DOWNHOLE SELF CLEANING SOLIDS FILTERING SYSTEM FOR ROD PUMPING SHOWS PROMISE

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INTRODUCTION

Rod pumping has been challenged by solids contained in the produced fluids, as they can reduce pump run life (failed pumps and stuck pumps) and limit production. Solids and their abrasion risks have escalated in horizontal wells, as multistage hydraulic fracturing practices have exponentially increased: the number of frac stages, the amount of frac sand being pumped, the amount of lower quality of frac sand (namely, the amount lower quality frac sand that can crush into finer solids particles) and the amount of finer frac sand (e.g., 100 mesh). To reduce or avoid solids reaching and damaging a rod pump, control attempts have been Individual component based (as opposed to system based) and have included downhole solids separators and filtering screens. All have realized limitations, especially with finer particle sized solids, and therefore improved designs and systems are needed.

To effectively separate finer solids from liquid, filtering is required, but filtering has the obvious risk of plugging. A downhole self cleaning solids filtering system was developed and field implemented with promising results.

DOWNHOLE SOLIDS SEPARATORS

In a rod pumping environment, downhole separators are required to separate solids over broad solids particle size distribution (PSD) and flow rate range. In other words, the need to have a high or wide turn down ratio. This requirement has made downhole solids separation challenging.

From a process sequence point of view, solids are more easily separated from liquid after the liquid has been degassed. If a gas phase is present, it can volumetrically take up most of the flow path cross sectional area and thereby will substantially increase the liquid phase velocity, the level of liquid turbulence and the level of erosion risk. Therefore, the presence of gas in a flow stream makes solids separation from liquid far more challenging and complex. So ideally, a system should be designed to efficiently separate the gas from the liquid first, then attempt to separate out the solids from the degassed liquid. This is a major limitation and risk for packer-style downhole separators, as they must attempt to remove solids before the liquid is degassed.

Three forms of downhole liquid-solid separators are commonly used for rod pumping:

1. Gravity
2. Cyclonic-Gravity
3. Filtering Screens

Downhole solids separator designs (1 and 2 above) that are designed to impart fluid forces to the solids particles have typically been gravity or cyclonic-gravity based. A cyclonic-gravity based solids separator uses the benefits of cyclonic separation to enhance the gravity separation process. Moderate cyclonic or centrifugal forces concentrate larger particulate solids into a portion of a fluid stream, which can then allow for more efficient gravitational solids settling. Separated solids are then commonly contained downhole in closed chambered "mud joints" or "mud anchors".

Other forms of cyclonic separators, common in surface processing facilities but not downhole, are hydrocyclones and centrifuges. These devices generally target finer solids particles and impart very high centrifugal forces (for example, 2000 g's) for separation of 150 micron and less sized particles. In the case of centrifuges, the absence of high flid velocities requires high centrifugal forces to be generated through motor driven rotational components and they generally do not require a specific vertical or horizontal orientation. In other words, they do not concurrently rely on cyclonic and gravitational forces for solids separation. Such separators are outside the scope of this document and have not had successful application for downhole oil and gas well environments.

Downhole filtering screens are highly effective in separating (or trapping) a complete range of solids particle sizes, when sized appropriately, but they suffer the risk of solids plugging, solids erosion and/or scaling. They are also highly tolerant to sluggy inconsistent flows and varying solids concentrations in the liquid. The general approach with filtering screen (and downhole sand inflow control in general) has been to filter and retain the solids particles at the filter screen, a form of three-dimensional filtering screen, with a design intent to resist plugging (see SLB[i] screens which retain harmful solids).

Figure 1 illustrates the process flow of a downhole solids separator, either a gravity or cyclonic-gravity type. Both types have an underflow path of heavier solids fraction liquid of concentrated solids and an overflow path of lighter solids fraction liquid (ideally with no solids).

Figure 2 illustrates a design variation in the process flow where the addition of a bypass separation stage is introduced to the system. A bypass feature provides an additional stage of solids separation, where the fluid stream or path is split into two separate flow paths, one with a heavier solids laden fraction (underflow with higher solids concentration and larger particle size in the fluid stream) and one with lighter solids laden fraction (overflow with a lower solids concentration and smaller particle size in the fluid stream). The lighter solids laden fraction flow path is subsequently processed in a second stage of solids separation. Both stages of underflow are then commingled in parallel to contain the separated solids in the mud joints. The overflow paths from each stage are not commingled.

Figure 3 illustrates the process flow of a downhole filtering screen. There is no underflow flow stream, as the solids are all retained at the filter screen (if the screen is sized appropriately).

LIMITATIONS OF DOWNHOLE GRAVITY BASED SOLIDS SEPARATORS

Gravity based solids separators are the simplest form of downhole solids separator. They are analogous to a natural solids separator in a vertical wellbore where a cellar or sump exists below the perforations and pump intake.

Figure 4 illustrates a packerless poor-boy style gas and solids gravity based separator. The upstream and directionally upwards flow of liquid, solids and gas from the formation enters the separator's inner annular conduit (an annulus formed between the separator body and the separator's pump intake dip tube). The flow path direction changes from upward to downward once inside this inner annular conduit. Gas is separated first and released back into the wellbore from the separator and flows up the outer annular conduit of the well's casing and production tubing. Liquids and solids continue downward in the separator's inner annular conduit until they reach the bottom of the pump intake dip tube. In theory, as liquid turns upward into the pump intake dip tube, solids separation from the liquid occurs – Stokes' Law's principles for solids settling with gravity and velocity momentum, forces the solids to continue moving downward to be contained in the mud joints. The pump intake dip tube is theoretically designed such that the upwards velocity of the solids-laden fluid within the tube is lower than the settling velocity of the particulate matter in the fluid. In other words, the solids settle faster than the liquid rises – but this in reality is highly unlikely, as is discussed in the following paragraphs.

Stokes' Law[ii] is the governing equation for gravity based separators and solids settling, which has been accepted for predicting the theoretical performance of a liquid-solid separation process. According to Stokes' law, the solids particle sedimentation or settling terminal velocity/rate is proportional to the density difference between the solid and the liquid, is inversely proportional to the viscosity of the liquid, and is proportional to the square of particle diameter as follows:

$$V_S = d^2 * g * \rho_S - \rho_L \,/\, 18 * \mu$$

where
V_S = settling rate under the force of gravity, ft/s.
d = particle diameter, feet.
g = gravitational constant, 32.2 ft/s^2.
ρ = density of solid (S) and liquid (L), lbs/ft^3.
μ = viscosity of fluid, lbs/ft-s,

During a rod pump's intake or upstroke, the inner annulus conduit of a poor-boy gravity based solids separator has a downward liquid velocity which is designed to speed up the overall velocity of the solids particles settling in the downward direction. The momentum change as the solids "turn the corner" and reverse direction up into the pump intake dip tube contributes to the separation effect in addition to the pump intake dip tube being designed to have an upward flowing velocity that is lower than the settling velocity of the solids. Typically these velocities are calculated based on the average daily fluid rates from the well and leads to under-performance of a separator design since velocities through a separator are not steady state during rod pumping.

Complicating the calculation of settling velocities, high concentrations of solids can hinder the free motion of individual particles and reduce the settling velocity predicted by Stoke's Law to less than 20% of the theoretical prediction [iii]. Furthermore, Stokes' Law is predicated on spherical particle geometry, to which nature rarely adheres (on all but the planetary scale), and many engineering empirical relationships have been determined for various flow regimes and particle shapes across the engineering disciplines, such as those found in Song et al.[iv]

The downward liquid velocity inside a poor-boy separator ranges widely each pump stroke – from zero (0) to over 16 feet/second (5 meters/second). Figure 5 from Guzman's[v] research shows a pump's plunger velocity during the intake upstroke and the corresponding liquid rate into the pump. It is very important to understand that the plunger velocity and intake liquid rate vary from zero (0) to over four (4) times the average. This importantly points out that a well that is producing an average 200 bbls/day of liquid with a rod pump has instantaneous peak liquid rates entering the pump at over 800 barrels/day (each pump stroke). To this end, the technical engineering consideration for downhole solids separation design is that the pump intake liquid rates vary over an extensive rate range.

The velocity of solids laden downward flowing liquid in the poor-boy's annular conduit (to the pump intake dip tube will) exceed the Stokes' Law solids settling rate for the majority of the pump's upstroke (during pump fluid intake). Part of the theory and design intent of a gravity based solids separator is such that the solids retain this additional velocity as downward momentum at the point where liquid turns upwards into the pump intake dip tube. Such directionally downward momentum encourages the solids to continue downward into the mud joints rather than making the turn upwards into the pump intake dip tube.

The efficiency of this downhole solids separation process has not been adequately researched, rather results seem mostly empirical, anecdotal, or speculative. More laboratory research is certainly needed.

Mud joints are a closed chamber for solids containment, with no fluid flow or movement within, so there is no continuous fluid movement overflow of a separate heavier solids laden fluid stream entering into the mud joints (as per a hydrocyclone's overflow). As such the dead or static fluid interface between the closed chambered mud joints and the bottom of the pump intake dip tube will likely limit the effectiveness and efficiency of solids separation depending on particle size distribution, particle shape, and fluid velocity – in other words, there is an apparent risk that solids simply carry-over to the pump intake dip tube with the motion/movement of the fluid into the pump intake dip tube (i.e., finer solids suspend in the liquid stream portion that is physically moving and carry over into the pump intake dip tube). Some turbulence at this interface may encourage larger sized solids to settle into the mud joints, albeit at relatively poor efficiency, and may act to retain the finer solids in suspension (which carry over upwards in the pump intake dip tube into the pump). This form of poor-boy solids separation process will likely have very low efficiency with finer particle solids, as they have a greater affinity to suspend in moving fluids and/or turbulent flows.

Solids concentrations in the liquid phase reaching the separator can also be highly variable, as sluggy inconsistent flows emanating from a horizontal wellbore can transport solids in highly concentrated masses. How more solids concentration affects the efficiency of a gravity based solids separator in transient flow conditions is not well studied in literature but should be apparent to the reader that the efficiency is significantly reduced as solids concentration increases.

LIMITATIONS OF DOWNHOLE CYCLONIC-GRAVITY BASED SOLIDS SEPARATORS

Downhole cyclonic-gravity solids separators are commonly referred to as downhole desanders. They operate using both cyclonic and gravity forces for optimizing solids settling.

An example of a downhole cyclonic-gravity desander solids separator is shown in Figure 6[vi], The Cavins Desander. The operating principle and process sequence of a downhole cyclonic-gravity desander solids separator was described by Langbauer[vii] in Figure 7 and as follows:

1. "The fluid-particle feed mixture enters the system through the intake and reverses its flow direction from upward to downward.
2. In a single annular path fluid-particle mixture tangentially enters the swirl vanes.
3. While passing through the swirl vane section, rotational movement is imposed onto the fluid-particle mixture.
4. The rotational motion causes radial forces onto the fluid/particle mixture. The magnitude is proportional to the density – thus the denser particles move closer to the outer wall of the downhole desander's single path fluid stream.
5. Once at the outlet of the swirl section, the larger particles have separated themselves and are moving gravitationally downward closer to the outer wall.
6. The inlet pipe to the pump is located in the center of the swirl vane outlet. The fluid flow direction is then diverted into the inlet pipe to the pump.

7. The separated particles cannot follow this rapid change in flow direction and sink toward the bottom of the separator and in the adjacent sand tubes."

Ditria [viii] also appropriately summarized how cyclonic-gravity separators functionally operate: "fluid is directed tangentially into the hydrocyclone which causes it to spin. The spinning motion generates strong centrifugal forces which induces the solid and liquid to separate into a heavier fraction and lighter fraction in the flow path. The heavier phase is forced outward toward the wall of the hydrocyclone tube and this displaces the lighter phase which migrates toward the center where it forms a core. By controlling the pressure across the tube the core is forced to flow through the overflow and the heavier solids or liquid are directed to the underflow. This process provides a simple but effective separator with no moving parts." Their research also pointed out that for cyclonic solids-liquid separators "higher particle densities and sizes are easier to separate."

In Figure 8, Joseph[ix] illustrates a surface facility hydrocyclone, with no moving parts, comprising an underflow heavy solids fraction fluid stream that is continuously moving or flowing. This continuous underflow fluid stream flow provides a significant separation efficiency benefit to the Stokes' Law settling equation, as wherein narrowing diameter of the cone increases the centrifugal g-force exerted on the solids particles, such that they are forced to the outside wall of the cone due to increasing angular velocities at a constant fluid flow rate. The heavy fraction of solids moves outwards (is separated) into the containment chamber, allowing the centralized lighter fraction of fluid flow stream to enter the pump intake. The containment chamber is not a closed chamber and as such allows for this continuous and beneficial downward fluid movement. Downhole cyclonic-gravity separators do not posses this separation efficiency benefit, as the mud joints are a closed chamber that does not permit fluid movement in the downward direction (they only permit solids settling in a static fluid environment).

SLB [x] stated that "downhole desanders are simple and inexpensive, but they are ineffective at removing a wide distribution of particle sizes" and "from a conventional or unconventional well, grain size and distribution are important considerations, but they may be unknown." Martins [xi] revealed cyclonic-gravity separators are best fit for continuous operation rather than to slug flow and concluded that larger solids particles are easier to separate than smaller ones with a cyclonic separator.

Solids and their abrasion risks have escalated in horizontal wells, as multistage hydraulic fracturing practices have exponentially increased: the number of frac stages, the amount of frac sand being pumped, the amount of lower quality of frac sand (namely, the amount lower quality frac sand that can crush into finer solids particles) and the amount of finer frac sand (for example, 100 mesh). Nystrom's[xii] research article noted that "horizontal well designs have become progressively longer and more intense in terms of proppant usage. Virtually the entire industry has switched from high-permeability grade proppants like 30/50 to lower permeability grades such as 100 mesh." Figure 9[xiii] shows the finer frac sand solids particles and their typical size distribution range, noting the 100 mesh frac sand particles are mostly larger than 120 microns but smaller than 200 microns.

Martins[xiv] research in Figure 10 showed that downhole cyclonic-gravity separators fail to separate solids smaller than 200 microns.

Shaffee [xv] explained that downhole cyclonic separators designed for solid-liquid separation have been found to be unable to achieve its intended separation efficiency especially if any gas phase is present in the fluid stream. In other words, sizing of a cyclonic separator for solids-liquid separation is very challenging and will likely under perform if any gas volume fraction is present in the fluid stream – a condition that is highly likely during rod pumping as no downhole gas separator has proven able separate all of the gas from the liquid. In terms cyclonic separator handling of solids particle size distribution and range, Shaffee concluded that they will not be able to separate the entire range of sand in the hydrocarbon stream and especially smaller sized particles. For effectively separating finer sized solids particles their new design added a filtering stage in combination with a cyclonic separator. The difficulty in sizing a single static cyclonic separation system for a wide particle size distribution is perhaps demonstrated simply by the Dyson hand-held vacuum[xvi], which uses both a cyclonic separator for the larger solids particles and a filtering separator for the finer solids particles.

Kimery[xvii] explained that it is very common for unconventional horizontal wells to posses inconsistent sluggy flows and its these sluggy inconsistent flows that transport solids to the separator in highly concentrated masses. This transport process is described as saltation or in other words, solids accumulate and form dunes along the horizontal wellbore and these dunes migrate in the direction of flow.

Shaffee further described where cyclonic separators designed for solids-liquid separation under performed during “varying inlet stream upstream conditions, for example during well flowrate decrease the required flow will fall below optimum cyclonic separation conditions leading to sand carryover to the outlet stream” and “flow stability, i.e., liquid slugging negatively affect cyclone efficiency”. Such variable inlet conditions are obviously present during rod pumping. Shaffee showed that only 16% of their cyclonic separators were online and with a sand separation efficiency of “at best” around 50%. The root cause of this low efficiency being an inability for separators to handle varying inlet rates or have a lack of turn down ratio. A cyclonic separator needs threshold level of centrifugal force from the incoming feed flow velocity. If inlet rates are predictable and consistent, cyclonic separators should exhibit high performance for solids-liquid separation. If inlet rates into a cyclonic separator are too high, erosion (reduced reliability) and excessive turbulence (solids carry over into the overflow stream) risks arise. Langbauer in Figure 11 studied how limiting or narrow the flow rate operating envelope is for downhole cyclonic-gravity separators (using solids particles greater than 250 micron) and that they do not possess the ability to manage the flow rate range experience during a rod pump intake stroke.

Cyclonic separators also face the reliability risk of erosion due to their inherent angular momentum solids separation design. DNV RP-0501[xviii] discusses erosion as a function of impingement angles; see Figure 12. Ideally a flow path change in angle for limiting erosion risks should be less than ten (10) degrees and for example twenty (20) degrees is really no better than forty five (45) degrees. All downhole cyclonic-gravity separators require a flow path angle change greater than ten (10) degrees otherwise they would not be able to generate adequate angular momentum for creating a heavier fraction portion of the flow stream. Since the radius of turn inside the cyclonic-gravity separate is high, erosion risks will be high if velocities exceed 5-10 meters/second; see Figure 13 from DNV RP-0501[xix].

An increase level of corrosiveness in the produced liquids will greatly increase material losses within the cyclonic solids separator in the form of corrosion-erosion. Sani[xx] showed when a corrosive environment exists that the rate of material loss becomes a function of both the corrosion rate and erosion rate added together, leading to material losses at multiple times faster than in a non-corrosive environment. Therefore, when corrosion risks are likely, downhole cyclonic solids separators should consider use of corrosion and abrasion tolerant materials (which can increase costs) or be avoided.

For the downhole bypass cyclonic-gravity solids separation system discussed previously in Figure 2, to affect and receive separated solids particles, the singular feed fluid stream requires flow fractions within that singular fluid stream to be concentrated into a heavier fraction and lighter fraction prior to the bypass. This can only be physically achieved by imposing angular momentum forces using cyclonic-gravity separator component. That is, both cyclonic and gravitation forces are imparted to the fluid stream to concentrate solids in a portion of the fluid stream centrifugally to the outside of the flow path but also gravitationally to the low side of the flow path. The concentrated portion of the flow stream is directed into the bypass. The bypass effectively splits the fluid stream into two flow paths. As such, the bypass's flow path receives the underflow's heavier solids fraction of the fluid stream and the overflow's flow path receives the lighter solids fraction.

It could be concluded that the trend to finer frac sand solids particles, the excessive slugging tendency of horizontal wells, expected gas being present in the fluid stream at the point of solids separation, and highly variable intake flow rates with a rod pump discloses a considerable limitation and an under performance risk with downhole cyclonic-gravity separators. For finer solids less than 200 micron, it is highly apparent that solids filtering is required.

LIMITATIONS OF DOWNHOLE FILTERING SCREEN SOLIDS SEPARATORS

To effectively separate solids from liquid over a broad size and flow rate range, filtering is required. As discussed previously, finer solids particles less than 200 microns are most challenging and likely require filtering to separate them from the liquid.

If a downhole filtering screen is in a flow path where the flow is always in one direction or is upstream of mud joints, then there is no where to contain separated solids other than on the filtering screen itself, which leads to inevitable plugging. Pumping a flush operation from surface to reserve flow purge the filtering screen is then often required, which is a highly diminishing return practice, as the solids have nowhere to be contained and therefore simply re-plug the filtering screen once production is restarted. Running more filter screens for more filter screen surface area can extend the run life before plugging, but cost economics quickly come into play.

SLB[xxi] revealed that “if 2D tubing screens are not configured appropriately, the results can be detrimental to the economics of your well. Sand screen pores that are too small may result in premature plugging, halting production and requiring a remedial workover. If they are too big, they allow solids to freely enter the production flow, which can erode tubing, destroy artificial lift pumps, wash out surface chokes, and fill up your surface separators, requiring sand jetting and disposal.”

Use of bypass differential pressure valves with filtering screens just means the screen is bypassed once it is plugged, exposing the pump to damaging solids once again.

Solids can damage sand screens from erosion. Filter screen designs need to minimize fluid velocities and use erosion resistant materials, which can escalate costs. If placed upstream of a gas separator, the fluid stream volumetric flow rate will be dominated by the gas phase volume and high liquid/solids velocities and associated erosion will be likely. Such velocity risks should be multiphase flow modeled, using transient flow model such as Nagoo and Associates Multiphase Analytical Prediction Engine MAPe_v7[xxii] and evaluated according to erosion risk criteria as specified in erosion management recommended practices such as DNV RP-0501.

Scaling is a plugging risk for filter screens. Anywhere in a flow path system that imposes an abrupt pressure drop will face the risk of scaling. Ghareeb[xxiii] described “another limitation of the screen is experienced when scale is encountered in the well. Over time, scale can build up on the surface of the screen, slowly coating the opening and restricting the flow of oil and gas. This is a problem that will clearly limit the ability of the screen to function properly and can cause the well to plug completely.”

IMPROVING DOWNHOLE SOLIDS SEPARATION – A SYSTEM BASED APPROACH

A system based approach (i.e., a group of components working harmoniously together) versus a component based approach, for solving a problem, was believed it would provide a higher probability for designing a better downhole solids control solution.

This system solution mindset led to research and study of solids control and management practices in surface oil and gas production facilities and waste-water treatment facilities. These facilities have been successfully using self cleaning solids filtering systems. Two variations were most common: (1) a self cleaning solids filter that uses mechanical means (reciprocating piston of rotating auger) to periodically scrape off the solids filter cake that forms on the filter and then contains the solids out of harms way, and (2) a self cleaning solids filtering system that uses an automated piping and valves system that periodically reserves flows to back flush the filter and contain solids out of harms way.

Figures 14[xxiv] and 15[xxv] are example the flow paths for surface self cleaning solids filtering systems. It was hypothesized that these surface based self cleaning solids filtering system technologies could be adapted to the downhole environment with a rod pump and could resolve the limitations of current downhole solids separators.

A conceptual design was developed and flow loop tested. Key and highly novel parts of the system were engineering a periodic back flush of the downhole filter screen and resolving where to contain the solids once they were back flushed off the filter screen. The system was designed such that it would continuously clean the filter screen without having to stop or interrupting pumping operations. It would also need to be designed under the risk scenario that if the filter screens were to plug, the filter screens could be automatically bypassed.

Figure 16 shows the process flow diagram of the improved solids separation system and it was called the SharkNET. First, gas is efficiently separated from the liquid/solids stream using a liquid fall back separator that is designed to tolerate sluggy flow conditions and for maximizing gas separation by taking advantage of naturally occurring multiphase flow reversals (liquid fallback) – see SPE technical paper 209755[xxvi]. Liquid and solids are then filtered and held by the filtering screen during the pump's upstroke. The pump then back flushes the filtering screen at the start of the pump's downstroke, which in combination with gravitational forces, releases the solids from the filtering screen. The back flushed solids then gravity settle during the pump's downstroke (when no fluid movement is occurring at the filtering screen) downwards into the mud joints for containment.

Figure 17 details key system components and their strategic location in the flow path, as well as the process sequence during a complete pump stroke. This process sequence is repeated each pump stroke and as such, shows that the self cleaning of the filtering screen is an incremental continuous process.

The filtering screens were positioned in the only location in the bottomhole assembly that would allow for out of harms way solids containment – the base of the gas separator's pump intake tube and down into the top mud joint(s). In this unique location the liquid flow changes from downwards to upwards or in other words, where the liquid "U-turns". Figure 17's first sequence step shows that liquid will be leaking off through the filtering screen during the pump's upstroke and solids will be building a filter cake on the outside diameter of the filter screen (and will be held on the screen when liquid is moving through the screen). The filtering screen is engineered to be long and permeable enough such that all the liquid has completely leaked off or U-turned through the filtering screen prior to flows reaching the bottom of the filter screen (which is open ended). This means some of the filtering screen is always and intentionally in a static portion of the liquid column down inside the mud joints. Figure 18 shows flow loop testing demonstrated this U-turning of liquid through the upper portion of filtering screen with a coloured dye and no liquid movement in the lower portion of the filtering screen – at 200 barrels/day of water only the top couple of feet of the filter screen experienced fluid flow where liquids are U-turning through the filter screen and upwards to the pump intake tube and to the pump.

Figure 17 then shows the next system process step where at the commencement of the pump's downstroke a filtering screen back flushing event occurs. Flows are momentarily reversed to "bump" or "pulse" the solids filter cake off the filter screen. This back flush was engineered by delaying the closure the rod pump's standing valve. A small portion of the liquid drawn into the pump barrel during its upstroke is used to back flush the filtering screen (this flush occurs systematically on each pump stroke).

Figure 17 subsequently shows a third step in the process, during the rod pump's downstroke, when importantly the standing valve is closed, the system takes advantage of a zero flow condition across the filtering screen. When there is no flow present at the filtering screens, solids can efficiently settle downwards from the filter screen/intake and (eventually) into the mud joints for permanent capture/containment.

The specialized engineered system components were as follows:

- a filtering screen engineered to hold and release (not retain) solids down to 120 micron particle size; solids do not get retained in or on filtering screen when fluid flow ceases during the pump's downstroke,
- placement of the filtering screen sequentially after the gas separation stage and inside the uppermost mud joint – in this location, the solids laden liquid's flow path U-turns from downwards to upwards through the filtering screen, with solids being filter out/retained on the outside diameter of the filtering screen.
- continuous self-cleaning of the filtering screen is achieved with a specially designed rod pump standing valve that intentionally back flushes the filtering screen each pump stroke – a reverse pressure pulse wave and a back flush liquid volume each pump stroke releases solids from the filtering screen,
- a tubular filtering screen that is open-ended at its bottom for allowing bypass in the event of filter plugging, and
- solids are settled down into and permanently contained downhole into standard mud joints.

FILTER SCREEN DESIGN METHODOLOGY

Surface self cleaning solids filtering systems commonly use filtering screens that are designed to hold (trap) solids in one fluid flow direction but then easily release solids in the reverse fluid flow direction. This means the preferred filtering screen type is a two dimensional filtering screen, which is characterized by a single layer of screen hole apertures (or mesh). It is therefore highly undesirable to use a filtering screen that is designed to retain solids once they are filtered from the liquid – a common design feature for three dimensional sand screens such as is described in SLB[xxvii].

Research and evaluation was extensively conducted for identifying an ideal two dimensional filtering screen that met our hold/release filtering design criteria, was relatively low cost, was readily available and could be reliably run downhole in an oil and gas well environment. Figures 19 and 20 show the outcome from this research – use proven drilling rig solids shaker screen technology. Drilling rig shaker screens provided the ideal fit for the purpose for a self cleaning two dimensional filter. Drilling rig shaker screens have been designed to effectively filter and then release solids over a very broad range of solids particle size. They are also robust and tough. Stainless steel versions have high corrosion resistance, have low coefficient of friction for preventing blockages and scale adhesion and provide good erosion/abrasion tolerance.

316 stainless steel drilling rig shaker screens were sized to filter 120 micron and larger solids particles and were wrapped around a structural 316 stainless steel perforated mandrel – see Figure 20. See also Figures 21 and 22 for detailed filtering screen dimensional information. Each individual screen is approximately 5 feet (1.5 meters) in length, which corresponds to the width of a common drilling rig shaker screen. Two outside diameters and threaded connections were chosen: 1.6" by 1.0" NPT for 2-3/8" (60.3mm) EUE mud joints and 1.8" by 1.25" NPT for 2-7/8" (73.0mm) EUE and larger mud joints. These filter screen outside diameters inside the respective tubing size mud joints was deemed an adequate amount of annular clearance to avoid solids blockage during settling in that annulus – however, this dimension must be continuously evaluated and optimized as experience and well solids production history dictates.

It is of utmost importance that the solids expected to be encountered are analyzed for their solids particle size distribution and the smallest expected particle size determined. Filtering screens finer than 120 microns can be used if required, however the foaming tendency of the emulsion should be considered during screen sizing. Self cleaning a filter using back flushing means it will be highly unlikely that multiple solids particles will form stacked bridges of themselves across the pore throats (that are larger than the solids) of a two dimensional filtering screen. This solids bridging mechanism is commonly applied for drilling fluid borehole filter cakes where the flid pressure differential is consistently in one direction (i.e., no back flushing) is discussed by Hui[xxviii]. So the determining the smallest individual particle size must be used for filtering screen mesh sizing.

For determining filtering screen length requirements, the system design requires a lower portion of the filtering screen to remain in static liquid inside the closed chamber mud joints. The filtering screens are therefore sized for the expected maximum instantaneous pump intake fluid rates for a specific well's expectations. As discussed in Figure 5, instantaneous pump upstroke plunger velocities can exceed four (4) times the average with consequence high liquid intake rates. This is required to prevent liquids and solids from bypassing around the open ended lowermost filtering screen. For example, flow loop testing confirmed that at 200 bbls/day approximately 1.2 feet of filtering screen length experienced U-turning fluid flow, so instantaneous pump intake rates can be as high as 1600 bbls/day, so 1600/200 x 1. = minimum of 9.6 feet of filtering screen (two by 5 foot long filtering screens) is required for well that produces an average of 200 bbls/day of liquid. More simply, one by 5 foot filtering screen for every 100 bbls/day of average daily liquid production – this dimension must also be continuously evaluated and optimized as experience dictates.

The lowermost filtering screen is to be open-ended at its bottom for allowing bypass in the risk event of filter plugging.

DEVELOPMENT OF A ROD PUMP BACK FLUSHING STANDING VALVE (BFSV)

Continuous filter self cleaning is achieved with a specially designed rod pump with a standing valve that back flushes – a back flushing standing valve or BFSV. Delaying the closing of a standing valve to create a back flush of liquid was engineered using an extension tube or sleeve inside a double length standing valve as shown in Figure 23. The valve's ball must now travel an extra 2 inches (50.8mm) through a tight tolerance sleeve before is reaches its seat – this extra length of ball travel and ball clearance to the extension sleeve must be continuously evaluated and optimized as experience dictates.

The design intent is such that the standing valve's ball travels downwards at the commencement of the pump's downstroke and as it enters the extension sleeve it creates a reverse pressure pulse wave plus a back flush volume that dislodges solids (bumps or pulses) solids off the filter screen. This then allows the solids to gravitationally settle downward into the closed chamber mud joints during the entire pump downstroke timeframe (when no flow is present at the filtering screen). The pressure pulse created when the ball enters the sleeve travels at the speed of sound and "hits" the screen which promotes an initial solids release from the filter screen followed by the back flush volume.

Figure 24 details the ball and seat designs and the material selection. It is recommended to use titanium carbide balls and tungsten carbide seats. A lighter weight ball has less momentum when it contacts the seat and therefore reduces seat damage risks from the extra ball travel length versus a standard standing valve cage. Silicon nitride balls have also been used and have proven to be reliable.

MODIFICATION OF THE LIQUID FALLBACK GAS SEPARATOR

Figure 25 shows the design changes to the liquid fallback gas separator for integration of the solids filtering screens. The oval pump intake tube now has an NPT threaded pin end connection that is located at the lowermost part of the gas separator. The filtering screens are simply threaded on to the separator's pump intake tube. The original singular flow path gravity based solids separation solids weir and velocity acceleration dip tube have now been removed. This original gravity based solids separation feature adequately performed for larger solids particles but did not adequately handle finer solids particles like 100 mesh frac sand (for the gravity solids separator limitation reasons discussed previously).

DESIGN OF STAND ALONE SYSTEM (NO GAS SEPARATOR)

Figure 26 shows an engineering drawing of a stand alone intake sub when applications do not require a high performance gas separator. This sub allow wellbore produced fluids and solids to be drawn into an annular space where fluids are then directed downward along the side the self cleaning solids filtering screens. The stand alone intake sub also provides a connection for standard mud joints.

The rod pump still requires a back flushing standing valve (BFSV) for the system to operate effectively as designed.

WELLBORE BOTTOMHOLE ASSEMBLY CONFIGURATIONS

Figures 27 and 28 show example wellbore bottomhole assembly configurations. Both configurations are relatively simple and low operational risk.

Figure 27 shows a typical configuration with the liquid fallback gas separator.

Figure 28 shows a configuration with the stand alone intake sub and no gas separator. This was an application where solids volumes were expected to be large, so the mud joints were left open ended for allowing solids to continue settling down into the well's casing cellar (for containment of a large volume of solids). This also meant the lowermost filtering screen was required to be bull plugged.

CASE STUDIES

Field implementations of the downhole self cleaning solids filtering system commenced in the middle of 2022 are showing early time promising results for extending rod pump run life. With over 30 installs of this system effective March 2023, statistically meaningful results and system improvements are being compiled. Some relevant case studies are as follows. These case studies will be updated as more time-based reliability results are compiled.

Case Study 1 – Figure 29 shows pump cards from a relatively shallow well in California (approximately 2,500 feet deep). The top right portion of one of the surface cards that is not showing fluid pound (highlighted in yellow) indicated the delayed closing of the standing valve and showed this delay as approximately 2' inches of downward plunger travel. This confirmed operability of the back flushing action by the back flushing standing valve. This well utilized a stand alone intake sub with no gas separator and a 2.25" BFSV cage dressed with an API silicon nitride ball and tungsten carbide seat.

Case Study 2 – Figure 30 shows a pump's run time with cycling from an install in California. This well had a history of repeatedly failing pumps from solids within 30 days. Since installation in August of 2022, the well has continued to successfully pump. This well utilized a stand alone intake sub with no gas separator and a 2.25" BFSV cage dressed with an API silicon nitride ball and tungsten carbide seat. The lowermost filtering screen was bull plugged as opened ended mud joints were used (see Figure 28), so the pump cycling is indicative of filter screen plugging and restriction fluid into the pump intake. Liquid production rates were approximately 1,000 bbls/day of high water cut and 3 by 5 foot long by 1.8” outside diameter filtering screens were used. Note that the pump cycle events would cease for a period of two weeks and then it would repeat, indicating the filtering screens were able to self clean and that back flushing is necessary.

Case Study 3 – Figure 31 shows photographs of plugged filtering screens. This solids laden heavy oil California well used a stand alone intake sub (no gas separator) in the bottomhole assembly with open ended mud joints and the lowermost filtering screen was closed off (bull plugged). It did not use a back flushing standing valve (BFSV) in the rod pump. The filtering screen plugged very quickly and had to be pulled. The photographs show the filtering screens being plugged with fine solids particles and with tar-like heavy oil. This result strongly suggests that the self cleaning back flushing process is necessary and that a BFSV is required as part of the system for successful operation.

Case Study 4 – Figures 32, 33, and 34 show results from a North Dakota Bakken horizontal well. The self cleaning filter system did not improve pump run life over the previous historic pump failure frequency (due to fine particle solids) of approximately every 45 days. The well used a 4.5” outside diameter liquid fallback gas separator, a 2.25” BFSV cage dressed with an API titanium carbide ball and tungsten carbide seat and 3 by 5 foot long by 1.8” outside diameter filtering screens. Production from the well was approximately 350 bbls/day of light oil, 150 bbls/day of water and 700 Mscf/day of gas. Figure 32 shows a produced fluids solids grind out indicating very few solids are making it to surface during production/pumping. Figure 33 shows the solids mass collected from the pump after it had failed and was retrieved at surface – very fine particulate solids were observed. Figure 34 shows the lab analysed solids size distribution recovered from the pump – solids were on average smaller than 120 microns (crushed 100 mesh frac sand), therefore solids will be able to pass through the filtering screen.

Case Study 5 – Figure 35 show a solids distribution analysed prior to the installation of the downhole self cleaning filter system. The solids particle sizes are mostly larger than 120 microns. The results from this North Dakota Bakken horizontal well are positive, as the well continues to run without a pump failure longer than the historic pump failure frequency and is producing at 30-50% high production rates (which is indicative of more solids being encountered at the separator). The well used a 4.5” outside diameter liquid fallback gas separator, a 2.25” BFSV cage dressed with an API titanium carbide ball and tungsten carbide seat and 3 by 5 foot long by 1.8” outside diameter filtering screens.

Case Study 6 – Eagleford horizonal well that has been prone to high frequency pump failures (less than 120 days) with 100 mesh frac sand. The well used a 3.5” outside diameter liquid fallback gas separator, a 2.25” BFSV cage dressed with an API titanium carbide ball and tungsten carbide seat and 3 by 5 foot long by 1.8” outside diameter filtering screens. A positive result with the well continuing to steadily operate after more than 120 days.

Case Study 7 – Figure 24 Glauconite Canada. A troublesome light oil well with a history of frequent pump failures due to solids (once every 3 to 6 months). This well used a stand alone intake sub, a 2.25” BFSV cage dressed with an API titanium carbide ball and tungsten carbide seat and 3 by 5 foot long by 1.8” outside diameter filtering screens. A positive result with the well continuing to steadily operate after more than 6 months.

IMPROVING THE SELF CLEANING FILTER SYSTEM – VIBRATION AND AGITATION

To improve the system’s performance for self cleaning of the filter, it has been found that vibration and agitation can be beneficial to the system.

Experience with field implementation of the downhole self cleaning solids filtering system showed in some instances that level of filtering screen plugging does occur – this was indicated by the well pump cycling. Pump cycling occurs when a rod pump is temporarily shut down by its controller due to an indication of incomplete pump fillage or a restricted pump intake.

Experiments with “light” tapping of the rod pump revealed that pump cycling could be eliminated completely. Vibration and mechanical agitation appear to help to release solids from the filter screen, thereby allowing more effective and efficient gravitational settling of solids into the mud joints.

The authors do not recommend placing rod pumps “on tap”, as a loss of reliability can normally be expected. Design of speciality and proprietary downhole components for creating vibration and mechanical agitation of the filter screen during the “no flow” period of the pump’s downstroke is ongoing.

CONCLUSION

A system based and engineered design for controlling finer particle solids risks to a rod pump has been developed. A first-of-a-kind downhole self cleaning solids filtering system that avoids filter screen plugging risks by including a rod pump with a unique back flushing rod standing valve (BFSV) is showing promising results.

The authors note that efficient downhole gas separation from liquid is an important first process sequence step for allowing efficient solids separation from the liquid.

FIGURES

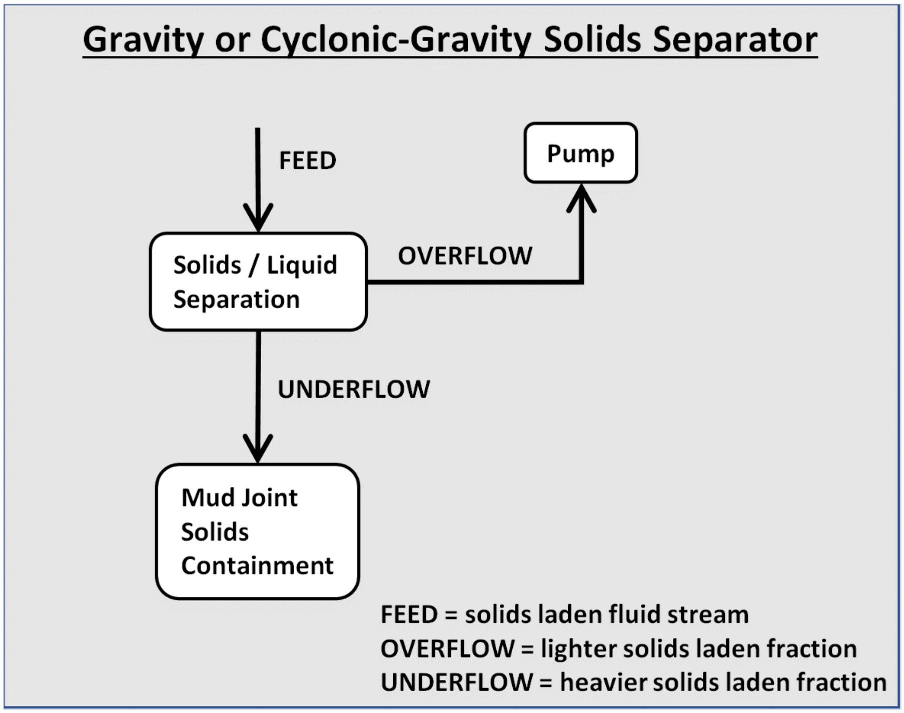


FIGURE 1 – GRAVITY OR CYCLONIC-GRAVITY STYLE SOLIDS SEPARATORS

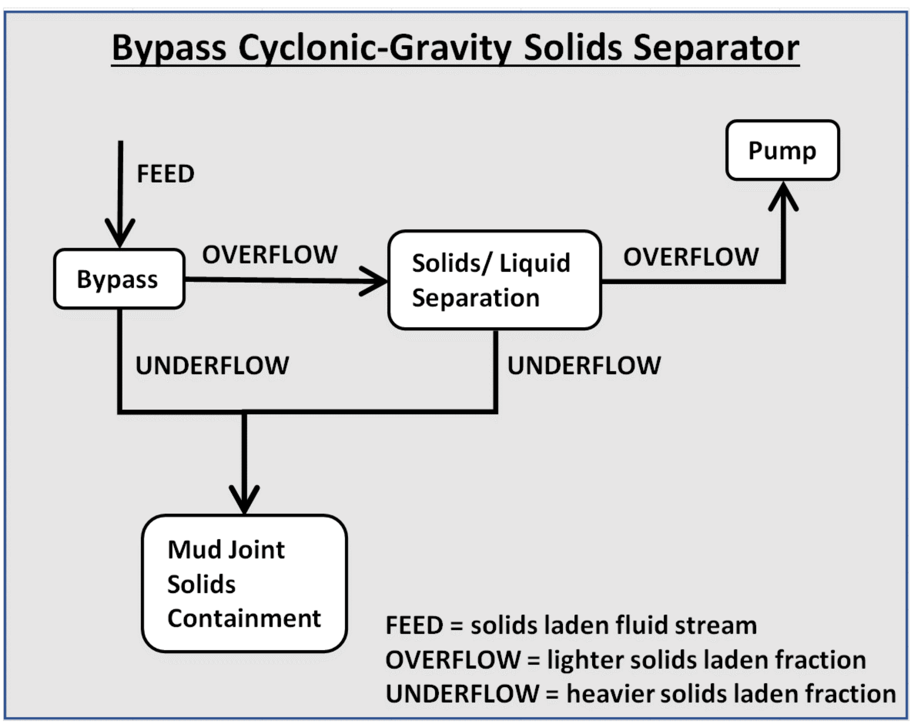


FIGURE 2 – BYPASS CYCLONIC-GRAVITY DOWNHOLE SOLIDS SEPARATOR

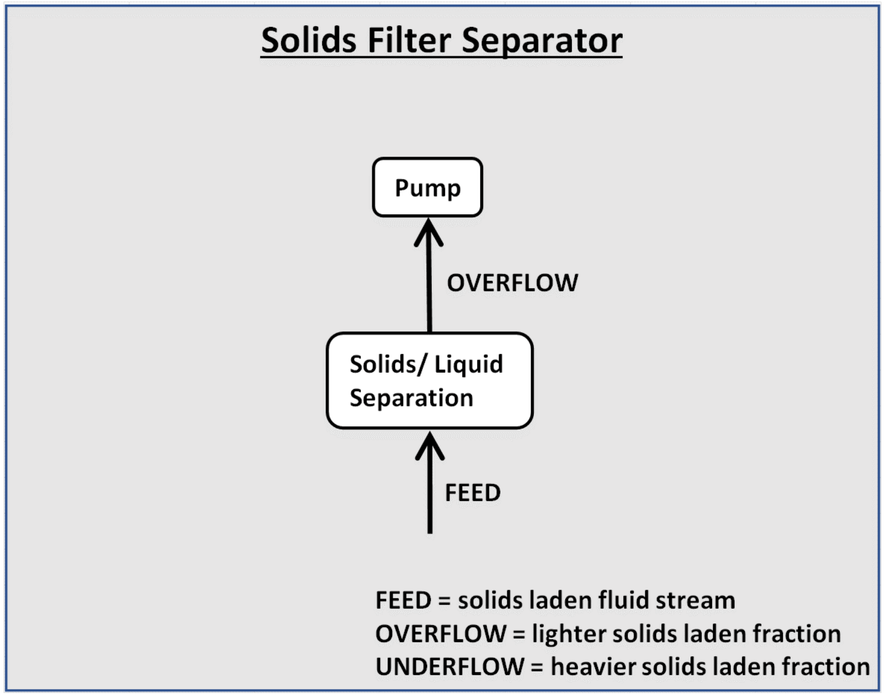


FIGURE 3 – FILTER STYLE DOWNHOLE SOLIDS SEPARATOR

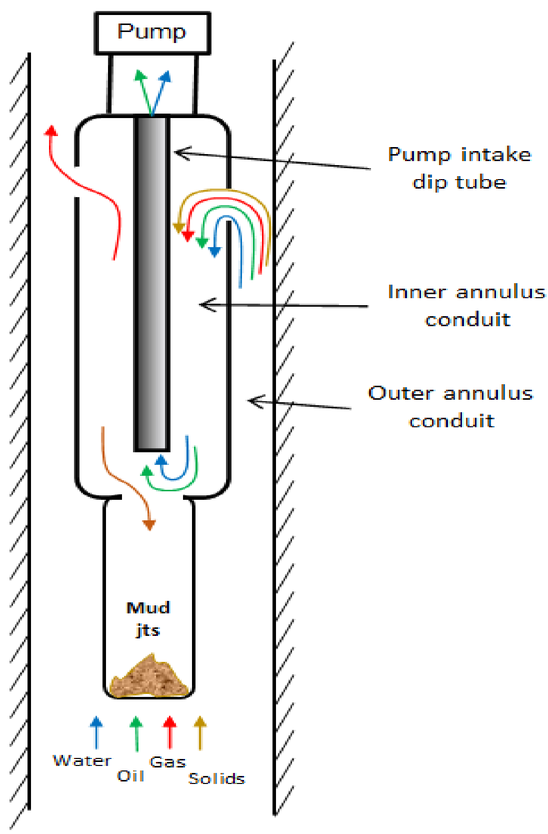


FIGURE 4 – POOR-BOY GAS AND SOLIDS SEPARATOR WITH MUD JOINTS

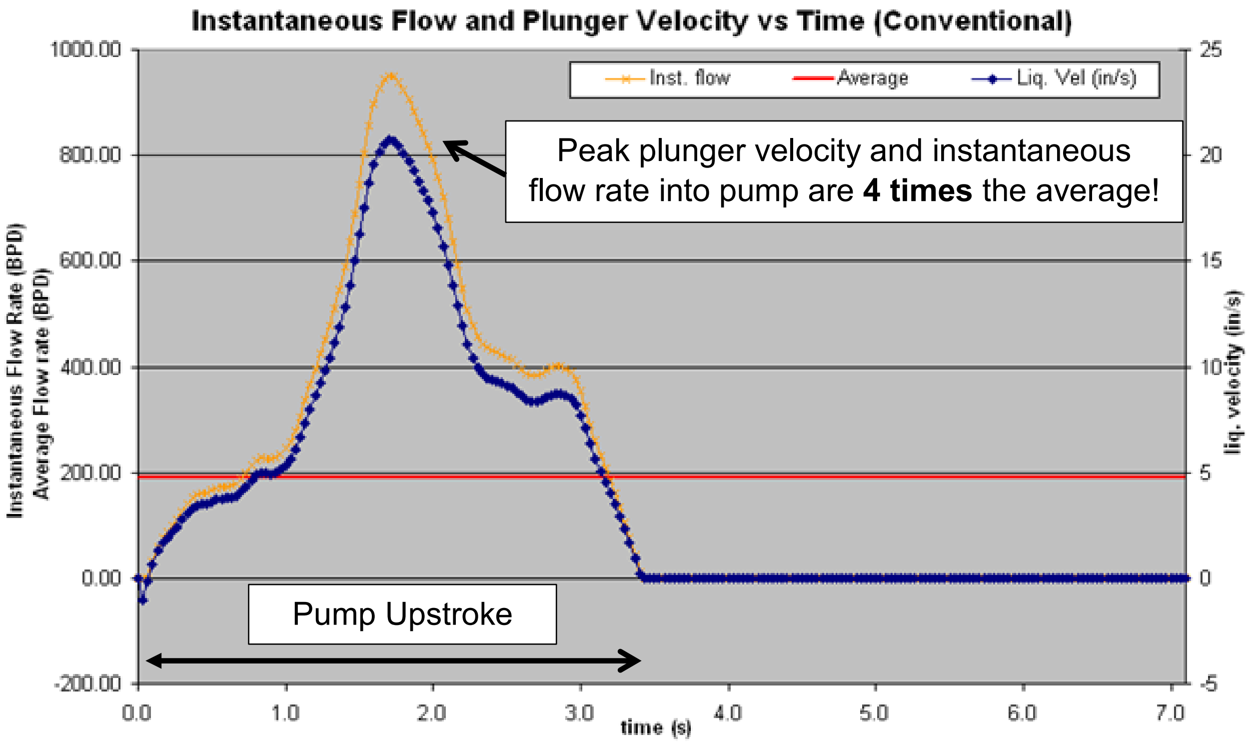


FIGURE 5 – INSTANTANEOUS FLOW RATE AND PLUNGER VELOCITY

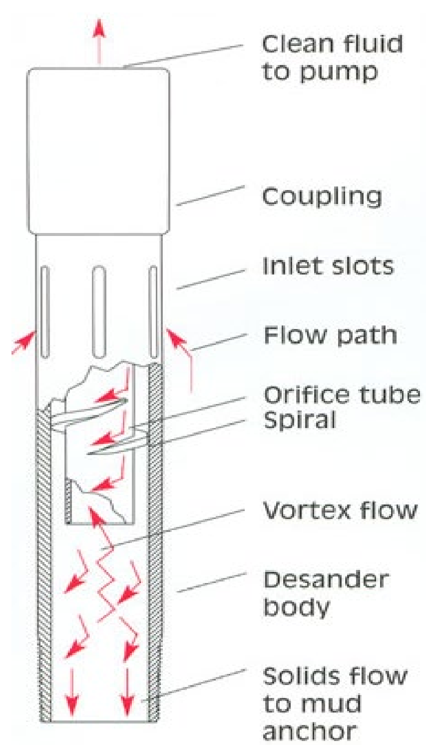


FIGURE 6 – CAVINS DESANDER CYCLONIC-GRAVITY SOLIDS SEPARATOR

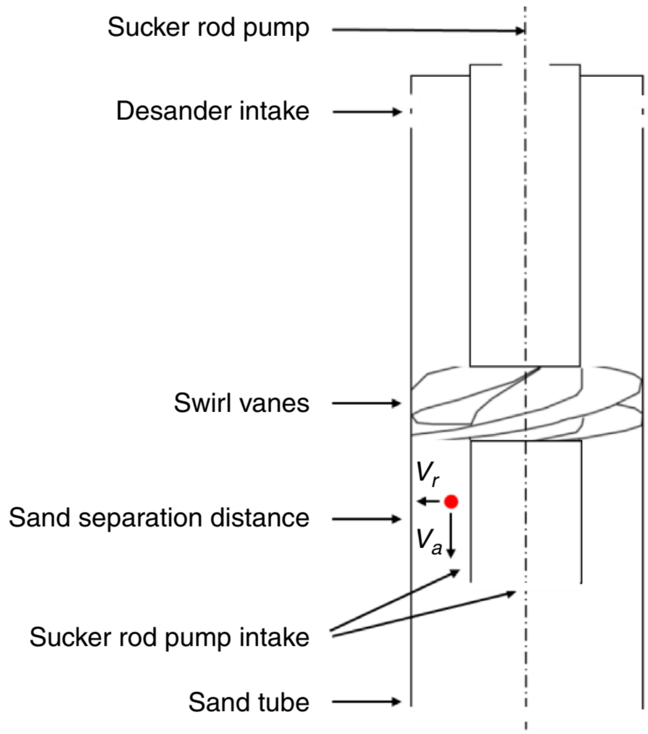


FIGURE 7 – DOWNHOLE CYCLONIC-GRAVITY SOLIDS SEPARATOR

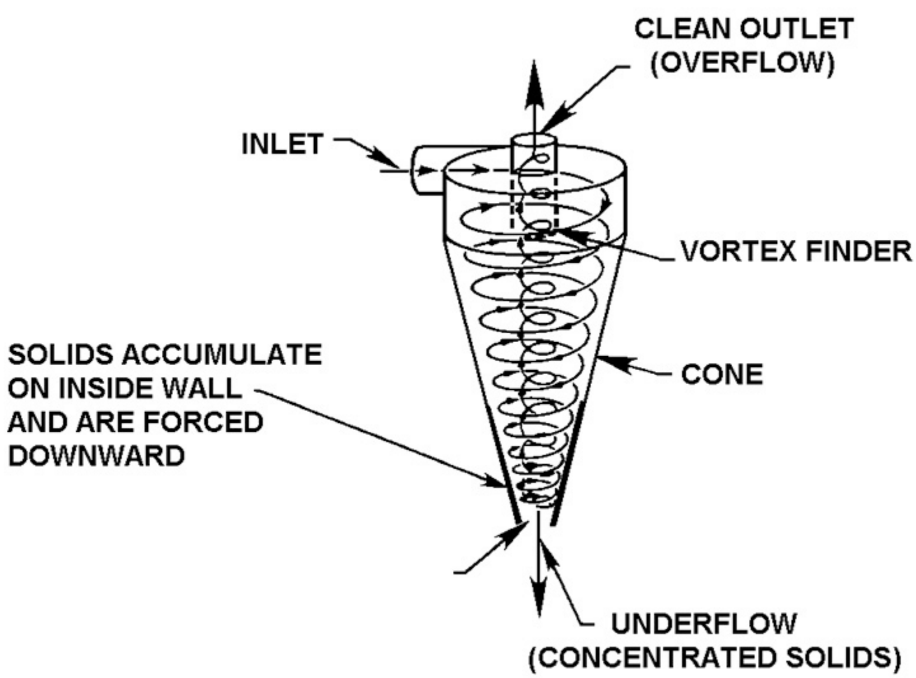


FIGURE 8 – HYDROCYCLONE SEPARATOR WITH CONTINUOUS UNDERFLOW

Southern Ohio Sand 100 Mesh Sand

Quick Chek ✓			ISO 13503-2	50/140 Frac Sand Public Values	100 mesh
Particle Size Distribution, mm		Mesh size			
	0.425	40	≤ 0.1	0	0
	0.300	50		0.1	2.8
	0.212	70		22.5	35.1
	0.180	80		36.2	24.4
	0.150	100		27.7	23.1
	0.125	120		9.4	11.0
	0.106	140		3.3	2.7
	0.075	200		0.7	0.8
	<0.075	Pan	≤ 1.0	0.1	0.1
		Total		100	100.0
		% In Size	≥ 90	64	96.3
Mean Particle Diameter, mm					0.195
Median Particle Diameter (MPD), mm					0.190

FIGURE 9 – TYPICAL 100 MESH FRAC SAND PARTICLE SIZE DISTRIBUTION

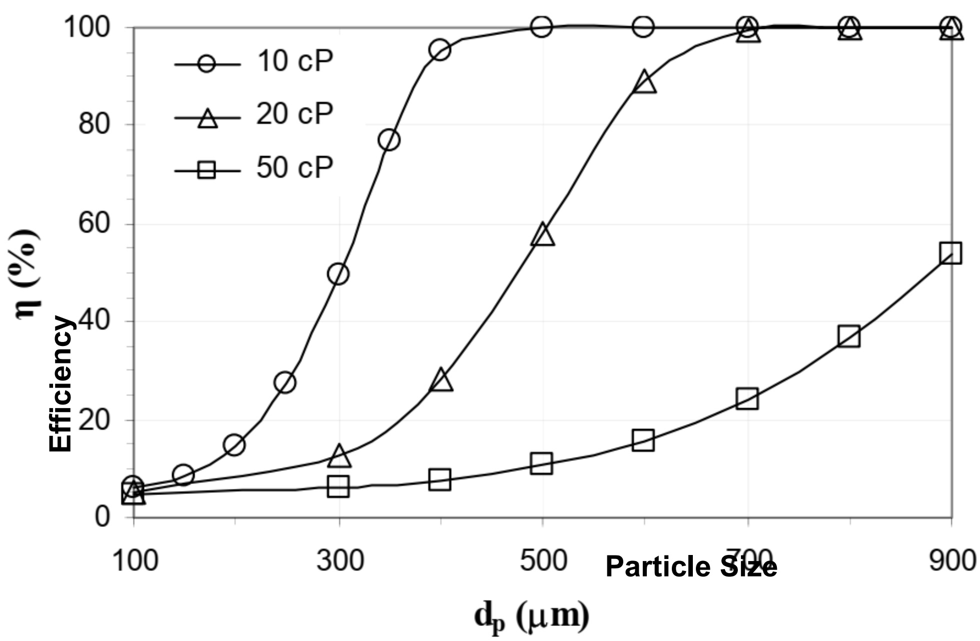


FIGURE 10 – DOWNHOLE CYCLONIC-GRAVITY SEPARATOR EFFICIENCY AS A FUNCTION OF PARTICLE SIZE

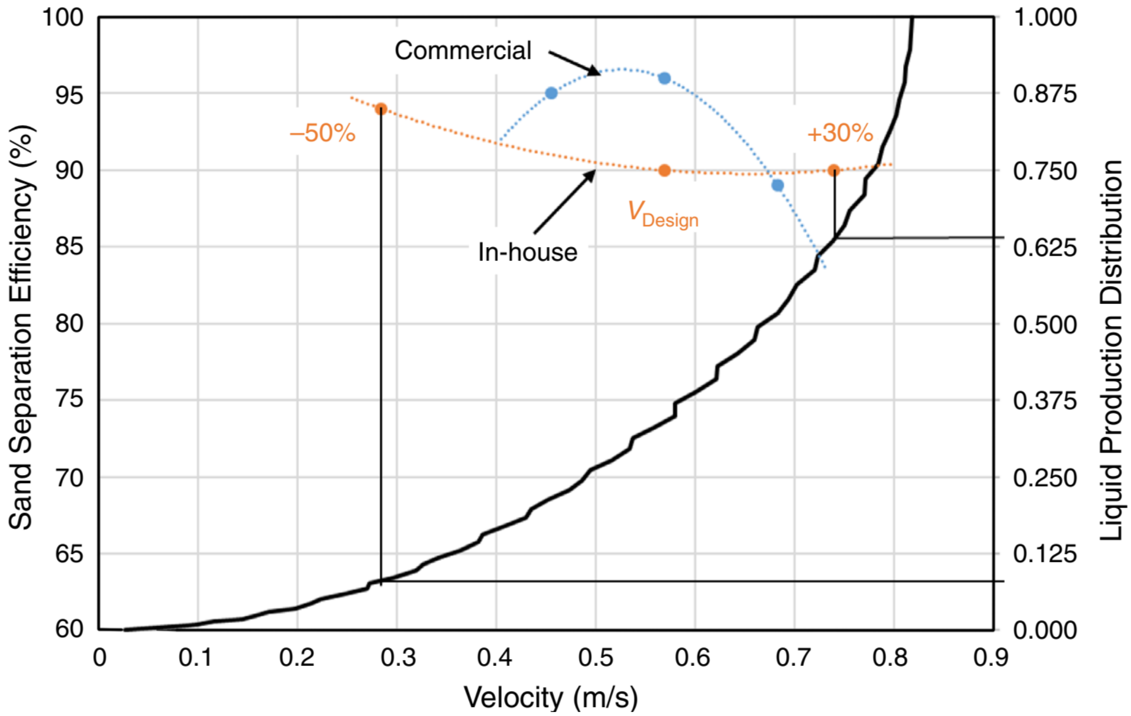


FIGURE 11 – DOWNHOLE CYCLONIC-GRAVITY DESANDER'S LIMITED SOLIDS SEPARATION ENVELOPE

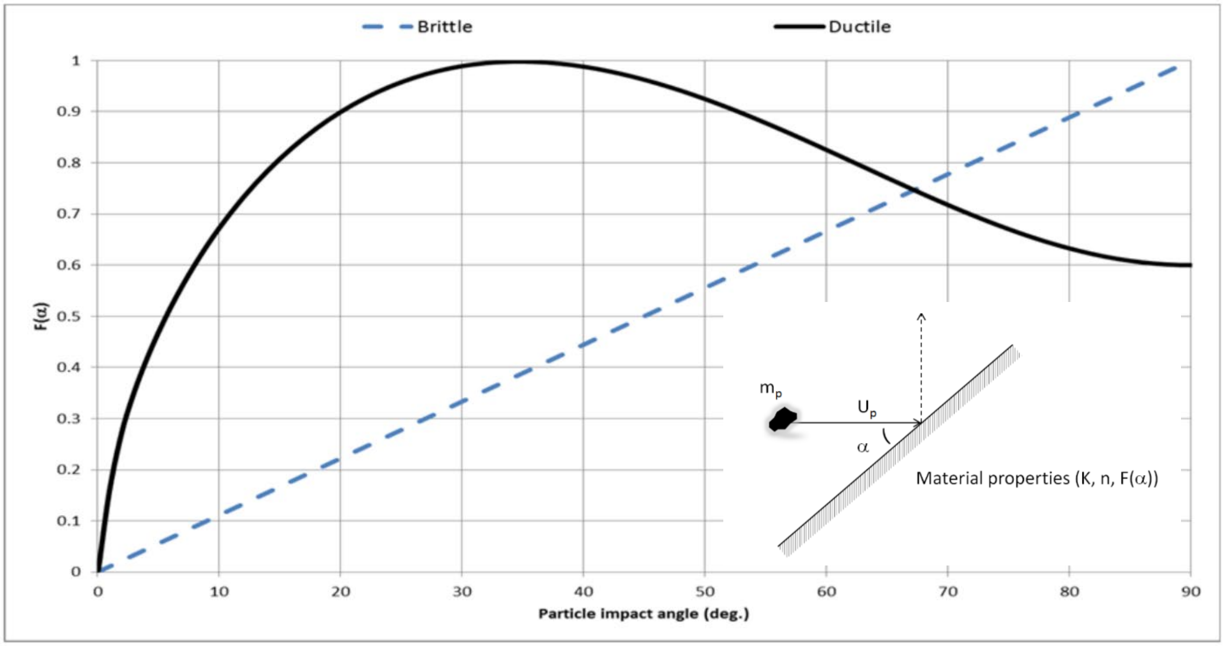


FIGURE 12 – CHANGE IN FLOW PATH ANGLE EROSION RISK

Erosion Class	*Pipework Bulk Flow Velocity V_m (m/s)*	*Definition*	*Relative erosion potential 1)*	*Description*
6	**50 - 70**	*Extremely high erosion potential*	5000	System needs to be operated close to sand free. Safeguards to monitor erosion should be in place and closely monitored
5	**30 – 50**	*Very high erosion potential*	1500	Tolerable sand production limited by risk of erosion
4	**20 – 30**	*High erosion potential*	500	Tolerable sand production will in most cases be dictated by erosion rather than sand handling capacity
3	**10 – 20**	*Medium erosion potential*	100	Tolerable sand production may be limited both by erosion and sand handling capacity
2	**5 – 10**	*Low erosion potential*	25	A large amount of sand is required to cause erosion. The acceptable sand load will in most cases be limited by the sand handling capacity in the process system
1	**0 – 5**	*Extremely low erosion potential*	1	Effects of plain erosion, i.e. not considering any combined effects of flow accelerated corrosion, can normally be neglected for realistic sand loads

1) Relative erosion potential is given for the average velocity in each velocity interval

FIGURE 13 – FLOW VELOCITY EROSION RISK

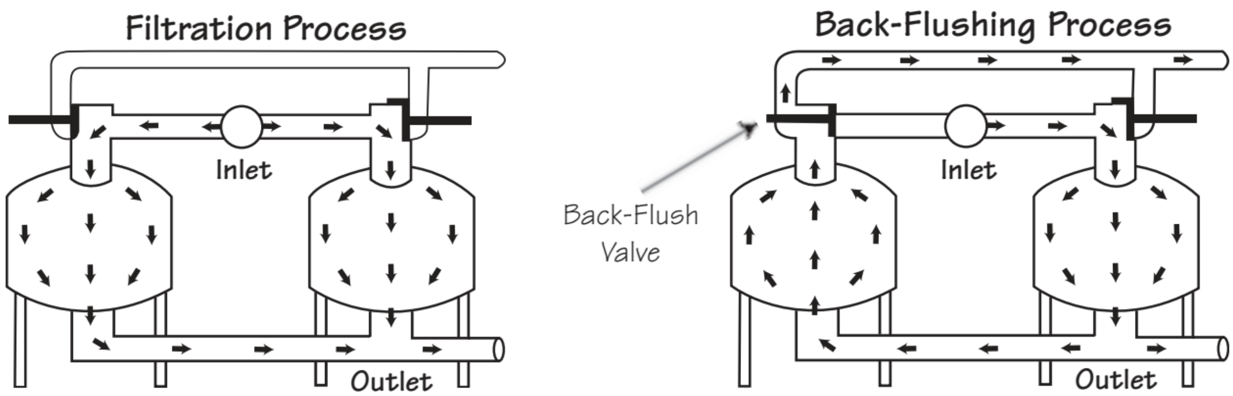


FIGURE 14 – SURFACE FACILITY BACK FLUSHING FILTER SYSTEM

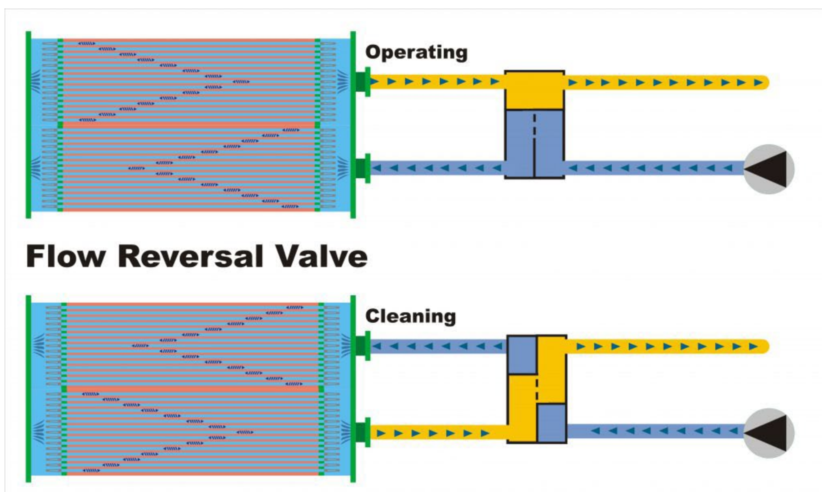


FIGURE 15 – EXAMPLE SURFACE SELF CLEANING SOLIDS FILTERING SYSTEM

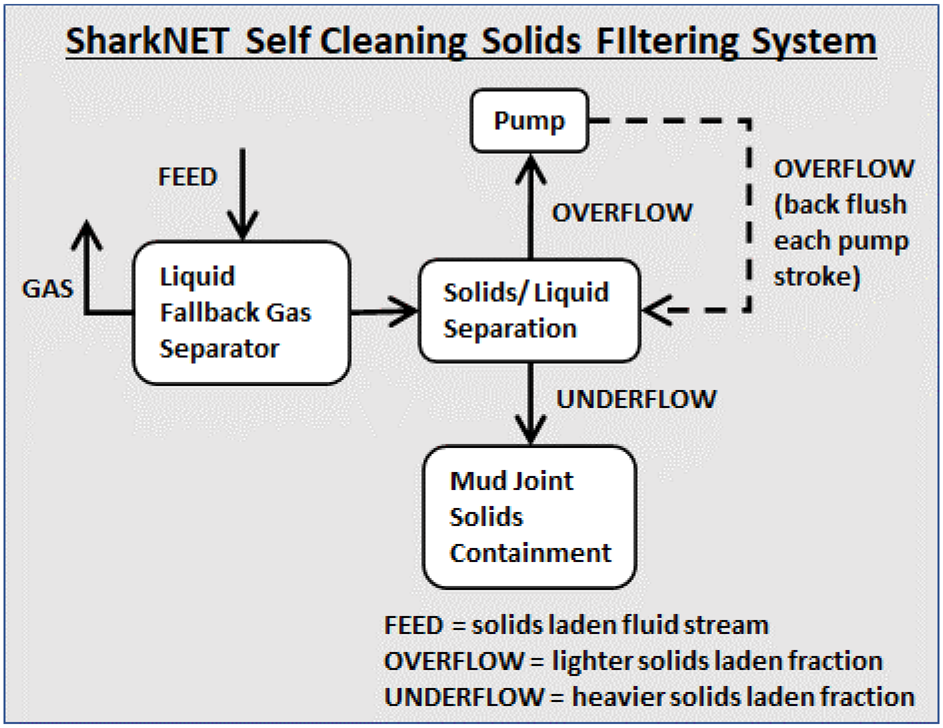
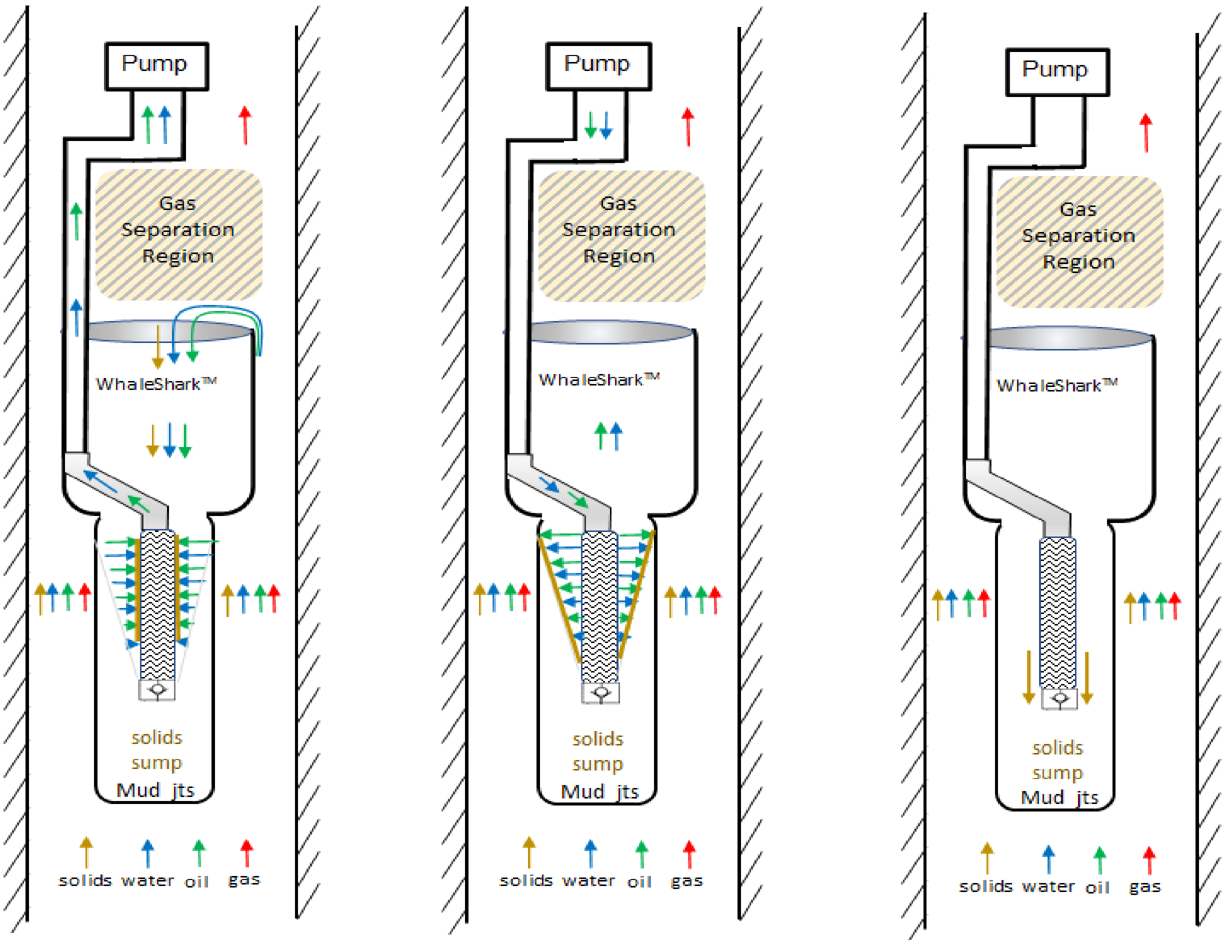


FIGURE 16 – DOWNHOLE SELF CLEANING SOLIDS FILTERING SYSTEM



Pump Upstroke
(drawing fluid through filter and filtering out solids on filter wall)

Start of Pump Downstroke
(reverse flow pulse at filter as pump standing valve closes, removes solids from screen face)

Pump Downstroke
(standing valve closed and no flow, solids gravity settle into mud joints)

FIGURE 17 – PROCESS SEQUENCE FOR THE DOWNHOLE SELF CLEANING SOLIDS FILTERING SYSTEM THAT USES A BACK FLUSHING STANDING VALVE

FIGURE 18 – FLOW LOOP TESTING WITH DYE AND SOLIDS

D 100 Separation(Micron)	API Screen Number
>1850.0 TO 2180.0	API 10
>780.0 TO 925.0	API 20
> 462.5 TO 550.0	API 35
> 390.0 TO 462.5	API 40
> 275.0 TO 327.5	API 50
> 231.0 TO 275.0	API 60
> 196.0 TO 231.0	API 70
> 165.0 TO 196.0	API 80
> 137.5 TO 165.0	API 100
> 116.5 TO 137.5	API 120
> 98.0 TO 116.5	API 140
> 82.5 TO 98.0	API 170
> 69.0 TO 82.5	API 200
> 58.0 TO 69.0	API 230
> 49.0 TO 58.0	API 270
> 41.5 TO 49.0	API 325

*US Mesh**	*Microns*	*Inches*	*Millimeters*
35	500	0.0197	0.5000
40	400	0.0165	0.4000
45	354	0.0138	0.3540
50	297	0.0117	0.2970
60	250	0.0098	0.2500
70	210	0.0083	0.2100
80	177	0.0070	0.1770
100	149	0.0059	0.1490
120	125	0.0049	0.1250
140	105	0.0041	0.1050
170	88	0.0035	0.0880
200	74	0.0029	0.0740
230	63	0.0025	0.0630
270	53	0.0021	0.0530
325	44	0.0017	0.0440
400	37	0.0015	0.0370
450	32	0.0013	0.0320
500	25	0.0010	0.0250
635	20	0.0008	0.0200

**Values are based on the American National Standard for Industrial Wire Cloth (American Standard ASTM - E 11).*

FIGURE 19 – DRILLING RIG SHAKER SCREENS AND PARTICLE SIZES

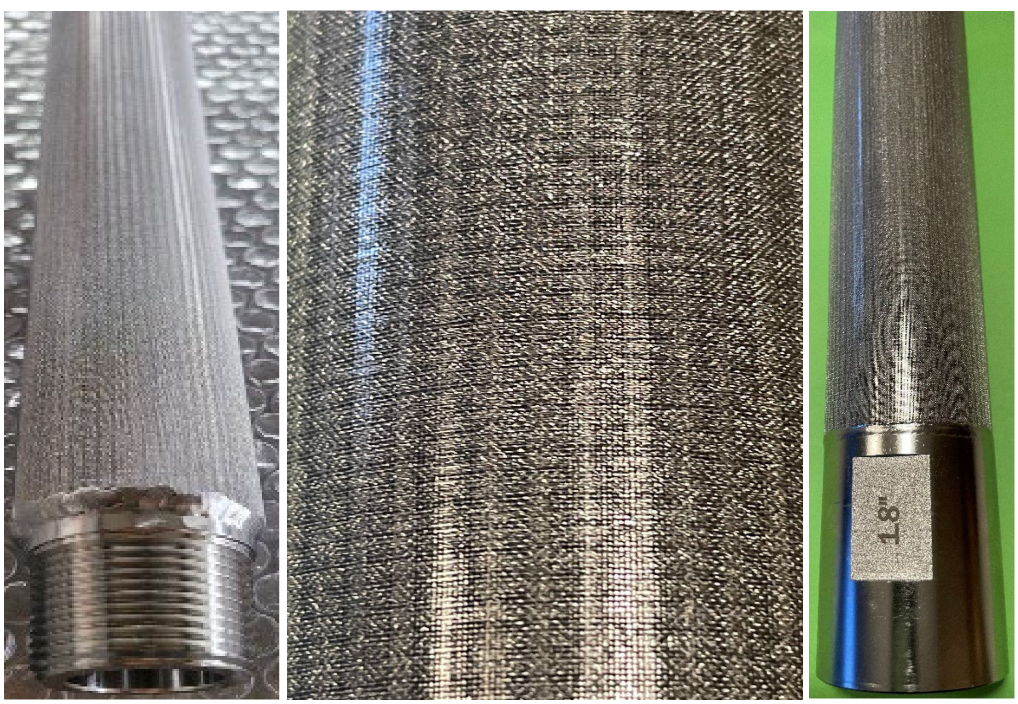
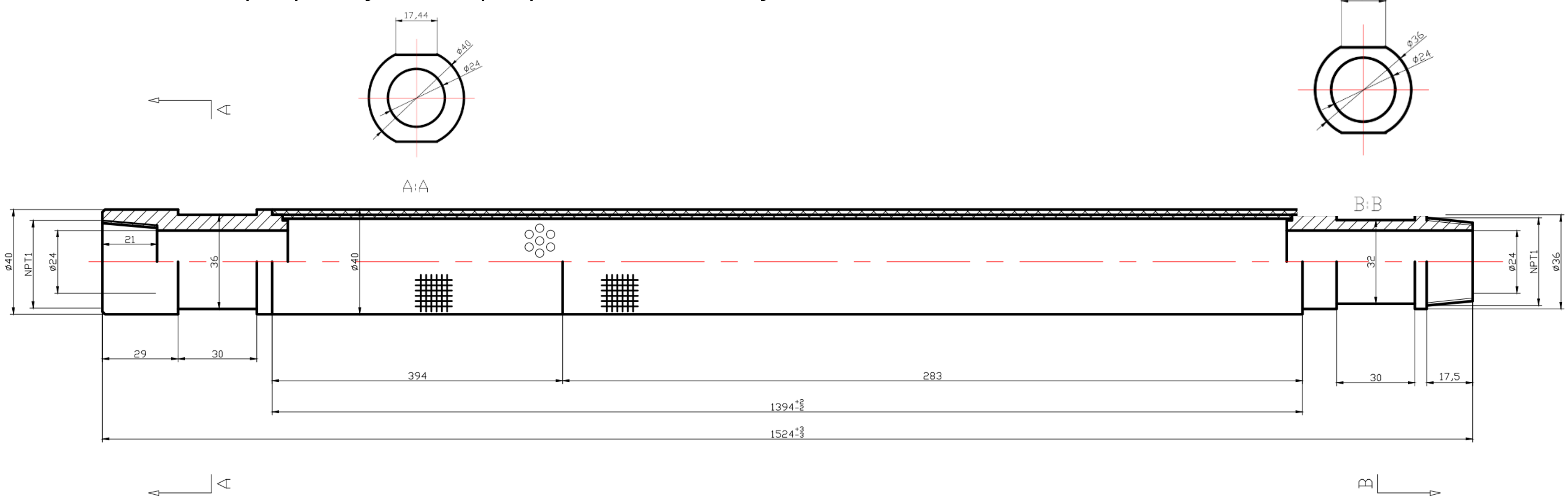


FIGURE 20 – TUBULAR FILTERING SCREEN, 120 MESH (120 MICRON)

Filter Screen Specifications		
Series Model Name	16ss	18ss
Outside Diameter, in [mm]	1.6 [40.6]	1.8 [45.7]
Length per Section, feet [m]	5.0 [1.52]	5.0 [1.52]
Connections, box and pin, in [mm]	1.0 [25.4] NPT	1.25 [31.75] NPT
Make up Torque ft.lbs [N.m]	112 [152]	154 [208]
Filter Rating, mesh [micron]	120 [120]	120 [120]
Filter Material	316 SS	316 SS

FIGURE 21 – FILTER SCREEN SPECIFICATIONS

Model 16ss – 40.6mm (1.6”) OD by 25.4mm (1.0”) NPT Connections by 316 stainless steel



Model 18ss 45.7mm (1.8”) OD by 31.75mm (1.25”) NPT Connections by 316 stainless steel

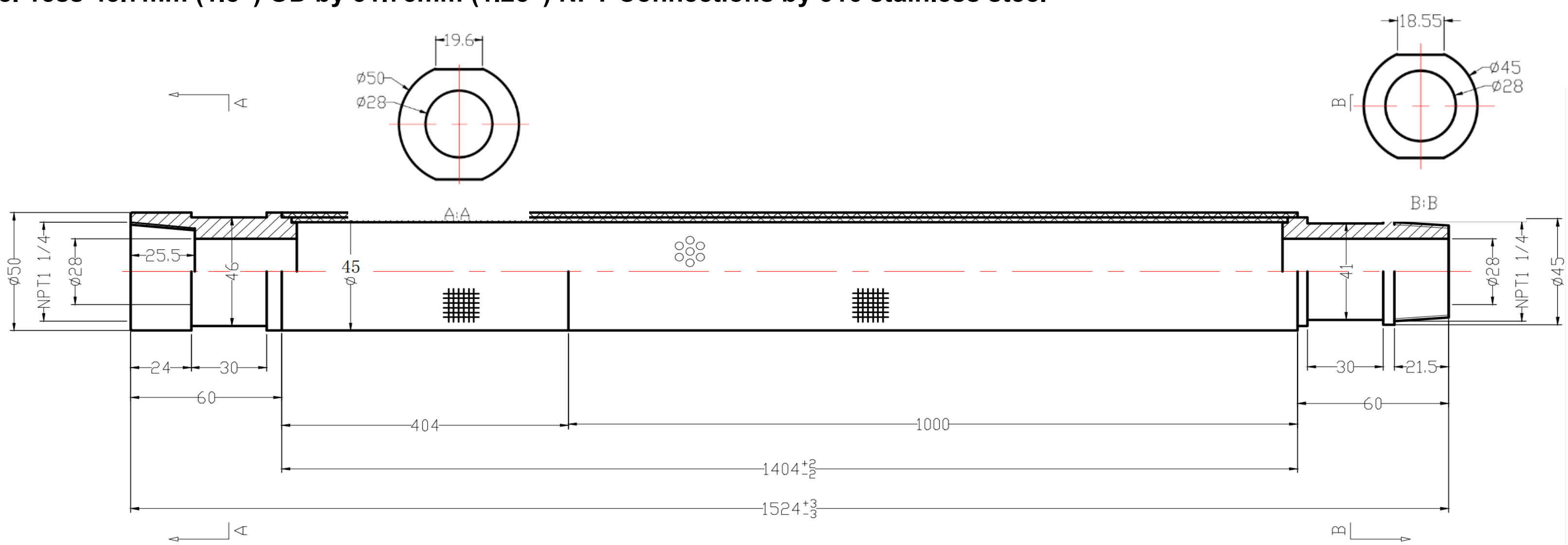


FIGURE 22 – SharkNET™ FILTER SCREEN DIMENSIONS (metric in millimeters)

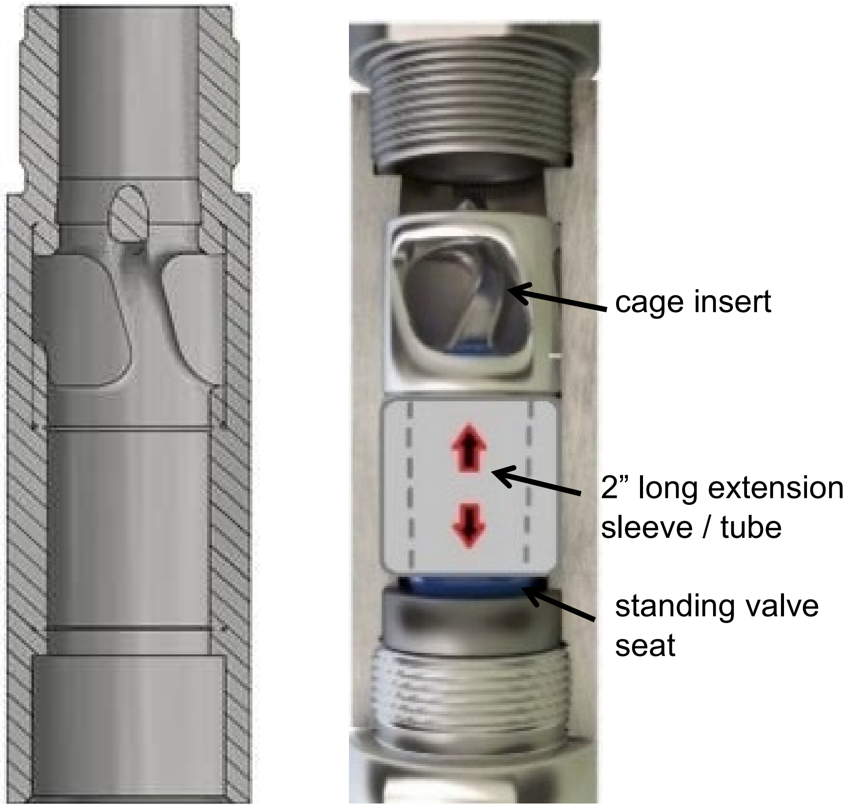


FIGURE 23 – BACK FLUSHING STANDING VALVE (BFSV)

Back Flushing Standing Valve (BFSV) Specifications		
Size, in [mm]	1.75 [44.5]	2.25 [57.2]
Cage Body Material	Monel / SS	Monel / SS
Insert Cage Type	Q2 Flow, Turbine	Q2 Flow, Turbine
Seat Material	tungsten carbide	tungsten carbide
Ball Material	titanium carbide	titanium carbide
Ball Size (API), in [mm]	1.125 [28.6]	1.375 [34.9]
Extension Tube Material	Monel / SS	Monel / SS
Extension Tube Clearance, thou	45	45
Extension Tube Length, in [mm]	2.0 [50.8]	2.0 [50.8]

FIGURE 24 – BACK FLUSHING STANDING VALVE (BFSV) SPECIFICATIONS

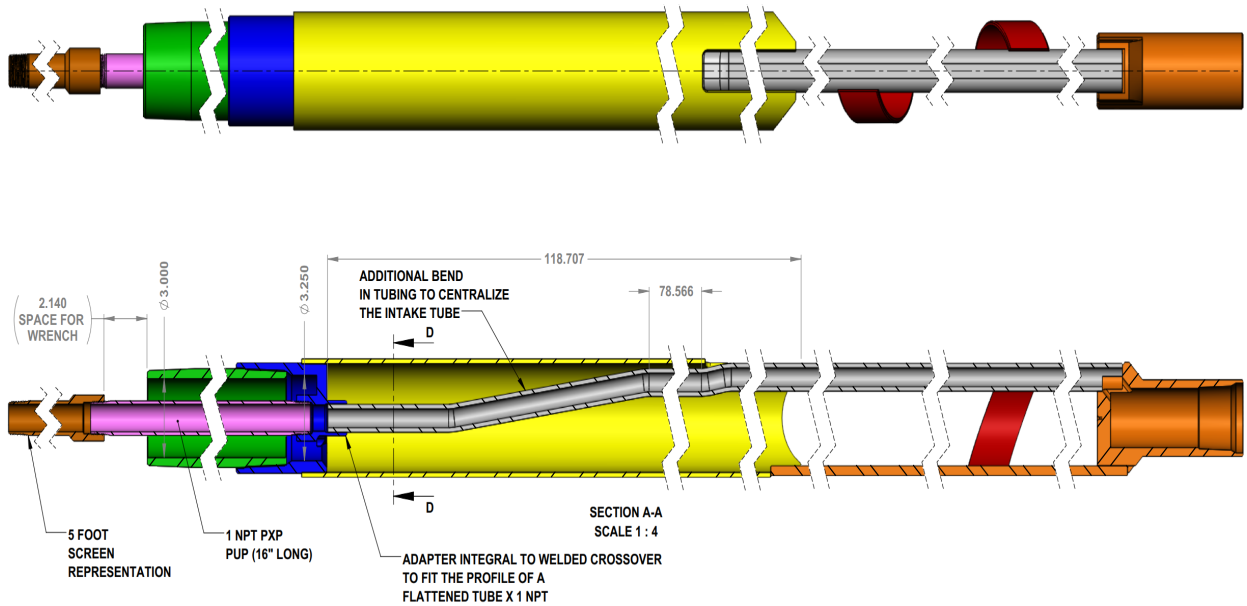


FIGURE 25 – LIQUID FALLBACK SEPARATOR MODIFIED FOR FILTER SCREENS

ITEM NO.	PART NUMBER	DESCRIPTION	WEIGHT (LB)
1	OLY-FS-2.875-MP-01	INTAKE NIPPLE, 2.875 EU PIN	16.287
2	OLY-FS-2.875-MP-03	COUPLING, 2.875 EU WITH 1 NPT	6.750
3	1" NPT PUP	1 NPT PUP, 30" LONG, MCMASTER-CARR #4816K927	4.21

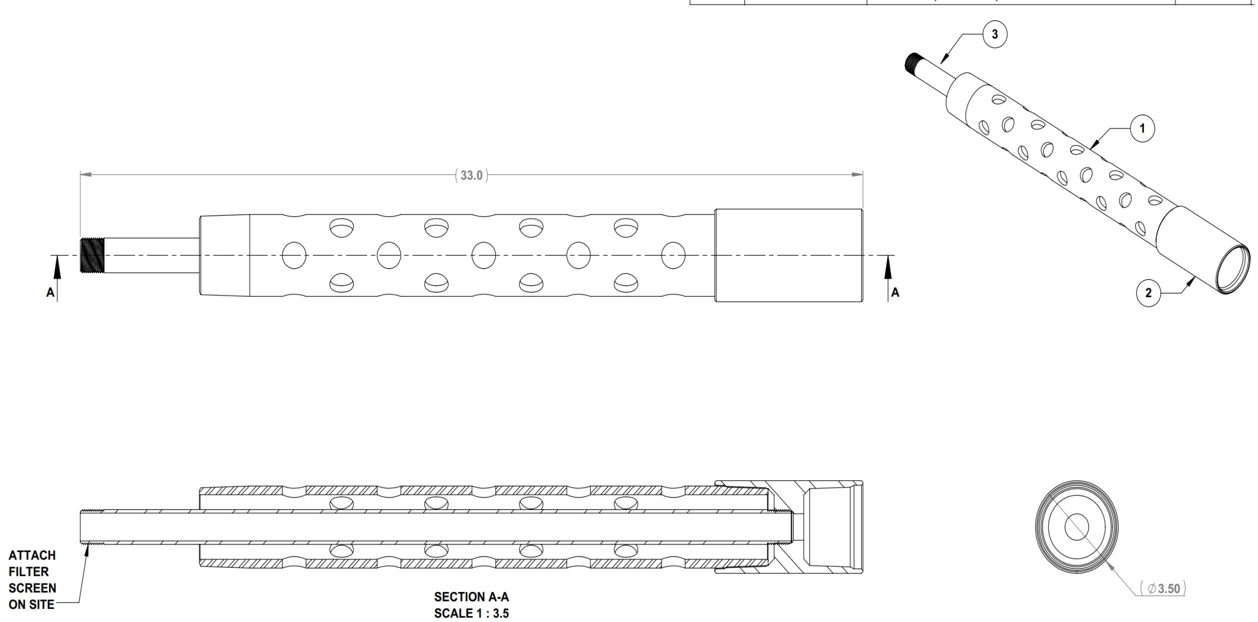
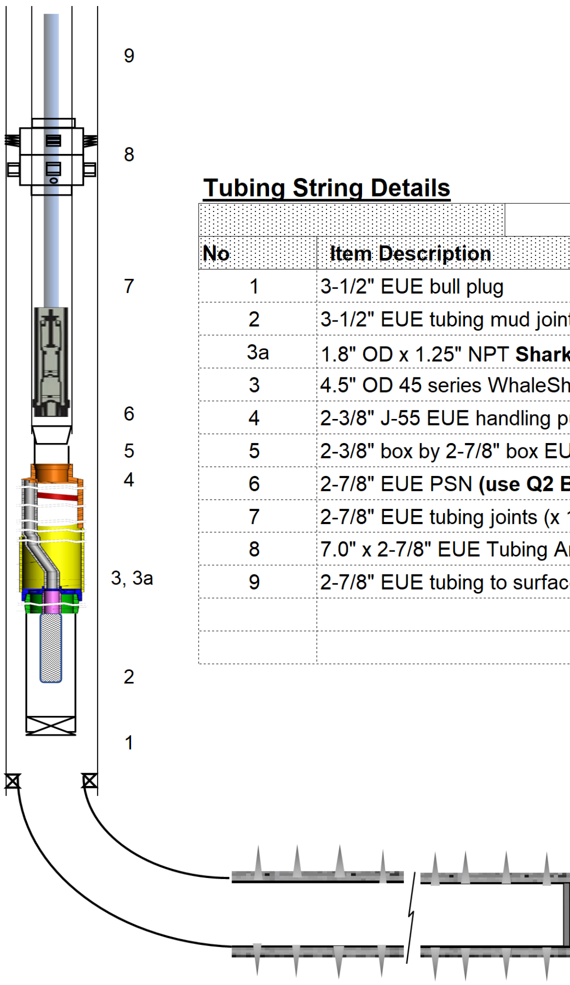


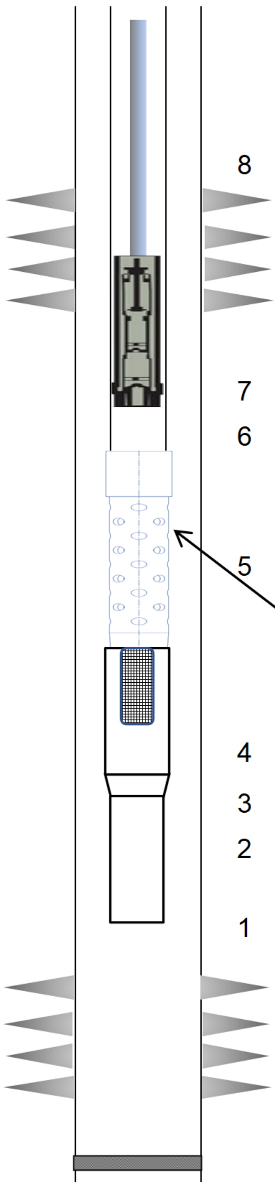
FIGURE 26 – FILTER SCREENS STAND ALONE INTAKE SUB (NO GAS SEPARATOR)



Tubing String Details (Number from bottom up)

No	Item Description
1	3-1/2" EUE bull plug
2	3-1/2" EUE tubing mud joints (x 6)
3a	1.8" OD x 1.25" NPT **SharkNET^{TM}** 316ss screen filters (x 4 by 5 feet long each)
3	4.5" OD 45 series WhaleShark™ packerless separator **ENC Coated (45 ENC SCR)**
4	2-3/8" J-55 EUE handling pup joint
5	2-3/8" box by 2-7/8" box EUE combo collar
6	2-7/8" EUE PSN **(use Q2 Back Flushing Standing Valve in pump, Ti carb ball, Tn Seat)**
7	2-7/8" EUE tubing joints (x 10)
8	7.0" x 2-7/8" EUE Tubing Anchor Catcher (Slimhole equivalent)
9	2-7/8" EUE tubing to surface

FIGURE 27 – WELLBORE CONFIGURATIONS, WITH GAS SEPARATOR



Tubing String Details (Number from bottom up)

No	Item Description
1	open ended
2	2-7/8" EUE tubing mud joints (x 2)
3	2-7/8" pin by 3-1/2" box EUE crossover
4	3-1/2" EUE tubing mud joints (x 1)
5	3.5" OD **SharkNET™** perforated intake sub c/w 2.0" OD screen filters (x3 by 4 feet)
6	2-7/8" EUE tubing handling pup joint (x 1)
7	2-7/8" EUE PSN (bottomhold down insert pump c/w **back flushing standing valve**)
8	2-7/8" EUE tubing to surface

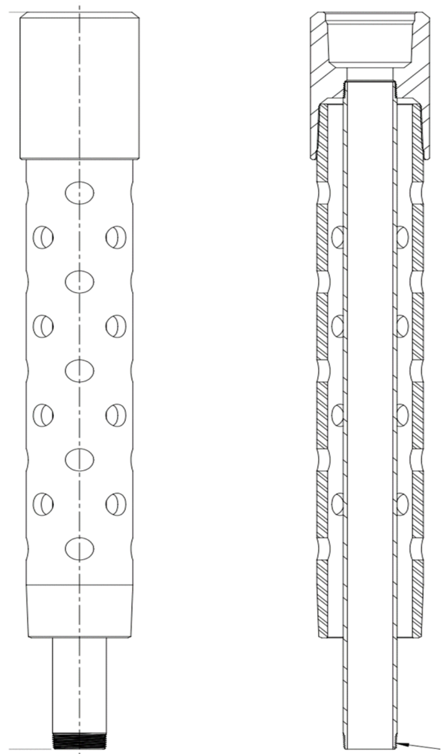


FIGURE 28 – WELLBORE CONFIGURATIONS, WITHOUT GAS SEPARATOR

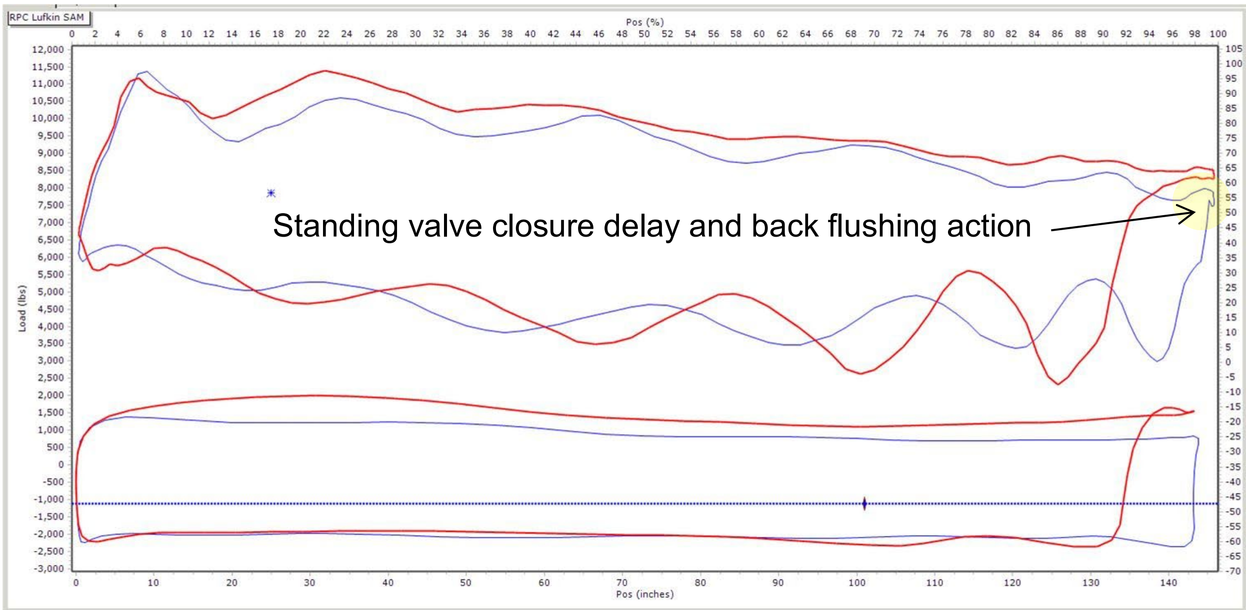


FIGURE 29 – CASE STUDY #1, SURFACE PUMP CARD SHOWING BFSV ACTION

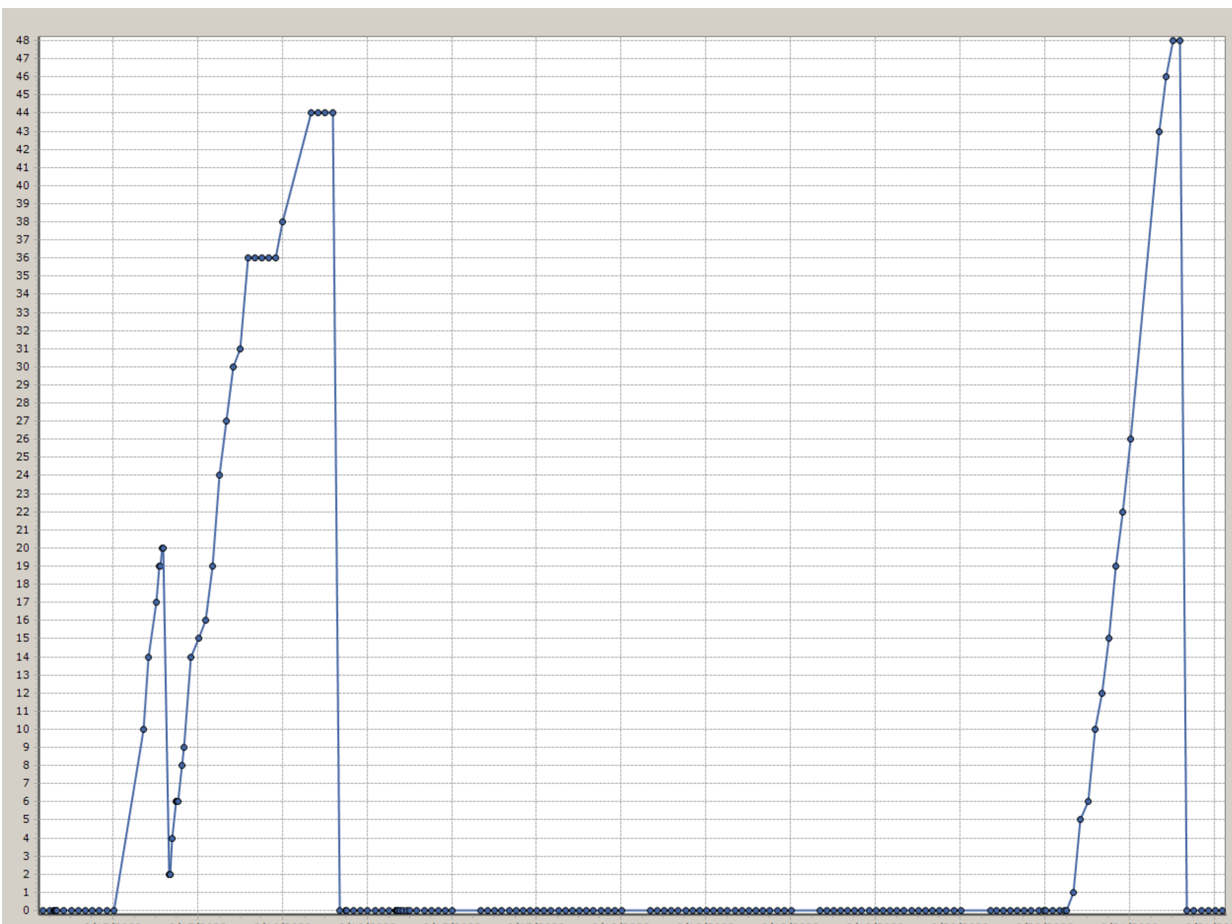


FIGURE 30 – CASE STUDY #2, RUNTIME SHOWING CYCLING THEN NO CYCLING

FIGURE 31 – CASE STUDY #3, PLUGGED FILTERING SCREENS, NO BFSV USED

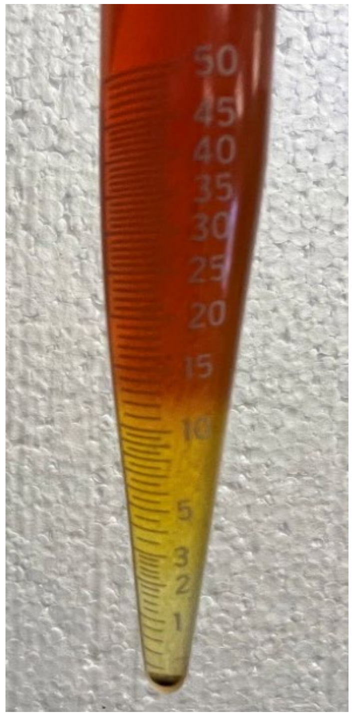


FIGURE 32 – CASE STUDY #4, SOLIDS GRIND OUT AT SURFACE

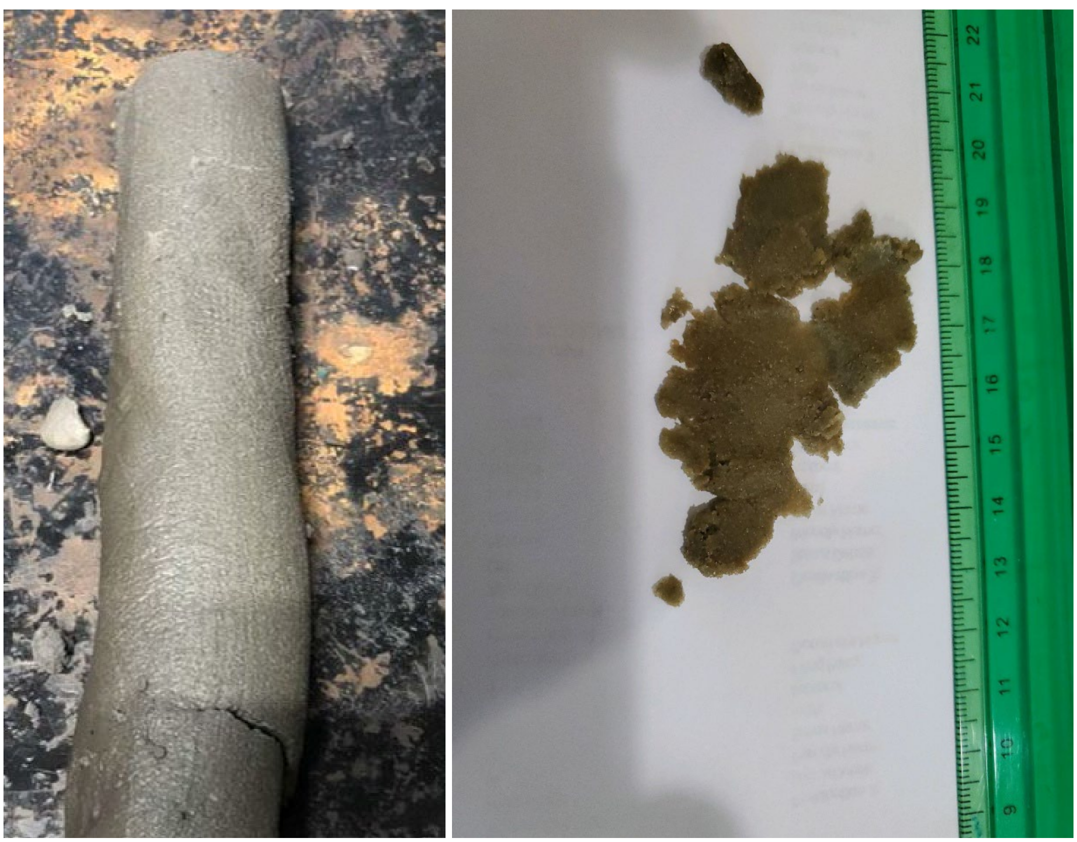


FIGURE 33 – CASE STUDY #4, BAKKEN WELL FINE SOLIDS FOUND IN PUMP

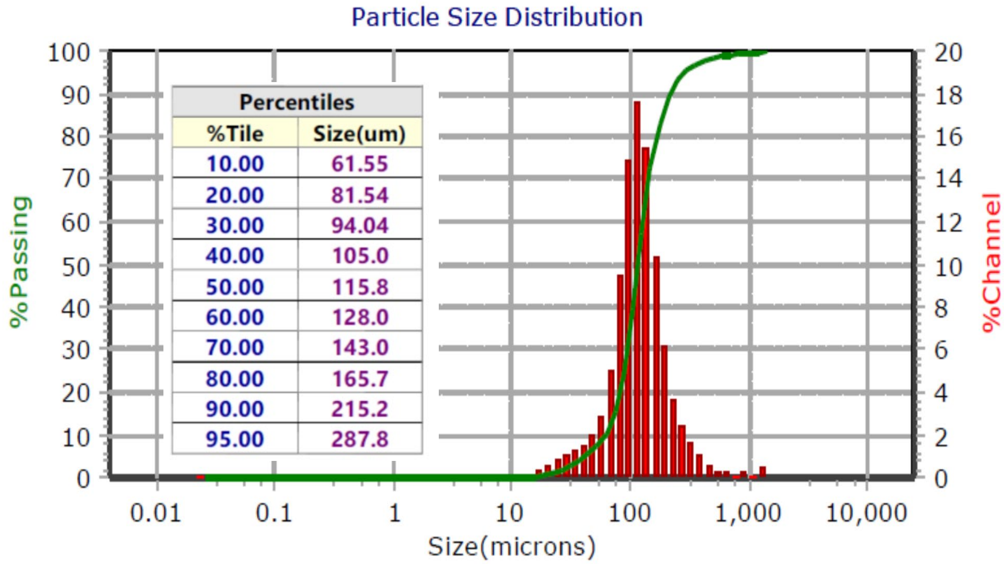


FIGURE 34 – CASE STUDY #4, BAKKEN WELL SOLIDS DISTRIBUTION MOSTLY LESS THAN 120 MICRON

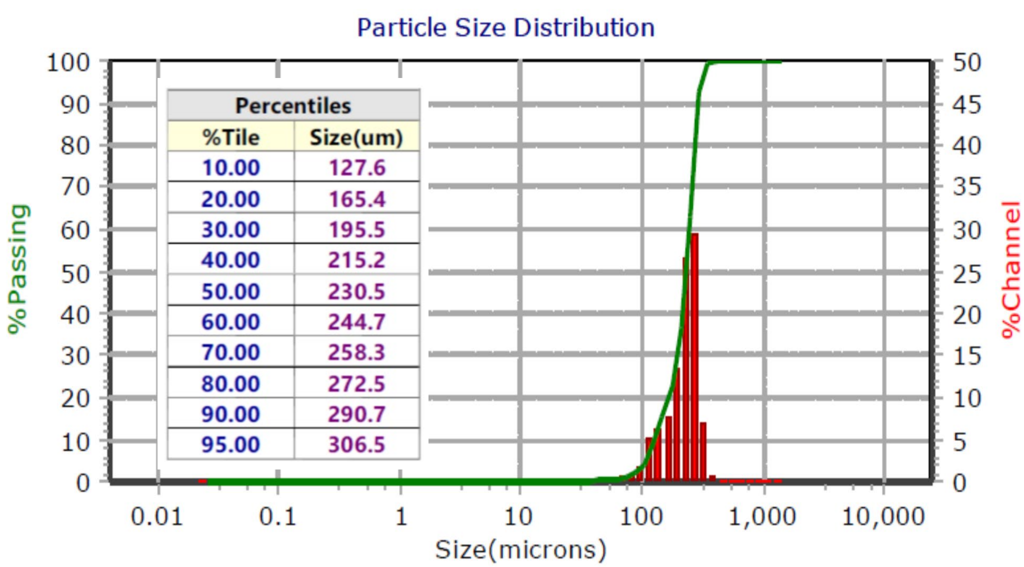


FIGURE 35 – CASE STUDY #5, SUCCESSFUL APPLICATION BAKKEN WELL SOLIDS DISTRIBUTION

ENDNOTES

[i] SLB Website. Accessed October 14, 2022. https://www.slb.com/-/media/files/sand-control/product-sheet/meshrite-screens-ps.ashx/

[ii] Bridges, S., Robinson, L., A Practical Handbook for Drilling Fluids Processing, 2020. Accessed Dec 4, 2022, https://www.sciencedirect.com/topics/engineering/stokes-law#:~:text=According%20to%20Stokes'%20law%2C%20the,the%20square%20of%20particle%20diameter

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[iv] Song Zhiyao et al, “A Simple Formula for Predicting Settling Velocity of Sediment Particles”, Water Science and Engineering, Mar 2008, Vol 1, No 1, 37-43.

[v] Guzman, M., Podio, A., "Downhole Gas Separator Performance In Sucker Rod Pumping System", presented at the Artificial Lift Research and Development Council Beam Pumping Workshop. Houston, Texas, October 4-7, 2005. page 6.

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