A NEW TYPE OF OIL-WATER SEPARATOR FOR BETTER WATER QUALITY MANAGEMENT

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by

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TABLE OF CONTENTS

Chapter Page

V. SUMMARY AND CONCLUSIONS

LITERATURE CITED

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

BACKGROUND AND INTRODUCTION

For centuries, humanity has known that oil and water do not mix - at least not very well. What ancient man did not appreciate is that oil and water will mix under certain conditions, and the resulting emulsions can be very difficult to separate.

Mixtures of oil and water in aquatic environments become more troublesome each year because of increasing volumes of oil dumped into rivers and the ocean. Each year it becomes more difficult to protect the environment from the encroachment of mankind.

Natural oil has been seeping into water for centuries. The Greek historian Herodotus reported petroleum and tar as early as 450 B.C. (Nelson, 1969). Laws (1981) noted that natural gas from the Kirkuk oil field in Iraq has been burning since biblical days, and that reports of oil seeps in the ocean off Coal Oil Point in California were noted as early as 1629. Until the advent of the automobile as a major mode of transportation, however, petroleum was little used except as a lubricant and eventually as a replacement for whale oil in oil lamps.

Today, many freshwater systems are polluted with oil, and the largest single source of oil discharge to the oceans is river runoff (Laws, 1981). In a National Academy of Sciences study quoted by Laws, it was estimated that in 1970 total discharges to the marine environment were about six million (6,000,000) metric tons per year, of which ten percent (10%) came from river runoff. In order to protect the marine environments and their precious resource of fish and plants, it is therefore necessary to protect the rivers and streams that run into the oceans.

Objectives of the Study:

The objectives of the study were to:

a) Test a newly developed oil-water separator to determine its capabilitiets for oil and solid particle handling/removal and resistance to plugging by the solid particles often present in oily waste water streams.

b) Determine the design parameters for such a separator so that additional separators could be designed.

c) Devise a method of cleaning such a separator to readily remove solid contaminants if plugging does occur.

CHAPTER II

LITERATURE REVIEW

Oil and Problems Associated with Oil

Crude oil is a variety of complex hydrocarbon substances composed of thousands of different kinds of molecules. Crude oil from different fields can have varying properties. Some light crudes have specific gravities as low as 0.85, while others have specific gravities up to 1.15 (Nelson, 1969). Crudes may contain mostly alkanes, alkenes, aromatic compounds, or asphaltic compounds. Alkanes and alkenes are often lumped together under the term aliphatics. Most contain mixtures of one or more of these types. Refined products have an even greater range of properties than crude oils because many have molecular structures not commonly found in nature.

Both natural and refined products may also contain sulfur or nitrogen compounds that change their characteristics. Small concentrations of metals may also be present in crude oil, especially iron, nickel, arsenic, and vanadium (Nelson, 1969). Most of these metals are removed in the early stages of the refining process because their presence in the process can cause corrosion or poison refining catalysts.

Aliphatic compounds are the predominant hydrocarbons in gasoline, but aromatic compounds are used in percentages ranging up to forty percent (40%) and ethers such as methyltertiarybutyl ether (MTBE) in percentages up to fifteen percent (15%) (Nelson, 1969, Wilson, 1992). Aliphatics also predominate in kerosene, diesel fuel, and jet fuel. Even though leaded gasoline is being phased out under current EPA regulations (Findley and Farber, 1992), it is still available in many localities, and the tetraethyllead content makes it very toxic.

In addition to the petroleum related compounds, vegetable oils and animal fats are also considered to be oils (Romano, 1990). Since these are generally biodegradable, they are usually not considered a problem unless they are present in very large quantities. For purposes of this investigation, the term oil will be taken to mean petroleum-based hydrocarbons. The petroleum based hydrocarbons are also somewhat biodegradable.

Toxic effects of oil fall into two categories (Laws, 1981):

1) Effects due to smothering or coating of an animal or plant with the oil. These effects are most often associated with crude oil. Coating effects are most often associated with sea birds and some sea animals such as sea otters, seals, etc. Coating effects are most noticeable when large amounts of free oil are present as in an oil spill. Coating effects are not

usually found when only parts per million (ppm) are present as is the case in an industrial plant effluent. 2) Disruption of the animal or plant's metabolism due to the ingestion of the oil and incorporation of the oil into the organism's fatty tissues. Generally, those compounds that are not water soluble are oil soluble and thus tend to accumulate in body fat. This accumulation of toxic compounds in the fatty tissues is damaging to an animal or human being. These effects are seen in oil spill cases, and also as effects of industrial effluent and urban runoff pollution. It is now thought that aromatic hydrocarbons are the most toxic, followed by cycloalkanes, olefins (alkenes), and lastly alkanes.

Benzene, one of the aromatic components of gasoline, is known to be carcinogenic. Some other gasoline components, notably toluene, ethyl benzene, and xylenes are also aromatic compounds. Some other hydrocarbon based chemicals, notably Polychlorinated Biphenyls (PCBs) are aromatics and also known to be carcinogenic. Generally, hydrocarbons are not soluble in water. Some hydrocarbons do have a small solubility in water and unfortunately the lighter, more water soluble hydrocarbons have a tendency to be more toxic than the heavier, less soluble ones (Laws, 1981).

The Los Angeles Times conducted a study of chemicals (from spills) causing deaths or more than 50 injuries from 1982-1991. The results of this study show that six of the seven worst hazards could be classified as oil or petroleum products (Parrish, 1992).

Potential Sources of Oil in Water

Many possible sources of oil in water exist. Ignoring natural seeps, these can be divided into five general categories (adapted from Laws, 1981):

1) Industrial continuous sources;
2) Industrial spills;
3) Oil spills;
4) Urban runoff; and,
5) Domestic/Miscellaneous sources

Industrial continuous sources are the easiest to deal with as they are generally "point sources", have generally constant flow and constant oil content. These sources, such as refinery water outfalls, are often large sources of hydrocarbons. Point sources can be dealt with either by installation of oil-water separators or by elimination of individual sources of oil within the refinery or other industrial plant. From a regulatory standpoint, "oil and grease" content of these sources are regulated under the NPDES program. Industrial spills are likewise a problem that is relatively easy to deal with because it is possible to predict where spills may originate and to take preventative measures to capture spills before they enter the environment.

Spills from oil tanker accidents such as the *Exxon Valdez* disaster have the potential of being very damaging and various plans have been advanced to safeguard against such problems. Spills from oil wells, especially onshore ones, have become infrequent due to increased efforts to alleviate this problem (Green and Trett, 1989). Urban runoff water is primarily caused by storm water from streets and highways. Hydrocarbons in this water include primarily gasoline fractions, diesel fuel, and automotive and truck crankcase oil leaks. Of these, crankcase lubricating oil predominates in runoff water (Romano, 1990).

Domestic/Miscellaneous sources are much harder to eliminate as they are so diverse. These sources of oil include (Romano, 1990, Stenstrom, et al., 1984, Green and Trett, 1989):

1) Non-highway leaks from vehicles, especially crankcase oil.
2) Illicit dumping of used motor oil into storm drains.
3) Discharges from motorboat exhaust and leaks from boats.

Laws and Regulations

Oil in water discharges from industrial and other facilities are governed by a variety of federal, state and local laws. Included are the Clean Water Act (CWA) and its amendments, the Oil Pollution Act of 1990, the Coastal Zone Management Act and others (Findley and Farber, 1992).

Most hydrocarbon wastes are not covered by the Resource Conservation and Recovery Act of 1976 and its amendments (RCRA) or the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) also known as the Superfund Act (Findley and Farber, 1992). These wastes, produced by the extraction, transportation, refining, or processing of oil and natural gas, are specifically exempted from being regulated as "hazardous wastes" under any other laws. Congress's evident intent in providing this specific exemption is to ensure that these wastes may not be construed as hazardous under <u>any</u> other laws (Findley and Farber, 1992).

The basic law covering discharges is the Clean Water Act. It was originally enacted as the Federal Water Pollution Control Act of 1972, but was amended extensively in 1977. The 1977 amendments, in conjunction with the earlier legislation, became known as the Clean Water Act. Under the terms of this Act, amended Section 402 created the National Pollutant Discharge Elimination System (NPDES) permit system. Permits for point sources under this system are granted by the Environmental Protection Agency (EPA) or by states with EPA approved programs. After enactment of this law, any discharges other than those covered by the permit are illegal. Although the Clean Water Act was enacted primarily to control discharges from Publicly Owned Treatment Works (POTW's) and toxic discharges from industrial plants, it also controls discharges of petroleum and other hydrocarbons into the waters of the United States.

The courts have ruled that the EPA has the power to set effluent limitations by classes of facilities (E.I. DuPont de Nemours & Co. v. Train, 430 U.S. 112 (1977)) and that the EPA does not have to consider the quality of the receiving waters in setting effluent limitations (Weyerhaeuser Co. v. Costle, 590 F.2d 1011 (D.C. Circuit.1978)) (Findley and Farber, 1992). The EPA has shared regulatory powers with state and local governmental bodies.

Most states and localities require discharges to contain 15 ppm or less oil and grease, based on a 24 hour composite sample. Oil and grease may include petroleum hydrocarbons as well as animal and vegetable oils. Some localities have established lower discharge limits. King County, Washington, which includes the Seattle area, requires discharges to be less than 10 ppm. (Romano, 1990).

Also important are the new storm water management rules published by the EPA in 1990 (NPDES Permit Application Regulations for Storm Water Discharges; Final Rule, 1990). The reasoning behind stringent regulation of storm waters is included in the "National Water Quality Inventory, 1988 Report to Congress", as discussed in the Federal Register, November 16, 1990. This report concludes that "pollution from diffuse sources, such as runoff from agricultural, urban areas, construction sites, land disposal, and resource extraction is cited by the States as the leading cause of water quality impairment." These sources appear to gain in importance as discharges of industrial process waste waters and municipal sewage plants come under increased control. A study conducted by the Huron River Pollution Abatement Program (Federal Register, November 16, 1990) detected illicit discharges to storm sewers at a rate of 60% (of the number of businesses surveyed) in businesses related to automobiles such as auto dealerships, service stations and body shops. This study noted that most of these discharges had been legal when installed.

Storm water discharges were covered under the CWA but not required to have permits under the NPDES system until the final rules were published in the Federal Register, November 16, 1990. "Storm water discharges" refer to discharges consisting entirely of rainwater runoff, snowmelt runoff, or surface runoff and drainage. Waters that do not meet this definition are not covered by these regulations. The new rules specify that facilities with storm water discharges from "areas containing raw materials, intermediate products, finished products, by-product, or waste product located on site" will require a NPDES permit. Several categories of facility are specifically exempt from these regulations, notably storm water runoff from mining operations, oil and gas exploration, production, processing, or treatment operations, and parking lots whose rainwater sewers are not interconnected with manufacturing facility sewers.

A study has shown (Hunter, et al, 1979), that runoff water from highways can contain an order of magnitude more hydrocarbons than runoff from other urban areas. Most of the hydrocarbons in runoff are associated with particulate matter. This indicates that separators designed to deal with storm water should also be designed to handle the associated solids, and that the design of the separator should be based on the composite specific gravity of the oily solids. Hunter, et al. indicated that roughly 30% of the hydrocarbons in runoff are aromatic while the balance are aliphatic.

Systems for Removing Oil from Water

Systems for removing oil from water range from very simple holding ponds with or without skimming arrangements to very elaborate membrane technology-based systems. Most of the following discussion will concentrate on common methods used to provide separation intended to meet regulatory requirements with minimum cost and maintenance.

Gravity Separation

Spill Control Separators

The simplest possible separator is an empty chamber with room for containing spills. A typical spill control separator is shown in Figure 1 (Romano, 1990). A spill control separator is too small to intercept small droplets and is only suitable for intercepting spills of oil or

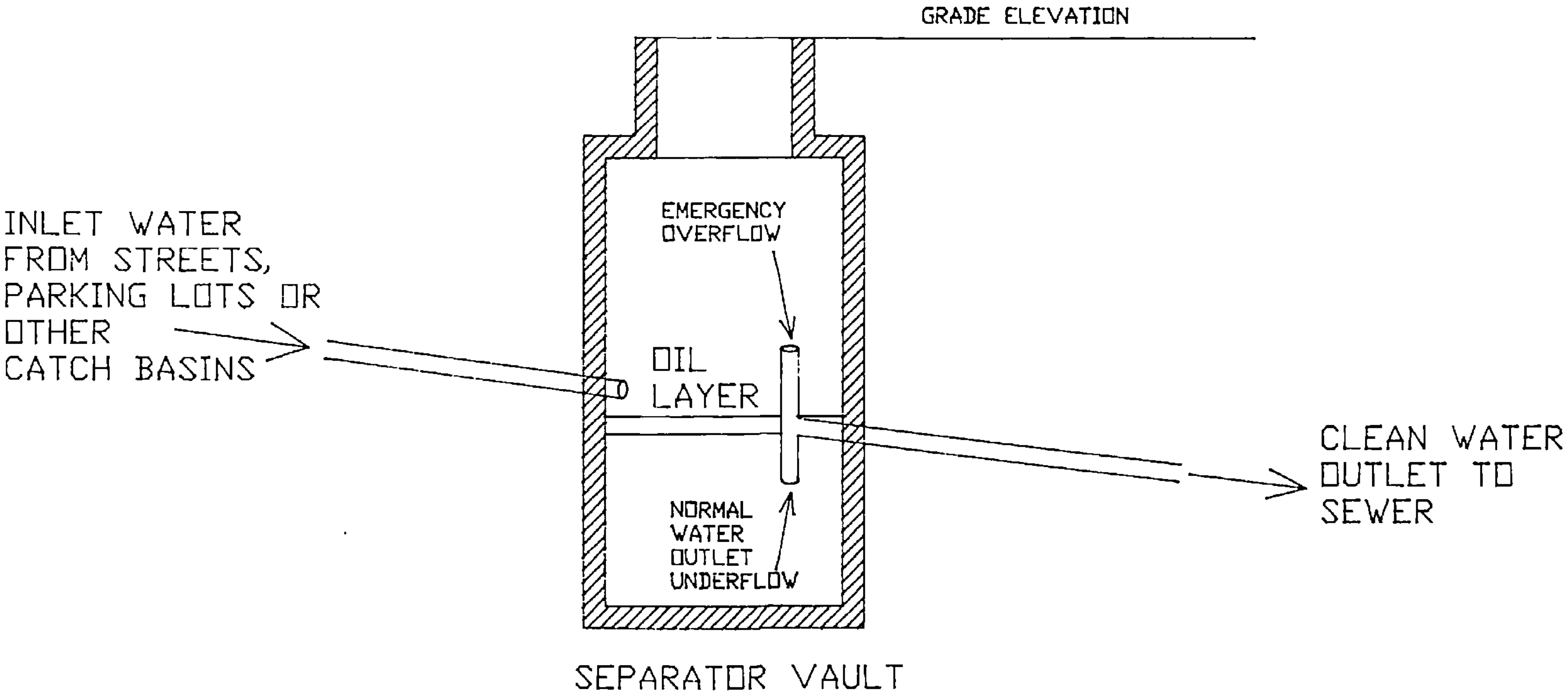


Figure 1. Spill Control Separator

grease. Spill control separators are only effective if any accumulated oil is removed regularly. If the oil is not removed regularly, a storm may flush the accumulated oil out of the separator into the downstream sewer (Romano, 1990).

API Separators

The American Petroleum Institute (API) provides design criteria for oil-water separators. A design method is provided in the API Manual on Disposal of Refinery Wastes, Chapters 5 and 6- Oil-Water Separator Process Design and Construction Details (API publication 1630, 1979). API separators are gravity type separators like spill control separators, but are generally larger, more sophisticated, more effective, and are usually equipped with oil removal facilities. These separators are extensively used in oil refineries and chemical processing facilities where waters containing relatively large amounts of oil are present and need to be processed to meet the requirements of NPDES permits. A diagram of a typical API separator is shown in Figure 2 (Adapted from API Publication 421, 1990).

The API separator has successfully been used in refineries for many years. It is much more effective than simple holding ponds or spill control separators. Advantages of the spill control separator and API separator are simplicity of design, low cost, low maintenance, and resistance to plugging with solids. The primary disadvantage of these simple gravity separators is the poor quality of separation that they provide.

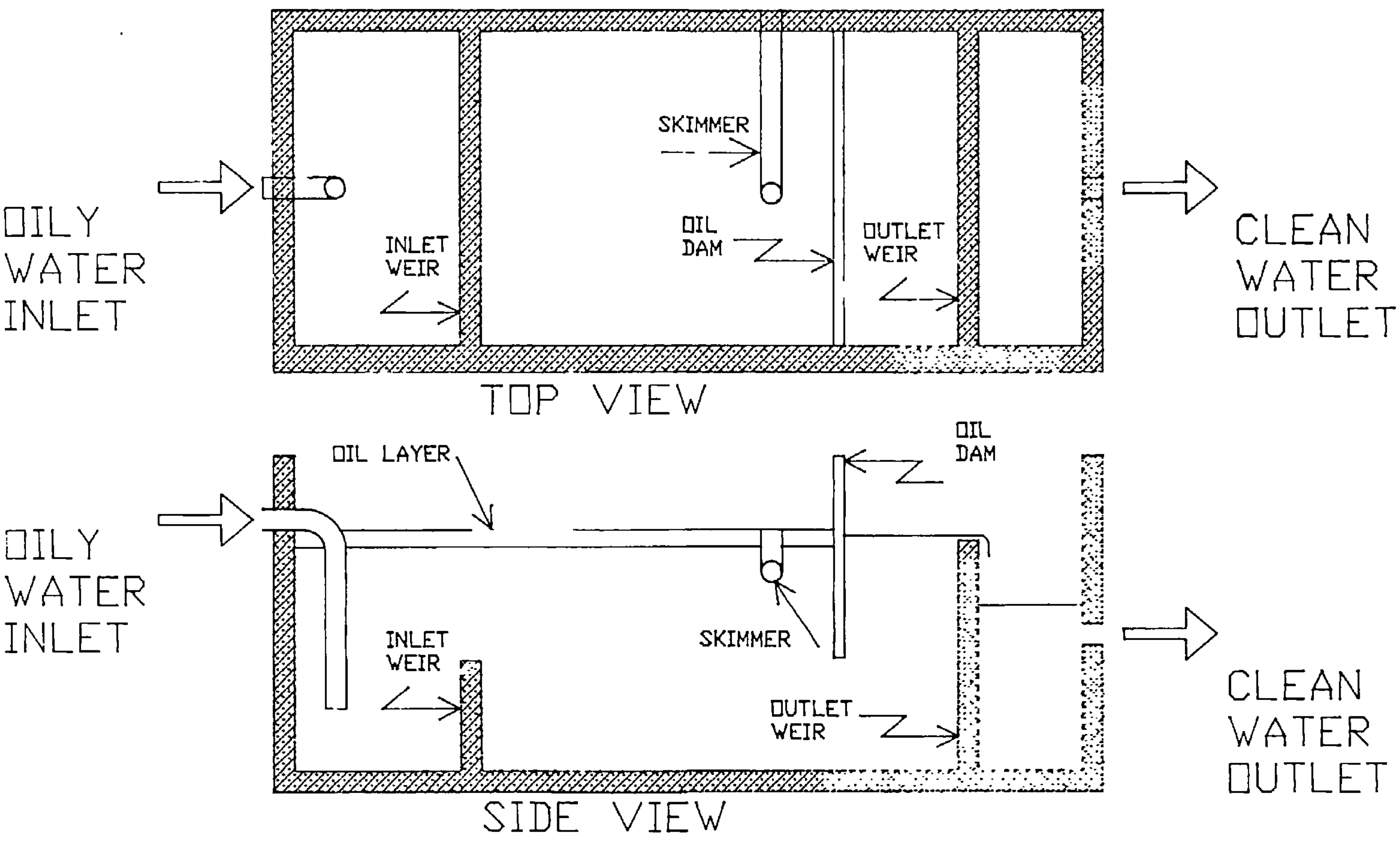


Figure 2. Typical American Petroleum Institute (API) Separator Pit

Enhanced Gravity Separation

Various types of enhanced gravity separators have been used to provide better separation quality than is possible with simple gravity separators while maintaining the low capital and maintenance cost benefits of the simple systems. In many ways, the enhanced gravity separators substitute sophisticated design for the settling time provided in pure gravity separators. These enhanced gravity separation systems have some similarity to API separators, but include additional internal features that enhance the separation of oil and water. These internal features are basically a substitute for the additional residence time provided by the API separators.

Designs that have successfully been used are:

1. Coalescing plate separators;
    a) Inclined plate separators;
    b) Flat corrugated (Horizontal Sinusoidal) plate separators;
    c) Multiple angle separators;
2. Coalescing tube separators; and,
3. Packing type separators.

Inclined plate separators

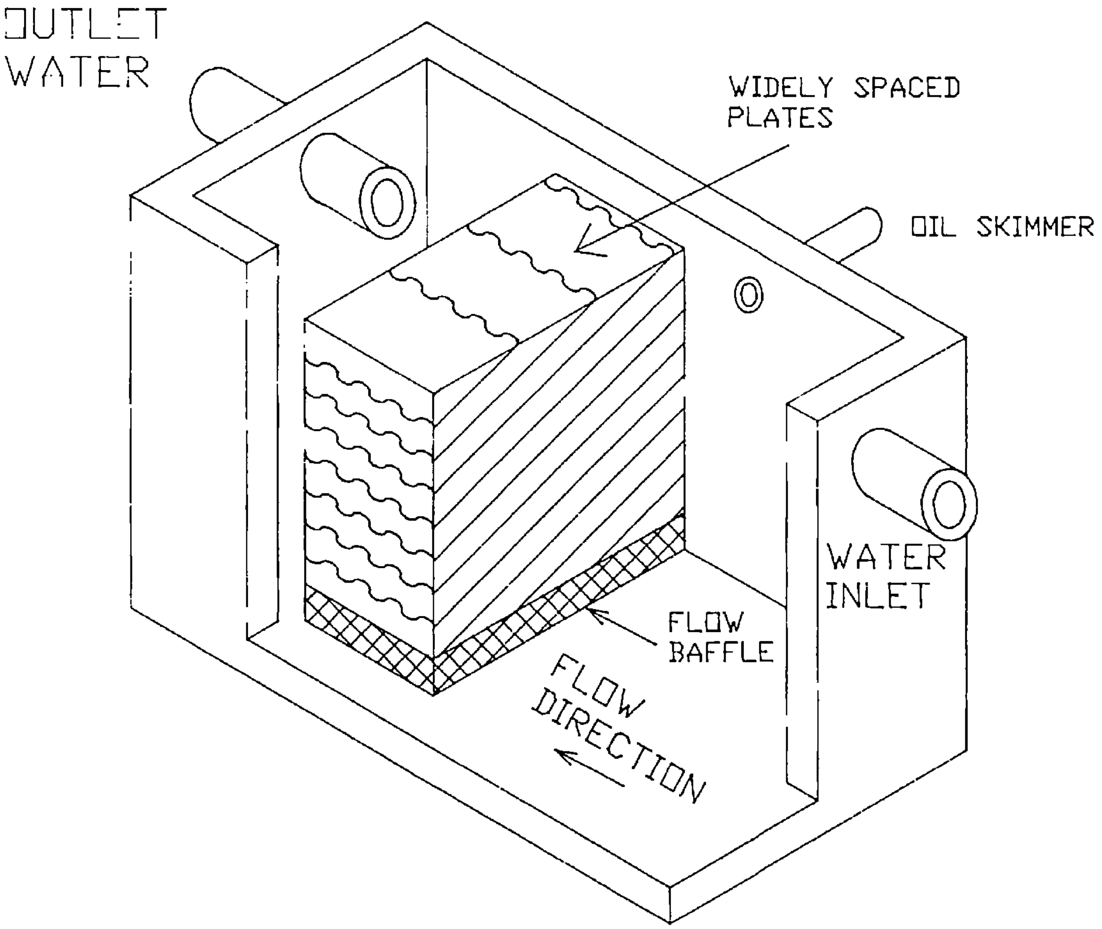
Inclined plate separators have been used successfully for many years.(Romano, 1990). These systems are usually made in large modules constructed of fiberglass corrugated plates packaged in steel or stainless steel frames. The oil droplets entering the system rise until they reach the plate above, then migrate along the plate until they reach the surface. Plates in this type system are often 3/4" apart, but may be as much as 4" apart (Romano, 1990, McTighe, 1992).

Advantages of this system include improved efficiency at removing both solids and oil (over API type separators) and resistance to plugging with solids (Romano, 1990). Figure 3 shows a schematic of a typical inclined plate separator (Romano, 1990).

Flat Corrugated (Horizontal Sinusoidal) Plate Separator

Flat corrugated plate separators often use horizontal oleophilic polypropylene plates stacked one on top of another in vertical stacks and fastened into packs with rods or wires. Figure 4 illustrates a drawing of a typical flat corrugated plate separator system (Facet International Environmental Products Catalog, 1992).

The system works by causing the oil to collect and be separated from the water using a combination of laminar flow coalescence and oleophilic attraction. Slowing the flow of water to such low velocities that laminar flow regimes exist minimizes turbulence. Turbulence causes mixing of the oil and water and reduces oil droplet sizes. Stokes's law states that larger droplets will rise faster and thus separate better. The oleophilic nature of the plates attracts the oil droplets and encourages them to coalesce into larger ones which will rise faster. These plates



NOTES:
1. FLOW BAFFLE PROVIDED UNDER PLATES TO PRECLUDE FLOW UNDER THE PACK AND PROVIDE SPACE UNDER THE PACK FOR SEPARATED SOLIDS STORAGE.
2. FIGURE PROVIDED WITH HALF OF PLATES REMOVED TO SHOW FLOW BAFFLE.
3. INLET AND OUTLET PROVIDED WITH FLOW DISTRIBUTORS (NOT SHOWN)

Figure 3. Inclined Plate Separator

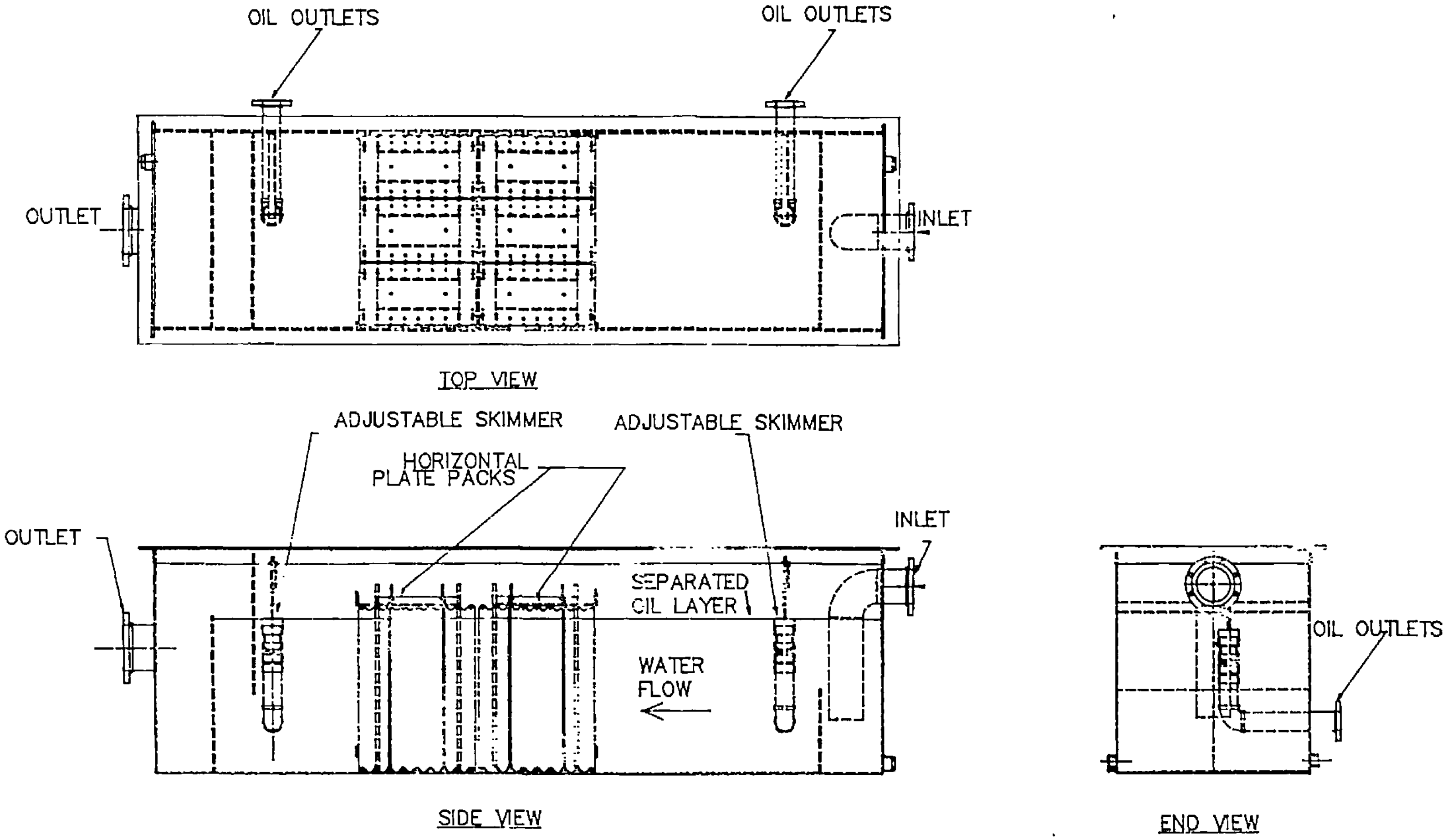


Figure 4. Flat Corrugated (Horizontal Sinusoidal) Oil–Water Separator

provide better separation than could be arrived at without plates. The advantages of this system are that the plate packs are modular and relatively small in size compared to the inclined plate modules. Corrugated plates in this type system are spaced a nominal 0.25" to 0.5" apart (Facet International Environmental Products Catalog, 1992). Because the plates are corrugated, rise distances of droplets in the vertical direction are greater than the perpendicular distance between plates. The oil droplets must rise approximately 0.4" for the nominal 0.25" spacing and 0.7" for the nominal 0.5" spacing. Because spacing varies slightly due to variations in plate molding and assembly the spacings are referred to as nominal 0.25" and 0.5" while varying somewhat from these dimensions. Figure 5 provides a detail of part of a separator pack and includes a graphic depiction of rise distances (Facet Coalescing Plate Separator Manual, 1989). Because the vertical rise distance to be covered is less than for the inclined plate systems, the same size particle is separated in less time. Conversely, the same amount of space time provided within the plate area causes effective separation of smaller size particles.

Disadvantages of this system are possible plugging of the plate packs by solids and possible damage to the plates by solvents that could attack the polypropylene plates. If it is known in advance that this may be a problem, plates placed vertically help to alleviate plugging by solids.

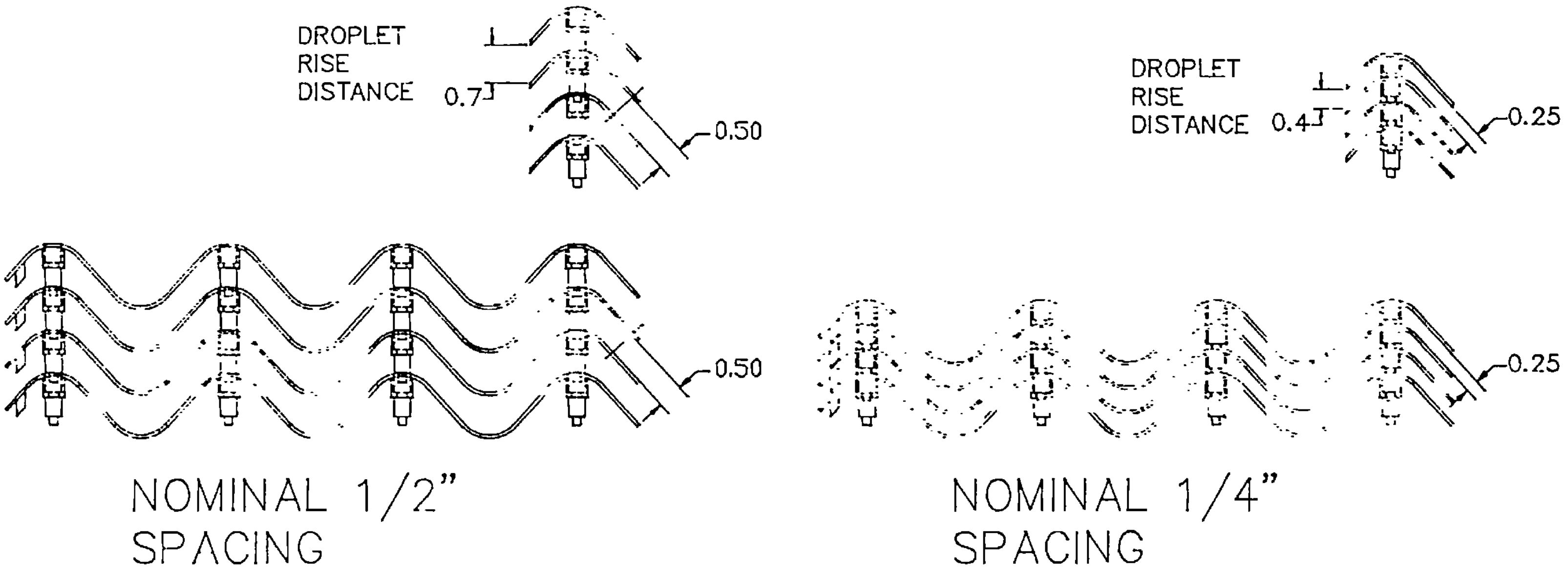


Figure 5. Flat Corrugated (Horizontal Sinusoidal) Plate Pack

Multiple Angle Plate Separators

The "MPak" multiple angle plate separators (testing of which forms the main subject of this paper) were developed to take advantage of the virtues of the horizontal sinusoidal separator plates while eliminating as many as possible of the disadvantages. A drawing of a multiple angle separator is contained in Figure 6 (adapted from Facet International Environmental Catalog, 1992).

These separator plates when seen from the end are "M" shaped, and the system is referred to as "MPaks". The plates are corrugated in both directions, making a sort of "egg-carton" shape. Spacers are built into the plates, constructed so that two spacings (nominal 0.25" and 0.5") can conveniently be made. Figure 7 shows a drawing of a multiple angle plate pack assembly (adapted from Facet International Catalog, 1992). Advantages of the "MPak" system are:

a) The plates are designed to shed solids to the bottom of the separator, avoiding plugging and directing the solids to a solids collection area. In inclined plate systems, solids must slide down the entire length of the plates whereas in the "MPak" systems the solids only have to slide a few inches before encountering one of a multitude of solids removal holes. The solids drop directly to the bottom of the separator through the holes.

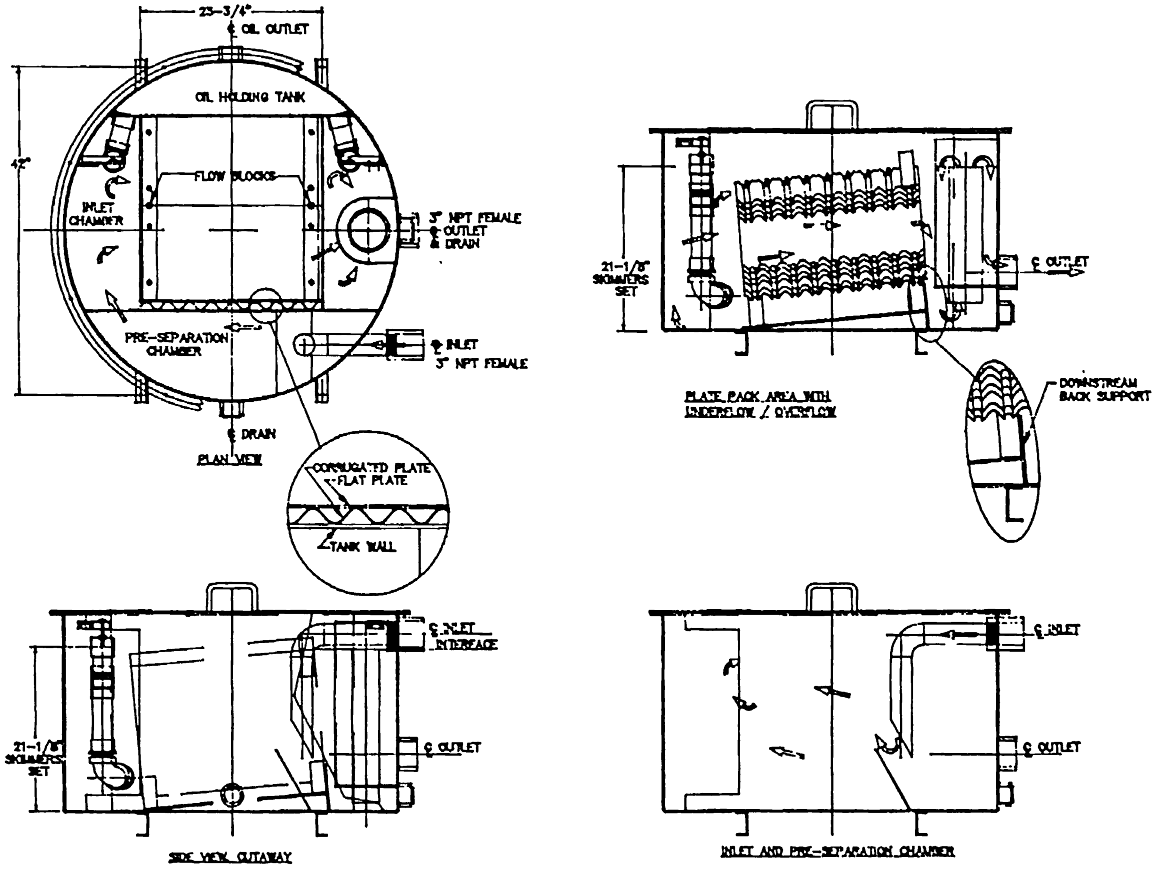


Figure 6. Multiple Angle ("MPak") Separator:
The HEROWS Unit

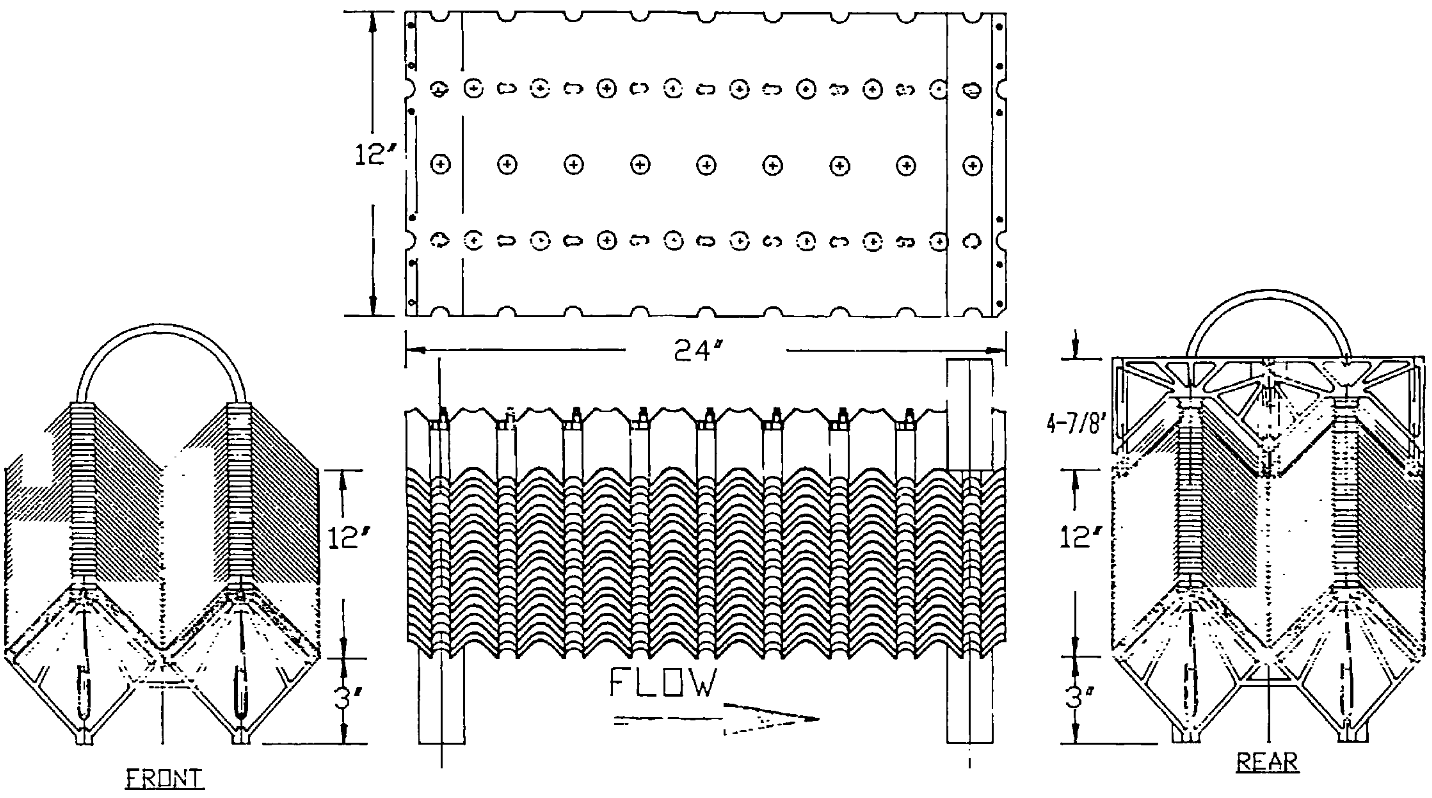


Figure 7. Multiple Angle "MPak" Separator Plate Pack

b) The supports that form part of the package also provide a space under the plates that constitutes a solids collection area.

c) The double corrugations provide surfaces that slope at a forty five (45) degree angle in all directions so that coalesced oil can migrate easily upward.

d) The upper support system provides a solids and oil dam that discourages bypassing floating solids above the plate pack into the effluent. This is important because oil can be carried through a separator attached to a solid particle.

e) The holes in the plates that constitute the oil rise paths and solids removal paths also provide convenient orifices for insertion of cleaning wands. Other types of pack systems are not provided with such holes and are more difficult to clean when plugged with solids.

Testing of the plates was conducted in a steel tank intended for above-ground installation. This unit is referred to as a HEROWS (High Efficiency Round Oil-Water Separator) unit. It was designed specifically to take advantage of the virtues of the "M" plates. Further description of this unit is provided in the Methods and Materials Chapter.

"MPaks" may be used in either above-ground units such as the HEROWS unit or in below-grade concrete vaults. The advantages of the above-ground units are that they are factory fabricated and require a minimum of field installation time. Most large units are designed utilizing plates installed in in-ground vaults. The primary advantages of vault installations are that the cost per unit flow is minimized and the below-grade installation is both convenient for gravity flow applications and does not waste valuable plant area.

Coalescing tube separators

Coalescing tube separators utilizing perforated plastic tubes for separation have been used for separation of oil and water. The advantages of the use of this type separator are low cost and enhanced separation due to the oleophilicity of the packing. The disadvantage is that the oil separation from the tubes is more or less random and therefore not optimized. Figure 8 shows a drawing of a coalescing tube separator (adapted from AFL Industries Catalog, 1977).

Packing type separators

One other system that can be used for coalescence is routing the emulsion through a bed of packing such as excelsior (Love, 1948). Experimental data indicates that most of the coalescence occurs in the first few inches of excelsior. This type of coalescer is often used in conjunction with gravity separation or inclined plate separation as a polishing stage. Similar packs have been made of other materials, including stainless steel and polypropylene. Systems of this type can be efficient, but

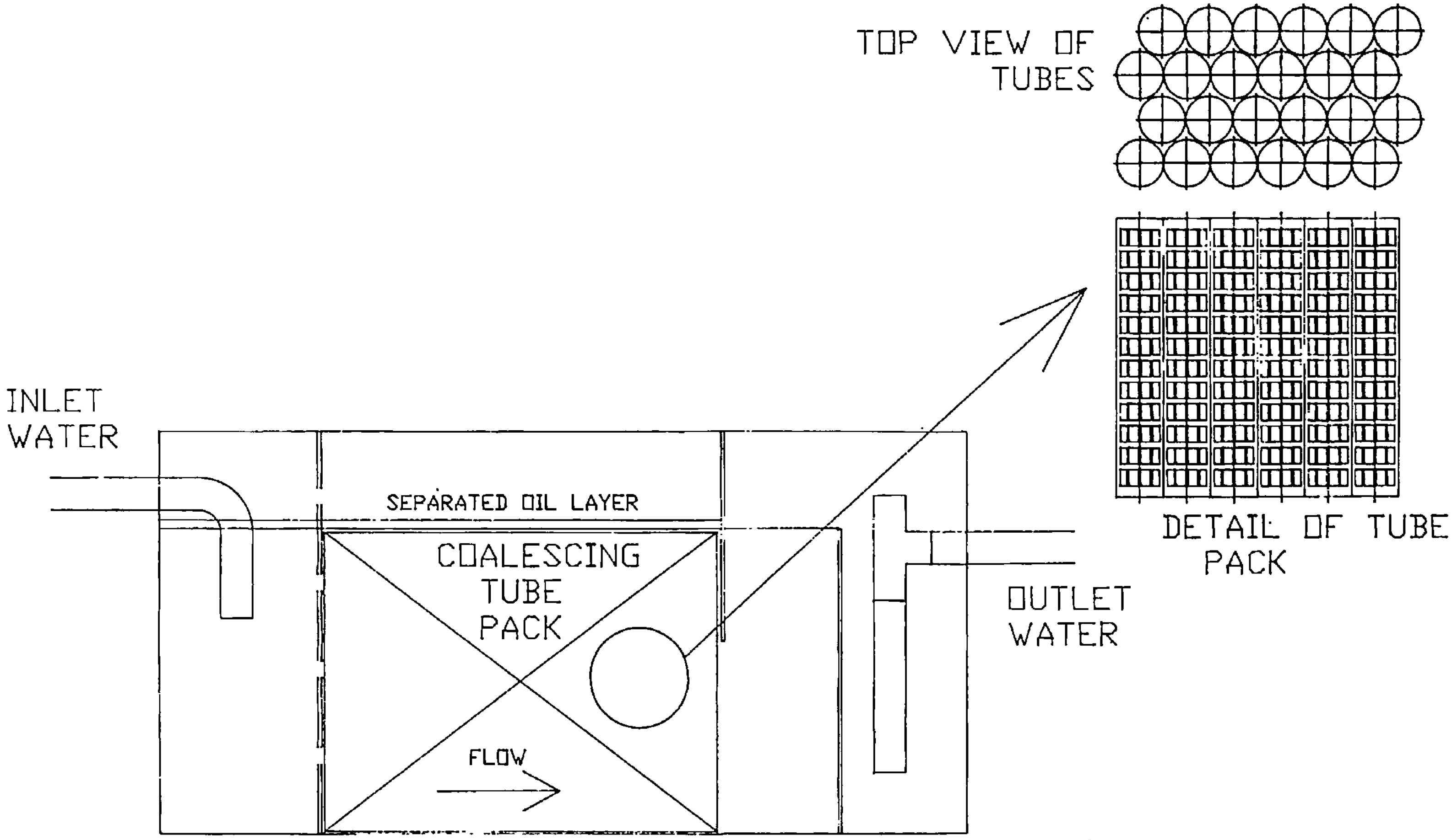


Figure 8. Coalescing Tube Separator

the tightly packed coalescing media can experience plugging problems. Coalescing media of this type is often used as a second stage after a plate type first stage of separation. In this type application, it is common to use plastic woven mesh of the type often used as demister pads in distillation columns. Figure 9 is an illustration of this type separator (Adapted from McTighe Industries, Inc. Catalog, 1991).

Exotic systems

Reverse osmosis membranes and other exotic means of removing oil from water are sometimes used, but these units are usually so expensive that they are not used for waste water treatment. Dissolved air flotation is also used.

Another expensive but effective means of removing residual oil in water is the use of activated carbon. Carbon is sometimes used as a polishing step, but can be prohibitively expensive if the first stages are not effective (McNicoll, 1992).

Applications of the Different Systems

In recent years, more stringent effluent requirements have caused the conversion of numerous API separators to more efficient designs. New facilities are being engineered with these requirements in mind and are utilizing the more sophisticated of the above discussed designs. Spill control and API separators are still used for many non-critical uses and where the effluent will be treated by other means downstream.

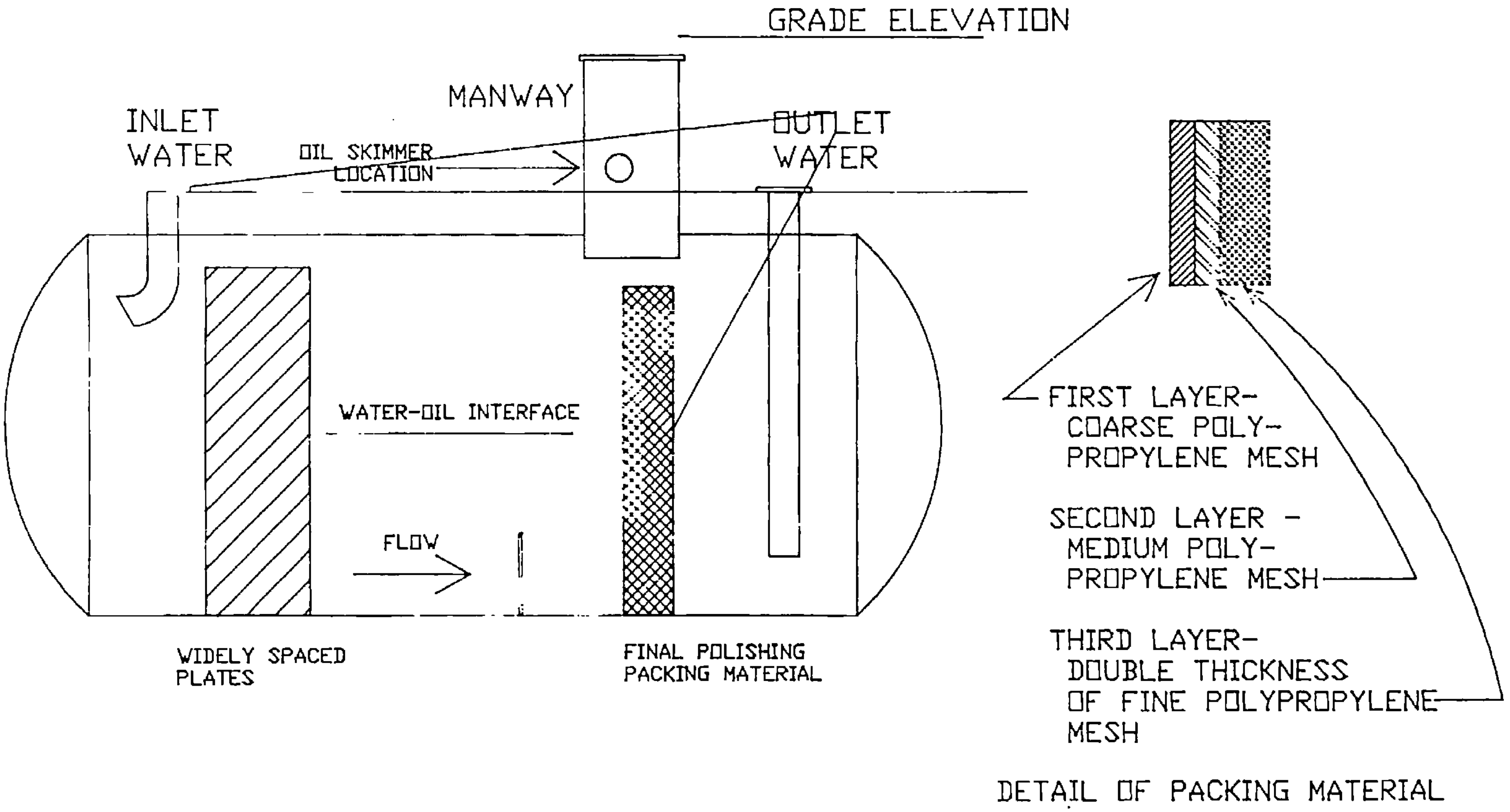


Figure 9. Packing Type Separator

Plate type systems, those utilizing coalescing tubes, and other enhanced gravity separation systems offer better performance than the simpler systems, but at higher costs (Romano, 1990). It is often necessary to balance cost versus benefits to ensure that regulatory requirements are being met, an operable system has been provided, and installation and operating costs are minimized. Exotic systems may be required where virtually zero oil in water discharge is required.

THEORY OF OIL-WATER SEPARATION

Separation of oil and water is different than the settling separation of solids in a clarifier. Oil droplets coalesce into larger, spherical droplets, while solids agglomerate into larger masses but do not coalesce into particles that have lower surface/volume ratios like oil.

Settling of Solids Particles

The settling solid particles in a clarifier, whether primary or secondary, is governed by Stokes's Law. This function, simply stated, is (Perry, 1963):

$$V_p = \frac{G}{18 \times \eta} \times (d_p - d_a) \times D^2$$

Where: Vp = particle rising or settling velocity, cm/sec

G = gravitational constant, 980 cm/sec^2

η = absolute viscosity of continuous fluid, poise

d_p = density of particle (or droplet), gm/cm^2

d_o = density of continuous fluid, gm/cm^2

D = diameter of particle, cm

A negative velocity is referred to as the particle (or droplet) rise velocity. Assumptions Stokes made in this calculation are:

1) Particles are spherical
2) Particles are the same size
3) Flow is laminar, both horizontally and vertically

From the above equation it may be seen that the most important variables are the viscosity of the continuous liquid, specific gravity difference between the continuous liquid and the particle, and the particle size. After these are known, the settling velocity and therefore the size of clarifier required may be calculated.

The velocity cf settling or rising is dependent on the hydrodynamic drag exerted on the settling particle by the continuous fluid. This drag is dependent on the shape of the particle as well as the viscosity of the continuous fluid. This is the same sort of situation that is found in other cases where a falling object has a high surface area/mass ratio. In a vacuum, a feather falls at the same rate as a lead ball. In air or any other resistant media the ball will fall faster due to the air resistance. The same sort of phenomenon governs the settling of solid particles in a clarifier or other liquid-containing vessel. They do not perfectly obey Stokes's Law because of their particle shape.

The pure Stokes's Law calculation depends on knowing the particle size and assuming that it does not change. Solid particles do, however, flocculate into larger particles of irregular shape that settle somewhat like snowflakes. An example of the problems that can be caused by the surface area/volume ratio is the poor settling of "pinpoint" flocs in secondary clarifiers (Montgomery, 1981).

The use of Stokes's Law described above is a very simplified version of the calculations required for determining clarifier sizing. More rigorous calculations are required to take care of such functions as hindered settling. These calculations are treated extensively in Montgomery (1981).

Rising of Oil Droplets

The rise rate of oil droplets is also governed by Stokes's law. If the droplet size, specific gravity, and continuous liquid viscosity are known, the rise rate and therefore the required vessel size may be calculated. Some typical rise velocities for different size and specific gravity droplets as calculated according to Stokes's Law are shown in Table 1 below.

TABLE 1

RISE VELOCITIES OF TYPICAL OIL DROPLETS

(inches per minute @ 68 Degrees F.)

Droplet Diameter,	Droplet Specific	Droplet Specific
10	0.0193	0.0129
20	0.0772	0.0514
30	0.1736	0.1157
40	0.3087	0.2058
50	0.4823	0.3215
60	0.6945	0.4630
90	1.5625	1.0417
150	4.340	2.894
300	17.361	11.575

(Facet International Environmental Products Catalog, 1992)

To calculate the size of an empty-vessel gravity separator, it is first necessary to calculate by the use of Stokes's Law the rise velocity of the oil droplets. The size of the separator is then calculated by considering the path of a droplet entering at the bottom of one end of the separator and exiting from the other end of the separator. Sufficient volume must be provided in the separator so that the oil droplet entering the separator at the bottom of the separator has time to rise to the surface before the water carrying the droplet exits the opposite end of the separator.

Calculation of rise rate by this method is a gross simplification of actual conditions because oil droplets are not all the same size, and they tend to coalesce into larger droplets. Large droplets exhibit trailing tails much like raindrops. The tails are due to the droplet being distorted by the hydrodynamic drag noted above.

Droplet rise follows Stokes's law so long as laminar flow conditions prevail. Laminar flow regimes (in the direction of rise) prevail with small droplets. The rise rate of larger droplets may exceed the velocity of laminar flow, in which case flow begins to be turbulent. Particles of this size and larger do not rise as rapidly as would be expected from calculations based on Stokes's law. When the droplets coalesce, they do not form flocs as the solid particles do, but become larger droplets. Interfacial tension (sometimes referred to as surface tension) of the liquid tends to make the droplets assume spherical shapes since this is the smallest possible shape for a given mass.

The Stokes's Law calculation is accurate for oil drop rise in the same way that it is accurate for solids settling - only if the particle size and continuous liquid viscosity are accurately known. The problems with this calculation are therefore:

1. What is the particle size?
2. What is viscosity of the continuous liquid?

The viscosity of the continuous liquid is readily obtained from literature data. The design of such separators usually requires design over a wide variety of temperatures (and therefore viscosities) to account for summer and winter conditions as well as possible process upsets, so several viscosities may be considered during design.

The oil droplet size, however, is much more difficult to determine. Particle sizes of solid particles are fairly easy to determine in the laboratory, but oil droplet size information is much more difficult to obtain. One tedious way to determine oil droplet sizes is to take a microscopic photograph of droplets in water and count the various size droplets. Other methods have been used with varying success, as noted by Rommel, et al (1992) and Au, et al. (1992). These include use of particle counters such as electric sensing zone particle counters.

It might be possible, with ultrasonic or other methods of dispersion, to generate quantities of oil droplets of generally equal size, but the droplets encountered in normal field operation vary widely in size from particles less than 5 microns (cited in Romano, 1990) to the great quantities of oil found in major oil spills like that caused by the grounding of the *Exxon Valdez*.

If the droplet size is not known, or a large range of droplet sizes is present (the normal situation), how then is it possible to determine the rise rates of the droplets and therefore the size separator required? Because the volume of oil in a droplet is proportional to the cube of the diameter, it follows that very small droplets contain extraordinarily small quantities of oil. This project will only be concerned with the examination of oil droplets large enough that, if a number are present, the quantity of oil represented by the droplets may cause environmental problems if discharged into surface or subsurface waters. In order to minimize the possibility of such discharge, it is wise to proceed carefully and cautiously in the design of oil-water separator systems.

Considerations for the Selection and Design of Oil-Water Separator Systems

General Design Considerations

Numerous factors must be considered in the selection and design of oil-water separation systems. Among these are (Facet Coalescing Plate Separator Manual, 1989):

1. flow rate and conditions;
2. degree of separation required - effluent quality;
3. amount of oil in the water;
4. existing equipment;
5. emulsification of the oil;
6. treated water facilities; and
7. recovered oil disposal method.

For industrial and some municipal applications, flow rate, amount of oil, flowing temperature, and other conditions affecting separation such as whether flow is laminar or turbulent may be easily determined. For storm water applications, however, it may be necessary to estimate water flow quantities. The degree of separation required is usually a matter of statutory or regulatory requirements, but if the water is discharged to a POTW or industrial treatment plant it may be negotiable. The amount of oil in the water may be known, especially in industrial applications, but it will often be necessary to estimate the quantity in storm water applications. Equipment manufacturers can provide guidance about quantities to be expected, and some information has been published about storm water quality (Hunter, et al., 1979, Hoffman, et al., 1982, Wakeham, 1977, and Stenstrom, et al., 1984). Existing equipment such as API separators may affect the design of equipment to be used. Often it is possible to retro-fit existing equipment with more sophisticated internals to enhance separation quality. The degree of emulsification of the oil is difficult to assess, but steps can be taken to discourage the formation of emulsions and encourage the breakup of emulsions that are inadvertently created. It may be necessary to substitute quick-break detergents for conventional detergents that are also emulsion causing. Quick-break detergents are those detergents designed to remove the oil (or grease) from the item to be cleaned and then quickly dissociate again from the oil, leaving the oil as free hydrocarbon droplets in the water. It is necessary to ensure that adequate size piping is provided for downstream treated water removal to avoid flooding the separator and perhaps filling the oil reservoir with water.

A downstream test point should be provided to allow for effluent testing. Adequate storage facilities for the removed oil should be provided and means for recycling the oil included. Careful records of removed and recycled oil should be kept to avoid possible future regulatory problems.

The following is a discussion of several of the points touched briefly on above concerning design of oil-water separation systems.

Emulsions and their Properties

An emulsion is a mechanical mixture, not a solution, consisting of droplets of one immiscible fluid dispersed in another continuous fluid. A good definition, offered by Love (1948), is: "An emulsion is an apparently homogenous mixture in which one liquid is dispersed as droplets throughout a second immiscible liquid." In the case of water and oil, two types of emulsion are common, depending on which is the continuous phase (Love, 1948).

1. Oil in water emulsions.
2. Water in oil emulsions.

A third type, water in oil in water, is possible but very uncommon.

Many emulsions will separate by gravity if given the necessary time, however some are so thoroughly combined that they will virtually never separate if undisturbed. Examples of this type emulsion occur in oil field and chemical waste products (Love, 1948).

The property describing the separability of emulsions is referred to as the stability of the emulsion. Very resistant emulsions are referred to as "tight" emulsions. Several factors affect the stability of emulsions (Love, 1948):

1. the emulsifying agent;
2. the viscosity of the continuous phase;
3. the differential specific gravity of the two phases;
4. percentages of the two phases; and
5. age of the emulsion.

Often, the major influence on the stability of emulsions is the emulsifying agent. The substance that holds two immiscible fluids bound tightly together is an emulsifying agent (Woodruff, 1962). Emulsifying agents include surfactants, (both natural and artificial), iron oxide, iron sulfide, paraffins in the oil, bacteria, and dirt (Woodruff, 1962).

Bacterial growth and emulsions seem to be linked. Green and Trett (1989) note that, in a study of growth of freshwater bacteria on hydrocarbons, emulsification of the hydrocarbons was found in every case where bacterial growth occurred. Bacteria which could not produce extracellular emulsifying agents were not capable of growth utilizing a crude oil substrate.

The separation properties of the emulsion also depend greatly on the viscosity of the continuous phase. In oil-water separation, this is usually the water phase. Bansbach (1970) notes that the viscosity of the continuous phase plays a dual role:

a) In a low temperature (and therefore relatively high viscosity) environment, a given amount of agitation will not break up the oil phase into droplets as numerous or as fine as in the case of a higher temperature, lower relative viscosity system.

b) Viscous continuous phase liquids hinder the separation of the mixture because the droplets must overcome more viscous drag in their journey to the top of the mixture.

The viscosity of the oil phase also has an effect on the emulsion in that higher viscosity oils retard the movement of emulsificant to the surface of the droplets. This retards the aging effect on the stability of the emulsion, thus making the emulsion easier to treat (Bansbach, 1970). If the specific gravity of the oil is very close to that of the water, then there is little gravitational driving force for separation of the emulsion.

Temperature has a dual effect on settling rate: in addition to affecting the viscosity as noted above, it also affects the differential specific gravity (Love, 1948). It is also believed that as temperature increases, the resulting expansion of the oil drops causes stress on the film of the emulsificant and at high temperature may cause it to rupture (Bansbach, 1970).

Age of the emulsion seems at first glance to be a property that would not be expected to make a difference to the stability of the emulsion. As an emulsion ages, the surface-active agent (surfactant) which causes the emulsion tends to migrate to the interface. The surfactant concentrates more and more at the interface between the oil and water, thus strengthening this interface (Bansbach, 1970). It is preferable to separate the oil and water at the earliest possible moment to avoid this problem. For this reason, it is often best to provide on-line oil water separators instead of collecting the oil-water emulsion and treating it batch-wise.

Influent Conditions and Feed Stream

Much of the performance of an oil-water separator depends on the influent conditions (Woodruff, 1962). Because smaller droplets are more difficult to separate, equipment or conditions that form small droplets in the influent to the oil-water separator will cause the separator to be larger so as to accommodate the additional time required for the smaller droplets to coalesce.

Conditions that form small droplets are any conditions that cause shear in the incoming water. The following are (more or less in order of severity) some factors that can cause small droplet sizes (Facet Environmental Products Catalog, 1992):

1. pumps, especially centrifugal pumps;

2. valves, especially globe valves;
3. other restrictions in flow such as elbows, tees, other fittings, or simply unduly small line sizes; and,
4. vertical piping (horizontal is better).

Emulsifying agents as discussed elsewhere in this paper greatly contribute to small droplet sizes in addition to discouraging coalescence.

From the above, it may be inferred that to encourage good oil-water separation, good inlet conditions for an oil-water separator would be:

1. gravity flow (not pumped) in the inlet piping;
2. inlet piping sized for minimum pressure drop;
3. inlet piping straight for at least ten pipe diameters upstream of the separator (directly into nozzle); and,
4. inlet piping containing a minimum of elbows, tees, valves, and other fittings.

Most separators are provided with an inlet elbow or tee inside the separator pointing down. This is an exception to the above rules and is intended to introduce the influent water below the oil layer on the surface, thus not disturbing the surface oil and re-entraining some of it.

While gravity flow conditions are not often obtained except in POTWs, storm water, or some process water applications, a positive displacement pump such as a progressive cavity type pump may be used as they provide minimum disturbance of the fluid.

Inlet piping should be as smooth as possible to avoid turbulence caused by pipe roughness. Smooth PVC is preferable to rough concrete.

Effluent Conditions

Effluent designs are also important in the operation of oil-water separators (Facet Coalescing Plate Separator Manual, 1989). Downstream piping and other facilities must be adequately sized to process the quantity of water (and oil) from any likely event.

Effluent piping must be designed with siphon breaks so that it is not possible to siphon oil and water out of the separator during low flow conditions. One way to do this is to provide the sampling/overflow tee in the effluent line as shown in Figure 1 (Romano, 1990). One problem that can occur if the effluent arrangements are not properly designed is that a vortex from the effluent pipe can "reach up" to the interface and cause discharge of oily effluent water even if the interface is clear (Bansbach, 1970). Oil must be removed manually from spill control separators by a maintenance crew equipped with a vacuum truck or other equipment for oil removal. If this is not done on a regular basis, this oil may become re-entrained at the next rainfall event and reintroduced into the environment (Romano, 1990).

CHAPTER III

METHODS AND MATERIALS

General Experimental Procedures and Equipment

Testing of the plates was done utilizing a prototype oil-water separator known as the HEROWS unit. HEROWS is an acronym for High Efficiency Round Oil Water Separator. The HEROWS unit was originally designed to process a flow of twenty (20) gpm of oily water with an inlet concentration of two thousand (2000) ppm of diesel fuel (specific gravity: 0.85) at sixty (60) degrees Fahrenheit. Design water effluent quality was to be fifteen (15) ppm oil or less. Water content of the recovered oil was not considered in the design, although a minimum water content is desirable.

This vessel is constructed of carbon steel, forty-two inches (42") inside diameter and twenty-five inches (25") high. The vessel is provided with a three inch (3") pipe size inlet and outlet. Figure 6 (page 22) contains an outline drawing showing the flow scheme of the unit. The vessel is provided with an inlet elbow directed down to introduce the flow below the surface. Both a pre-separation chamber and an inlet chamber are provided prior to the plate section. Two chambers are provided so as to make the maximum possible use of the space available in a cylindrical unit. In the plate section, two identical packs of thirty one (31) multiple angle separating plates are provided. A drawing of the plate packs used in this unit is shown in Figure 7 (page 24). These plates are also known as "M" plates after the general shape of the end of the plates and the system is referred to as "MPaks". The plates and plate supports are proprietary parts, patented by Facet International, Inc., and manufactured by Facet for use in oil-water separators. MPak is a trademark of Facet International, Inc. Flow baffles and an outlet underflow/overflow weir are provided to direct the water flow.

Testing was performed to determine removal of oil-type contaminants as well as solids contaminants. Testing was also performed to determine the best method of cleaning solids out of the packs. Properties of the test hydrocarbon contaminants are shown in Table 2 and a definition of "Navy Mix" is provided in the notes for Table 2.

TABLE 2

PROPERTIES OF TEST HYDROCARBON CONTAMINANTS

CONTAMINANT	SPECIFIC GRAVITY
No. 2 Diesel Fuel (Commercial Grade)	0.85 @ 60°F
Lubricating Oil (1)	0.91 @ 60°F
"Navy Mix" (2)	0.87 @ 60°F (freshly mixed) 0.875 @ 60°F (after circulation)

Notes:

1) Lubricating oil used was a non-detergent lubricating oil blending stock.

2) "Navy Mix" is a mixture intended to simulate the hydrocarbon contaminants found in the bilges of Naval vessels. It consists of the following:

Navy Lubricating oil MIL-L-9000 (9250)	25%
Navy Lubricating oil MIL-L-17331 (2190)	25%
#2 Marine Diesel Oil (MDO)	50%

(Commercial #2 Diesel fuel was substituted for MDO)

Lubricating oil 9250 (MIL-L-9000) absorbs water and forms a tight emulsion that is difficult to separate.

Properties of AC Test solid contaminant are provided in Table 3. AC Test solid contaminant is a proprietary mixture of size-graded dust that is made for testing filters by the AC Spark Plug Company.

Piping and tanks were provided for mixing the oil and water and subsequently introducing it to the unit. The oil

TABLE 3

AC COALESCER TEST SOLID CONTAMINANT SPECIFICATION

MICRON SIZE RANGE	PERCENT IN RANGE	CUMULATIVE TOTAL, PERCENT SMALLER THAN UPPER LIMIT
125-176	3.6	100
88-125	14.3	96.3
62-88	14.2	81.9
44-62	12.1	67.6
31-44	11.1	55.5
22-31	8.9	44.4
16-22	7.0	35.5
11-16	5.1	28.4
7.8-11	4.6	23.2
5.5-7.8	3.7	18.6
3.9-5.5	4.6	14.8
2.8-3.9	4.0	10.1
<2.8	6.0	6.0

Notes: 1) Above specification for test dust provided by vendor, AC Spark Plug Co.
2) Testing was conducted using a mixture of garden dirt and the above described dust.
3) Information in this table included to indicate that many small particles were provided in the test contaminant, and is not necessarily representative of all solid particles employed in test. Information on solid particle sizes in the mixture of garden dirt and test dust used for testing is provided in the Results section in Table 9.

removal test schematic is shown in Figure 10. The fresh water tank is a carbon steel vertical tank of approximately 110 gallons capacity, with the water supply replenished from the City of Tulsa supply via a float-actuated valve. The water supply pump is a standard centrifugal pump, electrically driven. It is a Gorman-Rupp Model 8 13 x .5 3P with a 1/4 hp motor. A flow switch was provided to prevent damage to the pump in the event of failure of the city water supply. The water flow meter used was a Brooks Model 13-1110-10 rotameter type. Oil supply was from a 50 gallon capacity aluminum tank. The oil pump was a Roper Model 71201 GHL Type J positive displacement pump. The oil and water streams were blended prior to introduction into the HEROWS unit. Inlet and outlet sampling pitot tubes were provided.

Tests were performed in a manner intended to simulate gravity flow of oily water by introducing the oil downstream of the water pump. This testing was performed generally per the U.S. Coast Guard procedure for testing oil/water separators, found in the *Code of Federal Regulations:* 46CFR 162.050-17. Different inlet mixing pipe sizes (determined per the Coast Guard procedure) were provided. Various mixing pipes were used during testing to provide different inlet Reynolds numbers. Descriptions of the mixing pipes used, with the corresponding Reynolds numbers are shown in Table 4. Reynolds numbers were calculated per the following (McCabe and Smith, 1967):

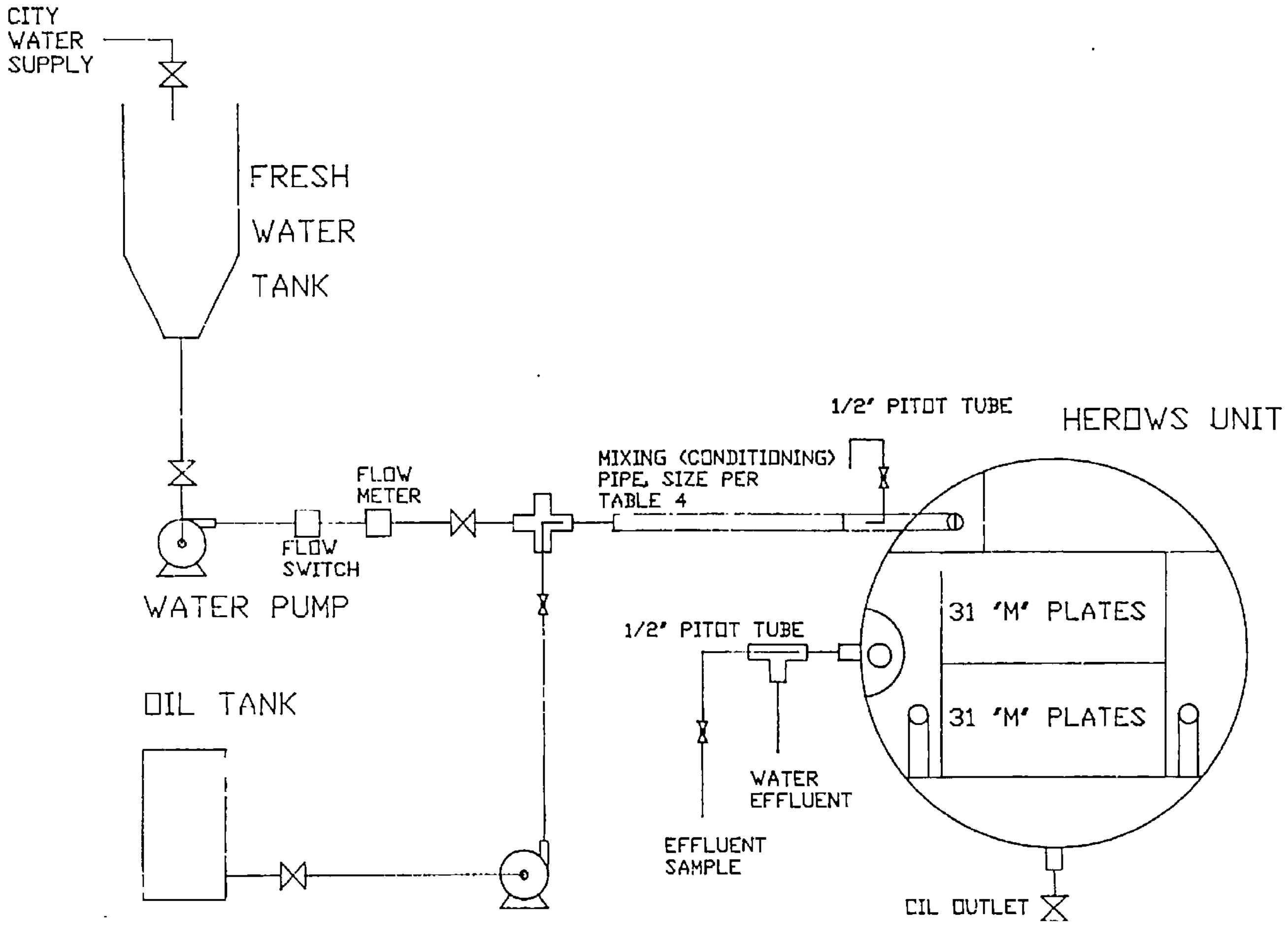


Figure 10. Schematic of Flows During Oil Removal Testing

$$N_{Re} = \frac{DV\rho}{\mu}$$

Where: D = Diameter of pipe, m

V = Average linear velocity of fluid, m/sec

ρ = Density of fluid, g/m^3

μ = Viscosity of fluid, centipoise

Other consistent sets of units may be used as well.

Single samples of outlet water were taken at intervals for analysis for hydrocarbon content. Inlet samples were not taken due to the difficulty in taking accurate samples at the relatively high concentrations of oil in the inlet. For this reason, concentrations in the inlet were calculated from the inlet oil and water flows. Some tests were conducted for solids removal capability determination. In the solids removal tests, samples were taken of both inlet and outlet water for solid content and particle size analysis. The solid particles do not present the same problems in sampling that oil does as they do not coalesce as the oil does. Testing for oil removal, solids removal, solids deposition and the ability to clean solids from partially plugged packs were performed. Detailed descriptions of testing, sampling, and analyses are provided below.

Analysis of oil content in the water samples was completed using a Perkin-Elmer Model 1605 FT-1R infrared spectrophotometric analyzer. Analysis of solids removal samples was completed by gravimetric methods as well as a

TABLE 4

INLET MIXING (CONDITIONING) PIPES USED FOR FLOW TESTING

PIPE NO./ NOM. FLOW	PIPE SIZE IN.	ID. IN.	LENGTH IN	REYNOLDS NUMBERS AT VARIOUS FLOW RATES							
				15 GPM	20 GPM	25 GPM	30 GPM	35 GPM	40 GPM	45 GPM	45 GPM
1/15	1.25	1.380	27.6	30500			61000				
2/20	1.5	1.610	32.2		34900		52400				
3/25	2.5	1.661	35.4			39700	47600				
4/30	2.0	1.939	38.8				43500	50800	58000	65200	72400
5/10	1.5	1.100	22.0				76600				

Notes:
1. Reynolds Numbers only shown for combinations of pipe size and flow rates actually used for testing.
2. Pipe sizes shown are nominal. Different wall thicknesses were chosen to provide the appropriate Reynolds Numbers.
3. Reynolds Numbers calculated at water viscosity of 1.125 Centistokes (approximately 60 degrees F.).

Coulter Model TA II Particle counter. Sample analyses are discussed further in Analytical Methods Section below.

Oil-Water Separation Testing

Testing was performed using mixtures of water and (1) Diesel fuel, (2) Lubricating Oil, and (3) "Navy Mix". "Navy Mix" is a special mixture of two lubricating oils and diesel fuel intended to simulate the oily water mixture found in the bilges of a Navy ship. The operating conditions and results of these tests are shown in Tables 5-7 in the Results and Discussion section below.

The purpose of this part of the testing was to determine the optimum flow rate for the vessel-plate system as defined by the oil removal capabilities of the system. Water flow through the unit was on a once-through basis while oil was collected for reuse. All samples were taken in glass bottles and were approximately 1 liter each. Single samples were taken at approximately 20 minute intervals as detailed below. Water volumetric capacity of the test unit is about 110 gallons, and most tests were completed at 30 gpm water rate. This provided throughput of approximately four hydraulic retention times of the unit between samples at 30 gpm flow. At the lower flows tested, the throughput ranged as low as approximately 1.8 retention times (at 10 gpm).

Test Procedure for Oil Removal Testing (Generalized):

1. Install appropriate mixing pipe,
2. Set water flow rate,
3. Adjust water underflow/overflow weir and oil skimmers,
4. Set oil injection flow rate to equal 5% of inlet water flow. Inject at this rate for 15 minutes to allow system to stabilize,
5. Reduce oil injection rate to 1000 ppm and inject at this rate for 15 minutes or until system stabilizes,
6. Operate at this rate for one hour, taking effluent samples at twenty minutes, forty minutes, and sixty minutes,
7. Stop oil injection and operate for 15 minutes,
8. Set oil injection rate to 5000 ppm and operate for one hour, taking effluent samples at twenty minutes, forty minutes, and sixty minutes,
9. Stop oil injection and operate for 15 minutes,
10. Set oil injection rate at 10000 ppm (1%) and operate for one hour, taking effluent samples at twenty minutes, forty minutes, and sixty minutes,
11. Stop oil injection and operate for 15 minutes.
12. Set oil injection rate at 50000 ppm (5%) and operate for one hour, taking effluent samples at twenty minutes, forty minutes, and sixty minutes,
13. Stop oil injection and operate for 15 minutes, then

secure the system; and,

14. Analyze samples per the EPA test procedure (contained in 46CFR162.050-017) to determine the oil content. Samples were preserved with NaCl and HCl per ASTM Method number ASTM-D-3414-79 and refrigerated until analyses could be completed.

The above steps were repeated for different flow rates and different hydrocarbon contaminants.

Solids Removal Testing

Testing was performed using AC Filter test dust in combination with garden dirt injected into the inlet water. An automatic continuous solids feeder (BIF Manufacturing Model BM-A-613892), an approximately 50 gallon mix tank, and a continuous mixing/agitation (Lightnin Mixers Model L) system were provided. A schematic showing the arrangement of equipment used for solids removal testing is provided in Figure 11. Both inlet and outlet solid particle concentrations and flow rates are shown in the Results section in Table 8. Particle distributions of both inlet and outlet streams are presented in the Results section in Table 9.

The following steps were followed when performing the solids removal tests:

1. The mixing pipe sized for 30 gpm was installed,

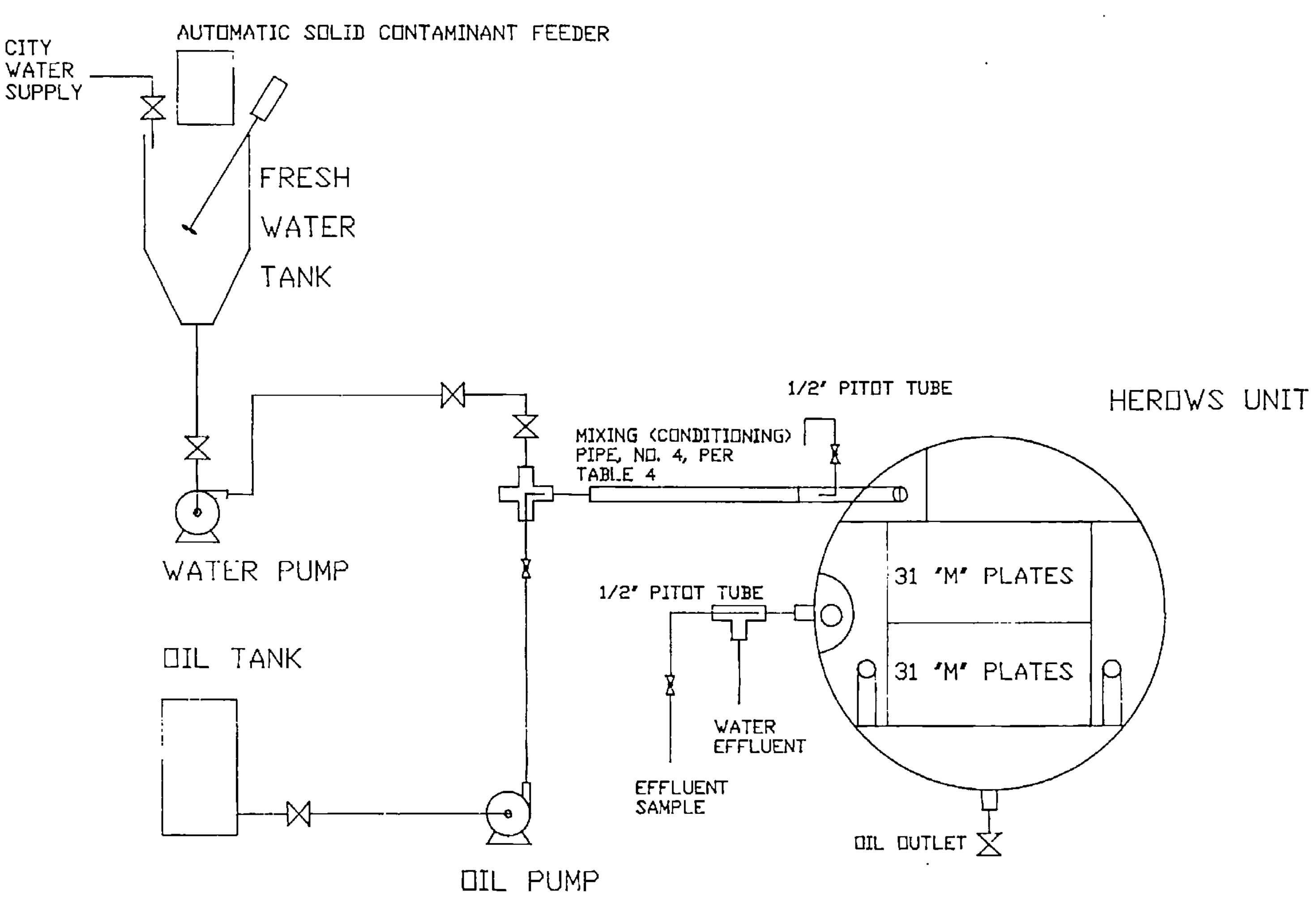


Figure 11. Schematic of Flows During Solids Removal Testing

2. Operate unit on clean water at 15 gpm flow rate for 15 minutes prior to injection of solids,
3. Inject 500 mg/l solids with approximately 75 ppm of diesel fuel for 30 minutes, take a 1 liter sample of influent and a 1 liter sample of effluent water,
4. Increase solids injection to 1,000 mg/l (with 75 ppm diesel fuel) and operate for 30 minutes. Sample influent and effluent again,
5. Stop solids injection and operate the separator for 30 minutes,
6. Drain and flush separator, washing down inside of separator with clean water,
7. Restart flow and operate at 30 gpm on clean water for 15 minutes,
8. Inject 500 mg/l solids with 75 ppm diesel fuel for 30 minutes. Sample influent and effluent, same as step 3 above,
9. Increase solids injection to 1,000 mg/l with 75 ppm oil and operate for 30 minutes. Sample influent and effluent,
10. Stop solids injection and operate the separator for 30 minutes,
11. Drain and flush separator, washing down inside of separator with clean water,
12. Install solids dam on top of packs,
13. Restart flow and operate on clean water for 15

minutes at 30 gpm flow rate,

14. Inject 1000 mg/l solids with 75 ppm diesel fuel for 30 minutes. Sample influent and effluent, same as step 3 above,
15. Install mixers in inlet chamber (two Lightnin Model L),
16. Inject 1000 mg/l solids with 75 ppm diesel fuel for 30 minutes. Sample influent and effluent, same as step 3 above,
17. Stop solids injection and operate the separator for 30 minutes,
18. Drain and flush separator, washing down inside of separator with clean water,
19. Analyze for solids content of solids samples; and,
20. Determine particle size distribution of effluent solids samples.

Solids Deposition Testing

Testing was performed using mixtures of AC Filter test dust and Oklahoma garden dirt procured locally, suspended in the inlet water in the same manner as the solids removal testing, but mixed with 5000 ppm of lubricating oil instead of 75 ppm of diesel fuel. This mixture was agitated and the resulting suspension processed through the separator. Two propeller type mixers (Lightnin Mixer Model L) were provided in the pre-separation chamber to attempt to retain the solids in suspension.

Testing was performed with both oil and solids injected into the inlet water simultaneously. The following steps were followed when conducting this series of tests:

1. The mixing pipe sized for 30 gpm was installed along with two mixers in the inlet chamber,
2. Unit was operated in gravity flow mode for 15 minutes prior to injection of oil and solids. This procedure was used to ensure stabilization of the flow patterns and water level,
3. Lubricating oil at 5,000 ppm and solids at approximately 1,000 mg/l were injected into the water flow,
4. The deposition test was to continue until either:
    a) Effluent oil greater than 15 ppm
    b) Plate packs plug
    c) One week of solids injection

    (Testing was actually stopped when plate packs became partially plugged, not at any of the intended stopping conditions.)
5. After securing the test, the water was drained slowly so that solids accumulations would not be disturbed; and,
6. Inspect the system to determine where solids accumulations occur and develop a plan for removal of solids.

Solids Cleaning Testing

After deposit of solids by the above procedure, cleaning methods were tested using the procedure as follows:

a) Cleaning using city water pressure (approximately 60 psig) and a cleaning wand consisting of a 14" length of 1/4" stainless steel tubing, open at the end. The wand was provided with a valve to start and stop the water flow. A positive displacement "Sandpiper" pump was provided for removal of the solids (along with some water) after they had been fluidized by the cleaning process. Solids were captured for re-use later in the test sequence. The specifics for using this cleaning wand are:

1. Using the cleaning wand, fluidize the dirt in the pre-separation chamber and inlet chamber and draw it out with the pump,
2. Insert the wand in one of the cleaning holes in the row nearest the inlet of the pack. Start water flow through the wand to begin moving the solids out of the inlet end of the pack into the inlet chamber where the pump could remove them,
3. Push the wand gently down into the cleaning hole until it reaches bottom, maintaining water flow through the wand. Move the wand up and

down through the hole to ensure that the plates in the vicinity of the hole are thoroughly cleaned,

4. Move the wand to another cleaning hole in the same row and repeat the process; and,
5. Continue cleaning the area served by each hole in turn until the entire pack area has been cleaned of solids.

b) Cleaning of the plate packs utilizing city water pressure and a modified cleaning wand, revised so that the cleaning jet projected at right angles to the tubing. This was intended to direct the water flow between the plates for more effective dirt removal.

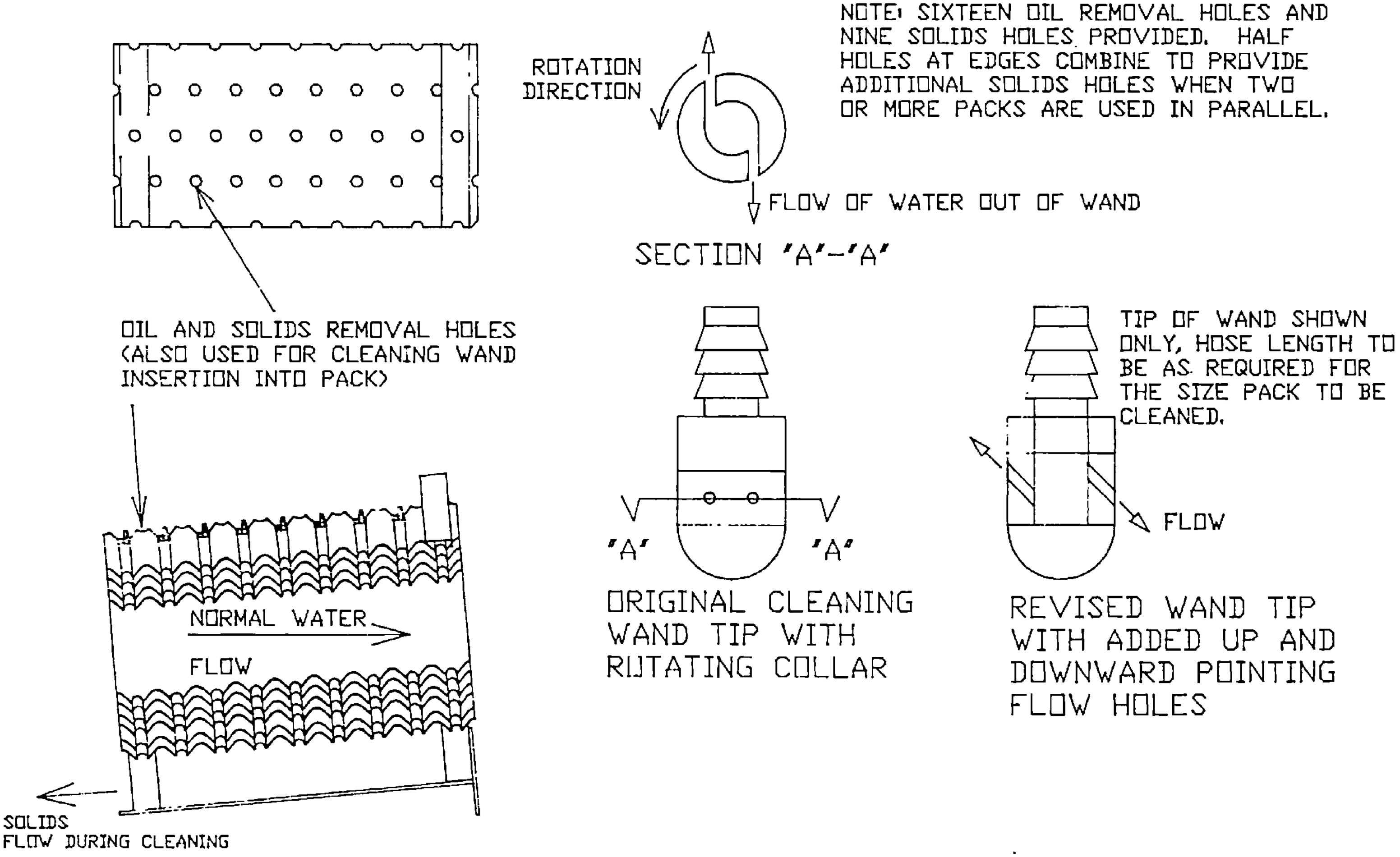
The system was again loaded with dirt by operation of the system to deposit additional dirt and steps 1-5 above were repeated.

Because it was noted that solids fluidized in the pack had a tendency to settle again within the pack, the outlet end of the test separator was elevated two inches (2"). It was thought that this would "encourage" the solids to flow back to the inlet end where they would be removed by the Sandpiper pump.

c) Cleaning of the plate packs utilizing a flexible hose-type cleaning wand with a rotating collar that directs cleaning water flow in a radial pattern as well axially was tested to determine its effectiveness. Flow of the water, directed tangentially by the holes in the collar caused the collar to rotate rapidly, thus directing water in a radial pattern. This was intended to enhance the cleaning effect by loosening dirt in all directions, not merely in the direction of the jet utilized in b) above. Figure 12 shows the oil and solids removal holes in the plates as well as a sketch of the cleaning wand tip.

The system was again loaded with dirt (by deposition) and steps 1-5 above were again repeated. Because of mechanical problems with the wand's rotating collar, the test was stopped before the unit was entirely cleaned. It was also determined that the holes in the wand were not large enough to provide sufficient water flow for cleaning. The separator was not entirely cleaned at this time.

The flexible cleaning wand was then modified by the addition of jets pointing both up and down at forty-five (45) degree angles in addition to the tangential jets. Larger holes were provided in the wand for additional water flow to provide better cleaning. Steps 1-5 above were repeated and the cleaning of the separator was completed. Figure 12 also includes a sketch of the revised wand with upward and downward pointing holes.



NOTE: SIXTEEN OIL REMOVAL HOLES AND NINE SOLIDS HOLES PROVIDED. HALF HOLES AT EDGES COMBINE TO PROVIDE ADDITIONAL SOLIDS HOLES WHEN TWO OR MORE PACKS ARE USED IN PARALLEL.

TIP OF WAND SHOWN ONLY, HOSE LENGTH TO BE AS REQUIRED FOR THE SIZE PACK TO BE CLEANED.

ORIGINAL CLEANING WAND TIP WITH ROTATING COLLAR

REVISED WAND TIP WITH ADDED UP AND DOWNWARD POINTING FLOW HOLES

Figure 12. MPak Cleaning Wand and Cleaning Diagram

Analytical Methods

Oil in water analyses were completed utilizing the Procedure for Oil in Water Analysis used by the United States Environmental Protection Agency; taken directly from the *Federal Register (September 13, 1979, pp. 53371-53374)*. This procedure is similar to the ASTM test procedure for oil in water analysis - ASTM-D3414-79. Samples were taken in new or cleaned bottles, with NaCl and HCl added in the same manner as ASTM D3414-79. Samples were refrigerated and subsequently analyzed using a Perkin-Elmer Model 1605 FT-1R Infrared spectrophotometer.

Solids Removal Efficiency Testing

Samples of both inlet and outlet water were taken per the procedure above. Removal efficiency was determined by gravimetric methods and particle size and removal efficiency determinations were performed using a Coulter Counter Model TA II particle counter. Solids analysis was completed according to ASTM-D2276-73, which is a gravimetric method utilizing vacuum filtration.

Particle size analyses for the inlet and outlet samples which were taken during solids testing were determined by use of a Coulter Counter Model TA II particle counter. A good description of the operation of this system is included in the equipment operating manual:

> "The COULTER COUNTER Model TA II determines the number and size of particles suspended in a conductive liquid by forcing the suspension to flow through a small aperture, and monitoring an electrical current which also passes through the aperture. Electrodes are immersed in the conductive fluid on opposite sides of the aperture.
>
> As a particle passes through the aperture, it changes the resistance between the electrodes. This produces a current pulse of short duration having a magnitude proportional to the particle volume. The series of pulses is electronically scaled and counted."

Particle size analyses were completed per the manufacturer's instructions. A short synopsis is provided below:

Solid particles recovered from the "determination of amount of solids" procedure described above are re-suspended in an isotonic saline solution and are placed in the instrument for analysis by the counter. Results from the counter are presented in sixteen (16) channels that show both counts of particles within the sixteen size ranges and a cumulative count. Both numbers of particles and mass of particles are included as percentages of the total. No analyses were performed during solids cleaning tests.

CHAPTER IV

RESULTS AND DISCUSSION

Oil-Water Separation Tests

The primary purpose of the design of the "MPak" system was to provide quality separation of oil from water in a smaller, less expensive package than was previously available while at the same time offering guaranteed low oil content in the separator effluent. The system was designed with basic oil-water separation principles in mind:

1) Providing an area in the inlet portion of the separator for large oil droplets to disengage from the water before the contaminated water enters the packs.
2) Ensuring laminar flow and therefore the validity of Stokes's law in the plate pack section of the separator.
3) Ensuring that sufficient oil removal arrangements have been included.
4) Design of the outlet section of the separator is such that any residual oil not removed by the plate packs is not subsequently re-entrained and allowed to leave the separator through the water

outlet.

5) Ensuring that the solid particles so often associated with oily pollutants do not adversely affect the operation of the separator.

Three test hydrocarbon contaminants were utilized to simulate field operating conditions. Diesel fuel was used to simulate light hydrocarbons, "Navy Mix" was used to simulate medium gravity oils, and lubricating oil stock was used to simulate heavy oils. The properties of these contaminants were given in Table 2. Testing was done utilizing different diameter inlet pipes to simulate different inlet conditions of mixing. Reynolds numbers calculated for the different diameter mixing pipes were given in Table 4.

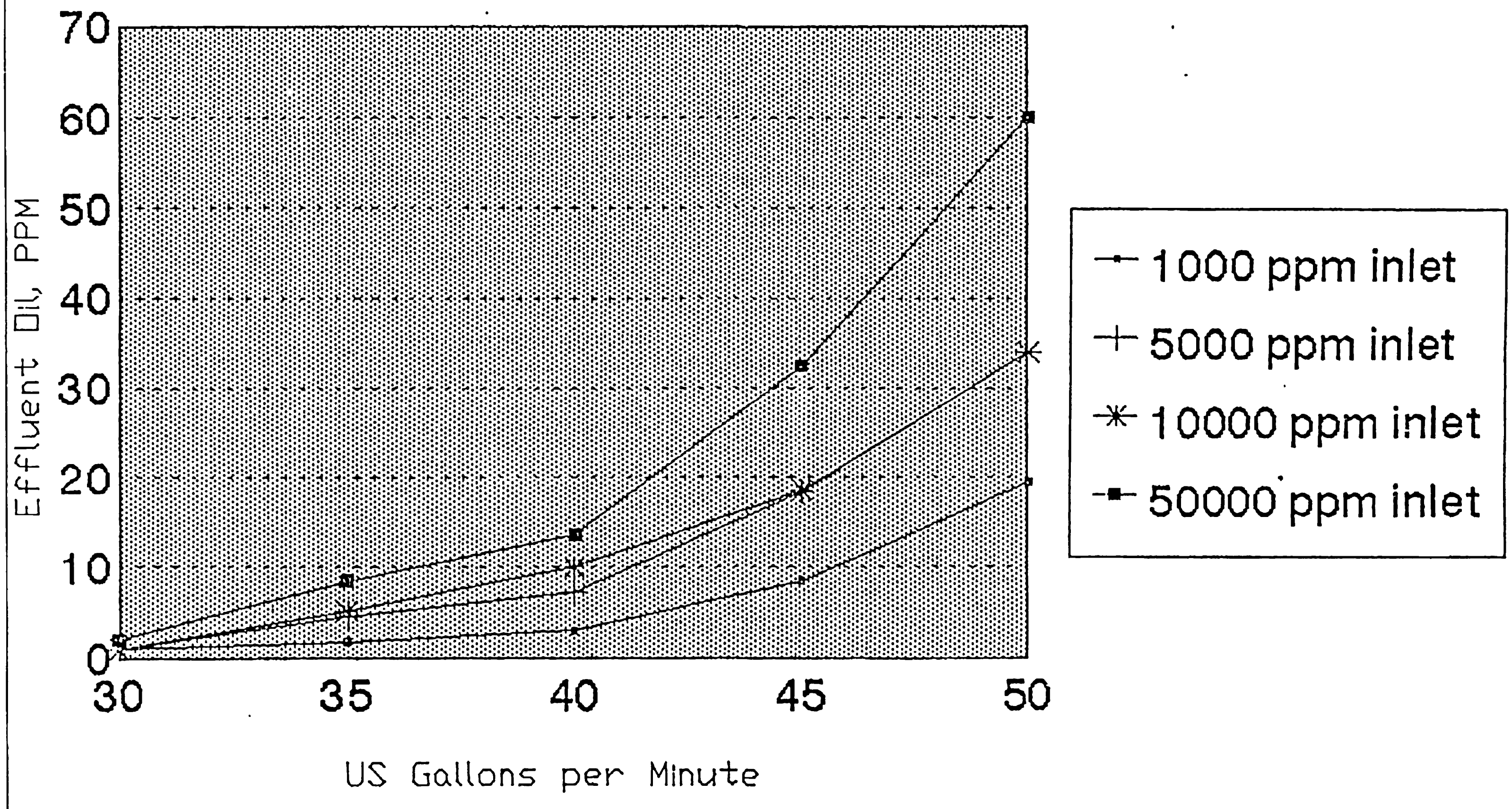
The initial run of tests was conducted using Diesel fuel. Tests indicated that, for flows up to 35 gallons per minute and at Reynolds numbers (in the mixing pipe) up to about 52,000, the effluent water contained less than 10 ppm of diesel fuel at all inlet quantities of contaminants. For flows up to 40 gallons per minute and inlet Reynolds numbers up to 58,000 the effluent water contained less than 15 ppm of Diesel fuel. At flows greater than 40 gpm or inlet Reynolds numbers greater than 61,000 the effluent contained greater than 15 ppm of Diesel fuel. In most locations this would not be acceptable, and some localities require less than 10 ppm. Results of this testing are summarized in Table 5 and shown graphically in Figure 13. The results

TABLE 5

TEST RESULTS:
TESTING WITH DIESEL FUEL UNDER GRAVITY FLOW CONDITIONS

TEST NO.	FLOW RATE GPM	INLET COND. PIPE NO. (4)	INLET VEL. FT/SEC	REYNOLDS NO.	EFFLUENT OIL CONTENT AT VARIOUS INLET CONCENTRATIONS			
					1,000 PPM INLET	5,000 PPM INLET	10,000 PPM INLET	50,000 PPM INLET
1	15	1	3.21	30500	<1	<1	<1	<1
2	20	2	3.15	34900	13.5	1.5	2.0	<1
3	25	3	3.25	39600	4.3	<1	<1	<1
4	30	4	3.25	43400	<1	<1	<1	2.0
5	35	4	3.79	50900	1.8	4.5	5.2	8.5
6	30	3	3.45	47600	<1	2.0	<1	3.5
7	30	2	3.80	52300	2.0	1.7	2.0	3.5
8	30	1	6.42	61000	2.5	4.4	6.4	22.7
9	50	5	10.12	76600	15.8	>40	>60	N/A(2)
10	35	4	3.79	50900	1.8	4.3	5.1	8.6
11	30	4	3.25	43400	<1	<1	<1	2.0
12	30	3	3.45	47600	<1	<1	<1	3.6
13	30	2	3.80	52400	1.9	1.9	2.0	3.8
14	30	1	6.42	61000	2.5	4.2	6.0	24.0
15	DATA LOST DUE TO INADVERTENT SAMPLE DESTRUCTION							
16	40	4	4.34	58000	3.0	7.3	10.0	13.6
17	45	4	4.88	65200	8.5	18.4	18.5	32.5
18	50	4	5.34	72400	19.5	34.0	34.0	50-60

Notes:
1. Tests 10-15 confirming tests for 4-9.
2. Test 9 terminated at 10,000 ppm as test results indicated much more hydrocarbon in outlet than would be acceptable. Testing not performed at 50,000 ppm.
3. Test numbers from original laboratory work - not renumbered.
4. See Table 4 for Conditioning pipe sizes.
5. Effluent sample taken at 1000 ppm inlet concentration in test 2 believed to be incorrect. This is possibly due to analytical error.



Note: Gravity flow through 62 'M' Plates @ 60 Deg. F., Conditioning Pipe #4.

Figure 13. Oil in Effluent, Contaminant: Diesel Fuel, S.G. = 0.85

indicate higher effluent oil contents at higher flow rates for the same influent oil content. They also show higher effluent oil contents at higher influent oil contents for the same flow rate. This is what might be expected under these circumstances because higher velocities would tend to carry more droplets through the plate area. Higher inlet concentrations would also be expected to produce higher outlet concentrations due to additional droplets in the water stream.

Testing was also conducted using a heavy lubricating oil of 0.91 specific gravity. Tests indicated that, for flows up to 40 gallons per minute and at Reynolds numbers (in the mixing pipe) up to 58,000 the effluent water contained significantly less than 10 ppm of hydrocarbons. At flows up to 50 gallons per minute and Reynolds numbers up to 72,400 the effluent water contained less than 15 ppm of hydrocarbons. Results of this testing are summarized in Table 6 and presented graphically in Figure 14. The data from the Lubricating oil testing are not as regular as that obtained for Diesel fuel and the "Navy Mix" (discussed below), but shows generally the same trends as the other hydrocarbons tested. It is believed that analysis problems may have caused the erratic behavior of the data points. The testing was not repeated, however, as all of the data points were below the 15 ppm maximum target.

Additional testing was conducted with "Navy Mix". Tests indicated that, for flows up to 40 gallons per minute

TABLE 6

TEST RESULTS: TESTING WITH LUBRICATING OIL UNDER GRAVITY FLOW CONDITIONS

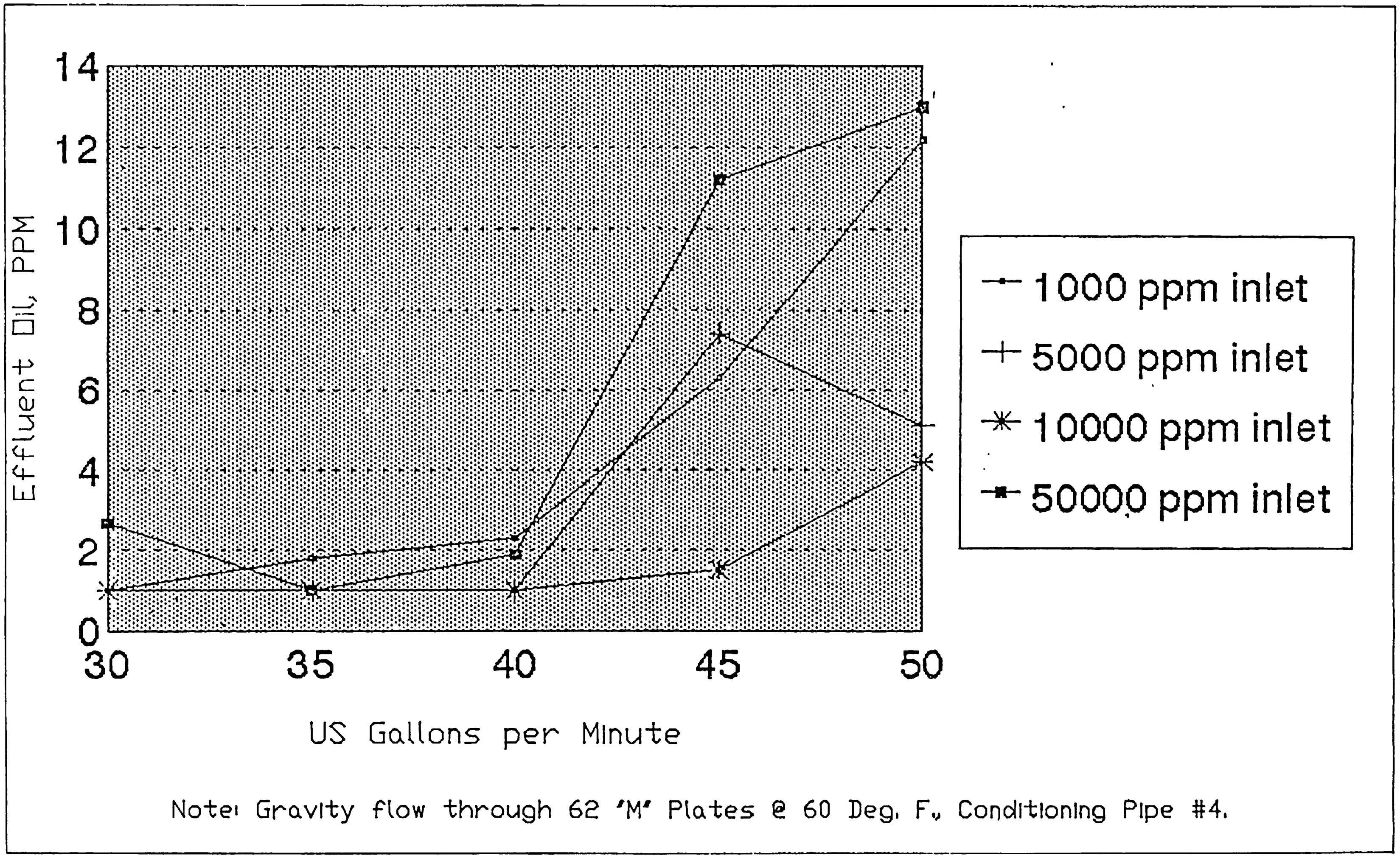
TEST NO.	FLOW RATE GPM	INLET COND. PIPE	INLET VEL. FT/SEC	REYNOLDS NO.	EFFLUENT OIL CONTENT AT VARIOUS INLET CONCENTRATIONS			
					1,000 PPM INLET	5,000 PPM INLET	10,000 PPM INLET	50,000 PPM INLET
3	30	4	3.25	43500	<1	<1	<1	2.7
4	35	4	3.79	50800	1.8	<1	<1	<1
5	40	4	4.34	58000	2.3	<1	<1	1.9
6	45	4	4.88	65200	6.3	7.4	1.5	11.2
7	50	4	12.2	72400	12.2	5.1	4.2	13.0

TABLE 7

TEST RESULTS: TESTING WITH "NAVY MIX" UNDER GRAVITY FLOW CONDITIONS

TEST NO.	FLOW RATE GPM	INLET COND. PIPE	INLET VEL. FT/SEC	REYNOLDS NO.	EFFLUENT OIL CONTENT AT VARIOUS INLET CONCENTRATIONS			
					1,000 PPM INLET	5,000 PPM INLET	10,000 PPM INLET	50,000 PPM INLET
1	25	4	2.7	36200	<1	<1	<1	<1
2	30	4	3.25	43500	<1	<1	1.4	2.0
3	35	4	3.79	50800	1.3	2.0	2.0	3.7
4	40	4	4.34	58000	2.7	5.5	7.4	10.5
5	45	4	4.88	65200	4.0	8.7	10.5	19.2
6	50	4	5.43	72400	7.0	17.5	21.0	41.0

Notes: 1. Test numbers from original laboratory work - not renumbered.
2. For conditioning pipe sizes, see Table 4.



Note: Gravity flow through 62 'M' Plates @ 60 Deg. F., Conditioning Pipe #4.

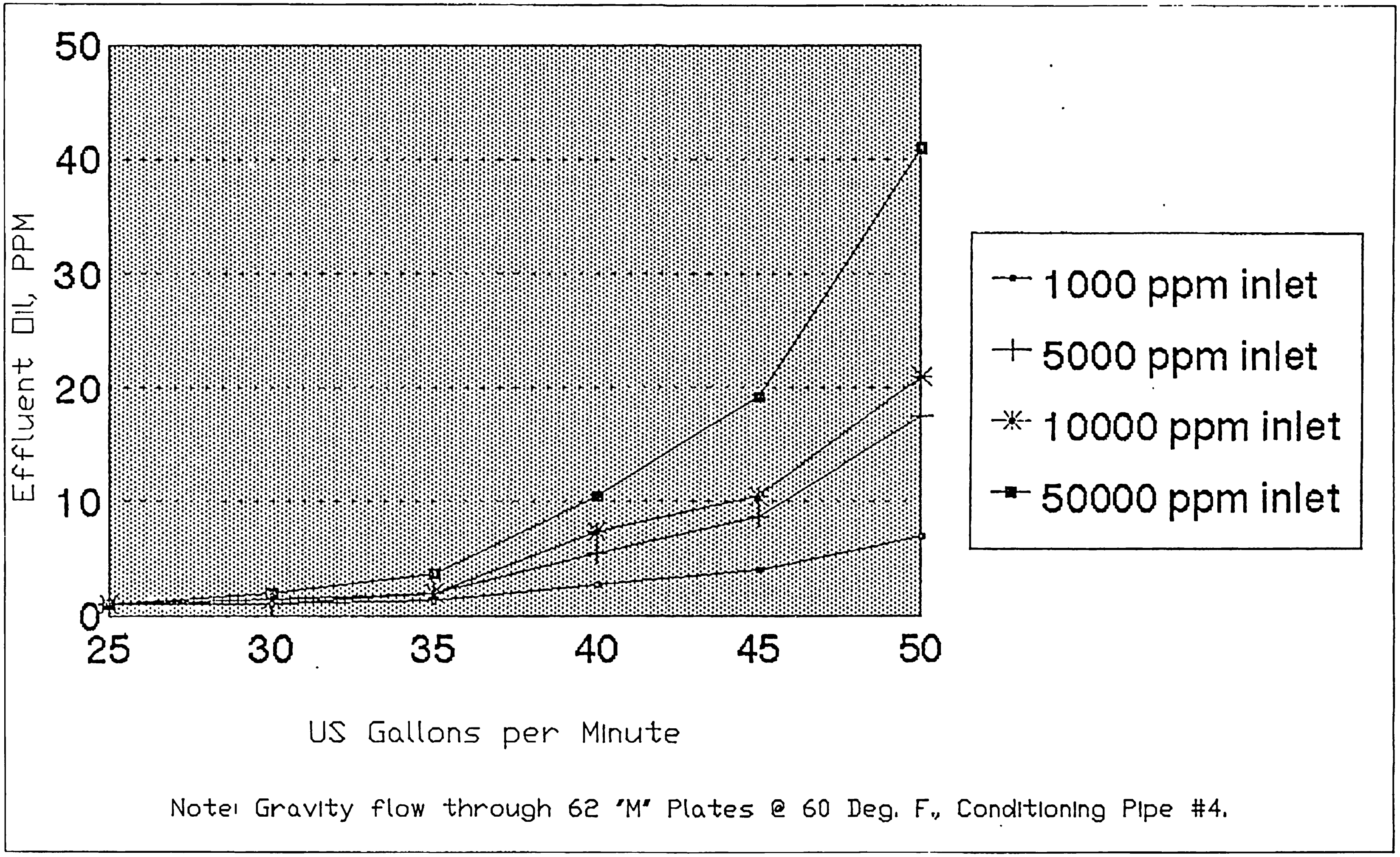
Figure 14. Oil in Effluent, Contaminant: Lubricating Oil, S.G. = 0.91

and Reynolds numbers up to 58,000 with an inlet concentration less than 10,000 ppm of mixed hydrocarbons, the effluent water would contain less than 10 ppm of hydrocarbons. At flows up to 45 gallons per minute, with Reynolds numbers less than 65,200, effluents are less than 15 ppm as long as influent hydrocarbons are less than 10,000 ppm. Results of this testing are summarized in Table 7 (page 72) and presented graphically in Figure 15. These results are similar to the Diesel fuel testing in that the results indicate higher effluent oil contents at higher flow rates for the same influent oil content. They also show higher effluent oil contents at higher influent oil contents for the same flow rate.

Comparison with Literature Information

Under somewhat similar circumstances, using a Highland Tank Company Model POWS-1000 separator and 200-800 ppm of fuel oil (.9 specific gravity, Pedneault (1982) reported effluent concentrations of 1.4-2.8 ppm. The system tested in this study performed in a similar manner, but somewhat more efficiently, producing effluent less than 1 ppm effluent at 1000 ppm (0.91 specific gravity) inlet concentration. The flow rate for the Highland Tank unit was not given, but was noted as "normal".

Au, et al. (1992) reported effluent concentrations of 1.4 to 2.6 ppm at 200 ppm influent concentrations (no



Note: Gravity flow through 62 'M' Plates @ 60 Deg. F., Conditioning Pipe #4.

Figure 15. Oil in Effluent, Contaminant: 'Navy Mix', S.G. = 0.87

Solids Removal Tests

While the main purpose of an oil-water separator system is not for removal of solids from water streams, this happens incidentally, and the resultant plugging of the plate packs in previous designs can be troublesome. In the case of the MPaks, it was intended to design a separator system that would be very tolerant of particles in the inlet water. Holes in the coalescing plates were provided for the dual purpose of allowing solids to migrate to the bottom of the separator and to allow for introduction of cleaning wands when the solids have accumulated and begun to plug the system. It was desired to have a general idea of the solids removal efficiency and resistance to plugging of the MPaks.

Solids deposition testing was necessary to provide this information. The vessel and coalescing pack system was designed to:

1. remove as many solid particles as possible in the quiescent pre-separation and inlet chambers; and
2. be very efficient at removal of oil from water while effectively shedding any solid particles that did make their way through the pre-separation and inlet chambers and into the plate area.

Because solid particles in quantity are so troublesome, it was not only necessary to know if the design actually removed solids, but also to know what percentage of particles were removed and the general size range of particles allowed to pass. Testing was therefore conducted using a mixture of filter test dust, Oklahoma garden dirt, and oil. This was intended to simulate operations of an actual separator. A relatively large amount of solids (up to 946 mg/l, as shown in Table 8) were introduced to accelerate the testing. Test dust was included to ensure that at least some small particles (Table 3 shows size distribution) would be present in the inlet suspension. Garden dirt was included in the testing because of the prohibitive cost of exclusive use of test dust and because it contains some organic matter. Analyses of particle sizes on the garden dirt or the mixture of solids introduced into the system were not performed, but the solids particles ranged from about 1/16" in diameter (by inspection of particles deposited) to particles at least as small as 2.5 microns (as determined by the particle counter analysis). Even though mixers were used in the laboratory to help determine the capacity of the plates to manage solids loadings, normal engineering system design would be to provide a settling chamber before the unit if large quantities of solids particles are expected.

Samples of both inlet and outlet streams were taken, dried, filtered, and the particulate matter weighed. This testing indicated that, at low flow rates, solids removal ranged from 67% to 76%. At higher flow rates, removal ranged from 60%-61% (and up to 63% with the solids dam discussed below). Inlet and outlet particle concentrations

TABLE 8

TEST RESULTS:
SOLIDS REMOVAL TESTING UNDER GRAVITY FLOW CONDITIONS

TEST NO.	FLOW RATE GPM	NOMINAL MG/L SOLIDS IN	CALCULATED MG/L SOLIDS IN	CALCULATED MG/L SOLIDS OUT	PERCENT REMOVAL
1	15	500	528	127	76%
2	15	1000	792	260	67%
3	30	500	493	192	61%
4	30	1000	818	330	60%
4A	30	1000	946	353	63%
5	30	1000	909	356	61%

Notes:

1) Test Numbers from original laboratory work - not renumbered.
2) Tests 1-4 without solids retention dam, Test 4A is a repeat of Test 4 with solids retention dam installed.
3) It was noted during Tests 1-4 that some solids settled out in the inlet chamber. In an attempt to measure the solids removal capabilities of the packs only, two mixers were installed in the pre-separation chamber and Test 5 performed.
4) Tests conducted with approximately 75 ppm diesel fuel oil in inlet.
5) Solids concentrations determined by gravimetrically measuring quantities of solids in a sample per ASTM-D2276-73 and back calculating concentrations.

and percent removal are presented in Table 8.

Additional samples were taken at the same time and the particulate matter in the samples processed through a particle counter to determine the number and mass of the particles in suspension. Results of this determination are included in Table 9. The greatest number of particles was found, as would be expected, to be of the smallest size, while the largest mass of solids was in the larger particles, even though there were very few of the larger particles.

Because the removal of particles in the system was 67%-76% (at low flows as noted above), it is expected that the system will operate satisfactorily even when the inlet stream contains a great deal of particulate matter. Solids removals quoted are for the entire unit, not just plate section. Future separators of this type will be designed with similar inlet arrangements so that the data provided by this testing will apply to additional designs.

Visual inspection of the system during testing indicated that some of the solid particles may have been migrating over the top of the plate packs. A solids retention dam was therefore provided at the downstream end of the plate pack, with the result that the solids removal rate increased 3%. This solids retention dam has been incorporated in subsequent designs. Data on the tests (4A and 5) conducted after installation of the solids retention dam have also been included in Table 8.

TABLE 9

SOLIDS REMOVAL TESTING EFFLUENT PARTICLE SIZE DISTRIBUTION

TEST NO.	FLOW RATE GPM	CALC. SOLIDS MG/L	PARTICLES	PARTICLE SIZE RANGE, MICRONS								
				<2.5	2.5 - 3.2	3.2 - 4.0	4.0 - 5.0	5.0 - 6.3	6.3 - 8.0	8 - 10.1	10.1 - 12.7	>12.7
1	15	INLET 528	% BY NUMBER	28.8	23.2	18.8	12.7	7.5	4.1	2.3	1.3	0.6
			% BY WEIGHT	1.8	2.7	3.9	5.5	6.4	6.9	7.5	8.9	8.4
		OUTLET 127	% BY NUMBER	32.5	24.8	18.8	11.7	6.5	3.3	1.5	0.6	0.3
			% BY WEIGHT	4.3	6.6	9.2	11.9	13.2	12.8	11.8	10.4	19.8
2	15	INLET 792	% BY NUMBER	29	23.2	18.5	12.5	7.3	4.2	2.4	1.4	1.4
			% BY WEIGHT	1.6	2.6	3.8	5.2	6.1	6.9	7.7	9.0	56.4
		OUTLET 260	% BY NUMBER	25.2	23.3	20.3	14.2	8.5	4.4	2.3	1.1	0.7
			% BY WEIGHT	2.3	4.2	6.6	9.6	11.5	11.7	11.6	12.0	30.5
3	30	INLET 493	% BY NUMBER	32.6	23.8	17.8	11.2	6.5	3.5	2.2	1.2	1.2
			% BY WEIGHT	2.2	3.2	4.3	5.8	6.6	6.9	8.7	9.3	53.0
		OUTLET 192	% BY NUMBER	31.1	23.6	17.9	11.8	6.9	4.0	2.4	1.2	1.1
			% BY WEIGHT	2.4	3.4	5.0	6.8	8.1	9.0	10.0	11.3	44.0
4	30	INLET 818	% BY NUMBER	26.8	23.1	19.4	13.4	7.6	4.3	2.5	1.4	1.5
			% BY WEIGHT	1.6	2.8	4.3	6.1	6.8	7.4	8.7	9.7	53.0
		OUTLET 330	% BY NUMBER	31.3	23.9	18.2	11.8	6.7	4.0	2.1	1.2	0.8
			% BY WEIGHT	2.8	4.2	5.9	7.9	9.0	10.5	10.5	11.8	37.4

Notes: 1) Distributions shown are for individual "grab" samples taken during test runs, not composities of samples.

Solids Deposition Tests

Although it is possible to estimate the likely positions of deposition of solid particles based on the velocity required to maintain particles in suspension, it was deemed necessary to test to confirm the position of deposition of the solids particles. A schematic of the test arrangement is shown as Figure 11. (This is the same test arrangement as was used in the solids removal tests.)

It was found that larger particles (sand and grit particles larger than about 1/16", size determined by inspection) were deposited directly below the open end of the inlet distributor. Only small quantities of these particles were present in the inlet, which is representative of most oil/water separator applications. In most field applications, separation tanks or ponds (similar to the grit removal tanks used in a POTW) upstream of the separator would be used for removal of most of 1/16" and larger particles. The position of deposition of these and the other solids are shown in Figure 16.

Smaller particles of mud and clays were deposited in the pre-separation and inlet chambers. Because the deposition rate in the pre-separation chamber was so great, mixers were employed to keep the solids particles in suspension long enough that some could be introduced into the plate pack to determine the plates's removal capabilities. Those particles that did enter the packs were

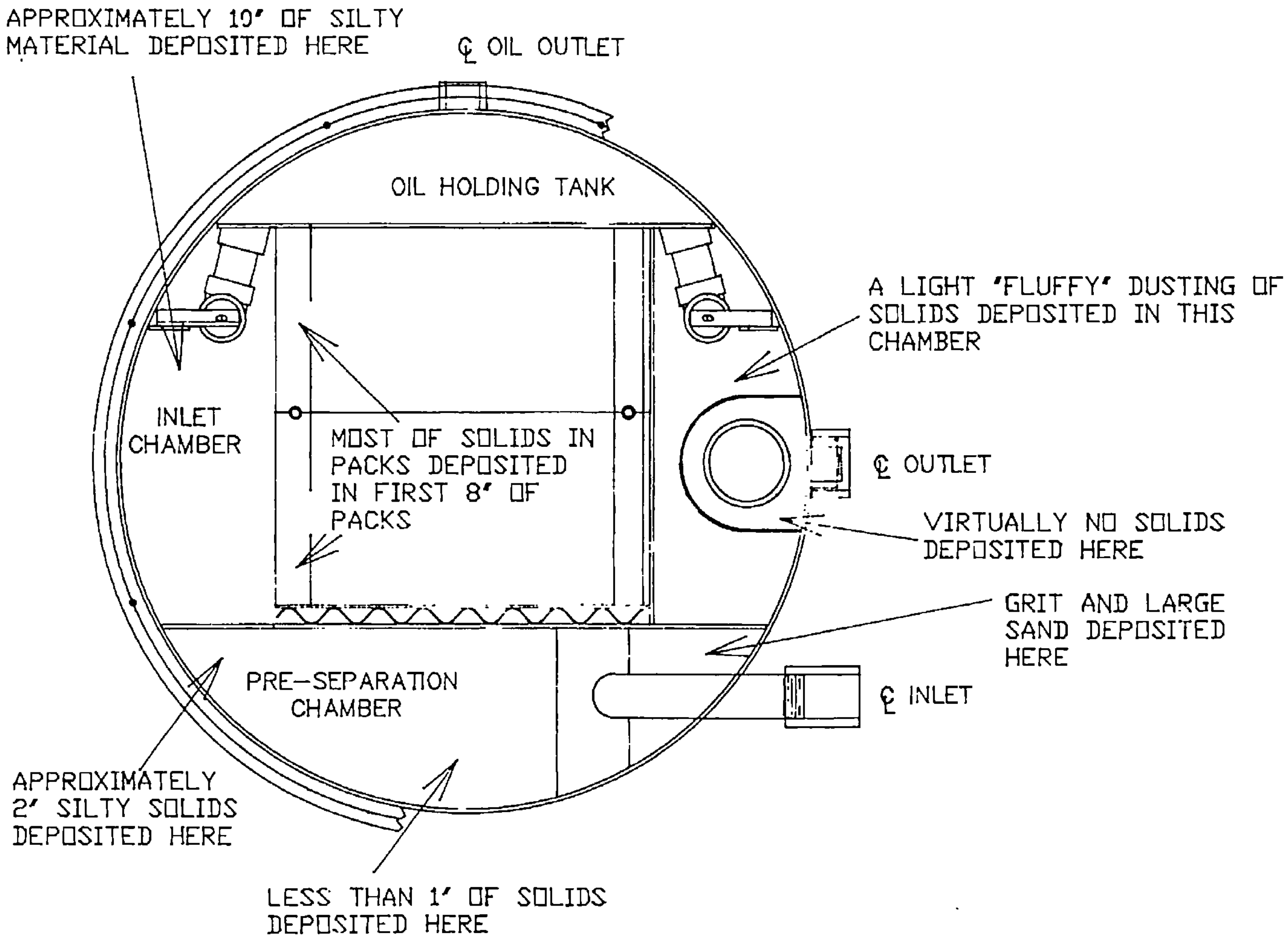


Figure 16. Results of Solids Deposition Testing

found mostly in the first three valleys of the packs and did not migrate much downstream from this position.

Only a light deposit of solids about 1/8" thick was found in the outlet chamber, even with as much as ten (10) inches of solids in the inlet chamber. The solids in the outlet chamber were very light and "fluffy" in appearance. The size of these solids were not measured, but they would be expected to be similar in size to those found in the effluent as noted in the solids removal tests above.

Solids removal has an added benefit in that oil in water is often associated with the solids due to partitioning effects. Hoffman, et al (1982) noted that as much as 93% of the oil in some storm water samples (parking lot runoff) was associated with the solids in the runoff water.

Solids Cleaning Tests

Quantitative data were not sought in the solids cleaning tests, only qualitative data. The solids cleaning tests were intended primarily to determine an effective method of removing deposited solids from the packs after they were deposited. It is not the primary purpose of the system to capture solids, and deposition of solids in the unit is considered a nuisance, so separation of oil was given the highest priority in testing. It was desired to know how effectively various methods of removing deposited solids from the system would perform. It was determined by observation that the system utilizing a flexible cleaning wand and rotating tip with upward and downward pointing holes (as shown in Figure 12) performed best.

Two basic methods were investigated in this part of the study:

1) Use of a rigid cleaning wand with jets in the end to hydraulically remove the solids to the front of the pack where they could be sucked out of the unit. Two types of wands were tried, one with a hole in the end, and one with holes in the side, but near the end. The wand with the hole in the end was found not to be effective. The wand with the holes in the side was found to be effective, although it was necessary to ensure that the water stream was pointing in the upstream direction so that the solids would be directed out of the pack. The disadvantages of the rigid wand are that such wands would be difficult to handle in lengths for large packs, and that in some applications overhead room for use of a long wand would not be available.

2) In an effort to overcome the disadvantages of the rigid type wands noted above, a flexible type wand with a rotating spray head was tested. The first such wand had flow holes that were too small, and a different wand with larger flow holes and additional holes pointing both up and down at approximately 45 degree angles was tested. The larger holes provided a

better water flow, and the angled holes did a good job of cleaning the solids from the packs. The disadvantage of this wand is that the cleaning tip is larger in diameter than the flexible part of the wand, so it tends to be difficult to remove from the pack.

Inclining the floor under the packs to enhance solids cleaning proved successful and was incorporated in subsequent testing and designs. Inclination of the packs is shown in Figure 6.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary and Conclusions

The MPak system including the HEROWS vessel was found to be effective at removing oil and solid particles from water and to be readily cleanable when enough solids are in the inlet stream to partially plug the unit.

Environmental regulations are steadily becoming more restrictive and requiring lower concentrations of hydrocarbons in effluent water. The EPA's new storm water regulations require treatment of large quantities of water not previously treated. Some states and municipalities such as King County, Washington, as noted above, require lower effluent standards than even the EPA mandates.

Unfortunately, budgets for wastewater treatment are always very limited, especially now due to the poor state of the economy. At this time, it is necessary to provide more effective waste water treatment while utilizing fewer resources. Sometimes, treatment systems for oil removal can be as simple and inexpensive as spill control separators.

In rare cases, it may be necessary to provide costly, elaborate methods of treatment such as reverse osmosis systems. The most appropriate method of treatment is the least expensive method that provides the required effluent quality.

The new "MPak" separator plates, in conjunction with units such as the HEROWS unit, are very effective oil-water separators. The design of these units overcomes plugging problems of previous designs while providing removal of coalesced oil to below levels required by regulatory agencies and retaining the convenience of modular design. Results of this study have been used in the design of four additional HEROWS units with nominal flow rates from 15 gpm to 135 gpm. Additional units were scaled up and down based on the flow rate per "stack foot" (because the plates are two feet in length, a "stack foot" equals two cubic feet of plates).

It is expected that the new "MPak" separator plates in conjunction with properly designed separators and influent/effluent systems will provide a cost effective method of ensuring effluent water quality that meets or exceeds the requirements of federal, state, and local regulations.

The objectives of the study were met in that:

1. The system was proven to be able to produce effluent qualities of less than 10 ppm of oil even with influent oil contents up to 50,000 ppm if

Reynolds numbers in the inlet piping are kept below 61,000. Reynolds numbers are controlled by the flow rate and inlet piping geometry.

2. It was found that the system would remove between 60%-76% of solid particles in the system, depending on the flow rate.
3. It was found that the solids cleaning system devised, which includes an inclined floor and a solids cleaning wand that utilizes pressurized water to clean the packs is very effective at removing gross amounts of solids deposited in the packs.

Future Research

Based on experience gained as part of this project, the following paths for future research are suggested:

1. Even though the system was not specifically designed to remove particles, its behavior in this service indicates that there may be additional uses for this technology in removing particulate matter, perhaps in small biological treatment plants in place of a conventional clarifier.
2. A revised cleaning wand with rotating collar, a tip the same diameter as the flexible part, angled holes, and an inlet screen to prevent solids in the washing water from plugging the tip should be

designed and further testing done.

3. Research to determine oil droplet sizes and distributions, perhaps utilizing a particle size analyzer such as an electric sensing zone particle counter as discussed above, could make more accurate predictions of separator performance possible.

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Professional Experience: Technical Services Engineer, Amoco Oil Co, Texas City, Texas, June, 1969, to September 1970; U.S. Navy Reserve (Active Duty), October, 1970 to March, 1973; Operations Engineer, Amoco Oil Company, Texas City, Texas, April, 1973 to December, 1974; Systems Engineer, The M.W. Kellogg Company, Houston, Texas; January, 1975 to May, 1979; Senior Project Engineer, Scientific Design Company, Bellaire, Texas, June 1979 to October, 1981; Process Engineering Manager, Petrofac, Inc., Tyler, Texas, November, 1981 to July, 1984; General Products Manager, Perry Equipment Corp., Mineral Wells, Texas, September, 1984 to July, 1988; Project Engineer, Facet International, Inc., Tulsa, OK, July 1988 to present.