Designing and Obtaining Optimally Productive High-Rate Gas Wells From Horizontal Openhole Gravelpacked Completions: The Hibiscus Experience

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Abstract
This paper summarizes the systematic methodology & engineering process employed to identify and refine the highly effective fluid-train solutions used to drill, and install the highly productive, long horizontal gas well completions of the NCMA Hibiscus Project offshore Trinidad. It presents and discusses the unique fluids design, pre-project evaluation, and the integrated application efforts undertaken to: 1.) Minimize formation and completion damage; and 2.) Maximize gravelpack placement and filtercake removal efficiencies. The paper will identify important reservoir drilling and completion fluid service integration points (metrics), laboratory validation methods employed, and provide completion process details that lead to the successful high-rate gas well installations in an unconsolidated sandstone reservoir.

Introduction
Project Background:
The North Coast Marine Area (NCMA) lays North-northwest of Trinidad. (Figure 1) The original Hibiscus gas field development plan comprised a nine-well drilling campaign, utilizing a Minimum-Area Self-Elevating (MASE) rig aboard the Hibiscus platform. As a result of the high deliverability the first development phase was concluded after completing seven wells. Hibiscus was a “fast-track” gas development with the first completion to be installed less than 16 months after project sanction. First gas was required in July of 2002 at full contractual rates of 240 MMcfd/d. Initial well deliverability modeling predicted that a minimum of 4 horizontal wells would be required to meet this demand. The modeling suggested that the producing intervals in these wells would need to be 8.5” in diameter and between 1500 and 2000 ft in length to effectively exploit the reserves and meet the delivery requirements. The basis of design for the project imposed zero sand-production tolerance on the processing facilities. Although this permitted more economic design of the production facilities, it placed considerable emphasis on installing effective sand control.

Geological Description of the Reservoir:
Reservoir formations in the Hibiscus field of the NCMA consist primarily of unconsolidated sand with interstitial clays and interbedded shales. The lithology of these formations is that of sandy, mixed and muddy turbidites. Extensive core and formation analyses including CAT-scan, XRD, granulometry, Hg porosimetry, and SEM microstructure were performed to characterize the rock and understand the potential damage mechanisms that might impact the target sands. This work indicated that the average clay & shale content ranges from approximately 7 to 10% with distribution being primarily intergranular, with occasional shale streaks. Porosity in these sands ranges from 10 to 21% with permeability from 10md to 1.0 Darcy. The average permeability is approximately 125 md. The net to gross for the Hibiscus wells was estimated to range from 75 to 100%. Granulometry of the prospective producing sands indicated that the uniformity coefficient (d40/d90) varied from 2.2 to as high as 16.4 with d90 values as low as 5µ.

Specific topics discussed will include: the design and implementation of: the optimized Reservoir Drilling Fluid (RDF), RDF to Completion Fluid displacement, gravelpacking process, and the filtercake removal treatment. Finally, the paper will present case histories of the five completions installed in the Hibiscus reservoir and provide comparisons of: 1.) RDF drilling performance, 2.) gravelpacking efficiency, and 3.) well performance (productivity) of a stand-alone screen completion versus the gravel packed wellscreen completions that employed the unique RDF and filtercake cleanup treatments.
General Completion Design:
In order to achieve the required high-rate gas production plateau required, it was therefore crucial that the sand face completions were designed and installed in a manner that provided effective sand control and maximum productivity. Gravelpacking was selected as the primary sand control mechanism, and premium sintered laminate (115µ) wellscreens were selected to provide secondary control. As a result of the operators successful recent experience gravelpacking wells of this length, and because of the screen weight and screen base-pipe limitations that would be imposed by the use of shunted (and shrouded) screens, the operator selected high-rate water packing as the process to be employed in installing the lower completions. The unconsolidated nature of the rock, the variability in the uniformity coefficient, and the clay & fines content suggested that fine (40/60) gravelpack sand would be required for effective sand-control. The reservoir mineralogy, and in particular the shale and clay-content, suggested potentially adverse (damaging) fluid interactions might occur during drilling and completion operations.

Completion Process Considerations:
As a result of the (MASE) rig logistics and the extended reach drilling (ERD) design of the wells, the area available on the platform for intervention equipment was minimal. Therefore, the functional specifications for the completions called for an interventionless design and installation process. The operator recognized that a design and installation process, of this type, would result in fewer people on the rig and require a smaller number of discrete well operations. This could, in turn, reduce the risk of accidents as well as non-productive time, and result in a safer operation. However, ensuring that such a design would be successful meant that all the key processes and procedures (services) required to install optimally productive wells would need to be carefully integrated and effectively performed. An overall completion process that emphasized collaborative design, effectively integrated solutions, and careful solution validation would therefore stand the greatest chance of success.

Defining the Potential Problems
The key challenges to the project were: wellbore stability; the requirement for effective sand control; high productivity; logistics and minimal rig space. All of these challenges are interdependent and rely heavily on fluid selection and optimization, both for drilling and gravel pack operations. There were three primary areas of concern:

Reservoir Drilling Fluid
Drilling and stabilizing an extended length productive wellbore in the marginal to unconsolidated sands would require a non-invasive drilling fluid that would develop a thin effective filtercake. In addition, careful management of fluid filtration rate control, lubricity, formation overbalance and especially surge & swab effects would be necessary.¹

Gravelpack Installation
To protect the screen completion, from potential damage by formation solids at the high inflow rates envisioned, excellent gravelpack efficiency would also be required. In turn, this would require the combination of a stable resilient filtercake (to resist erosion and prevent premature losses during the high rate waterpacking process) and gravelpacking tools that would prevent or minimize the risk of swabbing or premature lift-off of the filtercake.

Filtercake Cleanup
Obtaining a highly productive sustainable completion, following the high rate waterpacking process, would require effective removal of the filtercake between the formation sands and the gravelpack. The MASE rig configuration meant that any filtercake removal treatments should be performed without the use of additional rig deployed equipment (coiled tubing, etc).

Key Drilling & Completion Concerns
Given the information developed above it was clear that formation/fluid, and fluid/fluid interactions would need to be minimized to effectively complete the sands in the Hibiscus field. Furthermore the openhole completion design (40/60 gravelpack with premium screen) and the selected installation process (waterpacking) meant that the installed completion would potentially be very sensitive to plugging by residual filtercake solids and mobilized formation fines. Therefore careful integration of fluids and process would be necessary to ensure that both formation and completion impairment was minimized.

Based upon the above, the following key drilling and completion concerns were identified:
- **Wellbore Enlargement and/or Collapse** as a result of the unconsolidated nature of the formations.
- **Time-related Wellbore Instability** resulting from potential reactivity of the overlying and interbedded shales and clays with the sequence of fluids used during the drilling and completion process.
- **Reservoir Impairment** caused by reservoir drilling fluid (solids) invasion, as a result of inadequate bridging and sealing of the formation. The critically important factors were; the reservoir permeability contrast, variation in the uniformity coefficient of the sands, and the drilling & completion overbalance.
- **Completion Fluid Invasion** (losses) to the reservoir as a result of filtercake lift-off, mechanical damage and/or wellbore collapse.
- **Reservoir Impairment** caused by swelling and/or disassociation of formation clays and fines as a result of drilling and/or completion fluid invasion.
- **Incomplete Annular Gravelpack** as a result of filtercake lift-off, erosion or wellbore collapse.
- **Completion Impairment** as a result of RDF (filtercake) or formation solids impairment of the gravel pack and/or screens.
Finding the Solutions

In order to develop effective, integrated solutions for the above issues the operator, RDF/completion fluids provider, and completion installation provider worked closely together to develop: fluids, processes and procedures that would reduce the risks of the occurrence of the above issues. It was apparent that the keys to project success would be found in formation damage & completion impairment control.

In order to identify the formation damage mechanisms posing the highest risk, a systematic and extensive suite of core studies at reservoir conditions were undertaken. The information developed as a result of the core study and the key project objectives, were communicated to the service providers selected for each of the key activities: drilling, gravelpacking, and filtercake cleanup.

Individual solutions were developed using a systematic method involving: solution development, engineering analysis, and laboratory validation. A case-based-reasoning approach was applied to integrate the individual service solutions into a composite completion process. Using this approach, proposed solutions for any issue were not considered optimal if they compromised any of the other primary areas of concern.

Complete fluid-train (drilling and completion fluid sequence) testing was employed to validate all proposed solutions and identify any potentially detrimental interactions. All solution validation testing was performed using representative core and formation brine from the Hibiscus MIV reservoir unit.

This process validated the technical correctness of each phase of the proposed operation (drilling, gravel pack, etc.) and confirmed that the complete operational sequence would not compromise the key project objectives (i.e. productivity, etc.). This procedure: Solution Development followed by Process Integration and Laboratory Validation, was essential in order to provide the team with a clear understanding of the behavior of the total process so that the fluid systems and operational processes could be most effectively integrated.

Reservoir Drilling Fluid (RDF) Design

Because four of the seven key drilling and completion concerns identified related to RDF/reservoir interaction, RDF compatibility with the rock was considered the key to the drilling and maintenance of the wellbore into which an effective completion would have to be installed.

The preferred RDF would be a water-based fluid, with a required density from 10.5 to 12.5 lbm/gal (for wellbore stability), have proper hole cleaning capabilities, produce minimal ECD’s and have a working temperature range of 160 to 170ºF.

Reservoir stability and impairment concerns were resolved by taking core and shale material, from immediately above and within the reservoir, and performing evaluations for compatibility with the proposed RDF, RDF base-brine (and completion brine), and freshwater. Shale stability testing included: Dispersion, Swelling, CEC and direct fluid contact to confirm the applicability of the water-based fluid. A base fluid consisting of KCl and Sodium Bromide was selected for the RDF and for use as the Completion fluid due to its ability to provide the required density and supply Potassium (K+) ions for clay & shale stabilization.

Formation Porosimetry analysis suggested that mud solids invasion of the reservoir would be a major threat to producing an effective completion. Reservoir invasion while drilling was minimized by selecting a calcium carbonate bridging particle size distribution (PSD) that optimized the bridging & sealing efficiency of the drilling fluid, and provided the thinnest possible filtercake. This would also provide an advantage for filtercake cleanup treatments. Although the average pore size of the reservoir sands was evaluated as 5 microns, the broad variation in the uniformity coefficient of the sands required identification of a blend of graded calcium carbonate particles that would efficiently bridge a pore size range from 1.5 to > 21.0 microns. (Figure 2) The Ideal Packing Theory was utilized to optimize the selection of the bridging particles. Figure 3 illustrates the match between the RDF PSD and the optimum value. This distribution would not only provide a thin tight seal on the sandface, it would also pass through the premium production screen preventing damage to either screen or formation.

Because sustainable high-rate gas flow was the overall project goal, potential return flow to gas was also evaluated in the laboratory. (Figure 4) Variables investigated included: the RDF formulation, the quantity of (insoluble) drilled-solids that might accumulate in the RDF, and various cleanup treatment designs. Insoluble drilled-solids accumulation in the filtercake and potential reservoir fines migration emerged as factors that increased the risk of completion impairment if not addressed proactively in both the drilling & completion plans.

In addition to reservoir and completion compatibility, the RDF was also required to effectively drill the moderate length horizontal intervals. Product selection and concentration were important in establishing & maintaining the optimum drilling properties required to provide: hole cleaning while drilling at rapid rates, lubricity while making directional corrections, inhibition for wellbore stability, and to provide the flexibility to increase density as necessary. In addition, no products could be used that would compromise the efficiency of the completion or the filtercake cleanup treatment. As a result the type and ratio of starch and biopolymer was carefully evaluated to minimize filtration and ECD, while maximizing carrying capacity for hole cleaning.

A unique, dual-purpose lubricant & shale inhibitor was also selected to enhance shale inhibition and reduce the coefficient of friction in the NaBr/KCl fluid. More importantly this dry product functioned at a low concentration (1 lbm/bbl) and did not interfere with the functionality of the filtercake cleanup treatment.

Key RDF Maintenance Limits

Filtercake clean-up and lift-off testing by Brady etal illustrated the impact that insoluble drilled-solids (and especially clay) accumulation in a water or brine based RDF can have on productivity of gravelpacked wells. Laboratory validation testing, specific to both the RDF and the completion design for Hibiscus, focused on delivering sustained well productivity, that led to the recommendation that the accumulation of insoluble drilled-solids within the RDF be limited to less than 2.0% by volume, with a stretch goal that...
the accumulation of clay in the RDF be further limited to no
more than 1.0% by volume.

Minimizing the filtercake thickness, and therefore the total
volume of material that would need to be removed from the
sandface after gravelpack placement was also viewed as a key
objective for the RDF. For this reason low HTHP filtration
rates limits, <5.0 ml/30min, were established. Laboratory
results indicated that these limits would ensure that the
filtercake produced while drilling was optimally soluble and
that the residual insoluble materials would minimally impact
the final completion productivity. (Figure 4)

Gravel Packing Requirements
Reservoir characteristics (lithology, granulometry and
formation strength) clearly indicated the need for effective
gravelpacks to ensure that the screens were protected from
formation sand (particulate) erosion at the high gas flow rates
anticipated during production. Recognizing the potential for
wellbore collapse and/or incomplete screen coverage when
waterpacking, premium sintered laminate screens were
selected to provide a secondary level of protection against
sand production. However, the primary goal and metric for
the gravel packing operation was to achieve packing
efficiencies (PE) in excess of 100%, of the theoretical volume
between the screen O.D. & wellbore diameter. Therefore any
action, prior to or contiguous with the gravelpack process, that
would have the effect of increasing the risk of filtercake
failure and precipitate a premature sand-out during the
waterpacking operation was viewed as unacceptable.

Filtercake Cleanup Treatment Requirements
The high-rate water packing technique depends upon the
presence of a stable effective filtercake to prevent premature
screen-out. When gravelpacking efficiency (PE) is high the
low permeability filtercake is effectively trapped between the
gravelpack and the sandface. Although evaluated during
solution development, placing filtercake dissolving chemicals
into the fluid used to transport the gravel into the wellbore, as
is employed in simultaneous gravelpacking and clean-up with
shunt tubes 5, was considered too great a risk to obtaining the
gravelpack efficiencies required. It was also discounted from
an operational standpoint, as it would have increased the total
fluid volumes used, and prevented the re-use of brine for new
RDF and could have resulted in mud plant contamination.

Therefore a technique was required that allowed placement
of filtercake dissolving chemicals into the completion
basepipe immediately after gravel placement, but before the
upper completion installation. Additionally, the preferable
technique would not; involve extra trips, require the
deployment of additional equipment (such as coiled tubing) or
extend the overall completion time significantly. The
chemistry as deployed would need to have adequate dissolving
power to remove virtually all of the filtercake, but should not
cause the rapid onset of losses that are common with acid and
which make effective cleanup along the entire length of an
extended interval difficult. A secondary concern was the
potential for corrosive damage to the screens, due to
potentially long contact times with the chemicals prior to
initial production.

Evaluation of the filtercake deposited by the optimized
RDF indicated that the filtercake remaining after the high rate
water packing operation could be effectively removed by the
use of a specialized chelant & enzyme solution7. The
treatment would be spotted within the completion basepipe
immediately following gravel placement. This limited volume
treatment would need to slowly disintegrate the filtercake and
dissolve or reduce the particle size of the calcium carbonate
bridging agents sufficiently to allow unimpeded flowback with
initial production. Additionally the treatment developed
needed to act slowly enough to allow the gravelpack service
tools to be withdrawn from the lower completion before the
onset of losses and have very low order corrosivity toward the
sintered laminate screens.

A unique, modified gravelpack service tool was assembled
to allow placement of the chelant & enzyme treatment within
the screen basepipe and blank pipe below the packer. The tool
allows circulation down the washpipe and up the screen
basepipe from the toe to the heel of the completion after all the
gravel is placed. The feature is activated immediately before
the service tool & washpipe is pulled and the flapper or FIV is
closed. This tool module was successfully used for the first
time on the Hibiscus project. In addition the modified service
tool was also assembled with an anti-swab service tool
(ASST) module to help prevent premature filtercake lift-off
that frequently causes fluid losses during packer setting and
service tool manipulations. These tool modifications were
viewed as an essential aid and enable for the successful
placement of the unique filtercake cleanup treatment. Full-
scale stack-up tests of the new equipment were performed to
test the function and refine the application process.

Project Metrics

Recognizing that achieving the key project goal (sustainable
gas delivery rate from the four planned wells) would be
dependent upon the successful achievement of the individual,
(but critically interdependent) processes required to drill and
complete the wells, performance metrics were therefore
established for each of the three key (and interdependent)
processes identified during project design and planning.

Drilling: Metrics for the RDF provider
• Drill the reservoir intervals without significant loss of
  fluid to the potentially fluid sensitive formation.
• Provide adequate penetration rate and hole stability.
• Limit the accumulation of (insoluble) drilled-solids
  within the RDF, and therefore within the filtercake,
  to no more than 2% by volume.
• Limit the accumulation of clay in the RDF to no
  more than 1% by volume. (Stretch Goal)
• Produce a wellbore having a thin, slick filtercake into
  which screens could be run without problems.
• Maintain the correct CaCO3 PSD & Concentration to
  ensure minimum filtercake thickness and minimum
  filtrate invasion.
Gravelpacking: Metrics for the Gravelpack provider
- Obtain the highest possible screen placement efficiency as a % of openhole length.
- Pump gravelpack schedule and pressures as per plan, verified against simulation.
- Achieve gravelpack placement efficiencies of 100% or higher.
- Minimize losses of completion fluid to the reservoir.
- Effectively place filtercake removal treatment into the lower completion immediately after completion of the gravelpack.
- Continuously improve completion time, well to well.

Completion: Metrics for Filtercake Removal Treatment
- Ensure the treatment design & volume placed has sufficient dissolving capacity for the mass of filtercake expected.
- Treatment placed in contact with filtercake should not exhibit breakthrough within the time frame required to: place the chemical, pull the service tool & washpipe, and close the formation isolation valve.
- The filtercake removal treatment should effectively minimize completion system impairment and produce high sustainable well PI values.
- The Filtercake removal treatment should not damage or impair either completion hardware or formation.

Laboratory Validation of Potential Solutions
Reservoir condition core-flood testing was undertaken on representative cores to assess the effects of fluid choice on formation damage. Measurements of gas permeability and scanning electron and cryogenic microscopic evaluations helped identify the damage mechanism(s) and optimize the completion and clean up procedures for the NCMA development.

Four separate phases were executed sequentially to establish the most favorable fluids and full sequence for field operations.
- Phase 1: RDF evaluation with candidate water based mud systems.
- Phase 2: Base brine evaluation with candidates from water based mud formulations for potential use as carrier fluid in gravel pack operations.
- Phase 3: Full operational sequence evaluated with carrier fluid incorporating the gravel pack assembly.
- Phase 4: Full operational sequence evaluated with enzyme or acid packages within the carrier fluid incorporating the gravel pack assembly.

Well Case Histories
General Completion Process Description:
In all cases the drilling design called for setting 9 5/8” casing just into the top of the reservoir, and drilling the horizontal interval with the optimized NaBr/KCl brine-based polymer carbonate RDF. Drilling rates to total depth were largely defined by directional control and the necessity to ensure that ECD did not exceed fracture gradients in the unconsolidated sands. The ECD was controlled to no more than 2.5 lbm/gal over the static mud density. To ensure a clean wellbore and minimize cuttings bed development while drilling, a precautionary wiper trip was conducted every 5 stands. This action also ensured sufficient cleaning of the 9-5/8” casing. Average on bottom ROP’s for the reservoir sections was 70 – 90 ft/hr.

For the purposes of obtaining the minimum completion impairment, a maximum limit for the accumulation of insoluble drilled-solids within the RDF was set at 2.0% by volume. A further target (and preferred limit), specific to clays, was set at 1.0% by volume (8.4 lbm/bbl) to ensure optimum filtercake cleanup. In order to maintain the drilled-solids content below these limits, 230 mesh screens were selected for use on the secondary shale-shakers. High-speed centrifuges were also employed to help remove drilled-solids from the circulating system before they could degrade to a size that would allow their retention in the RDF. Although the total insoluble drilled-solids limit was exceeded during the drilling of each of the reservoir intervals, the (preferred limit) maximum clay-content of 1.0% by volume was never exceeded.

The adequacy of the RDF conditioning was validated in the field by the use of a Production Screen Tester (PST), which evaluates screen plugging potential using actual screen samples and the RDF in use on the well.

After drilling to TD, during the cleanout run, a specially formulated solids-free displacement fluid was spotted in the open hole to stabilize the filtercake, facilitate screen installation, and minimize leak-off due to filtercake damage while running the screens. The used RDF in the cased-hole interval, above the solids-free displacement fluid, was displaced to brine during the wellbore clean-out to ensure that it would not plug the premium sintered laminate screens as they were run into the well. In every instance the well-screens were run to bottom without rotation or reciprocation. Following running of the screens to depth, the openhole intervals were circulated to brine and the packer was set in preparation for the gravelpacking operation.

The First Well
Completed in May of 2002 the 1742 ft (531m) 8.5” openhole interval was drilled to TD with 11.4 to 11.7 lb/gal (1.37 to 1.40 s.g.) RDF. The optimized polymer/calcium carbonate RDF, designed for the formation, performed well, providing excellent hole cleaning, a stable wellbore and exhibited an average HTHP filtration rate of less than 5.0 ml/30min at 170°F. Drilling rates were very good, averaging 70 ft/hr (21.3 m/hr) and there were no losses of the fluid to the reservoir. The openhole interval included approximately 350 ft (107m) of non-productive formation (shale). The maximum total
drilled-solids accumulation in the RDF during the interval reached 4% by volume, twice the maximum limit. However the maximum total clay-content reported was only 0.8% by volume significantly below the stretch goal.

The sand control screens were run into position without problems but while setting the packer (prior to gravelpacking), a service tool misalignment prevented the new ASST from functioning properly. This lead to a filtercake-swabbing event resulting in a completion fluid loss rate that exceeded the gravelpack design limitations (total brine losses for the section were 1188 bbl). The completion process decision-tree called for installing the screens without the gravelpack or filtercake cleanup treatment and as a result the 1st well was completed as a stand-alone premium screen installation. Losses were cured with a proprietary LCM engineered to bridge on the inside of the screens.

When the upper completion was installed and the well was tested, initial productivity was very good at 97 MMcfd with a 275 psi sandface drawdown. The initial PI was 352 kcf/d/psi, with the PI/ft of screens at 0.253. A production test performed after 7 months of production indicated an improvement in well performance as evidenced by an increase of the PI/ft value to 0.348kcf/d/psi. The productivity of this well became the defacto benchmark for the performance of the remaining wells to be drilled.

The Second Well
This well was completed after drilling a 1667ft (508m) horizontal section. RDF density for the interval was slightly lower, at 11.1 to 11.5 lbm/gal (1.33 to 1.38 s.g.) than the previous well. The RDF again performed well providing an average ROP of 75 ft/hr (22.8 m/hr) with no losses. Some minor hole enlargement was observed near the heel of the wellbore, with the average callipered diameter being 8.5 to 10.2 inches. The total drilled-solids content for the interval varied between 2.7 and 3.8% by volume, while the clay content varied between 0.48 & 0.7% by volume.

Screens were run to TD without problems and the new anti-swab service tool functioned well. The openhole interval was gravelpacked with 40/60 sand, achieving a packing efficiency (PE) of 139%. Approximately 153ft (47m) of openhole was covered with blank pipe, due to the presence of non-reactive shale. No losses were observed during the completion. Total completion time was reduced significantly (-56.9%), versus the original completion.

Immediately following the gravelpack the lower completion basepipe and blank was filled with the enzyme & chelant filtercake cleanup treatment, the service tool & washpipe were pulled and the FIV closed. A pressure test of the closed FIV indicated a slight leak and an attempt was made to open and re-close the FIV to resolve the apparent leak. The attempt resulted in the unplanned opening of the port closure sleeve and the onset of minor losses.

The initial well test on Aug 20th, 2002 produced gas at a rate of 104 MMcfd at a sandface drawdown of only 185 psi. The initial well test therefore indicated a PI of 562 kcf/d/psi, and a PI/ft of screen equaling 0.369 kcf/d/psi. It was also noted that the second well cleaned up, during initial production, in (5 hrs) less than half the time of the previous well. Further wellbore clean up indicated an improvement of performance with time as evidenced by an increase of the PI/ft value to 1.061 kcf/d/psi after six months of production.

The Third Well
This well was completed after drilling a production interval of 1785ft (544 m) with 8.5 inch wellbore. The RDF density for this interval was 11.0 to 11.1 lbm/gal (1.32 to 1.33 s.g.) with an average HTHP filtration rate of < 4.5 ml/30min. The total drilled-solids content in the RDF ranged from 1.8 to 4.1% by volume while the total clay content stayed between 0.36 and 0.65% by volume. The optimized RDF drilled the interval at an average ROP of 90 ft/hr (27.4 m/hr) producing a wellbore diameter of 8.5 to 9.0 inches. Approximately 70 bbls of the RDF were lost to the reservoir interval.

1796 ft of wellscreen was run to bottom without problems and the anti-swab service-tool and treatment placement modules functioned as designed. The openhole interval was gravelpacked with 40/60 sand, achieving a packing efficiency (PE) of 143%. The third well was also treated with the chelant & enzyme filtercake cleanup treatment. Approximately half of the 285 bbls of completion brine lost to the reservoir occurred during or after placement of the filtercake removal treatment but before the washpipe was pulled and the FIV was closed.

The well test produced 110 MMcfd with a sandface drawdown of only 168 psi. The initial well test PI was 655 kcf/d/psi and the PI/ft of screens was 0.364 kcf/d/psi. The well cleaned up in 7 hours approximately half the time of the first well. Further wellbore clean up indicated an improvement of performance with time as evidenced by an increase of the PI/ft value to 1.075 kcf/d/psi after three months of production.

The Fourth Well
Resulting from the inability to get the 9-5/8” production casing to TD, the 4th well was completed using a 7-5/8” liner top set in the reservoir. A 7.0 inch, 1638 ft (499.2 m) wellbore was drilled through the Hibiscus sands with an optimized RDF having a density of 10.9 to 11.0 lbm/gal (1.31 to 1.32 s.g.). Average ROP with the fluid in the reduced size wellbore was 72 ft/hr (21.9 m/hr). Again the RDF drilled the interval without losses, and provided excellent hole cleaning and wellbore stability. The total drilled solids content in the RDF for the interval ranged from 1.9 to 2.7% by volume while the total clay content varied between 0.36 and 0.53% by volume.

The 4th well was completed in the 7.0 inch wellbore by gravelpacking the 4.86 inch O.D. (3.54 inch I.D.) premium sintered laminate screens with 40/60 gravel. The upper completion configuration was also reduced from the previous combination of 7.0 and 5.5 inch tubing to all 5.5 inch tubing. The smaller basepipe meant that only 38.3 bbls of the chelant & enzyme filtercake removal treatment were placed in the lower completion, and the entire treatment operation including tool movements required 87 minutes. Approximately 385 bbls of the NaBr/KCl completion brine was lost to the hole during the completion process.

This well was tested to a maximum rate of 102 MMcfd with a sandface drawdown of 244 psi. The initial PI for the well was 418 kcf/d/psi and the PI/ft of screens was 0.255 kcf/d/psi. Subsequent production well test indicated an improvement of performance with time as evidenced by an
increase of the PI/ft value to 0.277 kcf/d/psi based on February 2003 data.

The Fifth Well
The 5th well was the longest drilled during the campaign with an openhole section length of 2,320’ (707 m) and TD at 16,566’ (5,049 m). RDF density for the interval was between 10.9 to 11 lbm/gal (1.31 to 1.32 s.g.). The RDF again performed well providing an average ROP of 93 ft/hr (28.3 m/hr) with minor losses of 22 bbl.

Screens were run to TD without problems and the service tools functioned well. The openhole interval was gravelpacked with 40/60 sand, achieving a packing efficiency (PE) of 102%. Approximately 595ft (181m) of open hole was covered with blank pipe, due to the presence of non-reactive shale. The total completion was run within 160 hrs, when the well was tested, initial productivity was good at 100 MMcfd with a 182 psi sandface drawdown. The initial PI was 547 kcf/d/psi, with the PI/ft of screens at 0.318.

Well performance is negatively affected by the presence of a boundary, however again subsequent production well test indicated an improvement of performance with time as evidenced by an increase of the PI/ft value to 0.612 kcf/d/psi.

Well Comparisons
(Note: The data supporting the well comparisons can be found in Tables 1, 2 & 3.)

Reservoir drilling fluid performance:
The brine-based polymer/starch/ and size-optimized calcium carbonate RDF performed very well fulfilling the design objectives for the project in virtually all respects. Drilling performance was very good with consistent ROP’s, averaging 70 to 90 ft/hour, and excellent hole cleaning and wellbore stability were delivered for all the wells. The carefully optimized filtration control program and rheological properties helped to ensure that potentially damaging fluid losses to the reservoir sands were effectively minimized.

Drilled-solids accumulation was carefully monitored and because the RDF system was stored, reconditioned and reused, drilled-solids control was of paramount importance. The secondary shale shakers, fitted with 230-mesh screens, and an aggressive “Dump & Replace” plan was utilized effectively to control the accumulation of clay within the RDF. Although the total drilled-solids content (primarily fine sand) was generally near or above the 2.0% target limit, the preferred clay-content limit (stretch goal 1.0% by volume) was never exceeded. In fact the median clay-content, as measured by MBT, for each of the well intervals drilled was between 0.41 and 0.59% by volume, and well below the identified maximum limit.

Gravel pack efficiency:
Although the first well was not gravelpacked, due to losses incurred while setting the packer, the remaining wells were all gravelpacked successfully. The average gravelpack efficiency for the four wells was 146%, indicating excellent screen coverage and effective sand control potential was installed. Completion time requirements were reduced successively for each of the four completions, with the final job requiring only 144 hours from pre-job safety meeting to the opening of the FIV for the posterior well test.

Filtercake cleanup treatment performance:
All four Hibiscus wells that were gravelpacked were treated with chelant & enzyme filtercake removal solutions. The placement design called for filling the screen basepipe and blank pipe below the gravelpack packer with the non-aggressive, non-corrosive treatments immediately prior to pulling the gravelpack service tools and washpipe from the lower completion. The completion brine type and the volume capacity of the basepipe and blankpipe, with respect to the mass of the filtercake and the gravelpack pore-space volume, imposed significant dissolving capacity design limits as well as placement issues. The non-gravelpacked well, although an unfortunate event, provided an excellent benchmark against which the performance of the gravelpacked and treated wells could be compared.

Well test drawdown data clearly illustrated the well performance improvement provided by the gravelpack & filtercake cleanup treatment. The completion drawdown pressure profile of the second well was significantly lower than the un-treated standalone screen installed in the first well. Initial well clean up test data and screen lengths were utilized to determine the productivity index per foot of installed screen for all five wells. (Table 2) The 8.5 inch wellbores showed a 126% to 146% improvement in PI/ft of screen versus the un-gravelpacked well, while the smaller (7.0 inch) gravelpacked wellbore and basepipe of the fourth well produced a PI/ft equivalent to the first larger diameter well. Further well clean up during normal production further increased the performance gap between the gravel packed and non-gravel packed wells ranging from 176% to 309%. This performance ranking is supported by the length normalized and maximum producing rates recorded for the wells after several months of production.

Conclusions
1. The performance of the Hibiscus high-rate gas wells was optimized by carefully integrating the application of the reservoir drilling fluid with the completion installation fluids and process.
2. Reservoir condition core floods in conjunction with scanning electron and cryogenic microscopy aided in the selection of candidate fluids and optimized the fluid sequences required for gravel pack operations.
3. Reservoir drilling fluids can and should be formulated and maintained to minimize the potential for impairment of both the formation and the installed completion. Especially for sand control completions;
   a. Specific limits should be established for the accumulation of total insoluble solids and clays within the RDF system while drilling.
   b. RDF additive selection should consider both drilling functionality and the facilitation of filtercake removal by chemical treatment.
c. The completion engineer should therefore seek and expect collaborative interaction between the RDF and Completion service providers.

4. Chemical filtercake removal treatments should be designed such that they:
   a. Will not damage the installed completion components or the reservoir (i.e. Are non-aggressive in nature) despite long contact periods.
   b. Are operationally compatible with the applied completion installation process and equipment.

5. Filtercake removal treatments based upon the combination of chelants and enzyme can be effective even when applied in limited capacity situations.

6. Performance metrics established for operational processes, involved in the drilling and completion of a reservoir interval, should be directed toward (focused on) final well performance objectives.

7. Where well inflow optimization is crucial, both the reservoir formation and the installed sandface completion system should be evaluated in the laboratory for their response to the entire drilling and completion fluid sequence, not simply to discrete (individual) fluid interactions.

8. Post wellbore clean up during normal production results in improved well performance, indicating that the completions were not negatively affected by fines production.

Acknowledgements
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References


Figures & Tables

Figure 1. Location of the Hibiscus Field

![Location of the Hibiscus Field](image)

Figure 2. Example of Hibiscus sand pore geometry (by Image Analysis) and pore size range in the reservoir.

**Statistics**
- **Samples:** 294
- **Minimum:** 1.5 µ
- **Maximum:** 21.0 µ
- **Mean (D50):** 5.09 µ
- **Mean (D90):** 8.90 µ
- **Std. Dev:** 4.00

![Pore Throat Size Distribution](image)

Figure 3. Plot of Ideal Packing Theory optimization of bridging agent particle selection.

**Optimum Bridging Agent Blend**
- **D10 Target / Blend:** 0.2 / 0.3 microns
- **D50 Target / Blend:** 4.0 / 3.5 microns
- **D90 Target / Blend:** 13.0 / 16.8 microns

**Optimum Blend for 0 to 100 % CPS Range**

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Bridging Agent (lb/bbl)</th>
<th>Vol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = Safe-Carb 2 (VF)</td>
<td>22.4</td>
<td>74.63</td>
</tr>
<tr>
<td>B = Safe-Carb 10 (F)</td>
<td>7.6</td>
<td>25.37</td>
</tr>
</tbody>
</table>

**Simulation Accuracy**
- **Calcium Carbonate added:** 30 lb/bbl
- **Avg Error 0 - 100 % CPS Range:** 2.23 %
- **Max Error 0 - 100 % CPS Range:** 9.92 %

![Cumulative Particle-Size Distribution](image)

Figure 4. Results of gas return flow tests (non-steady state region) after filtercake breaker solution treatment:

1.) Reference system with no filtercake.
2.) System with filtercake from RDF having 8 ppb drilled-solids.
3.) System with filtercake from RDF having 16 ppb drilled-solids.
4.) System with filtercake from RDF having 16 ppb drilled-solids and no cleanup treatment.

![Nitrogen Gas Flow vs. K Gas](image)
### Table #1: Integrated Drilling & Completion Process
Comparison Information for Hibiscus Wells.

<table>
<thead>
<tr>
<th>Well in Sequence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion Date</td>
<td>22/05/02</td>
<td>20/08/2002</td>
<td>30/9/2002</td>
<td>3/12/2002</td>
<td>23/04/2003</td>
</tr>
<tr>
<td>Openhole Interval Length: ft</td>
<td>1,742</td>
<td>1,667</td>
<td>1,785</td>
<td>1,638</td>
<td>2,320</td>
</tr>
<tr>
<td>Openhole Diameter (Gauge): inch</td>
<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
<td>7.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Caliper Range (Diameter, Min./Max.): inch</td>
<td>8.5 / 9</td>
<td>8.5 / 10.2</td>
<td>8.5 / 9</td>
<td>7.8</td>
<td>8.5 / 9</td>
</tr>
<tr>
<td>RDF type: NaBr/KCl based Polymer &amp; Optimized CaCO3</td>
<td>RDF RDF RDF RDF RDF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDF Density Range, (Min./Max.): lbm/gal</td>
<td>11.4/11.7</td>
<td>11.1/11.5</td>
<td>11.0/11.1</td>
<td>10.9/11.0</td>
<td>10.9/11</td>
</tr>
<tr>
<td>CaCO3 Bridging Solids, start/finish: lbm/bbl</td>
<td>26/27</td>
<td>25/26</td>
<td>31/42</td>
<td>25/30</td>
<td>24/29</td>
</tr>
<tr>
<td>RDF Total Drilled Solids, (Min./Max.): lbm/bbl</td>
<td>0/36.85</td>
<td>21.0/39.5</td>
<td>17.0/38.0</td>
<td>19.0/27.0</td>
<td>9/28</td>
</tr>
<tr>
<td>RDF Clay Content, (Min./Max.): lbm/bbl</td>
<td>0/6.5</td>
<td>3.0/4.5</td>
<td>3.0/5.5</td>
<td>2.5/4.5</td>
<td>1.5/5</td>
</tr>
<tr>
<td>HTHP Filtration Rate @ 170°F/500 psi: 30 min</td>
<td>&lt;5.0</td>
<td>&lt;5.5</td>
<td>&lt;4.5</td>
<td>&lt;5.0</td>
<td>&lt;4.3</td>
</tr>
<tr>
<td>Average Rate of Penetration: ft/hr</td>
<td>70</td>
<td>75</td>
<td>90</td>
<td>72</td>
<td>93</td>
</tr>
<tr>
<td>Completion Style:</td>
<td>OH-SAS</td>
<td>OH-HRWP</td>
<td>OH-HRWP</td>
<td>OH-HRWP</td>
<td>OH-HRWP</td>
</tr>
<tr>
<td>Gravel Size:</td>
<td>mesh</td>
<td>none</td>
<td>40/60</td>
<td>40/60</td>
<td>40/60</td>
</tr>
<tr>
<td>Gravel Pack Efficiency:</td>
<td>%</td>
<td>n/a</td>
<td>139</td>
<td>143</td>
<td>199</td>
</tr>
<tr>
<td>Length of Screens: ft</td>
<td>1,391</td>
<td>1,524</td>
<td>1,796</td>
<td>1,638</td>
<td>1,720</td>
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<tr>
<td>Screen O.D:</td>
<td>inch</td>
<td>6.38</td>
<td>6.38</td>
<td>6.38</td>
<td>4.86</td>
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<tr>
<td>Base Pipe I.D.:</td>
<td>inch</td>
<td>4.892</td>
<td>4.892</td>
<td>4.892</td>
<td>3.54</td>
</tr>
<tr>
<td>Completion Tubing (13-Cr): size</td>
<td>inch</td>
<td>7&quot;/5.5&quot;</td>
<td>7&quot;/5.5&quot;</td>
<td>7&quot;/5.5&quot;</td>
<td>5.5&quot;</td>
</tr>
<tr>
<td>Completion Time Requirement: hrs</td>
<td>446</td>
<td>192</td>
<td>169</td>
<td>144</td>
<td>160</td>
</tr>
<tr>
<td>RDF lost in Hole</td>
<td>bbl</td>
<td>0</td>
<td>70.0</td>
<td>0.0</td>
<td>22.0</td>
</tr>
<tr>
<td>Brine lost in Hole</td>
<td>bbl</td>
<td>1188</td>
<td>0</td>
<td>287.0</td>
<td>385.0</td>
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<tr>
<td>Filtercake Clean Up Treatment type:</td>
<td>none</td>
<td>enzyme &amp; chelant</td>
<td>enzyme &amp; chelant</td>
<td>enzyme &amp; chelant</td>
<td>enzyme &amp; chelant</td>
</tr>
<tr>
<td>Production Clean Up Time: hrs</td>
<td>12</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>5</td>
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</table>

### Table #2: Comparison of Initial Well Performance based upon Initial Well Test Data and Early Production Figures.

<table>
<thead>
<tr>
<th>Initial Well Test &amp; Early Production Data</th>
<th>Well #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Well Test Data</td>
<td>Gas Rate: mmcf/d</td>
<td>97</td>
<td>104</td>
<td>110</td>
<td>102</td>
<td>99.6</td>
</tr>
<tr>
<td>Sandface Drawdown Required for Rate: psi</td>
<td>275</td>
<td>185</td>
<td>168</td>
<td>244</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>Initial Well Test Productivity Index (PI): kcf/d/psi</td>
<td>352.7</td>
<td>562.2</td>
<td>654.8</td>
<td>418.0</td>
<td>547.3</td>
<td></td>
</tr>
<tr>
<td>Initial Productivity Index / foot of screen: PI/ft</td>
<td>0.253</td>
<td>0.369</td>
<td>0.364</td>
<td>0.255</td>
<td>0.318</td>
<td></td>
</tr>
<tr>
<td>% Improvement vs 1st well:</td>
<td>-</td>
<td>146%</td>
<td>144%</td>
<td>101%</td>
<td>126%</td>
<td></td>
</tr>
<tr>
<td>Production Test Date:</td>
<td>Jan '03</td>
<td>Feb '03</td>
<td>Dec '02</td>
<td>Feb '03</td>
<td>May '03</td>
<td></td>
</tr>
<tr>
<td>Production Test Gas Rate: mmcf/d</td>
<td>96</td>
<td>98</td>
<td>99</td>
<td>92</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td>Sandface Drawdown Required for Rate: psi</td>
<td>198</td>
<td>90</td>
<td>86</td>
<td>282</td>
<td>148</td>
<td></td>
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<tr>
<td>Well Test Productivity Index kcf/d/psi</td>
<td>484.8</td>
<td>1088.9</td>
<td>1151.2</td>
<td>326.2</td>
<td>673</td>
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<tr>
<td>Well Test PI / foot of screen: PI/ft</td>
<td>0.348</td>
<td>1.061</td>
<td>1.075</td>
<td>0.277</td>
<td>0.612</td>
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<tr>
<td>% Improvement vs 1st well:</td>
<td>-</td>
<td>305%</td>
<td>309%</td>
<td>80%</td>
<td>176%</td>
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### Table #3: Discrete Fluids Sequence by Well

<table>
<thead>
<tr>
<th>Openhole Fluid Exposure Sequence</th>
<th>Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDF = Reservoir Drilling Fluid</td>
<td>1</td>
<td>RDF</td>
<td>RDF</td>
<td>RDF</td>
<td>RDF</td>
<td>RDF</td>
</tr>
<tr>
<td>SF = Solids Free Drilling Fluid</td>
<td>2</td>
<td>SF</td>
<td>SF</td>
<td>SF</td>
<td>SF</td>
<td>SF</td>
</tr>
<tr>
<td>GPF = Gravel Pack Fluid</td>
<td>3</td>
<td>CF</td>
<td>GPF</td>
<td>GPF</td>
<td>GPF</td>
<td>GPF</td>
</tr>
<tr>
<td>CUT = Clean Up Treatment</td>
<td>4</td>
<td>CUT</td>
<td>CUT</td>
<td>CUT</td>
<td>CUT</td>
<td>CUT</td>
</tr>
<tr>
<td>CF = Completion Fluid (Brine)</td>
<td>5</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
</tbody>
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