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Texas A&M University

Cavity Like Completions in Weak Sands

Preferred Upstream Management Practices

Final Technical Report

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TABLE OF CONTENTS

Disclaimers 2
Executive Summary 4
Objectives of the Project 4
Fundamentals of CLC 4
Conditions Favoring Successful Cavity Creation? 4
Designing a CLC: Key Points 5
Estimating Performance of a CLC 7
Field Demonstration Study – Mustang Island 787 7
Conclusions 8
Chapter I…Development of Unified Model from Theoretical Studies Laboratory Tests, and Field Trials (TASK 2) 9
Introduction 9
Parameters Affecting Cavitation Success 9
Factors Affecting Sanding 10
Stiffness Characteristics 13
Shear Strength 14
Tensile Strength 14
Unconfined Compressive Strength (UCS) 15
Recap - Strength and Stiffness 16
Influence of Perforations: Size, Density and Phasing 16
Influence of Particle Shape, Size and Distribution 20
Influence of Depth and Pressure 21
Influence of “Bean-up”, Shut-down, Permeability and Fluid Type 22
Factors Affecting Decisions to Prevent or Induce Sanding 25
Key Points 27
Chapter II….Field Test of Cavity Completion Technology (TASK 3) 28
South Pass 28
Field Demonstration Study – Mustang Island 787 28
Chapter III….Hybrid Cavity Completions (TASK 1) 31
Cavity Pack: 31
Suicide Pack 32
Perf Pack 32
Pre Frac and Pack: 33
Cavitate and Stabilize with Expandables 34
Horizontal Well Cavitation 34
Pre-Completion Cavitation 35
The Next Step: 35
Chapter IV….Best Practices (TASK 1) 36
Cavitation Mechanics: 36
General Cavity Modeling Considerations 37
Complex Cavity Models 40
Modeling of Cavities with ENHANS 40
Skin Factor Decrease With Sand Volume Produced: 45
Conclusions 46

EXECUTIVE SUMMARY

The technology referred to as Cavity Like Completions (CLC) offers a new technique to complete wells in friable and unconsolidated sands. A successfully designed CLC provides significant increases in well PI (performance index) at lower costs than alternative completion techniques.

CLC technology is being developed and documented by a partnership of major oil and gas companies through a GPRI (Global Petroleum Research Institute) joint venture. Through the DOE-funded PUMP program, the experiences of the members of the joint venture will be described for other oil and gas producing companies. To date six examples of CLC completions have been investigated by the JV.

Objectives of the Project

The project was performed to introduce a new type of completion (or re-completion) technique to the industry that, in many cases, offers a more cost effective method to produce oil and gas from friable reservoirs.

The project's scope of work included

Further develop theory, laboratory and field data into a unified model to predict performance of cavity completion
Perform at least one well test for cavity completion (well provided by one of the sponsor companies),
Provide summary of geo-mechanical models for PI increase and
Develop guidelines to evaluate success of potential cavity completion.

The project tracks the experiences of a joint industry consortium (GPRI No. 17) over a three year period and compiles results of the activities of this group.

Fundamentals of CLC

The concept of a cavity completion is to increase the effective wellbore radius, and reduce skin by removing pre-existing, near-wellbore damage. A small volume of sand removed can reduce a high positive skin factor dramatically. High positive skin factors that are normally associated with cased and perforated completions can be reduced dramatically with a properly designed CLC. In several cavity-like completions where reliable information is available from the field, low skin factors have been indicated. The promise of cavity-like completions is to be able to initiate the well with a low skin factor, or to re-complete and realize increased productivity.

Conditions Favoring Successful Cavity Creation?

Cavitation can be considered for conditioning a well (removing skin), creating higher porosity near the wellbore region or creating a stable cavity. The ideal condition is to have a formation that is weak enough to be broken loose with drawdown while having sufficient strength to stabilize. A weakly cemented formation with a UCS in the range of 20 to 50 psi is likely to work in a typical with depth and pressure setting. For a well that is depleted, a proportionally higher UCS would be required. Thus, whereas for a new well (or in short-to medium term) small UCS is preferable, as the reservoir matures and conditions change, different and more appropriate strategies must be considered. Some of the scenarios include:

- In a vertical well, with a relatively thin pay (e.g., <30 ft) overlain by a competent cap rock, it is possible to form a stable cavity under the cap rock since depletion and other types of weakening should not impact it.
- To manage the volume of sand, it is best to consider thinner layers.
- In most cases, cavities resulting from sand production cannot remain stable forever due to exposure of the sand face to “wear and tear” resulting from shutdowns and start-ups, fluctuations in drawdown and depletion (exceptions include cavities under cap rock discussed above). It may be necessary to repeat cavity creation periodically.

Designing a CLC: Key Points

- To develop and sustain a stable cavity, it is essential for the formation to have some degree of cementation. This allows for the near wellbore sand to be produced while maintaining a stable sand face.
- A controlled clean-up strategy is crucial for assuring that a stable sand face can be developed.
- In totally un-cemented sand that has experienced sanding and is choked back, an effective measure is to expedite the sanding by applying a higher drawdown (in a controlled fashion) so that a sand free state can be resumed once the drawdown is reduced.
- For any sand, there is an upper limit to sand free drawdown; exceeding that will result in continuous sanding.
- In unconsolidated sands, perforation strategy plays a role in sand stability that is due to arching. Other factors include depth (effective stress), particle size distribution (coarser particles can provide improved intergranular strength).
- Sanding is generally triggered by concurrent mechanisms (e.g., loss of mechanical cementation, removal of capillary cohesion and rapid changes in pressure).

Understanding cavity growth and stabilization requires consideration of the combined effects of fluid flow, changing in-situ stresses, material failure and material deformation. This is best done by modeling. Some of the recommended considerations [“Best Practices”] that have been developed for modeling are contained in this report and summarized here.

<u>Geomechanics Modeling of Cavities: Best Practices</u>

An effective numerical, analytical or visual model/representation of the cavity completion operation needs to incorporate certain geomechanical features. We commonly use the word geomechanical without specifying what it means. It represents the relationship between stresses, deformations, fluid pressure and flow and changes in these caused by natural or engineered changes in the reservoir, the wellbore or at the surface. Geomechanical modeling can represent the relevant cavity mechanics as we know or approximate them now, and can forecast or approximate cavity geometry and the consequences of cavity creation. Basic modeling concepts are discussed; with particular emphasis on one model, ENHANS*. ENHANS is used strictly as a platform for illustration of principles. Other models function as well.

Several key modeling results include:

Universal curve: Developments of a "universal" curve that statistically encompasses modeling and fieldwork to indicate anticipated skin for a specific volume of sand removed.

Economics modeling: By necessity, all completion operations require economic justification. Economic specifics will vary from company to company. One cavity-specific model has been developed and is available for download.

Caprock modeling: Caprock integrity is a concern in cavity operations, both for the cavity itself and for the superjacent completion.

A presentation outlining the key concepts that can be used for predicting sand volumes, is available online from the Document Downloads page, under "Sand Volumes." One of the key messages was that it is necessary to understand that failed material must be moved to the hole by a flow mechanism (hydrodynamic drag, etc.). Field examples are provided demonstrating prediction of sanding volumes. This report extends and synthesizes these comments into some practical recommendations.

A presentation of these well histories is available online from the Document Downloads page, under "New Case Studies." This summarized new cavity-like completions in the GoM. There were some definite successes. Also, there was one case where the well continued to kill itself by loading up with sand - surface equipment could not handle the sand. A key point overview of these wells is provided in this report. On line there is a second presentation, specifically dedicated to the success at Mustang Island. This presentation is available online from the Document Downloads page, under "Mustang Island Cavity Trial."

During Phase III, methodologies for ranking cavity candidates were developed. An overview presentation of this is available online from the Document Downloads page, under Rank Candidates. From the same online downloads table, one can get access to the Best Practices site, which attempts to incorporate these ranking considerations. See also, the presentation available online from the Document Downloads page and is entitled Cavity Completions – Best Practices.

Online access is available for a presentation and for a related Word document addressing the risks of Buckling. Similarly, a presentation on Cavitation Risks is available online from the Documents Download page. Universal Skin Factor is briefly recapped in this final report. A full presentation is available online. Also available online from the Document Downloads page is a Cavity Completions Economics spreadsheet.

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* EHANS tm is the product of BP upstream technology. (Reference page 41) EHANS is not a part of the DOE project.

Estimating Performance of a CLC

The Figure below shows an estimate of the PI increase expected for a given completion or re-completion, based upon the effective wellbore radius achieved by production of sand. The dashed line indicates that a skin of -4 represents 150% increase in productivity.

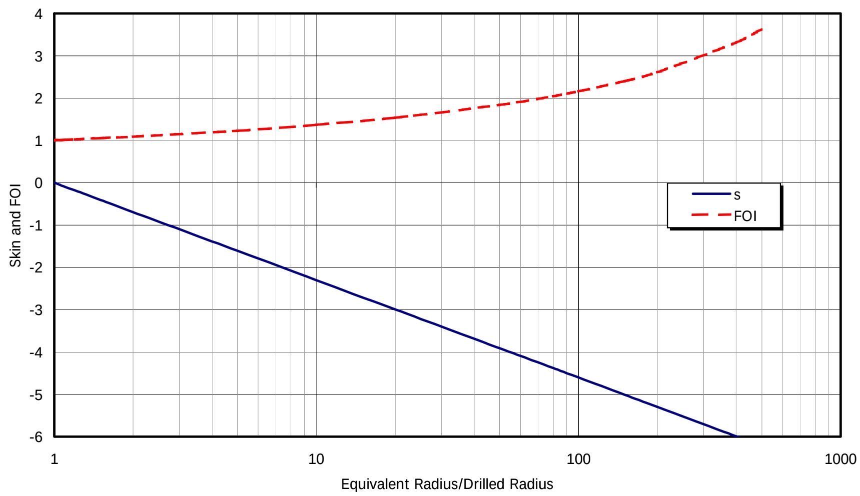

Figure ES-a. Estimate of PI increase as a function of Skin and effective wellbore radius.

Field Demonstration Study – Mustang Island 787

Summary of Re-Completion

In this successful cavity completion in the GOM Shelf, the sand-free flow rate was increased from 1 to 4.5 MMscfD after ~10 bbl of sand were produced. The well was offshore GOM on the Shelf and before cavitating it was producing ~1 MMscfD. The well was choked back due to sand production. It would also load up due to water production at these low rates. Prior to the cavitation workover, a desander system was put in place, ahead of a dual choke, to reduce erosion. A strap-on acoustic sand detector was deployed to continuously monitor sanding. BS&W shakeouts were continuously taken every 30 minutes; the sampling frequency was increased to every 15 minutes after the choke was opened up, to provide "ground truth", and to calibrate the sand detector.

Attributes:

The attributes of this well that seemed to delineate it as an effective cavity completion were:

- Good reservoir pressure
    - Pay zones are small: 4' and 3' TVD (8' and 6' MD)
    - Semi-caprock above top pay zone

- Sand has some strength: cavity may stabilize sooner rather than later
- Fresh pay zones-.no significant prior sand production

Results:

- The well was making 0.5-1.0 MMscfD before the cavity completion
- Well made ~5 MMscfD after cavity completion, with occasional trace sand that the platform could deal with
- Sand produced ~10 bbl, and sand stabilized (rough agreement with prediction)
- Incremental revenue was ~$12,800/day, cf. cost $5,700/day => $7,000/day profit during trial
- The well was flowed at a rate of 4.5 MMscfD for ~6 months before watering out.
- After cavity, profit was ~$40,000/month, or $4.8 million per year

Conclusions

The final report concentrates on several recent tasks. These include:

1. A summary is provided for the factors impacting successful cavitation and sand management.
2. An overview of cavity geo-mechanics modeling.
3. A key point overview of the Phase III field trials is provided. More information is available in the online presentations.
4. A discussion of some of the possible hybrid completion technologies that may include cavitation as a component.
5. An overview discussion of some of the concepts for cavity creation in other lithologies, is provided.

CHAPTER I…DEVELOPMENT OF UNIFIED MODEL FROM THEORETICAL STUDIES LABORATORY TESTS, AND FIELD TRIALS (TASK 2)

Introduction

There are several interrelated factors that impact the outcome of cavity completion, as well as managed sanding; particularly affecting the geometry and characteristics of the region participating in sanding. These factors apply to any sanding completion/operational procedure; including induced (intentional) sanding under controlled conditions, coping with a pre-determined level and rate of sand, and re-stabilization of a sanding episode. All are of concern to designing an effective cavity completion program.

The key to achieving a stable, productive cavity is to understand the sand behavior under the prevailing reservoir state and the imposed boundary conditions. Factors controlling cavity evolution and effectiveness are discussed below.

Parameters Affecting Cavitation Success

As in most geomechanics problems, there are usually three categories of input parameters that you need to deal with. There are existing natural conditions that are difficult or impossible to alter. There are imposed conditions - those conditions that can be varied to afford optimal cavitation, and there are constraints that control how much leeway you have in creating and controlling the cavity. Example parameters in these three categories are summarized below and discussed through the rest of the section.

Natural Conditions

Natural conditions controlling cavitation include:

1. Shear and tensile Strengths
2. Stress-strain characteristics of the rock, in particular, the degree of brittleness. Does the material work harden or soften? What is the energy dissipation after the peak stress?
3. Particle size, shape and distribution
4. Effective stress state (depth, reservoir pressure, tectonic history, depositional and uplift history)
5. Phases present in the reservoir and in the flow stream, particularly elevated water cut (in water-wet reservoirs).
6. Absolute and relative permeability
7. Stratigraphy of the pay zones and over-/underburden and the inherent degree of vertical and areal heterogeneity.

Imposed Conditions

The drilling and completion practices as well as how the reservoir is managed allow one to impose some control on the cavitation procedure. Characteristic imposed conditions include.

1. Type of sandface completion (e.g., C&P, openhole, screens, etc)
2. Completed thickness(es)
3. Wellbore deviation and azimuth
4. Production strategy, including the shut-in frequency, rate of clean-up, operating drawdown level
5. Depletion level
6. Injector strategy

Constraints

Finally, there are engineering factors that are inherited or cannot be manipulated. Consider these to be constraints. Examples include:

1. New well or existing producer or injector
2. Drawdown and associated rate needed to lift the sand
3. Sand handling capability (wet or dry tree, subsea or platform, sand separator and desander equipment, tolerance to erosion, etc)
4. Choke type – specifically the minimum pressure change that can be applied.

Factors Affecting Sanding

Since most of the factors above are interlinked it is difficult to discuss each in isolation. The same factor can have a different influence early in a well's life as opposed to near maturity. In addition, many sanding events can be due to a combination of events (e.g., aggressive clean-up, high drawdown, frequent shut-downs, sand particle size/distribution, degree of depletion, water cut, etc.) rather than just one single factor. As such, the following discussion of sanding, under any specific heading, can diverge into other areas that are related.

General Concepts and Principles

Figure 1a is a schematic representation of the interrelationship between drawdown and depletion in terms of sanding. It also illustrates concepts about re-stabilization – i.e., stopping sand production without abandonment. A cased and perforated completion is presumed in this figure and rock types with varying ductility are considered. Figure 1b is a closer examination of a brittle reservoir rock, with respect to regulating drawdown in order to stabilize a failed perforation.

Consider some of the specifics shown in Figures 1a and 1b. It is constructive to start the discussion from drilling and evaluate near-wellbore response through the productive life of the well.

1. Drilling and initial drawdown create shear bands, leading to localized disaggregation of the rock near the completion. Unless the sand is very

weak (totally uncemented), sanding at this stage is likely to be very limited and basically confined to the materials within the localized shear bands and/or perforation debris. Some extensile failure is also possible, but again, volumes of produced material are expected to be small in normally pressured reservoirs. This will be particularly true in drilling phases where, at the very least, the drilling engineer will weight up to subdue reservoir pressure, if not to prevent sloughing entirely.

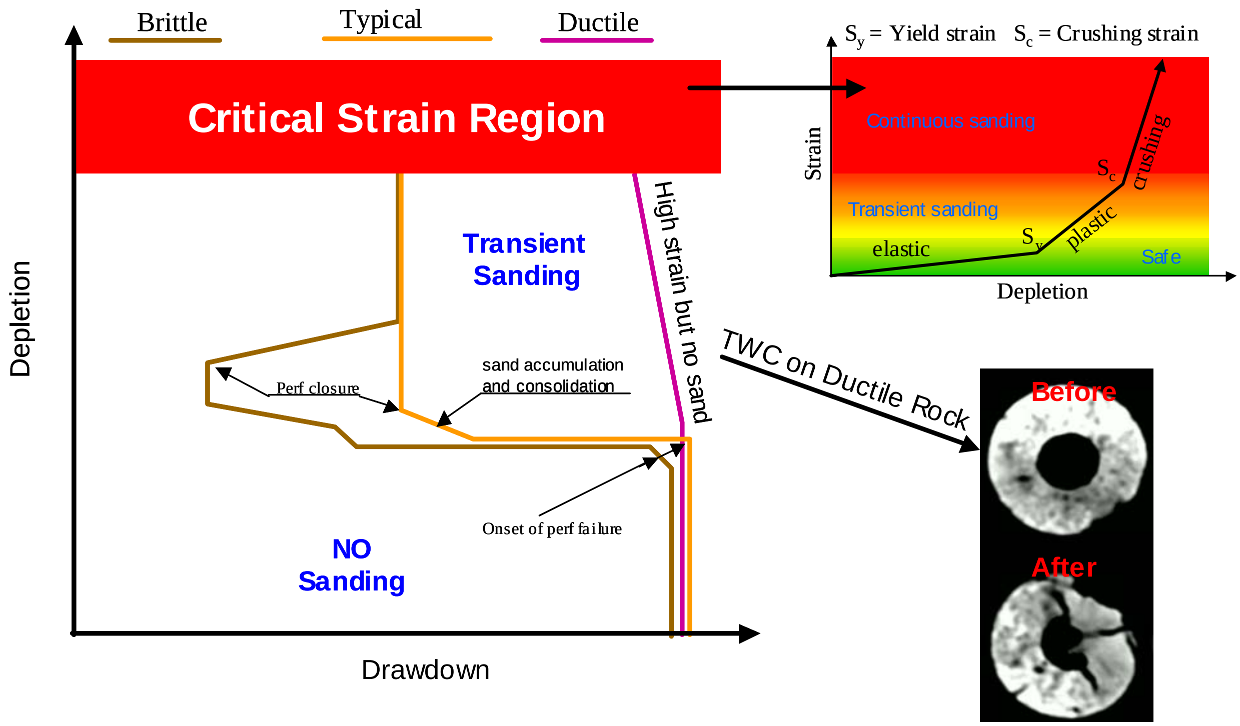

Figure 1a. Rock failure is a function of shear strength. Sand production is also a function of tensile strength, stiffness characteristics, drawdown, and total strain

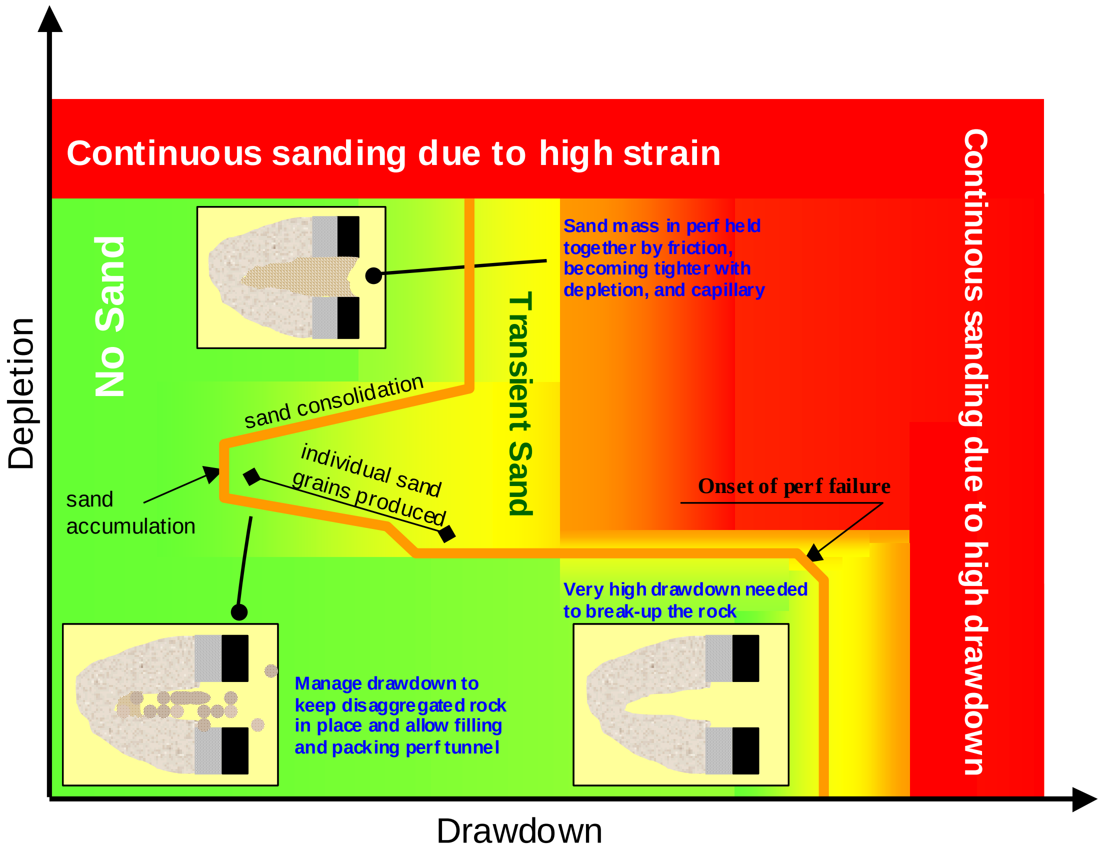

Figure 1b: Schematic "pathway" leading to rock disaggregation, sand production and stabilization.

2. With continuing drawdown, shear and other dislocation bands coalesce to form an annulus of disaggregated material around the well. Sand can be produced under high flow conditions. If sand production occurs, quantities are expected to be limited (not necessarily small) to the volume of the most broken up zones within the annulus. The sanding, in essence, will be transient in the form of sand bursts. The presumption again is that there is some inherent strength and that it is kinematically difficult to move the blocks that exist between dislocations through the perforations or other completion orifices.

3. With continuing production, unless pressure support is provided, depletion increases. When depletion reaches a high enough level inter-particle cementation will fail and near-perforation disaggregation can free smaller grain clumps – possibly individual grains - see Figure 1b). With continuing pressure reduction this "decementation" will evolve over a larger region around the well, thus increasing the supply of disaggregated sand. Production of the sand, however, depends on adequate seepage pressure (from drawdown).

   However, note that in unconsolidated formations, depletion can improve sand stability. The elevated effective stress will increase the inter-granular frictional resistance. In such formations there is also laboratory and anecdotal information which suggests that perforation tunnels never really exist and initiation of sand production may be inhibited by arching across the perforation opening in the casing/cement sheath. Don't forget however, that unless the cement is very green, there will be a tunnel of sorts, there will be a free surface that formation sand is exposed to, there will be converging flow with high drag through this and arching can be overcome.

4. Under very high depletion levels, sand production can occur due to high strain and crushing of the solid grains into a finer sand mass. Whether the frictional resistance is increased or decreased cannot be stated a priori since it will depend on the grain size distributions. However, there will be a supply of transportable fines. This mode of sanding is purely mechanical and can occur even under minimal flow conditions. Stress-strain characteristics determine the critical depletion for this to occur. While rare, crushing-induced sanding is almost imminent beyond the crushing level. Figure 1a (top right schematic) illustrates this mechanism.

5. Increases in the near-well wetting phase saturation (often water) can significantly increase sanding potential (for a given drawdown). This saturation increase destroys the capillary force holding the disaggregated particles. Viscosity changes due to multiphase characteristics can also change the drag forces that are exerted on particulates by fluids flowing into the wellbore. Increasing water saturation can also increase the potential for failure due to a reduction in the relative permeability and associated increases in drag. It is felt that this is less significant than the loss in strength associated with capillary suction at low wetting phase saturations. [That assertion may or may not be true for coarse-grained, uniform sands with large pore throats or for reservoirs that already exist at saturations well above so-called "irreducible" levels]. The impact of water is most visible and serious late in the life of the reservoir when a great deal of disaggregated sand is held back – often largely by the capillary adhesion (in addition, breakthrough may not occur until mid or late well life). In naturally unconsolidated sands, the impact of saturation changes can be seen right away. In general, drawdown must be reduced to stabilize disaggregated sand in the presence of water.

Stiffness Characteristics

To complete explaining the concepts shown in Figure 1a, consider the impact of the degree of brittleness (or conversely, ductility). The potential for sand generation and production due to perforation tunnel failure (development of shear bands and deformation of the perforation cavity) depends on the degree of brittleness of the rock, as well as the prevailing drawdown to carry out the sloughed sand grains. We intuitively expect that the stronger the rock, the less the chance of sanding. This is not the whole story. Weak rocks that are highly ductile may fail and deform significantly but not produce any sand (sand grains do not "snap off" the sides of the perforation tunnel). It is necessary to consider both strength **and** stress-strain response.

Field observations provide strong support for this. For instance, in very weak carbonates that have experienced high depletion (several times larger than their strength would indicate possible) and which have deformed substantially, " sanding" has not occurred because of the intrinsic ductility. Figure 1b (lower right) shows this behavior in a thick walled cylinder (TWC) test. In that test, after being subjected to increasing confining stress the inner bore deformed significantly but did not generate any discrete, producible components.

Shear Strength

Shear strength is used to determine the pressure required to disaggregate a rock.

- In highly ductile rocks, some carbonates and many granular, weakly cemented sands, shear failure can occur, along with significant deformation. However, strain hardening or high residual strength following strain softening, inhibit massive disaggregation.

- On the other hand, in highly brittle rocks, deformation is likely to result in disaggregation of the rock mass into a combination of individual sand grains and sand mass blocks/rock slabs. The individual sand grains can potentially be carried out if the pathway towards the perforation opening is clear and the seepage conditions are sufficient to drag the sand out. So, **while depletion is required to disaggregate the rock, it is the drawdown level (seepage gradient) that drives out the broken up sand mass.**

This ductility dependence is well known to mining engineers dealing with “explosive” rock bursts. Brittle rocks store substantial amounts of energy that is released catastrophically when yield is reached/exceeded. Alternatively, energy is consumed for strain hardening materials and/or energy is released more gracefully for less brittle materials (see for example, discussions of post-peak behavior, Jaeger and Cook, 1979[1]).

Tensile Strength

In weakly cemented formations (i.e., measured unconfined compressive strength, UCS < ±100 psi) or in formations that have become disaggregated due to high depletion, **tensile strength must be regarded as the key factor in sanding**. Tensile strength represents the combination of cementation and capillary cohesion (or adhesion). The latter is generally quite small in magnitude, typically in the order of 2 psi,[2] but it does play an important role in keeping a totally un- or de-cemented sand mass together with a significant contribution to arching resistance.

Measurement of tensile strength is not often done. In the absence of measurements, measured UCS (not wireline inferred) can be used to estimate

[1] Jaeger, J.C. and Cook, N.G,W.: Fundamentals of Rock Mechanics, Chapman and Hall, New York, 1976.

[2] The magnitude of the capillary cohesion depends on the saturation level and the size of the pore throats.

tensile strength – the published and measured factors vary and indicate that the tensile strength might fall in the range of 10 to 25% of the unconfined compressive strength.[3]

Unconfined Compressive Strength (UCS)

The unconfined compressive strength is a reflection of the shear strength characteristics of a material. It is particularly relevant to cavity completions - where one of the principal effective stresses is zero. Success of cavity completions strongly depends on the UCS.

In new wells in a normally pressured reservoir, if the UCS is above 100 psi, it is difficult to induce sanding: very high drawdown, rapid surging, chemical treatments, … may be required to break up the rock and to ensure that the broken-up sand mass becomes finely disaggregated (more likely it would break up in chunks). Under typical conditions (normally pressured reservoirs at TVD > 7,000 ft), sand with a UCS of about 20 psi[4] is ideally suited for cavitation - the sand can be broken down in a managed and progressive manner. This can be achieved using a properly tailored clean-up strategy.

Whether a cavity remains stable over time depends on the frequency of shutdowns, the re-start strategy and the depletion. If the reservoir is pressure supported (minimal depletion), it is feasible to maintain a stable cavity using an optimized clean-up. The cavity size, however, is likely to grow with the frequency of shut-downs and may eventually become too large to support the overburden - unless the sand is overlain by a strong caprock, in which case it can grow to significant distances (>50 ft). The geometry under these conditions, particularly close to the tip of the sand depleted zone will diverge from a cylindrical/conical cavity towards a wedge and subsequently transition to a worm-like feature.

In existing wells that have experienced sanding, it should be determined whether the sanding has been a result of sudden and/or excessive drawdown or moderate drawdown under increasing depletion.

- In the former case, sanding is purely due to tensile failure (seepage gradient exceeding the available extensile strength near the wellbore) and sanding should quickly stabilize with the likelihood of having formed cavities around the sanding perforations.
- In the latter case, drawdown has to be reduced to balance the strength of the disaggregated rock mass in order to stabilize the sand. The region subjected to disaggregation is much larger than just the material within the close proximity of the wellface. The likelihood for a **sustainable** cavity is small particularly in an increasing depletion environment.

[3] Conventional interpretation of wireline logs can significantly overestimate the UCS in weak to totally unconsolidated sands (anything less than 100 psi).
[4] Much more than this and it can be hard to create a cavity. Much less than this and it may be difficult to stabilize the sand production.

Recap - Strength and Stiffness

For weakly cemented rock and a cased/perforated completion, the following observations are possible.

- High drawdown can create tensile failure. This can lead to sloughing of the near wellbore sand face. It will be localized and sporadic.
- If the drawdown is kept below this critical level, sanding may occur if depletion reaches a high enough level to substantially deform perforation tunnels.
- Sand grains break off if a material is brittle. Otherwise, perforations will continue to deform plastically. For sand grains to be produced, the drawdown [drawdown causes flow, a pressure gradient and drag on the particles] must be sufficient to overcome the grain-to-grain friction in the broken up sand mass.
- Arching must also be overcome. The degree of stabilization attributable to arching depends on the relative size of the average sand grain with respect to the perforation opening
- Capillary cohesion may hold some of the sand grains together. It will need to be overcome.
- **In essence, rock failure, rather perforation deformation, is not the onset of sanding but one of the conditions that must be satisfied for sanding.**
- Since a finite drawdown is required to produce the sand grains into and from the perforation tunnels, one can rationally postulate that sanding can be managed by controlling the drawdown while depletion increases.
- Once a perforation tunnel totally closes up, drawdown can be increased since the opportunity for individual sand grains popping through the perforation openings no longer exists. This is not to say that there will not be consequences of increased drawdown in other unplugged perforations (sanding, coning ...).
- Under these conditions, a safe drawdown is one that is below the resistance of a tight sand pack that becomes gradually tighter with increased depletion.
- This can continue until strains become large enough to push the sand pack through the perforation tunnel.
- With increased water saturation, the permissible safe drawdown may have to be adjusted to allow for the loss of adhesion between sand particles. [5]

Influence of Perforations: Size, Density and Phasing

DP or Bighole?

One school argues that sand control can be improved by using small, deep penetrating charges. The smaller the hole size, the greater the arching effect. This is schematically shown in Figure 2. Factors affecting arching potential include particle shape and size distribution. In situations where the perforation opening is

[5] More detailed discussion is found in SPE 77683.

large in relation to the mean or median particle size, it will be more difficult to stabilize sanding, particularly under high water cut conditions.

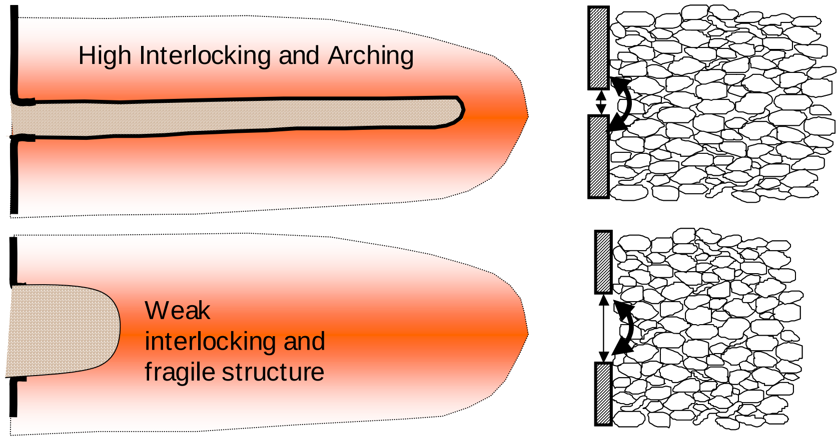

Figure 2. Arching is a function of the relative difference between the perforation opening and the average particle size.

Density and Phasing

With regard to the shot density and phasing, the objective is to minimize the potential for coalescence of the failure zones; both the enlarged cavities and the shear bands. Figure 3 is a schematic representation of the concept. Theoretically 4 spf appears to set the perforations far enough apart to prevent or minimize coalescence under moderate conditions (moderate drawdown in a moderately consolidated material). In practice, shot density is often higher (e.g. up to 12 spf±) since not all perforations may participate in flow and this may compromise productivity. Increasing drawdown to make up for the PI degradation increases the risk of larger sanding events that may lead to a more intense commingling of the failed zones.

Perforation interaction with increasing drawdown and consequent growth of a failed zone around perforations is shown in Figures 4a and b. These were simulations using ENHANS. Figure 4a is the output for a case where the drawdown was not sufficient to cause coalescence of the failure zones around two adjacent perforations; the red zone is the cavitated region while the green shading shows the extent of the plastic sheared zone (some of the shearing was due to the initial drilling of the well). Figure 4b is the same case but the level of drawdown is doubled. In this case, there is a significant overlap of the failed zones, rendering an almost cylindrical cavity around the well similar to what would theoretically be the case in a straight hole, barefoot completion.

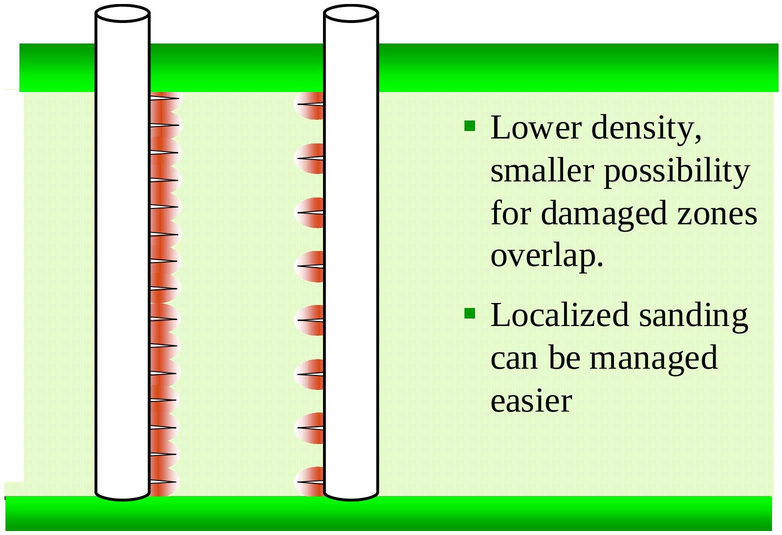

Figure 3. Schematic illustration of the relationship between perforation shot density and the potential for failed zone coalescence

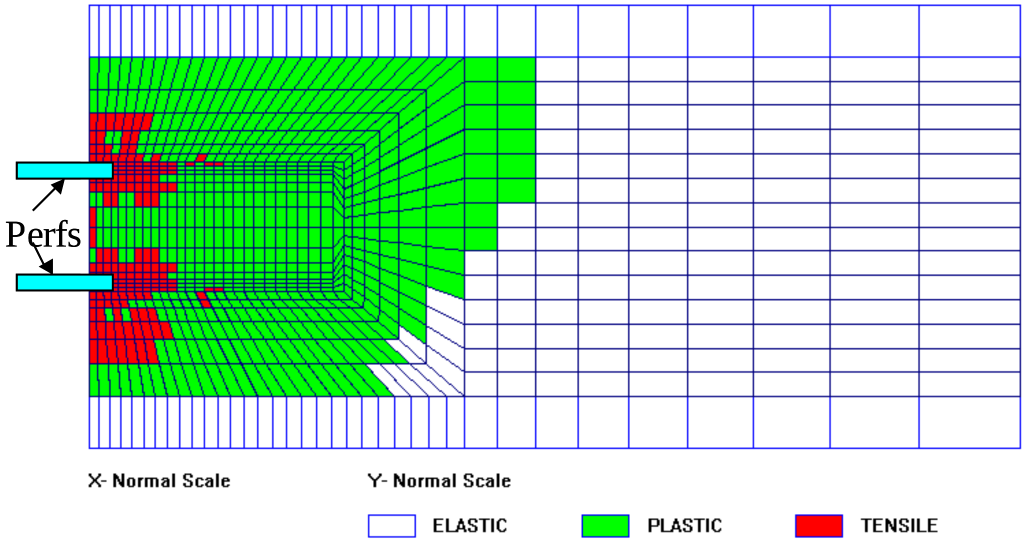

Figure 4a. Finite element simulations show the enlarged cavity and shear failure around a disc-shaped perforated region for a given drawdown (Red: zone participating in sanding; Green: sheared zone); mesh representation is in log-scale (i.e., cavitated zone much smaller in dimension than appears).

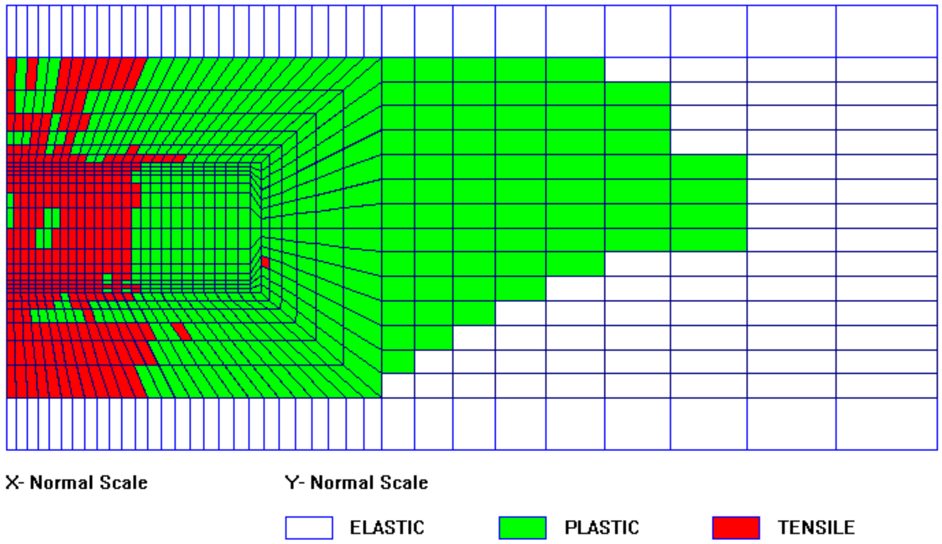

Figure 4b. As in Figure 4a but the drawdown is doubled, increasing the potential for overlapping of failed zones around individual perforations.

What about phasing? Effective phasing can serve to increase the distance between perforations at higher shot densities. This is shown in Figure 5a (shot pattern) and Figure 5b (phase diagram). Work by Karakas and Tariq[6] is useful in understanding perforation interaction.

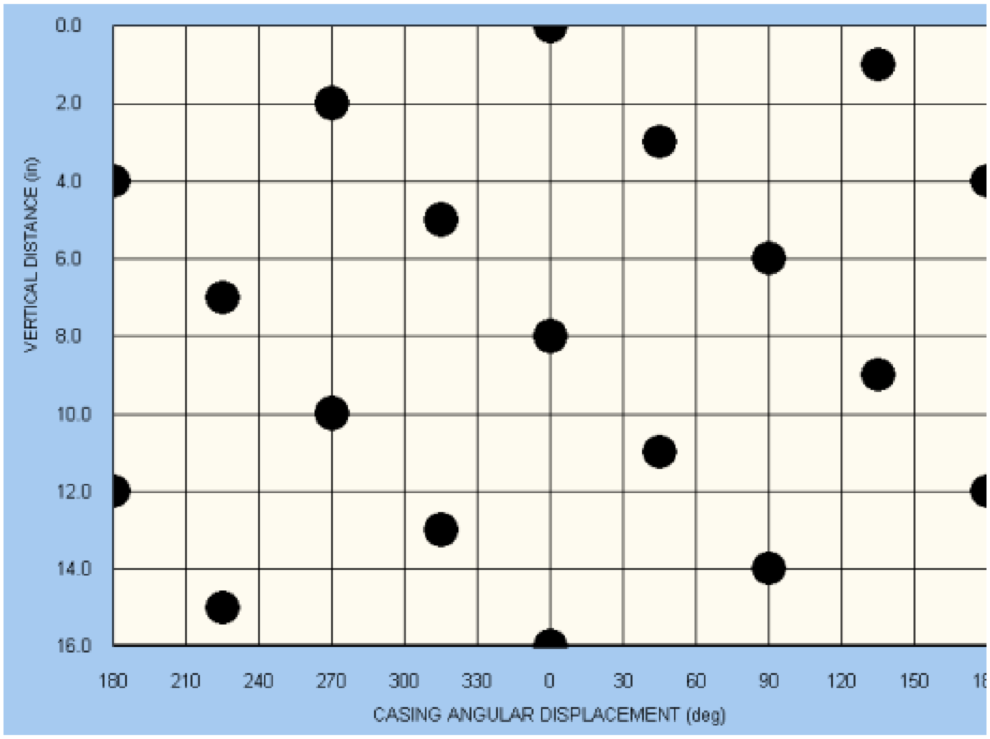

Figure 5a. Shot pattern optimized to maximize distance between adjacent perforations.

[6] Karakas, M. and Tariq, S.: "Semi-Analytical Productivity Models for Perforated Completions," paper SPE 18247, SPE ATCE, Houston, TX (October 2-5, 1988).

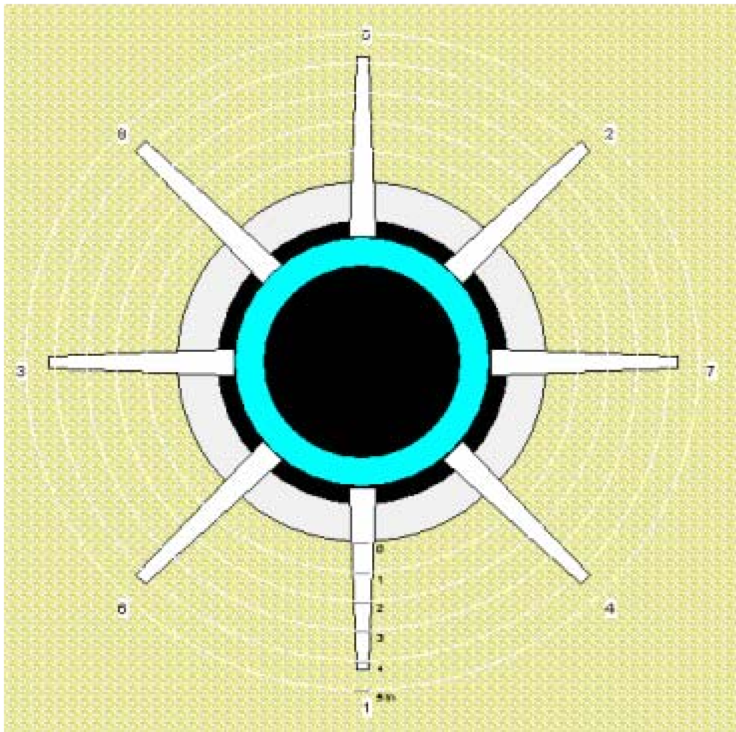

Figure 5b. Phase diagram, 12 spf.

Perforation Orientation

This is particularly relevant to horizontal or extended reach wells where the overburden stress is commonly the maximum principal stress. In cemented rocks, under these conditions, perforation failure can be deferred (relative to depletion) by using low-high side perforations (vertical perforations). This is a good strategy provided that the final expected depletion is insufficient to disaggregate the rock and the likelihood of substantially changing water cut is small.

If the rock becomes disaggregated, the vertical high side perforations become quite vulnerable to sanding due to gravitational effects coupled with seepage. Sanding could worsen with water. Under these conditions, it may be preferable to use lateral (horizontal) and only low side perforations (skip the high side). This would result in quicker disaggregation of the rock but it would be less susceptible to sanding under moderate levels of drawdown (say less than 700 psi with no water - in a typical well at about 8,000 ft TVD or deeper). Arching and gradual closing of the perforations would help to avert sanding and make it more manageable.

The aforementioned are not generic recommendations, rather a consideration in light of the fact that perforation failure is not equivalent to sand production.

Influence of Particle Shape, Size and Distribution

There are two major influences. These are:

Mechanical Strength

- Particles that are angular or sub-angular develop a higher friction angle and dilatancy characteristics (due to higher grain-to-grain interlocking potential); both of these factors act to increase strength in unconsolidated sand.
- Larger particles (e.g., >300 μm), particularly if they are angular have a much higher bearing capacity than fine particles
- Larger particles are less mobile and can be more stable under high seepage conditions, particularly if the associated flow paths are larger and the formation Reynolds' number is consequently smaller.

Arching Potential

- While larger and more angular particles generally have a greater interparticle arching potential, the relative size of the perforation opening (or slot width in a slotted liner, or the nominal mesh size in a screen) to the average particle size (D_{50}) has a large influence on the stability of the arch.

Influence of Depth and Pressure

This topic pertains to the effective stress state and directly affects strength or resistance to failure. The fundamentals are not repeated but a short practical discussion on the likely behavior may be useful.

- In unconsolidated, normally pressured formations at TVDs less than 1,300 feet, continuous sanding is expected at any drawdown (even as low as 10 psi). Such formations cannot be managed without robust sand control (gravel pack, fracpack or expandable screen).
- In reservoirs at depths between 2,000 and 6,000 ft, some degree of real cementation must be available for managing sand. The deeper the reservoir within this range and the greater the particle size, the better the chances of achieving sand stability. However, the maximum applied drawdown should be limited to 500 psi and much less if water is encountered.
- Reservoirs in the 6,000 to 10,000 ft range are generally manageable (sanding can be stabilized) unless the following combination exists:

  high drawdown expectation
  plus
  very weak sand (almost unconsolidated)
  plus
  fine particle size (D_{50} < 100 μm).

- At 10,000 ft or deeper, conditions for sand management can become more favorable even in totally unconsolidated sands. However, there are some constraints on drawdown. These depend on the depletion, the water saturation (S_w), particle size and shape, etc. In vertical wells with no water cut, it is quite safe to expect successful controlled sanding for drawdowns below 600 psi. With cementation and other favorable factors, the safe drawdown level can be elevated.

Influence of "Bean-up", Shut-down, Permeability and Fluid Type

The aspects of the fluid that are of interest include:

- Mobility (permeability/viscosity) affects the magnitude and duration of pressure gradient for a given change in pressure,
- Flux (fluid flow velocity), and
- Capillary cohesion.

One effective means of regulating cavity creation and stability is the bean-up process. (Bean-up is defined as the ramp up of production over time.) To maximize sanding (cavity creation), apply the largest drawdown steps over the shortest time period. Conversely, to mitigate sanding (stabilizing a cavity), use small drawdown steps, where each step is applied after pore pressure change from the previous step has almost reached equilibrium near the well. The minimum recommended region around the well where equilibration should exist before increasing the choke size is four times the size of the plastic sheared zone. The plastic radius varies with the strength of the rock, the size of the cavitated zone (the zone participating in sanding), and the pressure state. The plastic radius is typically 10 ft or less but can become as large as 30 ft in a severely damaged well (one subjected to many cycles of rapid clean-up and shut downs).

For illustrative purposes, consider a vertical well in a gas reservoir with a permeability of ~300 md. Pore pressure equilibrium can be approximately reached in possibly 20 minutes to an hour, depending on the phases and the viscosity. For a horizontal well, equilibrium may take longer to establish. It is not necessary to wait to reach full pressure equilibrium; 75% or so should be adequate. Waiting any longer than is necessary for pressure equilibrium will not change the effective stress state and this is the main issue.

In general, conventional procedures for cleaning-up a new well appear to be done over a much longer time than is necessary (in terms of the overall duration) but are not necessarily conservative since the pressure step magnitudes are often larger than would be safe for minimizing the potential for creating tensile failure or fines generation.

Each pressure step magnitude may not necessarily have an appreciable effect. The cumulative effect will gradually destroy light cementation and damage the sand mass fabric. Figure 6 shows conventional cleaning (for a new well) and an alternate choke schedule that is based on sand failure and transport.

To demonstrate the impact of rapidly bean up, finite element analyses were performed for two situations:

1. Very rapid bean-up - lasting 30 seconds, and
2. Optimized bean-up comprised of well-selected pressure steps and time intervals.

The former is purely hypothetical and is used to exaggerate the effect - in practice the clean-up process is never done instantaneously. Computational results for these cases are shown in Figure 7. Regardless of the clean-up operation, there is an upper limit to the drawdown. If this is exceeded, sanding will occur. For the case shown in Figure 7, that critical drawdown is about 500 psi.

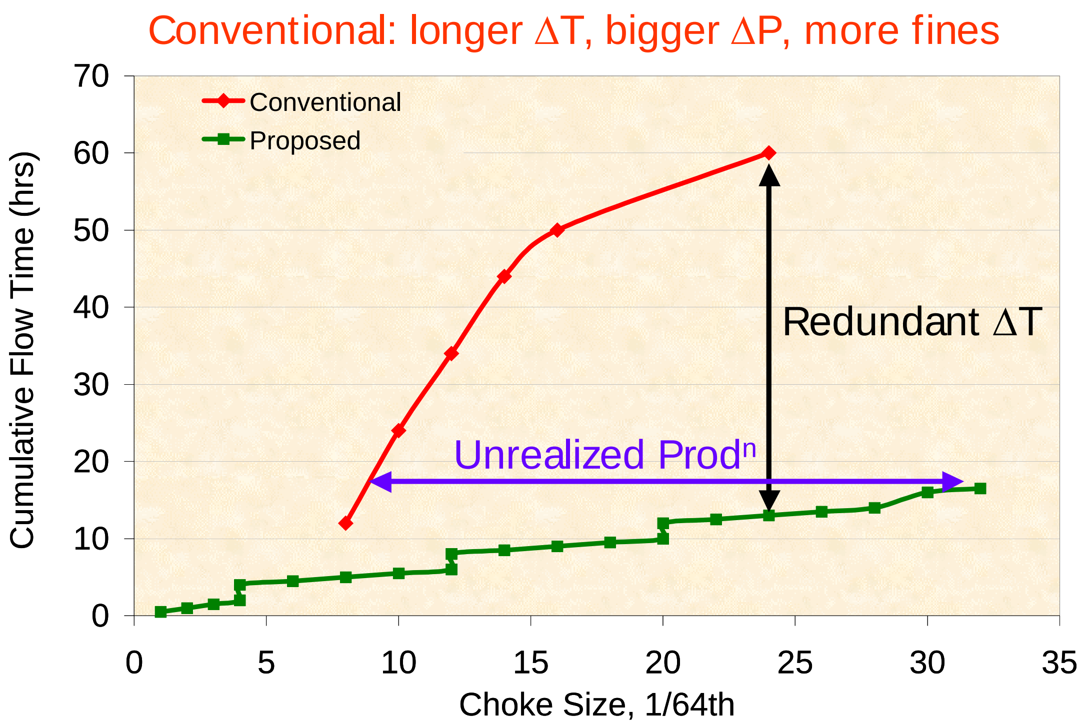

Figure 6. Conventional ineffective beanup profile (production ramp up) – step and wait, and a clean-up program that will prevent substantial post-cavity sand production.

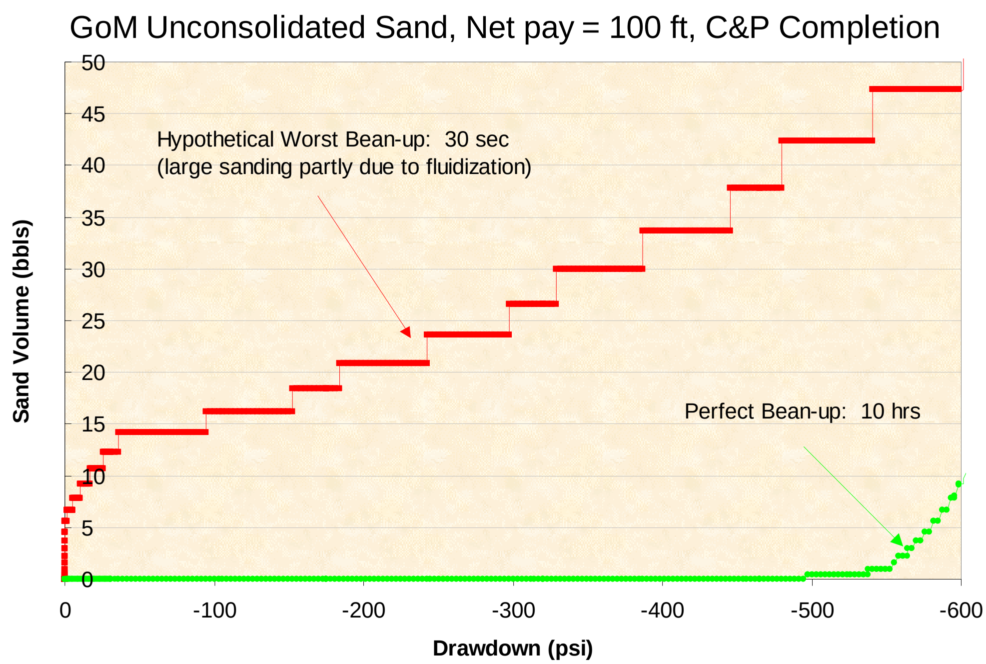

Figure 7. Influence of the clean-up rate on sand production.

Since optimized clean-up varies with the cementation and particle size distribution, as well as the type of sand control, a generic guideline cannot be given. In general, the larger the pressure step, the greater the potential for solids movement and fines generation. This may cause sanding or increase skin. The best practice is:

- Keep ΔP's small with short Δt's,
- Minimize the frequency of shut-downs, and,
- Avoid rapid shutdowns.

Figure 8 is an example of a bean-up (ramp-up of production) schedule that was successfully used in a weakly cemented formation at a depth of about 9,000 ft.

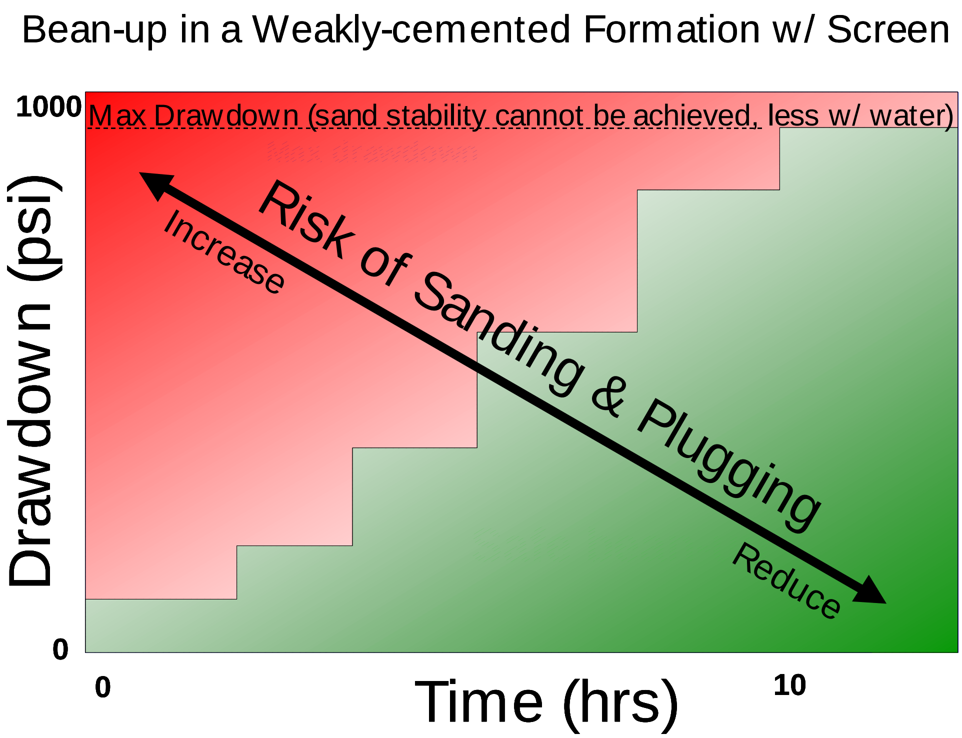

Figure 8. Example of an optimized clean-up in a weakly cemented sand.

Frequency of shutdowns and the rate at which the process is completed affect the integrity of the cementation. While an individual episode is unlikely to result in a noticeable event (for a cemented formation) the effects are cumulative, resulting in eventual "breakdown" of the sand matrix with fines generation and solids production.

Figure 9 schematically shows the elastic rebound following shutdown. It is considered harmful to weakly cemented bonds. The magnitude of the rebound is a function of the elastic modulus of the formation, the string dynamics, the rate of shutdown and the magnitude of the drawdown. Sanding is most likely to occur during the initial stages of clean-up after a rapid shutdown particularly if the clean-up rate is aggressive. For cavity creation, surging is an effective means of duplicating the physics described here. A related consideration will be avoiding water hammers.

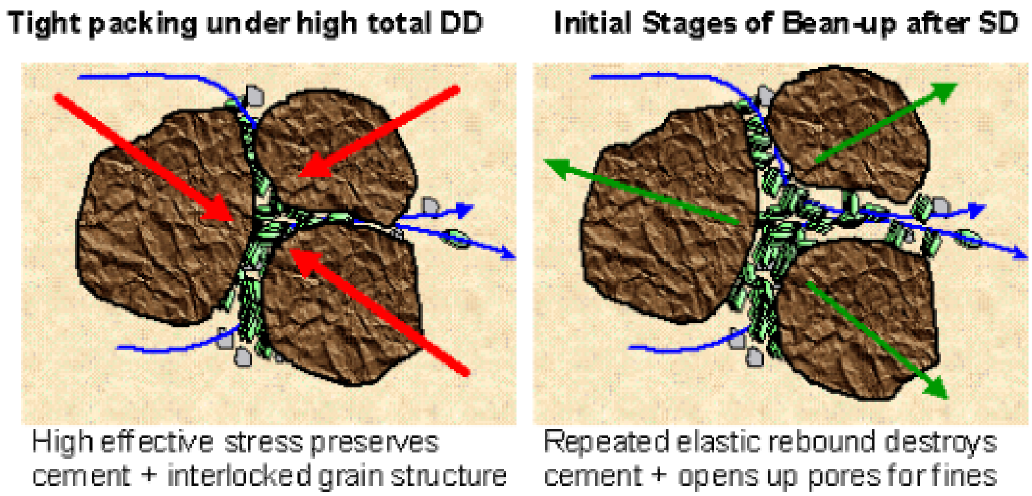

Figure 9. Illustration of the effects of drawdown and shutdown on the sand matrix. An engineer should consider the potentially devastating effects of water hammer caused by rapid ESD.

Factors Affecting Decisions to Prevent or Induce Sanding

Is the well new or is an existing well with some history of sanding

In general, in a well that has not sanded yet, it is best to adopt clean-up procedures that increase production but with no sanding. In wells that have experienced sanding and are currently choked back to manage the sand, several items need to be examined. For example:

- **What is the principal factor responsible for sanding?** If it is controllable, for instance, caused by poor clean-up and shutdown practices, it is best to correct that. If the primary reason is excessively high drawdown, then choking back is the best course of action. Depending on the completion and formation properties, it may be possible to increase drawdown later (e.g., if the perforations pack and stabilize).
- **What flow rate is required to transport the sand up hole?** If the drawdown needed to get an adequate rate to lift sand is predicted to be appreciably higher than the available sand resistance, managed sanding is not likely to be successful. Cavity completions may still be possible if the sand can be removed before the well is on line and if the sand will not accumulate.

For instance, if the sand is unconsolidated and water wet, there is an upper limit to an allowable drawdown no matter how the clean-up is performed. For a hypothetical case, suppose that this limit was only 200 psi. Should the requirement for lifting the sand be a rate caused by a drawdown of 600 psi, it would not be possible to reach a stable condition.

- **If sanding is localized, sand production is likely to be transient.** Localized implies that a relatively small annulus around the wellbore has lost integrity. This material can be removed, using a properly designed clean-up operation, resulting in a stable sand free state. In many cases it is possible to even increase the drawdown beyond previous operating levels.

In wells that have been shut-in due to excessive sanding, the same principles apply. There are, however, some additional caveats.

- **Was the sudden sanding due to encountering water?** If so, can the water be shut-off? If not, definite consideration should be given to operating the well at a significantly reduced drawdown.
- **Was sanding due to a gradual increase in drawdown?** This often happens, particularly if the operator is solely concerned with maintaining rate. By maintaining a constant rate, there may be a false sense of comfort that formation sand is not becoming increasing unstable. This is not so, particularly in situations where the skin has increased or the reservoir has depleted appreciably beyond initial conditions. If higher drawdown is indeed the culprit, it is possible to re-establish a sand free state by returning to a smaller drawdown.
- **Was sanding due to rapid increase in drawdown (aggressive clean-up)?** If so, it is possible to re-establish sand free state using better production practices.
- In general, for a shut-in well, attempts to **remove sand** naturally (using higher drawdown or rate) may not be the most reasonable option unless the specific cause(s) of sanding can be remedied. This is a serious issue in thick zones where a higher drawdown can create a fresh failure in another zone that was previously stable. It is likely preferable to use coiled tubing or other mechanical cleanout procedures.

What About Screens?

In stand-alone screen completions, it is best not to cavitate intentionally unless it can be assured that a uniform failure along the entire well length is likely. In vertical wells, with small pays and homogeneous unconsolidated sands this may be possible. Otherwise sand breakout will be patchy (confined to the weakest layers) and the shock applied to create that sanding is likely to stir up fines and lead to premature plugging. The uneven loading is always a concern.

Conditions Favoring Successful Cavity Creation?

Cavitation can be considered for conditioning a well (removing skin), creating higher porosity near the wellbore region or creating a stable cavity. The ideal condition is to have a formation that is weak enough to be broken loose with drawdown while having sufficient strength to stabilize. A weakly cemented formation with a UCS in the range of 20 to 50 psi is likely to work in a typical with depth and pressure setting. For a well that is depleted, a proportionally higher UCS would be required. Thus, whereas for a new well (or in short-to medium term) small UCS is preferable, as the reservoir matures and conditions change, different and more appropriate strategies must be considered. Some of the scenarios include:

- In a vertical well, with a relatively thin pay (e.g., <30 ft) overlain by a competent cap rock, it is possible to form a stable cavity under the cap rock since depletion and other types of weakening should not impact it.
- To manage the volume of sand, it is best to consider thinner layers.
- In most cases, cavities resulting from sand production cannot remain stable forever due to exposure of the sand face to “wear and tear” resulting from shutdowns and start-ups, fluctuations in drawdown and depletion (exceptions include cavities under cap rock discussed above). It may be necessary to repeat cavity creation periodically.

Key Points

- To develop and sustain a stable cavity, it is essential for the formation to have some degree of cementation. This allows for the near wellbore sand to be produced while maintaining a stable sand face.
- A controlled clean-up strategy is crucial for assuring that a stable sand face can be developed.
- In totally uncemented sand that has experienced sanding and is choked back, an effective measure is to expedite the sanding by applying a higher drawdown (in a controlled fashion) so that a sand free state can be resumed once the drawdown is reduced.
- For any sand, there is an upper limit to sand free drawdown; exceeding that will result in continuous sanding.
- In unconsolidated sands, perforation strategy plays a role in sand stability that is due to arching. Other factors include depth (effective stress), particle size distribution (coarser particles can provide improved intergranular strength).
- Sanding is generally triggered by concurrent mechanisms (e.g., loss of mechanical cementation, removal of capillary cohesion and rapid changes in pressure).

Understanding cavity growth and stabilization requires consideration of the combined effects of fluid flow, changing in-situ stresses, material failure and material deformation. This is best done by modeling. Some of the recommended considerations [“Best Practices”] that have been developed for modeling are summarized in the following section.

CHAPTER II….FIELD TEST OF CAVITY COMPLETION TECHNOLOGY (TASK 3)

South Pass

Two new wells were cavitated at South Pass, on the GOM shelf. These were:

- **SP67-A1-ST1:**
  - Well was shut-in due to a sand column or a bridge in the tubing
  - Desander equipment was moved in to try to cleanup the sand
  - Success! The well stabilized sand-free at ~500 BOPD.

- **SP60-G15 well:**
  - This well had been shut-in due to sand
  - Desander equipment was moved in to try to cleanup the sand
  - The sand did not clean up
  - Oil flow fell off too quickly: due to sand loading or ultra-small reservoir. One speculation is that insufficient sand was brought to the surface.
- **Mustang Island Well:**
  - This sand was somewhat stronger and this is a gas well.
  - 10 BBL of sand were produced, with water and it was possible to establish a sand-free rate of 4.5 MMscfD.
  - The incremental economics were estimated at ~+$400,000 per month.

A presentation of these well histories is available online from the Document Downloads page, under “New Case Studies.”

Field Demonstration Study – Mustang Island 787

Background

In this successful cavity completion in the GOM Shelf, the sand-free flow rate was increased from 1 to 4.5 MMscfD after ~10 bbl of sand were produced. The well was offshore GOM on the Shelf and before cavitating it was producing ~1 MMscfD. The well was choked back due to sand production. It would also load up due to water production at these low rates. Prior to the cavitation workover, a desander system was put in place, ahead of a dual choke, to reduce erosion. A strap-on acoustic sand detector was deployed to continuously monitor sanding. BS&W shakeouts were continuously taken every 30 minutes; the sampling frequency was increased to every 15 minutes after the choke was opened up, to provide “ground truth”, and to calibrate the sand detector.

Attributes:

The attributes of this well that seemed to delineate it as an effective cavity completion were:

- Good reservoir pressure

- Pay zones are small: 4' and 3' TVD (8' and 6' MD)
- Semi-caprock above top pay zone
- Sand has some strength: cavity may stabilize sooner rather than later
- Fresh pay zones-.no significant prior sand production

Other pertinent data are:

- Well inclination is 50° through the pay zone. This was a concern – there was some worry about sand settling. However, this seems to be a relatively uncommon GOM issue where fine sands are involved.
- Perforations were run on wireline, using the largest gun that could be used through the tubing. They were shot through tubing and casing at 6 spf, zero degree phasing.
- The estimated initial reservoir pressure was ~3370 psi.
- There is a semi-caprock above the top zone (the GR jumps by ~40 GAPI), but there is no obvious caprock above the bottom zone
- •There is rathole only in tubing: 74' of 2 7/8"
- •GWC is close to the two pay zones, may lie between them (this was always a concern in designing the cavity operations).
- •Porosity ~12-15%. Permeability ~100 md (guess) and S_w ~ 35%

Cavity Operations:

Over the first 4 days, the choke was opened up in steps, about every 6 hours. With each beanup, a sand burst (i.e., bottoms up) was recorded immediately, but sand production always declined and stabilized at low levels relatively rapidly.

The shakeouts never exceeded about 4% sand per unit water volume and this would gradually declined over time. After a few days, a choke was cut out, and it became clear that sand was not being captured by the desander system. The produced sand was overflowing into the main separator, where it collected (this had to be cleaned out).

The total operation took ~14 days, but the sand stopped coming after ~4 days. The best estimate of total sand recovered was ~10 bbl, and this agreed fairly well with modeling using ENHANS.

After ~4 days, the flow rate reached ~11 MMscfD, but the well was still producing trace sand. After cutting back to 4.5 MMscfD, the well was pretty much sand-free, and was operated at this level for ~6 months until the well watered out.

Bottom Line:

- The well was making 0.5-1.0 MMscfD before the cavity completion
- Well made ~5 MMscfD after cavity completion, with occasional trace sand that the platform could deal with
- Sand produced ~10 bbl, and sand stabilized (rough agreement with prediction)

- Incremental revenue was ~$12,800/day, cf. cost $5,700/day => $7,000/day profit during trial
- After cavity, profit was ~$40,000/month, or $4.8 million per year
- The well was flowed at a rate of 4.5 MMscfD for ~6 months before watering out

CHAPTER III….HYBRID CAVITY COMPLETIONS (TASK 1)

What is a Hybrid Cavity Completion?

Not all situations may be suitable for cavitation without supplementary sand control. This is presuming that it is possible to create a cavity in the first place. However, suppose that a cavity can be created, but the guarantees of long-term cavitation are not acceptable (loss of strength with future water cut) or there is zero sand tolerance (subsea completion). It would be desirable to take advantage of the benefits of producing sand for skin removal and ideally for sustaining production (the latter may not be possible). The solution may be what we are colloquially calling a hybrid completion. This would entail combining cavitation with other techniques to give a STABLE COMPLETION. The key is to add stability to a completion that might otherwise be unstable. All of us can think of examples of this. Certain types of exclusion/support are adaptable to this philosophy. Some examples are given below. The heritage (who proposed the method) is specified. That is not to say someone may not have proposed the concept earlier. The goal is simply to encourage innovation.

Cavity Pack:

This is one that we are familiar with. It involves creating a cavity and subsequently stabilizing that cavity with gravel and screens.

Heritage:

Many people have actually proposed this technique. To the author's knowledge, M.B. Dusseault, A.S. Abou-Sayed and Baker Oil Tools have suggested it …. at a minimum.

Protocols:

Conceptually, you would:

- Produce sand to create a cavity.
- Circulate and pack the cavity with gravel.
- Adaptations include pre-packing circulation or surging stages prior to gravel packing operations to remove drilling and completion fluid damage.
- Coiled tubing might be used to circulate out sand.

Issues:

Some of the issues that one would need to address and risk would include:

- You will have the same placement and carrier fluid damage issues as with a conventional gravel pack.
- Placement may be more difficult because of lower velocities in a cavitated zone.
- How much gravel to run will be more of an issue than in standard gravel packing operations. It may be difficult to know how big the cavity is.

- Because of the expanded hole size, complete placement may be more difficult.
- When do you run the gravel pack assembly and how do you prevent erosion and damage while you are cavitating?

Advantages:

It is easy to criticize methods like this. Consider however some significant opportunities:

- Potential improvements in stability and sand exclusion
- Removal of drilling damage before pack emplacement

Suicide Pack:

Heritage:

No one is willing to admit to it. The name comes from suicide or hesitation squeezing in cementing – where timing is everything.

Protocols:

- Produce sand up the tubing (cavitate).
- Coiled tubing or a parasite string (maybe even disposable) might be needed.
- Concurrently pump gravel down the backside.

Issues:

- Pipe sticking.
- Tool design (e.g., crossover or similar for when the cavity is packed).

Advantages:

- Potential improvements in stability and sand exclusion
- Removal of drilling damage before pack emplacement
- Reduced carrier fluid damage?

Perf Pack:

Heritage:

Marathon has a StimGun™ derivative called Pow*rPerf™ that uses perforation, followed by propellant placement of 20/40 bauxite.

Protocols:

One way or another, you are trying to do individual fracpacks on your perforations. You might do this with propellant or with high-pressure gas behind a diaphragm or valve or disc. Conceptually:

- Establish underbalance
- Charges are fired.
- Propellant drives 20/40 bauxite into the perforations, fractures are created. High-pressure nitrogen is an alternative.

Issues:

- Can adequately sized fractures be created to stabilize the perforations?
- How are the perforations adequately surged?
- Sticking the tool is a distinct possibility.
- Supplementary to this and some of the methods described could be weak resin consolidation – the bauxite could be resin coated to avoid a separate treatment. Of course, the issue of conductivity damage due to resin will need to be addressed.

Advantages:

- Despite initially filing this in the “crackpot” category, consider the potential merits if surging and stabilizing can be adequately carried out concurrently.
- Maybe this is a methodology for borderline lithologies – weak but not too unconsolidated. The perforations would nominally be stable until adequate depletion occurred.
- Is the cavity component really necessary? Maybe yes. Maybe no. If the permeability is high .... ???

Pre Frac and Pack:

Heritage:

Ian Palmer argues that this would increase entry potential for those perforations that did not take substantial sand during the frac and pack.

Protocols:

- Surge perforations before a frac pack to encourage production from off-fracture directions.

Issues:

- Sand removal.
- Uncertainties on the impact on subsequent fracture initiation and packing.
- After the frac pack, will these perforations contribute; will they have been damaged; will they produce back frac sand packed into them?

Advantages:

- Potential enhancement of stability
- Potential supplementary production

Cavitate and Stabilize with Expandables

Heritage:

Numerous. Various organizations are aggressively promoting expandable products. Within limits, this might be a very reasonable compromise technology.

Protocols:

- Cavitate.
- Run the mandrel or pressurize to push the expandable product against the cavity wall.
- Use screens or solid expandable tubing and perforate.

Issues:

- Sand removal.
- Uncertainties on the required degree of expansion.
- Oversized hole?

Advantages:

- Potential enhancement of stability.
- Damage removal.
- In addition, any inherent advantages from expandable products alone.

Horizontal Well Cavitation

Heritage:

C.T. Montgomery, at June 2003 GPRI Cavity Completions Meeting discussed this option.

Protocols:

- Cavitate horizontals, or,
- Allow/promote sand production by installing liners with large diameter slots or pre-perforated liners ….
- Handle sand at the surface.

Issues:

- Sand removal.
- Zonal isolation
- Cavity geometry that results
- Uncertainties as to pipe stress that would result and how the overburden load may act on the liner with time.

Advantages:

- Potential enhancement of stability

- Damage removal
- Supplementary, sustained production

Pre-Completion Cavitation

Heritage:

Hans Vaziri, in a personal communication, discussed this option.

Protocols:

- Tell the drilling department you want them to swab hard to remove damage on their final trip out of the hole.
- Be prepared to be insulted.
- The concept is to remove drilling damage when you are drilling. Swabbing may not be the only method. Aggressive underbalance may accomplish the same thing.

Issues:

- Stuck pipe
- Cementing damage may follow
- Hole fillup on last swab run

Advantages:

- Probably cheaper and more efficient than cavitating as part of some completion operations.
- Sand handling is not as much of an issue since cuttings will be being accommodated.
- You will know if catastrophic sand could be an issue before the completion is installed.

The Next Step:

As acknowledged in the text, some of these concepts will be categorized as being in the crackpot or you crazy category. Be that as it may, the principles are philosophical as well as technical. The status quo brings us comfort. It (gravel packing) can also bring us huge capital and other upfront expenditures and the thanks we get is a skin of 50. The intent is to only suggest that new supplementary techniques might be considered to reduce expenditure and completion skin, in those situations where cavities will not be patently stable or where there is no tolerance whatsoever for sand production.

CHAPTER IV....BEST PRACTICES (TASK 1)

Introduction:

An effective numerical, analytical or visual model/representation of the cavity completion operation needs to incorporate certain geomechanical features. We commonly use the word geomechanical without specifying what it means. It represents the relationship between stresses, deformations, fluid pressure and flow and changes in these caused by natural or engineered changes in the reservoir, the wellbore or at the surface. Geomechanical modelling can represent the relevant cavity mechanics as we know or approximate them now, and can forecast or approximate cavity geometry and the consequences of cavity creation. Basic modeling concepts are discussed; with particular emphasis on one model, ENHANS. ENHANS is used strictly as a platform for illustration of principles. Other models function as well.

Several key modeling results include:

Universal curve: Developments of a “universal” curve that statistically encompasses modeling and fieldwork to indicate anticipated skin for a specific volume of sand removed.

Economics modeling: By necessity, all completion operations require economic justification. Economic specifics will vary from company to company. One cavity-specific model has been developed and is available for download.

Caprock modeling: As we all know, caprock integrity is a concern in cavity operations, both for the cavity itself and for the superjacent completion.

Cavitation Mechanics:

To remind us of the physics of a cavity completion: if you take sand out of a well, you increase the effective wellbore radius, and this lowers the skin factor, and increases the sand-free flow rate (i.e., a larger cavity means a lower gas velocity at the face of the cavity, and less ability to pick up and carry sand into the wellbore). The increase can analytically be shown to be modest strictly on the basis of an equivalently larger wellbore. An even greater contribution to skin reduction can be attributed to physical removal of near wellbore damage of various types (from drilling, completion, stimulation or previous production).

To give a historical perspective, and sort out some possible confusion:

1. Sand management[7] involves back-producing very small amounts of sand

[7] Sanfilippo, F., Brignoli, M., Giacca, D, Santarelli,, F.J.: Sand Production: From Prediction to Management SPE 38185, SPE European Formation Damage Conference, The Hague, The Netherlands, 2-3 June, 1997.

(kilograms, for example),

2. Cavity-like completions encompass sand volumes that are modestly larger - generally greater than 10 bbl, and up to 100 bbl and more. The larger sand volume is the main reason they are called "cavity-like completions". The protocols include pre-production sanding (as at Mustang Island cavity) or continuous sanding during production (as in the Forties field). The recent Mustang Island cavity completion produced 10 bbl of sand (possibly a little more).

3. Because of the larger sand volumes, the cavity completion “procedure” IS inherently more risky since the well may sand up the casing may buckle, surface equipment can be damaged. No one denies the risks. The risks are difficult to quantify. The benefits appear to justify to risks in some reservoir and operational circumstances.

4. Regardless, when sand is produced, skin factors go down, and productivity goes up, as does revenue. This is not always acknowledged. The main operational emphasis has often been on avoiding the costs of sand production – erosion for example. An economic module has been developed to reflect some of the costs, the expenses and the net returns.

5. Cavity geometries can be round or cavities be elongated vertically or laterally. Actual cavities may not even exist – just cavity geometries filled with sloughed material, possibly with higher than native permeabilities.

6. The last item remains contentious. Some feel that if they have been able to increase the sand-free rate it is because they have created a cavity that is actually a void. They reasonably argue that if there were no void and sand was right next to the wellbore (it would have to be disaggregated), it should be transported by the increasing flow rate, and it should appear at the surface (i.e., the flow stream won’t be sand free). Others argue that some arching is possible.

General Cavity Modeling Considerations

What do you want to accomplish? There are several interrelated possibilities.

- For a given sand volume that is removed from the completed zone, predict the cavity size and shape.
- For a given sand volume that is removed from the completed zone, predict the increase in the PI (or the reduction in the skin factor).
- Predict the sand volume for the actual situation (drawdown increase, formation strength, pressure, permeability, etc), and simultaneously predict the cavity size and shape.

Volumetric Considerations:

At the simplest level, one can start with a measured sand volume at the surface and calculate what this volume would have been in the formation (using the porosity difference between surface and formation). Then, if one assumes a generic geometry for the void left by the produced sand, it is reasonable to back-calculate characteristic dimensions (e.g., radius of an axisymmetric cylinder, the wellbore being the access of symmetry). Various void geometries have been looked at in the past, depending on the lithologic and stress specifics. These include:

- A cylinder extending over the height of the weak zone.
- A spherical cavity, centered on the perforated zone, possibly bounded by adjacent lithologies.
- A conical cavity, wider at the top. Sonar caliper work has definitively shown that this shape can exist for some cavitated coals.
- A flat interfacial crack could exist, just under a caprock (an extreme form of a conical cavity). Laboratory centrifuge work and field evidence in Canada and elsewhere may support this.

This is just a material balance calculation, and neglects any change in formation porosity behind the cavity. If this porosity increases, due to shear failure for example, this would result in some formation displacement (strain) towards the wellbore, which might reduce the cavity volume. In sands with significant strength and/or where stresses are low, post-sanding interaction between the cavity zone and the adjacent material would be restricted. In ductile materials like chalk, and for unconsolidated sands with certain uniformity characteristics this could be large, and could even fill up the cavity.

To recap, the first considerations would be simple mass balance evaluations. These are contingent on informed assumption or simulation of stresses and seepage forces that specifically exist. Assume or simulate a cavity shape. Estimate or calculate the volume. Estimate or calculate the long-term integrity of a void, if any.

The Skin:

After estimating or calculating cavity dimensions, sophisticated models will correlate the material’s condition spatially (stress, strain, post-yield …) with a relative permeability. Production can then be estimated analytically, with commercial PTA packages or with sophisticated numerical models.

In the simplest terms, for back-of-the-envelope calculations, you can use a Hawkins[8]-type consideration of skin and equivalent radius. For example, for a cylindrical cavity (assumed to be empty) mass balance has yielded an effective wellbore radius, r_w’ equal to the cavity radius. Simplistically, for steady state flow, with an enlarged wellbore:

$$s = -\ln\left(\frac{r'_w}{r_w}\right) = \ln\left(\frac{r_w}{r'_w}\right) \qquad (1)$$

All other factors being equal, the folds of increase, FOI, can be estimated as:

[8] Hawkins, 1956

$$s = \frac{\ln(r_e/r_w)}{\ln(r_e/r'_w)} \qquad (2)$$

where:

r_w ....drilled wellbore radius,
r_e .... drainage radius,
r'_w ....equivalent cavity radius, and,
FOI .... folds of increase.

The folds-of-increase corresponds to steady-state radial flow, and gives the increase in well productivity due to the cavity. If the cylindrical cavity does not extend over the full perforated height, partial completion skin will make the overall skin less negative, and FOI will be reduced. If geometries other than cylindrical are used, equivalent radius can be estimated in alternative fashions.

Figure 19 is included to remind you that just increasing the size of the wellbore will do you little good. This is a simple example, for an 8-inch drilled hole and a 2000 ft drainage radius. The large radii ratios are unrealistic, approaching the dimensions of the drainage radius. The message is three-fold --- cavitation can remove mechanical skin, cavitation can alter the permeability outside of a physical void and cavitation-prediction can likely be improved by using more sophisticated simulations. The only reason for qualifying the previous sentence with likely would be the lack of input data.

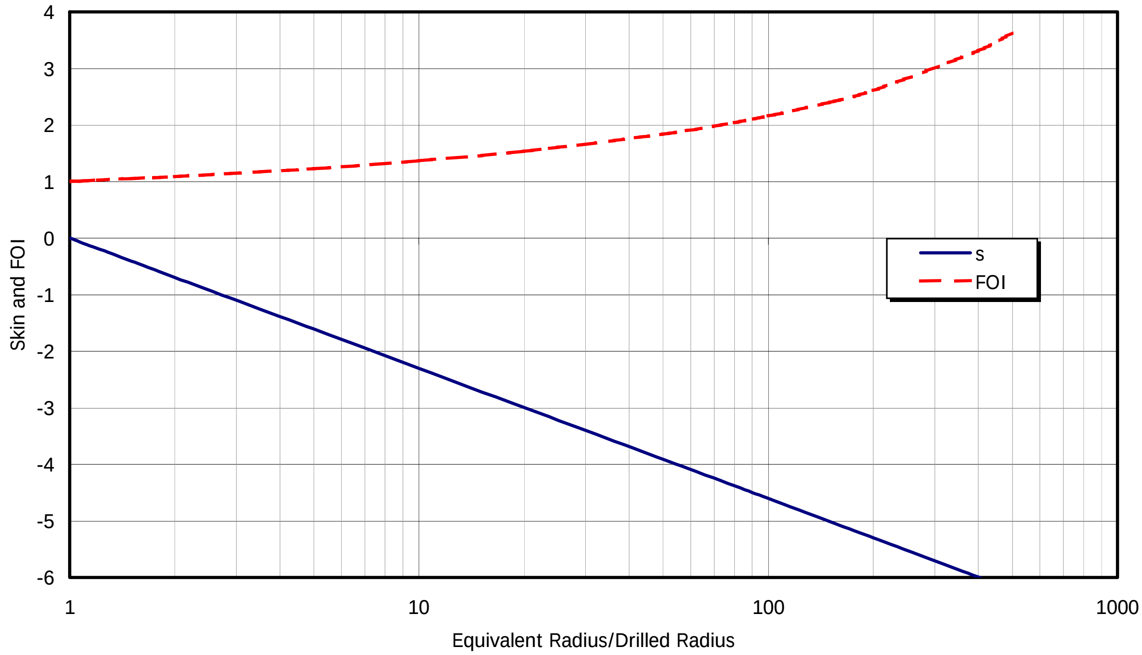

Figure 19. Analytical steady state calculations of skin and folds of increase. This is for an arbitrary 8" diameter well with a drainage radius of 2000 feet. You have to have a huge cavity before radius alone is a substantial contributor.

Complex Cavity Models

Most organizations have complex and sophisticated models that can predict sand volumes from fundamental parameters, such as drawdown, depletion, strength, pressure, permeability, etc. Ideally, the most sophisticated model will:

- Include both shear and tensile failure,
- Be fully coupled (for example, not only does the pressure distribution depend on the permeability, but the permeability depends on pressure via effective stress),
- Incorporate multi-phase, transient flow,
- Use sophisticated constitutive relationships and modified failure criteria (for example, a bilinear failure surface can be used to approximate low-stress dilatant that is often characteristic of very weak formations (ones that can be cavitated).
- Ideally, fully three-dimensional representations can account for deviated wellbores and complicated lithologic boundaries. Practical computing limitations may dictate using a model that assumes axial symmetry around the wellbore (axisymmetric) or is two-dimensional (plane strain).
- Conceptually, the cavity can be defined by where tensile failure (or extensile failure) has occurred, i.e., the sand is free to go. Beyond the cavity may be a shear failure zone (plastic zone), where permeability is enhanced by dilatancy and stress-dependent permeability.

The following section demonstrates results of ENHANS cavity modeling. The model is proprietary, and therefore not available to the consortium. However, a parametric study has been done, incorporating a large number of diverse cases. These simulations have been used to develop general relationships between skin and produced sand volume, which can be used by the consortium to estimate increase in PI as a function of sand volume (Universal Curve). Also, most organizations have proprietary software of their own. For example, Serguei Jourine and Jerome Schubert, TAMU, presented their code development (June 19, 2003). They described work at Texas A&M funded by MMS to evaluate the potential for bridging and underground blowout. Cavities are modeled and concepts for sand stabilization are summarized. This presentation is available online from the Document Downloads page, under “Cavity Model.”

Modeling of Cavities with ENHANS

The numerical model used, ENHANS,[9,10] differs from many conventional models since it can predict the episodic nature of sanding, compute the resulting volume of produced sand and assess the concomitant impact on productivity (or change of skin). The model uses fully coupled flow and stress formulations and as such, it is

[9] Vaziri, H.: “Analytical and Numerical Procedures for Analysis of Flow-Induced Cavitation in Porous Media.,”Int. J. of Computers & Structures, 54(2): 223-238, 1995.
[10] Vaziri, H., Wang, X. and Palmer, I.: “Wellbore Completion Technique And Geotechnical Parameters Influencing Gas Production,” The Canadian Geotechnical Journal, 34: 87-101, 1997.

capable of time-dependent simulation of boundary conditions generally employed for openhole cavity completion. The computational results include geometry of the “sand-depleted zone,” volume of the produced solids, flow rate, skin, and stresses as well as pressure distribution and displacements (or strains).

Essentials of a Numerical Model and Methodology

The numerical model used for forecasting during this project is called ENHANS. It predicts the episodic nature of sanding and computes the resulting volume of produced sand and its concomitant impact on productivity (or change of skin). The computational results of the model include geometry of sand depleted zone, volume of the produced solids, flow rate, skin factor, stress and pore pressure distribution and displacements (or strains).

The key to capturing the reservoir response throughout its life is to allow for the transformation of the material as it goes through various states. In terms of failure state, Figure 20 depicts various criteria that govern the response of a formation as it changes from an in-situ intact state (rock-like) to a totally disaggregated state with almost no cohesion (soil-like) and finally with even no adhesion when subjected to water influx. The bulk reservoir material does not jump from its intact state to a totally de-cemented state in one step. In modeling, it is important to allow for the transitional states. In fact, this is a requirement for predicting and quantifying transient sanding.

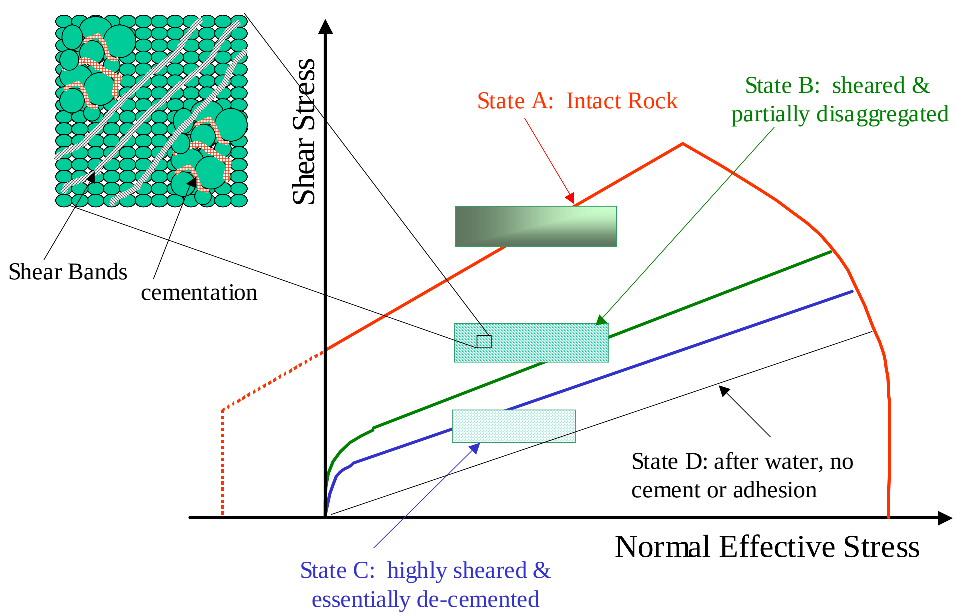

Figure 20. Gradual transformation of the reservoir material from intact to broken state.

In Figure 11, State A represents the intact condition in-situ. It is generally this state for which properties are measured (in the laboratory using thick walled cylinders, unconfined compression or triaxial testing) or inferred from logs. State B represents the strength behavior of the material after it has been sheared but not totally disaggregated. As shearing continues, more shear bands are generated. Cementation is generally destroyed around the shear bands. Note that State B is not unique. State B represents any condition between the intact (upper bound) and a totally “de-cemented” state (lower bound), State C. In State B, it is difficult to have smooth (continuous) sand production since the material may still be blocky and cannot be transported easily and readily the perforations.

State C represents the material state after it has been subjected to significant shearing and/or significant depletion has caused sufficient shear and compressive strains to destroy the cementation throughout. Following this, when the rock is broken down into its constituent grains, the sand can be produced if sufficient seepage forces or drag are available.

State D depicts State C after it has been subjected to sufficient water production to destroy its adhesion. In this state, sand has neither cementation nor adhesion to keep it together. Under these conditions, sand can be fluidized and produced with ease under moderate levels of seepage force. While capillary adhesion is rather small, it can provide considerable resistance against production.[11] Once it is taken out, the entire plastic zone, which late in the life of the reservoir becomes extensive, will be left with nothing to hold it in place. The profound influence of this adhesion force on sanding level is shown in Vaziri et al. (2002)[12].

The formulations and methodology employed allow for shear failure and tensile failure due to changes in stress, pressure and flow conditions. Corresponding changes to the permeability are also tracked; for instance, permeability increases in zones that dilate and become much higher in zones that have undergone sand production (loss of sand mass). This change in permeability is important for a number of reasons (e.g., computation of changes in skin with failure and sanding), however, the most important is its role in mitigating seepage-induced sand production where the increase in permeability in the failed zone reduces the pressure gradient and eventually leads to stability (hence a transient sanding event).

The strength parameters that ENHANS uses are shown in Figures 21 and 22 (before and after lost of capillary tension.

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[11] Skjaerstein, A., Tronvoll, J. Santarelli, FJ. And Joranson, H.: “Effect of Water Breakthrough on Sand Production: Experimental and Field Evidence,” SPE 38806, 1997 SPE ACTE, San Antonio, TX (October 5-8).

[12] Vaziri, H., Barree, R., Xiao, Y., Palmer, I. and Kutas, M.: “What is the Magic of Water in Producing Sand?,” 2002 SPE ACTE, SPE 77683, San Antonio, TX.

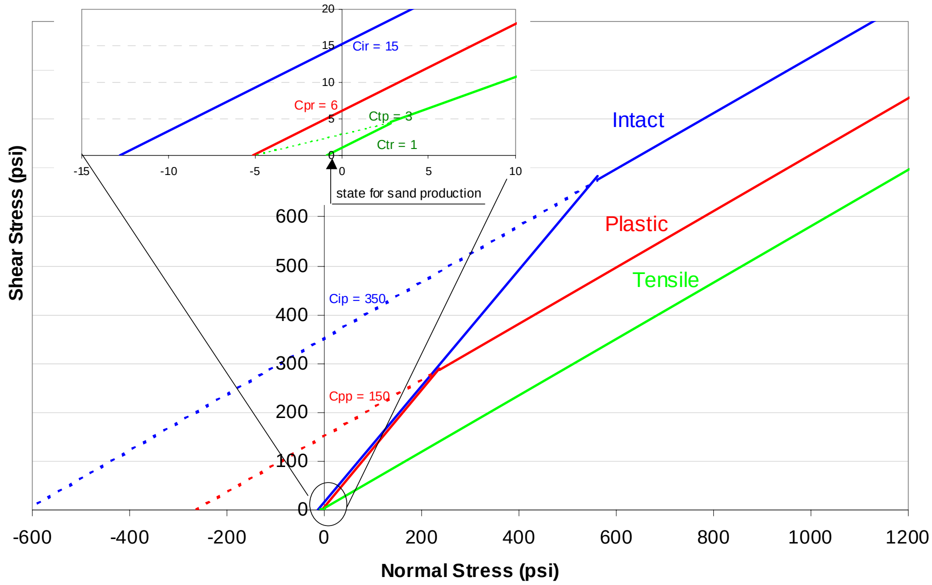

Figure 21. General strength parameters used to capture the reservoir response <u>before</u> water production (numbers shown are for illustration only).

Three sets of strength parameters are used to capture the response before water production. These parameters characterize the rock behavior under (1) an in-situ or intact condition, (2) within a shear or plastic failed state, and (3) under tensile conditions. If such parameters are not available or deemed too detailed, one can revert to using the basic set of initial (intact) values that can be inferred from logs or measured in the laboratory, assign very low values for the tensile state representing a disaggregated state and bypass all intermediate input requirements.

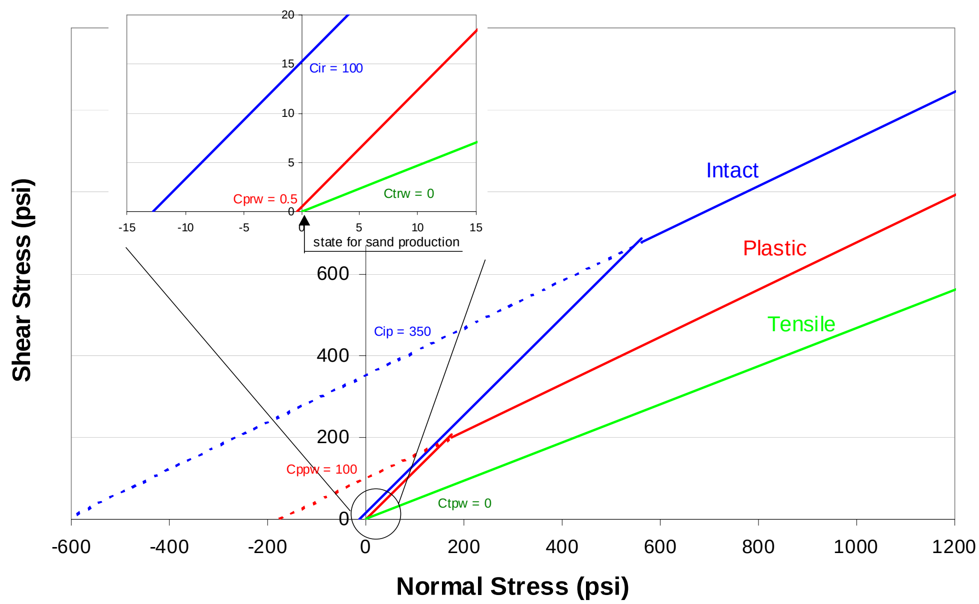

Figure 22. General strength parameters used to capture the reservoir response <u>after</u> water production (numbers shown are for illustration only).

There is a distinction between the plastic and tensile failure states. Plastic failure signifies development of shear-failed plane in the rock mass which is a necessary condition for sanding but not necessarily sufficient as the overall rock mass may still poses a great deal of strength (depending on the level of normal effective stress) and also the disaggregation of the rock mass may be rather localized (patchy) to render an easy and uninterrupted pathway for the sand production. Tensile failure reflects a condition that has been sufficient to breakdown the rock cementation in the region and in this state sand is capable of being produced if the flow rate is sufficient to overcome the adhesion (capillary tension) that holds the loosely disaggregated sand grains together.

The process that is typically followed numerically to compute failure and sanding is as follows. Drilling the well creates an annulus of shear-failed material around the well. The size of this annulus is inversely proportional to the intact strength of the formation (this annulus can be as little as few inches in radius to over a foot in weak formations). Right after drilling the wellface material is under a state of zero effective stress but generally no sanding is expected to occur if cementation and arching are sufficient to keep the material in place.

The potential for sanding occurs when flow provides the pressure gradient and seepage forces to overcome the available cementation and arching resistance. Material in a tensile state is basically in a disaggregated form and will be produced if the effective stress state becomes equal to – $c_{tr}\cot\phi$ (see the arrow in the inset in Figure 12), where ϕ is the angle of friction of the reservoir material (typically 30°). In a disaggregated state, C_{tr} is equal to the capillary tension (about 1 psi). Note that sanding is confined to the zone within which the effective stress reaches – $C_{tr}\cot\phi$. Once this sand is expelled, sanding will terminate. Thus any sanding created by excessive flow rate is transient. Transient does not imply that sanding necessarily will be over in an hour or a day - it takes time for the failed (disaggregated) sand to be expelled (e.g., the perforations provide a limited exit area). It is not unusual for a transient sand event to take several weeks to completely run its course and this can sometimes be confused with a continuous sanding (in such cases, ineffective countermeasures have often been adopted compromising productivity and adding unnecessary cost).

What happens after water production? Depending on the degree of water saturation (water cut, ratio of water production to oil), several hydromechanical effects can take place. For instance, water changes the multi-phase flow behavior via changes in the relative permeability. Water can also lead to strength weakening in materials whose constituents react adversely to water (e.g., shale, clay some chalks, some carbonate cement). While the aforementioned effects do have a legitimate influence, in many situations where there has been an almost instantaneous and strong sanding response with water, it is difficult to quantitatively link such observations to these mechanisms with conviction. This is particularly so late in the life of a reservoir where the reservoir material in the vicinity of the well has already been weakened due to shear failure and localized disaggregation.

It is advocated that lost capillary tension is the main culprit for sand production. Others have noted this mechanism. In Vaziri et al, 2002, its importance is quantified at least in one well-documented field case is shown where it is the principal mechanism. The effect of water is represented by modifying the strength parameters to account for the loss of capillary tension. Figure 13 shows the parameters that are employed after a sufficient level of water saturation has been reached to destroy adhesion.

In a typical analysis drilling is simulated first. Then a time-dependent pressure boundary at the wellface is applied. These processes may create a sheared failed zone and tensile failure. As these occur, the program makes the relevant adjustments to the material behavior (e.g., strength properties, permeability) and computes the sand volume (tensile failed volume), the extent of plastic or shear failure, the skin and a number of other parameters (deformation, stiffness properties, etc).

The program cannot determine the onset of water production. This is a user-determined stage in the analysis. Once water production is considered to have occurred, the program makes the relevant changes in the plastic and tensile failed strength parameters in accordance with the input properties. By far, the most dominant factor here (in terms of increasing the sand production volume) is the reduction in cohesion within the plastic zone followed by that in the tensile zone. The reason for this is that the shear-failed zone is generally rather extensive (typically several wellbore radii depending on the level of drawdown and sand strength). Therefore, water production can mobilize quite a large volume of previously disaggregated sand that had been only held together with capillary cohesion.

The skin factor is taken as:

$$S_t = \sum_{i=1}^{N} \left[\frac{k_u}{k_i} - 1 \right] \ln\left[\frac{r_i}{r_{i-1}} \right] \tag{3}$$

where k_u is the unaltered formation permeability, the interval between r_{N-1} and r_N represents the outermost zone with altered permeability, k_N, r_0 is the wellbore radius, and the interval between r_0 and r_1 is the cavitated zone where the permeability is infinite ($k_1 \approx 10^4$ k_u).

Skin Factor Decrease With Sand Volume Produced:

This is one of the more important products from exercising the numerical model. A full write-up is available on the website and will not be repeated here. ENHANS was used to run a large number of theoretical cases where sand is produced by increasing the drawdown. The skin factor was computed from variations in permeability around a well (as sand is produced, porosity increases, and so does permeability). The model and the cavity were axisymmetric [this means that the reservoir properties can vary vertically and radially away from the well but that there is no angular dependency – also, the cavity will always have a circular cross-section at any specific depth although the radius can vary with depth]. As more sand is produced, the skin factor decreases.

A simple parametric (regression) equation is then found which computes skin factor, as a function of the sand volume that has been produced, and agrees well with the numerical model results. The sand volume is actually normalized by dividing it by the volume of the perforated casing (or the original openhole well in the pay zone). With the cases run, the skin factor falls to about -3.2, when a single drawdown step is applied. If surging (i.e., pressure cycling) and water influx are included, more sand comes out, and skin factors fall to -3.5. It would seem that in the formations evaluated that this can be regarded as a lower limit to the skin factor. The results are consistent with data from the field, although there are more field data points at larger sand volumes that we have not been able to model. Still, this modeling study adds definition to well productivity increases that can be found by deliberately producing sand. There may be an upside to all this: we have assumed an axisymmetric cavity, but in the field there is evidence that cavities may be elongated, and this should make the skin factors more negative.

Conclusions

The final report concentrates on several recent tasks. These include:

6. A summary of some of the factors impacting successful cavitation and sand management.
7. An overview of cavity geomechanics modeling.
8. A key point overview of the Phase III field trials is provided. More information is available in the online presentations.
9. A discussion of some of the possible hybrid completion technologies that may include cavitation as a component.

An overview discussion of some of the concepts for cavity creation in other lithologies is provided.

Several key modeling results include:

Universal curve: Developments of a "universal" curve that statistically encompasses modeling and fieldwork to indicate anticipated skin for a specific volume of sand removed.

Economics modeling: By necessity, all completion operations require economic justification. Economic specifics will vary from company to company. One cavity-specific model has been developed and is available for download.

Caprock modeling: Caprock integrity is a concern in cavity operations, both for the cavity itself and for the superjacent completion.

A presentation outlining the key concepts that can be used for predicting sand volumes is available from the GPRI, as part of the CLC project, specifically under "Sand Volumes." One of the key messages was that it is necessary to understand that failed material must be moved to the hole by a flow mechanism (hydrodynamic drag, etc.). Field examples are provided demonstrating prediction of sanding volumes. This report extends and synthesizes these comments into some practical recommendations.