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The Subsea Sand Management Challenge – What to Do with the Sand?

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Abstract

Sand is a limiting design factor for facilities in terms of operability, throughput, and maintenance. These effects are more critical when dealing with subsea processing due to the equipment access and risk exposure. Technologies for erosion management, sand separation, and solids disposal are well proven for surface facilities. For example, the wellhead desander, located upstream of the choke, effectively separates sand from the multiphase well flow and can be marinized for subsea use. However, the crucial question is "What to do with the sand?" This white paper provides a focal point for the discussion on sand management in subsea processing. The broad categories for dealing with sand include neutralization of the effects, improvements in conventional design, and separation with disposal. These categories have been analyzed based on the conventional design, treatment of the solids, and removal of the solids. More than thirty discrete treatment routes were surveyed, including conventional production limits, flow path modification, chemical treatment, sand cleaning, mechanical attrition, slurry fracture injection, and accretion disposal. Many of these technologies have analogues in other particulate processing industries that can be adapted to upstream oil and gas production. This work is part of ongoing research in Facilities Sand Management with the goal of improving the hydrocarbon recovery through inclusionary sand production.

Introduction

A watershed Facilities Sand Management workshop was held on April 10, 2002. This SPE Gulf Coast Section event brought together more than 150 people to specifically discuss the effects of sand on all aspects of production and facilities in the upstream oil and gas industry. In analyzing the feedback from the attendees, the top five technology needs for the industry were collated. These were (in ascending order of importance) instrumentation, more case studies/examples, sand cleaning, integrated subsurface/surface approach, and seabed separation and disposal. The removal and handling of sand on the seabed was the number one technology interest identified at that time. This was near the start of the movement by operators to push more of the production into deeper waters – and they identified that handling solids in subsea processing would be an impediment to reliable, cost-effective operation.

Now that subsea production is deployed in all major deepwater producing regions, has subsea sand management been properly addressed, if at all? Some steps have been taken, but overall, the main approach has been to (attempt to) prevent sand from appearing at the subsea facilities or hope that sand never arrives. The costs of foolproof deepwater well completions, both in time and finances, can be prohibitive to achieving economic performance; thus, the option of handling sand in the facilities must be considered during the design phase of these fields. Ongoing research in Facilities Sand Management – which has the stated goal of improving hydrocarbon recovery through inclusionary sand production – includes the handling of sand in subsea production.

This current work will (Rawlins 2014):

- Identify the reasons and motivation to research subsea facilities sand management
- Provide a subsea processing discussion focal point focused on the question "What to do with the sand?"
- Identify and analyze the existing conventional, unconventional, and unique sand handling options to reveal technology gaps
- Research methods that include neutralizing the effects of sand, improving conventional design, and sand separation with disposal
- Investigate technology analogues from other industries that may be applied to subsea use

Surface Sand Management – Redux

All oil and gas wells produce sand; therefore, all production facilities must be capable of managing sand in the flow streams. When sand control is not economical or technically feasible or when controls fail, the surface facilities (offshore or onshore) must manage the produced sand. Surface sand handling is termed Facilities Sand Management (FSM). Sand coproduction, which requires FSM technology, is shown to increase hydrocarbon recovery (Rawlins 2017). This approach completes the well without a completion string – either barefoot or open-hole with large slots. Sand is produced with hydrocarbons to increase the reservoir interface area, decrease skin, and improve inflow. The sand must be separated and handled in the surface facilities without interfering with the equipment uptime.

The technologies for surface FSM are fully mature and are applied at one of the four nodes of sand separation in the production system, as shown in Figure 1.

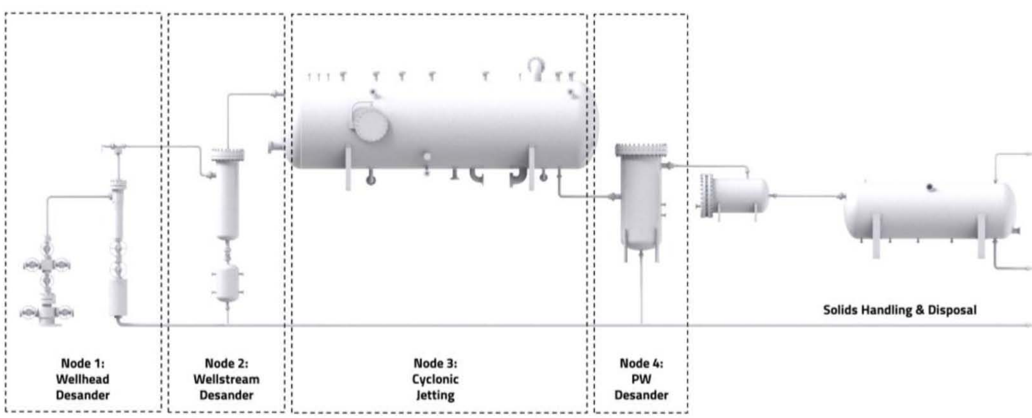

Figure 1—The four nodes of sand separation showing the locations in the process system.

Node 1: Upstream of the choke is the multiphase (wellhead) desander. This is the first, and the highest-pressure location where sand can be removed. The separation of sand with a wellhead desander (WHD) protects the choke, flow lines, separator, and produced water treating equipment (Rawlins 2017). This application has been in use for more than 20 years.

Node 2: The wellstream desander (WSD) operates in a similar way as the WHD but is mechanically packaged for multiphase flow between the choke and the separator. The WSD is installed on a manifold or near the inlet to the separator, and it may be used to process multiple wells. This application has been in use for more than 15 years.

Node 3: Solids are separated within the production separator, but on-line removal requires a jetting system (Rawlins 2016). Here, the separator and produced water system are not protected from sand, but sand is handled without shutting down the facility. This application has been in use for more than 40 years.

Node 4: The final location where sand is removed from the produced water stream using a standard (liquid) desander. This technology protects the oil removal equipment (i.e., deoilers and flotation cells), injection equipment, and the disposal reservoir. This application has been in use for more than 50 years.

Subsea sand management is a specific case of Facilities Sand Management. The same principles and practices are applied, but with a focus on the unique attributes of subsea processing. Facilities Sand Management handles sand and solids in any facilities equipment with a degree of skill. This is not a waste stream treatment exercise but a critical facilities flow assurance issue. The objective of FSM is to increase or maximize the hydrocarbon production while reducing or minimizing the operating costs (Rawlins 2013).

Subsea Sand Management

Produced Solids in Subsea Processing

The produced solids are defined as inorganic, insoluble, particulate material that accompanies well fluids to the surface (Rawlins and Hewett 2007). These solids originate from natural or artificial sources. Natural solids are indigenous reservoir materials that are produced in low, steady-state continuous production until a failure mode occurs (i.e., water breakthrough or completion failure), which results in an unplanned high concentration erratic production (e.g., slugging) event. Artificial solids are introduced from external sources as a planned event – these include frac sand, proppant, corrosion products, etc.

The four main issues caused by solids in production facilities – whether surface or subsea – are erosion, filling, interference, and oil-in-water content (Rawlins 2014). The specific issues that may occur in subsea processing equipment are illustrated in Figure 2. *Erosive* failure can occur in high-velocity flow regions, including the choke and control valves, pump and compressor rotors, short jumper flow lines that connect the wellhead to the processing equipment, or long tie-back flow lines that connect the processing system to the surface production facility (Shirazi et al 2010). *Filling* with solids occurs in low-velocity regions, such as those found in the gravity separator vessels, pipe expansions, or oversized flow lines. Long tie-backs will experience reduced flow from settled solids, and gravity-based production separators will likewise experience a degradation of the performance or an imposed reduction in the production rate (Eriksson and Kirkedam 2004). *Interference* occurs when the solid particles prevent a range of motion or movement of fluid flow within components. Examples include the pump seals and rotor clearances, valve movement, and instrument reading. An increased *oil-in-water* concentration is a concern when treating produced water for local discharge; however, local (subsea) discharge may never be allowed in subsea processing and is not currently investigated.

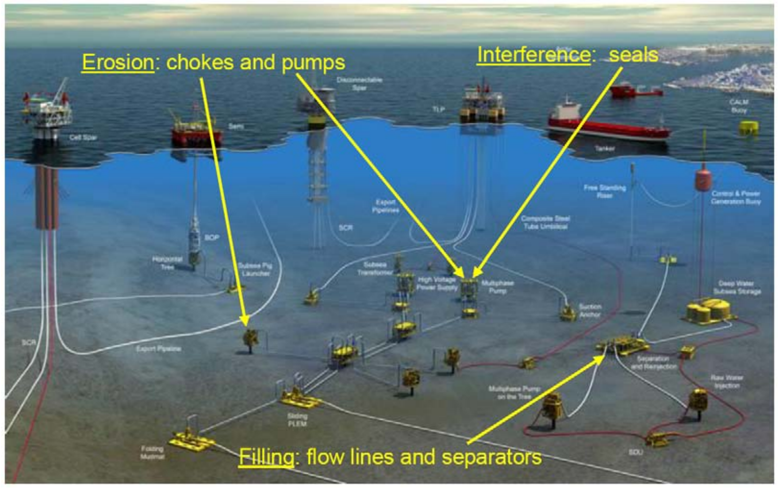

Figure 2—Locations in subsea processing where solids may cause problems (www.marinetechnologynews.com).

Solids must be removed from subsea production and processing to improve equipment reliability, maintain system uptime, reduce intervention frequency and duration, and prevent environmental contact, all while maintaining optimal hydrocarbon production.

Technology Gaps

In conducting this study, one goal was to delineate the existing, developing, and gap technologies. The existing technologies were those already deployed in subsea processing, or so well proven topsides that subsea application required very little further adaptation. The developing technologies were those that are used elsewhere in the oil and gas or other industries but have not yet been adapted for subsea use. Whereas the gap technologies are identified as those or were those that are or were still in the concept or research phase and required focused effort to be suitable for subsea use. Many of these technologies have analogues in other particulate processing industries – such as mining, construction, or ceramics – and as such should be adaptive to the upstream oil and gas industry.

The ranking system to identify these gaps is the Technology Readiness Level (TRL) scale. Adapted from work at NASA, TRLs are a method of evaluating or ranking the maturity of critical technology elements in a project. The oil and gas industry use the TRL scale to quantify the development state of new technology (DNV 2011). The technologies in this study were rated according to a seven-level scale as defined in API 17N. Table B-2 in DNV-RP-A203 defines the specific attributes of each level.

Sand Management Paths

In addressing the question "What to do with the sand?", three paths or categories for managing solids in subsea processing were identified.

1. Conventional Approach: Manage solids production with a system configuration using established design rules and technologies.
2. Solids Treatment: Modify the solids in situ to reduce or eliminate the deleterious effects on the production and processing system.
3. Solids Removal: Separate the produced solids from the well fluids and then manage as a separate flow stream.

Each of these paths was investigated to determine their applicability in the handling of sand within subsea processing systems. Within each category, multiple discrete actions were identified for study and ranking.

More than thirty discrete actions were categorized as shown in Figure 3. A description of each action within its category is listed in the following sections.

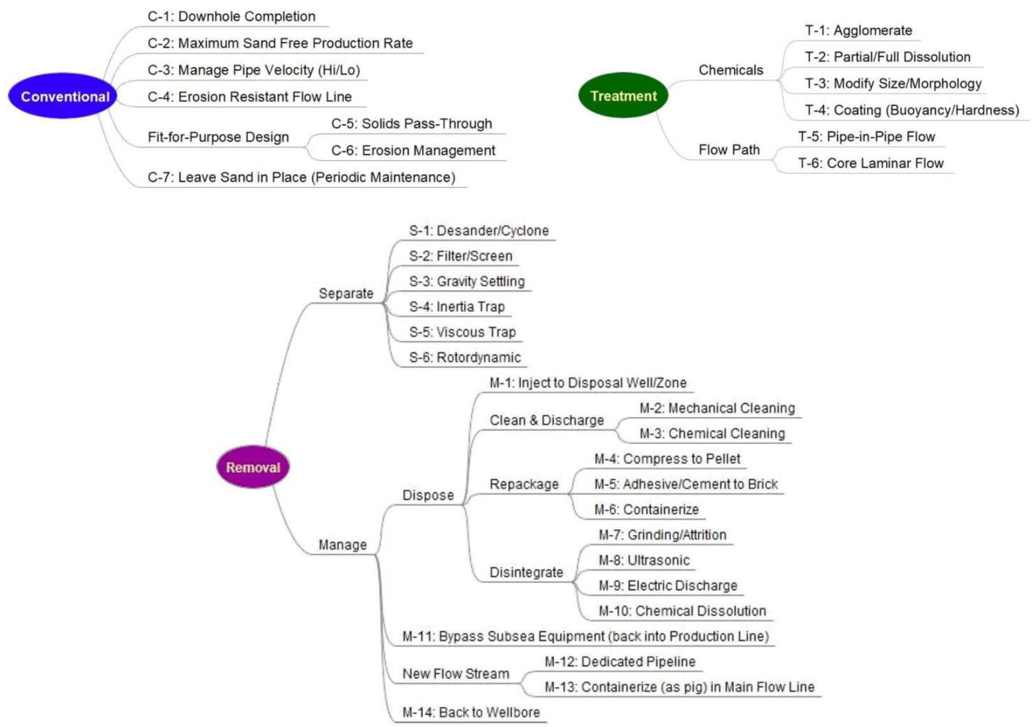

Figure 3—Sand management paths and potential actions in subsea processing.

Conventional Approach

The first path, entitled "Conventional Approach", manages solids production or configures the processing system using established rules or technologies. Seven actions within this category were identified as follows.

C-1: Downhole Completion. A completion includes a hardware barrier at the wellbore-reservoir interface that permits oil and gas production while preventing solids from flowing with the fluids. Over-completion prevents full hydrocarbon flow, and under-completion permits sand production (Rawlins 2017). Completion hardware has a finite operating life, with replacement required upon failure.

C-2: Maximum Sand Free Production Rate. This is a production methodology that restricts the hydrocarbon flow to a limit that prevents solids from flowing into or up the wellbore to the surface. The maximum sand free rate is therefore the limit to the hydrocarbon production. Step-changes in production (e.g., water breakthrough) require changes in the choke setting. Over-control reduces hydrocarbon recovery, while under-control allows sand to the facility.

C-3: Manage Pipe Velocity. The production flow line, either the jumper or tie-back, is sized to prevent excessive erosion (decrease the velocity) or solids settling (increase the velocity), whichever is the main concern. The resulting pipe diameter is appropriate for a specific range of flow rates only. As the production rate changes or wells are added/removed to/from the processing system, the velocity regime will change; however, the flow line cannot be changed in situ.

C-4: Erosion Resistant Flow Line. To prevent solids from settling in the flow lines, a small diameter pipe is used to maintain the carrying velocity at all projected well conditions. The result may be that the flow line now experiences erosion from the particles. To prevent excessive wear on the flow line, either a thicker pipe wall or wear-resistant pipe material is selected. The flow line may have a higher cost due to the increased weight or selected material.

C-5: Solids Pass-Through. This design paradigm applies to the subsea processing facility – specifically the gravity-based production separator. The velocity or flow path in the separator vessel is operated in a manner to keep the solids mobile and prevent settling. The solids pass through the vessel and are carried to the liquid outlet. The primary operation of the separator, two- or three-phase processing, must be balanced with the resulting higher velocities.

C-6: Erosion Management. This design paradigm also pertains to the subsea processing facility – in this case, the equipment may experience erosion. Either the flow path is modified (e.g., the velocity reduced) or materials are appropriately selected (e.g., thicker or wear-resistant material) to minimize erosion in that component. An example would be the choke valve plug and cage. The choke may be oversized to have lower velocity, or the cage be made thicker or of highly erosion-resistant material. The resulting choke may have a more limited operating range and/or a higher cost.

C-7: Leave Sand in Place (Periodic Maintenance). A common approach in dry surface facilities with low concentrations of sand is to allow the sand to settle and collect it in the production separator. Periodic or scheduled maintenance intervention removes the collected solids – either by shut-down and shovel or vacuum removal. While human intervention under subsea conditions is unlikely, the separator could be brought to the surface for maintenance or a subsea vacuum system employed to remove the sand. This is a costly approach with regards to production downtime and equipment access.

An evaluation of the conventional technologies C-1 to C-7 is provided in Table I in the Appendix. This table lists each action or approach, the issue treated (i.e., eliminating erosion, settling, or interference), the equipment protected (only major items shown), and the TRL. Additionally, specific challenges to the deployment of that action are listed. For example, downhole completion (C-1) can solve all solids issues (i.e., if used properly, it prevents sand from coming to the surface), and its location (downhole) protects all subsea processing equipment. The completions have a TRL of 7 – as they are widely deployed in all types of fields around the world. However, two challenges with these completions are (1) that they eventually fail and need replacement, with the failure leading to the in-rush of sand and the replacement in deepwater being costly, and (2) the completions inhibit maximum hydrocarbon recovery from the well.

All the technologies under the conventional path have a TRL at a level of 6 or 7, which is part of what makes them conventional. There are challenges to each of these actions. Actions C-2 through C-6 are all a moving target based on the expected solids size and concentration – as these parameters deviate from the design, which occurs during water breakthrough or commingling of new wells, the effectiveness of these actions may deteriorate. Actions C-2 and C-3 may inhibit maximum hydrocarbon recovery due to the limited production rate. Action C-7 is easy to implement, but access to the separator for sand removal prohibits its effectiveness.

Solids Treatment

In this path, the particulate solids are treated within the existing flow path to ameliorate the detrimental effects. The solids are not separated and then treated, but rather treated in situ. The treatment actions include chemical additions to modify the particle properties, so they cause less damage or change the flow path to segment the solids from a particular section of the processing system while still allowing them to flow. Most of these actions are at the concept or R&D phase. They are listed as gap technologies that, if fully developed, could provide a great advantage to production systems. These six action items are a target for development work.

T-1: Agglomerate. A chemical is added to gather the individual particles and adhere them together to form large/heavy agglomerates. These agglomerates, or clumps, settle to the bottom of the flow line and are swept out during a pigging run. Flocculant chemicals are widely used in the water treatment industries for similar effects.

T-2: Partial/Full Dissolution. A chemical is added to either partially or fully dissolve the solid particles. Full dissolution may be overkill for the design, but partial dissolution is achievable. The goal is to reduce the particle diameter below a critical size, which then has a negligible erosive effect. Published work on erosion in pipe elbows shows a steep drop-off in the penetration rate below a critical particle size (McLaury et al. 1997). An example is shown in Figure 7 in this reference, which shows several orders of magnitude decreases in the penetration rate for sand with a particle size below 100 microns in water and of 20 microns in methane. Possible chemicals include NaOH or organic acids.

T-3: Modify Size/Morphology. A chemical is added to remove the sharp, angular edges of the sand particles and impart a smoother morphology. Improving the roundness and removing the angular corners is shown to greatly reduce the erosive potential of sand particles. A sand sharpness factor is included in published erosion models (McLaury and Shirazi 1999). Table 2 of this reference shows the reduction in the erosion rate by 80% with improving roundness. Possible chemicals include NaOH or organic acids.

T-4: Coating (Buoyancy/Hardness/Morphology). A chemical is added that coats the free-floating sand particles. This coating reduces the particle effective density, hardness, or sharpness, any of which reduces the momentum transfer during impact with the flow line wall and reduces the erosiveness. This idea was patented for proppant injection and could be applied to the production side (de Grood 2010). Possible coating materials stated in this patent include fluoropolymers or resins.

T-5: Pipe-in-Pipe Flow. An in-line cyclonic or swirl device is used to direct and concentrate the solids towards the center of the main pipe flow. The concentrated solids are directed into a smaller pipe contained within the main flow line. The center pipe has a small diameter and does not need to maintain high-differential pressure to the outside environment. This sand-slurry pipe could be made of erosion-resistant material, while the main fluid flow continues through the annulus within the pipe of standard material.

T-6: Core Laminar Flow. This is a conceptual design where a series of in-line devices are used to create a swirling annular flow that is solids free, while the solids are directed towards the pipe center to be carried in an enclosed laminar flow stream.

Most of the approaches in the treatment path are in the conceptual phase at a TRL level of 0-2. These are ideas for future R&D. A chemical injection scheme could treat solids in situ and would eliminate the need for specific processing equipment. The challenge is to reach every single particle in a large-volume, dilute system and then make an effective change in that particle (i.e., make that particle smaller, smoother, or softer), and ensure that the injected chemical does not interfere with the existing equipment or treatment of the fluids downstream.

The one approach in this category that is past the conceptual phase is to use pipe-in-pipe transport technology (at a TRL level of 4). Instead of making the entire full diameter of the tie-back line with a thicker wall or with erosion-resistant material, the idea is to concentrate the flowing solids, in-line, and direct those solids into a separate flow line that is contained within the tie-back piping. This separate flow line would be small in diameter because it only needs to handle the solids and some carrying liquid, and it does not need to maintain a high differential with the outside pressure. The small diameter slurry line could be made from erosion-resistant material, thus keeping the expenses down. Umbilical tie-backs already contain multiple, bundled flow lines for utilities, chemicals, etc., and this would be added to the existing design. The in-line device to concentrate and direct the solids to the internal pipe is the primary gap that needs to be developed; however, in-line desanding systems have already been employed subsea (Daigle and Cox 2012).

Removal (Separate and Manage)

The removal path involves the separation of solids from the flow stream and then managing them through disposal. The full definition follows the five-step methodology – applied subsea just the same as in surface production operation (Rawlins 2013).

1. Separation: partition of the solid particles from the multiphase stream
2. Collection: gather the partitioned solids into one central location and isolate them from the process flow and pressure
3. Cleaning: remove the adsorbed hydrocarbons from the sand particles
4. Dewatering: remove the free liquids in the collected sand to minimize the disposal volume
5. Transport: bring the solids to a disposal location

The five-step methodology can be reduced to separate (steps 1-2) and then manage (steps 3-5) to delineate the investigated actions along the removal path. Six separation actions (S-1 through S-6) and 14 management (M-1 through M-14) actions are detailed. These can be combined in multiple ways (e.g., a multiphase desander S-1 to separate the sand, which is then put into a retrievable container M-6 or back into the tie-back line downstream of the separator M-13).

S-1: Desander/Cyclone. Cyclonic technology, embodied in the multiphase desander, removes sand from the flow stream upstream of the choke (wellhead desander) or upstream of the processing equipment (wellstream desander). This technology has the highest throughput-to-size ratio of any separation device and allows the separated sand to collect into a separate, isolatable accumulator. The multiphase desander can remove solids down to 20 microns using the process pressure and has an adjustable performance (Loong et al, 2014, Rawlins, 2017).

S-2: Filter/Screen. The filter-screen is an impact-retention device with a fixed separation size. This technology can remove sand from multiphase flow upstream of the choke or production separator. The separated sand is collected within the body of the screen and requires a backflush for removal. The separation size is fixed and ranges from 150-400 microns.

S-3: Gravity Settling. The sand is separated by settling to the bottom of the gravity-based production separator. The collected solids are removed periodically by jetting and flushing (a spray nozzle or cyclonic type). Gravity separation is effective at removing particles with a diameter of 75-150 microns (Fantoft et al. 2004, Olson et al. 2014, Rawlins 2016).

S-4: Inertial Trap. The sand is collected in a pipe dead-leg or catch pot. The momentum of the sand carries it straight at a bend into the trap, while the fluid turns and continues to flow. The sand fills the dead leg for periodic removal or flushing. The pipe catch pots have a separation size of >300 microns (Han et al 2011).

S-5: Viscous Trap. The flowing sand particles impact a viscous fluid (i.e., grease) contained in a tee-section of the pipe and are trapped. Similar in design to the inertial trap, except the grease ensures that the trapped particles cannot be re-entrained. The trap mucilage needs to be hydrophobic and oleophobic and must remain viscous at the process temperature. Once the grease is filled with solids, it is removed and replaced. The separation size is on the order of >300 microns.

S-6: Rotordynamic. A rotordynamic separator, such as a disc-stack centrifuge or rotary separator turbine, separates the sand from the multiphase flow stream. Rotordynamic devices can separate solids down to 10 microns (Khatib et al. 1995, Rawlins and Ross 2001) and require power to operate. The separated sand is collected within the device for periodic flushing.

Given that the management actions of the removal path overlap with aspects of the conventional and treatment paths, some of the items will be repeated here.

M-1: Inject into a Disposal Well/Zone. The collected sand is injected into a specific disposal well or zone. This could be a slurry-fracture injection or an injection with the produced water. No sand cleaning is required. Sand disposal by well injection is used in both dry and subsea facilities (Nagel and McLennan 2010, Shaiek et al. 2015).

M-2: Mechanical Cleaning. The collected sand is cleaned by mechanical attrition to remove the adsorbed oil. The clean sand is disposed locally onto the sea floor as loose particles. Attrition-based cleaning systems using cyclones, pumps, or thermal friction are used topsides to treat both produced solids and drilling muds (Hodson, J.E. et al. 1994, Murray et al. 2008).

M-3: Chemical Cleaning. The collected sand is cleaned with chemical agents to remove the adsorbed oil. The clean sand is disposed locally onto the sea floor as loose particles. Commercial and biosurfactants are readily available for sand cleaning (Amani, H. 2015).

M-4: Compress to Pellet. The collected sand is first cleaned (by mechanical or chemical means) and then mechanically compressed into a hardened pellet without any binder additives (i.e., similar in action to a ceramic Carver® press). The pellets are stacked locally on the sea floor for permanent storage or periodic retrieval.

M-5: Adhesive/Cement to Brick. The removed sand is cleaned (by mechanical or chemical means), then an adhesive or cement is used to bind the loose particles into an extruded brick. The bricks are stacked locally on the sea floor for permanent storage or periodic retrieval. Alternately, a 3D concrete printer can be used to build a monolithic disposal pile.

M-6: Containerize. The collected sand, without cleaning, is transferred to a storage and retrieval container. This container can be a flexible bag, such as the geotextile containers used in soil washing, or a hard-sided bin or vessel (Loong et al. 2014). The container is periodically collected to the surface using a tether line, ROV, or flotation bag used for underwater salvage.

M-7: Grinding/Attrition. The collected sand is reduced in size below a critical limit, using grinding or attrition technology, and then put back into the process or flow line. Fine particle grinding technologies include mechanical methods (e.g., a ring and puck mill, disc pulverizer, or micropowder mill), media methods (e.g., a planetary or stirred media mill), or static methods (e.g., a jet mill). Sand cleaning is not required before grinding.

M-8: Ultrasonic. The collected sand is reduced in size below a critical limit using ultrasonic energy and then put back into the process or flow line. An ultrasonic wet-mill provides microgrinding of the collected particles (Heilscher 2018).

M-9: Electric Discharge. The collected sand is reduced in size below a critical limit using electric discharge energy and then put back into the process or flow line. This technology is being studied for downhole fracture and stimulation use in oil and gas production (Vazhov et al. 2010).

M-10: Chemical Dissolution. The collected sand is reduced in size below a critical limit using chemical dissolution and then put back into the process or flow line. Possible chemicals include NaOH, HF, and organic acids.

M-11: Bypass Subsea Equipment (back into production line). The collected sand, without cleaning, modification, or packaging, is put back into the subsea flowline downstream of the process where it may cause trouble (i.e., the multiphase pump or production separator). This flow scheme has already been employed in subsea processing (Shaiek et al. 2015).

M-12: Dedicated Pipeline. The collected sand, without cleaning, is introduced as a slurry into a separate flow line that takes the solids to the surface. A separate pump station may be required to provide energy to the transport fluid.

M-13: Containerize (as pig) in Main Flow Line. The collected sand, without cleaning, is packaged into a pig-based container that flows through the tie-back flow line to the surface.

M-14: Back to Wellbore. The collected sand, without cleaning, is transported back to the production wellbore and stored in a collection area below the production zone (i.e., the rat hole). A pump station and transport line are required to provide energy for the slurry to be delivered to the wellbore.

The separate and manage paths are combined to form the removal path. The six actions in the separate path are combined with the fourteen approaches of the manage path to form a full removal path. Most of the separation technologies have been widely deployed in offshore surface systems. Desanders, screens, gravity settling, and pipe dead-leg traps (all at a level of TRL of 5-7) are used around the world for separating and collecting solids in oil and gas production. In addition, most of these technologies have been addressed or used subsea; thus, the technology to remove sand from the well flow is at least initially accepted for subsea use.

Selecting the appropriate place to remove the sand – upstream of choke, upstream/in/downstream of the separator, in the produced water stream, etc. – depends on what equipment needs to be protected and where the sand will be disposed. The leading technologies specific for sand removal are the multiphase desander or gravity settling in the separator. A wellhead desander, such as that shown in Figure 4, is installed as a specific module within the subsea template before the choke, separator, or multiphase pump/compressor. Gravity settling does not require an additional process module but requires the separator vessel to have sand jetting and flushing systems and controls.

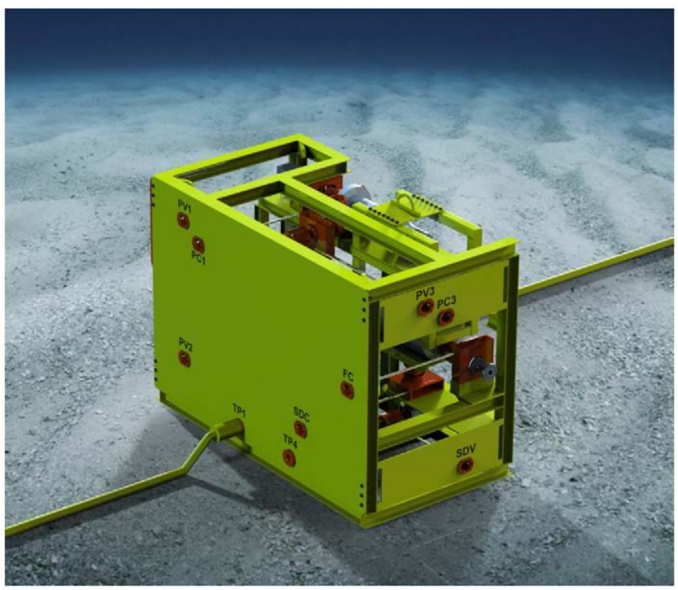

Figure 4—Subsea wellhead desander module for sand removal.

Once the separating approach is selected, sand management (i.e., the cleaning, dewatering, and transport) comes next. Broadly, these approaches can be partitioned into disposal, bypass, or new flow streams. Sand can be disposed of by injection into a well/zone (a TRL level of 6), cleaned for local (seafloor) discharge (a TRL level of 3), or disintegrated and put back into the flow stream (a TRL level of 2). Slurry injection is fully mature for use at topsides and eliminates the need for cleaning, removing hazardous contaminants or bringing the sand to the surface; thus, it is a leading candidate for subsea disposal (a TRL level of 6). It does require a designated pump and well to inject the slurry, which increases the complexity of the subsea template. Local (seafloor) discharge of the produced sand will probably never be sanctioned; thus, cleaning, repackaging, and disintegration are of R&D interest only at this time. One area of merit is containerizing the sand, which is then brought to the surface (a TRL level of 4). This can be accomplished using soft retrieval bags that are retrieved by wireline or ROV. Putting the sand back into the flow stream (i.e., bypassing critical process equipment) is a very feasible approach (a level of the TRL of 6). The sand needs to be removed at the surface (again), but this approach does protect the critical subsea items. A dedicated slurry transport line (a TRL level of 7) is technically feasible but adds significant cost to the entire subsea template.

Installed Systems Summary

A report published by the Research Partnership to Secure Energy for America (RPSEA) in 2012 provides further details on the anticipated design conditions for solids removal in subsea processing and what approaches have been tried in a deployed system (Daigle and Cox 2012). The bulk of the report focuses on the subsea produced water treatment and discharge, but the subsea solids discharge was also considered. Their results can be compared with previously detailed paths to compare feasible approaches.

Design Conditions and Disposal Requirements

The produced solids design condition identified for a "typical" subsea well was a 100 ppm sand concentration at both a low and high GOR (Table 2.4 of the RPSEA report) with a total solids production of 700 lbs. (318 kg) per day (Table 2.7 of the report). These suspended solids were expected from both natural (silt, clay, sand, precipitates, etc.) and artificial (proppant or corrosion products) sources. No specific size or density of the solid particles was stated.

The disposal requirements for the produced solids vary based on geographic location. The U.S. Gulf of Mexico prohibits the discharge of produced sand; thus, a ship-to-shore or injection process is required. In countries that allow ocean discharge of solids, the OSPAR convention (a limit of 1 wt.% oil in the dry sand) is followed. The requirements for produced water reinjection were solids at a ppmv concentration of <5 and <2 micron in size.

Included in the RPSEA report was a rating of the technology gaps for the components to treat the produced water. Most of the technologies were for oil removal; however, three components were rated regarding solids handling. Both desanders and solids handling and storage were rated at a TRL level of 3, while solids filtration was rated at a TRL level of 0 (Section 1.8 Executive Summary and Section 10.4 in the main body of the report). These levels were based on a seven-level TRL scale.

Review of the Installed Systems

The RPSEA report included a listing and review of the installed and planned subsea separation systems. Each of these installations was reviewed for the solids management path approach and grouped according to the design.

- Two-phase gas-liquid separation that keeps the sand flowing with liquids to the surface facilities
  - <u>Method C-5</u>
  - Petrobras Marimba, Congro, Malhado, Corvina, Canapu / Shell BC-10 and Perdido / Total Pazflor (includes backup sand flushing arrangement)
- Three-phase oil-water-gas separation with sand flowing with the produced water to the injection well
  - <u>Method S-3 with M-1</u>
  - Statoil Troll C
- Three-phase oil-water-gas separation with sand jetting to the desander for disposal in an injection well (with the produced water). The design changed to solids being reintroduced to the flow line to the surface.

    - The initial design was method S-3 and M-1, but changed to S-3 and M-11
    - Statoil Tordis

- Sand removed before the separator, with jetting in the separator, and with a desander from the produced water – all the sand was put back into the oil production line to the surface

    - Combining methods S-1 and S-3 with M-11
    - Petrobras Marlim

Most installations followed the conventional approach, specifically C-5, to keep the sand moving through the processing system. The next most common approach was separation (method S-3 separated sand in the production separator), followed by putting the collected solids back into the production line (method M-11). However, there was no published information on the success or effectiveness of each of the installed systems.

Report Recommendations
From the RPSEA study, three designs are recommended for subsea sand management. These conclusions are based on the equipment TRL and existing environmental regulations.

1. Remove solids from the well flow before the processing system using a multiphase desander. The collected solids are put into a retrievable container (method S-1 and M-6).
2. The solids flow with the liquids after the two-phase separation and are removed using a liquid desander. The collected solids are fluidized and reintroduced back into the production oil stream (combined methods C-5, S-1, and M-6).
3. Manage solids through the flow velocity in the processing and flow line systems (C-3 and C-5).

Conclusions

All oil and gas wells produce sand; therefore, all production facilities (dry or subsea) must be capable of managing sand in the flow streams. Exclusionary methods, such as completions or a reduction in the production rate, may not be technically or economically feasible. When these fail, the facilities must manage the produced sand. Handling sand in the facilities is termed Facilities Sand Management (FSM).

Subsea processing requires sand management. The sand produced will create erosion, filling, or interference problems with chokes, flow lines, pumps, separators, valves, and other subsea processing components. No new equipment is required to separate the sand (should that route be chosen) – proven equipment from surface facilities is available for efficient sand removal from the well flow (e.g., a multiphase desander). This technology must be packaged effectively for subsea use and evaluated through all TRL stages.

The primary concern with subsea sand management is what to do with the solids. Three categories, or paths for handling the solids, were investigated. These are the conventional approach to manage the system configuration using established rules or technology, treatment, which attempts to modify the solids in situ to reduce or eliminate their deleterious effects, and removal, which combines the five steps of sand management with the separation of solids from the well fluids and manages them as a separate flow stream.

Each subsea processing system will have different components depending on the field layout, process and fluid characteristics, and the tie-in to the topsides receiving station. There are common elements in each, such as chokes, jumper lines, shut-down valves, and tie-back flow lines and unique elements to each, such as multiphase pumps, compressors, and two- or three-phase separators. Identifying the problems that solids could cause and the elements they will impact will drive the solids management approach. The recommended approaches are as follows:

- Separate and bypass the critical equipment. The sand is separated upstream of the critical processing elements (e.g., chokes, multiphase pumps or gravity separators), then put back into the flow line downstream. The solids then flow along with the produced fluids to the surface for removal and handling. This approach protects the critical processing elements and is the simplest handling route for sand disposal.
- Separate and inject into a disposal well. The sand is separated upstream of the critical processing elements and then injected along with the produced water or as a separate stream into a disposal well. The sand does not require cleaning, and any hazardous elements are put back into the reservoir from which they came. This approach protects the critical processing elements and the tie-back flow line and eliminates further separation and disposal of solids at the surface facility. This approach requires a disposal well and an injection pump.
- Separate and put into retrievable containers. The sand is separated upstream of any critical processing elements and then collected into a retrievable container next to the subsea processing station. This container would be periodically retrieved using a tether line, ROV, or flotation lift. This method eliminates the need for a disposal well and injection pump but does require periodic retrieval of the sand container.
- Separate and put into a bag/tube/flexible container for seafloor storage. The sand is separated upstream of any critical processing elements and then collected into a flexible seafloor storage container, such as a geotextile bag located next to the subsea processing station. This container would be stored indefinitely, thus eliminating the retrieval of the sand container. The sand would not be discharged as loose particles floating around but placed into long-term seafloor storage. This storage container could be evacuated and retrieved during field decommissioning.

Further Work

The number of subsea wells worldwide shut in due to excessive solids production is difficult to evaluate, but some estimates provide a figure of 20–25%. This is a substantial/massive cost of shut-in capital equipment due to a solvable problem. Although this report addresses the design approaches identified for new field applications, there are many existing opportunities to reinstate existing subsea wells or increase the production with brownfield subsea wells.

Courses of action include the following:

- Identify shut-in subsea wells and choose the best candidates for action
- Evaluate the process design basis using wide contingencies - considering both start-up and ongoing production conditions
- Design an equipment package solution based on the design study outcome
- Fabricate the equipment-packaged solution and run in a subsea testing facility
- Install in a candidate shut-in subsea well – activate, commission, and monitor

Nomenclature

API = *American Petroleum Institute*
DNV = *Det Norske Veritas*
FSM = *Facilities sand management*
NASA = *National Aeronautics and Space Administration*
OSPAR = *Convention for the Protection of the Marine Environment of the North-East Atlantic*
ppmv = *parts per million by volume*
PWRI = *Produced water reinjection*

R&D = *Research and development*
ROV = *Remotely operated vehicle*
RPSEA = *Research Partnership to Secure Energy for America*
TRL = *Technology readiness level*

SI Metric Conversion Factors

micron	x1.0	E-06	= m
lbs.	x0.454	E-00	= kg

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Appendix

Table 1—TRL ranking of the subsea sand management technologies.

Sand Management Path		Issue Treated			Equipment Protected					TRL	Challenges
		Erosion	Settling	Interference	Choke	Jumper	Pump	Separator	Tie-Back	(0 - 7)	
CONVENTIONAL											
C-1	Downhole Completion	x	x	x	x	x	x	x	x	7	Eventual completion failure, inhibits hydrocarbon flow
C-2	Maximum Sand Free Rate	x	x	x	x	x	x	x	x	7	Moving target, requires on-line monitoring, inhibits hydrocarbon flow
C-3	Manage Pipe Velocity	x	x	x		x			x	7	Moving target based on solids size/concentration, inhibits hydrocarbon flow
C-4	Erosion Resistant Flow Line	x				x			x	7	Moving target based on solids size/concentration, may be costly
C-5	Solids Pass-Through		x					x		6	Moving target based on solids size/concentration, difficult to ensure all solids move through system
C-6	Erosion Management	x			x		x			6	Moving target based on solids size/concentration
C-7	Leave Sand in Place								x	7	Requires periodic intervention into separator for sand removal
TREATMENT											
T-1	Agglomerate	x							x	2	Dosage required reach all particles in high-volume, dilute system and chemical delivery system
T-2	Partial/Full Dissolution	x				x	x	x	x	1	Sand difficult to dissolve, chemicals may attack system components
T-3	Modify Morphology	x				x	x		x	1	Sand difficult to dissolve, chemicals may attack system components
T-4	Coating	x	x			x		x	x	2	Coating every particle in a high-volume, dilute system, chemical delivery
T-5	Pipe-in-Pipe Flow	x							x	4	Cost for dedicated pipe, efficiency of inline separating device
T-6	Core Laminar Flow	x							x	0	Paper concept only, difficult to maintain flow pattern along entire length of tie-back line
REMOVAL (SEPARATE & MANAGE)											
S-1	Desander/Cyclone	x	x	x	x	x	x	x	x	5	Not deployed subsea yet
S-2	Filter/Screen	x	x	x	x	x	x	x	x	5	Coarse separation size, prone to plugging, requires backflush support
S-3	Gravity Settling	x		x					x	7	Inhibits full use of production separator
S-4	Inertial Trap	x	x	x			x	x	x	6	Coarse separation and unpredictable performance
S-5	Viscous Trap	x	x	x					x	0	Maintaining viscous fluid and removal once full
S-6	Rotordynamic	x	x	x				x	x	3	Maintaining moving parts and providing power
M-1	Inject to Disposal Well/Zone									6	Requires pumping of sand slurry
M-2	Mechanical Cleaning									3	Maintenance of mechanical/moving parts, where to put clean sand
M-3	Chemical Cleaning									3	Supply of chemicals to subsea unit, where to put clean sand
M-4	Compress to Pellet									2	Power and moving parts for press, where to put the pellets
M-5	Adhesive/Cement to Brick									2	Supply of adhesive/cement, mixing and handling of sticky slurry, where to put the bricks
M-6	Containerize									4	Container retrieval
M-7	Grinding/Attrition									3	Power supply and maintaining moving parts for grinding mill
M-8	Ultrasonic									2	High power source
M-9	Electric Discharge									2	High power source
M-10	Chemical Dissolution									2	Sand difficult to dissolve, chemicals may attack system components
M-11	Bypass Subsea Equipment									6	Tie-back line not protected
M-12	Dedicated Pipeline									7	Extra pipeline cost
M-13	Containerize in Main Flow Line									4	Increased pigging frequency, putting sand into pig container
M-14	Back to Wellbore									3	Well rat-hole has fixed volume, transport back to wellbore