DESIGNING PRODUCED WATER TREATMENT SYSTEMS FOR OPTIMAL OIL RECOVERY

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Abstract:

Conventional production systems often do not do a thorough job of removing oil from the produced saltwater. This is due to a variety of reasons and can often be traced to the use of simple and easy-to-use traditional separation systems that are not efficient at removing the last traces of oil.

Likewise, saltwater injection systems often suffer problems including poor oil recovery from the inlet water, plugging of the final filter before injection, and plugging downhole from bacterial growth. These problems plaguing saltwater disposal systems can be avoided or at least alleviated by utilizing good design practices.

The high value of crude oil makes recovery of any residual oil in the produced water attractive and environmental regulation of oil in salt water disposal from oil and gas operations are becoming more stringent also. Many of the current methods such as gunbarrels which are used for recovery are older designs and not very efficient.

This paper will present design methods and suggestions to alleviate these problems:

- Design suggestions on piping and pumps
- Methods for removing residual oil and solids
- Methods to minimize operating and maintenance costs.

Both the design of new systems and revisions to existing systems will be discussed with photographs and examples.

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Introduction:

Oil and gas wells generally produce at least three phases and often four:

- various gases
- hydrocarbon liquids
- water – usually with high salt content
- solid particles – sometimes iron oxides or clays and often sand
- in addition to the four phases mentioned above, there are sometimes emulsions or near emulsions present.

The initial production separators, usually located at or near the wellhead are generally pressure vessels, sometimes horizontal and sometimes vertical. These are generally designed to remove the gases and make a rough separation between the oil and the water. They also remove the sand that may be present.

A typical vertical production separator is shown in figure 1 below.

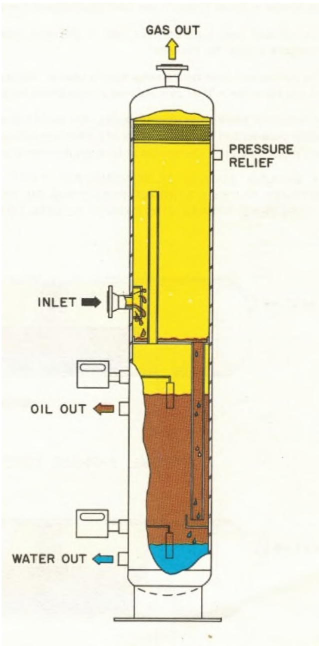

Figure 1 – Typical Vertical Production Separator

The water content of production fluid can range anywhere from almost nothing to 90+ percent. The water that is produced with the oil is usually salty and often very salty, it being the remains of ancient oceans.

The purpose of this paper is to discuss treatment of the produced water to remove almost all of the oil so that it can be marketed and to minimize downstream maintenance requirements.

Disposal of the produced water after treatment can be troublesome because of the dissolved solids (mostly salt) content. Some of this water can be reused in production facilities, and the balance is usually disposed of using saltwater injection wells.

When commercial oil production began, the resulting saltwater was often simply dumped on the ground, and this resulted in a number of pollution problems. There are still places in central Oklahoma where there’s no vegetation because of saltwater dumping 100 years ago.

Saltwater injection wells were established to eliminate the problem of disposing the saltwater at the surface. The injection wells are used to put the saltwater back in underground strata, usually a different strata than the oil is produced from, where it will not cause problems.

Before the water is reinjected, it is necessary to remove the residual oil and any non-dissolved solids that may be present. This is to reduce the amount of maintenance on the disposal equipment and the well and to recover as much oil as possible for sale.

Separation Systems:

In effect, there are two sets of separation equipment:

- a system at the wellhead that contains a separator or separators to make the initial separation between the oil and water so that the oil can be sold. The system is likely to also be designed to remove some or most of the sand, clay, and other solid particles that are produced with the oil and water. It may also be provided with a heater-treater in case emulsions are present or expected.
- A second system which is intended to make a much more efficient separation, removing smaller oil droplets and solid particles than the wellhead system does. This secondary system may be either located near the wellhead system or may be located at a saltwater disposal facility

If located near the wellhead system, the secondary system would usually be designed only to process the water from the well or wells at the site. The water that is to be processed in a saltwater disposal facility is likely to be trucked in from various well sites, often a substantial distance away, and mixed with other water from other well sites in an inlet tank. It will also vary substantially in oil and solids content and, depending on the source of the water may even vary in oil specific gravity.

Wellhead systems:

Common separations systems used in the oilfield include gunbarrel separators and horizontal separators. The gunbarrel separator systems as illustrated in Figure 2 below are simple gravity systems where the oil gas and water mixture comes to a preseparation system and the gas is supposed to separate out in the preseparation system and joined the gas which eventually separates out of the oil water mixture at the top of the gunbarrel. The oil and water mixture flows into the distributor near the bottom of the separator where the oil droplets are supposed to collect under the umbrella style distributor and weep upward into the oil layer water droplets are supposed to coalesce and come downward. Any water drops entrained in the rising oil will migrate into the oil layer above the water layer, and from there must fall back down through the oil layer to rejoin the water.

These systems are traditionally simple, easy to operate, and tolerant of solids but the flow pattern and lack of properly designed internals keeps them from being very efficient at removing smaller droplet sizes. This is because the design of the gunbarrel does not meet the laminar flow criteria for Stokes law to apply. Stokes law is discussed below.

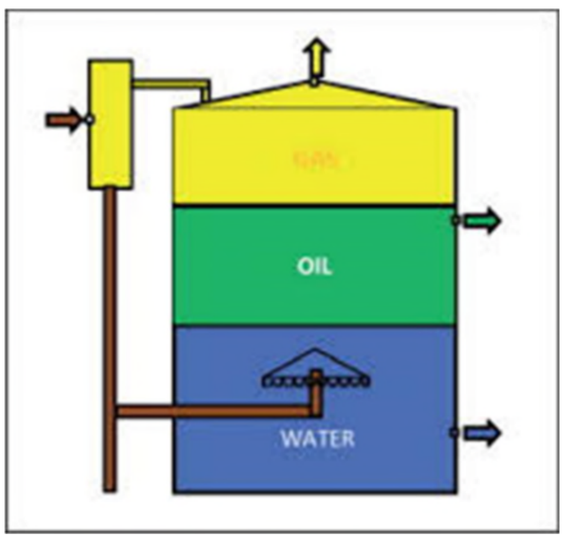

Figure 2: Typical Gunbarrel Separator

Another common separator design often used in the oilfield is a three-phase horizontal separator, as illustrated in Figure 3 below. In this system the oil and water and gas mixture enters through the inlet nozzle near the top and the gas immediately disengages prior to the inlet deflector and proceeds along the top of the separator to the opposite and where there may or may not be a separate gas outlet. The gas may also be combined with the liquid in the outlet. A water layer is maintained below the oil layer as shown in the figure.

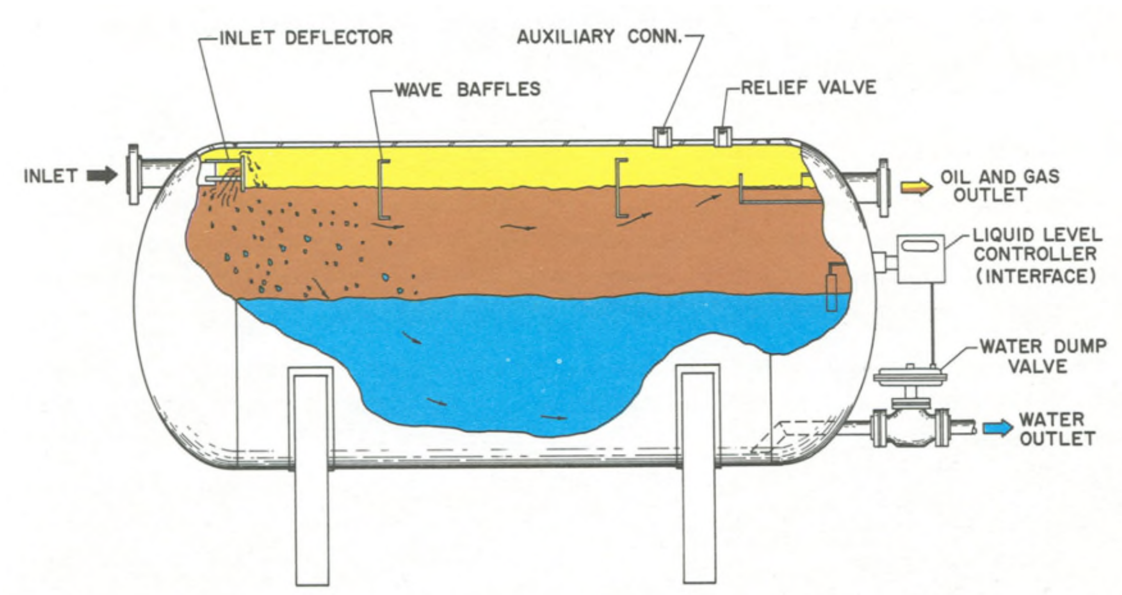

Figure 3: Typical Three-phase separator

Problems associated with this design are that all of the water in the inlet must pass through the oil layer to get to the water layer in the bottom of the separator. This causes entrained oil droplets to be carried downward into the water layer likewise there should be a movement of entrained water drops through the oil layer down to the water layer. Neither of these actions happens very efficiently because the systems do not meet the requirements for Stokes law and because they are designed so the droplets of one phase must pass through another phase.

Separation by Gravity:

In 1845, an English mathematician named George Stokes first described the physical relationship that governs the settling solid particles in a liquid. This same relationship also governs the rising of light liquid droplets within a different, heavier liquid. This function, simply stated is (Perry, 1963) to have:

$$Vp = \frac{G}{(18x\mu)} x(d_p - d_c) x D^2$$

Where:

Vp = particle rising or settling velocity, cm/sec
G = gravitational constant, 980 cm/sec2
µ = absolute viscosity of continuous fluid, poise
dp = density of particle (or droplet), gm/cm2
dc = density of continuous fluid, gm/cm2
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. *Laminar flow in this context means flowing gently, smoothly, and without turbulence.*

From the above, it can be seen that the variables are the density of the droplets, the viscosity of the continuous phase (temperature), specific gravity difference between the continuous liquid and the particle, and the average droplet size (square function).

The rise rate of oil droplets is also governed by Stokes's Law. If the droplet size, specific gravity, and viscosity of the continuous liquid are known, the rise rate can be calculated.

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 (residence time) must be provided in the separator so that an oil droplet entering the separator, at the bottom of the inlet end of the separator, has time to rise to the surface before the water carrying the droplet exits the opposite end of the separator.

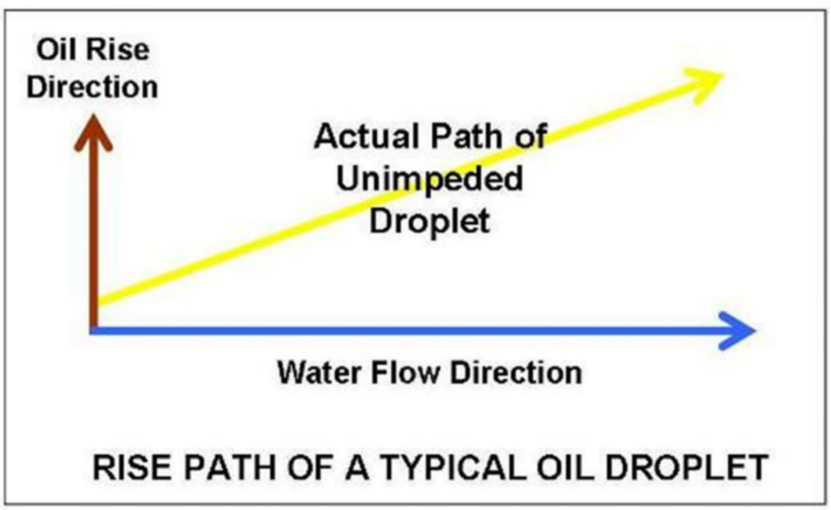

Figure 4: Droplet Rise Path

Calculation of the rise rate by this method is a gross simplification of actual field conditions because oil droplets are not all the same size, and they tend to coalesce into larger droplets. Furthermore, inevitable turbulence within a separator makes an orderly rise of very small droplets impossible.

Droplets will rise following Stokes' Law as long as laminar flow conditions prevail. When the particle size exceeds that which causes a rise rate greater than the velocity of laminar flow, flow around them (as they rise) 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 because of the hydrodynamic drag. However, they do rise very quickly in relationship to smaller droplets, and so, are removed by a properly designed separator.

Very small particles, such as those of 8-10 microns (micrometers) and less in diameter, do not rise according to Stokes' Law (or hardly at all) because the random motion of the molecules of the water is sufficient to overcome the force of gravity. As a result, they move in random directions. This random motion is known as Brownian Motion. Fortunately, the volume of a droplet decreases according to the cube of the diameter, so these very small droplets tend to contain very little oil by volume, and unless there are large, large quantities of very small droplets (such as would be created by using a centrifugal pump to pump the water), they contain negligible amounts of oil.

When the droplets coalesce, they do not form flocs as the solid particles can, but instead coalesce into 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. This is convenient for a separator designer because it is required by Stokes' Law.

Near wellhead systems:

Systems utilizing high-efficiency coalescing internals can conveniently be designed for use more or less directly downstream of the wellhead production separators. The flow rates, oil specific gravity, temperature and other information needed for design of a high-efficiency system would readily be available. Information about emulsions and other aspects of the system which could complicate separation design would also be available.

Saltwater Injection systems:

The systems installed in saltwater injection facilities are therefore plagued by the problems caused by upstream equipment but can still be designed to cope with a wide range of operating conditions and recover large quantities of oil for sale by the disposal well operator.

Saltwater injection systems often suffer problems including poor oil recovery from the inlet water, plugging of the final filter before injection, and plugging downhole from bacterial growth. These problems plaguing saltwater disposal systems can be avoided or at least alleviated by utilizing good design practices.

Separation system design:

Separation systems, either for near-wellhead installations or saltwater disposal generally consist of some upstream equipment which is intended to remove any solid particles in the incoming water as well as to recover as much oil as is easily captured for sale. The downstream equipment in these systems is designed to remove any residual oil and make the water therefore more acceptable for injection or other use. To make this happen without problems, a good deal of initial information gathering and planning is required.

The parameters for the inlet water are likely to vary a great deal from minimum flows when the field is not too active to maximum flows when there's a great deal of oil being produced. As fields age, it is likely that there will be more and more water being produced with the oil.

The information needed for design are:

1. design flow rate.
2. design inlet oil content.
3. design operating water temperature.
4. oil removal desired.
5. design solids content..
6. design solids configuration
7. possible variations in all of the above parameters, especially the operating water temperature.

Design flow rate:

While theoretically any design rate is possible, a flow rate of about 30,000 barrels per day results in a fairly large system and if flowrates larger than that are needed, it may be a good idea to install two or more systems. Many kinds of systems, and especially coalescing plate type systems, have high turndown rates. Coalescing plate systems become more efficient at lower flow rates (for the same size system). For this reason, it is a good idea to design for the maximum expected flow. Centrifugal type systems, however, have very limited turndown ratios, and may not operate satisfactorily below approximately one half of design flow.

Design inlet oil content:

In the near wellhead system the inlet oil content can be measured. It is usually wise to design for current conditions and check the design for whatever the conditions may be estimated to be later in the life of the field. In the case of saltwater disposal systems, the oil content of the inlet water may vary substantially from truckload to truckload. While it is uncommon for the producers operators or equipment to dump large quantities of crude oil into the saltwater to be disposed of, it does happen. Some producer's oil capture systems are very efficient and there will only be a few parts per million of oil in the saltwater and other producer's equipment is less efficient or may be poorly maintained and the oil content could be as much as 5%. It is good to design for the maximum oil content and check the design for a lower oil content (perhaps not for the lowest possible) to ensure that the range of operating conditions is covered.

Design operating water temperature:

In very hot climates, or if the use of heater-treaters is common, operating temperatures may be as high as 150°F (65° C). In cold climates, flowing water temperature may be as low as 32°F (0°C). According to Stokes law, oil droplets rise faster in lower viscosity water, and because viscosity is dependent upon temperature, the oil droplets rise faster in higher temperature water. This is convenient for the design of systems to remove the oil that temperatures below about 120°F (49°C), but if the temperature is too high the droplet size distribution can be less and there will be convection currents in gunbarrels and other large empty tank type separators. The convection currents that can happen at higher temperatures can cause droplets to not rise according to Stokes law and so the performance is not as good as would be predicted using Stokes law.

Oil removal desired:

Most producers and disposal well operators wish to remove *all* of the oil for sale and to preclude the problems caused by oil going downstream. This is not really possible because some droplets are so small they will not rise in an orderly manner, but it is possible to remove oil down to the nondetectable limit of laboratory testing, which for oil and water is usually about 2 mg/L.

Very small particles, such as those of 8-10 microns (micrometers) and less in diameter, do not rise according to Stokes' Law (or hardly at all) because the random motion of the molecules of the water is sufficient to overcome the force of gravity. As a result, they move in random directions. This random motion is known as Brownian Motion. Fortunately, the volume of a droplet decreases according to the cube of the diameter, so these very small droplets tend to contain very little oil by volume, and unless there are large, large quantities of very small droplets (such as would be created by using a centrifugal pump to pump the water), they contain negligible amounts of oil.

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Design inlet solids content / configuration:

Both the quantity and configuration of the solids may change substantially from one truckload of water to another, and it is difficult to know what those are unless the producing company has that information available. The best thing to do is to provide a large inlet tank to allow as much settling of solids as possible and to allow additional space in the inlet end of the oil separation system for additional settling. If coalescing media is provided to remove the fine oil droplets, this will also remove a substantial quantity of the solids which have not settled out in either the inlet tank or the inlet portion of the separator. If large quantities of small solid particles are present, it may be necessary to periodically clean the coalescing media.

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Design Suggestions:

Use large pipe sizes for the flows – this minimizes droplet size reduction due to friction. Also, avoid centrifugal pumps (upstream of oil removal) because they are very bad for droplet size distributions. If possible, use gravity flow into separation equipment.

Design example:

Following is an example of the procedure used to determine the appropriate size separation system for a saltwater disposal well facility. Please note that this example procedure is somewhat more complicated than is often required for determining the appropriate size. The customer wished to have some initial confirmation that the system would operate as they needed before committing to a full-scale system, so they chose to do some initial pilot scale testing.

Initial testing:

MSR is a designer and manufacturer of coalescing plate separators for use in many oil removal applications. The possible installation was reviewed to determine if it was a likely candidate for the use of coalescing media, and the relatively low density crude oil to be removed indicated it was likely that the application would work well using MSR's coalescing plate technology. An initial flow test utilizing a small MSR-11 separator was arranged.

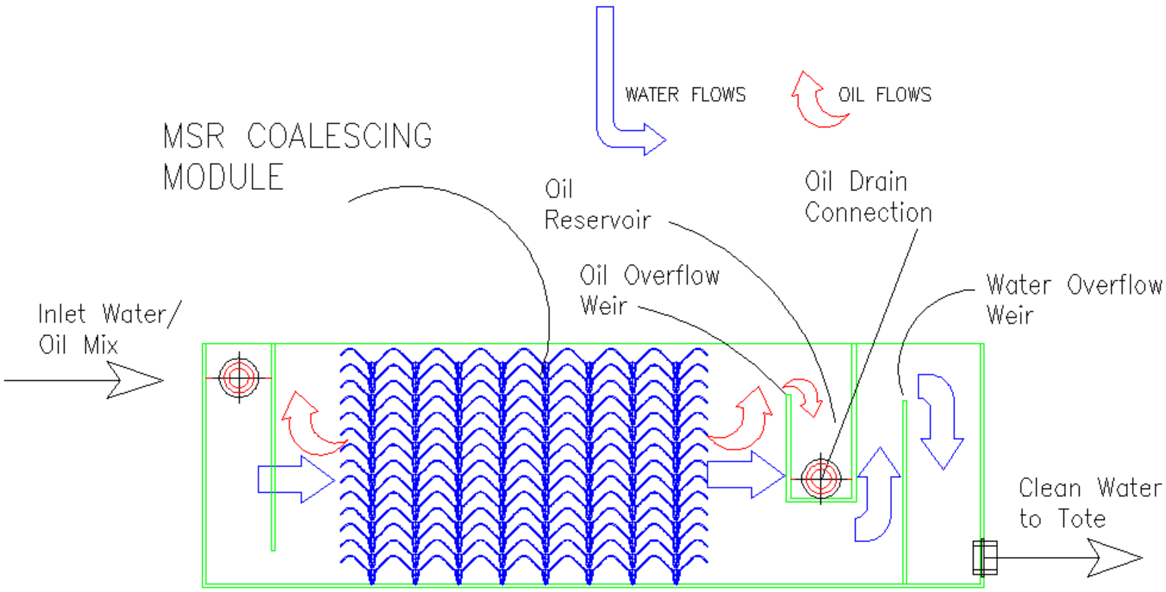

Figure 5: MSR-11 Test Unit

The MSR-11 pilot testing unit was installed at a customer owned facility in eastern New Mexico. Flow was by gravity from the bottom of the large storage tank through the stainless steel separator and the outlet water was directed to a tote. This arrangement was made so that testing could be done without disturbing operations of the plant. The photo below shows the separator mounted on a metal stand and the inlet hose may be seen from the tank, over the berm to the separator and the cleaned outlet water flow was then directed to the tote.

Figure 6: Pilot Test Setup

Initial visual comparison between the inlet and outlet samples indicated good separation. In figure 5 below, the inlet samples are number one and three from the left and the corresponding outlet samples are number two and four from the left.

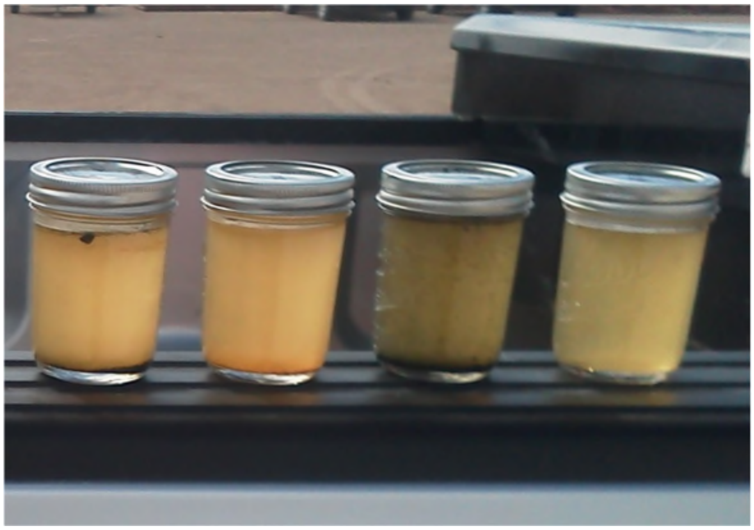

Figure 7: Pilot Testing typical Samples

The pilot testing program was conducted in September 2013. All of the test flow rate varied somewhat because of the test system design, average flow rate was approximately 1 US GPM. The separator operating temperature was approximately 100°F. Inlet sample concentrations varied from 77 mg/L to 128 mg/L, and the outlet concentrations varied from 21 mg/L to 28 mg/L. These were lower concentrations than initially expected by the customer, and it is believed that this was at least partly due to the sample flow being taken from a location near the bottom of the tank. Because the water is from various sources, it is likely that some truckloads of water will contain substantially more oil than was found during this test.

The average oil droplet size in the flow stream was back calculated based on the information provided by the test results. For the relatively low inlet oil concentrations used in that test program, the average oil droplet size was found to be about 15 µ. There are of course many larger droplets than 15 µ and some smaller ones. At higher concentrations, the average droplet size would be expected to be higher.

Full scale unit design:

Preliminary calculations and discussions with the customer indicated that a system installed in a 500 barrel frac tank would be convenient for processing approximately 36,000 barrels per day of water (1050 US gpm).

This size tank lends itself to a coalescing system consisting of one or more rows of our modules, seven modules wide and with a water height within the modules of 71.5 inches.

After deciding on the width and height of the coalescing system, MSR considered several possibilities with multiple rows of coalescing media. It was determined that the maximum amount of media that might possibly be required would be seven rows of media. The design of the system was therefore for any amount of media between one and seven rows. This design gives the flexibility of being able to use the same unit for substantially different applications by simply adding or subtracting media as required.

The particular customer application that the initial unit was designed for conveniently fit in a system with three rows of media. The design of the initial unit that was constructed is shown in the sectional drawing shown in Figure 6 below.

The initial unit was sized for an effluent quality of 50 mg/L or less of 0.82 specific gravity West Texas crude oil with an effluent quality of 50 mg/L or less utilizing three rows of media. Additional rows can be added if necessary for larger flows or lower effluents.

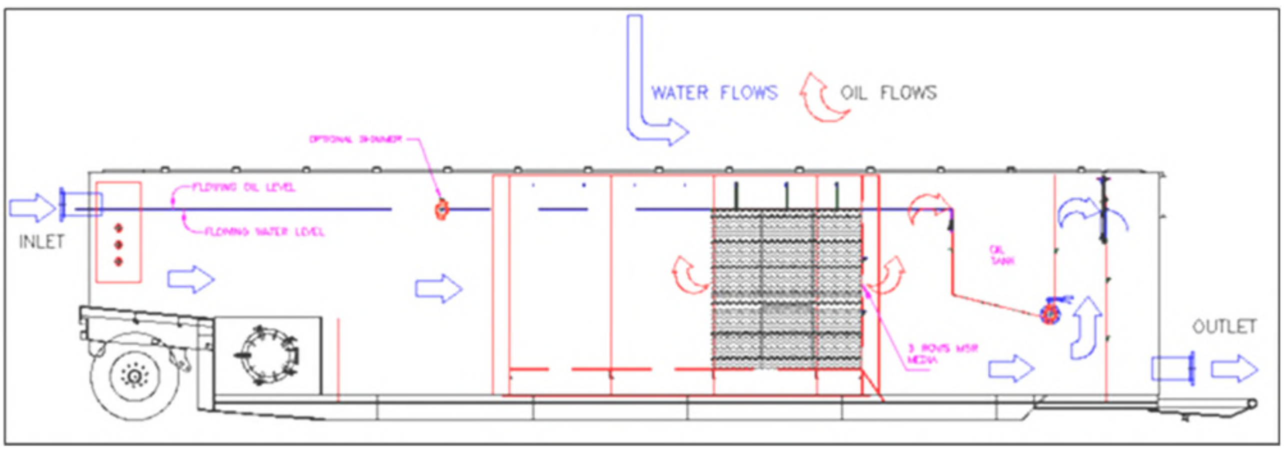

Figure 8: Full-Scale Unit Section

Because of the likelihood of some solids being present in the inlet, even though the bulk solids will have been removed upstream in other equipment, a solids trough was provided under the media area with holes that correspond to the holes in the valleys of the media. Solid particles fall on the top side of the media in the same way that oil droplets rise up and meet the underside of the media. The oil droplets are directed to the surface by the oil ports in the peaks of the coalescing plates and solid particles are directed downward to the solids sump through the solids dump holes in the valleys of the plates.

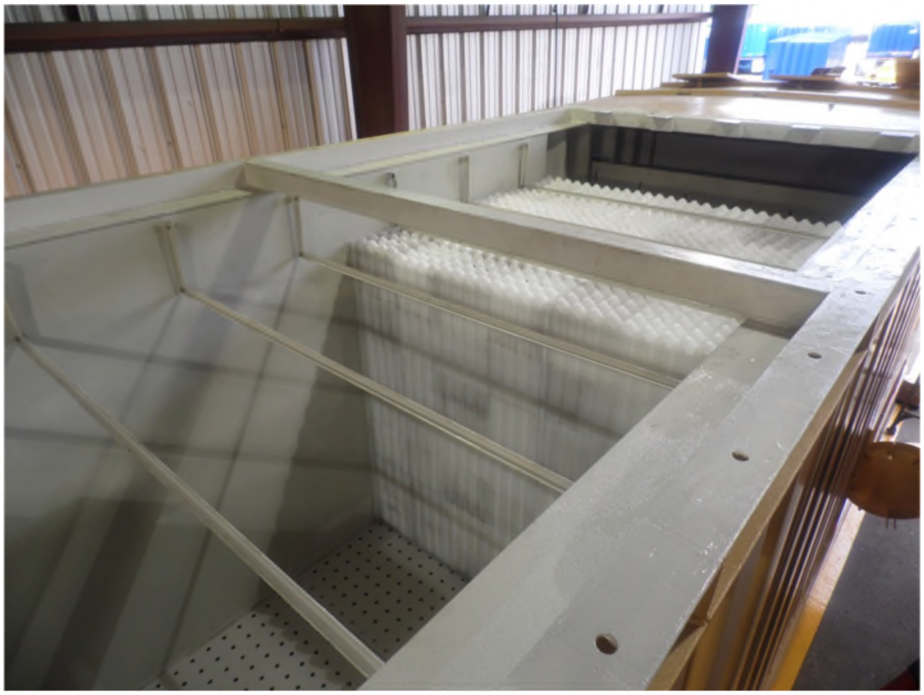

Figure 9: full-scale unit under construction

Please note plate hold downs are provided for all seven rows even though only three rows are installed. Solids dump holes in support plate over solids trough may be seen in the lower left of Figure 9 above. A large hatch has been constructed in the ceiling of the tank for use during both the original installation and subsequent maintenance.

Field operations:

The first of a series of three units was put into operation in July 2014. Operations were noted to be very satisfactory.

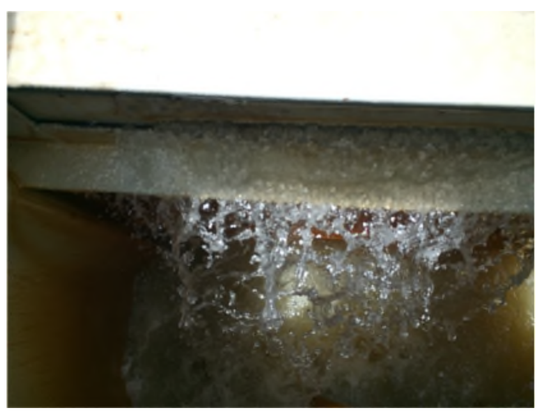

Figure 10A: Separator Installation, New Mexico   Figure 10B: Clean Water Overflow

Figures 10A and 10B above illustrate the initial commercial operations of this system. In figure 10A, the large outlet piping and smaller oil outlet piping may be seen at the rate of the photo. In figure 10B the cleaned water is shown overflowing the outlet weir into the outlet chamber.

Limited testing was conducted on the operation of the separator, which is proven to be very successful. Figure 11 below represents the test results.

Figure 11: Test results, Full-scale unit	
Inlet hydrocarbon concentration	Outlet hydrocarbon concentration
90 mg/L	13 mg/L
85 mg/L	14 mg/L
119 mg/L	7 mg/L
Unit placed in commercial operation: July 2014	

Selection of equipment:

The separator was designed to be very versatile and process up to about 36,000 barrels per day of salt water. In general, at lower flow rates effluent quality will be better than design. This design can be used in many circumstances with different oils and flow rates.

The information necessary for MSR to determine the appropriate design for a given set of requirements is:

- Operating conditions including
    - flow rate (maximum instantaneous flow rate)
    - operating temperature
    - oil specific gravity or API gravity
    - saltwater density
    - expected inlet oil content
    - if possible, information about the inlet flows such as pumps or chokes
- degree of separation required – the effluent quality desired
- any special issues to be considered such as possible differences in oil specific gravity

With this information, MSR can specify the appropriate size separator or if the flow rate is sufficiently large as to justify the use of a frac tank separator such as described in this paper, the number of rows of media to be installed.

Safety:

Any design for oil capture, either at the wellhead or at a saltwater disposal facility must include all possible provisions for safety to avoid hazardous situations for personnel and equipment damage and product loss. In January 2019, a saltwater disposal site in North Dakota experienced a massive explosion and fire, costing the owner approximately $1.4

million in lost product. Fortunately, no personnel were injured (Daily Mail, January 19, 2019)

Other Applications:

This technology can be used in virtually every situation where unwanted oil is present in water streams:

- oil refinery API separators/outfalls
- at tank farms for rainwater runoff water
- replace or supplement gunbarrels or other production separators

Green technology:

Coalescing plate separators are very sustainable, very green technology:

- gravity operated
- offer high-efficiency predictable oil removal
- can be designed for whatever maximum effluent oil content is required
- much smaller than other separators for the same flow rate
- coalescing plates are not consumed and can last for many years
- the recovered oil is not contaminated with flocculants or other chemicals and can readily be sold

Summary and conclusions:

Coalescing plate separators can be used to recover oil that would otherwise be lost, reduce plugging of disposal well strata by oil, reduce plugging of well strata by bacterial growth fed by the oil, improve operations and reduce maintenance.

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2. Daily Mail, “You feel the thunder and roar – massive explosion at North Dakota saltwater disposal site that destroyed $1.4 million worth of oil and gas”, January 19, 2019