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Title: Solid-Steel Expandable Liners for Refracturing Horizontal Wells in Shale Formations

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Synopsis

This paper discusses the use of solid-steel expandable refrac liners as mechanical barriers to isolate old perforations in the lateral section of horizontal shale-gas wells with declining production to allow re-perforation and fracture stimulation of new shale volume between the old perforation clusters. The technology and installation of expandable solid-steel refrac liners are presented with a summary of other refrac diversion methods. Two case histories demonstrating the application of solid-steel expandable refrac liners to ~3000 ft (914 m) laterals in the Barnett Shale are presented.

These case histories document the first successful use of solid-steel expandable liners to achieve frac-stage diversion when refracturing horizontal wells. The challenge was to use a solid-steel expandable 4-1/4 in. (107.95 mm) OD [outside diameter] liner in the 5-1/2 in. (139.7 mm), 17 lb/ft (25.30 kg/m) base casing as a mechanical barrier with elastomer seals on the exterior of the refrac liner placed to achieve both stage isolation and the desired degree of perforation isolation. Once in the setting position, the refrac liner, connections, and elastomer seals were expanded using a cone-driven process from the toe to the heel of the lateral to isolate frac stages and perforation clusters, and to maximize the ID [internal diameter] of the refrac liner. The multi-stage refracturing treatment was performed next after shooting new perforations for each stage through both the expanded liner and the base casing.

Offset wells served as benchmarks as they were refractured using other perforation diversion methods. For the first case history, gas production over a 23 month period following the refrac using the refrac liner exceeded that of the two offset wells by more than 161,000 MCF [1000 cubic ft.] (4.56 E06 m^3). For the second case history, gas production from the well with the refrac liner exceeded that of its offset well by 92,000 MCF (2.61 E06 m^3) over a 20 month period. The primary advantage of using the refrac liner, however, was that it provided a mechanical barrier to ensure injection into the desired interval for each stage of the frac treatment. This can lessen the requirement and cost for real-time fracturing diagnostics such as downhole microseismic, and eliminate interruptions during refracturing to make downhole adjustments to achieve stimulation objectives.

Introduction

Refracturing Wells in Shale Plays

Many times a well that must be hydraulically fractured to be economic will experience a decline in production that will make the attainment of the EUR [estimated ultimate recovery] of the well impossible. If significant reserves are in danger of being lost, the operator will consider re-drilling the well or working over the well to recapture reserves. In unconventional reservoirs such as shales with long laterals requiring multiple frac stages, it is often more economical to refracture the same lateral well bore rather than to drill a new well. In shale reservoirs, it is common to shoot 1 to 3 ft (0.305 to 0.914 m) long perforation clusters with 4 to 6 phased shots per ft (13 to 20 shots per m) with clusters spaced greater than 50 ft (15.2 m) apart. To effectively refracture the well, it is desirable to at least restimulate all the old perforations, but preferably it is desirable to seal-off the old perforations and shoot new perforations clusters between them, especially for widely spaced perf clusters. A common way of doing this is to squeeze off all the old perforations with cement, drill out the cement from the wellbore, and then conduct a standard plug and perf frac treatment from the toe to the heel of the well perforating between the old perforations. This may work assuming the cemented perforations, especially near the heel of the well where frac pressures are highest, hold up.

Other methods of refracturing use diverters such as 100 mesh sand, rock salt, perforation ball sealers, benzoic acid flakes, and biodegradable particulates (1). These are designed to plug the perforations taking the most flow thereby diverting flow to other perforations to get a more uniform injection of fracturing fluid and proppant along the lateral. These are also designed to unplug the perforations during flow back to allow production from all the perforations. Some diverters are soluble or degradable and will unplug the perforations over time.

Refracturing has been done in shale oil wells with uncemented liner, such as the Bakken, using methods such as the "pump and pray" method, where fracturing fluid slurry is bullheaded into the formation through the perforations or fracports. Wells initially fractured using the "pump and pray" method are thought to be good candidates for refracs which would imply they were understimulated initially.(2) It is interesting, however that, anecdotally, at least one operator has also had successful refracs using this method in the Bakken.

The other extreme is the use of mechanical isolation, such as a liner and packers placed in the well at locations to provide isolation for each frac stage from the old perforations up hole. However, this method using conventional packers and liners can severely reduce the effective ID of the wellbore available for refracturing operations.(3) For instance, for the refrac in a 5-1/2-in. (139.7 mm) 17 lb/ft casing (25.30 kg/m) with an ID of 4.892-in. (124.26 mm), the use of a 3-1/2-in. (88.9 mm) conventional liner with swellable elastomers would result in an available drift of 2.992-in. (76.00 mm) compared with a post-expanded drift of 4.151-in. (105.44 mm) when using the expandable 4-1/4-in. liner (107.95 mm). The solid-steel expandable liner would give ample room to run the large guns necessary for perforating two strings as well as the coiled tubing for drilling out the frac plugs.

Background of Barnett Shale Plays

The Barnett Shale is one of the largest shale gas plays in the U.S. with 43 TCF [trillion cubic feet] (1.218 E12 m^3) technically recoverable gas reserves (4), of which about 7 TCF (0.198 E12 m^3) have been recovered as of 2010.(5) Annual production was about 0.7 TCF (0.198 E11 m^3) by 2010. However, with the drop in gas prices after 2007, gas production is expected to level off or fall as operators stop drilling new gas wells and even shut in existing wells. The Barnett shale was the game-changing shale gas development in the U.S. where Mitchell Energy and Development Corporation experimented during the 1980s and 1990s to make deep shale gas production commercial in the Barnett Shale in North-Central Texas. The technology developed was the advent of multi-staged fracturing treatments of predominately horizontal wells with created hydraulic fractures running perpendicular to the lateral wellbore. In the Barnett Shale, laterals range in length from usually 2500 to 3500 ft (762 to 1067 m) although lengths as long as 5000 ft (1524 m) have been drilled. Barnett laterals are usually cased and cemented using 5-1/2-in. (139.7 mm) casing, and hydraulically fractured using the plug-and-perf method with multiple frac stages. Each frac stage is perforated with multiple perforation clusters where fractures are initiated. This technology is now being used in other shale plays across the U.S. and is being adopted now internationally. Over time, spacing of hydraulic fractures has become less and today the spacing of hydraulic fractures, or perforation clusters, is usually as little as 50 ft (15.24 m).

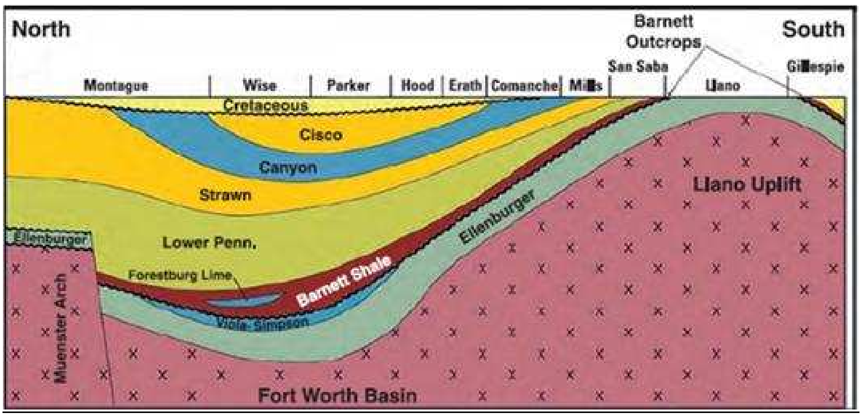
Barnett wells have been fractured with either crosslinked gels to get wider fractures and to carry more proppant (100 mesh to 20/40 mesh sand), or with water containing drag reducing additives (slick water) to allow high pump rates to better enable proppant transport and to encourage multiple fracture development. Presently, slick water is used more in shale-gas plays and crosslinked gels are used more in shale-oil plays. A typical slickwater frac in the Barnett Shale consists of 500,000 to 6,000,000 gal (1893 to 22,712 m^3) of fluid, 80,000–1,000,000 lb (36,287 to 453,592 kg) of sand, and uses pump rates from 50 to 100 bbl/min. (7.95 to 15.90 m^3/min.).(6) Greater quantities of fluid and proppant are used in horizontal Barnett wells as opposed to vertical Barnett wells.

Figure 1 shows the location of the Barnett Shale in the Fort Worth Basin and its neighboring stratigraphy. Fracture barriers are necessary in the Barnett Shale to control the height of the fracture so that fracture network creation will be maximized in the shale and to keep the induced fractures from intersecting any nearby water-bearing unit such as the Ellenburger formation below the Barnett Shale. Water encroachment into the Barnett from the underlying Ellenburger Group can be a significant problem. The Viola-Simpson limestone formation that lies between the Barnett and the Ellenburger over much of the Barnett Shale helps to provide a barrier to the downward growth of hydraulic fractures.(6)

Initial production of a Barnett horizontal gas well typically ranges from 1.6 to 2.5 MMCF/d [million cubic ft/day] (45,309 to 70,797 m^3/d) with well EUR of 2.4 to 3.5 BCF [billion cubic feet] (6.80 E07 to 9.91 E07 m^3). Declines in production can be 50-55% during the first year for a Barnett horizontal well.(6) When determining good well candidates for refracturing, one should consider other factors besides production decline. Reservoir quality and completions effectiveness including the azimuth of the fracture should also be considered.(2),(7)

In the Barnett Shale, refracs have been successful, especially when wells that were originally fractured with gelled fluids or foams have been refractured with slickwater. This was demonstrated quite convincingly in the second refrac of the Mitchell Energy "discovery" shale well using slickwater where the initial post-refrac production was triple those of the initial frac using foam and the first refrac using gelled fluid.(8) This is attributed to the slickwater bypassing polymer damage, opening smaller fractures than what gelled fluid could invade, and extending the fracture system more because of the larger quantities of slickwater used.(8) When new areas in the shale are exposed by a refrac, especially if re-perforated in new locations in the lateral, there should also be a gain in reserves.

Figure 1: Cross section of the Fort Worth Basin in North Central Texas showing the Barnett Shale(6)



Development

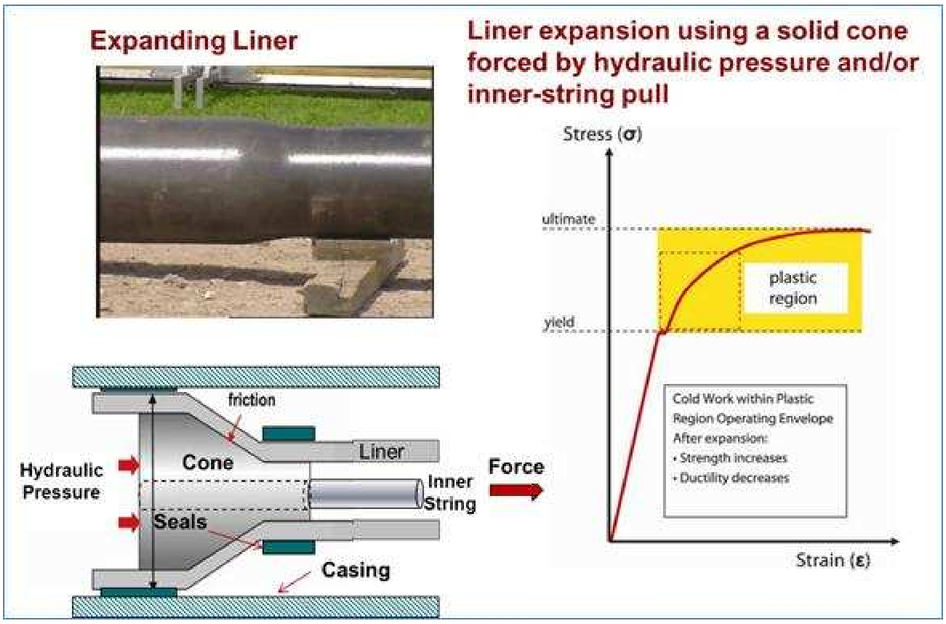
<u>Description of the Solid Expandable Technology in this Work</u>

General Description

There are several commercial processes for expanding solid-steel liner down-hole for wellbore repair and perforation isolation.(9) All of these use some form of hydraulic pressure and/or mechanical force to expand the liner and/or sealing elements downhole at in situ temperature and hydrostatic pressure conditions. The process used in this work is a hydraulically pressured cone-driven expansion assisted by mechanical pull from the innerstring running from the rig floor to the top of the cone as shown in Figure 2. Clean fluid pumped behind the cone through the innerstring exerts hydraulic pressure behind the cone which is machined using specially formulated hardened-steel. In addition, pull applied to the innerstring can increase the force available for the expansion. When the net stress applied to the liner exceeds its yield stress, the liner will start deforming in the plastic region of the stress-stain envelope, in a cold-working manner. The cone angle is designed such that the total deformation of the liner does not exceed the strain that creates the ultimate stress necessary for the material to fail. The strength of the liner actually increases during expansion although the remaining ductility is reduced.

The tubing used for the expandable liners is manufactured using ERW [electric resistance welding] and a special quality steel. This steel is designed to match the strength properties of L-80 steel but to have enhanced expansion properties and is available in a range of sizes. For refracturing purposes, the usual sizes are 4-1/4 in. (107.95 mm). for use in 5-1/2 in. (139.7 mm) base casing and 5-1/2 in. (139.7 mm) for use in 7.00 in.(177.8 mm) base casing. For higher pressure and temperature applications and for the smallest size base casing, 4-1/2-in.(114.3 mm), special partially expandable systems or single-joint liners, where connections do not have to be expanded, have been designed using 110 ksi (758 MPa) rated materials. This paper considers the application of refrac liners for the Barnett Shale and other shale formations where temperatures and refrac pressures are moderate enough to allow the use of liner with strength properties comparable to L-80 as well as connections with standard tensile loading ratings.

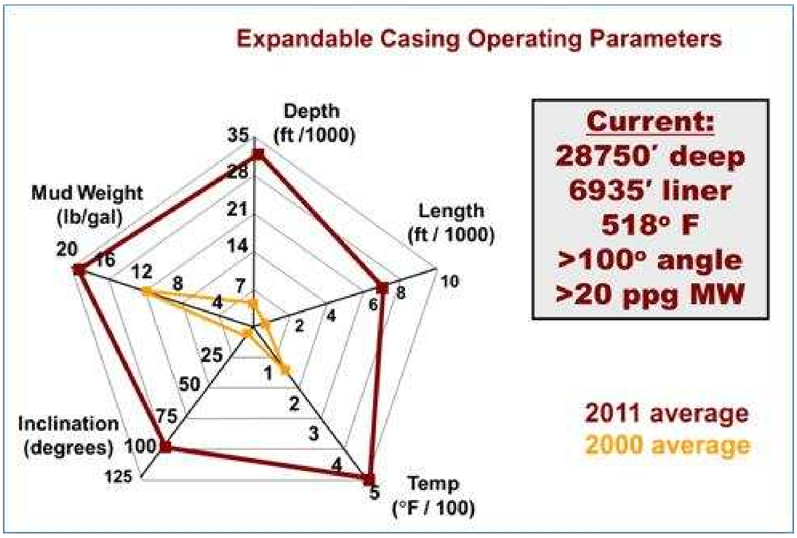
Figure 2: Cone driven expansion using hydraulic pressure and/or inner-string pull



The top photo in Figure 2 shows a liner in process of expansion. The amount of increase in ID during expansion varies from 5% to 18%, and depends on the size and weight of the base casing. However expansions have been done successfully above 20%. Wall thickness does not decrease much during the expansion, usually less than 4%. During the expansion, the liner also shrinks in length by a small amount, usually less than 5%. The illustration in the lower part of Figure 2 shows seals both uncompressed and compressed after expansion. The compressed seals support the liner in the base casing and provide isolation for frac stages. These also provide isolation from unwanted perforations as well as from casing damage. Cone expansion takes place at rates from 30 to 15 ft/min. (9.14 to 4.57 m/min.) although the effective rate is less when taking into account the time for disconnecting and laying down workstring joints. An internal lubricant is coated on the inner surface of the liner to minimize cone friction during expansion. Sometimes, a secondary lubricant is added to the wellbore fluid to assist in running the expandable liner into the wellbore. A special connection sleeve is installed with each connection to protect it from being damaged while running in the wellbore. This sleeve is usually 0.04 in. (1.02 mm) thick which adds 0.08 in. (2.04 mm) to the OD of the liner which should be less than the drift of the base casing.

This expandable liner process was first successfully implemented in 1998 and has undergone upgrades and refinements that now allow a wide range of operating conditions for drilling, production, and well completion applications. Figure 3 shows how the ranges for the various operating parameters have increased during the last 13 years. Presently, solid expandable solutions have been constructed and installed for applications requiring: lengths to 6935 ft. (2114 m), seals for temperatures to 400°F (204°C) (with special applications up to 518°F (270°C), up to 20 ppg [pound mass per gallon] (2397 kg/m^3) mud weight, installations to depths of 28,750 ft (8,763 m) MD [measured depth], and installations in wells with inclinations up to 100 degrees.

Figure 3: Operating Parameters for the Solid Expandable Liner



Description of the Well and Expandable Liner

The first case history will be used to provide a more detailed description of the well and expandable liner. The refrac liner used in the first case history was installed in the lateral section of a horizontal well in the Barnett Shale referred to here as Well #1. This well has 10,730 ft. (3270 m) of 5-1/2-in. (139.7 mm) 17 lb/ft (25.30 kg/m) N-80 production casing. Well #1 has a total length of ~10,800 ft MD (3292 m) and a TVD of ~7000 ft (2134 m). The well was initially completed with perforation clusters in the lateral section from 7633 to 10628 ft (2327 to 3239 m) spaced about 100 ft (30.48 m) apart. The initial fracturing treatment was done in 4 stages with total volumes of 32,000 gallons (121 m^3) of acid and 1.6 million gallons (6057 m^3) of slick water, and 713,000 lb (323,417 kg) of frac sand.

Well #1 was produced for 3 years during which time production dropped from a peak production of 2.6 MMCF/d to 0.4 MMCF/d (73,600 to 11,300 m^3/d) after which the decision was made to re-fracture the well. Mechanical isolation of perforations was designed to be done using ~3244 ft (989 m) of 4-1/4-in. (107.95 mm) expandable L-80-strength expandable liner. Table 1 shows the dimensions and properties of the liner before and after expansion.

Isolation of stages and frac clusters was done using joints of this liner with bands of elastomer thermally bonded to the liner surface. These joints are referred to as anchor hangers because of their ability to anchor the liner in place as well as to isolate frac stages and/or perforation clusters. Each of the interior anchor hanger joints contained three bands of elastomer bonded to the surface of the liner spaced evenly over a 30 ft (9.14 m) interval. The interior anchor hangers had an average length of 41 ft (12.5 m) each. The first and last anchor hanger joints were 21 ft (6.40 m) long with five bands of elastomer.

The refrac was planned to occur with an optimized number of stages with anchor hanger joint spacing designed to demonstrate both stage and perforation isolation. All anchor hanger joints, except for the first and last were positioned to straddle directly across each perforation cluster. The last perforation cluster at the toe of the well was left opened to facilitate the pumping of tools during the refracturing treatment.

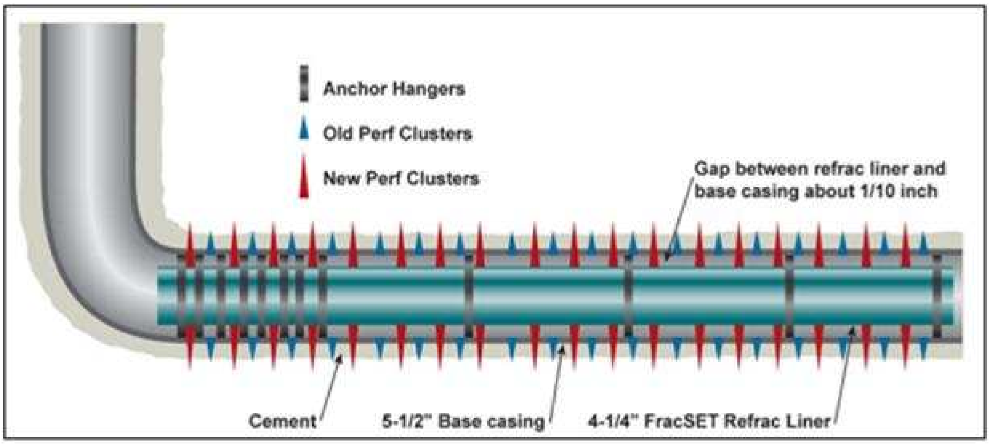
Table 1: Dimensions and Properties of the Expandable 4-1/4 inch liner.

Pre-Expansion Specifications		Post-Expansion Specifications	
Grade	EX-80	Expansion Ratio	12.3 %
Nominal Yield	80,000 psi	Collapse	3,980 psi
Nominal Weight	10.70 lb/ft	Nominal Weight	11.35 lb/ft
Nominal OD	4.250 in.	Nominal OD	4.688 in.
Nominal ID	3.750 in.	Nominal ID	4.210 in.
Drift ID	3.625 in.	Drift ID	4.151 in.
Wall	0.250 in.	Wall	0.239 in.
Internal Yield	8,240 psi	Internal Yield	7,348 psi

The concept for the anchor hanger spacing was that the lower 2/3 section of the refrac liner would have approximately 500 ft (152.4 m) spacing between anchor hanger joints whereas the upper 1/3 of the liner would use anchor hanger joints straddled across each existing perf cluster.

After the installation of the refrac liner, new perforation clusters were shot in between the old perforation clusters spaced at distances of approximately 100 ft (30.48 m). The refrac treatment was done using optimally positioned frac plugs. Thus, the first stages were over lengths of about 500 ft (152.4 m) in which the interior perf clusters were not isolated by the anchor hangers – only stage isolation was achieved. In the last stage, each of the old perforation clusters was isolated by an anchor hanger placed over them. It may be that the small gap of 0.102 in. (2.59 mm) between the expanded liner with OD of 4.688 in.(119.08 mm) and base casing with ID of 4.892 in. (124.3 mm) would be effective in preventing channeling down the annulus to neighboring perforation clusters, especially when proppant was being pumped. This gap is further reduced at the connections to 0.042 in. (1.07 mm) because of the presence of the connection sleeves. Fracturing diagnostics, such as downhole microseismic could be used to tell if fractures were being created uniformly over the stages and whether individual isolation of perforation clusters is necessary. Figure 4 shows an approximate illustration showing spacing of anchor hangers and perforation clusters. Here, the 1/10 inch (2.54 mm) gap is exaggerated to show how channeling in the annulus could occur, although as discussed, this would be expected to be minimal.

Figure 4: Illustration of anchor hanger and perf spacing for the refrac of Well #1.



Placing a frac plug above the previous anchor hanger and within the 500 ft (152. m) interval of interest would expose this portion of the refrac liner between the frac plug and the previous anchor hanger to a collapse condition. This point should be considered in refracturing design. Sufficient expandable liner was used such that the end of the post expanded liner was 100 to 200 ft (30.48 to 60.96 m) above the top most perforation cluster.

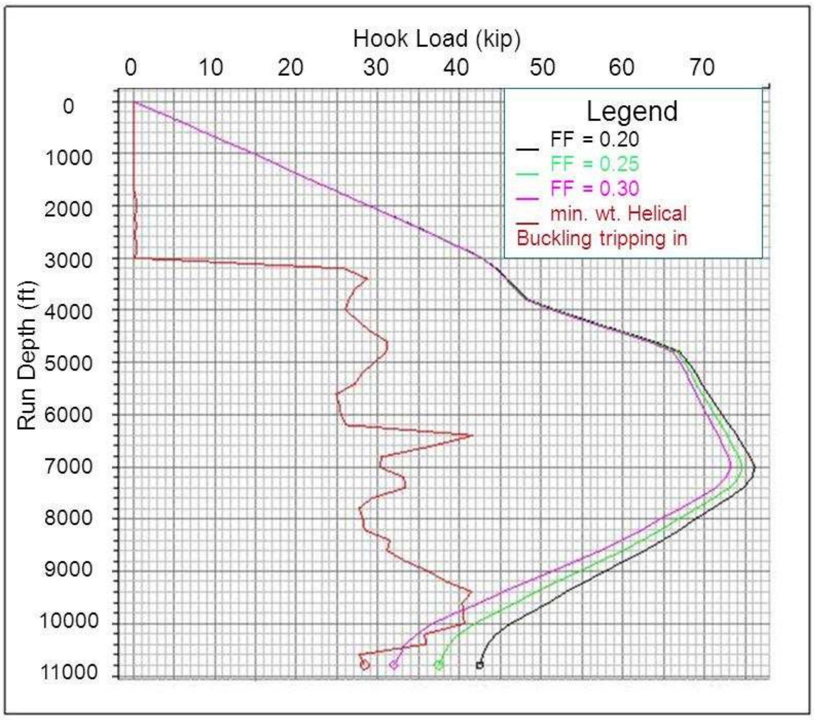
The Installation Process

Of primary importance is achieving a safe and successful installation as planned. To accomplish this requires quality assurance in engineering, manufacturing, and operations.

Engineering provided the specifications of the pre- and post-expanded liner (Table 1) as well as the elastomer specifications. Also calculated were the expected torque and drag requirements to avoid buckling and lock-up while running in the refrac liner. Such a calculation was modeled using a 2-7/8 in. (73.025 mm) workstring connected to the 4-1/4-in. (107.95 mm) refrac liner with well survey information for a range of friction factors from 0.2 to 0.3. The elastomer-clad refrac liner with its innerstring was modeled as a composite string. To avoid buckling, it was found necessary to use drill collars in the workstring. Figure 5 shows that buckling is observed at ~ 9600 ft (2926 m) with a friction coefficient of 0.3. However, it was believed that a conservative estimate of the actual friction factor was 0.25 considering the values for typical muds used.

A second analysis was performed to understand a safe overpull margin during the expansion. This analysis considered the refrac liner as stationary while the innerstring is pulled from the bottom. While pulling out using a 0.25 friction coefficient, the overpull margin between the actual hook load and 80% of yield was calculated as 120 kips (5.338 E05 N). With the anticipated pipe-body expansion force of 57 kip (2.535 E05 N), this would imply adequate overpull to expand the pipe considering the standard expansion technique relies on hydrostatic pressure as well.

Figure 5: Torque and drag analysis showing the impact of friction coefficient on hook load when running the refrac liner assembly downhole



Another engineering concern was the availability of technology to provide sufficient perforating of both the refrac liner and the 5-1/2-in. (139.7 mm) 17 ppf (25.30 kg/m) casing as well as the availability of composite frac plugs that could be run and set in the refrac liner. Commercially available perforating guns and frac plugs were identified that could perform in the expanded 4-1/4-in. (107.95 mm) refrac liner.

The liner was manufactured as per specification with proprietary expandable flush connections with collapse and yield ratings comparable to those in Table 1. The bonded elastomer seals were also designed and tested to have sealing capacity comparable to the yield ratings in Table 1. The inside of the launcher and refrac liner were coated with a special lubricant to aid expansion. All equipment was inspected before shipping and after arriving on location for any damage. The expandable liner was unloaded using special handling procedures to avoid damage with threads inspected onsite.

Before installation began, all string components were drifted with their standard drift for the innerstring and for the 2-7/8 in. (73.025 mm) tubing workstring. The wellbore was circulated until clean and then drifted to the setting depth using a special BHA with milling capability to ensure passage of the refrac liner and launcher. Water with calcium carbonate, LCM [lost circulation material], and liquid polymer helped plug off old perforations so circulation could be established on the clean out run. Viscous sweeps were circulated to ensure removal of any debris from the cleaning until returns were clean. Then the well fluid was treated with a lubricant to enable low friction running of the refrac liner into the horizontal section.

Throughout the installation, safety meetings were held before rigging up, tour and personnel changes, and the high pressure expansion step. The first step of the installation was to run the launcher made up to the lower anchor hanger into the well head. In this installation, liner was run using special handling equipment to avoid damaging the liner. The 0.06-in. (1.524 mm) connection sleeves were added over the connection pins of the liners and the liner joints were made up to the specified torque for this refrac liner. The ~3200 ft (975 m) of the liner were made up to the lower anchor hanger and held in the slips.

With the liner run into the wellhead, the casing tools were rigged down, and the innerstring running tools were rigged up. The innerstring was then run into the refrac liner comprising an upper safety sub followed by the joints of tubing and several joints with debris-catching devices to sweep debris away from the expanding cone. The innerstring was tagged on the lower safety sub on the expansion cone assembly and rotated to screw into it. The liner was filled with clean lubricated water. After the innerstring was made up, the innerstring tools were rigged down. A tapered guide was threaded unto the top of the upper anchor hanger to facilitate running of tools through the expanded liner such as composite frac plugs and perforating guns. The refrac liner assembly was then run down the wellbore using joints of 2-7/8-in. (73.025 mm) workstring connected to the innerstring using a crossover, followed by drill collars, and then another crossover.

During running down hole, the liner hung up 10 stands from the setting depth. It could not be washed down further although it was broken free so that its free pickup weight was determined as 130,000 lbf (5.78 E05 N). To force it downhole further, the backside was filled with water with the 2-7/8 (73.025 mm) stripper rubber installed and the refrac liner assembly was pumped down. The setting depth was confirmed by tubing tally rather than tagging bottom and pulling back because of concerns of encountering debris pushed downhole during the mill out operation.

The last stage of the installation was the expansion of the liner. A rig rental pump was found to be sufficient for pumping the expansion. From the pump, 2 in. steel chiksan lines were connected to the workstring, and lines were tested to 5,000 psi (34.5 MPa). The 2 in. steel lines were used to circulate and land the dart. One tubing capacity was circulated at 2 bpm (0.318 m^3/min) before pumping the dart to the float to pressure up and initiate expansion. The dart seated with 2800 psi (19.3 MPa) and the tubing was picked up with 130,000 lbf (5.78 E05 N) on the weight indicator. The rig pump was pressured up to 5000 psi (34.5 MPa) to initiate expansion at a rate of 0.5 bpm (0.0795 m^3/min) and an expansion rate of 28 ft/min (8.54 m/min). Expansion of the first anchor hanger (with elastomers) was continued until completed and the refrac liner anchored in the base casing as determined by putting on 20,000 lbf (8.896 E04 N) overpull. Expansion was completed making 50 full pulls to expand the liner racking back doubles with the aid of a DPC [drill pipe circulation] tool to speed up expansion. Average expansion pressure was 3,000 psi (20.69 MPa) with 20,000 lbf (8.896 E04 N) overpull. The liner was pressure tested to 4,500 psi (31.03 MPa) for 5 minutes before bleeding off. The float shoe in the nose assembly of the launcher at the end of liner was not drilled out.

In summary, the installation procedure went as planned except for getting hung up short of the setting depth when running the refrac liner. Backside pumping completed the run successfully. In future refracs a special lubricant was added to the wellbore fluid that allowed running of the refrac liner to the setting depth with no problems.

Production Results

First Case History

There is limited information regarding the details of the refrac of Well #1 except as was mentioned previously. It is known, however, that two offset wells on the same pad as Well #1, referred to here as Well #2 and Well #3, were also refractured at approximately the same time using other methods of perforation diversion such as mentioned in the introduction of this section. The monthly production data for these three wells are public information and the gas production is plotted in Figure 6. Well #1 with the refrac liner shows post-refrac gas production as good, or better than those for the two offset wells. Public information on these wells also indicates that the original fracturing treatments for these three wells were similar as shown in Table 2, and that the layout of these wells can be approximated as in Figure 7.

Figure 6: Gas production history pre and post-refrac for Wells #1, #2, & #3

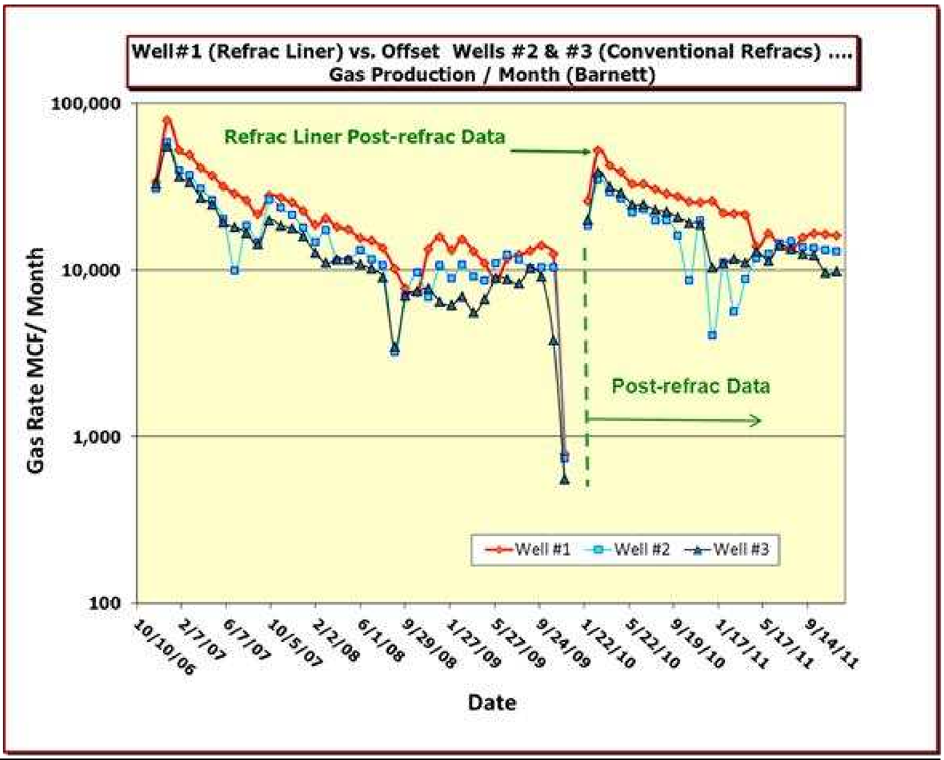


Figure 6 indicates that gas production for Well #1 with the refrac liner was better than that for the other two wells for both the initial frac and the refrac treatment. The post-refrac production of Well #1 exceeds that for Wells #2 and #3 by over 161 MMCF (4.56 E06 m^3) over the 23 month post-refrac period shown in Figure 5. Table 3 gives the cumulative post-refrac productions for each well, and shows that the ratio of the production for Well #1 to offset Wells #2 and #3 is 1.53 and 1.39 respectively. Many factors can contribute to this difference in production. Table 3 compares the ratios of various factors including interval lengths and fracturing material parameters. It can be seen that the ratios of interval length alone cannot explain the difference in production. When comparing Well #1 with Well #3, it can be seen that the ratio of amounts of frac fluid and proppant used could explain the difference, but this does not hold true when Well #1 is compared with Well #2. Of course, the increase in production for Well#1 vs. its two offsets could be an additive effect of all the variables. But, there are other factors that can also come into play, in addition to the fracturing parameters and the type of refrac diversion method. One is location of the well. Figure 7 shows that Well #3 was positioned in between Well #1 and Well #2 and could be impacted by hydraulic fracture overlap. Also, depending on the position of neighboring wells, the production for Wells #2 and #1 could also be impacted.

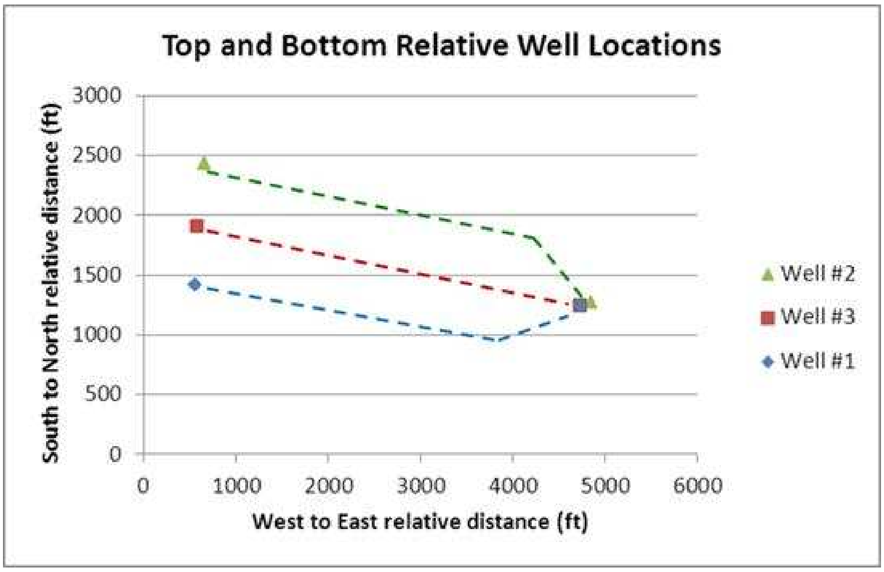
Table 2: Initial fracturing treatment information for Wells #1, #2, & #3

	Perf. Top MD ft	Perf. Base MD ft	Length Perf. Interval ft	Volume Acid gal	Volume Frac Fluid bbls	Proppant lbs	Avg. Proppant Conc. lbs/gal	Frac Fluid per ft of interval bbls/ft	Proppant per ft of interval lbs/ft
Well #1	7633	10628	2995	32000	37818	713000	0.45	12.63	238.06
Well #2	7917	10594	2677	24000	33012	625400	0.45	12.33	233.62
Well #3	7627	10186	2559	24000	21485	462860	0.51	8.40	180.88

Table 3: Ratio of Well #1 parameters to offset Wells #2 & #3 parameters

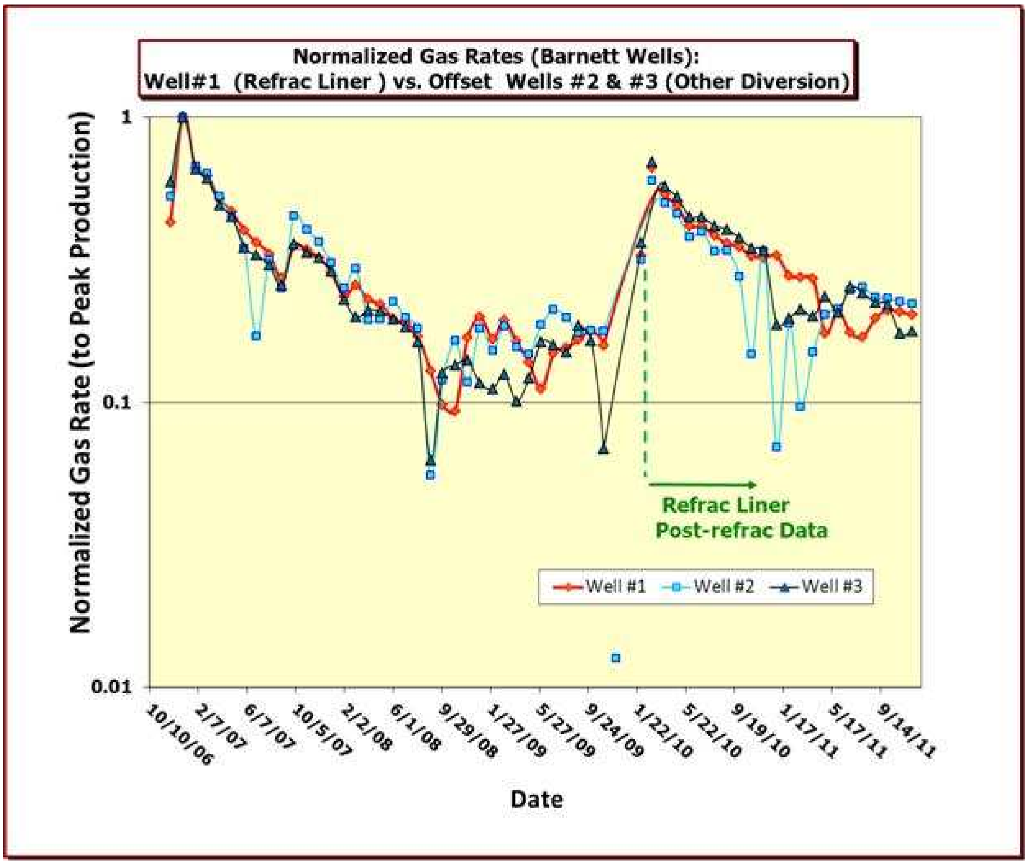
	Post-refrac Cumul. Prod. 23 month Mscf	Ratio of Well #1 to offset well:							
		Post-refrac Cumul. Prod. 23 month	Perf. Interval Length	Volume Acid gal	Volume Frac Fluid bbls	Proppant lbs	Avg. Proppant Conc.	Frac Fluid per ft of interval	Proppant per ft of interval
Well #1	574168	1	1	1	1	1	1	1	1
Well #2	374,523	1.53	1.12	1.33	1.15	1.14	1.00	1.02	1.02
Well #3	412397	1.39	1.17	1.33	1.76	1.54	0.88	1.50	1.32

Figure 7: Approximate relative positions of Barnett Wells #1, #2, & #3



To account for the various factors that can affect the post refrac production, the production data in Figure 6 were normalized to their initial peak post-frac production. In this way, it can be seen how the refrac performed relative to its initial frac, and thus, one can judge the effectiveness of the refrac and can compare it with the effectiveness of the refracs of the other wells. Figure 8 shows the monthly productions normalized to the peak initial post-frac production for each of three wells. They are surprisingly similar. The peak normalized production for the three wells after the refrac range from 60% to 70% with Well #1 having a peak normalized refrac production of 66% and Well #3 having the highest at 70%.

Figure 8: Normalized gas production data for Wells #1, #2, & #3



It is also interesting to look at the post-refrac water production for the three wells. Figure 9 indicates that the water production for Well #1 is much greater than that for the other 2 wells for the first 6 months of post-refrac production. Also, notable is that the post-refrac water production for Well #1 is about the same as its water production after the initial frac. This could indicate that more new rock is being fractured when using the refrac liner with more higher-pressured shale being stimulated than in the offset wells. The new more highly-pressured fracture network would be more likely to flow back injected fluids. Other explanations for these water production data could be the particular allocation of water production adopted if the three wells were flowed into the same tank, or variations in the artificial lift operations of these wells.

Figure 10 shows the water production normalized to the peak water production following the initial frac. Again this shows that Wells #2 and #3 had post-refrac water production significantly less than their initial post-frac water production, whereas Well #1 post-refrac production was similar to its initial water production. The variable nature of the water production for the three wells would suggest outside manipulation such as changing the well operating parameters or allocations.

Figure 9: Water production history pre and post-refrac for Wells #1, #2, & #3

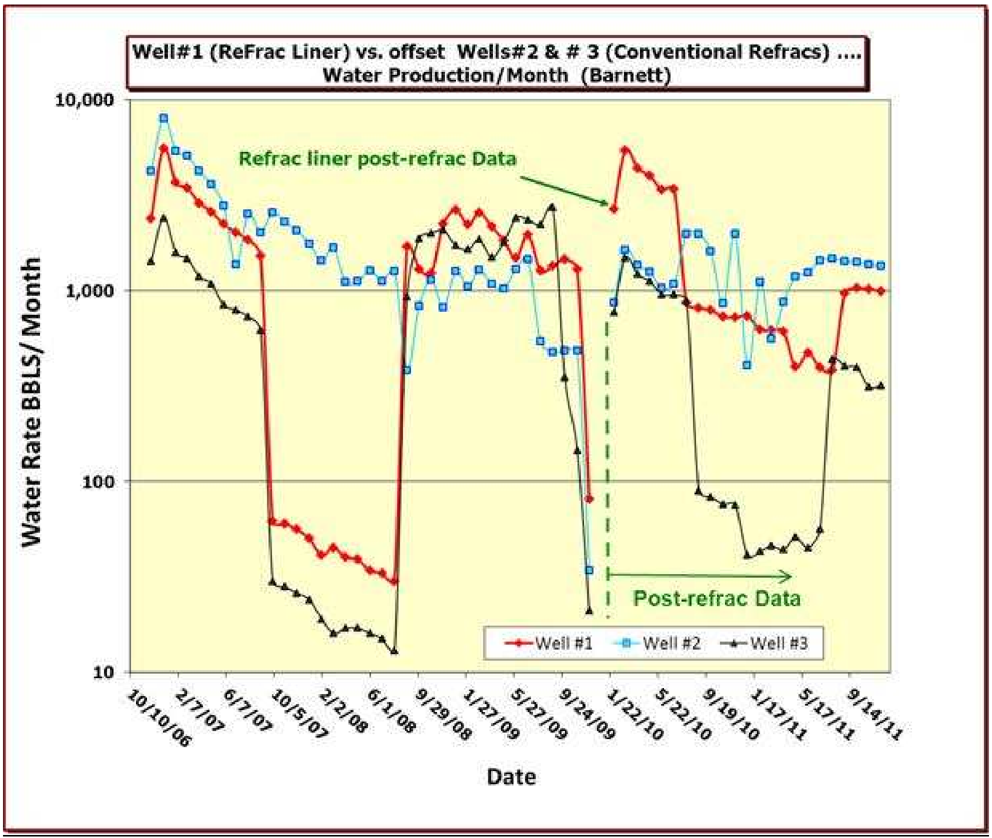
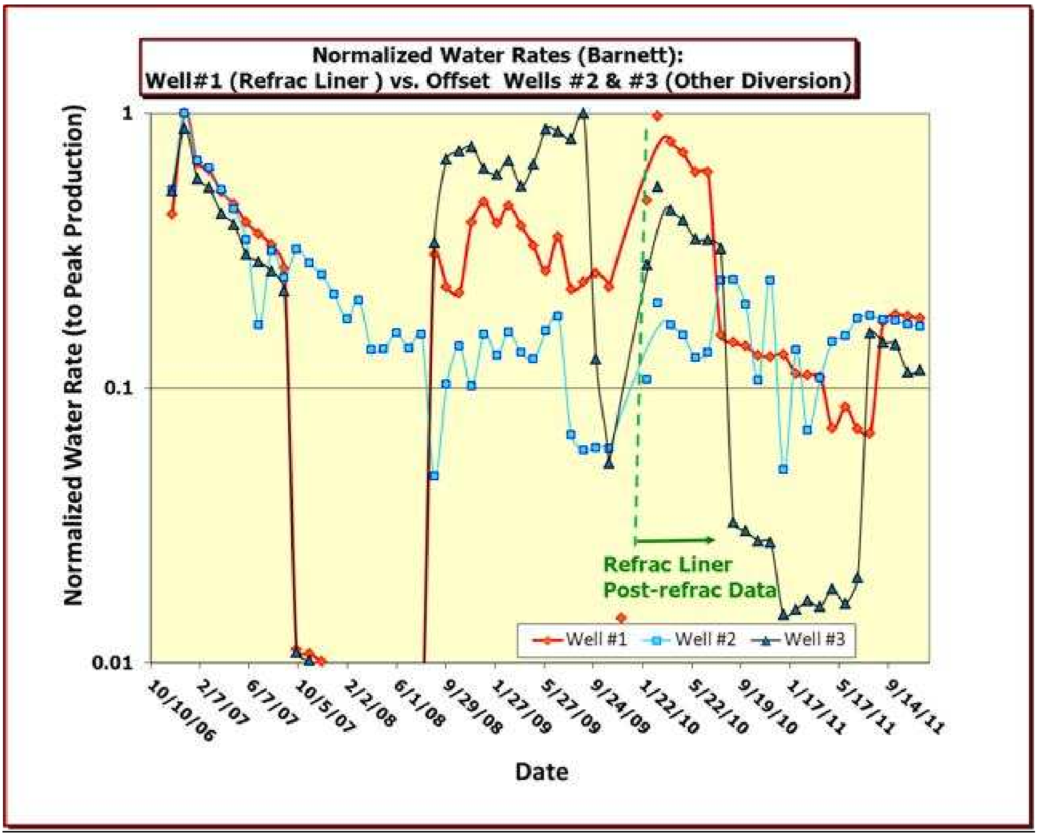


Figure 10: Normalized water production history pre and post-refrac for Wells #1, #2, & #3



Second Case History

For the second case history, another Barnett refrac was done on a different pad (Well B) using the 4-1/2-in. (107.95 mm) expandable liner in 5-1/2-in. (139.7 mm) 17 lb/ft (25.30 kg/m) casing for perforation diversion. Another well on the same pad (Well C) was refractured at nearly the same time using a different method of refrac diversion. Learnings from the first refrac (Well #1) were utilized when installing the refrac liner in Well B that facilitated the installation, most notably using the appropriate lubricant in the well fluid while running the ~3400 ft. (1036 m) of refrac liner. This lubricant was also used in the successful installation of ~4300 ft (1311 m) of 4-1/2-in. (107.95 mm) expandable liner in a lateral with 5-1/2-in. (139.7 mm) 20 lb/ft (29.76 kg/m) casing in the Marcellus Shale. However, this was for an initial fracture stimulation not a refrac, and the data will not be presented here.

The production performance of Wells B and C are shown in Figures 11 and 12 as the production rates and the normalized production rates respectively. Wells B and C show some similar trends to those for Wells #1, #2, and #3. The gas production rates for Well B with the refrac liner become greater after about one year of production. The total post-refrac gas productions for these wells are 465,274 MCF (1.318 E07 m^3) vs. 373,415 (1.058 E07 m^3) MCF for Wells B and C respectively. The normalized production rates in Figure 12 show Well B having significantly higher water rates than Well C. Moreover, these post-refrac water rates are substantially greater than the initial water production rates which may mean that these wells have fractured into water below (e.g. into the Ellenburger formation).

Figure 11: Gas and water production rate histories pre and post-refrac for Wells B and C

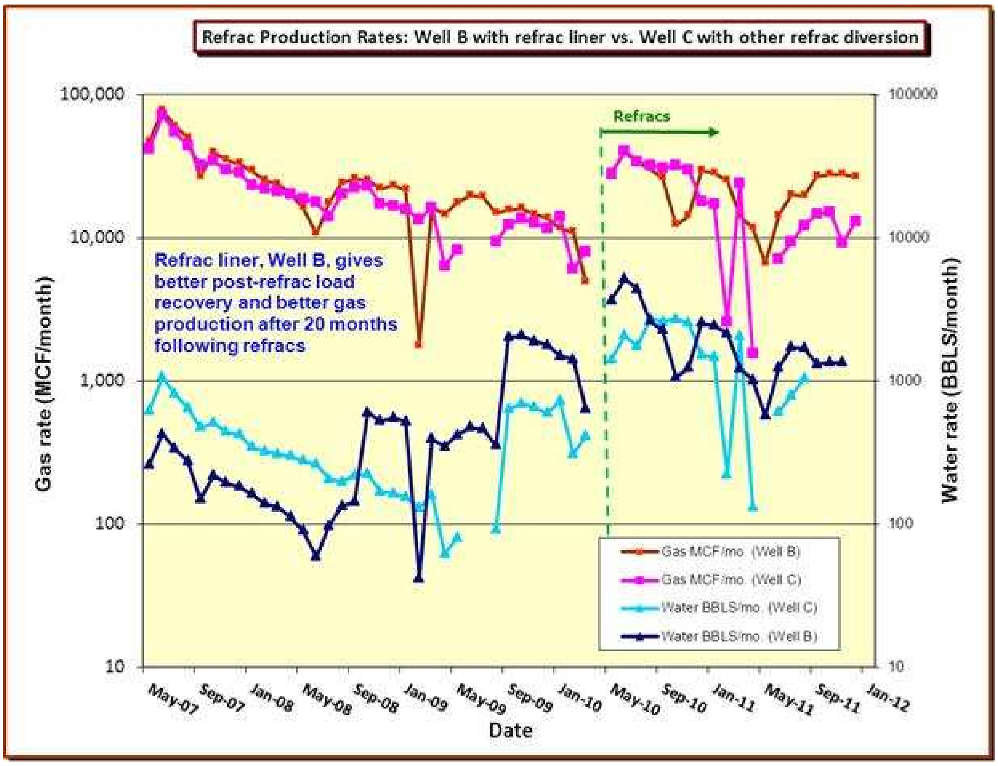
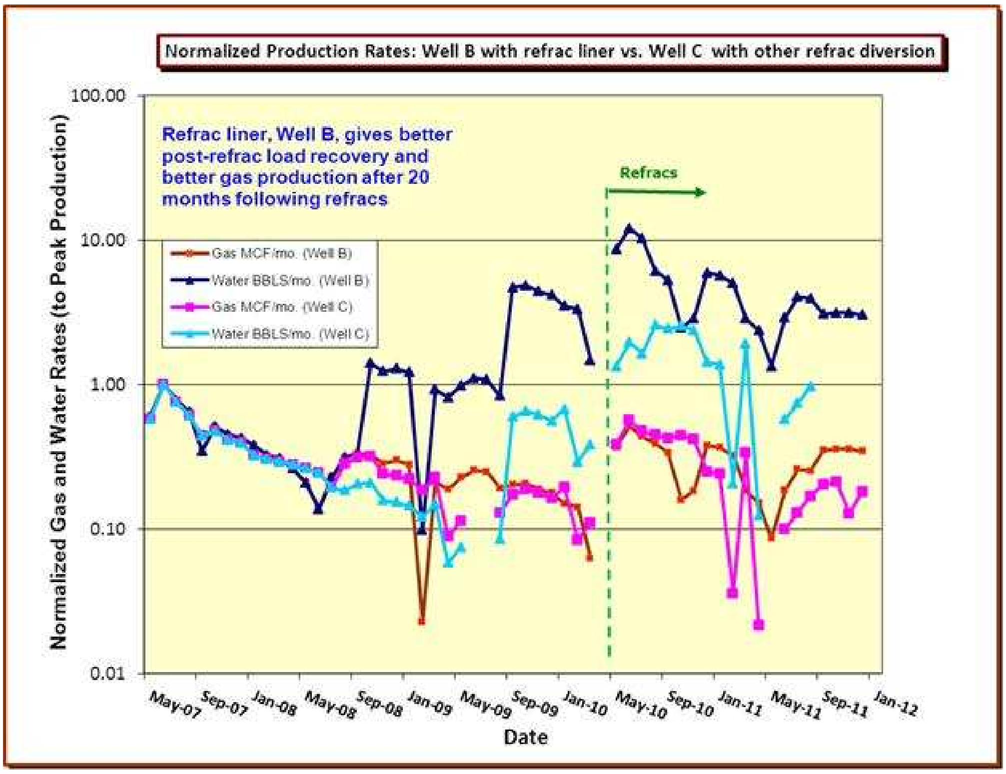


Figure 12: Normalized gas and water rates for pre and post-refrac for Wells B and C



Conclusions

This study has shown that solid-steel expandable liner with suitably positioned anchor hanger seals is a viable method for isolating perforations to ensure that staged fracturing proceeds as desired. The liner can be run to the desired setting depth in long laterals, expanded downhole to achieve frac-stage/perforation isolation and to maximize liner ID, and perforated between old perforation clusters to stimulate new rock to maximize reserves.

The two case histories presented here indicate that production results using the expandable refrac liner give comparable or better gas production than other methods of perforation isolation such as squeezing off the old perforations or diversion of flow from the old perforations using diverting agents. The results of the two sets of data show that initial water production following the refrac may be increased when using the refrac liner, which would be desirable to get the frac-fluid load back. However, continued water production is not conducive to production.

For these case histories, it is believed that individual perforation cluster isolation within each frac stage was not that necessary because of the small annular clearances between the base casing and expanded liner. Important steps for successfully running the liner were to circulate LCM to reduce flow into the old perforations to achieve good circulation for cleaning the wellbore, and to use suitable lubricants in the wellbore fluid to reduce drag. Torque and drag analyses for the liner and workstring are also required to determine the need for drill collars near the liner top to avoid buckling.

The main advantage of the refrac liner in these case studies was in giving the operator assurance as to refracturing a given planned frac stage. Once this refrac liner is installed, the subsequent frac treatment can proceed more easily with less real-time diagnostic expenses such as microseismic to monitor injection location, and interruptions into the fracturing treatment to make downhole adjustments to help achieve the desired injection objectives.

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Nomenclature and Unit Conversions

bbls to m^3 [barrels to cubic meters]: 1 bbls = 0.1590 m^3

BCF to m^3 [billion cubic feet to cubic meters]: 1 BCF = 2.832 E07 m^3

bpm to m^3/min [barrels per minute to cubic meters per minute]: 1 bpm = 0.159 m^3/min

EUR = estimated ultimate recovery

ft to m [feet to meters]: 1 ft. = 0.3048

ft/min to m/min [feet per minute to meters per minute]: 1 ft/min = 0.3048 m/min

gal to L [gallon to liter]: 1 gal = 3.785 L

gal to m^3 [gallon to cubic meters]: 1 gal. = 3.785 E-3 m^3

in. to mm [inches to millimeters]: 1 in. = 25.4 mm

kip to N [1000 pounds force to Newtons]: 1 kip =4.448 E03 N

ksi to Pa [1000 pounds force per inch^2 to Pascals]: 1 ksi = 6.895 E06 Pa

lbf to N [pounds force to Newtons]: 1 lbf = 4.448 N lbs (or lb) to kg [pounds mass to kilograms]: 1 lbs = 0.4536 kg

lbs/gal to kg/m^3 [pounds mass per gallon to kilograms per cubic meter]: 1 lbs/gal = 119.83 kg/m^3

lbs/ft to kg/m [pounds mass per ft to kilograms per meter]: 1 lbs/ft = 1.488 kg/m^3

MCF/month to m^3/month [1000 standard cubic feet per month to cubic meters/month]: 1 MCF/month = 28.32 m^3/month

MMCF to m^3 [1,000,000 standard cubic feet to cubic meters]: 1 MMCF = 2.832 E04 m^3

ppf to kg/m [pound mass per foot to kilogram per meter]: 1 ppf = 1.488 kg/m^3

psi to MPa [pounds force per $inch^2$ to megaPascals]: 1 psi = 0.006895 MPa

TCF to m^3 [trillion standard cubic ft to cubic meters]: 1 TCF = 2.832 E10 m^3