NOT ALL SPHERES ARE CREATED EQUAL

That's the lesson that producers have learned in the Permian basin. Traditionally, options for sand separators have been limited to using either low storage and flow-sensitive vertical cyclonics, or low efficiency generic spheres to manage sand. Functional differences in technology, design, innovation, and quality of material may not be apparent on the surface but ultimately impacts overall production in addition to bottom-line. Making it crucial for decision makers to understand the differences between separator technologies and how to manage produced sand most effectively.

VERTICAL SAND SEPARATOR DESIGN COMPARISON

Vertical cyclonic sand separators are some of the most common separators used in flowback operations due to their cost and high pressure rating. These factors make them easy to deploy in many different applications to remove sand and protect downstream equipment. However, a vertical separator has several disadvantages which make them a poor choice for sand separator selection, including:

1. Low overall separation efficiency of sand
2. Low storage capacity of sand
3. High fugitive gas emissions release during dumping
4. 'Turndown' at low gas rates resulting in decreased efficiency

Detailed modeling from Computational Fluid Dynamics (CFD) simulations is used to showcase the steady flow patterns which develop in the Sandtinel spherical separator and a vertical cyclone during operation. These CFD models are used at a typical flowback operating condition from the US Permian basin to estimate the efficiency of the two separator designs at one selected scenario. Simulations are also used to estimate the difference in fugitive emissions release. Sandtinel spherical separators outperform vertical cyclonics on each of these metrics.

Real field data is reviewed from three different applications in different basins, including the Delaware, Haynesville, and Permian basins, where a Sandtinel Defender went head to head against a vertical cyclonic sand separator. An abridged table of results is shown below.

PARAMETER	TRIAL #1	TRIAL #2	TRIAL #3
Basin	Delaware	Haynesville	Permian
Sandtinel device	G2-S Defender	G2 Defender	G2-S Defender
Vertical cyclone	10K cyclonic	10K cyclonic 5800 VSKO	FMC cyclone
Sand rate	210 lb./hr.	80 lb./day	20 – 200 lb./day
Sand capture	54% (cyclone) 91% (Sandtinel) 92% (both)	58% (U/S cyclone) >99% (Sandtinel) 3% (D/S cyclone)	97% (Sandtinel) 39% (FMC low flow) 81% (FMC high flow)
Test duration	5-10 days	10 days	6 days

Computer modeling and field data collection show that generic vertical cyclonic separators are unreliable, have low efficiency, and do not adequately protect downstream equipment from sand. Sandtinel spherical sand separators are a better option for sand removal along every metric studied and in every basin where they have been deployed.

PERFORMANCE METRICS

There are several metrics by which one may evaluate the performance of a sand separator. One challenging aspect of evaluating sand separator performance is that much of the separator's operation is opaque, or hidden to casual inspection. In practice, separators are usually recognized only when they are performing badly, and even then the available data can be quite sparse.

The best available data has been compiled for this report to compare key performance indicators.

1. Separation efficiency: The primary function of a sand separator is to remove sand; all other considerations are ultimately secondary. Separation efficiency typically varies based on a well's operating conditions (flow rates, temperature, pressure, oil content, oil thickness, etc.) and sand conditions (sand size, sand quantity, sand crushability, sand density, etc.). A typical sand separator will have a maximum separation efficiency at ideal conditions, and efficiency will drop off as the conditions change to become harder.

   Sandtinel provides a guarantee of 95% separation efficiency for 150 micron (100 mesh) sand while operating within a specified flow envelope.

2. Sand storage capacity: After separating sand, a sand separator needs to retain it prior to dumping. Virtually every sand separator on the market works in batch mode, meaning that it collects sand prior to being manually dumped to a larger collection basin or tank. Batch dumps require operator time and usually entail the release of fugitive emissions (below); unnecessary dumps also fill the collection basin with water which needs to be disposed of. Therefore it is desirable to have as high a storage capacity as possible so that separators do not need to be dumped very frequently.

   Sandtinel separators typically use a "Sand Lock" system to enhance storage capacity. They can generally hold between 200 – 600 lb efficiently before the efficiency starts to be affected. The maximum possible storage in a 48" Sandtinel sphere is approximately 2,000 lb, although they should generally be dumped prior to that.

3. Fugitive emissions: When performing a manual dump operation from a sand separator, some gas release is usually seen along with the collected sand slurry. This gas will typically be either vented to atmosphere or flared. It is preferable to keep these so-called 'fugitive' emissions as low as possible.

   Sandtinel sees some of the lowest fugitive emissions of any sand separator on the market. The Vapor Lock design philosophy isolates the gas in the upper hemisphere away from the sand drain port. Sandtinel typically sees less than 50% of the emissions during a dump compared to competing separator designs, and potentially down to 2% of typical, depending on the operating condition.

4. Ease of sand removal: Sand that has been collected in a sand separator needs to be dumped to a larger collection tank. To reduce production downtime and operator time requirements, it is preferable if it is a very simple process to remove accumulated sand from the sand separator.

   Sandtinel's dump is a very fast operation, and usually takes between 30 seconds and 2 minutes to complete, depending on the accumulated sand. It consists of turning three valves, and can either be done in one single drain, or in multiple shorter staggered drains. There is zero exposure to operators as the sand is dumped to a collection tank.

5. Turndown: Some sand separators have a 'sweet spot' or 'goldilocks zone' at elevated flow rates where they perform best. This target flow rate needs to be maintained to provide high efficiency sand removal, and performance will start to drop as the velocity reduces later in a well's lifespan. This phenomenon is called 'turndown,' and it is preferable if sand separators do not have a large turndown window so that they do not unduly dictate how a well can be managed.

   Sandtinel sand separators do not experience any notable turndown. They typically perform just as well at very low velocity as they do at higher velocities.

6. Pressure range: Sand separators usually work better when they are placed as close as possible to the wellhead. Operating on the high pressure side slows down the flow and increases the separation efficiency, and more importantly also protects the choke valve. Therefore, it is preferable for a sand separator to be have a high pressure rating.

   Sandtinel typically provides 48" spherical separators rated up to 5,000 psi, and also has a 44" spherical separator rated up to 10,000 psi.

7. Cost: Sand separators are only one piece of equipment in a flowback, and must pay for themselves in erosional reduction on the remainder of the system. Lower cost is preferable for sand separators to enhance the value proposition of the device. Similarly, wearable or sacrificial elements like filters are also undesirable, as they require operator time to change out along with the new parts needed.

   Sandtinel offers a range of sand separators to meet any requirement, from large 96" Generals for facilities and group well testing, to smaller 36" separators suitable for small projects. Accurate sizing and predictive modeling ensure that customers never overpay for the sand removal they need. Sandtinel has no sacrificial internal elements or filters.

Sandtinel has several different separator designs in its fleet, this report will be considering the 48" G2-S Sandtinel Defender, a robust design for many operating conditions.

DESIGN COMPARISON

The vertical cyclone, or vertical "sand knock-out" (SKO) is perhaps the most common sand separator currently used in flowback operations in the field. A vertical cyclonic separator is typically a hollow vertical shell of 10' or more in length, with a side-entry inlet towards the top of the shell and a vertical outlet coming out the top. There may be a drop pipe inside of the separator which descends towards the center of the separator.

A typical vertical SKO design.

Taking the listed performance factors for sand separators into consideration, the advantages and disadvantages of a vertical cyclone are shown below compared to several other separator types. Cost is omitted in this comparison since it depends on many factors such as the quantity of separators required and the overall risk of erosion to the downstream system.

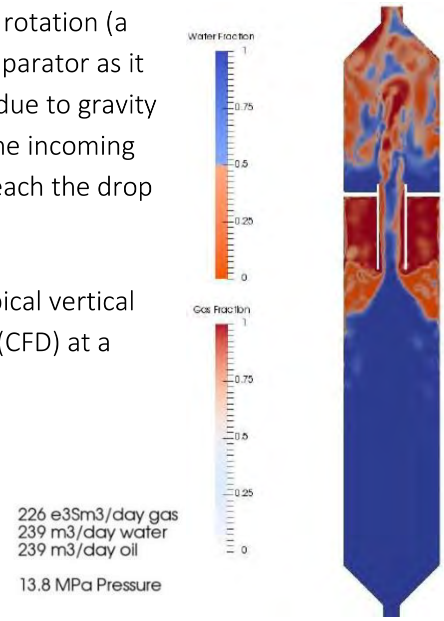
Separator design	Vertical cyclonic	Sandtinel sphere	Generic sphere	Horizontal	Sand auger
Efficiency	50% - 80%	95%+	70% - 85%	80% - 95%	95%+
Sand storage	50 - 100 lb	200 - 600 lb	100 - 200 lb	1000+ lb	No internal storage (not batch)
Emissions	High	Lowest	Low	Average	100% of gas is vented or flared
Sand dumping	Simple dump	Simple dump	Simple dump	Manual (rake out)	Clean-out as needed (continuous)
Turndown	Serious turndown at low velocity	No turndown	No turndown	No turndown	No allowable gas No liquid turndown
Pressure range	Often 10K - 15K	Up to 10K (44" sphere)	Up to 5K	Up to 5K	Atmospheric only

The primary advantages of using a simple vertical cyclonic separator are that it is low-cost, and it is easy to get one rated for a high pressure (as vertical shells are simpler to build to a high-pressure rating than spheres).

Compared to a high-efficiency spherical separator like a Sandtinel, a vertical cyclonic is lower efficiency, stores less sand, releases higher emissions, experiences a (sometimes quite significant turndown), and often needs to incorporate filters or other expensive replaceable elements to push the efficiency higher.

A vertical cyclonic sand separator works by developing a fast rotation (a cyclone) which spins incoming sand out to the edge of the separator as it settles down into the bottom of the shell. Sand knock-out is due to gravity and sand being directed into the bottom of the cylinder by the incoming flow. The flow circulates back up the middle of the shell to reach the drop pipe in the center of the vessel.

The image here shows the steady flow pattern inside of a typical vertical cyclone using modeling from Computational Fluid Dynamics (CFD) at a typical flowback condition.



There are several issues in the flow pattern of this vertical cyclonic separator which interfere with its efficient operation:

1. Sand in the bottom migrates towards the center of the cylinder. There, it is at a high risk of circulating back up to the outlet pipe where it will be lost as carryover.

2. With the fast-moving cyclonic action, trace oil and gas get stirred into the bottom of the vertical cylinder during operation. Manual dump operations performed drain out this oil and gas together with the sand slurry, resulting in high fugitive emissions during dumps.

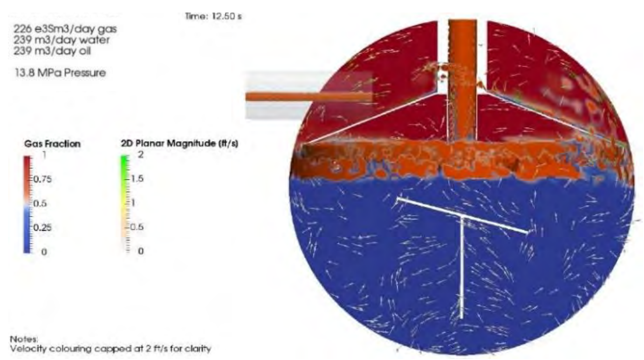
3. Separation relies on constant agitation, so a high incoming fluid velocity is needed to keep the sand pushed out to the outside of the cylinder. This typically results in a turndown problem when there is an insufficient fluid rate. The gas rate is typically the main driver of the fluid velocity, so insufficient gas rate often results in turndown.

4. At the high velocity needed to avoid turndown, a vertical cyclonic separator typically has a high amount of initial carryover (sand which diverts from the inlet pipe straight to the drop pipe outlet pipe) and a very low storage capacity of sand. These factors result in a low overall separation efficiency, especially for small sand.

The G2/G2-S Defender is the most common Sandtinel sphere in operation in the field. The Defender is a side-entry 48” spherical separator with a top outlet. The vessel operates in a steady state removing sand from the incoming fluid mixture of oil, gas, and water. Sand accumulates in the bottom of the sphere, where it can be drained while the well is still online and still producing.

A Defender uses a Vapor Lock design to handle a wide range of operating conditions. The gas in the sphere is isolated into the upper region of the flow, creating a calm and controlled water flow in the lower hemisphere. This design handles oil and emulsions by creating a controlled layer of liquid buildup where sand can break through into the slow water reservoir below. An offset inlet pipe creates a slow and steady rotation of flow about the interface which increases retention time and promotes settling.

The same flow condition as the cyclone model shown here for the G2-S Sandtinel Defender.



Compared to a vertical cyclonic separator, the Sandtinel has several advantageous flow features:

1. The velocity in the bottom hemisphere of the sphere (in the water) is very low, resulting in a low risk of sand recirculating through the outlet pipe.
2. The Vapor Lock design of the Sandtinel isolates the gas in the upper hemisphere, and controls the build-up of the oil layer. Thus, the fluid removed in dump operations is almost entirely a water and sand mixture. Fugitive emissions from the Defender are very low.
3. Sandtinel spheres have a higher radius at the central plane of sand separation (24”) than a vertical cyclonic (6-8”). At low velocities where sand is not pushed effectively to the outer edge, a large radius provides a long path for sand to settle out of suspension compared to the cyclonic. As a result, Sandtinel separators have no appreciable turndown condition.
4. Sandtinel separators use a “Sand Lock” system to reduce agitation and circulation in the bottom hemisphere of the vessel. This allows larger amounts of sand to build in the bottom of the separator before risk of sand carryover compared to a vertical cyclone.

CFD PERFORMANCE COMPARISON

The performance of the two sand separator designs (vertical cyclonic and G2-S Sandtinel Defender) can be evaluated in multiple different ways. CFD has been used to provide a comparison for both the overall separation efficiency and for the fugitive emissions.

At the operating condition shown in the previous CFD images, the separation efficiency of a typical vertical cyclone and the G2-S Sandtinel were modeled against each other.

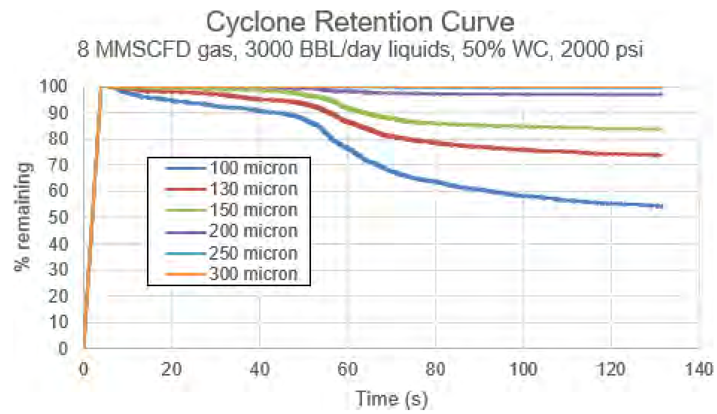
These operating conditions are listed in the chart seen here.

PARAMETER	SIMULATED VALUE
Gas rate [MMSCFD]	8
Liquid rate [BBL/day]	3000
Water cut [%]	50
Pressure [psi]	2000
Temperature [°F]	86
API gravity [°API]	46

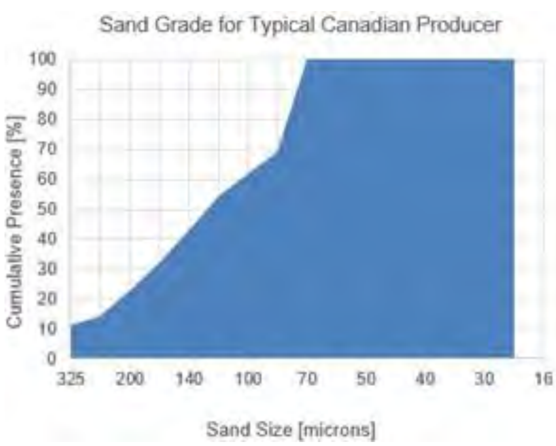
This condition was modeled in CFD for separation efficiency in both the cyclone and in the G2-S Sandtinel Defender. The sand behavior in the cyclone is shown in the images below over time:

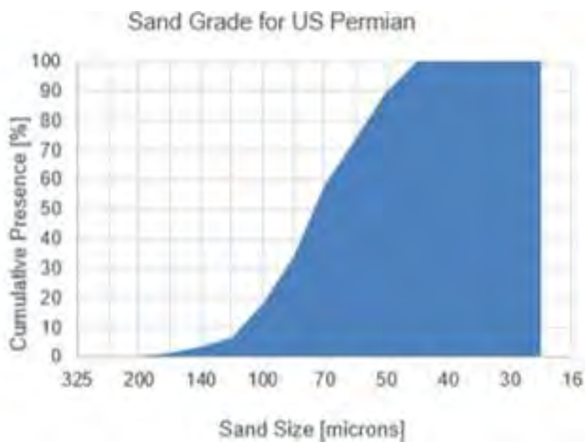
This set of images shows how sand initially spins down into the bottom of the cyclonic separator, but then is drawn back up the central axis and into the outlet pipe over time.

The overall separation efficiency over time is shown here for sand from 100 microns (140 mesh) to 300 microns (50 mesh) in size:



Two different typical sand blends (Canadian Producer and US Permian) were used as typical examples of sand mixtures often seen in operation. These sand size distributions are shown below:





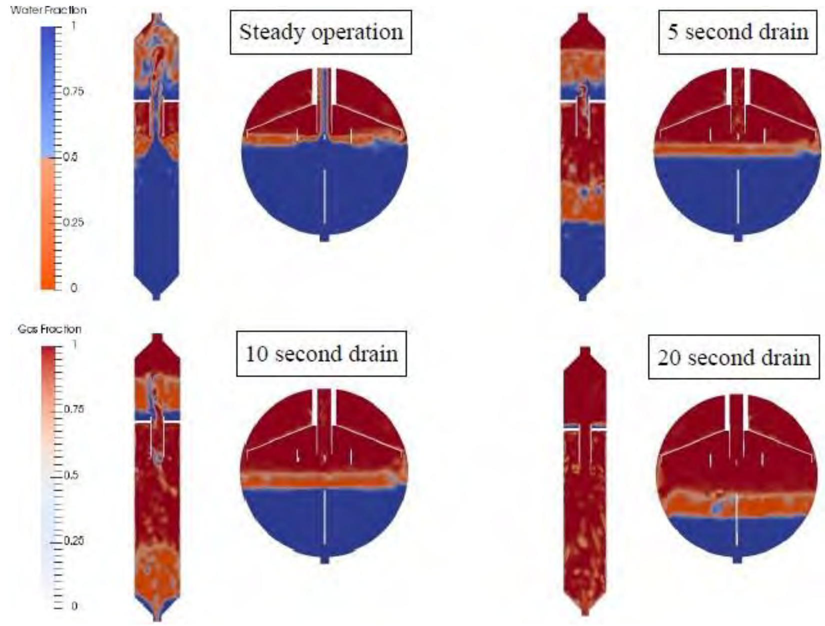
The typical Canadian sand blend is usually smaller on average than a normal "100 mesh blend" used in US fracs. The **separation efficiencies** of both the 48" G2-S Sandtinel Defender and a typical vertical separator are shown below for these different sand blends along with **storage capacity**:

VESSEL	Separation Efficiency at Specified Rates			Storage Capacity (US gal)
	100 mesh	Canadian Producer	US Permian	
48" G2-S Defender	~100%	99%	~100%	88
Cyclone	82%	88%	91%	36

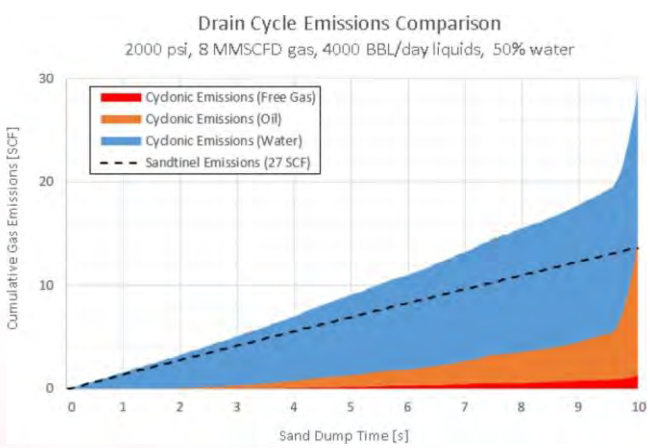
Overall, the G2-S Sandtinel Defender was found to outperform the typical cyclonic separator in CFD simulations for separation efficiency, especially at smaller sand sizes around 100 mesh.

With respect to **fugitive emissions**, a typical dump operation is shown below at different timesteps for both a typical vertical cyclone and the G2-S Sandtinel Defender:

This image shows how the body of water in the bottom of the Sandtinel acts as a buffer compared to the cyclonic separator which starts to lose liquid hydrocarbons and gas through the drain line very quickly.

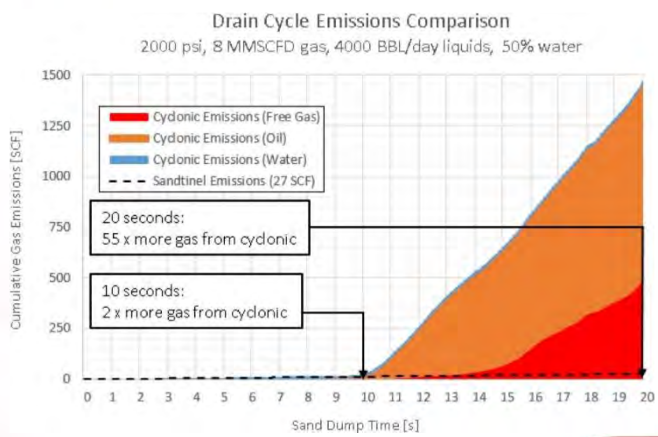


The overall magnitude of gas which is vented or flared from a cyclone depends on the operating condition, but a typical example is shown below, first for a 10-second dump interval and then for a 20-second dump interval:



A more detailed emissions comparison report is available upon request on this topic, comparing Sandtinel emissions to multiple different types of separator.

Overall, Sandtinel spheres consistently show lower emissions than vertical sand separators, resulting in less gas venting and flaring.



FIELD TRIAL COMPARISON RESULTS

Sandtinel has had multiple head-to-head field trial comparisons against generic vertical cyclonic separators. Three such trials are outlined in this section, demonstrating Sandtinel's advantages over vertical cyclonics.

The three trials are outlined in the following table:

PARAMETER	TRIAL #1	TRIAL #2	TRIAL #3
Basin	Delaware	Haynesville	Permian
Location	Road Runner	Caspiana	Big Eddy
Sandtinel device	G2-S Defender	G2 Defender	G2-S Defender
Vertical cyclone	10K cyclonic	10K cyclonic 5800 VSKO	FMC cyclone
Peak gas	8.3 MMSCFD	16 MMSCFD	0.260 MMSCFD
Peak liquids	11000 BBL/day	750 BBL/day	2610 BBL/day
Water cut	90%	100% (pure water)	90%
Pressure	2000 psi (cyclone) 600 psi (G2-S)	6950 psi (cyclone) 420 psi (cyclone/G2)	220 psi (FMC) 330 psi (Sandtinel)
Sand rate	210 lb./hr.	80 lb./day	20 – 200 lb./day
Sand capture	54% (cyclone) 91% (Sandtinel) 92% (both)	58% (U/S cyclone) >99% (Sandtinel) 3% (D/S cyclone)	97% (Sandtinel) 39% (FMC low flow) 81% (FMC high flow)
Test duration	5-10 days	10 days	6 days

These three field trials are discussed in more detail on the following pages.

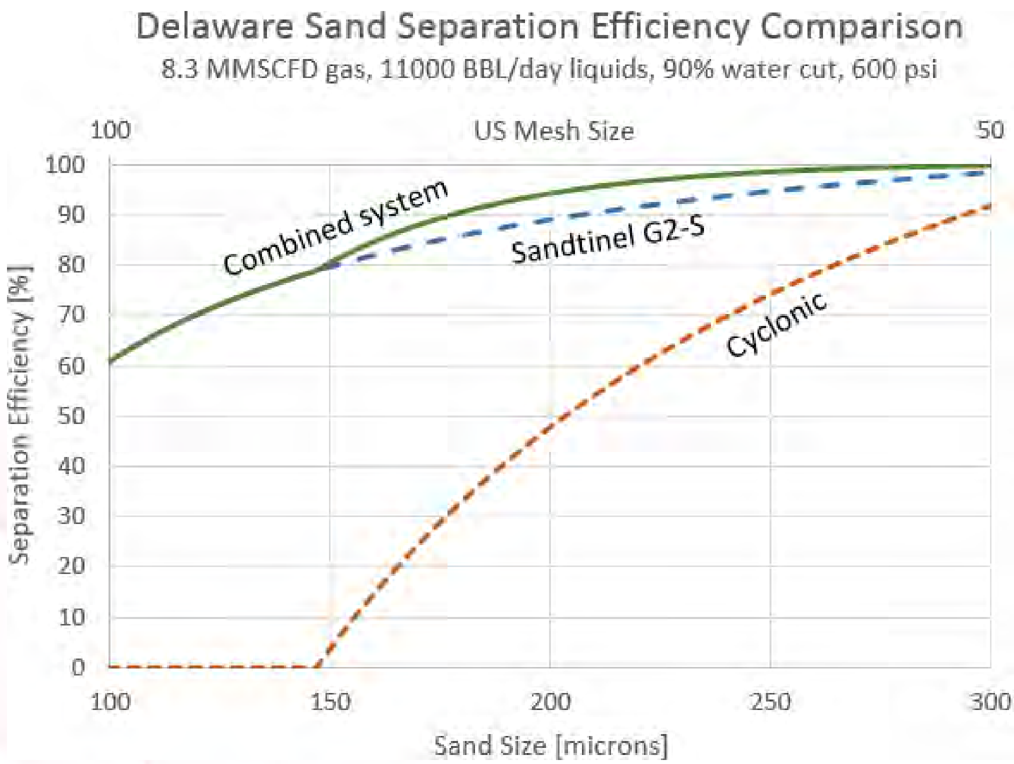
Trial #1: Delaware Basin (Road Runner)

The Delaware basin field trial saw a 10K vertical cyclonic separator at 2000 psi upstream of the choke, followed by a lower pressure (600 psi) 48" G2-S Sandtinel Defender. The cyclone saw approximately 54% separation efficiency on this high sand rate application. The Sandtinel removed 91% of the remaining sand which escaped the initial cyclone.

The efficiency of each of the individual separators and the efficiency of the combined system is shown here based on detailed CFD modeling.

LAYOUT	DELAWARE SAND BLEND REMOVAL EFFICIENCY
Cyclone	54%
Sandtinel G2-S	91%
Combined System (Cyclone + G2-S)	92%

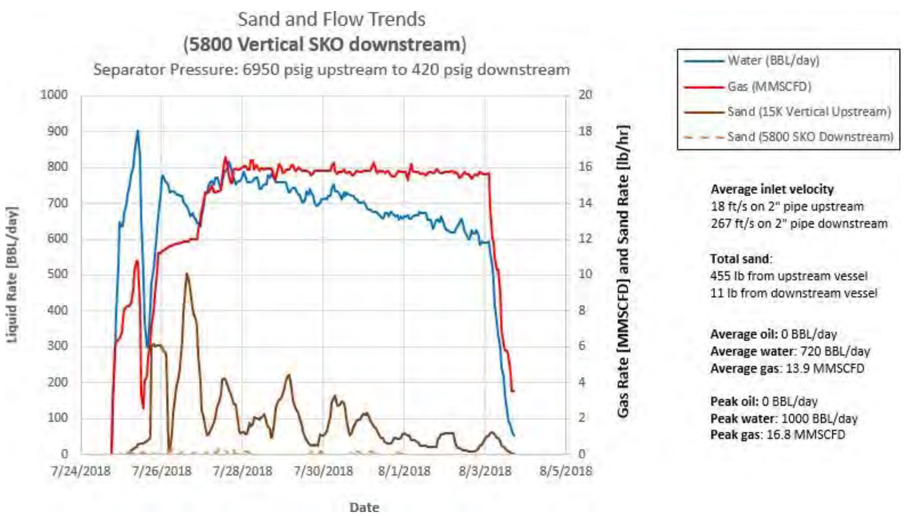
As shown in this chart, the G2-S Sandtinel Defender would have been expected to remove the majority of the sand even if the cyclone was not present, although its presence did provide some measure of protection for the choke valve.

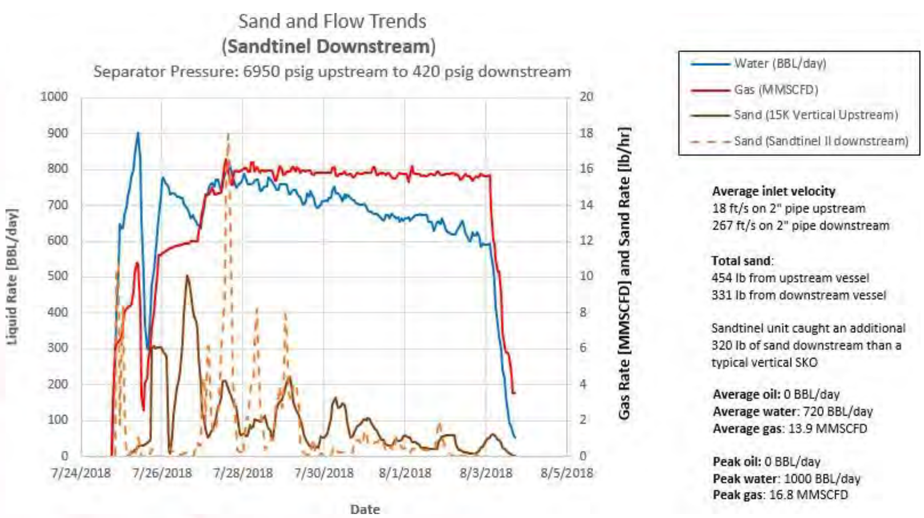


Trial #2: Haynesville Basin (Caspiana)

The Hayneville field trial saw a single upstream high pressure (6950 psi) cyclone, followed by a choke valve, which then split into two separators in parallel on the low pressure (420 psi) side. These two separators were a lower pressure 5800 vertical sand knock-out cyclone and a 48" G2 Sandtinel Defender.

Charts are shown below for these two separators:





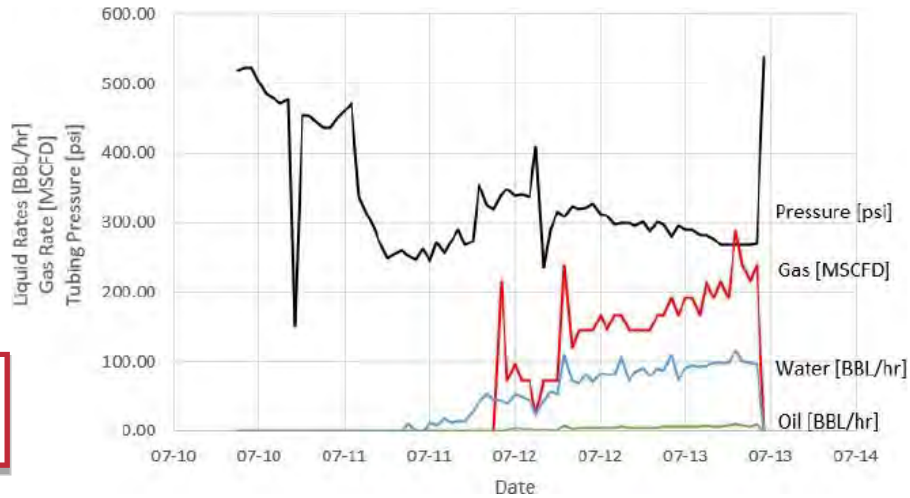
The upstream cyclonic separator removed 58% of the sand from the system; the remainder was almost entirely caught by the Sandtinel downstream. There was no carryover seen immediately downstream of the Sandtinel; significant carryover was seen downstream of the entire system which would have escaped the downstream cyclonic. This field trial also highlights that using multiple cyclones in series is not a good solution to try to achieve higher efficiency; anything which escapes the first cyclone is likely to also escape the second cyclone.

Trial #3: Permian Basin (Big Eddy)

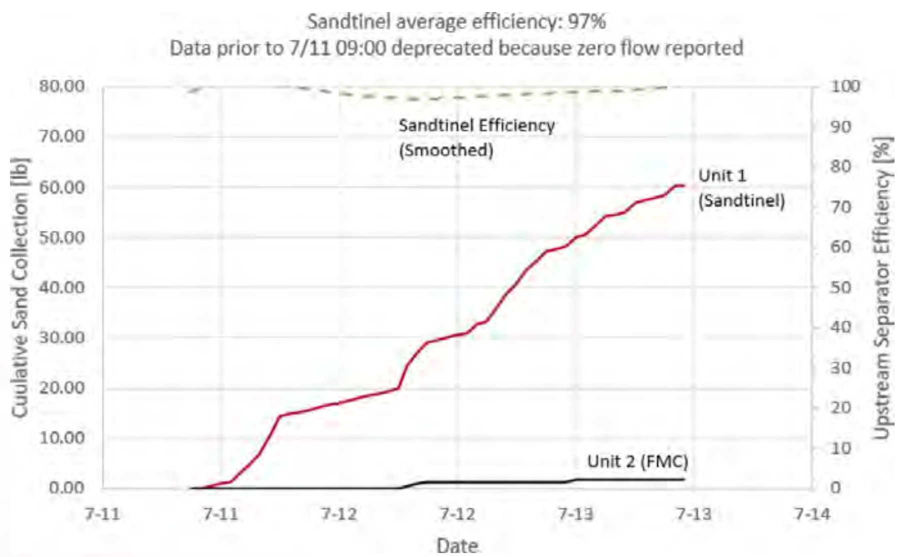
This Permian field trial had two wells, each with a combination of a vertical FMC cyclonic and a 48" G2-S Sandtinel Defender in series. One well had a Sandtinel followed by a vertical FMC cyclone, while the other well had a vertical FMC followed by a Sandtinel.

Flowback trends and sand collection trends are shown below for the first well, with a Sandtinel followed by a vertical cyclonic. As shown in these charts, the FMC vertical cyclonic captured virtually zero sand after the Sandtinel removed an average of 97% of the sand from the flow.

Well #1 Sandtinel upstream of FMC vertical

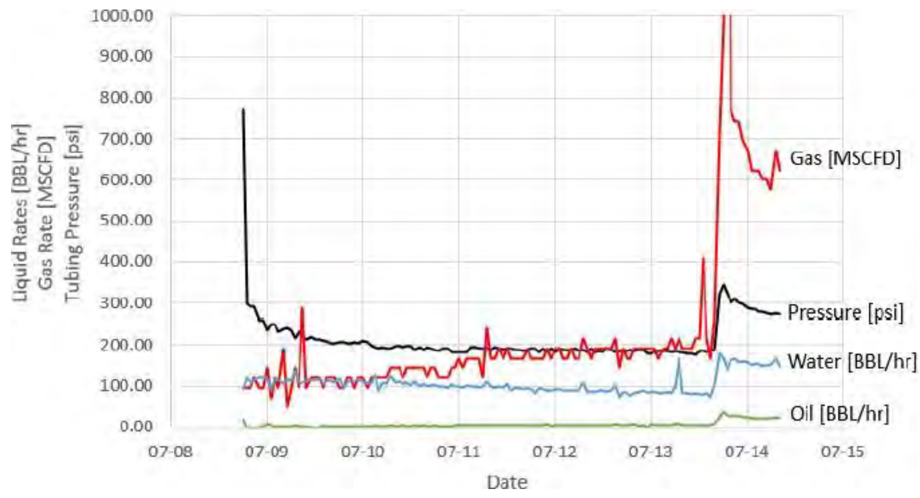


Sand trend

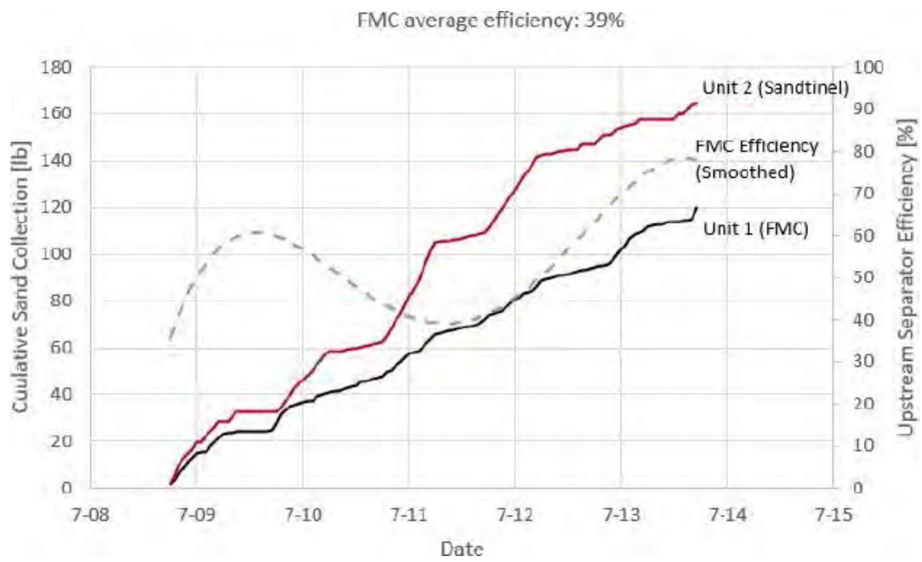


Flowback trends and sand collection trends are shown below for the second well, with a vertical FMC cyclonic followed by a Sandtinel sphere. As shown in these charts, the efficiency of the cyclone was initially very low, with the downstream Sandtinel actually catching more sand than the upstream cyclone. After the velocity increased on 7/13, the efficiency of the cyclone increased, highlighting the problem described as "turndown" which occurs at low flows.

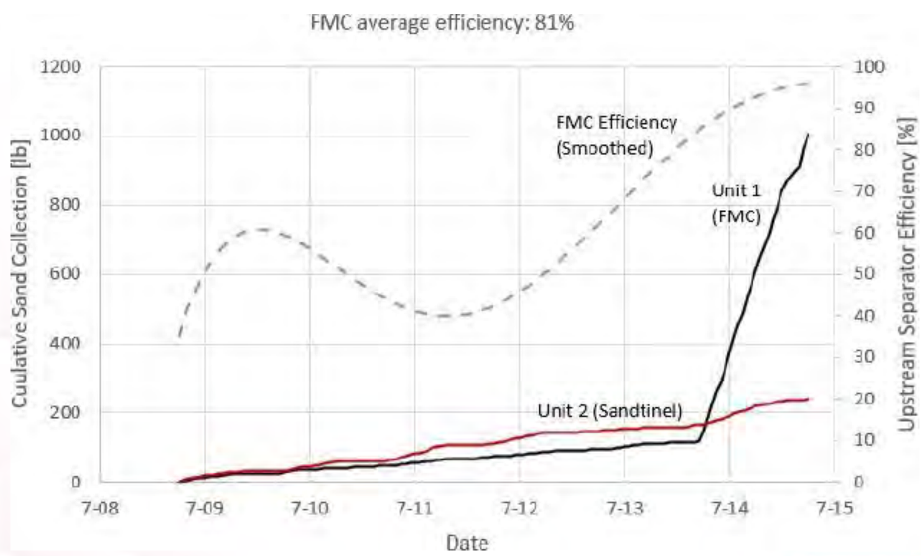
Well #2 FMC vertical upstream of Sandtinel



Early low flow sand trend



Full flowback sand trend



CONCLUSIONS

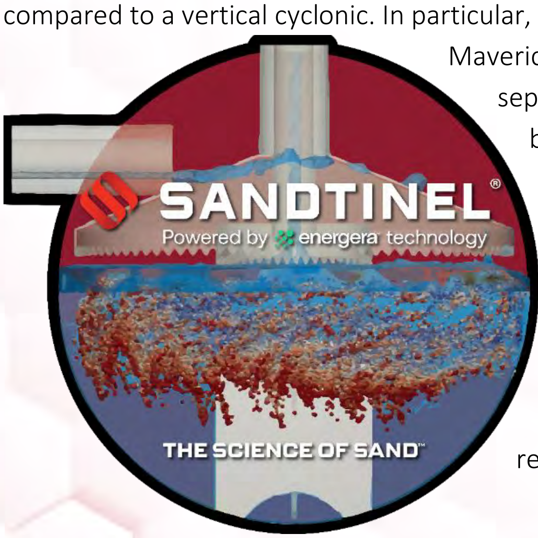
Overall, Sandtinel spherical separators have several key advantages over generic vertical cyclonic separators (regardless of the exact manufacturer):

- Higher overall sand removal efficiency, from 50-80% up to 90%-100% removal
- Larger storage capacity of sand, up to 600 lb. or more (based on velocity of the flow)
- Dramatically reduced fugitive emissions from the bottom drain during dump operations, of up to 98% reduction or more (depending on the conditions and dump duration)
- A reduction or elimination of 'turndown,' which is a loss of sand separation efficiency which develops in vertical cyclones at low flow rates

Detailed results from three different field trials in different basins (the Delaware, Haynesville, and Permian) confirm that the Sandtinel G2/G2-S Defender has a significantly higher separation efficiency compared to a typical vertical cyclonic sand separator.

There are some novel 'advanced' cyclone devices introduced in recent years (such as the TetraTech Sandstorm-Q or the Enercorp Sahara) which have significant improvements compared to a generic vertical cyclone. This report only covers the comparison of the Sandtinel against a typical vertical cyclonic separator, which will be similar to the design discussed in Section 2. These advanced cyclonic separators are not covered by this report, although many of the same factors (storage capacity, fugitive emissions, etc.) may apply to them. Sandtinel is currently gathering performance data compared to these more advanced units as of writing (Oct 2021) and will report on any findings in the future.

Overall, a Sandtinel separator is a significantly more effective sand removal device than the simple generic cyclones which have dominated the market for years. A Sandtinel sphere can remove more sand and hold it more effectively, while releasing lower emissions during the dump process, compared to a vertical cyclonic. In particular, the introduction of the 44" 10K Sandtinel G4-S2 Maverick provides a high-pressure option for sand separation where previously only a vertical shell would be able to be used to protect upstream chokes.



Sandtinel can provide CFD simulations, performance estimates, emissions comparisons, and more upon request for specified operating conditions. Advanced Sandtinel units are also available to tackle tougher challenges, including the Maverick and General lineup, whereas this report only discussed the G2 Defender series.