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Waterflood Operability—Process and Chemical Issues

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Abstract
In the last few years, Shell has implemented three deepwater waterflood systems. They are all on floating installations, employ relatively compact and light weight facility designs and are roughly the same capacity. While their overall designs are similar, important details of the designs are different, and the project management strategies were significantly different as well. The startup and initial run time experience of these waterfloods facilities differed greatly, ranging from significant downtime for the first project to nearly complete success for the last one. Shell is in the process of sanctioning a forth deepwater waterflood system that is larger and more complex than the previous three. Obviously, Shell has already learned a great deal about how to successfully implement a deepwater waterflood project. Before we develop the new project however, we are capturing our waterflood experience to date.

Introduction
In keeping with the theme of this OTC Session, "Challenges of Deepwater Waterflood Systems," this paper focuses on the challenges that are unique to deepwater waterflood systems. The list of challenges that are given below is based on a review of the startup and initial operating experience of three recently built systems. First the challengers are described, then the background on each of the waterfloods is given, then we describe how the different waterflood systems approached the challenges, and what the outcome of these different approaches were.

In this paper, the following challenges of deepwater waterflood facilities systems are considered:

1. **Material selection / corrosion engineering**
2. **Oxygen control**
3. **Filtration**
4. **Fluid dynamics**
5. **Anti-Souring / Reservoir Management Strategy**

There are other features of waterflood systems that are discussed below. The list above includes only those challenges that have been found to have a significant impact on the reliability uptime and operability of the project. In this section, these challenges are described in more detail and we give the reasons why they are challenging.

1) **Material Selection / Corrosion Engineering:** The corrosive properties of oxygenated seawater are significant and pose a challenge to all industries that are involved with seawater including shipping, marine fishing, recreational boating, bridge building, etc.. This problem has been around for many years. While there are many more materials alternatives available today, material selection is still a challenge. Also, due to chloride stress corrosion cracking, the marine environment poses material selection challenges for even those components that do not handle the seawater directly. Not only is material selection a challenge but also quality assurance is a challenge - i.e. making sure that you get the material that you selected.
2) **Oxygen Control:** Closely related to materials selection is oxygen control. In fact, oxygen control is such a challenge, that many waterflood teams consider the option of injecting "raw" seawater. To do so, the materials have to be resistant to oxygenated seawater, which trades one challenge for another. In the end, most projects select deoxygenation in part because of materials performance uncertainty and cost. Compounding the challenge for deepwater projects is that traditional methods (vacuum tower, gas stripping tower) are large and heavy. So there has been significant effort to develop relatively compact and lightweight deoxygenation systems. There are several variables that can affect the oxygen concentration throughout the control system. In addition to the challenges of oxygen control, oxygen sensing / measurement is also a challenge. Thus, there is always an uncertainty in the validity of the data. Significant time and effort are usually spent by the project team to overcome these challenges.
3) **Filtration:** Deepwater waterflood systems actually have less severe filtration challenges than near-shore waterfloods. Also, it is now commonly recognized that injectivity impairment is significantly reduced if injection pressure is maintained above frac pressures and this is the typical strategy employed. With these factors in mind, it would seem that filtration is not a challenge at all. However, filtration becomes a challenge because of one important decision – whether or not to use deep bed

(multimedia) filtration. Such filtration will surely work but it is heavy, particularly when liquid full, and occupies a great deal of space compared to alternatives such as cartridge filtration. If deep bed filtration is installed and not needed, it is a tremendous waste. If it is not installed, and it turns out that it is needed, the consequence is devastating in many ways. It is difficult, though not impossible to access accurately the filtration requirements prior to project design.

4) **Fluid Dynamics:** The fluid dynamic properties of a waterflood system are different from those of an oil / gas system. For people who know this fact, it goes without saying. But, in our experience, few people with traditional oil / gas experience understand the issues until they see the consequences such as waterhammer, flooding the vapor space of the deoxygenation units, and level / flow control problems. Waterhammer is at best damaging to the equipment and at worst, dangerous to operations personnel. Fluctuations in flow occur from filtration backwash cycles, variable demand from other users of the seawater system, and from pump startup and shutdown. While these are all typical occurrences in an oil / gas system, the dynamics of the waterflood are different. Flow control / level control problems can cause startup problems, and frequent shutdowns and lead to poor uptime.

5) **Anti-Souring / Reservoir Management Strategy:** In the last five years or so a great deal of information has been published about how to reduce the extent of reservoir souring. Much of this information has been obtained from waterflood experience spanning thirty or more years but only recently have operators come together with microbiologists, chemists and reservoir engineers to piece together a coherent picture of the processes at work. Two of the difficulties in understanding the souring mechanisms are that the system (the reservoir) is remote and not available for study, and the fact that there is typically a gap of a few to several years between implementing an anti-souring strategy and seeing the results. Also, it turns out that the mechanisms involved are fantastically complex. Nevertheless, the economic reward for reduced souring is significant and real progress is being made. The real challenge posed by souring reduction and reservoir management is the tendency to reduce the available timeline for the topsides development. Typically it can take months if not years for a waterflood project team to advance to the point of a decision regarding the anti-souring / reservoir management strategy. Since such a strategy is required at an early stage in waterflood project development and review, this reduces the time available for topsides design, review, approval, construction and implementation. This is particularly true when the reservoir is approaching bubble point, or when the waterflood is needed to stem compaction or boost production rates. As with any project, schedule constraints have a significant impact.

The list of challenges given above was developed by reviewing the experience of three Shell deepwater waterflood projects. These are the challenges that caused downtime, caused forced shutdowns for repairs, and in one case, resulted in abandoning a significant section of the original built system. Also, the anti-souring / reservoir management challenge, because it can require significant time to resolve, can impose tight project schedule constraints, once the project is approved.

One of the interesting features of these challenges is that they are not the challenges that were originally thought to cause the most problems. The potential challenges that were identified during the second waterflood for example, were challenges that are more typical of oil / gas systems. In that project, the emphasis was on getting the right balance between cost, availability, redundancy, sparing, schedule and quality for components such as:

- **High pressure pump**
- **Power source, power shedding strategy**
- **Booster pumps and air / nitrogen blowers**
- **Instrumentation sensors, PLC systems, control panels, control valves, etc..**
- **Nitrogen and instrumentation air cleanliness, supply**
- **Chemical injection meters, storage, pumps, etc..**

These are typical challenges for any oil / gas system and they are well recognized in the oil / gas industry. They are no less challenges in waterfloods and they did cause problems. For example, the high pressure pump caused problems on two of the waterfloods described below. But because these problems were identified, and are fairly well understood in the industry, reasonable solutions were obtained. Challenges 1 - 6 are unique to waterflood, and are discussed in this paper because they deserve the greatest attention at this stage of the development of deepwater waterflood technology and project management.

Background of the Three Waterfloods:

In this section we discuss the overall project drivers for the three waterfloods. Some of the important parameters are given in Table 1.

Table 1. Summary of Design Bases for the Waterfloods

	WF1	WF2	WF3
Installation type	FPSO	TLP	FPSO
Injection capacity (BWPD)	100,000	100,000	300,000
Date of initial injection	Aug 2003	Mar 2004	Dec 2005
Depth of water source (ft)	90	90	~150’
Depth of sea floor under the source water inlet (ft)	3,000	3,000	3300’

Note: WF3 has a higher overall injection capacity than WF1 and WF2. However, this is achieved by having two trains. Therefore, on a train by train basis, all three waterfloods have similar capacity. This fact will be used later to compare differences in vessel sizes and other equipment.

WF1 is a green-field project on an FPSO. The waterflood facility was built as part of the original facilities design and construction. Shell acquired the FPSO after the topsides construction was complete. Shell had essentially no influence on the design since the system was designed, built, and installed before Shell acquired the facility. One of the interesting features of WF1 is that it is roughly the same capacity as the other waterfloods but the design of the deoxygenation system is significantly different. The same vendor supplied the deoxygenation system design as for the other two waterfloods but the operating company did not have a strong influence on the design. This waterflood, like that of WF3, is needed to maintain reservoir productivity. In both WF1, and WF3, one barrel of injected water equates to one barrel of oil production. The target reservoirs are all turbidite sandstones. As is true of the other two waterfloods, the intention is to inject at pressures above the sandstone frac pressure. The installation for WF1 is an FPSO and all injection and producer wells are subsea. The materials used in the producer wells were selected without consideration of seawater waterflood and have little resistance against sulfide stress cracking from hydrogen sulfide exposure. Developing a robust hydrogen sulfide monitoring system, and the construction of a well bull heading system, for safe shut-in of a well in the case of escalating hydrogen sulfide were significant features that had to be added after waterflood implementation.

WF2 is a brown field project on a TLP. The TLP had been in operation over five years before the waterflood project was approved. Although waterflood was part of the original design basis, the footprint that had been originally planned for waterflood had been partially utilized for other projects. Not only had available footprint been reduced, but also the available weight had been reduced as well. In addition, the source water system had been tapped for various other systems such as drill rig cooling water and FGC cooling water. These seawater users would impose fluctuating backpressure on the overall seawater piping system. Also, use of the seawater for cooling would be a source of hydrocarbon leakage into the seawater feed to the waterflood. Thus, this waterflood had significant system integration challenges.

Another complicating factor existed for WF2. The oil producing wells which were drilled and installed in the original field development were based on the assumption that reservoir souring from waterflood would not be an issue. This assumption was partly due to the anticipated timing of waterflood where it was expected that the original wells would have reached end of life and new producer wells would need to be drilled anyway at which time, better, more H2S tolerant steel could be used. Another assumption was that reservoir souring would be significantly reduced, if not eliminated, by emerging technologies such as Sulfate Reduction Membranes. While this is true to very large extent, the size of a SRM system is just too large for this particular facility and could therefore not be employed to control souring. Thus, one of the major challenges for this project was to employ a means of reducing the reservoir souring in order to allow the safe production of waterflooded zones through wells that were not originally constructed for H2S exposure.

Reservoir souring can be a costly development in a waterflood field due to the toxic and corrosive properties of H2S. Deepwater reservoirs are typically deep beneath mud line requiring deep wells. Deep wells require high strength steel. High strength steel tends to be brittle and have a very low tolerance to H2S. Thus, there is a very large economic incentive to minimize reservoir souring. In the last several years, novel techniques to reduce souring have emerged. As these novel techniques are recognized, they are being applied relatively quickly. Because there are now various options, souring technology poses both a real challenge and opportunity.

For WF2, the souring issue required a few years altogether to resolve. The strategy adopted for souring control was to dose nitrate into the injected seawater from the initiation of the waterflood (day-one) and to apply rigorous microbiological control on the topsides in order to ensure the success of the nitrate treatment. Also, in order to reduce the extent and impact of souring, the strategy included a waterflood and reservoir management plan that would prevent reservoir pressure from dipping below bubble point pressures in the reservoir. The anti-souring strategy was aided by various other factors including high salinity and iron content of the formation water, some siderite in the reservoir rock, relatively high reservoir dip, and long injector / producer distances. While all of these factors did indeed indicate that souring would be minimized in this field, development of the anti-souring strategy took considerable time.

With the objective of maintaining reservoir pressure above bubble point, the waterflood facilities development had to be put on a fast track. Of necessity, a fast track project will drive the decision making process to the lowest levels of the project organization since, the argument goes, there is no time to float options up for review and approval. This would have significant consequences on the operability and uptime of the project, as discussed below.

WF3 was required to be online from day-one of production in order to maintain reservoir pressure. The overall production from the field is dependent on a highly successful waterflood, thus a high availability was required with minimal shutdown for extended periods of time. WF3 design and construction was developed in parallel with the startup and initial operations of WF1 and WF2. Learnings from those waterfloods were implemented relatively quickly with beneficial outcome.

Topsides Processes and Chemical Systems

In this section, the process schematic for each waterflood is presented. Common elements are presented in the first part, and details of each system are presented in the individual parts below.

In this paper, we do not use the names of vendors, nor the name of the technologies. Obviously, vendor selection is one of the keys of a successful waterflood project, but that is not the subject of this paper. We acknowledge that some of the equipment employed did have some problems initially but most of those problems were overcome and the learnings were shared with the vendors such the technology that is available today is significantly improved.

All three of the waterflood systems employed the same vendor-patented DeOx technology. However, the detailed designs of each waterflood DeOx system are different in some important details. In general, the customer has the option of purchasing the system as designed by the vendor, or the customer can have significant influence in the detailed design. In the case of WF1, Shell was not involved in any phase of the design since Shell purchased the field, and the facility, after the facility was built. The vendor, together with the topsides designer, provided the detailed design for WF1. Shell did have significant influence in the detailed design for WF2 and WF3, particularly in the control system design. There are important differences in the details of the design of the three DeOx systems and these differences account for significant differences in the runtime experience.

A generic Process Flow Diagram for the DeOx system is shown in Figure 1. There are two main streams, nitrogen gas, and seawater. The DeOx technology uses nitrogen gas stripping with a catalytic combustion system to regenerate an oxygen-free source of nitrogen gas. The system involves two stages. Each stage involves gas / seawater contact in a static mixer followed by subsequent gas / seawater separation. The overall flow of nitrogen through the system is counter-current. Nitrogen, lean in oxygen content enters the back, and nitrogen rich in oxygen exits the front. That is, lean nitrogen is fed into the system at the downstream end (last stage separator) where it strips oxygen from the seawater that has been discharged from the first stage separator. From the last stage separator, the nitrogen proceeds upstream to the first stage separator where it strips oxygen from the incoming raw seawater. From one stage to another, the nitrogen and seawater are traveling in opposite directions. Both separators are two-phase (water / gas).

While the DeOx system is counter-current overall, it is locally co-current within each stage. That is, nitrogen is injected into each stage upstream of the static mixer. The seawater / nitrogen mixture then travel together in the same direction through the static mixer and into the separator. Turbulent flow through the static mixer disperses the nitrogen into small bubbles which increases the gas / water interfacial area. The concentration of oxygen in the gas is low which drives oxygen out of the water and into the gas.

Since the nitrogen and seawater flow is countercurrent overall, the nitrogen regeneration system is situated on the gas discharge from the first stage separator. In the regenerator, the gas is purified by catalytic combustion of methanol over a palladium catalyst.

The literature [1] indicates that roughly 0.4 gallons of methanol are consumed per 1000 Bbl of seawater processed. When the stoichiometry is balanced, then water and carbon dioxide are generated. Obviously, the water leaves the system by combining with the seawater. The carbon dioxide must also leave the system. The main consequence of carbon dioxide generation is that the pH of the seawater decreases as a result of deoxygenation. This pH drop was measured for WF2 to be roughly 1.0 pH unit under steady state conditions. This agrees with the stated literature [1] value of 1.0 pH unit.

A certain amount of nitrogen from the gas system dissolves in the seawater. The amount that dissolves depends on phase equilibria, and it constitutes a volume of gas that must be made up. The original design of all three waterfloods uses instrument air to make up the gas losses. The main reason for makeup instrument air is for pressure control. For this purpose, there is an instrument air line tied into the PCV line, as shown in Figure 1. A secondary benefit of the air supply is to ensure sufficient oxygen to maintain the reactor outlet temperature. If there is sufficient oxygen being stripped from the seawater to perform these functions, there should be little to no demand for instrument air. In either event, the makeup air rate is supposed to be about 63 pounds per hour which equates to about 825 standard cubic feet per hour and should be on/off control via its pressure controller. The nitrogen generator is designed to provide a maximum of 3600 scfh of 98% purity nitrogen. This rate would use 23 percent of the design capacity of the nitrogen generator.

All three waterfloods use chemical injection of oxygen scavenger to achieve the target oxygen concentration of less then 50 ppb. WF2 uses 5 ppm oxygen scavenger injected into a slipstream of seawater for good mixing and reaction time, then the mixture is injected into the second stage DeOx unit. Manual oxygen testing is carried out at several locations using Chemetrics ampules. A continuous on-line analyzer is used also.

As mentioned, while all three waterfloods employ the same patented DeOx technology, there are significant differences in the details of the actual design. For WF1, the DeOx vendor designed the system. For WF2 and WF3, Shell controlled the design with input from the DeOx vendor and from experience of operating locations both of Shell facilities and other operators. Shown in Table 2, the size of the separator vessels in the DeOx unit varied significantly from WF1 to the other two waterfloods. The consequence of these differences is discussed below.

Table 2. Deoxygenation System Parameters

	WF1	WF2	WF3
Volume of stage 1 (Bbl)	28	50	53
Residence time stage 1 (seconds)	12	23	30
Volume of stage 2 (Bbl)	28	80	53
Residence time stage 2	12	37	30

The DeOx system relies on one or more gas blowers to move the nitrogen from one stage to another. The three waterfloods have a different approach to the blower system. WF2 employed 100 % redundancy in blowers, whereas WF1 and WF3 had no redundancy.

WF1 Process:

This waterflood was part of the original design for a new build facility on an FPSO. The process flow diagram is given in Figure 2. As shown, seawater is lifted from electrical submersible pumps installed in the seawater caissons. There are two caissons, each with a submersible pump. The caisson / pump combination represents a 2 x 100% redundancy. An off-take line, routed to overboard discharge, with a PCV is used to control pressure in the main seawater stream. This control strategy proved to be problematic, as described in detail in the section 4.0.

Two types of filtration are employed, course strainer filters, and deep bed multimedia fine filtration. Between the two sets of filters, a side stream of seawater is routed through two sets of coolers. The two sets of coolers are routed in parallel, with respect to the seawater. In one set, the relatively cool seawater is used to cool produced water before it is discharged overboard. In the other set, the seawater is used to cool the produced oil for storage in the FPSO, presumably to reduce the vapor pressure of the oil stored in the cargo tanks. This side stream of seawater then returns to the main seawater flow. Flow through these coolers is controlled using a PCV which proved problematic due to dynamic fluctuations in the system flow.

The DeOx system for WF1 has relatively small separator vessels, as given in Table 2. There is only one nitrogen blower with no redundant backup. Water from the deoxygenation system is routed to the seawater injection pumps. There are no booster pumps. Between the deoxygenation system and the injection pumps there is another off-take overboard discharge line with a PCV to control pressure (or perhaps flow) in the main seawater stream. This line is used to divert the excess water being supplied by the sea water lift pumps in the event that one of the sea water injection pumps shuts down. A Rosemount oxygen analyzer is used to monitor oxygen in WF1. It appeared to be working well.

WF2 Process:

As mentioned, this waterflood was a brown field development. A schematic of WF2 topsides is given in Figure 3. Seawater is provided by three vertically mounted, electrically driven, centrifugal source pumps, which draw seawater from a sea chest located at the bottom of one of the hull columns in the main structure of the TLP. The discharge from the source pumps is routed to course seawater strainers, where particles greater than 100 microns are removed. A small flow of seawater is taken from downstream of the strainers to supply the two hypochlorite generating cells where the slip stream is treated electrolytically to inject sodium hypochlorite into the main seawater stream downstream of the supply point. The hypochlorite system employs 2 x 100 % fully redundant electrochemical chlorinators. This proved to be an excellent strategy.

The waterflood source water system is comprised of seawater pumps, a side stream feed to the drill rig, and a set of seawater heat exchangers for gas cooling. The seawater heat exchangers had a history of leaking so a degassing vessel was installed to provide the primary interface between the source pumps and the waterflood topsides system. The upstream boundary of the waterflood system was essentially the discharge pumps from this degassing vessel. The filtration comprised of backwashable wedge wire strainers, followed by cartridge filters. No deep bed multimedia filtration was employed. This design decision was made after a long term field study of seawater filtration was conducted. For that study, a filtration skid was installed on the TLP and pressure drop was monitored across various types of filter media. Also, loop currents were studied for their impact on seasonal particulate loading. WF2 had a real time particle size analyzer installed downstream of the cartridge filters. This serves as a performance indicator for the overall filtration unit and also assists the reservoir team with injectivity modeling. Altogether, the decision not to use deep bad filtration was difficult but proved to be correct.

The basic design of the deoxygenation system has been described above. One of the details of this system is the use of 2 x 100 % fully redundant nitrogen blowers. Flow control is achieved by a flow meter input to a flow control valve on an off take overboard discharge line. The seawater discharge from the deoxygenation system feeds the booster pump skid which is comprised of 2 x 100 % fully redundant pumps. From there the water goes to the high pressure injection pump.

All three waterfloods use chemical injection of oxygen scavenger to achieve the target oxygen concentration of less than 50 ppb. WF2 uses 5 ppm oxygen scavenger injected into a slipstream of seawater for good mixing and reaction time, then the mix is injected into the second stage DeOx unit. Manual oxygen testing is carried out at several locations using Chemetrics ampules. A continuous on-line analyzer is also used. WF2 uses a Royce model 1000 and it works reasonably well. WF2 also has a galvanic corrosion probe which is not working due to neglect. It was a fall-back in case Royce didn't work. The chemical program for WF2 is given in Table 3.

Table 3. WF2 Summary of Chemical Injection

Chemical Type	Dose rate (ppm)
Oxygen Scavenger	5.0
Antifoam	0.5
Scale Inhibitor	25
Biocide	400
Methanol	25 ml/m3
Calcium Nitrate	100

DeOx: deoxygenation system
The nitrate dose is for the active nitrate anion in mg / L

WF3 Process:

A schematic of WF3 topsides is given in Figure 4. Water for the WF3 system is provided by two vertical mounted, electrically driven, centrifugal source pumps, which draw seawater from individual caissons below the vessel keel. The discharge from the source pumps is routed to the two seawater strainers, where particles greater than 100 microns are removed. A small flow of seawater is taken from downstream of the strainers to supply the two hypochlorite generating cells where the slip stream is treated electrolytically to inject sodium hypochlorite into the main seawater stream downstream of the supply point. The discharge flow from the package combines with the main seawater flow downstream of the seawater strainers, to achieve a target residual concentration of 0.5 ppm. Sodium hypochlorite from the generators is also dosed into the suction of the source pumps to prevent biological growth at the pumps inlet. The water then passes to the six multimedia filters (5 online, 1 in backwash), where the water is treated to remove solid particles down to 5 microns (98 % of particles greater than 5 microns). From the multimedia filters the water passes through the three waterflood cartridge filters (2 online, 1 standby) before passing to the two waterflood deoxygenators of the De-Oxygenation System. The cartridge filters remove 99.9 % of particles 5 microns are larger and 98% of particles 0.5 microns or larger. The deoxygenators treat the seawater from approximately 5 ppm to a desired level of less than 10 ppb dissolved oxygen. On the outlet of each De-Oxygenation System, oxygen scavenger is injected to polish off any residual oxygen and compensate for any minor fluctuations that may occur.

The injection water tank provides suction for the two injection charge pumps that feed the two high pressure waterflood injection pumps. These two turbine driven centrifugal pumps provide waterflood injection on demand and maintain a set pressure required for injection (up to a surface pressure of ~3000 psig). A manual overboard line from the discharge of each of the high pressure water injection pumps to allow the operation of low waterflood injection rates during start-up and low flow operations was installed. Excess high pressure water is directed overboard through multiple pressure drop devices to allow the pumps to maintain minimum flow rate and avoid the continuous operation of the existing minimum flow valve.

Waterflood chemical injection facilities are included to provide biocide and filter aid to the multimedia filters and methanol and anti-foam to the deoxygenation units. The chemical program is given in Table 4. Oxygen scavenger, biocide, and scale inhibitor chemical injection is also provided for the injection as required. Calcium nitrate is continuously injected for reservoir souring control.

The reservoir souring mitigation was a proactive approach of injecting calcium nitrate from day one and ensuring proper house cleaning topsides using rigorous biocide treatment. Calcium nitrate injection had been considered early in the design and provisions for possible injection were designed into the hardware, however was not the base case. The technology of reservoir souring prediction and control were followed, utilizing information gathered for and generated by WF2, and continuously compared to the assumptions made in the design of WF3. Newly retrieved water samples and subsequent revised souring predictions identified the possibility of reservoir souring above the basis of design limit. The outcome of this study identified the need to start injection of nitrate at the start of the seawater injection. In the case of WF3, this decision imposed no delay on the project, in part due to the information already available through involvement with WF2.

As discovered during operation of WF2, anti-foam is required for operation of the deoxygenation system. It is injected upstream of the static mixer to prevent foam formation that may reduce effective displacement of oxygen in the first and second stage vessels and also prevent mist carry over to the reaction vessel and compressor from first and second stage separators respectively.

Based on the experience of WF1, where full deoxygenation was ultimately accomplished using chemical alone, as a contingency plan, the ability to inject high rate oxygen scavenger upstream of the multimedia filters was installed.

Table 4. WF3 Summary of Chemical Injection

Chemical Type	Dose rate (ppm)
Oxygen Scavenger	6.2
Filter Aid	1.0
Antifoam	0.5
Scale Inhibitor	25
Biocide	600
Methanol	25 ml/m3
Calcium Nitrate	50

DeOx: deoxygenation system

Overall Project and Operating Experience:

In this section, the project development and operating history of the waterfloods is described. In the first part of this section, the experiences common to all waterfloods is discussed. This includes the early failure problems and the more difficult systemic problems as well. Then, in the later part of this section, the experiences for each waterflood are discussed individually.

All of the waterfloods suffered early failure problems. By that we mean, component failure that occurs early in the life of the waterflood that is the result of faulty component selection, faulty manufacture, faulty installation, or some combination of mistakes. Implied in this classification is that the magnitude of the failure is not so severe that it can not be overcome relatively quickly.

Early failures of the type that were encountered in these waterfloods are typical of any large complex project. Such problems can be minimized if enough time is spent to test components and systems prior to startup. To minimize such problems, adequate staff are required, schedule time must be available, replacement components must be available from the suppliers, and both time and funds must be made available to test components adequately before startup. These problems can be avoided altogether if necessary. The decision on whether to spend money to reduce or eliminate these early failure problems must be made based on project economics and will vary from project to project. However, if efforts are not made to control such problems, they will manifest themselves in terms of downtime and repair costs during the initial months of the project.

The issues that led to poor uptime, over the long run, are described here. As mentioned, while all three waterfloods employ the same patented DeOx technology, there are significant differences in the details of the actual design. For WF1, the DeOx vendor designed the system. For WF2 and WF3, Shell controlled the design, with input from the DeOx vendor and from other operating locations worldwide.

One of the problems encountered with WF1 was that whenever the course filters went into backwash, there was a significant fluctuation in the downstream seawater flow rate. This flow fluctuation caused level fluctuation in the first and second separators of the DeOx system. The fluctuation in level caused a fluctuation in the pressure in the separator. The pressure fluctuation is sensed by the pressure control system which ultimately leads to a surge of make-up air from the top-off system. This surge in air happens too quickly for the catalyst regeneration system to respond. That system has too high of a thermal mass to respond quickly. Also, the methanol rate is tuned manually for steady state operation. Thus, a surge of oxygen entering the regeneration system results in a surge of excess oxygen in the discharged water.

One of the proposed remedies for WF1 was to replace the make up gas / pressure control system. The original design used instrument air and the proposal was to replace it with nitrogen. This would represent a fairly significant nitrogen demand and there might still be a need to supply additional air to maintain sufficient temperature in the catalyst bed. As it turned out, there were even more severe problems with the waterflood which prompted the personnel to bypass the DeOx system altogether and to rely on chemical oxygen scavenger.

One of the consistent design features of the WF1 design is the use of pressure control to provide flow control. An example of this design philosophy is the use of a PCV on an overboard discharge bypass line installed downstream of the seawater lift pumps (see Figure 2), which is used to control pressure, and thereby flow, in the main seawater discharge system. There are no flow sensing devices. This approach proved to be problematic in this application, as well as in other applications in WF1.

Figure 5 shows, for WF1, the control system for managing sudden changes in flow rates downstream of the deoxygenating system. Shown there is a level controller and a pressure controller. The purpose of both of these controllers is to ensure that there is adequate level in the final separator which, in so doing, will ensure adequate feed flow to the high pressure pump. The level controller is a conventional level sensor tied to a PLC that transmits a signal to a ball valve. The pressure control system however, was ineffective as the response time to make the necessary flow rate changes based on pressure measurements was too slow. If the pressure sensor had been replaced with a flow sensor, it is believed that the then system might response time would have been adequate to have prevented the process upsets that resulted from flow changes. At this point in the process, the piping system is completely fluid packed, the hydrodynamics are extremely fast, and large variations in flow are associated with only small variations in pressure. A typical high speed multistage centrifugal pump has a flat pump curve (delta P versus throughput). This means that if the pump controller increases the pump speed, for example, then a relatively large increase in the flow through the pump would occur for a relatively small decrease in the suction pressure. The pressure sensor would only indicate a small change. If the PLC for the pressure sensor were tuned such that a small change in pressure resulted in a large change in valve position, then the system would be unstable since the water pressure depends on not only the flow rate but also it depends on the head space pressure, and level in the separator. Head space pressure varies with level in the first separator, and instrument air pressure. While it is possible to increase the dynamics of the pressure sensor / PLC / valve system, it is not possible to tune the PLC to be sensitive enough to respond to small pressure fluctuations. Thus, the level controller in the separator must act essentially alone to control level and must compensate for a sudden change in flow rate, due to pump speed changes or startup and shutdown without much assistance from the downstream pressure / flow control system. Given that the separator is relatively small, this system leads to frequent shutdowns due to level safety low.

The DeOx system for WF1 experienced a wide variety of problems including:

- shutdowns due to level / flow fluctuations;
- wear and tear on the pumps leading to significant pump maintenance due to the frequent shutdowns;
- failure of the blowers due to the presence of liquids in the blower suction;
- premature catalyst failure due to liquids entering the catalyst

A workshop was held with the De-ox system vendor as well as several Shell experts which identified the problems that had been experienced and developed solutions to those problems. However, the cost of the modifications proved to be uneconomical when compared to a solution where oxygen scavenger would be injected. As a result, the original deoxygenation unit was taken out of service, bypassed and oxygen scavenger was used to achieve deoxygenation.

The risk in using only chemical to remove oxygen is that a portion of flow line / well tubing may be exposed to oxygenated seawater before the scavenger has fully reacted to eliminate the oxygen. Shell experienced this problem at Ram Power where the upper tubing section of the A-8ST2 waterflood injection well developed pits of a maximum depth of 80 mils after about 1.5 years of operation. However, for WF1, the location of the FPSO is such that the seawater temperature is relatively warm. This has two beneficial effects in deoxygenation. Warm seawater temperature reduces the solubility of oxygen in water. This decreases the amount of oxygen scavenger that is required. Also, since the reaction is first order in scavenger concentration, the warm water temperature reduces the amount of scavenger that is needed to achieve deoxygenation quickly, which makes monitoring and control of oxygen and residual scavenger more reliable. By bypassing the DeOx system, the uptime went from 55 % to over 95 %.

As shown in Figure 6, WF2 used a system that different in a couple of important details. As shown in Figure 6, there is both a level controller and an actual flow sensor and controller. The level controller and the flow controller both utilize an overflow overboard discharge line. This allows the system to respond rapidly and without unintended downstream propagation of flow or pressure fluctuation. If more flow is needed, then flow is taken out of the overboard discharge. If less flow is needed, then excess flow is thrown into the discharge. In this system, the level controller is able to respond to fluctuations from upstream of the separator while the flow controller is able to prevent fluctuations from downstream to be propagated upstream to the separator. This system was found to be very effective. Also, aiding in the overall dynamics is the larger relative size of the final separator in WF2 compared to WF1, as given in Table 2.

The original WF3 control system was designed on a ‘demand based’ philosophy hence the system was designed to provide and treat only enough seawater as required for water injection. In this approach, the injection tank is, from a controls standpoint, at the center of the control system maintaining constant level. Based on the difficulties experienced with level and flow control in WF1, and based on the relative success of the system employed in WF2, an operability review was conducted with the understanding that stable flow through the waterflood system is the key to successful operation. The group developed several alternative flow schemes and evaluated these options by comparing dynamic modeling results, capital cost, schedule impact and operability. Dynamic modeling showed that the base design control system is susceptible to both minor and major flow disruptions resulting in valve oscillations, backwashes, out of specification oxygen levels and numerous system shutdowns. Complex operator intervention was also deemed required to maintain operation. An injection water tank spillover option was selected as the alternative of choice based on best performance, lowest operability / maintenance and low impact to the already ongoing construction cost and schedule. This option effectively decouples the high pressure section of the waterflood system from the low pressure section and provides a constant flow rate through the low pressure section of the waterflood system including the DeOx facilities. Excess water, that is not required for high pressure injection, is allowed to spill overboard at the injection water tank. The new control system is also simplified and is not as operator intensive. Overall the strategy for WF3 extends that employed for WF2.

Because the new design called for continuous over boarding of water an environmental impact risk assessment was undertaken. The results of the risk assessments indicated that none of the currently selected continuously dosed waterflood chemicals pose any significant risks to the marine environment.

In all three waterflood DeOx systems, instrument air is used to provide makeup gas. The manner in which that makeup gas is tied into the pressure control system, means that fluctuations in level, flow or pressure result in fluctuations in oxygen content of the seawater discharge from the unit. None of the waterfloods had installed instrumentation to measure the oxygen content of the rich or lean nitrogen. Therefore trending the relationship between any of these variables and the oxygen content of the nitrogen was not possible.

It was proposed for both WF2 and WF3 to install a nitrogen (oxygen) analyzer upstream (rich gas) and downstream (lean gas) of the regenerator catalyst bed, and to add nitrogen supply to the makeup air in such a way that both oxygen concentration and pressure can be controlled. That is, the top up valve would be controlled both with respect to pressure, in first stage separator, and oxygen content entering oxidizer. Pressure control in the second separator is suggested to be replaced with PIC controlled PV, replacing existing PCV. Additionally pressure control on the nitrogen seal gas to the blowers would be replaced with flow control. While these modifications were considered to be reasonable, given the seriousness of the problem, they have not yet been carried out due to the fact that they are somewhat involved.

In the meantime, the WF3 engineers evaluated the control system in the design of their waterflood. The level control scheme is cascaded to level three with several variables both on the input and output legs. This control scheme generates flow fluctuations in the level of the tank as it tries to react to variations in the multimedia filter (e.g. going offline for backwashing or coming back online after backwashing) and ramping speed of the high pressure water injection pump up or down due to injection demand of the wells as the chokes opening varies. This eventually leads to level fluctuation in both the first and second stage separators of the Minox unit. They confirmed the relationship between flow control and oxygen control and changed the control system to make flow and level more steady such that top-off air is only needed at a relatively steady rate and does not incur strong fluctuations.

All three waterfloods had problems with seawater carryover from the separator vessels. For WF1, the problems were relatively more severe due to the small separator vessel size. For that waterflood, it was proposed to put an inlet scrubber in the line going to the catalyst bed. The DeOx unit of WF2 was started without any defoamer injection. Excessive carryover was evidenced by scaling in the piping downstream of the first separator / upstream of the catalytic regenerator. Within a few days, the system was shutdown and cleaned. On startup, a glycol-ether based defoamer was applied. After a few days of operation with the glycol-based defoamer, a severe solids deposit problem was found in the gas/gas heat exchanger downstream of the first stage separator. Analysis showed that the salt was mostly divalent cations (calcium, magnesium) and divalent anions (carbonate, sulfate). While no extensive analysis was carried out, the results were consistent with compounds analogous to multivalent cation binding crown ethers. The theory is that the glycol ether based defoamer is carried over in a fine mist with seawater when foam bubbles burst. The mist travels through the gas discharge and eventually into the heat exchanger where it dries and forms a hard cake deposit. The system was shutdown again and cleaned. The glycol-based defoamer was replaced with a silicone based defoamer at a rate of about 1/2 gal per 1000 bbl of seawater. The system could not be operated without defoamer.

Seawater discharged from the first stage separator contains approximately 300 – 400 ppb residual oxygen. As discussed below, seawater discharged from the second stage separator contains about 150 to 200 ppb oxygen. To test the performance of the DeOx unit on WF2, the chemical oxygen scavenger was turned off for roughly an hour. The oxygen content of the discharge seawater out of the second stage separator was measured using Chemetrics oxygen ampoules. The reading obtained was in the range of 150-200 ppb. The on-line analyzer indicated roughly 200 ppb. After the test, the oxygen scavenger was turned back on and the oxygen level when back to 0 ppb within 3 minutes, measured by Chemetrics and indicated by the oxygen analyzer. This provided an effective test procedure for both the DeOx system and the oxygen monitoring instrumentation and procedures.

Specific WF1 Operating Experience:
In this section, we present the operating experience of WF1 of the other components besides the DeOx system.

The materials selected for this waterflood were typical of oxygenated seawater systems and included fiberbond in the low pressure sections, and internally plastic coated carbon steel in the higher pressure sections. The piping components worked well.

As described above, quality control was inconsistent across the project. The fine filtration system started leaking after only two months of service. When it was opened the extent of damage was observed to be severe. Also, it was apparent that the vessels were not built in compliance with the specifications. The vessels were neither internally coated, or protected with anodes. Replacement filters could not be obtained for several months and the corrosion was so severe that the vessels could not be repaired. The filters were bypassed for the sake of continued injection. Injectivity was tracked using Hall plots over several months and it was determined that injectivity did not suffer. Due to the complete failure of this system and its potentially significant impact on the reservoir had fine filtration really been required, this is not classified as an early failure problem. Instead it is classified as a waterflood challenge.

After roughly a year of operation, one of the WF1 high pressure injection pumps failed. Initially, it was thought that inadequate lubrication might have led to the failure. This proposed failure mode was based on concerns regarding the quality of the lube oil, the possibility of lube oil contamination, and high lube oil temperature during operation. Also, there were indications of loss of lubrication pressure of the machine on rundown. However, lube oil was eliminated on the basis of the following.

1. The pump employs a balanced rotor design and any problems with the lube oil would have also affected the inboard side of the thrust bearing as well as the radial bearing on that end of the pump.
2. Lube oil problems would also have affected the thrust collar which was found to be in perfect condition.
3. The appearance of the surface of the failed thrust bearing pads is consistent with an overload. The babbit surface seems to be evenly wiped off in one direction.

A root cause failure analysis determined that the pump thrust bearing failed on the outboard side as a consequence of the frequent shutdowns caused by the inability of the DeOx system to handle flow transients. Trending of axial thrust bearing data showed that the bearing failed at the time of a pump shutdown resulting from a trip of the DeOx system (i.e. the DeOx system shut down, stopping pump suction flow taking the machine down on a low suction flow / pressure trip).

The root cause failure analysis determined that the detailed failure mechanism was as follows. When suction pressure drops too low before the pump actually stops turning, cavitation starts on the first couple of stages. This causes a loss of the thrust forces from those impellers, creating a thrust force unbalance in the rotor. The pump impeller geometries are such that the net axial force from each impeller is toward the suction of the impeller. Given this net thrust force on each impeller, and the way that the rotor is stacked, it appears that the "normal" thrust direction of this rotor is away from the motor. Since the first 5 stages of the pump have a net axial force toward the motor, loss of some of these stages contribution to the rotor's thrust balance would tend to load up the outboard side of the thrust bearing (the one that failed).

A proposed solution to the problem was to change the shut down scheme so that the pump shuts down while there is still enough pressure to prevent cavitation. Because frequent shutdowns of the system were virtually eliminated, when the DeOx system was replaced with oxygen scavenger injection, this solution was no longer necessary.

Specific WF2 Operating Experience:
This waterflood had Shell oversight of design, construction, installation, and commissioning. The operating experience of this waterflood was significantly better than that of WF1, but there were still some problems. There were several early failure problems that are already described above. There were also some more difficult problems that led to only about a 50 % uptime in the first year of operations. Overall, the main cause of problems for this waterflood was the extremely short timeline available for facilities development. As described already, this project was put on a fast track in order to make up for the time required in addressing the very challenging anti-souring / reservoir management strategy.

Overall the area of materials selection suffered somewhat from the fast track implementation of this waterflood. A great deal of effort was put into the selection and qualification of high quality materials for the piping and for the coating and anode protection of the vessels. Nevertheless, there was a catastrophic failure within the first year of the waterflood. The bolts used on the high pressure turbine were made of a material that is susceptible to chloride stress corrosion cracking. These bolts, made of proper material, are apparently not generally available and the loss of a single bolt caused several weeks of downtime. Thus, despite the attention paid to materials selection for this project, the wrong material was supplied in a key area.

Filtration was one of the success areas for this waterflood. As described above, a field trial was carried out prior to selection of the filtration system. That study indicated that cartridge filtration would be sufficient and that deep bed filtration would not be required. The project team adopted this strategy which resulted in significant savings of space and weight. After nearly one year of operating experience, there was no sign of injectivity impairment and the cartridge filters did not require frequent changing.

Fluid dynamics was an area of problems for this waterflood. Waterhammer occurred, associated with rapid closure of a butterfly valve, and led to leaking seals and the telltale signs of PSV release (ruptured rupture pins). Due to the rapid dynamics, the presence of waterhammer was difficult to identify in data trending. However, once it was accepted that waterhammer was occurring, it was relatively easy to adjust the control system parameters to eliminate it. Another problem occurred associated with the DeOx system. The control system did not work properly on initial startup. It was dismantled and not used again for several months. Without a proper controls system, the system could only be started manually. As a result, the catalyst bed of the deoxygenation system was inadvertently flooded upon every attempt to start the system. Upon flooding the catalyst bed, it would take several hours to raise the temperature and dry-out the bed. Once the problem was understood it was fixed by installing a proper startup control system. However, it took several months to diagnose and correct the problem.

In practice, the anti-souring strategy employed for this waterflood was a challenge. Calcium nitrate was injected from day-one but the system suffered so much downtime in the first two years, that the effectiveness of the nitrate strategy for anti-souring was called into question. Also, biological monitoring and control was intended to be a significant component of the anti-souring strategy. Nevertheless, biological control was less than what had been originally intended when the anti-souring strategy was developed.

Specific WF3 Operating Experience:

As already discussed, this was the latter of the three waterfloods to be started up. Two of the engineers involved in final design of WF3, commissioning, and startup were actually on the site of WF2 for several months during the startup of that waterflood, and they obtained the learnings from WF1 as well. Based on that experience, several improvements were made, as discussed above, before the end of the construction phase of the project.

At the maximum rated flow rate of the system, gas carry under is experienced in the injection tank, downstream of the DeOx unit. Vessel internal modification are being considered. At current rates however, this has not been a significant problem.

The initial uptime for just the waterflood equipment alone was 91 %. The actual injection uptime was 80 % due to upstream components, power supply, and other utility supplies having downtime which affected the waterflood. In any case, 80 % initial uptime overall is considered very good.

Conclusions

There was a dramatic improvement in the recognition of challenges between WF1, and that of WF2 and WF3. WF1 suffered from failure of the filtration system, the DeOx system, and the high pressure pump failed both in the electrical and bearing systems. The outcome was excessive downtime, and a complete abandonment of the DeOx system. In contrast, WF2 endeavored to address many of the challenges highlighted in this paper. The fundamental problem that faced WF2 was the short timeline to design, construct, and implement the waterflood. This short timeline was driven by reservoir management / anti-souring strategy. WF2 had a robust control strategy and employed sufficient redundancy in pumps, instrumentation, and sensors. However, the short timeline resulted in mistakes in some critical areas which led to initial downtime.

WF3 had the benefit of the experience from the previous waterfloods, particularly WF2. Two engineers for WF3 participated in the startup and early operations of WF2 for several months. The experience proved valuable to not only WF3, but it also proved valuable to WF2 where they helped solve several important problems in the deoxygenation system. The engineers from WF3 saw first hand the critical details in WF2 and took immediate corrective action to address the potential problems in WF3, which resulted in a significant improvement in uptime when WF3 was put into service.

Acknowledgements

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Reference

1. C.L. Deuel, “Compact Seawater Deoxygenation System Improvements for Floating Production Facilities,” SPE 74358, presented at SPE Conference in Villahermosa, Mexico (10-12 February 2002).

Figures

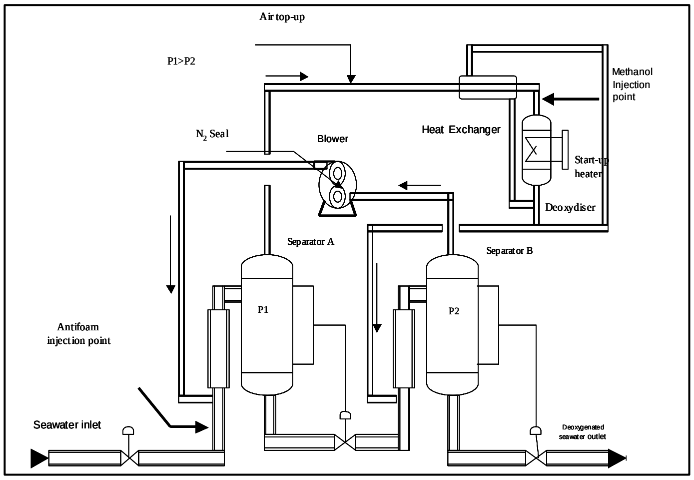

Fig. 1. Process Flow Diagram for the DeOx System

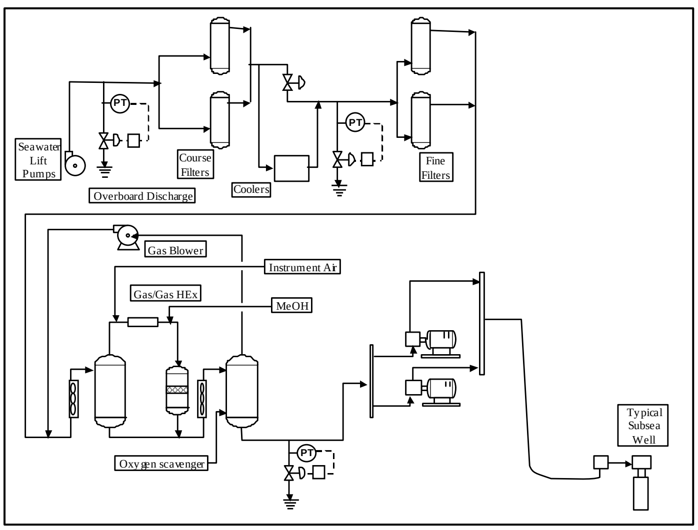

Fig. 2. WF1 Process Flow Diagram.

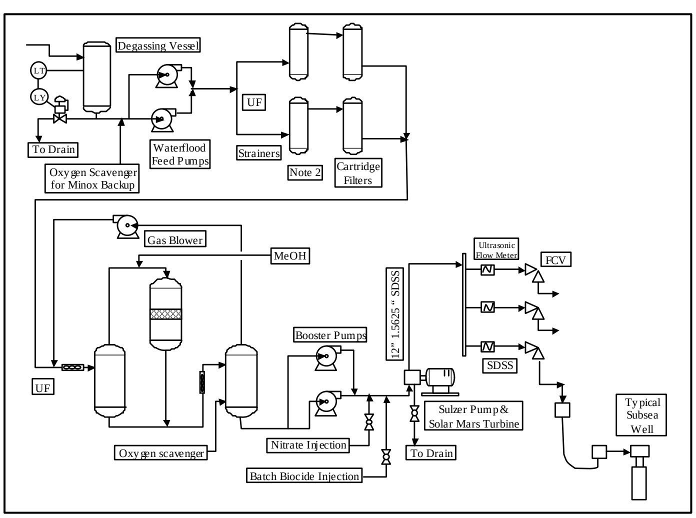

Fig. 3. WF2 Process Flow Diagram

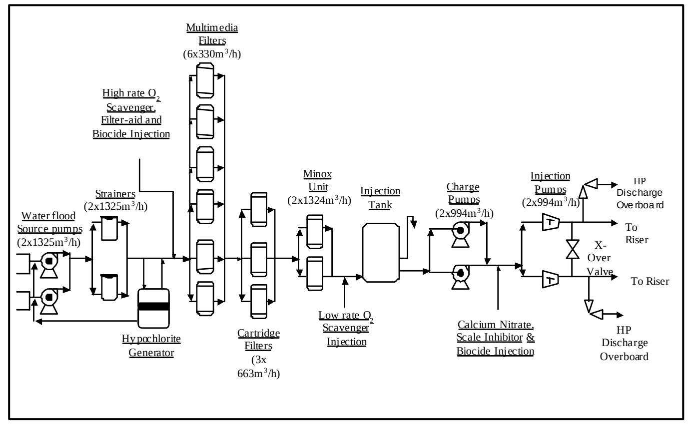

Fig. 4. WF3 Process Flow Diagram

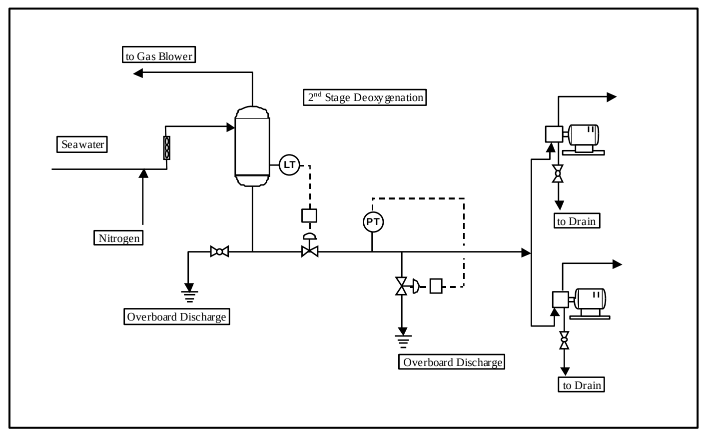

Fig. 5. WF1 Level / Flow Control System

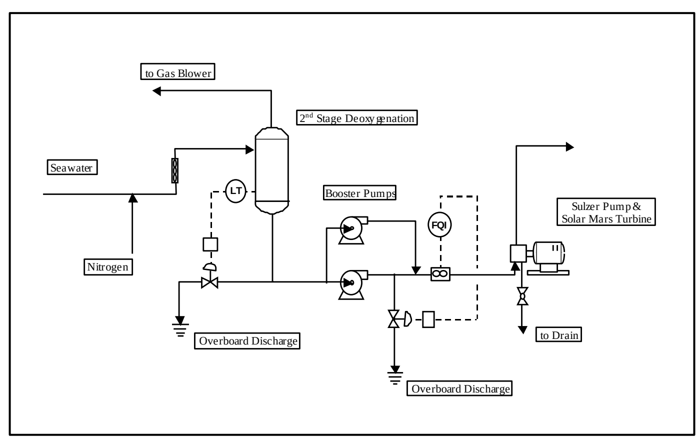

Fig. 6. WF2 Level / Flow Control System