determined. The experimental flow rate is set by the feed pressure, but will be approximately 1 gallon per minute. The overflow/underflow ratio is also changed to get an idea of how this variable affects the separation in the hydroclone. The overflow and underflow valves are initially fully open to give an overflow/underflow ratio of about unity. The underflow is choked off two different times to give overflow/underflow ratios ranging up to about 4.5.

5. RESULTS

5.1 Introduction

The results for this research are presented in the following sections and the actual data is shown in Appendix D. The solid and liquid separation efficiencies are shown first as a function of overflow/underflow ratio. This gives an indication of separation performance of the hydroclone unit for the immiscible liquids in the feed stream. The solid separation efficiency however is high and difficult to make determinations from the plots. The next section shows the solid separation efficiency on a log plot to better characterize the results. Finally, the data is presented in the slightly more usable format of fractional recovery. Here the fraction of each component separated to the appropriate stream is plotted as a function of overflow/underflow ratio. The results are then summarized in some concluding remarks.

5.2 Solid and Liquid Separation

Because the main emphasis of this research is the removal of solids, solids removal data are presented. The solids removal is characterized by an efficiency given as:

$$E_S = \frac{Q_U Y_U}{Q_F Y_F} \tag{38}$$

This removal is also characterized by a fraction of solids recovery in the underflow. See Appendix E for an illustration of a typical sample recovery from the hydroclone. As previously noted, the liquid feed ratios vary from 90% water to 90% oil. The solids concentration in the feed tank is kept constant at 3% throughout all of the experimental trials. The solids separation efficiency is shown on the same plot as the liquid separation efficiency for the sake of comparison in a series of plots.

Figure 9 shows the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consists of a 10:90 oil-to-water feed ratio (volumetric). The solids separation efficiency shows a slight decrease with increasing overflow/underflow ratio but is consistently greater than 90%. The experimental liquid separation efficiency also shows a decrease from the initial value of about 70% to about 20%, as the overflow/underflow ratio increases. The experimental liquid separation efficiency is close to the theoretical maximum separation efficiency (as predicted by Equation 26) for this feed. The solid separation efficiencies have an average standard deviation of 0.0189 and the liquid separation efficiencies have an average standard deviation of 0.0615. See Appendix F for a sample calculation of the average standard deviation.

Figure 10 shows the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consists of a 30:70 oil-to-water feed ratio. The solids separation efficiency shows a slight decrease with increasing overflow/underflow ratio but is consistently greater than 95%. The experimental liquid separation efficiency also shows a decrease from the initial value of about 70% to about

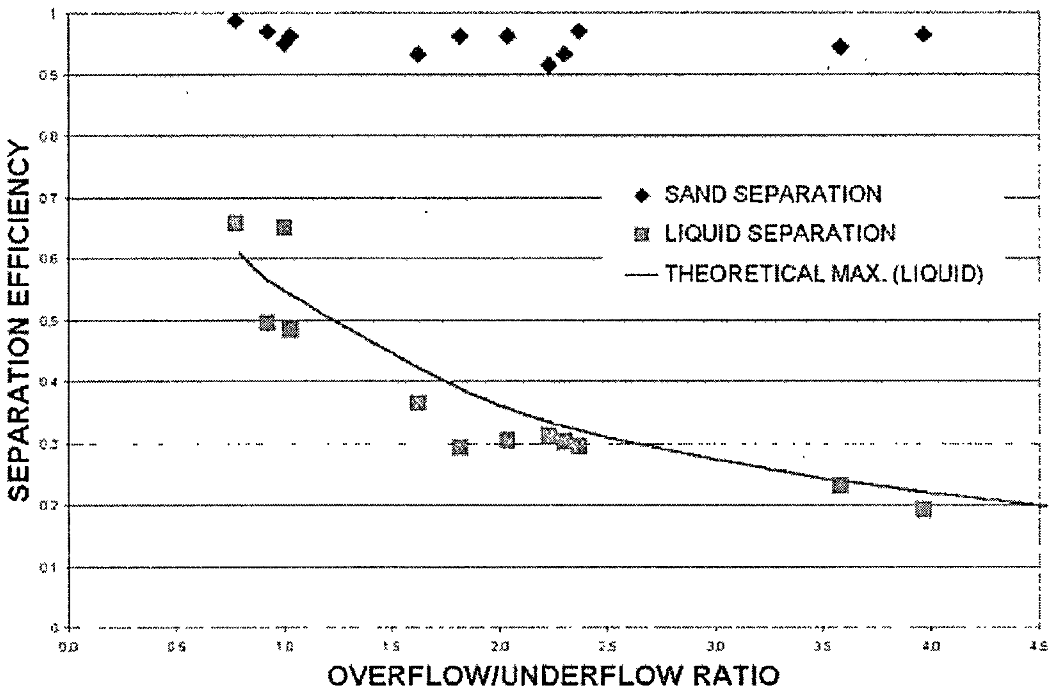


Figure 9 – Separation Efficiency versus Overflow/Underflow Ratio (10-90 oil-to-water volume ratio)

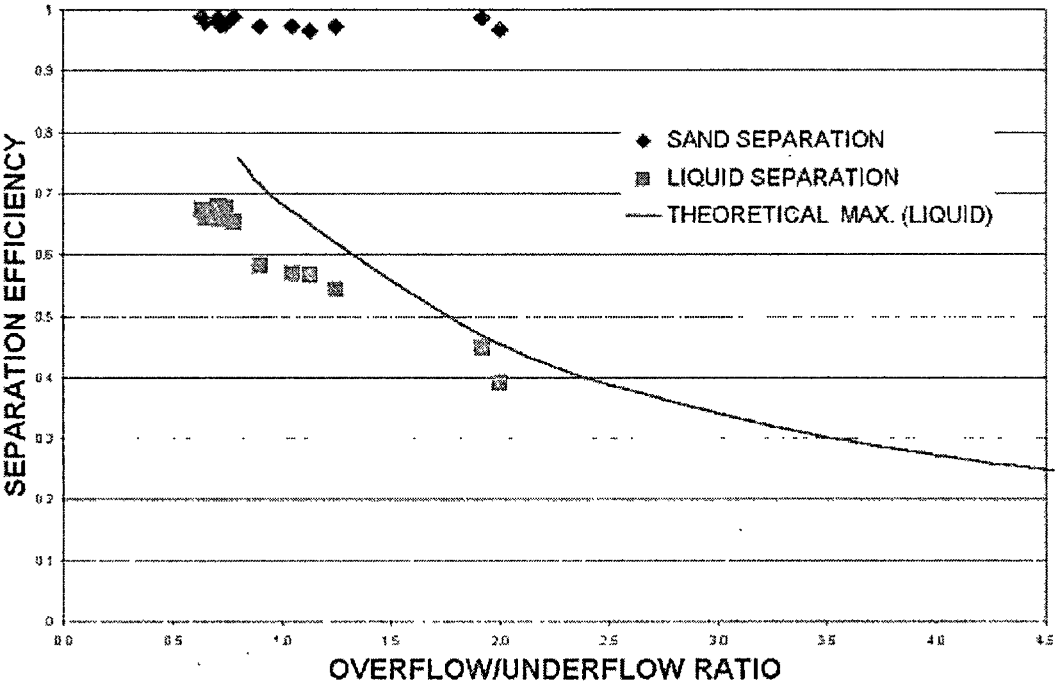


Figure 10 – Separation Efficiency versus Overflow/Underflow Ratio (30-70 oil-to-water volume ratio)

40%, as the overflow/underflow ratio increases. The experimental liquid separation efficiency is close to the theoretical maximum separation efficiency (as predicted by Equation 26) for this feed. The solid separation efficiencies have an average standard deviation of 0.0065 and the liquid separation efficiencies have an average standard deviation of 0.0263.

Figure 11 shows the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consists of a 50:50 oil-to-water feed ratio. The solids separation efficiency shows a slight decrease with increasing overflow/underflow ratio but is consistently greater than 95%. The experimental liquid separation efficiency also shows a decrease from the initial value of about 60% to about 40%, as the overflow/underflow ratio increases. The experimental liquid separation efficiency is not as close to the theoretical maximum separation efficiency (as predicted by Equation 26) for this feed as Figure 10. The initial liquid separation efficiency is less than the theoretical maximum liquid efficiency, but as the overflow/underflow ratio increases, the measured liquid separation efficiency approaches the theoretical maximum liquid efficiency. It should be noted that with a 50:50 mass ratio of oil to water fed to the unit, the maximum liquid separation efficiency should be unity at a mass-basis overflow/underflow ratio of one. The overflow/underflow ratio as used in this report is on a volume basis, except for the previous example. Due to the density differences, the maximum liquid separation efficiency in Figure 11 is slightly less than one. The solid

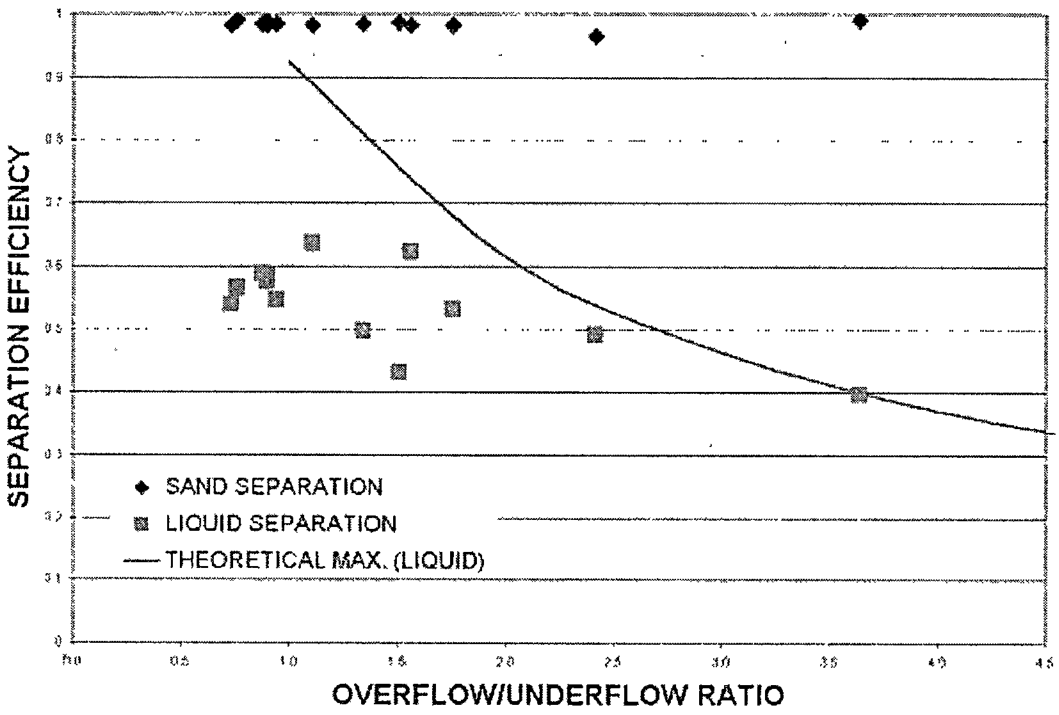


Figure 11 – Separation Efficiency versus Overflow/Underflow Ratio (50-50 oil-to-water volume ratio)

separation efficiencies have an average standard deviation of 0.0042 and the liquid separation efficiencies have an average standard deviation of 0.0432.

Figure 12 shows the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consists of a 70:30 oil-to-water feed ratio. Data for higher overflow/underflow ratios were taken but the data did not seem consistent with surrounding data. After careful examination of these data, the feed pressure was found to be lower than the suggested operating pressure of the equipment used. Based on this analysis, the data were determined unreliable and not included in the plot. The solids separation efficiency for this feed is consistently above 90% but shows no apparent trend. The experimental liquid separation efficiency shows a value of about 5% for the overflow/underflow ratio studied. The experimental liquid separation efficiency is not very close to the theoretical maximum separation efficiency (as predicted by Equation 26) for this feed. The solid separation efficiencies have an average standard deviation of 0.0052 and the liquid separation efficiencies have an average standard deviation of 0.0199.

Figure 13 shows the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consists of a 90:10 oil-to-water feed ratio. The solids separation efficiency shows a slight decrease with increasing overflow/underflow ratio but is consistently greater than 90%. The experimental liquid

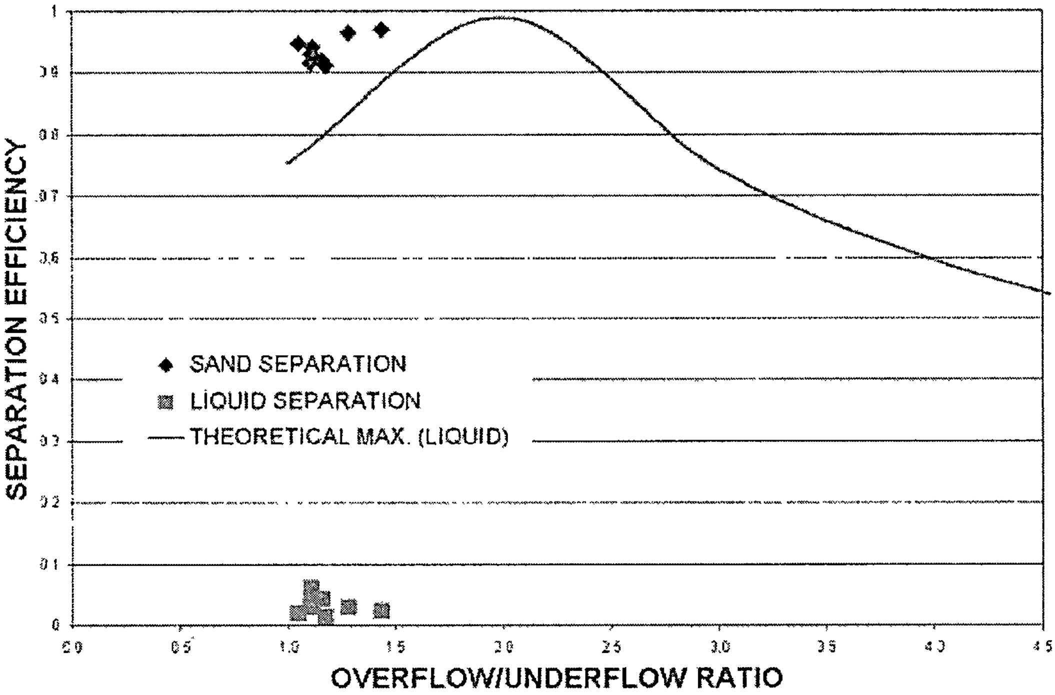


Figure 12 – Separation Efficiency versus Overflow/Underflow Ratio (70-30 oil-to-water volume ratio)

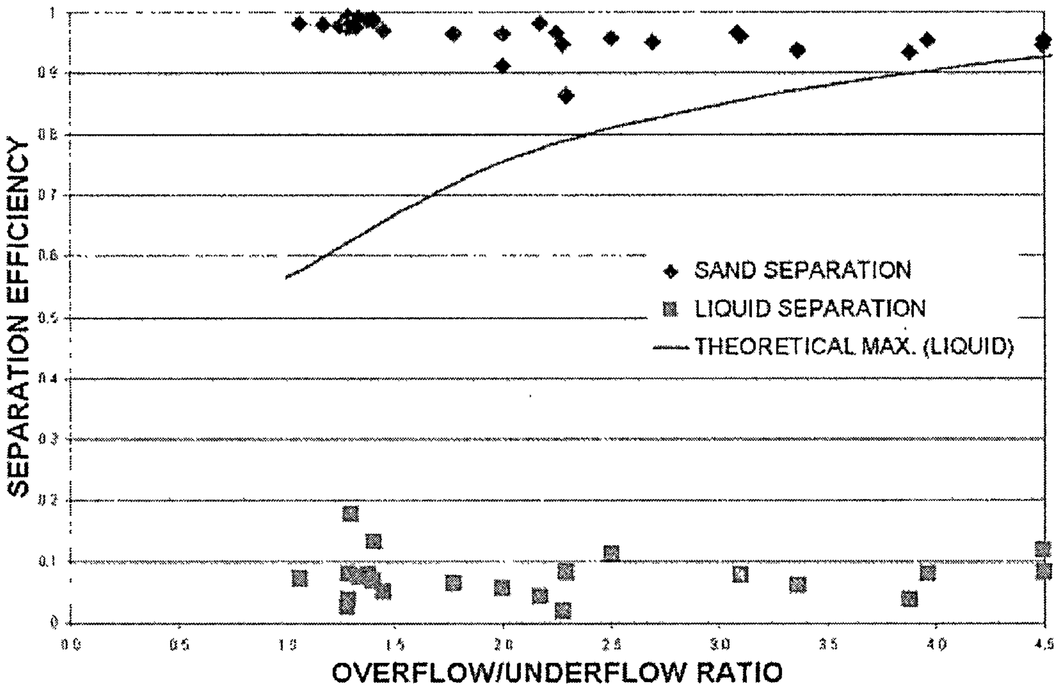


Figure 13 – Separation Efficiency versus Overflow/Underflow Ratio (90-10 oil-to-water volume ratio)

separation efficiency shows a increase from the initial value of about 5% to about 12%, as the overflow/underflow ratio increases. The experimental liquid separation efficiency is not very close to the theoretical maximum separation efficiency (as predicted by Equation 26) for this feed. The solid separation efficiencies have an average standard deviation of 0.0166 and the liquid separation efficiencies have an average standard deviation of 0.0476.

5.2.1 Discussion

Here are some general comments and conclusions on Figures 9-13 discussed above. One note is that while the liquid separation efficiency is considerably less than the theoretical maximum liquid efficiency for feeds that are 70% and 90% oil, Day reports that feeds that are mainly oil are harder to separate and result in a drastic drop in the liquid separation efficiency.[12] The predominantly oil experiments have more water carry over into the oil stream (overflow) than do the predominantly water experiments. These data agree with those reports. The theoretical maximum liquid efficiency could be used to predict the liquid separation efficiency in water-rich systems, but not in oil rich systems.

5.3 Solids Separation Semi-Log Plots

The solids separation efficiency is now studied using the log of the solid separation efficiency versus the overflow/underflow ratio. This allows a different look at the separation efficiency to analyze trends that are not evident in the previous plots. The following plots do indicate some interesting trends that were not obvious in the preceding figures. The first case is the 10% oil feed.

Figure 14 shows the log of the solids separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 10:90 oil-to-water ratio. These data yield a slope of –0.0024. The conclusion drawn from this figure is that the solid separation efficiency decreases with increasing overflow/underflow ratios.

Figure 15 shows the log of the solids separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 30:70 oil-to-water ratio. These data yield a slope of –0.0023. The conclusion drawn from this figure is that once again the solid separation efficiency decreases with increasing overflow/underflow ratios.

Figure 16 shows the log of the solids separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 50:50 oil-to-water ratio. These data yield a slope of –0.0005. The conclusion drawn from this figure is that the solid separation efficiency decreases with increasing overflow/underflow ratios, but not as drastically as seen in the feeds that contain less oil.

Figure 17 shows the log of the solids separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 70:30 oil-to-water ratio. These data yield a slope of +0.0522. The conclusion drawn from this figure is that the solid separation efficiency increases with increasing overflow/underflow ratios.

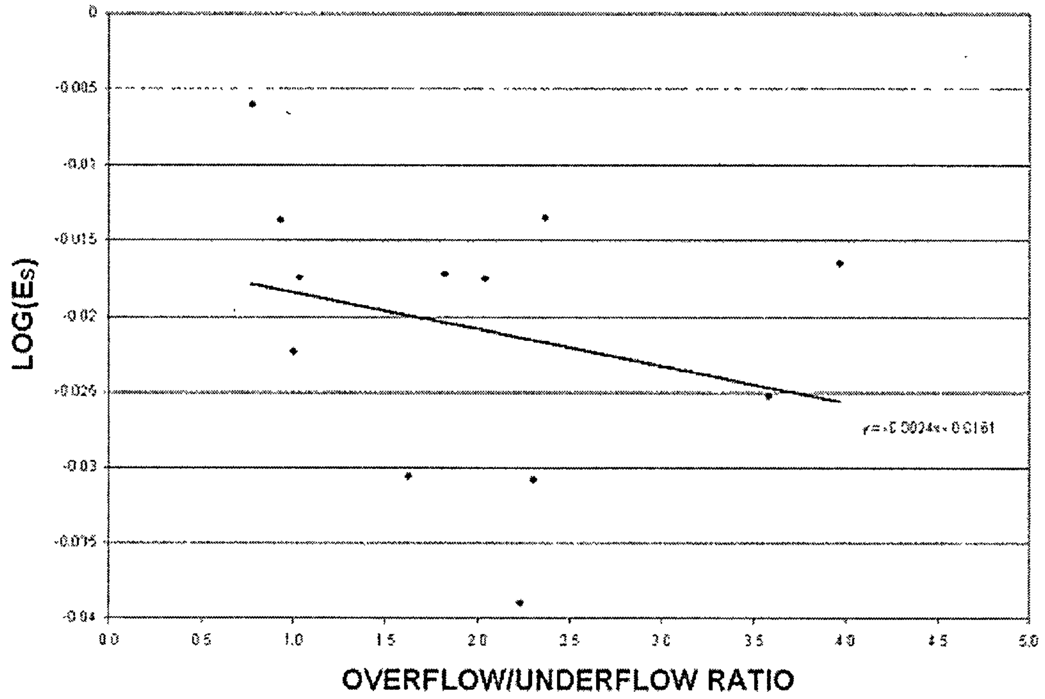


Figure 14 – Log of Solids Separation Efficiency versus Overflow/Underflow Ratio (10-90 oil-to-water volume ratio)

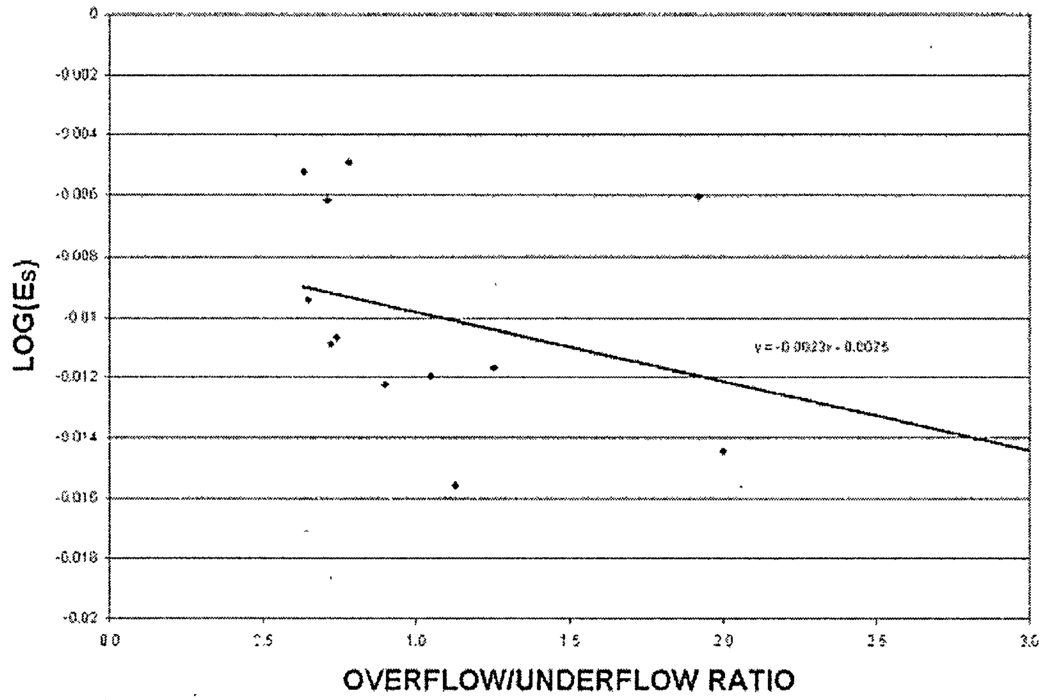


Figure 15 – Log of Solids Separation Efficiency versus Overflow/Underflow Ratio (30-70 oil-to-water volume ratio)

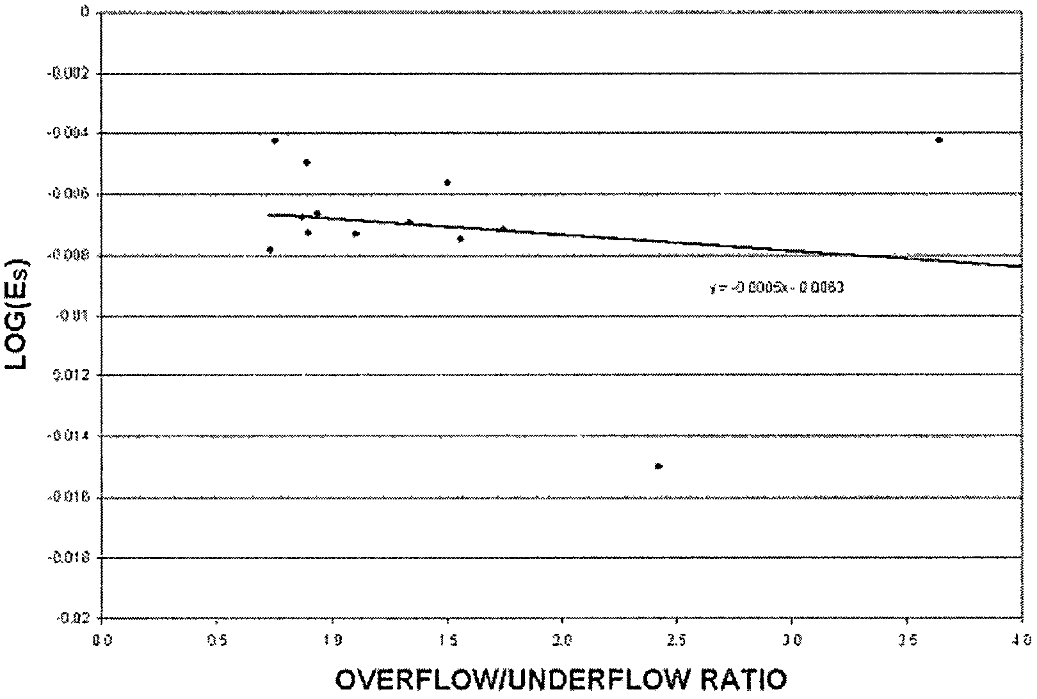


Figure 16 – Log of Solids Separation Efficiency versus Overflow/Underflow Ratio (50-50 oil-to-water volume ratio)

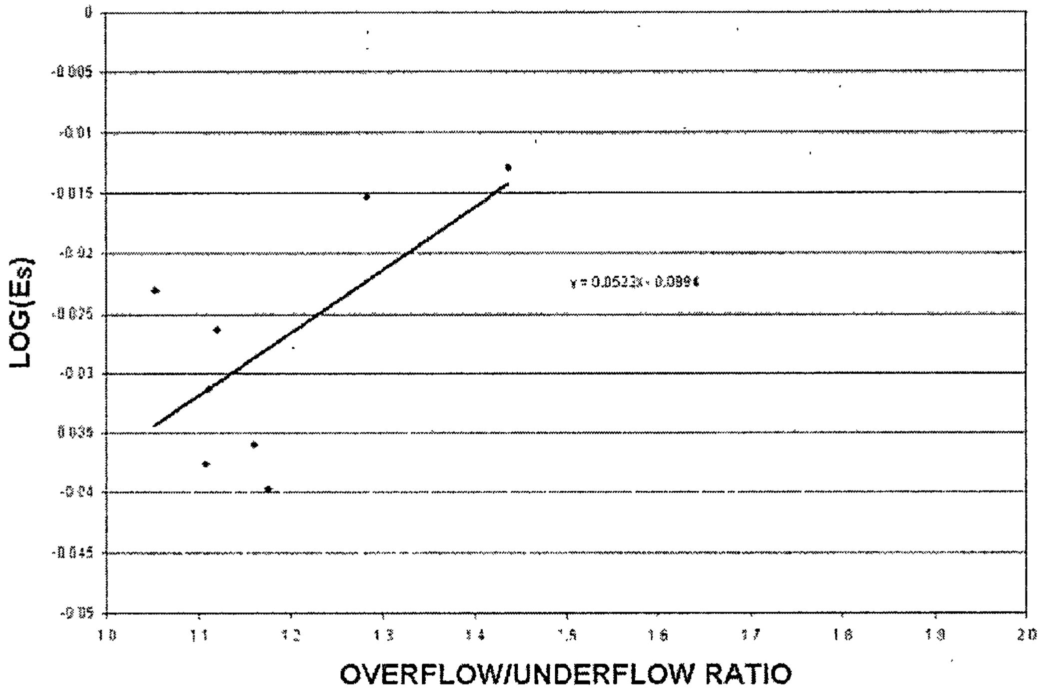


Figure 17 – Log of Solids Separation Efficiency versus Overflow/Underflow Ratio (70-30 oil-to-water volume ratio)

Figure 18 shows the log of the solids separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 90:10 oil-to-water ratio. These data yield a slope of –0.0065. The conclusion drawn from this figure is that the solid separation efficiency decreases with increasing overflow/underflow ratios. This conclusion is the same regardless of the feed composition.

Table 3 shows a summary of the slopes obtained in the previous discussion of solids separation. This table also includes the errors associated with each slope. The errors are obtained using a 95% confidence interval. From the above table, the feeds that contained 10%, 30%, and 50% oil did have a negative slope, but when looking at the errors associated with each, zero is included. This indicates that there is also the

Table 3 – Slope of Log(E_S) for Solids Separation as a Function of Oil-Water Ratio

Oil-Water Ratio	Slope
10-90	-0.0024 ± 0.0027
30-70	-0.0023 ± 0.0023
50-50	-0.0005 ± 0.0009
70-30	0.0522 ± 0.0556
90-10	-0.0065 ± 0.0015

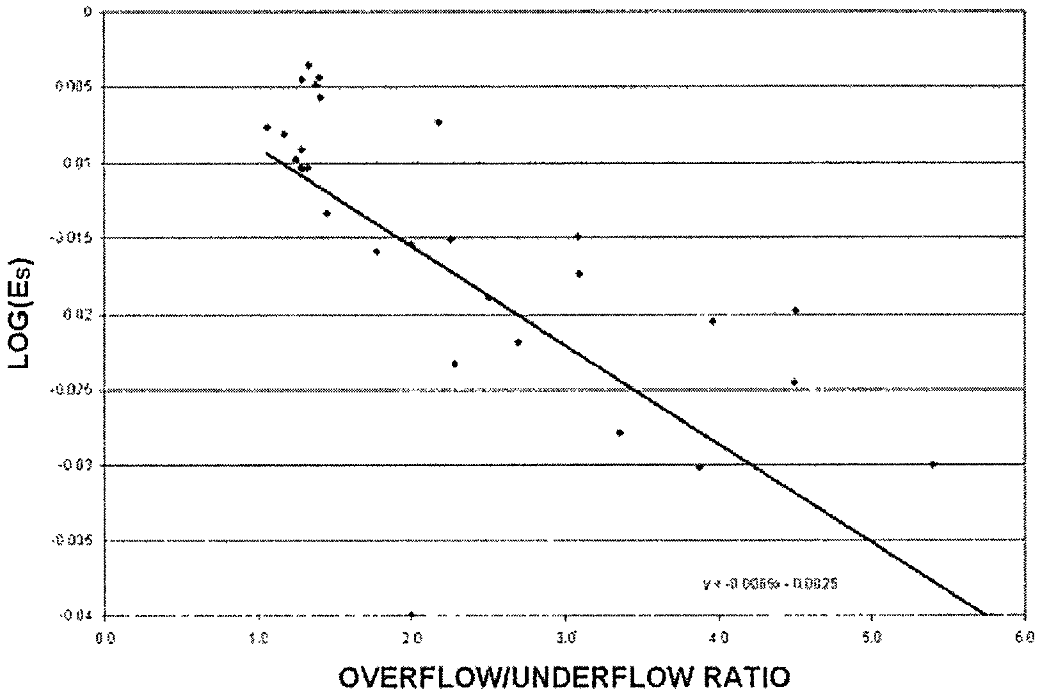


Figure 18 – Log of Solids Separation Efficiency versus Overflow/Underflow Ratio (90-10 oil-to-water volume ratio)

possibility that there is no effect of overflow/underflow ratio on these three separations. The feed that contained 60% oil has a negative slope, but the error associated with this point includes zero. This again indicates the possibility that there is no effect on the separation by changing the overflow/underflow ratio. The feed that contained 90% oil has a negative slope, even when looking at the error associated with it.

5.3.1 Discussion

The previous discussion indicates that increasing the overflow/underflow ratio sends more solids to the overflow. From the predictions of the cut size discussed in Chapter 3, this increase does not appear to be due to an estimated change in the cut size. The cut size predicted in Chapter 3 is considerably less than the actual particle size of the solids used. The assumption drawn is that approximately 100% of the solids should be removed, even at 100% oil feeds. The decrease in the efficiency is probably due to an increase in the short-circuiting of the unit. As more of the fluids are routed to the overflow, more of the solids go with the fluid. This short-circuiting is due to the solids simply entering the unit and exiting in the overflow without going through the hydroclone and being separated. The increased flow out of the overflow, increases the short-circuiting. Based solely on this data, it appears that the best operating conditions for the removal of solids is at low overflow/underflow ratios.

5.4 Liquid Separation Semi-Log Plots

In this section, we look at the plots of the log of the separation efficiency of the liquids versus the overflow/underflow ratio. The following plots look at the liquid separation and attempt to determine the best operating conditions with respect to separating the oil and water in the unit.

Figure 19 shows the log of the liquid separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 10:90 oil-to-water ratio. These data yield a slope of –0.1532. The conclusion drawn from this figure is that the liquid separation efficiency decreases with increasing overflow/underflow ratios. The best operating point for this data (in order to separate the liquids in the hydroclone) appears to be at a low overflow/underflow ratio. A note for this data is that the efficiency is an indication of how well the cyclone unit does at separating the oil and water into two different streams. This is important when utilizing the hydroclone as the primary separation device.

Figure 20 shows the log of the liquid separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 30:70 oil-to-water ratio. These data yield a slope of –0.1585. The conclusion drawn from this figure is that the liquid separation efficiency decreases with increasing overflow/underflow ratios. The best operating point for this data (in order to separate the liquids in the hydroclone) appears to be at a low overflow/underflow ratio.

Figure 21 shows the log of the liquid separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 50:50 oil-to-water ratio. These data yield a slope of –0.0626. The conclusion drawn from this figure is that the liquid separation efficiency decreases with increasing overflow/underflow ratios. The

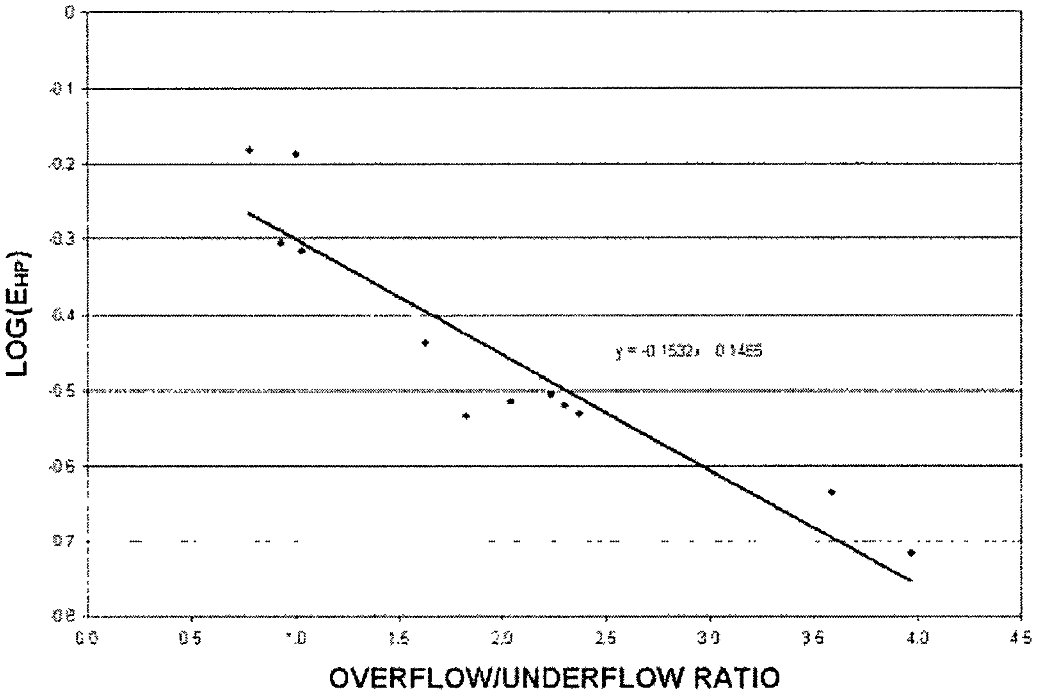


Figure 19 – Log of Liquid Separation Efficiency versus Overflow/Underflow Ratio (10-90 oil-to-water volume ratio)

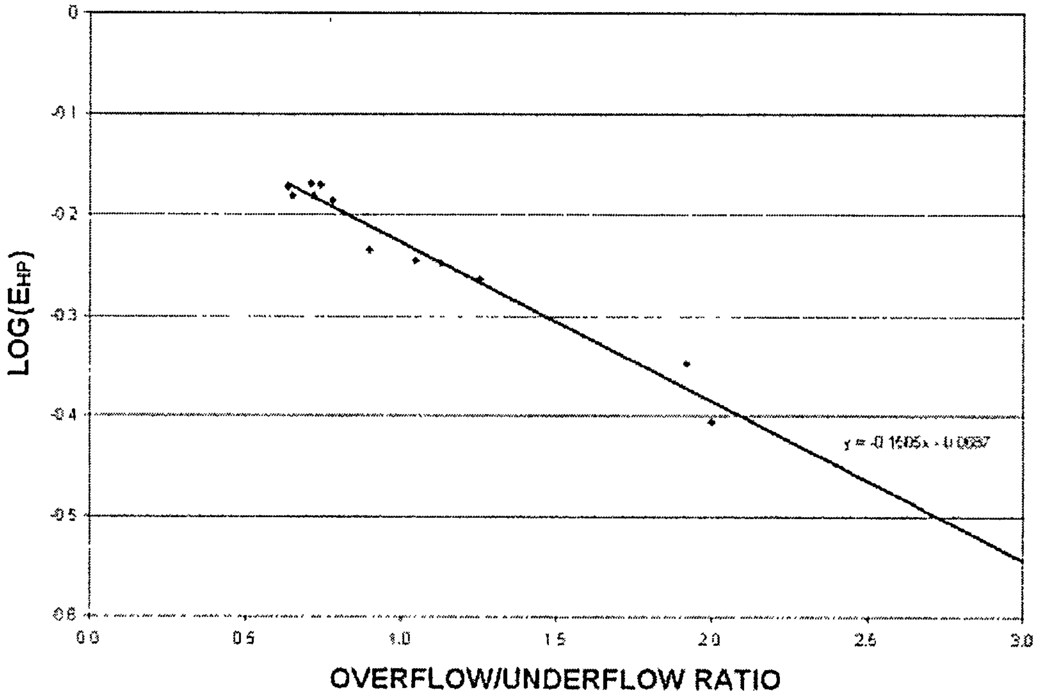


Figure 20 – Log of Liquid Separation Efficiency versus Overflow/Underflow Ratio (30-70 oil-to-water volume ratio)

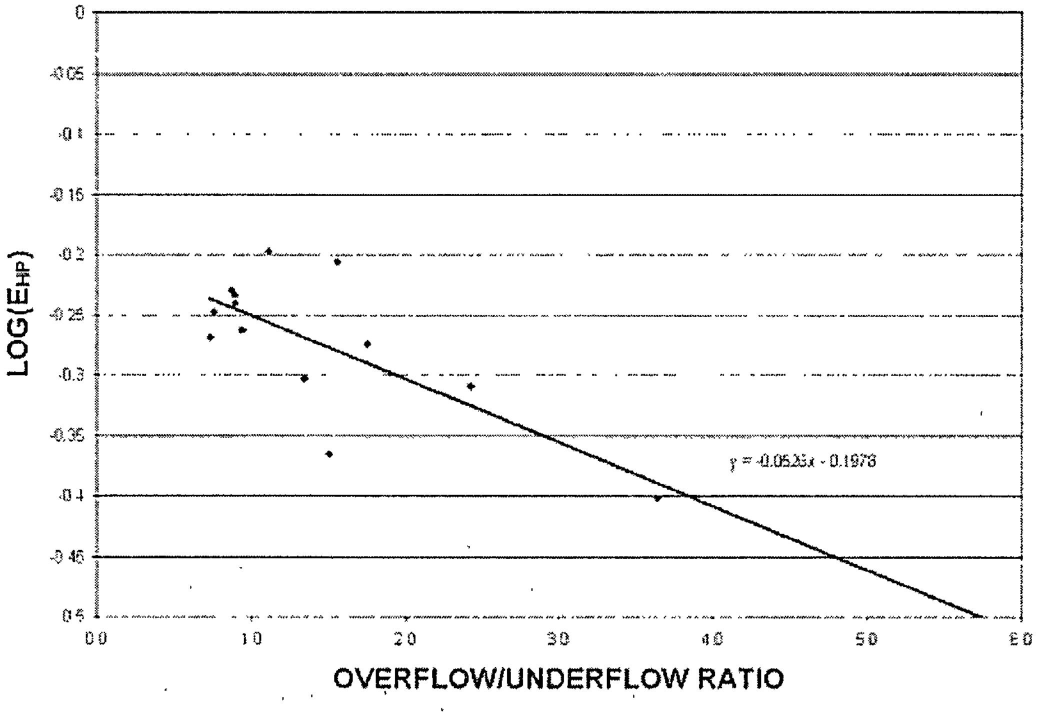


Figure 21 – Log of Liquid Separation Efficiency versus Overflow/Underflow Ratio (50-50 oil-to-water volume ratio)

best operating point for this data (in order to separate the liquids in the hydroclone) appears to be at a low overflow/underflow ratio.

Figure 22 shows the log of the liquid separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 70:30 oil-to-water ratio. These data yield a slope of -0.3413. The conclusion drawn from this figure is that the liquid separation efficiency decreases with increasing overflow/underflow ratios.

Figure 23 shows the log of the liquid separation efficiency as a function of overflow/underflow ratio. The feed stream for this data consists of a 90:10 oil-to-water ratio. These data yield a slope of +0.0145. The conclusion drawn from this figure is that the liquid separation efficiency increases with increasing overflow/underflow ratios. The best operating point for this data (in order to separate the liquids in the hydroclone) appears to be at a high overflow/underflow ratio.

Table 4 – Slope of Log(E_{HP}) for Liquid Separation as a Function of Oil-Water Ratio

Oil-Water ratio	Slope
10-90	-0.1532 ± 0.0194
30-70	-0.1585 ± 0.0095
50-50	-0.0526 ± 0.0151
70-30	-0.3413 ± 0.6782
90-10	0.0145 ± 0.0319

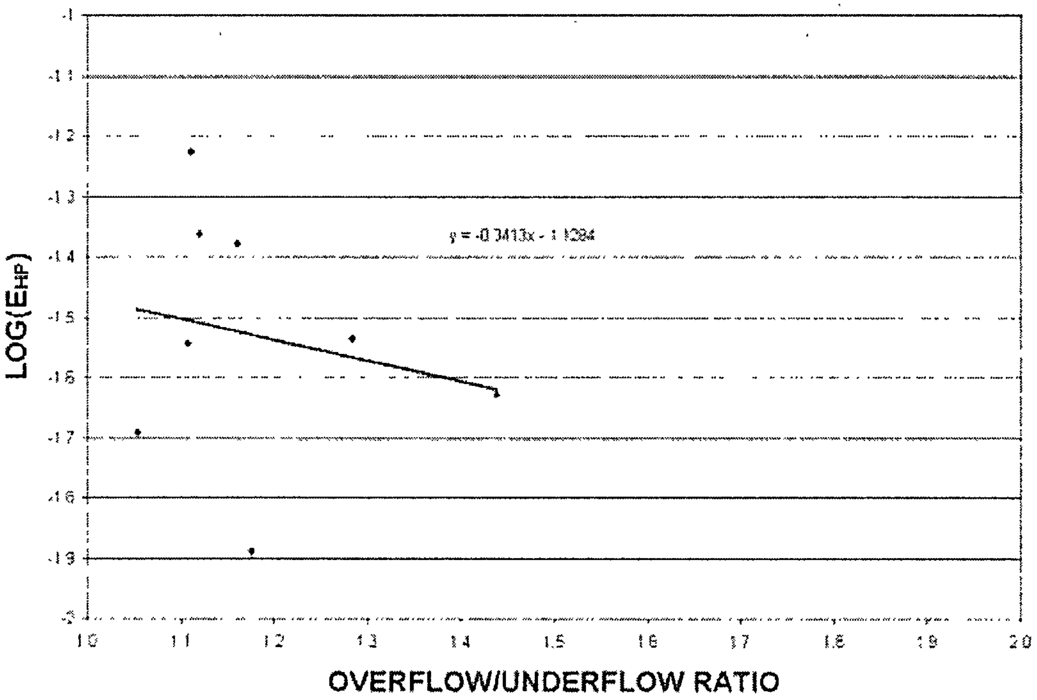


Figure 22 – Log of Liquid Separation Efficiency versus Overflow/Underflow Ratio (70-30 oil-to-water volume ratio)

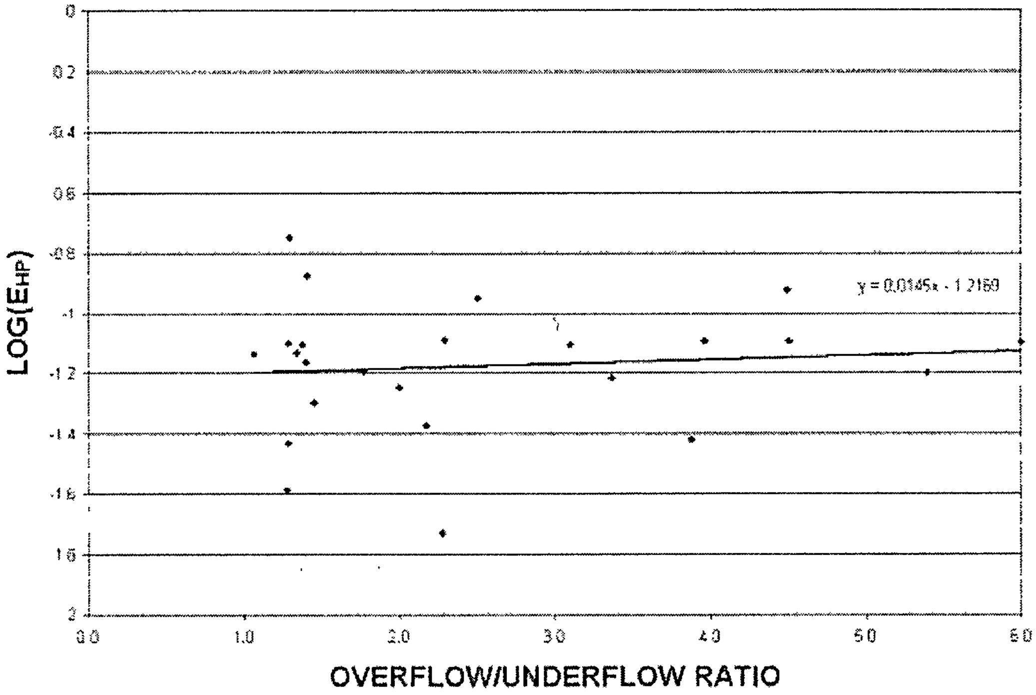


Figure 23 – Log of Liquid Separation Efficiency versus Overflow/Underflow Ratio (90-10 oil-to-water volume ratio)

Table 4 shows a summary of the slopes obtained in the previous discussion of liquid separation. This table also includes the errors associated with each slope. The errors are obtained using a 95% confidence interval. From the above table, the feed that contained 70% oil has a negative slope and the feed that contained 90% oil has a positive slope, but when looking at the errors associated with each, zero is included. This indicates that there is also the possibility that there is no effect of overflow/underflow ratio on this separation. The remaining feeds, even when looking at the error associated with each, did not include zero. This shows that trends for the liquid separation seem to be consistent for predominately oil and predominately water feeds.

5.4.1 Discussion

The indication from this data is that in the feeds that are mainly water, the slope is negative. This means that the lower overflow/underflow ratios yield the best liquid separation in the hydroclone unit. As the feed goes to mainly oil however, the slope of the trend line changes sign. This indicates that at high oil concentrations in the feed, the best liquid separation occurs at high overflow/underflow ratios. As you cutback the underflow, the separation of the two immiscible liquids gets better. This change of sign in the slope, shows that the concentration of the feed can have a big impact on the separation efficiency of the liquids in the hydroclone.

5.5 Recovery

Now we consider the separation data in a slightly different format. Instead of assessing the overall efficiency for the separation of the hydrocyclone, consider the fractional recovery in the respective streams. The goal of this research is to provide as much of the oil and water in the overflow of the hydroclone as possible, while minimizing the amount of solids. With this in mind, let's look at how the hydrocyclone performs. The solids recovery in the underflow is the fraction of solids that entered in the feed, and exited in the underflow. With respect to the liquids, the goals are that the fractional recovery of oil in the overflow to be high with the recovery of water in the underflow low. This method of plotting the data is used because some water must exit in the underflow to carry the solids.

Figure 24 shows the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data are for a feed ratio of 10:90 oil-to-water. The fraction of solids fed into the system that are removed in the underflow is consistently above 90%. With respect to the liquids, about 60% of the water goes into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow drops to about 20%. The oil recovery in the overflow starts at about 95% at low overflow/underflow ratios and increases to about 99% with increasing overflow/underflow ratio.

Figure 25 shows the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data are for a feed ratio of 30:70 oil-to-water. The fraction of solids fed into the system that are removed in the underflow is consistently above 95%. With respect to the liquids, about 75% of the water goes into the underflow at low overflow/underflow ratios. At high

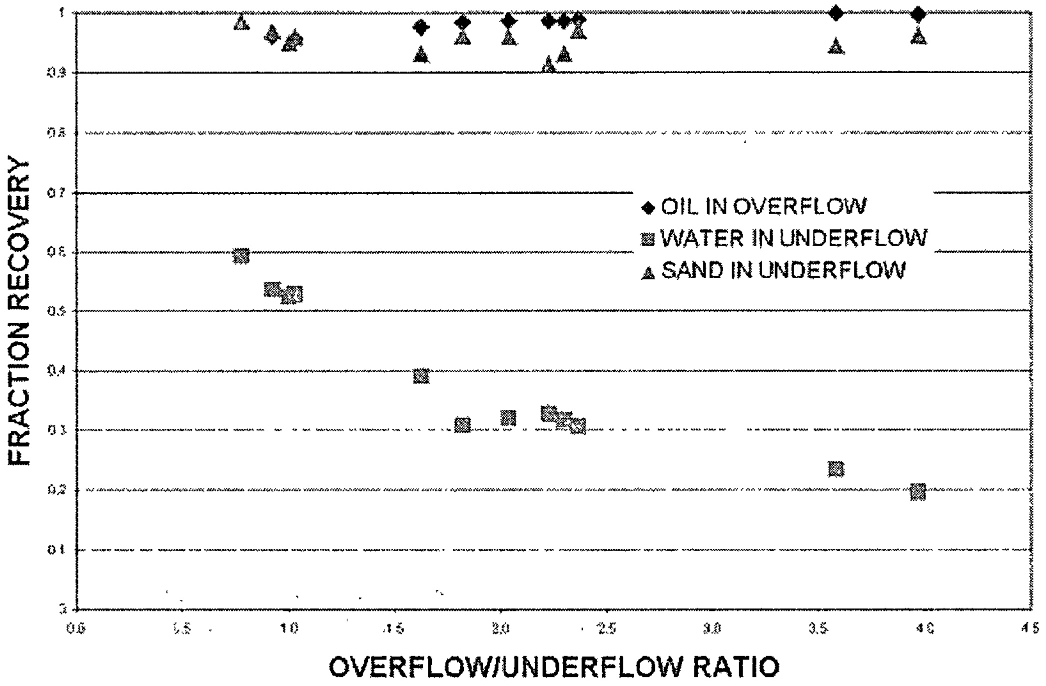


Figure 24 – Recovery versus Overflow/Underflow
Ratio (10-90 oil-to-water volume ratio)

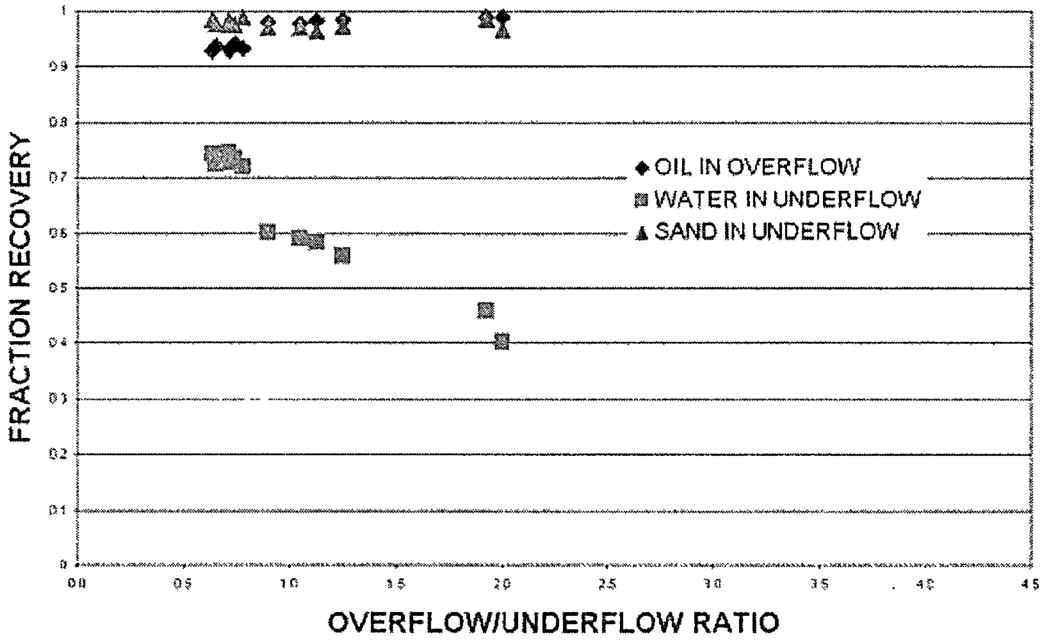


Figure 25 – Recovery versus Overflow/Underflow Ratio (30-70 oil-to-water volume ratio)

overflow/underflow ratios, the water recovery in the underflow drops to about 40%. The oil recovery in the overflow starts at about 95% at low overflow/underflow ratios and increases to about 99% with increasing overflow/underflow ratio.

Figure 26 shows the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data are for a feed ratio of 50:50 oil-to-water. The fraction of solids fed into the system that are removed in the underflow is consistently above 95%. With respect to the liquids, about 75% of the water goes into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow drops to about 40%. The oil recovery in the overflow starts at about 80% at low overflow/underflow ratios and increases to about 99% with increasing overflow/underflow ratio.

Figure 27 shows the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data are for a feed ratio of 70:30 oil-to-water. The fraction of solids fed into the system that are removed in the underflow is consistently above 93%. With respect to the liquids, about 50% of the water goes into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow drops to about 28%. The oil recovery in the overflow starts at about 55% at low overflow/underflow ratios and increases to about 85% with increasing overflow/underflow ratio.

Figure 28 shows the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data are for a

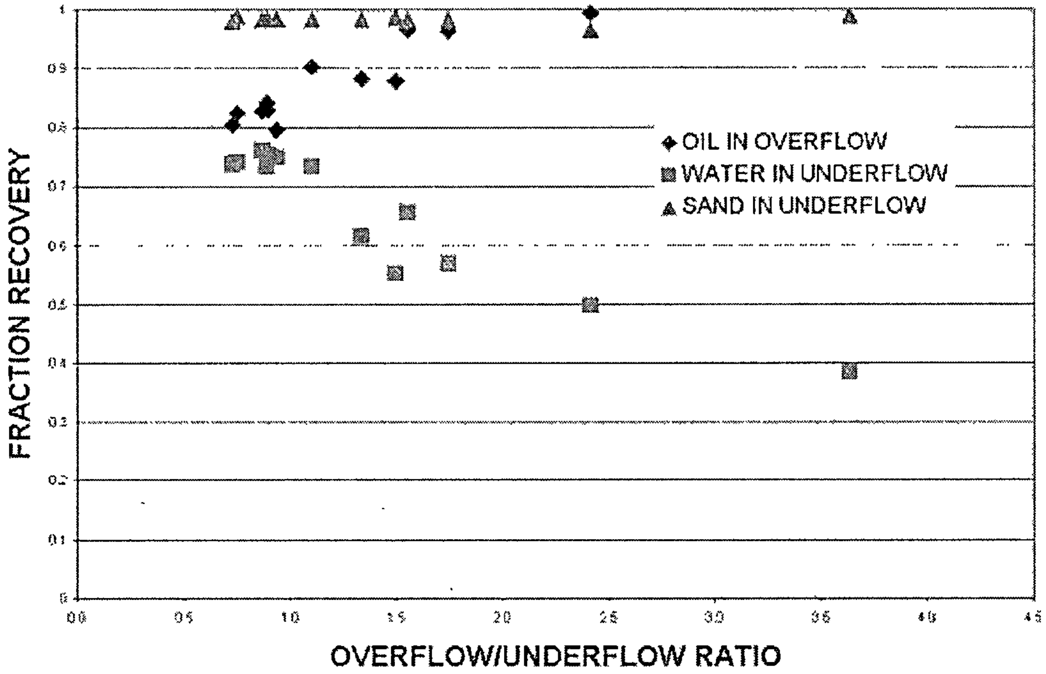


Figure 26 – Recovery versus Overflow/Underflow
Ratio (50-50 oil-to-water volume ratio)

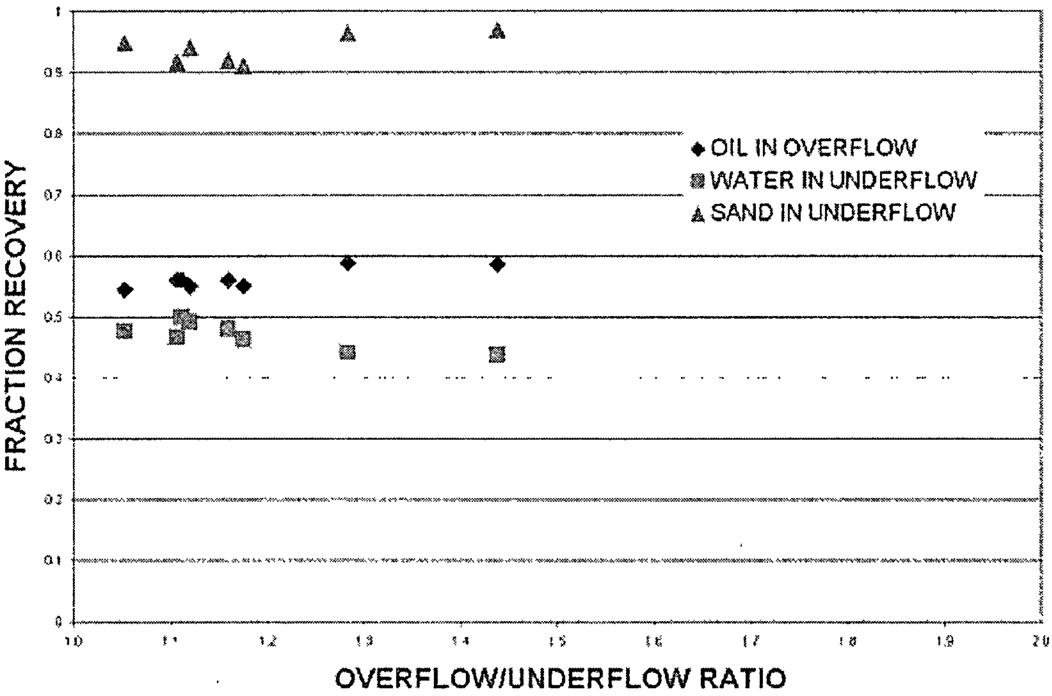


Figure 27 – Recovery versus Overflow/Underflow Ratio (70-30 oil-to-water volume ratio)

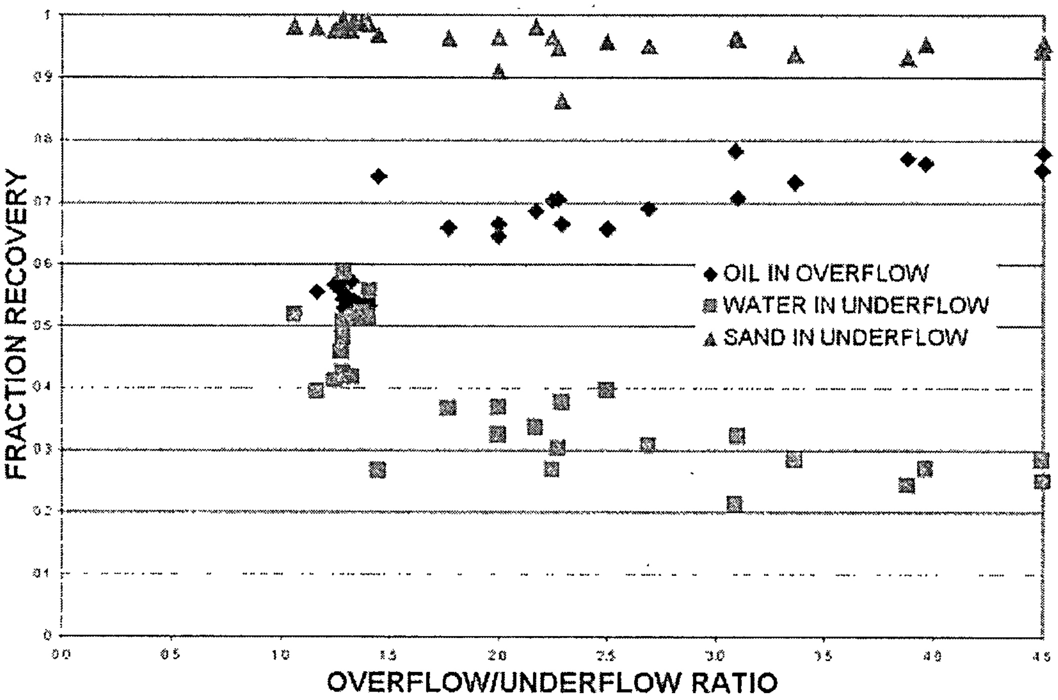


Figure 28 – Recovery versus Overflow/Underflow
Ratio (90-10 oil-to-water volume ratio)

feed ratio of 90:10 oil-to-water. The fraction of solids fed into the system that are removed in the underflow is consistently above 90%. With respect to the liquids, about 55% of the water goes into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow drops to about 25%. The oil recovery in the overflow starts at about 55% at low overflow/underflow ratios and increases to about 80% with increasing overflow/underflow ratio.

5.5.1 Discussion

Here are some concluding comments on the recovery of the various feed components into the appropriate streams. The above discussion indicates that an increase in the overflow/underflow ratio is desirable for the liquid separation but is a hindrance in the desired results of the solids separation. In general, as more oil is present in the feed, the recovery of the oil in the overflow decreases. Even more oil recovery may be possible at higher overflow/underflow ratio, but the current equipment limits this value to about 4.5 (when solids are present), due to plugging of exit lines that involve small streams.

5.6 Concluding Remarks

As discussed in Chapter 3, the cut size for the solids separation is predicted to decrease with an increase in the overflow/underflow ratio. This decrease in the cut size of the particles separated in the unit means that the solids recovery, or solids separation efficiency, is predicted to decrease as the split is increased from an overflow/underflow ratio of 1.0 to one of 4.5. However, the actual solid particles are chiefly well above the highest cut size, indicating a prediction of nearly 100% solids removal. While the solids removal trend agrees with the model, the fraction removal of solids from the feed is less than 100%. The difference is likely due to short-circuiting or other small variations in the hydroclone such as effective viscosity.

Recovery could approach ~100% of the oil in the overflow (feed to centrifugal separator) when the feed is 50-50 or lower in oil concentration. When the oil becomes the dominant phase, the feed becomes more difficult to separate, to the point where all of the oil cannot be sent to the overflow, and some is lost to the underflow. The water in the underflow starts out at a high recovery in all of the feed cases. By reducing the underflow, the amount of water exiting in the underflow is decreased. The indication from these results seems to be that the higher overflow/underflow ratios give the type of operation desired. This indication is true for all feed concentrations, but the higher oil concentrations do not perform quite as well as the higher water concentrations. This performance agrees with literature studies of liquid/liquid hydroclones. The conditions achieved by cutting back the underflow are high oil and water recoveries in the overflow, which is then fed into the centrifugal separator. Achieving a high recovery of solids in the underflow is also possible. Typically most of the solids can be removed, even at the higher splits and with the more viscous oil dominant feed.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- Solids can be effectively removed from a three-component feed by using a hydroclone
- Oil can be nearly 100% recovered in the overflow in a water continuous feed
- Some oil is lost to the underflow if the feed is oil-continuous
- Liquid phase separation efficiency is nearly 100% for water-continuous feeds (separating oil from water)
- Liquid phase separation efficiency is very poor for oil-continuous feeds (separating water from oil)
- Controlling the split can minimize water lost to the underflow
- Solids separation can be accurately predicted for this system
- Data gathered compared very favorably to previous research

6.2 Recommendations

- In future research, use different oils, including actual crude oil
- Study a more diverse particle size of solids
- Research is planned to connect the centrifugal separator to the hydroclone unit

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APPENDIX

APPENDIX – (A)

$$\frac{Q_O(y_O - y_F)}{Q_F y_F(1 - y_F)} = \frac{Q_U(y_F - y_U)}{Q_F y_F(1 - y_F)}$$

numerators.must.be.equal

$$Q_O(y_O - y_F) = Q_U(y_F - y_U)$$

$$(Q_F - Q_U)(y_O - y_F) = Q_U y_F - Q_U y_U$$

$$Q_F y_O - Q_F y_F - Q_U y_O + Q_U y_F = Q_U y_F - Q_U y_U$$

$$Q_O y_O + Q_U y_O - Q_F y_F - Q_U y_O = -Q_U y_U$$

$$Q_O y_O + Q_U y_U = Q_F y_F$$

MATERIAL.BALANCE

APPENDIX – (B)

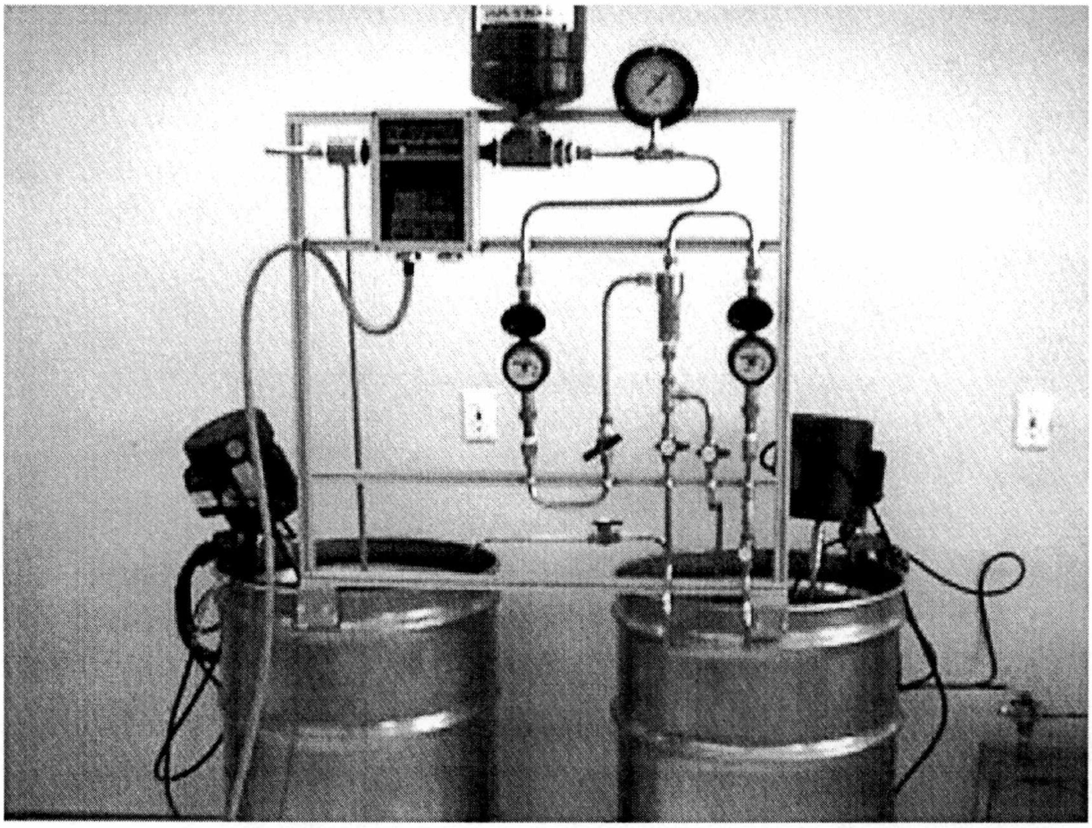


Figure 29 - Experimental Apparatus Used in the Research

APPENDIX – (B) (cont.)

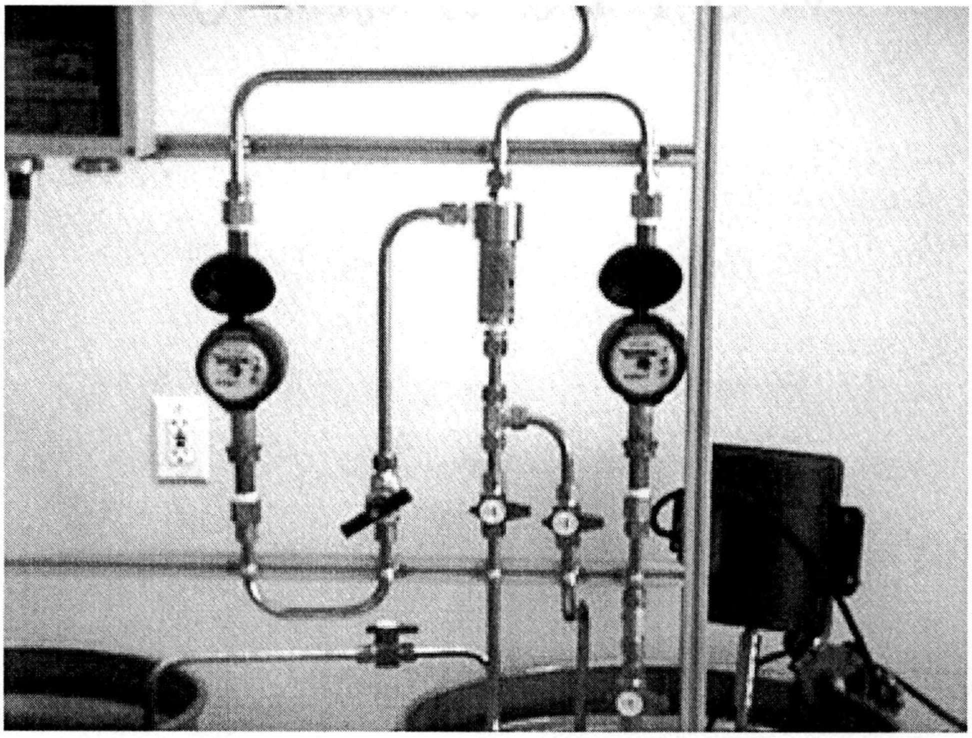


Figure 30 - Experimental Apparatus Used in the Research

APPENDIX – (B) (cont.)

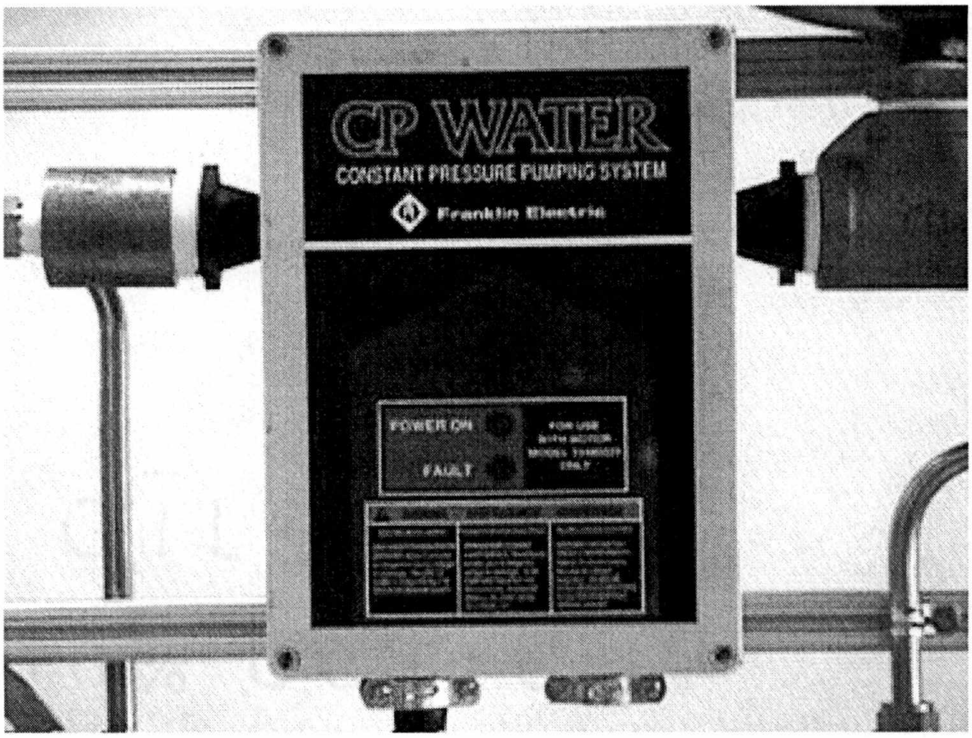


Figure 31 - Control Box for the Submergible Feed Pump

APPENDIX – (C)

Substitute Ocean Water

Prepared by: ASTM D1141-90

Stock Solution #1

$MgCl_2 * 6H_2O$	1944.5 grams	(Fisher Chemical)
$CaCl_2$ (anhydride)	202.8 grams	(Fisher Chemical)
$SrCl_2 * 6H_2O$	7.4 grams	(Aldrich Chemical)

Dissolve in water and dilute to 3.5 liters.

Stock Solution #2

KCl	243.1 grams	(Fisher Chemical)
$NaHCO_3$	70.35 grams	(Fisher Chemical)
KBr	35.20 grams	(Aldrich Chemical)
H_3BO_3	9.50 grams	(Aldrich Chemical)
NaBr	1.05 grams	(Aldrich Chemical)

Dissolve in water and dilute to 3.5 liters.

Prepare "Substitute Ocean Water"

NaCl	1962.72 grams	(Fisher Chemical)
Na_2SO_4	327.52 grams	(Fisher Chemical)

Dissolve in about 70 liters of water. Slowly add while stirring, 1600-mL Stock Solution #1 then 800-mL of Stock Solution #2. Dilute to make 80 liters.
Adjust the pH to 8.2 using 0.1N NaOH solution.

White quartz sand	(Aldrich Chemical)
NaOH	(Mallinckrodt Chemical Inc. of Paris Kentucky)

APPENDIX – (D)

10-90 OIL-WATER

Q_F	Q_U	y_O	y_F	y_U	Y_F	Y_U	E_{HP}	E_{SOLIDS}	O/U	Oil Recovery	Water Recovery	Sand Recovery	(psig)	(gpm)
314.0278	181.1181	0.0615	0.0245	-0.0028	0.0302	0.0517	0.6580	0.9863	0.8	1.065	0.593	0.986	49	1.03
292.3985	149.7384	0.0449	0.0195	-0.0047	0.0095	0.0177	0.6495	0.9499	1.0	1.125	0.525	0.950	49	0.95
294.1278	152.0887	0.0432	0.0218	0.0018	0.0104	0.0194	0.4840	0.9606	1.0	0.956	0.528	0.961	49	1.04
286.8136	149.7446	0.0530	0.0264	0.0021	0.0159	0.0295	0.4942	0.9691	0.9	0.959	0.535	0.969	49	0.99
301.5232	90.9887	0.0279	0.0198	0.0010	0.0133	0.0422	0.2925	0.9611	1.8	0.985	0.308	0.961	50	0.98
290.8058	90.0904	0.0260	0.0182	0.0008	0.0073	0.0219	0.3020	0.9316	2.3	0.987	0.315	0.932	50	0.94
298.1937	93.5041	0.0322	0.0224	0.0011	0.0111	0.0339	0.3055	0.9604	2.0	0.985	0.320	0.960	50	0.99
303.2265	91.3007	0.0277	0.0196	0.0008	0.0145	0.0465	0.2951	0.9694	2.4	0.988	0.307	0.969	50	1.01
288.1604	55.0903	0.0327	0.0265	0.0005	0.0139	0.0702	0.1924	0.9627	4.0	0.996	0.196	0.963	49	0.94
297.7036	68.1168	0.0299	0.0231	0.0003	0.0085	0.0351	0.2312	0.9435	3.6	0.997	0.234	0.944	49	0.97
272.5409	103.8257	0.0364	0.0231	0.0014	0.0084	0.0205	0.3655	0.9321	1.6	0.976	0.389	0.932	49	0.91
290.7752	92.7235	0.0336	0.0232	0.0010	0.0075	0.0216	0.3128	0.9142	2.2	0.987	0.326	0.914	49	1.02

30-70 OIL-WATER

Q_F	Q_U	y_O	y_F	y_U	Y_F	Y_U	E_{HP}	E_{SOLIDS}	O/U	Oil Recovery	Water Recovery	Sand Recovery	Pressure (psig)	Flowrate (gpm)
268.3447	165.6187	0.4560	0.1879	0.0217	0.0232	0.0371	0.6724	0.9881	0.6	0.929	0.744	0.988	42	0.92
268.5483	161.5551	0.4347	0.1848	0.0194	0.0186	0.0302	0.6607	0.9786	0.6	0.937	0.724	0.979	42	0.85
268.4340	158.9197	0.4479	0.1958	0.0221	0.0218	0.0364	0.6529	0.9888	0.8	0.933	0.720	0.989	42	0.94
251.5153	113.4931	0.3546	0.1974	0.0063	0.0147	0.0316	0.5442	0.9735	1.3	0.986	0.559	0.973	42	0.86
253.9684	94.9147	0.2996	0.1896	0.0052	0.0275	0.0725	0.4486	0.9862	1.9	0.990	0.459	0.986	42	0.93
254.4959	84.6621	0.2636	0.1776	0.0052	0.0164	0.0476	0.3927	0.9673	2.0	0.990	0.402	0.967	42	0.86
251.1412	19.9122	0.2471	0.2284	0.0116	0.0008	0.0014	0.0976	0.1331	8.3	0.996	0.102	0.133	42	0.88
283.0918	24.6825	0.2772	0.2537	0.0077	0.0012	0.0064	0.1133	0.4799	7.7	0.997	0.116	0.480	42	0.97
289.6414	22.9463	0.2616	0.2414	0.0074	0.0009	0.0032	0.1012	0.2965	14.0	0.998	0.104	0.296	42	0.95
295.4005	183.8338	0.4509	0.1829	0.0202	0.0249	0.0394	0.6775	0.9859	0.7	0.931	0.746	0.986	50	1.08
307.1771	188.4323	0.4215	0.1751	0.0198	0.0178	0.0283	0.6594	0.9753	0.7	0.930	0.729	0.975	50	1.01
288.7460	177.2795	0.4338	0.1778	0.0169	0.0191	0.0304	0.6759	0.9758	0.7	0.942	0.734	0.976	50	0.94
279.0845	138.8243	0.3506	0.1797	0.0071	0.0180	0.0353	0.5826	0.9722	0.9	0.980	0.602	0.972	50	1.00
262.6493	25.2366	0.2632	0.2387	0.0087	0.0009	0.0029	0.1216	0.3182	8.2	0.996	0.125	0.318	50	0.87
286.4288	141.8387	0.3244	0.1673	0.0072	0.0167	0.0329	0.5692	0.9729	1.0	0.979	0.590	0.973	50	0.97
278.9953	135.1845	0.3336	0.1749	0.0062	0.0162	0.0322	0.5664	0.9647	1.1	0.983	0.584	0.965	50	0.90
301.5263	22.5055	0.2003	0.1859	0.0076	0.0008	0.0024	0.0880	0.2148	8.6	0.997	0.091	0.215	50	1.13
264.2291	29.3106	0.2502	0.2232	0.0068	0.0013	0.0054	0.1384	0.4817	7.4	0.997	0.142	0.482	50	0.90

APPENDIX – (D) – (cont.)

50-50 OIL-WATER

Q_F	Q_U	y_O	y_F	y_U	Y_F	Y_U	E_{HP}	E_{SOLIDS}	O/U	Oil Recovery	Water Recovery	Sand Recovery	Pressure (psig)	Flowrater (gpm)
290.1974	162.3440	0 6300	0.3486	0.1270	0.0288	0.0507	0 5460	0 9849	0.9	0 796	0 750	0.985	50	0 98
307 4168	171 5273	0.6310	0 3364	0.1031	0.0237	0 0417	0.5833	0.9834	0.9	0.829	0.754	0.983	50	1.05
301.6487	168 7162	0 6449	0 3435	0.1060	0 0210	0 0370	0.5891	0.9846	0.9	0.827	0.762	0.985	50	1.02
294 1898	86.1354	0 5869	0.4180	0.0101	0.0106	0.0349	0.4909	0.9660	2.4	0.993	0.498	0 966	50	1.08
270.5144	107.3050	0 6668	0 4164	0 0355	0 0218	0 0541	0 6217	0.9830	1.6	0.966	0.656	0.983	50	0.97
292.2871	153.1927	0.6232	0.3286	0.0611	0.0196	0.0369	0.6355	0.9834	1.1	0 903	0.733	0.983	50	1 07
284.2577	19 2268	0 4307	0.4038	0.0317	0.0013	0 0095	0 1045	0.4921	15.3	0 995	0.110	0 492	50	0 98
289.2296	26 2003	0 5114	0 4696	0 0492	0.0022	0 0195	0.1529	0 7959	11.5	0.991	0.162	0.796	50	0.99
280 5260	23 2289	0 5168	0 4765	0.0306	0.0009	0 0061	0 1480	0 5345	16 2	0 995	0.153	0 534	50	1 04
277.9187	158.0270	0.5558	0.2845	0 0786	0.0281	0 0489	0.5751	0.9887	0.9	0 843	0.732	0 989	40	0 97
273.4920	154.4532	0 5859	0 3173	0 1103	0 0187	0 0325	0.5396	0 9822	0.7	0 804	0 736	0 982	40	0.98
284 5454	164 2022	0 5658	0 2902	0 0882	0 0280	0 0480	0 5659	0.9904	0 8	0 825	0.741	0 990	40	1 00
245.1251	95.1774	0 5323	0 3379	0.0316	0.0282	0 0714	0 5315	0 9837	1 8	0 964	0 568	0 984	40	0 87
264.3734	118 2340	0 5393	0 3380	0.0892	0 0265	0 0584	0 4973	0 9842	1.3	0 882	0 615	0 984	40	0 94
250 2509	100.1821	0.5192	0 3548	0.1084	0.0284	0 0700	0.4309	0 9872	1 5	0 878	0 553	0 987	40	0 91
240 6402	53.8144	0 5266	0.4037	-0.0229	0 0146	0 0648	0 3963	0 9903	3.6	1.013	0.384	0 990	40	0.81
288 4756	33 8035	0.4732	0.4243	0.0562	0.0044	0.0348	0.1766	0.9232	8.3	0.984	0.192	0.923	40	1.03
289.7615	39.2305	0.4849	0 4292	0.0739	0.0048	0 0329	0 1964	0 9221	7.4	0 977	0.220	0 922	40	1.06

APPENDIX – (D) – (cont.)

70-30 OIL-WATER

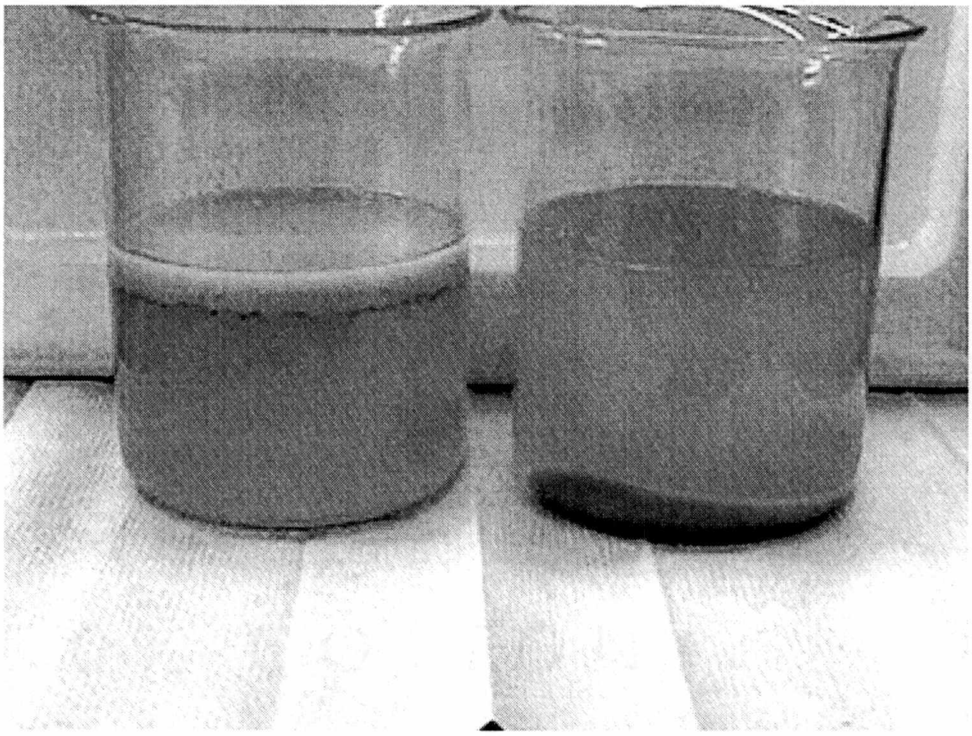
										Oil	Water	Sand	Pressure	Flowrate
Q_F	Q_U	y_O	y_F	y_U	Y_F	Y_U	E_{HP}	E_{SOLIDS}	O/U	Recovery	Recovery	Recovery	(psig)	(gpm)
227.0130	103.1750	0.6459	0.6280	0.6064	0.0173	0.0350	0.0419	0.9206	1.2	0.561	0.481	0.921	29	0.86
224.6528	101.1297	0.6200	0.6076	0.5924	0.0170	0.0347	0.0286	0.9172	1.1	0.561	0.468	0.917	29	0.94
219.9450	99.9892	0.6322	0.6267	0.6201	0.0169	0.0339	0.0129	0.9127	1.2	0.550	0.463	0.913	29	0.86
277.2522	117.1648	0.6265	0.6335	0.6429	0.0167	0.0383	-0.0172	0.9692	1.3	0.571	0.412	0.969	38	1.00
274.9698	115.9875	0.6417	0.6322	0.6192	0.0159	0.0365	0.0236	0.9707	1.4	0.587	0.437	0.971	38	1.06
282.0626	119.4005	0.6445	0.6327	0.6167	0.0162	0.0368	0.0292	0.9654	1.3	0.587	0.442	0.965	38	1.07
303.7108	16.4045	0.6820	0.6724	0.5041	0.0137	0.0467	0.0413	0.1840	12.8	0.960	0.082	0.184	45	1.09
333.2595	17.2180	0.7106	0.7022	0.5494	0.0120	0.0501	0.0378	0.2149	15.2	0.960	0.078	0.215	45	1.28
301.5707	15.5111	0.7075	0.7027	0.6144	0.0114	0.0438	0.0217	0.1968	13.4	0.955	0.067	0.197	45	1.14
269.5768	124.4657	0.6880	0.6797	0.6701	0.0157	0.0323	0.0203	0.9483	1.1	0.545	0.476	0.948	40	0.98
248.9762	115.1729	0.6868	0.6689	0.6482	0.0155	0.0315	0.0433	0.9412	1.1	0.552	0.492	0.941	40	0.95
252.0396	115.6076	0.7037	0.6798	0.6515	0.0153	0.0310	0.0595	0.9304	1.1	0.560	0.499	0.930	40	0.90
215.3783	50.0862	0.7102	0.6731	0.5509	0.0128	0.0380	0.1293	0.6919	3.4	0.810	0.320	0.692	26	0.82
207.0891	40.5414	0.7037	0.6709	0.5362	0.0151	0.0387	0.1194	0.5026	4.3	0.844	0.276	0.503	26	0.75
207.0361	35.8913	0.7229	0.7016	0.6001	0.0154	0.0278	0.0840	0.3137	4.9	0.852	0.232	0.314	26	0.84
212.5941	12.6190	0.7269	0.7186	0.5864	0.0139	0.0397	0.0388	0.1701	13.5	0.952	0.087	0.170	26	0.78
212.1666	12.5991	0.7081	0.7045	0.6477	0.0125	0.0374	0.0162	0.1775	13.6	0.945	0.071	0.177	26	0.79
228.2093	13.1504	0.7381	0.7320	0.6334	0.0125	0.0372	0.0290	0.1717	12.5	0.950	0.079	0.172	26	0.86

APPENDIX – (D) – (cont.)

90-10 OIL-WATER

										Oil	Water	Sand	Pressure	Flowrate
Q_F	Q_U	y_O	y_F	y_U	Y_F	Y_U	E_{HP}	E_{SOLIDS}	O/U	Recovery	Recovery	Recovery	(psig)	(gpm)
323 6065	137.8280	0 9255	0 9257	0.9259	0.0063	0 0148	-0 0017	0.9944	1.3	0 574	0 424	0.994	50	1.27
302.6616	135.6888	0.8996	0 8861	0 8696	0 0070	0.0154	0.0736	0.9918	1.3	0.541	0.514	0 992	50	1.11
304.1139	136.8888	0.8992	0.8867	0.8714	0.0083	0 0183	0.0686	0.9901	1.4	0.540	0.511	0.990	50	1.14
322.3665	145.3886	0.9040	0.8899	0 8728	0 0062	0.0136	0.0788	0 9889	1 4	0.538	0.521	0.989	50	1.20
318.0213	142 8944	0 8706	0 8626	0.8529	0 0070	0 0154	0.0368	0.9896	1.3	0 544	0.481	0.990	50	1 27
300 8636	133.6408	0 8879	0 8590	0 8227	0 0069	0 0154	0.1328	0 9870	1.4	0 532	0 558	0.987	50	1 03
315 9207	97.3920	0 8673	0 8525	0.8193	0 0077	0 0214	0.0815	0.8631	2.3	0 665	0.378	0.863	50	1.25
304.1609	96 0577	0 8368	0 8233	0.7940	0.0089	0 0271	0 0636	0 9641	1.8	0 660	0 368	0.964	50	1 23
311 2995	93 1727	0 8687	0.8615	0.8446	0.0102	0.0335	0 0424	0.9832	2 2	0 687	0 336	0.983	50	1 16
291.8807	52.0301	0.8937	0 8835	0.8368	0.0107	0 0575	0 0809	0 9555	4.5	0.778	0.250	0.955	53	1.05
284.4243	56.4723	0 8964	0 8862	0.8452	0.0098	0.0469	0.0809	0 9539	4.0	0.764	0.270	0.954	53	1.03
288 3576	51.9371	0.8902	0 8742	0 8012	0.0088	0.0463	0.1195	0 9451	4 5	0.751	0 285	0.945	53	1.04
287 0638	125.2134	0 9079	0 8947	0.8776	0 0083	0.0186	0.0791	0 9791	1.3	0.553	0.507	0 979	44	1.04
286.1652	125.0330	0 8939	0.8545	0 8038	0.0085	0.0190	0 1782	0 9763	1 3	0.530	0 589	0.976	44	1.03
283.1225	123 6530	0.8353	0.8288	0.8204	0 0091	0 0203	0 0257	0.9764	1.3	0.558	0 458	0.976	44	1.01
287.9068	86.7594	0 8610	0 8393	0.7890	0.0075	0.0240	0.1125	0.9574	2.5	0.657	0.396	0.957	41	1.11
277.4920	87.0223	0 8408	0 8504	0 8714	0 0095	0 0294	-0.0518	0.9659	2 3	0 703	0 270	0.966	41	1 03
283.5279	90 7132	0.8846	0 8755	0 8562	0 0107	0 0323	0.0566	0.9653	2.0	0.665	0 370	0.965	41	1.09
280.4119	44.4171	0.8493	0 8291	0.7222	0 0075	0 0422	0.1195	0.8927	6.1	0.733	0 257	0.893	41	1.01
271.2720	43.0056	0.8601	0.8552	0 8294	0 0082	0 0464	0.0330	0 8992	6.4	0 816	0.187	0.899	41	1.06
277 9407	42.8286	0 8575	0 8479	0.7953	0.0107	0.0647	0.0629	0 9334	5.4	0.793	0 207	0.933	41	1.01
189.9942	58 9752	0.8370	0.8377	0.8393	0 0098	0.0299	-0 0037	0 9510	2.7	0.691	0.307	0.951	58	0.76
154.5767	57.5832	0.7904	0.8050	0 8298	0 0078	0 0192	-0.0587	0.9122	2.0	0.647	0.325	0.912	58	0.52
157.5289	73 4305	0.7620	0.7900	0.8221	0.0245	0.0516	-0.0903	0 9815	1 2	0.556	0.395	0.981	58	0.62
200 8026	47.0109	0.8489	0 8381	0.8028	0.0111	0.0444	0.0609	0.9379	3 4	0.734	0.285	0 938	57	0.76
317 9769	71.9789	0.8309	0 8213	0 7887	0 0138	0 0589	0 0504	0.9698	1.4	0.743	0 268	0.970	57	1 47
292 0570	66 3336	0 8262	0.8292	0 8395	0.0138	0.0589	-0.0166	0.9662	3 1	0 782	0.213	0.966	57	1.05
312 4240	134 3765	0 8324	0 8361	0 8410	0 0112	0 0255	-0.0154	0.9765	1.3	0.573	0 417	0.976	58	1.14
281 3531	124.1025	0.8112	0.8204	0.8321	0.0111	0.0246	-0.0350	0.9778	1 2	0.567	0.412	0.978	58	1.07
275.3434	127.3047	0.8095	0.7867	0.7603	0.0128	0.0272	0.0728	0.9826	1.1	0.520	0.520	0.983	58	1.08
265.7244	25.5494	0.8734	0 8619	0.7538	0 0062	0 0450	0.0874	0 7035	9.2	0.790	0.171	0.703	41	0.97
279.7678	32.4620	0.8729	0.8615	0.7744	0.0094	0.0615	0.0846	0.7620	6 8	0.795	0.189	0 762	41	1.09
320.7747	67.5529	0 8735	0.8680	0.8473	0.0134	0.0593	0.0380	0.9329	3 9	0.771	0.244	0.933	41	1.18
295.7356	40.9033	0 8767	0 8659	0 7987	0.0067	0 0429	0 0800	0 8808	6.0	0.795	0 208	0.881	50	1 11
299 0539	19 4861	0 8590	0 8442	0.6312	0 0051	0 0382	0.1055	0.4875	12.3	0 699	0 154	0.487	50	1.10
313 8183	90 4400	0.8511	0.8478	0 8395	0.0123	0.0405	0.0185	0.9478	2 3	0.705	0.304	0 948	50	1.16
340 9224	20 2450	0 8740	0 8593	0.6263	0 0116	0 0664	0 1144	0.3390	15.0	0 686	0 158	0.339	57	1.27
329.5414	84.7764	0.8565	0 8426	0 8022	0.0120	0.0449	0.0782	0.9608	3 1	0.707	0.323	0 961	57	1.30
348.7661	24.4735	0 8546	0.8387	0 6280	0.0061	0.0530	0.1093	0.6104	14.4	0.696	0.162	0.610	57	1.32

APPENDIX – (E)



(Left - Oil and water) **(Right – Water and sand)**

Figure 32 - Typical Samples Collected in the Research

APPENDIX – F

30:70 oil-to-water volume ratio of feed

E_S	Overflow/underflow	Standard deviation
0.9881	0.6	-
0.9786	0.6	0.0057
0.9888	0.8	-
0.9735	1.3	-
0.9862	1.9	0.0096
0.9673	2.0	-
0.9859	0.7	-
0.9753	0.7	0.0060
0.9758	0.7	-
0.9722	0.9	-
0.9729	1.0	0.0045
0.9647	1.1	-

Average standard deviation = (0.0057 + 0.0096 + 0.0060 + 0.0045)/4 = **0.0065**

VITA

Larry Willis Perkins was born in Richlands, VA on August 12, 1977. He attended high school at Harriman High School in Harriman, TN. He continued his education by attending Roane State Community College where he obtained an Associate of Science degree. He then attended Tennessee Technological University in Cookeville, TN, where he graduated with a Bachelor of Science degree in Chemical Engineering in May 1999. He received the Master of Science degree in Chemical Engineering from The University of Tennessee, Knoxville in May 2001. He is a member of the American Institute of Chemical Engineers, as well as the American Chemical Society. He is also a Christian and serves the Lord as a deacon in Big Emory Baptist Church.