Gas Flotation Tanks (GFT) – A Comparison of 2 Chamber vs 4 Chamber Design Performance

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1.0 ABSTRACT

The induced gas flotation process has been used in the oil and gas industry as a secondary oil removal process for over a century. The process has basically remained unchanged from its inception until about 10 to 15 years back when produced water started to become a greater technical challenge to the oil and gas industry. Driven by higher water cuts, heavier oil , presence of difficult emulsions and stricter environmental laws, various attempts were made to change the basic design to improve oil removal efficiency. Several design changes were adopted and one of them was moving from a single flotation chamber to a multi chamber design and then more recently from “underflow” or “overflow” partial walls to fully isolating walls to have discreet chambers. Further the process was also adapted from smaller rectangular tanks and pressure vessel design to larger API tank based designs.

Though the advantages of sequential Removal of oil from the produced water was well known in conventional flotation technologies such as IGF or ISF no data was available on the much larger retention timed Gas Flotation Tank (GFT) technology. This paper reviews the performance of a 2 chamber versus a 4 chamber GFT based on testing completed on commercially installed units.

2.0 INTRODUCTION TO MICRO-BUBBLE FLOTATION

The Micro-Bubble technology is a further development of the Induced Gas Flotation technology which existed in its basic form for several decades. Gas flotation technology was first used in the mining industry in separation of the iron from the Iron ore, in a process called froth flotation. Here the mineral ore mixed with water was introduced into the single cell gas flotation vessel in the form of slurry. Air was introduced at the bottom of the vessel through sparge pipes. As the air bubbles came in contact with the iron particles in the slurry, it attached itself and was floated to the surface. The separated iron particles appeared on top of the vessel in the form of a froth which was skimmed off to get concentrated mineral which was further processed to form Iron ingots. The same technology was applied in various other industries including oil and gas to clean produced water without much modification. Here the technology was used to separate oil from produced water. Over the years Educators were used to draw gas and mix with cleaner water to introduce bubbles for flotation purpose. These technologies had little control over the size of the bubbles generated. A number of research projects conducted in this field have concluded that the size of the bubbles has a great impact on the oil separation process. The findings show a positive correlation between increasing removal efficiency of oil droplets and decreasing bubbles size. In essence smaller bubbles are better able to remove small oil droplets and in general improve removal efficiency.

A number of significant technical advancement have been made to gas flotation technology over the years, of these we would draw attention to the following as having the greatest impact:

1. Shift from Single cell to multi cell design *(we note that recent developments in Compact Flotation are beginning to reverse this trend again)*
2. Recycling of gas and positive pressuring of the flotation system to reduce the environmental impact
3. Development of adjustable weirs to optimize skimming during vessel turndown.
4. Improved skimming technology using the hydraulics within the vessel and eliminate mechanical paddles and associated motors, reduction gear boxes seals etc. This eliminated a maintenance issue but more importantly removed a common source of oil re-entrainment
5. Use of Computational Fluid Dynamics (CFD) to optimize internal design for velocity , retention time, gas bubble distribution, surface release of droplets and oil skimming
6. The bubble generation was removed outside of the flotation vessel make it more flexible, maintenance friendly and reduced down time.
7. Development of micro-bubble generators which generate bubbles much smaller than traditional Eductors or internal mechanical frothing devices.
8. The partial wall design “underflow” was changed to fully isolated (discrete) cells. This drastically reduced short circuits.
9. Flexibility in internal design allowed shift from pressure vessel based design to non pressurized design where by gas flotation can also be carried out in an API tank or any other redundant vessel can be retrofitted.

3.0 APPLICATION OF INDUCED GAS FLOTATION IN AN API TANK

Until recently Induced Gas Flotation (IGF) was always conducted within a small vessel with 4 to 7 minutes retention time. In recent years this has broadened to now also include flotation within an API tank with using a patented internal design referred to as a Gas Flotation Tank (GFT). Since the tanks were much cheaper to build size and retention time was no longer a constraint as in the case of a conventional IGF. In this design the tank is divided into discrete chambers where each chamber acts as an independent flotation cell where micro-bubbles are used to clean the produced water. As the water passes from one chamber to the other the water gets progressively cleaner as fresh micro-bubbles are added at the inlet of each chamber. Hence the oil particles that manage to escape one chamber get repetitive opportunity to come in contact with fresh bubbles in each chamber, increasing the probability of attachment and removal.

The picture in figure A shows a two chamber GFT along with the Micro-bubble generator (GLR reactor) to generate the micro-bubbles.

Figure A - Two Chamber GFT with GLR reactor Installation.

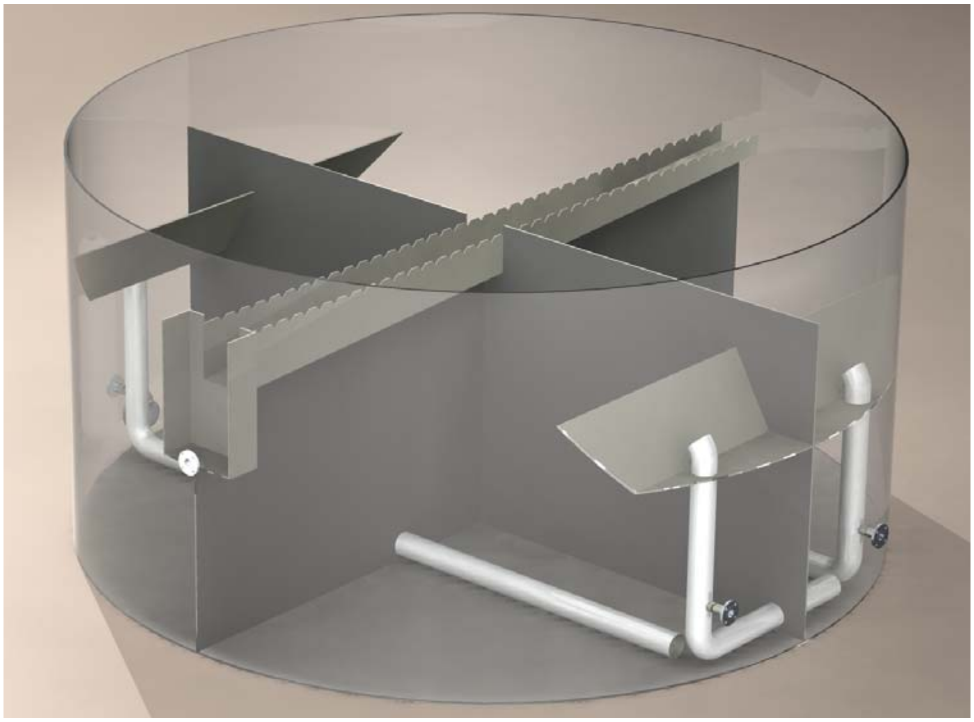

Figure B - Internal Design of a 4 chamber Gas Flotation Tank

The above rendering in Figure B shows a 4 chamber GFT, where the tank is divided into four equal chambers by dividing walls. In each chamber there is an inlet box, which receives the produced water and the recycle flow containing the micro-bubbles.

The inlet boxes in each chamber are positioned such that the outlet weir of the box is parallel to the oil collection trough. The oil collection trough runs diametrically across the tank along the line of one of the baffle walls and collects the skimmed oil from each chamber. As the oily froth floating on top of the bubble layer flows over the inlet chamber weir it continues across the surface and flows over the weir of the oil collection trough.

The weir of the inlet box slopes back towards the tank wall and the bottom of the box is connected to the tank wall. In the first chamber, which receives the water, the inlet box weir extends closer to the tank wall than those of the other boxes then extends vertically downwards for about 3 meters. This box is open at the bottom to allow any solids in the water to be directed to the bottom of the tank and not fill up the inlet box.

The produced water enters the inlet box in the first chamber where it meets a recycle stream of cleaned water containing the micro-bubbles. The oil extracted from the water by the bubbles floats across the chamber and flows over the oil trough weir. The cleaner water leaves the first chamber and enters the second chamber through an interconnecting pipe positioned between the two chambers.

The water from the first chamber is mixed with a second stream of recycle water containing micro-bubbles. The oily froth flows across to the oil collection trough and the clean water leaves the second chamber through an outlet in the dividing baffle wall between the second and third chambers and is piped to the inlet box of the third chamber.

The water from chamber three is mixed with a stream of micro-bubbles to extract more oil, which flows across the surface to the oil collection trough. The clean water from the third chamber leaves through an outlet in the dividing wall between the third and fourth chambers and is piped to the inlet box of the fourth chamber for further mixing with a stream of micro-bubbles. The remaining oil floats to the oil collection trough and the clean water exits the tank from the bottom of the fourth chamber.

The water flows by gravity through the tank and the interconnecting piping between each chamber is sized to minimize the pressure drop through the system. The bottom of the oil trough is sloped towards the outlet at a sufficient slope to ensure flow. It is important to note that the tank design incorporates water flow patterns to ensure that even heavy oil in the skim can be removed hydraulically with no requirement for mechanical skimming devices.

4.0 BENEFIT OF SEQUENTIAL OIL REMOVAL

Removal of oil using a sequence of isolated chambers is an established method for achieving significant improvements in oil removal. Fundamentally the factor that governs the rate at which oil is removed by gas-flotation is the rise velocity of oil and gas particles, in particular the rise velocity of the combined particles, which is function of size, gravity, water viscosity and particle density. Theoretically all that is needed is time; so the division of a chamber into several sub-units while retaining the same overall retention time for the entire vessel should not in itself lead to an improvement as per the mathematical expression given below

$$\frac{C_n}{C_{in}} = \left(\frac{1}{e^{k\theta t}}\right)^n \quad \text{or} \quad \frac{C_n}{C_{in}} - \left(\frac{1}{e^{nk\theta t}}\right)$$

Where C is the oil concentration,

t is residence time per chamber,

K is an oil removal constant,

θ is a chamber cell constant related to how efficient any one chamber is at removing oil.

In the above equation if number of chambers are doubled and half the residence time per chamber (t) then the result is same, which means there would be no difference in performance. However, data from both laboratory and commercial scale gas flotation equipment of a variety of designs conflicts with this conclusion as oil removal efficiency does reliably improve with an increased number of chambers.

Further review reveals that these equations have assumed perfect hydraulic conditions (no impact from walls or other internal structures), such that both K and θ remains the same for each chamber. This is unlikely when the initial concentrations of oil are high, which will cause the quantity of oil skimmed in the first chamber to be significantly greater than that skimmed in subsequent chambers. The impact this has on the constant k for each chamber can be debated. Further the oil removal efficiency in each chamber reduces as the amount of residual oil to be removed decreases. Further the residual oil would be smaller oil particles which missed the opportunity to get attached with a gas bubble or got detached after an attachment. To counter this a fresh stream of micro-bubbles are introduced along with the water entering the second chamber or subsequent chambers. This has a further improvement in K.

These equations in its current form do not take this into account, further supporting the argument of a modified constant which is related to individual cell performance.

Therefore the equation becomes

$$\frac{C_n}{C_{in}}=\prod_{i=1}^{n} exp(-k_i\theta_i t)$$

Alternatively the cumulative removal efficiency (CRE) is

$$CRE=1-\prod_{i=1}^{n} \exp\left(-k_i\theta_i t\right)$$

For the purpose of defining these constants (*k* and *θ)* for a general, unknown, inlet oil concentrations only the product $K_i = k_i\theta_i$ needs to be considered.

Figure C illustrates the cumulative performance of an nth chambered vessel, on the basis of the above equation. For a four chamber unit, with a one minute residence time per chamber the overall removal efficiency is over 95%. With a two chamber unit, now with 2 minutes residence time per chamber, the removal efficiency drops to 94%, where as a single chamber unit with 4 minutes residence time would only remove 92% of oil.

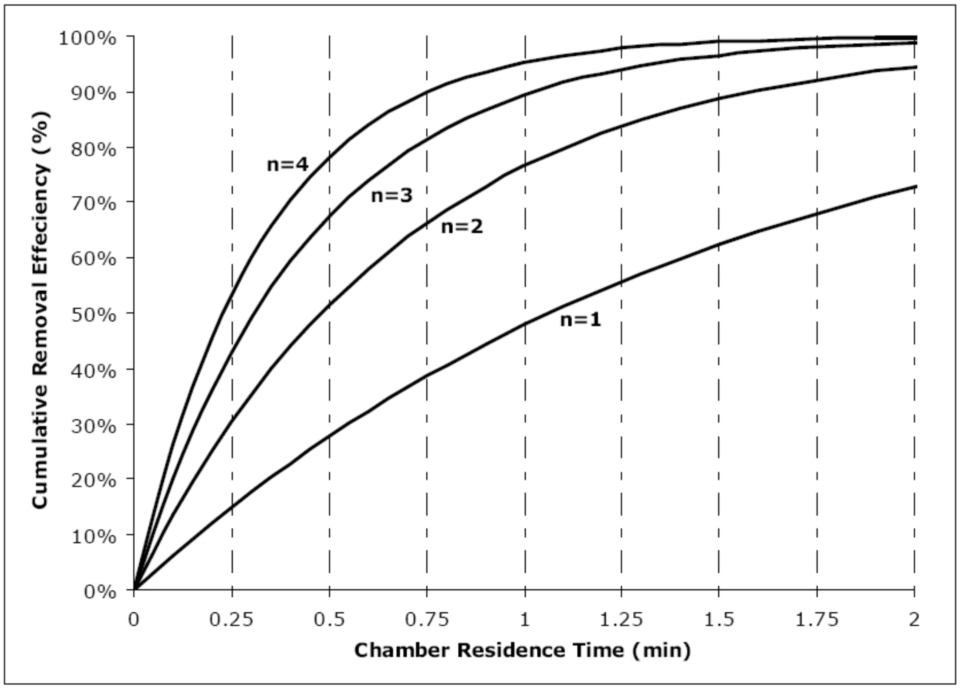

Figure C - Removal Efficiency as a function of Residence Time

To better understand the benefit of sequential removal of oil let's consider an example of hand washing a piece of cloth. First the dirty cloth is dipped in clean water, then soap is applied and scrubbed to remove the dirt and then the excess soap is squeezed out. To remove the remaining soap we use clean water to rinse it out. Let's consider two different processes to rinse out the soap from the cloth, where we are given only a fixed volume of water.

In the first process the piece of soapy cloth is dipped into the given quantity of water, rinsed and squeezed to remove the soap. The remaining soapiness in the cloth is noted.

In the second case divide the given amount of water equally into four vessels. Rinse the soapy cloth in the first vessel, squeeze to remove the soap, and then rinse the cleaner cloth in the second vessel and again squeeze to remove the soap. Repeat the process until the 4th vessel. Check the cloth for remaining soapiness in this case and compare with the previous case. It is needless to say that in the second case the cloth came out with less amount of soap remaining though the amount of water used was same in both the cases. The reason for the better performance in case two was that the bulk of the soap was removed in the first rinsing and then fresh water was used to clean it further in each of the remaining three rinses. In this example the fixed amount of water would compare to the fixed retention time in a single chamber and a multi chamber gas flotation unit. Hence theoretically we can expect that the 4 chamber tank would perform better for oil removal than a single chamber or a 2 chamber tank with the same retention time (same volume of tank)

5.0 TWO CHAMBER AND FOUR CHAMBER DESIGNS

In the two chamber design the tank is divided into two discreet chambers and the produced water is introduced into the first chamber where it received about 60% of the micro bubbles generated. The oil droplets are floated to the surface with the help of the micro bubbles introduced. The cleaner water exists the first chamber into the water weir in the second chamber via a chamber interconnect pipe which is strategically located to provide maximum retention time and to allow only cleaned water to be transferred to the second chamber. The remaining 40% of the micro-bubbles are introduced into the chamber interconnect pipe where the cleaner water from the first chamber with fresh micro-bubbles are introduced into the water weir in the second chamber. Here again the process is repeated and clean water exist the tank via the outlet pipe in chamber 2.

In a four chamber design the tank is divided into four discrete chambers and the internals are similar to the two chamber design. Here the process is the same as in the two chamber design but the process is repeated four times. The micro-bubbles are distributed in the ratio of 50, 25, 20 and 5% to the 4 chambers.

Several internal studied conducted and our review of the technical literature available indicated that a multi chamber design gave a better performance while keeping the retention time the same. As a result Exterran Water Solutions started providing the 4 chamber GFT design for more challenging applications as a standard in an effort to gain the higher removal efficiency performance compared to the prior two chamber designs sold.

We recently took the opportunity to monitor the performance in each discrete chamber of our four chambers GFT to quantify this performance. Slip steams were taken from each chamber where the water has been cleaned and ready to be transferred to the next chamber. The data we have on the two chamber GFT only provides overall performance and not individual chamber performance as when those tanks were designed they did not contain sampling lines at the outlet of Chamber 1. However we have analyzed the data available and are still able to make firm conclusions on the performance.

6.0 PERFORMANCE EVALUATION OF 4 CHAMBER DESIGN VS 2 CHAMBER DESIGN

Case #1 – 2 Chamber GFT

For the first case study we have considered two sites where our 2 chamber GFTs are operational for the same client. Following are the process information for these two sites:

	Site I	Site II
Designed Flow rate (BWPD)	52,000	208,000
Oil density	872	932
Water density	1003	1005
Operating temperature (Deg C)	60	50
No of chambers	2	2
Designed Retention time (Min.)	60	60
Micro-bubble Generator	MB Pump	GLR reactor

Figure D - 2 Chamber Inlet Process Conditions

We used the Petrocam™ in-line particle analyzer to measure OIW and optimize the GFT operation. A slip steam of the fluid to be analyzed is taken into the instrument where the results for particle concentration and particle size distribution are displayed in real time. Algorithms built into the instruments software characterize the particles as either oil droplets or solid particles in the resulting data output. The benefit of using online particle analyzers is a quick and efficient means to optimize the system to achieve the best results in a shorter time than it would take to wait for lab samples to be analyzed. In addition we gain hundreds or thousands of data points due to the real time online analysis of the produced water being treated,

The following two graphs show the oil droplet profile for the two sites. The graph in Figure E shows the particle size distribution profile on the inlet water to the GFTs. As you can see both the sites follow somewhat of a similar profile from approximately 12 micron and larger, but a shift in where the mean droplet size lies.

The graph in Figure F shows the particle size distribution of oil droplets in the outlet of the two chamber GFTs. Although the inlet specifications, water quality and the outlet specs of each tank are different it can be observed that the outlet in both the case is restricted to below 30 microns.

Further the high percentage of oil droplets below 5 micron in the outlet shows that particle size of 5 microns and above was effectively removed thereby shifting the particle size distribution to a much lower mean particle size.

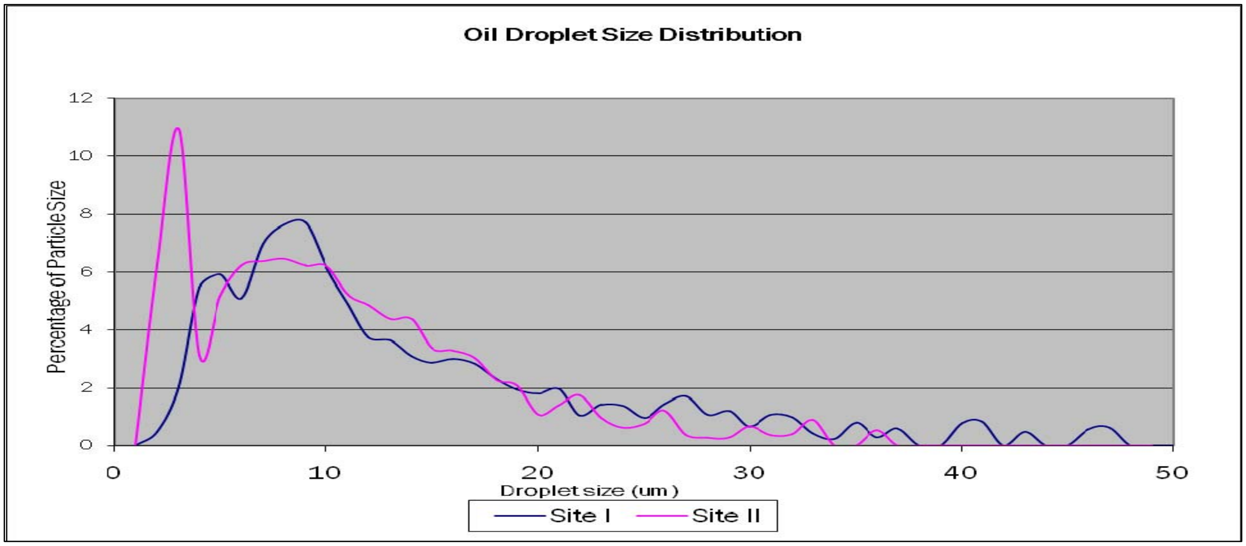

Figure E - 2 Chamber GFT , Inlet Oil Droplet Size Distribution

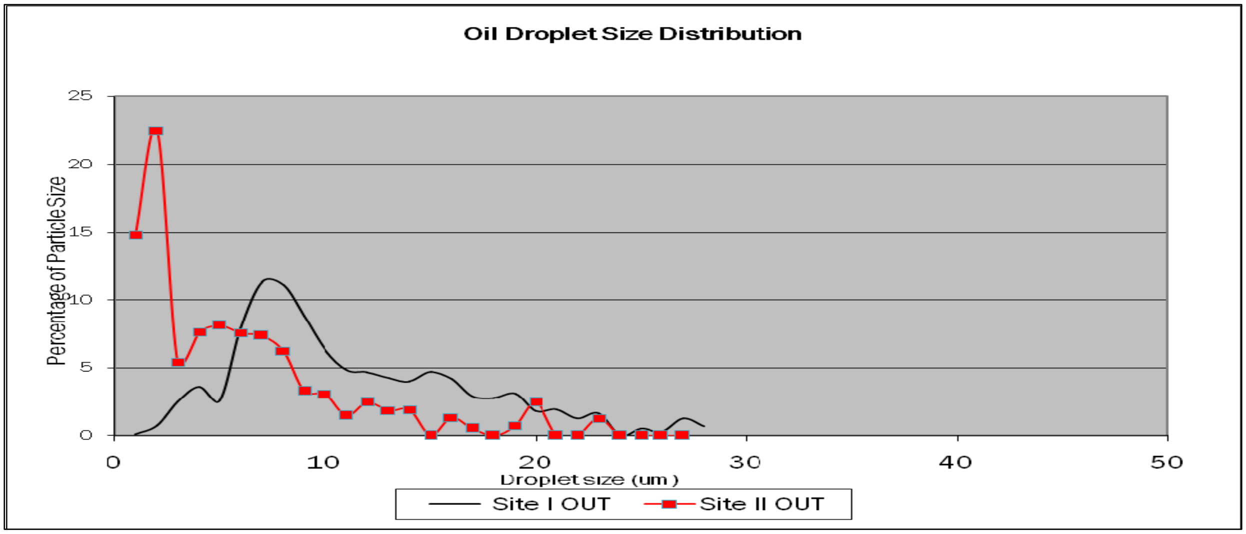

Figure F – 2 Chamber GFT , Outlet Concentration vs Droplet Size

Theoretical removal efficiency of a 2 chamber MBF tank utilizing the droplet profiles as shown above (significant % of particles < 6 micron cutoff for highest efficiency) should range between 83% to 86%. However data collected from field trials and operational units that with MBF results are consistently at 95% + of oil droplets 6 microns and above. The results in Figures E and F further support this.

Case #2 - 4 Chamber GFT

For the second case study we have considered two sites where 4 chamber GFTs are operational for two different clients. The following is the process information for these two sites:

	Client 1	Client 2
Designed Flow rate (BWPD)	85,000	44,000
Oil density	876	910
Water density	1000	1002
Operating temperature (Deg C)	50	80
No of chambers	4	4
Designed Retention time (Min.)	60	60
Micro-bubble Generator	MB Pumps	MB Pumps

Figure G - 4 Chamber Inlet Process Conditions

Oil removal efficiency (concentration vs droplet size) was measured in each of the 4 chambers to find a trend in performance if possible and also to find if there is any benefit in sequential cleaning while keeping the overall retention time constant. The water was again analyzed using the Petrocam ™ in-line analyzer.

	Client 1 (oil ppm)		Client 2 (oil ppm)	
	Day 1	Day 2	Day 1	Day 2
Inlet	159	135	515	205
Chamber 1	35	27	144	64
Chamber 2	22	22	121	66
Chamber 3	15	12	25	21
Outlet	14	13	5	3

Figure H. Oil Concentration at Outlet of Individual Chambers (4 chamber GFT)

Cumulative Chamber Removal Efficiency				
	Client 1		Client 2	
	Day 1	Day 2	Day 1	Day 2
Inlet	0	0	0	0
Chamber 1	78%	80%	72%	69%
Chamber 2	86%	84%	77%	68%
Chamber 3	91%	91%	95%	90%
Outlet	91%	90%	99%	99%

Figure I - Cumulative Oil Removal Efficiency By Chamber (4 chamber GFT)

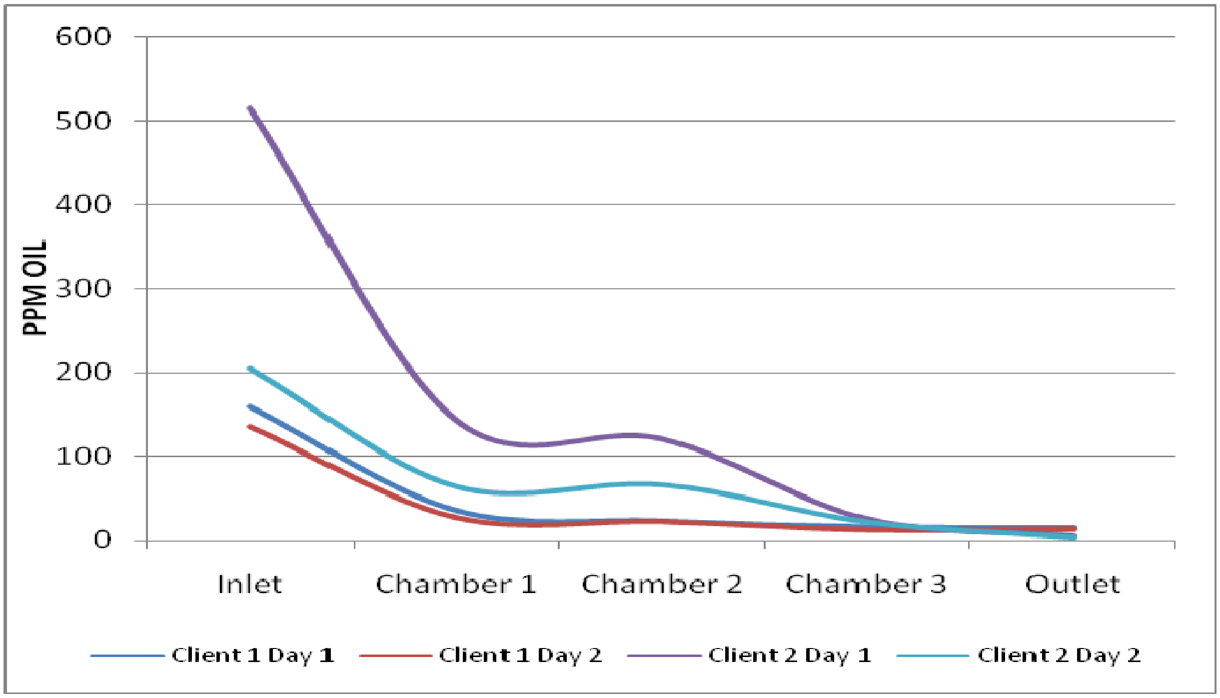

Figure J – Mean Oil Concentration by Chamber (4 chamber GFT)

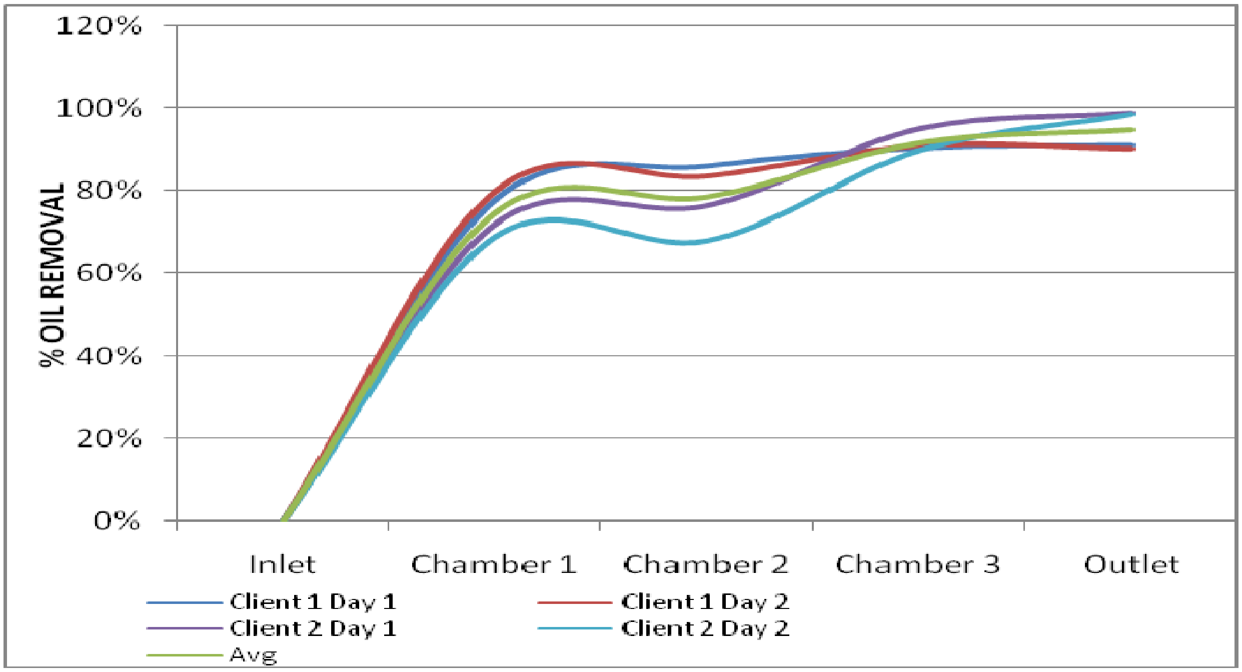

Figure K - 4 Chamber cumulative Oil Removal Efficiency

The data for oil concentration in Figure J shows the chamber wise performance of the 4 chamber GFTs. Numerous separate measurements of oil concentration as well as particle size were taken over a two days period at each site and the mean values reported.

From graph in figure J we find that client 2 experienced an upset on day one during which time the inlet oil went up to 500 ppm. However the outlet was still maintained at the same level as on day two when the OIW was normal at 200 ppm. This demonstrates the ability of the first chamber in a 4 chamber GFT to absorb large upsets. This characteristic of buffered upsets has been observed in many other GFT installations as well.

For client 1 the oil characteristics were different than for client 2 however the outlet performance was similar. We observe with client 2 the inlet oil is raised well above the 150 ppm inlet level seen for client 1, however the outlet can still be expected more or less at the same level due to the ability of the GFT to absorb the upset.

Figure L - Water samples from each chamber (Client 1)

The Figure L shows a photograph of the water samples collected from the outlet of each chamber which further demonstrates the progressive cleaning of the water.

The graphs in figures M through P show the particle size distribution of Oil at the outlet of each chamber for client 1 when the inlet oil concentration was between 135ppm and 159 ppm.

Though the mean oil ppm at the outlet in each chamber progressively decreases (continuous in-line sampling by Petrocam), we also observe a few spikes in the particle size distribution at the large end of the size spectrum. The water samples were drawn though sample points located on the wall of the tank, we hypothesize the spikes are created by oil droplets coalescing on the inlet of the sample pipe/and or the wall of the tank which periodically detatch and are drawn into the particle analyzer as time passes.

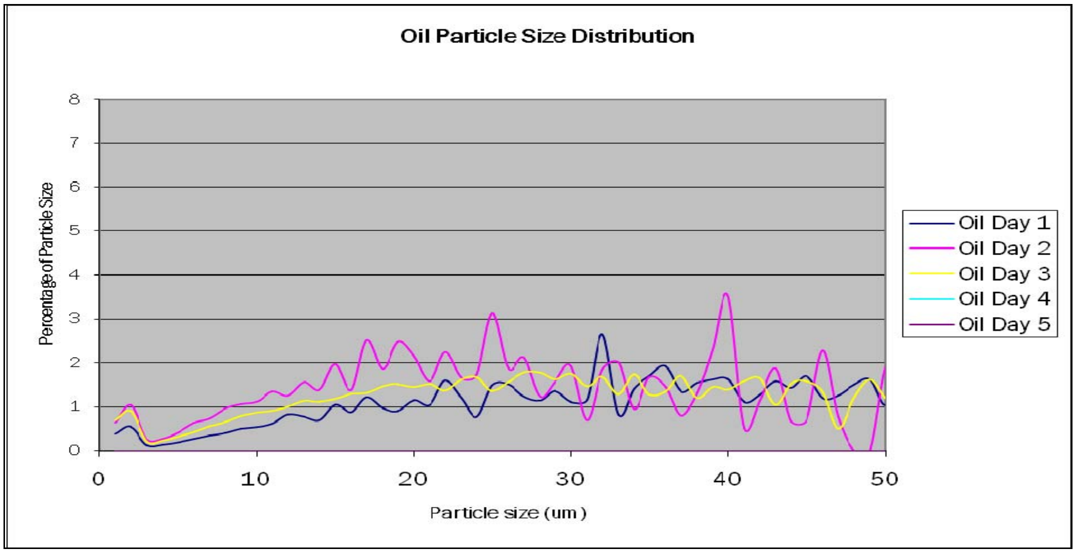

Figure M - Client 1, Chamber 1 Outlet Particle Size Distribution

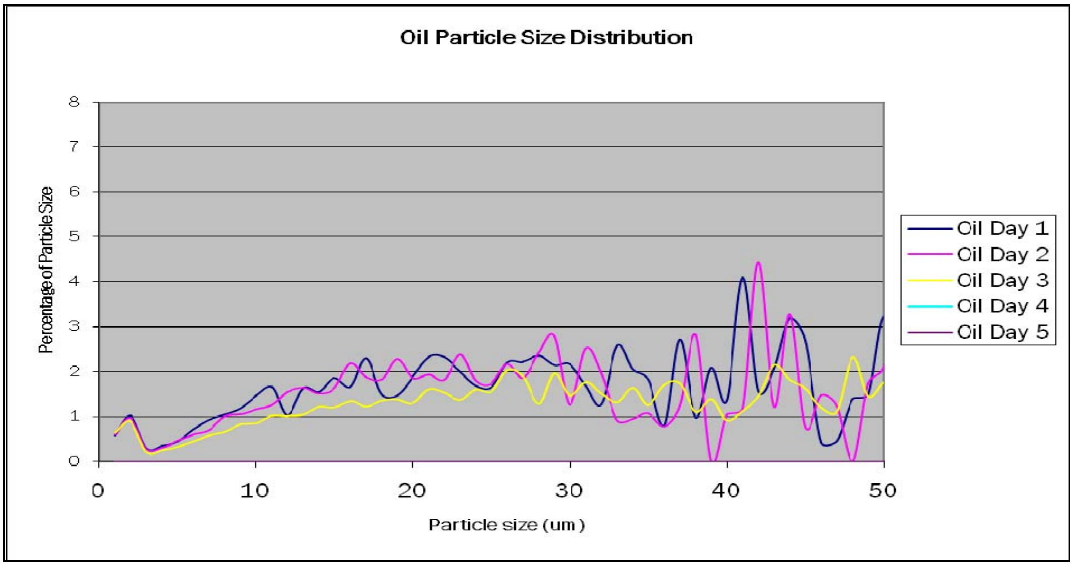

Figure N - Client 1, Chamber 2 Outlet Particle Size Distribution

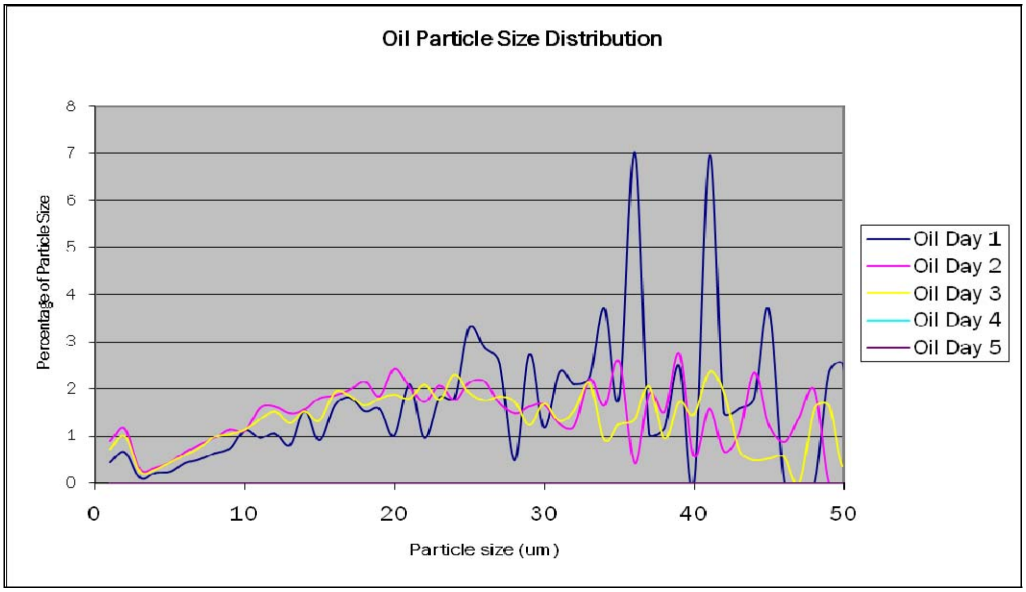

Figure O - Client 1, Chamber 3 Outlet Particle Size Distribution

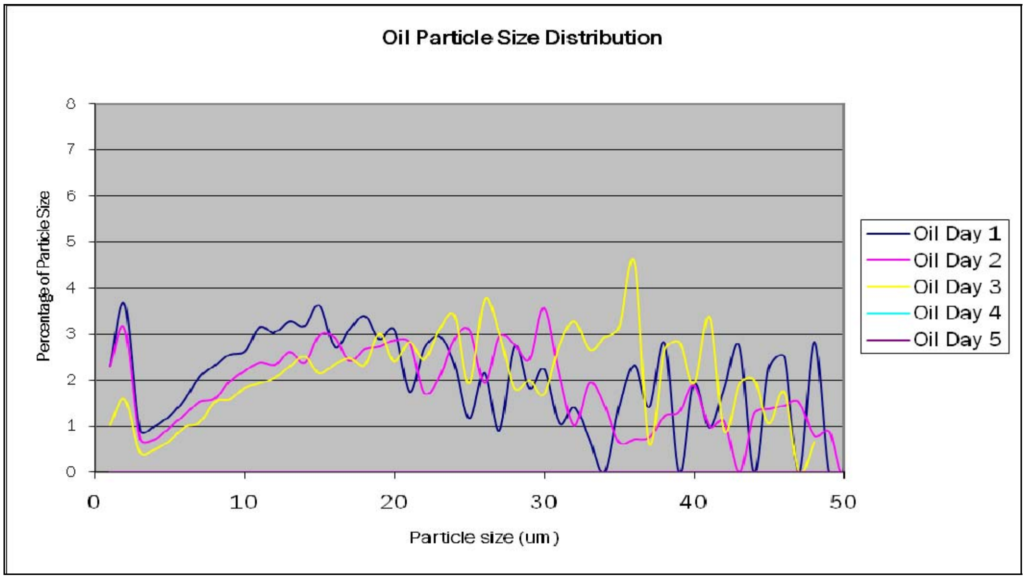

Figure P - Client 1, Chamber 4 Outlet Particle Size Distribution

Observations:

1. The overall removal efficiency of a two chamber GFT and the cumulative efficiency observed at the outlet of the second chamber of a four chamber GFT are similar. This is in spite of the fact that in the 4 chamber design the retention time is reduced to half per chamber (velocity per chamber is double) where overall retention time is one hour
2. Figure J & K shows similar outlet performance profile for two sites in which 4 chamber GFT tanks have been utilized. Client 1 had lighter oil at approximately 28 API, where as client two had heavier oil at 24 API, and further had higher inlet oil concentrations. However the profiles trended very similar and the outlet concentrations by chamber 4 came into alignment.

3. From Fig J & K it can be observed that the bulk of the oil is removed in chamber 1. Chamber 1 acts as a buffer for handling upset.
4. Individual chamber efficiencies are not constant; it is a function of the concentration of oil, oil droplet size, specific gravity, viscosity and many other factors.
5. As the water gets cleaner from chamber to chamber, it becomes more difficult to remove the residual oil which results from smaller oil particles and droplets that are much larger distances apart (lower probability of attachment). Here the fresh bubbles and further retention time helps in the finer polishing. This result supports the findings in Section 4 that the oil removal efficiency is not equal in each chamber as the inlet condition to each chamber changes.
6. The Oil concentration measured at the outlet of a 4 chamber GFT is far lower than the 2 chamber GFTs though the overall retention time was the same.
7. It has been observed in commercial operations that 4 chamber designs are more robust in handling upset conditions where large surges in flow or large volumes of oil are directed to the GFT. In these conditions the additional chambers act to buffer the outlet water quality for a longer period of time as oil is retained predominantly in the 1st and 2nd chamber allowing chambers 3 and 4 to operate under more normal conditions.

7.0 CONCLUSION

1) In a 4 chamber design the oil removal performance from the second chamber is similar to that of the overall performance of a 2 chamber GFT design. The reduction in the retention time per chamber does not have a significant impact. Hence addition of the 3rd and 4th chamber significantly improves performance.
2) Additional chambers helps in containing upset scenarios where the inlet oil loading is predominantly contained within the 1st chamber. Though for Client 2 the inlet was far higher than for client 1, the outlet was similar or a bit lower than for client 1. It can be concluded that for more challenging waters and higher inlet oil concentrations/upset conditions a 4 chamber design would be more preferable.
3) Sequential cleaning helps in improving the overall efficiency of the system for a given retention time (or given volume of vessel). Overall efficiency seen in the 2 chamber case studies were 83% to 86% which in contrast is improved to 91% to 99% efficiency in the 4 chamber case studies. We feel the trending is more significant than the actual measured performance as we recognize there are significant differences in particle size distribution that account for much of the individual differences.
4) The overall removal efficiency for each chamber in a 2 chamber or a 4 chamber GFT can be accurately predicted if the inlet concentration and particle size distribution is well characterized.

8.0 REFERENCES

1. Lee, Douglas W . Bateman, William and Owens, Nicholas "Efficiency of Oil/Water Separation Controlled by Gas Bubble Size and Fluid Dynamics within the Separation Vessel" *Produced Water Society Annual Technical Conference (2007)*