PRACTICAL APPLICATION OF PRODUCED WATER TREATING TECHNOLOGY FOR LAND-BASED INJECTION OPERATIONS

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I. INTRODUCTION

Produced water is the aqueous liquid phase that is co-produced from a producing well along with the oil and/or gas phases during normal production operations. Usually, the fluids that are removed from the reservoir by the producing well are brought to the surface and separated into an oil stream, a gas stream and a water stream. The main components of the water stream that is separated are:

- Water
- Suspended oil
- Dissolved oil
- Suspended solids (scale, corrosion products, sand, etc.)
- Dissolved solids
- Dissolved Gases (CO_2, H_2S, O_2)
- Bacteriological matte?
- Added materials (treating chemicals, kill fluids, acids, etc.)

It should be noted that, over the life of the well or field, the volume of water produced will exceed the volume of oil produced by a factor of 3-6 times. Unfortunately, at the present time, the produced water is not a saleable product of the operation. Hence, an operator is faced with a serious challenge of how to handle relatively large amounts of produced water at the lowest possible cost. In many land-based production operations, the produced water is either injected into a disposal well or the water is injected into a producing formation for enhanced oil recovery purposes via waterflood or steamflood operations. Before being injected for either disposal or enhanced recovery, the produced water must undergo treatment to render the water suitable for use. The purpose of this paper is to present a general, but practical, overview of the equipment and technology involved in water treating for a produced water injection project. This paper is not meant to present an exhaustive coverage of the material but to provide basic, general information with which an operator can become familiar with the primary decisions required to properly treat produced water for injection. To be covered are produced water treating objectives, produced water treating technology and equipment, and a thought process for the practical application of this equipment to land-based injection operations.

II. PRODUCED WATER TREATING OBJECTIVES

Once the decision is made to inject produced water into a subsurface formation for either disposal purposes or for enhanced oil recovery purposes, it then becomes necessary to give consideration to the produced water treating requirements. Produced water treatment is necessary due to the potential negative impacts that produced water may have on the formation. In general, produced water will have five main categories of “contaminants” from a produced water injection point of view:

- Suspended solids
- Suspended oil
- Scales that form when dissolved solids precipitate
- Bacteriological matter
- Corrosive dissolved gases (CO_2, H_2S, O_2)

Therefore, the objective of the produced water treating system is to remove or reduce these contaminants to a level that makes the produced water suitable for use. Furthermore, the system should be designed to result in the lowest possible capital and operating life-cycle costs.

Suspended solids in produced water may originate from solid material from the formation, scale deposits, corrosion products or bacterial activity. Depending on such factors as size, shape and concentration, particulate matter in the injection water may have a tendency to cause plugging in the formation. In turn, the plugging will result in higher injection pressures and, eventually, lower injection flow rates. Therefore, one of the primary objectives of the produced water treatment system is to remove the suspended solids material to minimize plugging in the formation.

Produced water for injection that is taken from the water outlet of the Production Separator, Oil Treater or other primary oil/water separation device can contain suspended oil (also known as residual oil) in the range of 500 mg/l to 5,000 mg/l or higher. Prior to injection into the formation, the oil content of this water must be reduced for two reasons. First of all, the oil in the injection water may cause damage to the formation. Hence, the oil content of the injection fluid must be reduced to a suitable level for use. Secondly, the oil that is recovered from the produced water is routed to the oil sales meter to generate cash for the operation.

The amount of dissolved solids in the produced water can vary greatly. For instance, the dissolved solids content of some produced waters are comparable to fresh water while others are at the other end of the spectrum at upwards of 300,000 mg/l and higher. **As** the concentration of dissolved solids increases, the potential for the dissolved solids to precipitate and form scales deposits in the surface piping and equipment or in the formation also increases. Various types of analyses can be performed to determine the scaling tendency of the injection water. If there is a high scaling tendency, then consideration should be given to injecting scale inhibitor chemicals.

Microbial growth in oil field water systems may be either bacterial or fungal in nature. These microorganisms are of concern because as they multiply they can cause or enhance corrosion of pipes and vessels, plugging of injection wells, and degradation of chemicals used in enhanced recovery operations. Organisms that thrive in oxygen-containing environments are called aerobes, while those to whom oxygen is detrimental are called anaerobes. An important group of bacteria that can survive in the presence of oxygen but need an anaerobic environment for growth is called facultative anaerobes. Another classification in use relates to the growth habits of the organisms. Those which float freely in the liquid phase are said to be planktonic, while those which prefer to grow attached to a solid surface are said to be sessile. It should be remembered when evaluating the results of a bacterial monitoring program that many tests depend on detection of planktonic individuals, and that these individuals, even when present in low concentrations, may be indicative of the presence of large colonies of sessile bacteria. It is recommended that operations personnel collect samples and have these tested for bacterial activity. If necessary, chemical biocides can be injected to control the proliferation of these microorganisms.

Produced water from sour formations may contain some amount of dissolved H_2S and/or CO_2. These gases form corrosive acids when dissolved in water. The effects of these gases can be mitigated by removing the gas from solution or by use of corrosion inhibitor chemical additives.

Oxygen is also a corrosive agent when dissolved in water. Although oxygen is not normally a component of produced water when it comes up from the formation, oxygen may leak into the produced water during separation or treating processes at the surface. Therefore, the oxygen content of the water should be monitored and if leaks are found, these should be sealed. Furthermore, equipment or processes that are open to the atmosphere should be avoided so as to minimize the intrusion of oxygen in the produced water. Sometimes it is necessary to commingle a small stream of aerated produced water into the main stream. In these cases, the aerated stream should be treated with an oxygen scavenger chemical prior to mixing with the main stream.

III. PRODUCED WATER TREATING TECHNOLOGY

The technology for accomplishing these objectives is described below. For each objective, several common technologies, from the most basic to the more complex, are given. The proper application of the technology is key to reaching both the performance objectives and the financial objectives of a particular project.

Suspended Solids Removal

As explained earlier, suspended solids have a tendency to plug the injection formation thereby tending to cause the produced water injection pressure to increase and the produced water injection flow rate to decrease. In order to predict the nature and extent of any problems that may arise due to contamination of the produced water by suspended solids, it is advisable to collect samples of the produced water, if possible, to perform a suspended solids analysis. This type of analysis will provide detailed information that is required to properly specify a treatment scheme. The suspended solids analysis will report on such issues as the density of the solids, the concentration of solids in the water stream, the size distribution of the solids and the type of solids. Having this information helps operating personnel better understand the problem that needs to be solved.

Suspended solids that are present in the water will exist as distinct particles of varying sizes and densities dispersed throughout the water phase. Particles that are heavier than water will tend to drop to the bottom of the pipe, vessel or other type of container at various rates. There may also be very small particles or oil-coated particles that are neutrally buoyant such that they tend to remain in the water phase. Stoke's Law describes the vertical velocity at which a particle falls through a liquid phase. Stoke's Law can be related by the following equation:

$$v = \frac{g}{g_c} \frac{\Delta\rho (d_p)^2}{18\mu_L}$$

where:

$\Delta\rho =$ difference in density of the dispersed particle and the continuous phase,
g = "g-force" acceleration factor,
$g_c =$ gravity acceleration constant,
$d_p =$ dispersed particle diameter, and
$\mu_L =$ viscosity of the continuous phase.

The information obtained from the solids analysis is used along with the Stoke's Law equation to properly evaluate and select a solids removal system.

A primary objective in the design and engineering of water treating equipment for solids removal is to maximize the vertical velocity or settling velocity of a solid particle. In other words, the higher the settling velocity, the easier it is to remove the solids from the produced water stream. Based on the Stoke's Law equation above, it is clear that the settling velocity can be increased by:

1. Increasing the size of the solid particles (i.e. by using chemical agents), or
2. Increasing the difference in density between the oil droplet and the water phase, or
3. Lowering viscosity of the water (i.e. by operating at the highest possible temperature), or
4. Increasing the "g-force" imposed on the fluid (i.e. by centrifugal motion)

Solids removal is usually done in stages from primary bulk removal to final polishing. The number of stages required is a function of the type of solids in the stream, the size distribution of the solids, the concentration of the solids and the level of removal required for the application.

As already stated, large and relatively dense particles will be easiest to remove. The separation of relatively large, high-density solids can be accomplished by simply allowing enough time for the solids to settle by gravity to the bottom of a tank or vessel. This is termed gravitational settling. This is the most simple and least costly solution to solids removal. Gravitational settling can be accomplished by using settling tanks or skimmer tanks. These types of tanks are commonly installed at land-based operational facilities due to the fact that space and weight constraints are not very stringent and the installed cost is relatively low.

The speed of solids removal via gravitational settling can be greatly enhanced by use of inclined parallel plates (See Figure 1). **A** section of closely spaced, inclined parallel plates can be placed in a rectangular tank or in a cylindrical vessel through which a produced water stream containing suspended solids flows. Equipment designed on this principle is termed a parallel plate interceptor (PPI) or a corrugated plate interceptor (CPI). The plate pack accomplishes two things: 1) it shortens the distance that a solid particle must travel before it reaches a settling surface; and 2) it provides plenty of surface area for solids to settle out of the water stream. Hence, not only is the settling process faster but the equipment required is smaller and lighter. However, the capital cost of the equipment may be more than a simple skim tank. See Figure 2.

Hydrocyclone technology can also be used to separate suspended solids from produced water. Solid-liquid hydrocyclones work by converting pressure energy to centrifugal motion in order to increase the applied gravitational force field. Increasing the gravitational force increases the settling rate of the solids and therefore results in smaller, lighter equipment. In addition, particles of a smaller diameter can be separated due to the improved separation efficiency afforded by the higher g-forces generated by the solid-liquid hydrocyclone. See Figure 3.

Solids that are too small to be efficiently removed by the use of a PPI/CPI equipment or solid-liquid hydrocyclones may require mechanical filtration for removal. In land-based injection operations, the types of filters commonly used are cartridge filters, nutshell media filters and granular media filters. As contaminants build up on or in the filter, the pressure drop across the filter increases and, eventually, the flow rate of produced water decreases. Hence, periodically, filtration equipment must either be cleaned or replaced.

Nutshell media filters and granular media filters are designed to be self-cleaning. Nutshell media filters utilize crushed nutshells from pecans and/or walnuts as the filtering media. Granular media filters utilize sand, anthracite and/or garnet as the filtering media. As contaminants are removed from the produced water stream, they collect in the media bed and the media bed must eventually be cleaned. These filters use what is termed a backwash sequence to remove solids that have accumulated in the media bed. The backwash process uses a reverse flow of water to wash the contaminants from the media bed. The filtration efficiency of the media bed after the backwash process is virtually the same as it was before the backwash. Since the water used for cleaning becomes contaminated with solids and/or oil from the media bed, a separate treatment system must be provided to treat this dirty backwash water. See Figures 4 and 5. In oily water service, nutshell filters are preferred as nutshell filters are less susceptible to fouling. However, with proper attention to proper operating procedures, granular media filters have been used successfully in oily water service. It should be noted that granular media filters are able to remove somewhat smaller particles than the nutshell media filter.

Cartridge filters are not recommended for use in produced (oily) water service due to the tendency of paraffin or other waxy material in the oil to coat the cartridge filter and lead to more frequent filter change-outs and higher cartridge replacement costs. However, if a particle removal specification is very tight, there may not be an alternative. In this case, the operator must compare the cost of cartridge filter replacements over the life of the project versus the cost of more frequent injection well remedial cleanout operations. Most operators use cartridge filters that are simply replaced after becoming loaded with contaminants. In such cases, a differential pressure device measures the differential pressure across the filter element(s) so the operating personnel can determine when a filter change is needed.

Suspended Oil Removal

Suspended oil must be removed prior to injection into a subsurface formation due to possible damage to the injection formation and to recover salable oil. Most water treating equipment used for oil removal takes advantage of the density difference between the oil and water phases. It is advisable to collect samples of the suspended oil and the water phases, if possible, to perform an analysis of the physical properties of each phase. The analysis will provide detailed information that is required to properly specify a treatment scheme. For instance, the analysis will report on such items as the density of the oil and water, the concentration of oil in the water stream and other vital information needed for a proper design. Having this information helps operating personnel better understand the problem that needs to be solved.

The oil in the water may be present as a separate oil layer floating on the surface of the water phase or as distinct droplets of oil dispersed throughout the water phase. Due to the difference in density between the phases, the dispersed oil droplets will tend to rise to the surface and combine with other oil droplets in the surface layer. As previously mentioned, when the flow regime is laminar, Stoke's Law can be applied to describe the rate of rise of the oil droplets. Oil removal is usually done in stages from primary bulk removal to final polishing. The number of stages required is a function of the type of oil in the stream, the size distribution of the oil droplets, the concentration of the oil and the level of removal required for the application.

Of course, the larger lighter-density particles will be easiest to remove. Separation of oil droplets in this category can be accomplished simply by allowing enough retention time for the droplets to rise to the oil layer at the surface. This is termed gravitational settling. This is the most simple and least costly solution to oil removal. Gravitational settling can be accomplished by using large settling tanks or skimmer tanks. These types of tanks are common to land-based operational facilities due to the fact that space and weight constraints are not very stringent and the installed cost is relatively low.

The speed of oil removal via gravitational settling can be greatly enhanced by use of parallel inclined plates inside of a rectangular tank or cylindrical vessel (PPI or CPI equipment). Placing a section of closely spaced, parallel inclined plates in the flow of a produced water stream containing suspended solids accomplishes two things: 1) it shortens the distance that an oil droplet must travel before it reaches a coalescing surface; and 2) it provides plenty of surface area for oil droplets to collide and coalesce into larger, easier to remove droplets. Hence, not only is the settling process faster but the equipment required is smaller and lighter. However, the capital cost of the equipment may be more than a simple skim tank. See Figures 1 and 2.

Hydrocyclone technology can also be used to separate suspended oil from produced water. Liquid-liquid hydrocyclones work by converting pressure energy to centrifugal motion in order to multiply the gravitational force field. Multiplication of the gravitational force increases the settling rate of the oil droplets and therefore results in smaller, lighter equipment. In addition, the separation process itself is more efficient, in terms of the smallest droplet that can be removed. See Figure 6.

Flotation technology is also used as a polishing step for removing small amounts of small oil droplets and oil-coated solids from produced water. Flotation, as the name implies, is a technique whereby the contaminants in the produced water are made to "float" to the surface much faster. This is accomplished by introducing natural gas bubbles (or air bubbles) into the produced water stream. These bubbles then attach themselves to either oil droplets or oil-coated solids and "float" these contaminants to the surface for removal. Chemicals having a high charge density are used to promote the attachment of gas bubbles to the oil and solids contaminant substances. Many land-based flotation devices incorporate cylindrical vessels divided into four active cells, or compartments and one collection cell. The produced water flows sequentially from cell to cell. Gas is injected into each active cell so that an incremental amount of oil and oil-coated solids are removed in each cell. Finally, the clean treated water enters the final chamber for collection and disposal. See Figure 7.

Oil droplets that are too small to be efficiently removed by PPI/CPI, liquid-liquid hydrocyclones or flotation technology may require mechanical filtration for removal. In land-based injection operations, the types of filters used are nutshell media filters and granular media filters. As contaminants build up on or in the filter, the pressure drop across the filter increases and, eventually, the flow rate of produced water decreases. Hence, periodically, filtration equipment must either be cleaned or replaced.

Nutshell media filters and granular media filters are designed to be self-cleaning. Nutshell media filters utilize crushed nutshells from pecans andor walnuts as the filtering media. Granular media filters utilize sand, anthracite and/or garnet as the filtering media. As contaminants are removed from the produced water stream, they collect in the media bed and the media bed must eventually be cleaned. These filters use what is termed a backwash sequence to remove solids that have accumulated in the media bed. The backwash process uses a reverse flow of water to wash the contaminants from the media bed. The filtration efficiency of the media bed after the backwash process is virtually the same as it was before the backwash. Since the water used for cleaning becomes contaminated with solids and/or oil from the media bed, a separate treatment system must be provided to treat this dirty backwash water. See Figures 4 and 5. In oily water service, nutshell filters are preferred as nutshell filters are less susceptible to fouling. However, with proper attention to proper operating procedures, granular media filters have been used successfully in oily water service. It should be noted that granular media filters are able to remove somewhat smaller particles than the nutshell media filter. See Figures 4 and 5.

Chemical Treating for Control of Bacteria

Control of biological organisms in water systems is primarily dependent upon the use of chemical agents; however, there are physical measures which can help to minimize bacterial problems and which will make chemical treatment more effective, perhaps reducing the chemical dosage required. Chief among these measures is cleanliness. Accumulations of scale and sludge or other deposits form an ideal environment for bacterial growth. In addition, they limit the exposure of the bacteria to chemical treatment agents injected into the stream. Cleaning of lines by periodic pigging and flushing with surfactants or solvents is strongly recommended.

The chemicals employed for biological control are usually either an inorganic oxidizing agent or one of a variety of organic compounds. These function by poisoning the organism, oxidizing some component of the cell, or destabilizing a structural component of the cell (cell walls or cell membranes) or a combination of these effects.

Commonly used inorganic oxidizing agents are chlorine (Cl_2) and sodium hypochlorite (NaClO). Chlorine is an effective and inexpensive sterilizing agent for source water. It is very effective against planktonic organisms but much less so against sessile ones. It reacts with oxygen scavengers, corrosion inhibitors, scale inhibitors, and corrosion products, so the presence of these materials can be cause to use some other biocide. In some cases, it may be desirable to use chlorine supplemented with an organic biocide. In this way, it is possible to combine the sterilization potential of chlorine with the persistence of another biocide. Chlorine and hypochlorous acid (HCIO) can be generated electrolytically by hydrolysis of brines on site. Chlorine residuals should be monitored regularly with a chlorine based control system. The potential of chlorine to produce chlorinated hydrocarbons that render water unsuitable for surface discharge and that may foul refinery catalysts should always be considered. Sodium hypochlorite, as a 3% solution, may be used in much the same way as chlorine or hypochlorous acid. However, it decomposes easily, especially with heat and light, and is corrosive; therefore It suffers from higher costs of transportation and storage.

Most organic biocides are based on oxygen compounds such as phenols, polychlorophenols, aldehydes, and peroxyorganics or on nitrogen compounds such as amines and quaternary ammonium derivatives. Many commercial preparations contain more than one active ingredient.
The effectiveness of these materials varies widely from one situation to another; so screening tests are usually needed to pick the most desirable treatment. Procedures for conducting these tests are given in API RP 38. Since the biocide will probably be less effective In the system than in the screening test, anything producing less than total kill should be eliminated. Sessile bacteria are much more difficult to control than planktonic ones, yet the screening tests are related to planktonic kills. However, screening tests give valuable information regarding the effect of background water chemistry on the action of the biocide. Due to the limitations of screening tests, it is essential that careful monitoring of the system be carried out after treatment is begun. Attention should be given to growth of sessile bacteria on corrosion coupons, the presence of hydrogen sulfide, and changes in water analyses. Correlation of operating experience and bacterial population will provide the best guidelines to the degree of control required for cost effective operation.

Application of biocides can be done using either continuous injection or intermittent slugs. The former is usually more expensive, but some situations do not respond well to slug treatment. The frequency of slug treatment can vary from every few days to monthly and must be determined by operating experience. Maintenance of an effective residual concentration of biocide through the system may require Injection at several points to overcome losses by physical adsorption and chemical reaction. If a microbial survey of the system reveals a source of exceptionally heavy contamination, e.g., in a storage tank, cost savings may be realized by injecting a larger dose of biocide at this point. Many bacteria are able to develop strains resistant to specific organic biocides over an extended period of exposure. Therefore, it is common for the effectiveness of a treatment program to decline. Selecting two effective biocides and rotating between them as soon as an increase in bacterial population is noted may often prevent this.

Chemical Treating for the Control of Scale

The kinds of scale deposits most common in produced water injection systems are calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate and iron sulfide. It is imperative that water chemistry analyses be conducted to determine not only the scaling tendency of the produced water, but also the existence of any incompatibilities between produced waters from different sources. Depending upon the circumstances, scale can be prevented by simply avoiding the mixing of incompatible waters. However, by far the most commonly used approach to scale control in produced water injection operations is to inject chemical scale inhibitors.

As the name implies, scale inhibitors act to retard the formation of or limit deposition of scale that would normally be present for a given water chemistry and set of operating conditions. Phosphate esters and phosphonates are the chemicals most often used in this service. To be effective, though, the chemical must be applied to the produced water stream at a location upstream of the point at which the scale will likely begin to form. Furthermore, the chemical must be injected on a continuous basis so as to be in solution to prevent scale formation at all times that the produced water is being injected.

Corrosion Control Techniques

Corrosion is the result of chemical attack on a metal. All corrosion reactions require the presence of four conditions. These are as follows:

1. Anodic Area - This is an area of the metal on which oxidation is occurring. The base metal dissolves to form metal ions, and electrons are released.
2. Metallic Conductor - A metallic path must exist to carry the freed electrons to the site of a reducing reaction.
3. Cathodic Area - This is an area of the metal at which reduction is occurring. Positive ions react with the free

electrons to produce reduced species.

4. Electrolytic Conductor - An electrolyte solution must connect the anode and cathode to conduct the ionic flow between them.

Corrosion can take several forms. These may be generalized as follows:

Thinning Corrosion. The metal thickness is reduced evenly over the surface undergoing corrosion. This type of corrosion is seen when relatively homogenous metals are exposed to mild acid solutions.

Pitting Corrosion-This is the result of localized attack caused by differences in surface free energy or differences in chemical environment across a metal surface. This is a common form of attack and is one that can produce rapid failure by penetration of pipes and vessels.

Intergranular Corrosion. Differences in potential between grain boundaries and metal grains produce this type of corrosion. It is of particular concern with complex alloys and can lead to loss of tensile strength resulting in structural failure.

Galvanic Corrosion. Potential differences associated with different metals which are in contact lead to chemical reactions in which the more active metal is oxidized. Differences in oxygen exposure can also lead to this type of corrosion.

Materials that may be dissolved in water and influence corrosion reactions include acids, acid gases (H_2S and CO_2), salts, and oxygen. All of these solutes can accelerate corrosion reactions. The mechanism by which acceleration occurs is often the removal of the products of reaction that tend to build up at the reaction site and limit the movement of ions. Limitation of ionic movement is called polarization.

Treating water for corrosion control involves either removing the solutes that aid corrosion or adding other chemicals to inhibit the reactions. Treatment methods include deaeration by mechanical or chemical means, degasification, and alkalinity control. Corrosion inhibitors are frequently added in conjunction with these methods. These function by forming tight layers of oxide, phosphate, or other metal compounds on the metal surface, or by forming an adsorbed layer of organic material on the surface.

Corrosion can also be controlled by the use of corrosion-resistant materials or by the use of sacrificial anodes, Corrosion-resistant materials are poor conductors of electrons and thus minimize corrosion by minimizing the flow of freed electrons. Sacrificial anodes are more reactive than the material used for the piping, valves, tanks or vessels in the system. Hence, the sacrificial anodes will be consumed in lieu of the production system components.

Other Chemical Treatment Needs

Produced water for injection may also require treatment for the following:

- Reverse demulsifier to resolve oil-in-water emulsions
- Chemical filtration aids (polyelectrolyte, coagulant) for filtration performance
- Surfactant chemical to assist in backwash of granular media

In view of the importance that chemical treatment has in the operation of a production, the following are a few of the important critical factors for achieving proper and effective chemical dosing:

1. Proper analysis of the chemical and physical properties of a representative water sample as the basis for treatment
2. Proper assessment of any incompatibilities or interactions between the injected chemical and other species in the produced water (including compatibility with other chemicals in use, mixing water compatibility analysis and scale prediction techniques)
3. Proper location of chemical injection points
4. Proper chemical concentration
5. Proper hydration or mixing of chemical, if required
6. Consideration of variations in flow (system surges) to minimize the occurrence of over-treating or under-treating of chemical

IV. PRACTICAL APPLICATION OF THE TECHNOLOGY

In order to properly apply produced water treating technology to a land-based oilfield water injection facility, the operator must first be equipped with as much accurate information as possible. To begin with, the reservoir characteristics must be fully understood. At best, whole-core samples from the injection formation should be analyzed to determine the water quality requirements of the proposed injection water in terms of the maximum particle size allowed and the maximum content of oil and solids allowed. The core should also be analyzed to determine if the compatibility of the formation with the components of the injected water. In addition, samples of the formation water, the injection water and any chemicals to be used must be analyzed for compatibility. Basic information such as operating pressure, operating temperature, flow rate profile, physical properties of the oiliwaterigaslsolids, presence of corrosive agents, presence of emulsions, concentration of oil in the produced water and concentration of solids in the produced water must also be determined. In the event that some of this information cannot be provided from the project under consideration, then reliable offset data from a nearby location can be used or an educated assumption can be made. However, not only should estimates and assumptions be minimized, but also careful notes should be made of any such estimates or assumptions.

Once the basic information has been gathered, an operating plan must be established. The operating plan should consider such ideas as the following (not necessarily in order of importance):

- Location of the facility (environmental factors; i.e. terrain, climate, soil conditions, etc.)
- Life of operation
- Plot space available for the plant (space/weight constraints)
- Operating experience/training of personnel
- Manned versus unmanned operation
- Remoteness of facility
- Availability of services (electricity, plant/instrument air, plant water, natural gas, etc.)
- Environmental constraints
- Regulatory constraints
- Capital expenditure constraints
- Operating expenditure constraints
- Public relations issues

These and many other issues must be addressed in the operating plan. After establishing the operating plan, then the process design and the selection of equipment can begin. The process of establishing the appropriate process becomes an exercise in balancing project costs with required system performance with the goal of optimizing system performance while at the same time minimizing project costs. In addition, the "keep it simple" principle must also be considered. To illustrate, please consider the following example.

An operator desires to treat a produced water stream for injection into a subterranean formation as part of an enhanced oil recovery project. Produced water for injection is from a central processing facility that handles producing wells from various fields in the region. The central producing facility is located in a tropical and remote location. The operator prefers an unmanned facility. The operator desires to minimize use of land to appease local concerns about destruction of plant and animal habitat. Furthermore, the reservoir department has issued a very tight specification for solids removal. Tests have determined that the oil has a relatively high specific gravity compared to the produced water. Finally, the operator has some media filters in the warehouse that management want to use. Here is the solution applied to this situation. See See Figure 8.

The strict requirements placed upon the project by reservoir personnel and public relations personnel dictated certain decisions. For instance, even though this is a land-based operation with no inherent space constraints, the decision was made to minimize land use due to sensitivity of the local inhabitants. Hence, downstream of the first-stage skim tank, liquid-liquid hydrocyclones and flotation equipment were selected and installed due to their smaller footprint requirements. Furthermore, the fact that the oil was relatively heavy required the use of equipment with higher separation efficiency, i.e. hydrocyclones and flotation. The tight solids removal size specification imposed by the reservoir department required the use of either granular media or cartridge filtration equipment. Since the customer had access to granular media filtration equipment, the decision was made to make use of this equipment. Since granular media filters are more susceptible to contamination by heavy oil, a nutshell filter was included in the equipment train upstream of the granular media filters as a pre-treatment step to reduce the oil content in water processed by the granular media filters. Downstream of the granular media filters the treated produced water enters a clean water storage tank. A highly sophisticated controls system was employed to operate the plant due to the fact that the site is unmanned. Furthermore, the chemicals were stored in tanks with enough supply for one month of operation between refills so as to minimize chemical transfer trips to this remote site. In this case, high-technology equipment was used in order to meet the requirements of the project, while also minimizing the overall capital and operating expense.

Consider another, more straightforward example. This operation is located in a West Texas oilfield. In this case, the facility is manned 12 hours a day with an operator on call for emergency after-hours situations. The water treatment equipment is to be installed at a central processing facility that collects produced water from various fields. There is plenty of area available for the equipment at this land-based facility, so there are no space or weight constraints. The report from the reservoir department indicates that the injection formation is not very tight so a "normal" level of water treatment will suffice. Furthermore, the oil and produced water properties are such that good separation can be achieved easily. Here is the solution applied to this situation.

Since this case does not have many of the constraints mentioned in the previous example, a "typical" low technology, low cost solution is sufficient. **A** skim tank is used as the first stage of treatment to remove the larger oil and solids contaminants. A nutshell filter as the final polishing stage follows the skim tank before entering the clean water storage tank. As can be seen, this system is much simpler, incorporating low technology equipment and resulting in a lower capital expense while still addressing the specific performance requirements of the project.

V. CONCLUSION

As can be seen from the foregoing discussion, the proper application of produced water treating technology to land-based injection operations is not always simple or straightforward. Good upfront planning is crucial to properly assessing the problem and selecting the correct process and equipment that result in the most economic solution. Data and information regarding the injection formation (from physical core samples), the formation fluids properties, the injection fluids properties, and any chemicals to be used must be collected and analyzed by trained personnel. Hopefully enough information is available to carry out an injection analysis to determine the level of produced water cleanliness required. The results of these analyses must then be considered during the planning stages and then a produced water treatment specification can be generated. This specification presents the design criteria for process and equipment selection to proceed. Also, if there are other factors, such as size and weight constraints, regulatory or environmental constraints, capital or operating budget constraints, these must also be given due consideration in the planning stages. In this manner, the optimum operating efficiency and economic efficiency of the project can be achieved.

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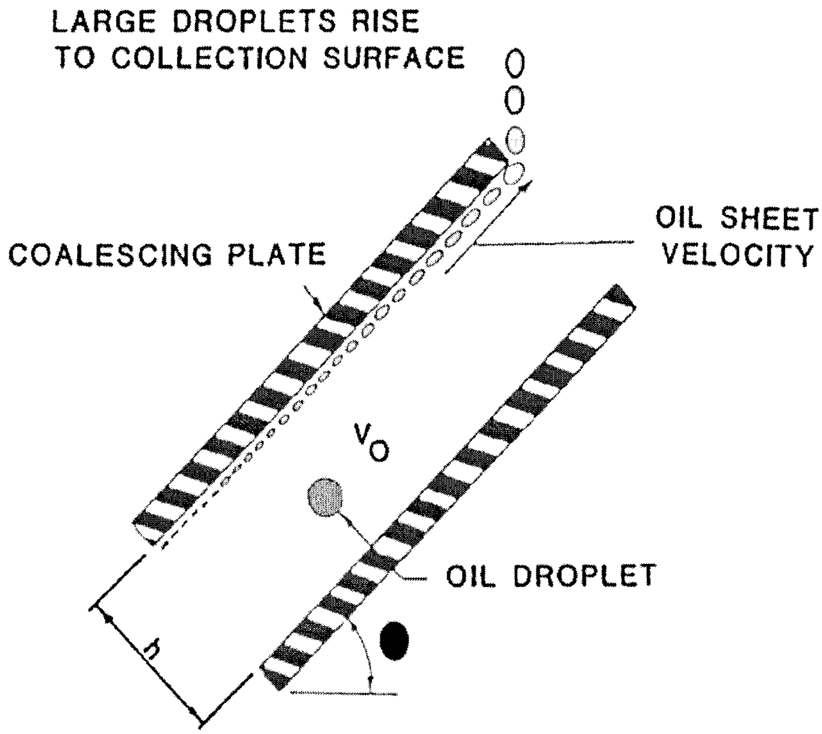

Figure 1- Parallel Plates

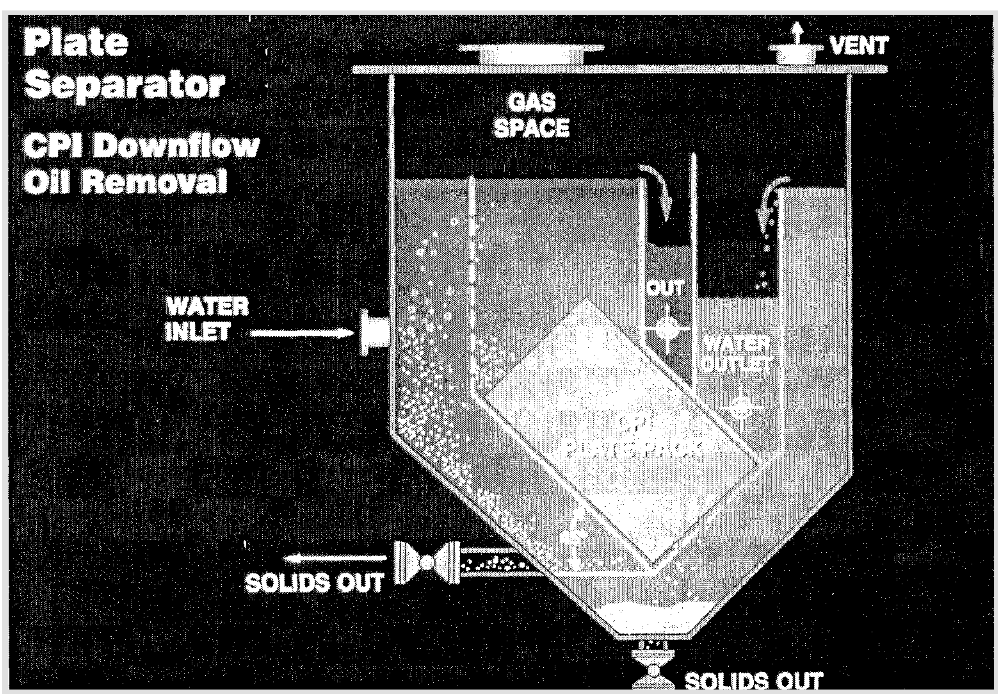

Figure 2 - CPI Unit

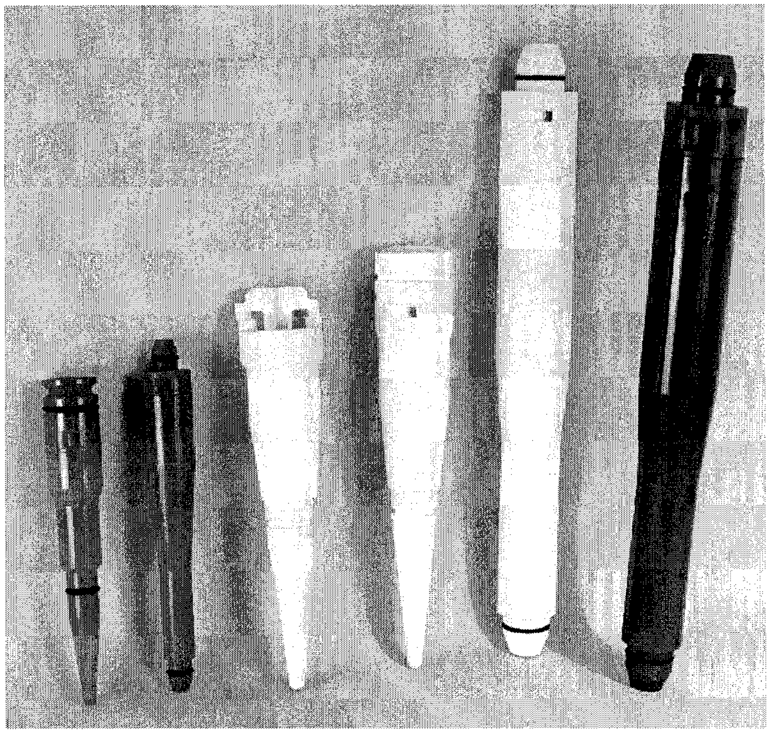

Figure **3** - Solid-Liquid Hydrocyclone Elements

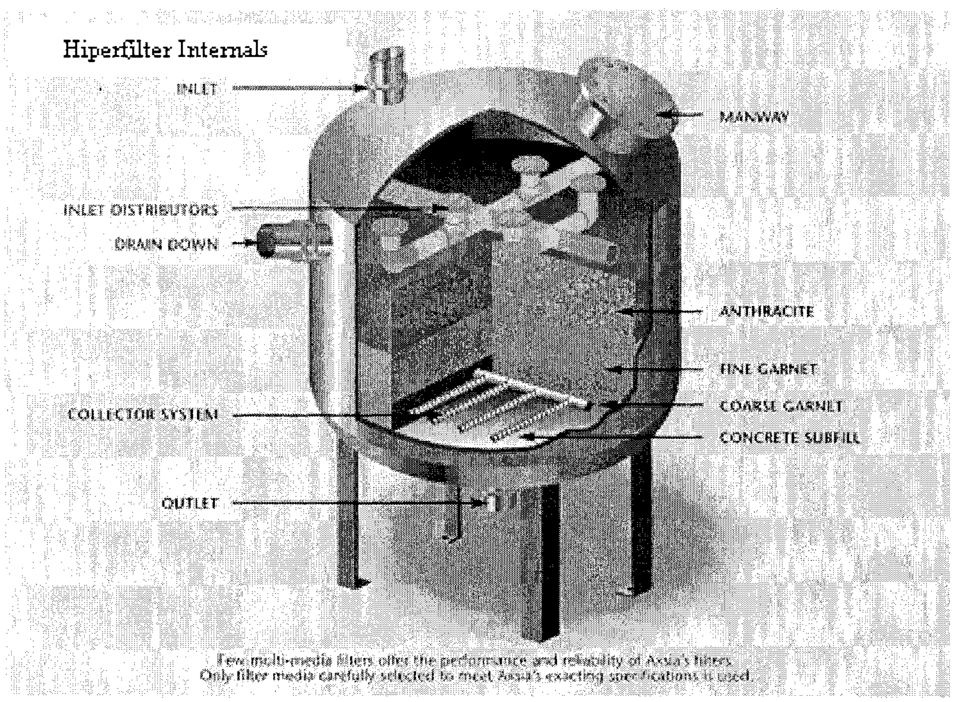

Figure **4** - Granular Media Filter Unit

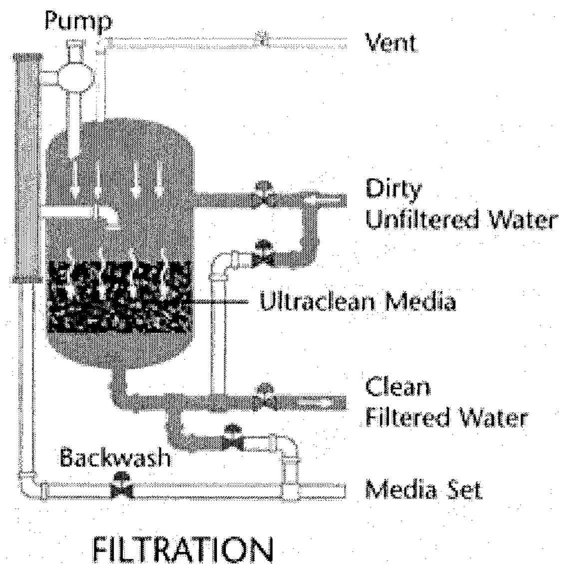

Figure 5 - Nutshell Media Filter Unit

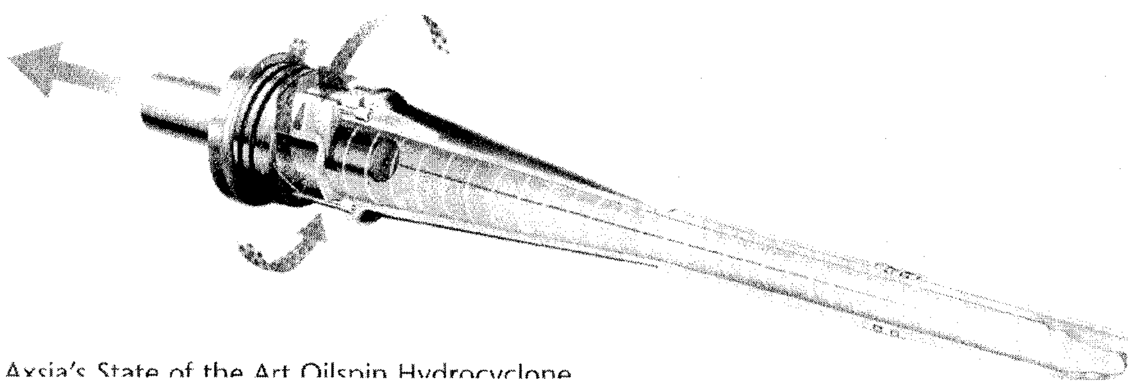

Figure 6 - Liquid-Liquid Hydrocyclone Element

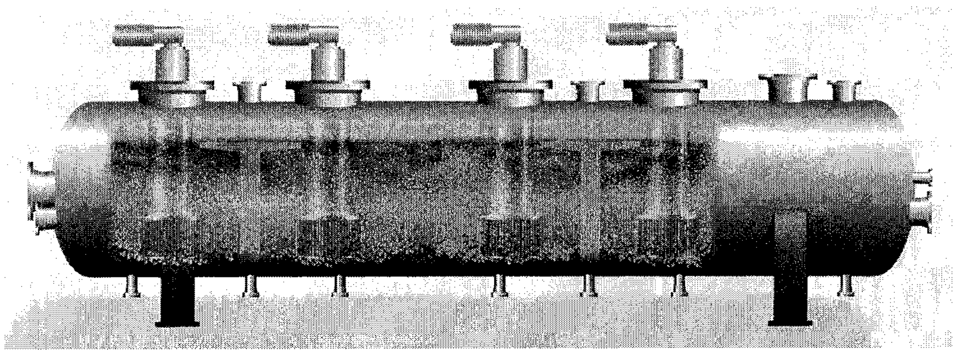

Figure 7 - Flotation Unit

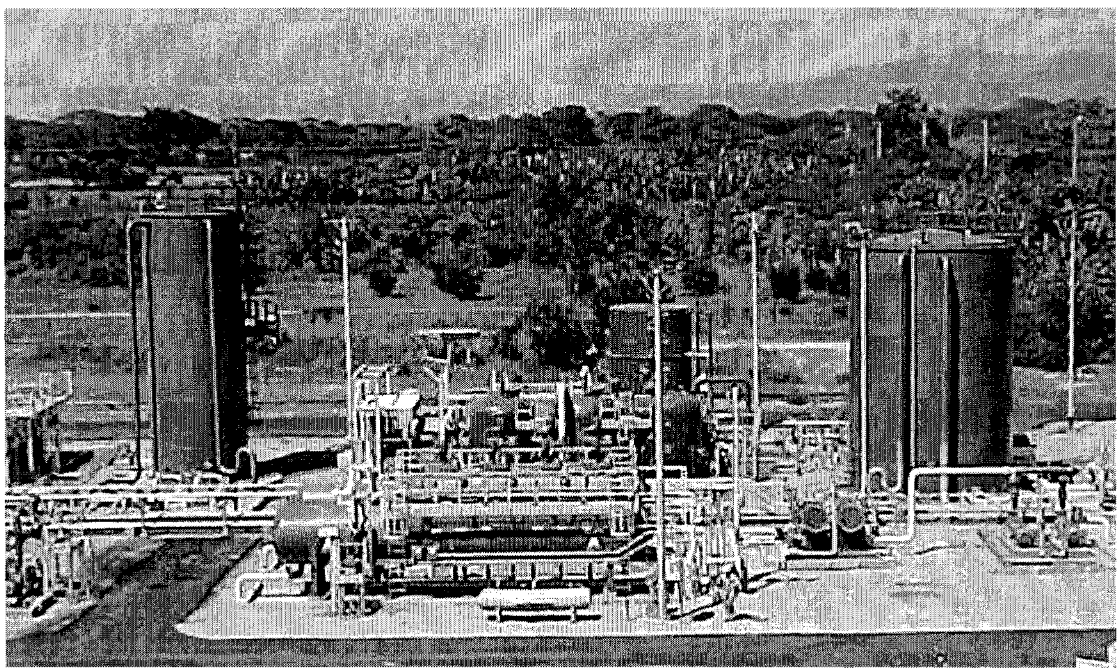

Figure 8 - Example #1 -Aerial View of Equipment