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A Practical Guide to Modern Diversion Technology

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Abstract

Success of a matrix acidizing or fracture stimulation treatment depends upon complete coverage of all zones. The diversion process is used to help ensure that stimulation fluids are distributed across the entire interval to be treated. The diversion method best suited for a particular situation depends on many factors, including the type of well completion, perforation pattern, zonal isolation method, and stimulation technique. Selection of the most appropriate diversion method is also influenced by variations in formation permeability or stress contrasts along the interval to be treated. The purpose of this paper is to provide a historical review of diversion technologies applied in matrix acidizing and hydraulic fracturing treatments and to build upon past experiences to allow optimization of modern diversion practices with self-degrading particulates. Diverter design guidelines will be provided guiding the reader toward the best practices for a) choosing the appropriate base material, b) selecting the correct particle size distribution, c) deploying the diverting agent properly, and d) monitoring the execution of the diverter stages. Laboratory and field data will be provided to supplement the design process.

Introduction

Success of a stimulation treatment often depends on complete coverage of all zones. To accomplish complete coverage, some placement aid may be used to divert the treating fluid from one zone to another. There are three broad approaches to achieving diversion in stimulation treatments: 1) mechanical diversion, 2) rate and pressure diversion, and 3) chemical diversion.

Mechanical diversion includes opposed cup packers, perforation wash tools, squeeze packers, retrievable bridge plugs, and sliding sleeves. While these methods are effective, there are costs and risks associated with mechanical intervention into a wellbore. Ball sealers can also be considered a method of mechanical diversion, although the efficiency is harder to evaluate.

Rate and pressure diversion, commonly referred to as limited entry diversion, was first introduced for hydraulic fracturing operations by Lagrone and Rasmussen (1962). An advancement to the limited entry technique, popular in high rate matrix acidizing, was coined MAPDIR (maximum pressure differential and injection rates) by Paccaloni (1995). The combination of these two approaches was taken to the extreme by Hansen and Nederveen (2002) when they introduced the CAJ (controlled acid jet) concept allowing effective stimulation of horizontal lateral sections up to 14,000 ft in length. Dons, Jorgensen and Gommessen (2007)

presented 4D seismic data verifying the CAJ technique could be used to stimulate ultra-long horizontal wellbores.

Chemical diversion involves the use of either viscous fluids or soluble particulate diverters to block higher permeability intervals, thereby directing the stimulation fluids to lower permeability or damaged zones. Viscous fluids are generally only effective in matrix stimulation, whereas particulate diversion has application in both matrix stimulation and hydraulic fracturing operations. Foam diversion can be considered a form of chemical diversion that combines the viscous effect with particle-like diversion, as the foam bubbles will bridge on the formation face. [Gdanski \(1993\)](#) provides practical guidelines for foam diversion in both sandstone and carbonate formation. This paper will focus on particulate diversion.

History

Solid diverting agents have been used to enhance stimulation treatments for over 80 years. [Harrison \(1972\)](#) provided a good overview of the first 4 decades of diverter development and usage. The earliest documentation of a diverting agent was in 1936 when a patent was issued to Halliburton Oil Well Cementing Co. for the use of a soap solution that reacted with calcium chloride to form a precipitate. This was a water-insoluble, oil-soluble calcium soap that acted as a diverting material in matrix acid stimulation. One year later Halliburton was issued a patent for the first viscous diverting system which utilized locust bean gum to gel calcium chloride and sodium chloride. Later, sulfuric acid was used as a diverting agent in connection with a conventional hydrochloric acid treatment. After the sulfuric acid was pumped into the wellbore, the pumps were shut down for a short time and then pumping of the hydrochloric acid was resumed. When in contact with the calcium carbonate, the sulfuric acid formed insoluble calcium sulfate, which was the diverting agent. This system was not widely accepted, owing, it is assumed, to the recognition that it could cause potentially permanent productivity damage. This short review introduces two of the most significant of the concerns, even today, that engineers have over the use of diverting agents: 1) can the chemistry be controlled, and 2) will the diverting agent result in a loss of well productivity?

[Nitters and Davies \(1989\)](#) pointed out that another challenge, equally important, is placement of the diversion agents. They presented the results of a theoretical and experimental study undertaken for the purpose of developing a better understanding of the diversion process. At the time, diversion was primarily used in matrix acidizing operations. A number of methods to divert the flow of fluids in a well were available at the time. Economically, chemical diverters were the most attractive choice; however, historically they had proven to be the least reliable approach. It was proposed that the poor performance of chemical diverters was due to lack of a proper design methodology. At the time, application was based on local experience, heavily influenced by subjective judgement with little basis for an engineered design.

Over the next 2 decades, a multitude of chemical diverters were introduced and field trialed. The most commonly used particulate diverting agents included rock salt, benzoic acid, naphthalene, wax beads and oil soluble resins. [Chang and Nasr-el-Din \(2007\)](#) and [Kalfayan and Martin \(2009\)](#) provide two of the most comprehensive reviews of the chemical and particulate diversion techniques used at that time.

Ten years ago, a novel diverting agent based upon a polymeric material that is gradually degraded by water through a process known as hydrolysis was introduced to the industry by [Glasbergen, et.al. \(2006\)](#). The initial application was for diversion in sandstone reservoirs in matrix acidizing operations. The material was also applied to shale reservoirs, in combination with fiber optic distributed temperature survey (DTS) to evaluate the effectiveness of fluid placement, resulting in a Meritorious Engineering Award for Production Operations (2006). Allison, [Curry and Todd \(2011\)](#) expanded the application of the degradable particulate material to fracturing applications. The material is generically referred to as a biodegradable diverter, based upon polylactide resin, also referred to as polylactic acid (PLA), and most often described on Safety Data Sheets with the Chemical Abstracts Service (CAS) number 9051-89-2.

Particulate Diverting Agents

All types of particulate diverting agents function in the same general manner. When fluids containing the particulate material are pumped, they will enter the zone of highest permeability (in the case of matrix acidizing) or zone of lowest stress (in the case of hydraulic fracturing), causing the buildup of a low permeability particle pack on the formation face, within the perforation tunnels or on the perforations. The added pressure drop caused by the particles increases flow resistance to the areas where the diverting agent has been deposited, causing diversion of flow to other parts of the interval where little or no diverting agent has been placed.

To be effective, a particulate diverting material must have a particle size distribution designed to deliver the appropriate flow resistance once placed across the zone of interest. The smaller the mean diameter and broader the particle size distribution; the lower the permeability of the pack. Diverting agents are divided into four size groups: coarse, medium, fine and very fine. The coarse particles have particle distributions in the range of 4 through 18 mesh, medium particles have particles distributions in the range of 20 through 70 mesh, and fine particles fall in the range of 100 through 200 mesh. Very fine, powdered materials will have an average particle size of 325 mesh and smaller. Table 1 summarizes the typical particle distributions in mesh size and millimeters.

Table 1—Typical particle size distributions of commonly available diverting agents

Diverter Size	Application	Typical Mesh Range	Larger Particles (mm)	Smaller Particles (mm)
Coarse	Divert on perforations, on open fractures and vugs in carbonate formations	4 to 18	0.1870	0.0394
Medium	Divert in perforations, on a proppant filled fracture, or behind slotted/wire wrapped sand screens	20 to 70	0.0331	0.0083
Fine	Bridge on the larger particles and reduce the permeability of the diverter pack	100 to 200	0.0059	0.0029
Very Fine	Further reduce the pack permeability and bridge on the formation in far field diversion applications	270 to 400	0.0021	0.0015

Coarse particles are required to divert on perforations, open fractures and large vugs in carbonate formations. Medium particles are used to divert in the perforations, behind slotted/wire wrapped liners in sand control completions, or on a proppant packed fracture during a multi-stage hydraulic fracture stimulation of an unconventional reservoir. Fine particles bridge on the larger diverter particles and reduce the permeability of the diverter pack. Very fine particles further reduce the permeability of the pack and are sometimes used to bridge on the formation in far field diversion applications. A general rule is the broader the mesh size distribution, the better. In some applications, two different diverter sizes will be mixed on location, for example, coarse and medium particles. Figure 1 illustrates the bridging of particles in a proppant filled perforation.

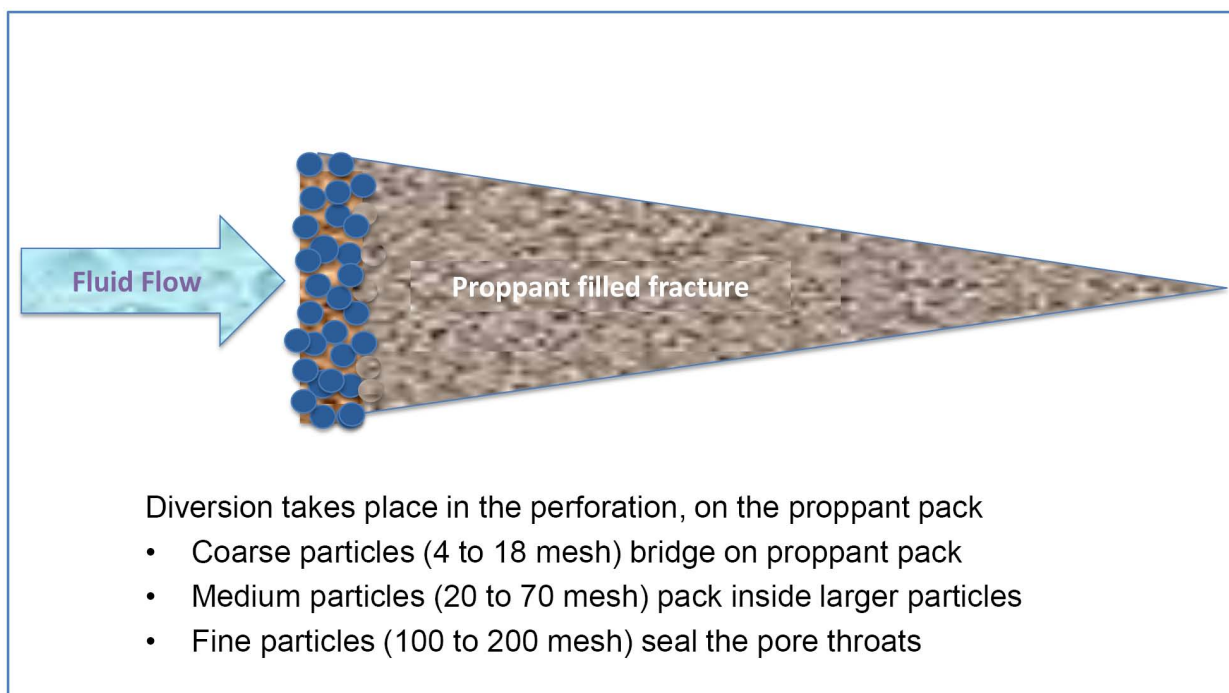


Figure 1—Bridging of particles in a proppant filled perforation

Figure 2 shows the sieve analyses for two commercially available PLA diverting agents which are typically mixed on location. The coarse blend has a particle size distribution primarily in the 6/14 mesh range. The medium to fine blend ranges from 18 mesh to 230 mesh, with the bulk of the particles in the range of 18/140 mesh. When combined on location, these two blends produce a particle size distribution that satisfies the requirements to divert on the most commonly used proppant sizes. Because the two blends are mixed on location, it is possible to vary the ratio and optimize real-time based on the specific well or stage responses.

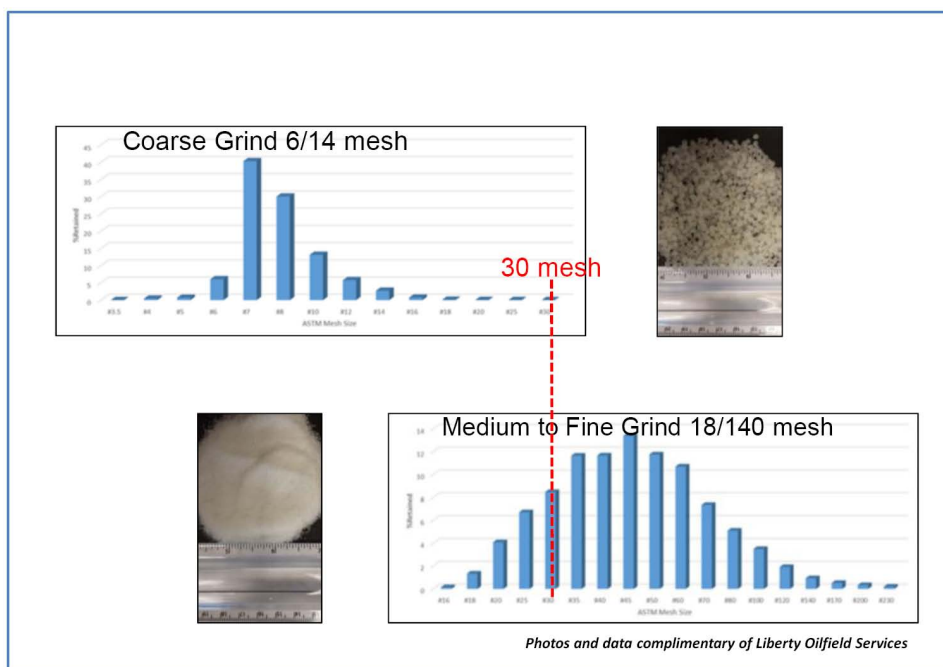


Figure 2—Sieve analyses for two commercial PLA diverting agents

In other applications, the different diverter sizes may be premixed in a bimodal particle size distribution. One such distribution is described by Tang (2014) and two examples are shown in Figure 3.



Figure 3—Example of bimodal PLA diverting agents

In addition to the particle size distribution, the shape of the diverting agents will affect the permeability of pack. Various manufacturing and grinding processes are used to produce particulate diverting agents. As a result, the diverting agents may be very round, very angular, elongated, flaked or even fibrous. Figure 4 shows several versions of commercially available PLA particles, clockwise starting at top left: round, chopped, ground and flaked.

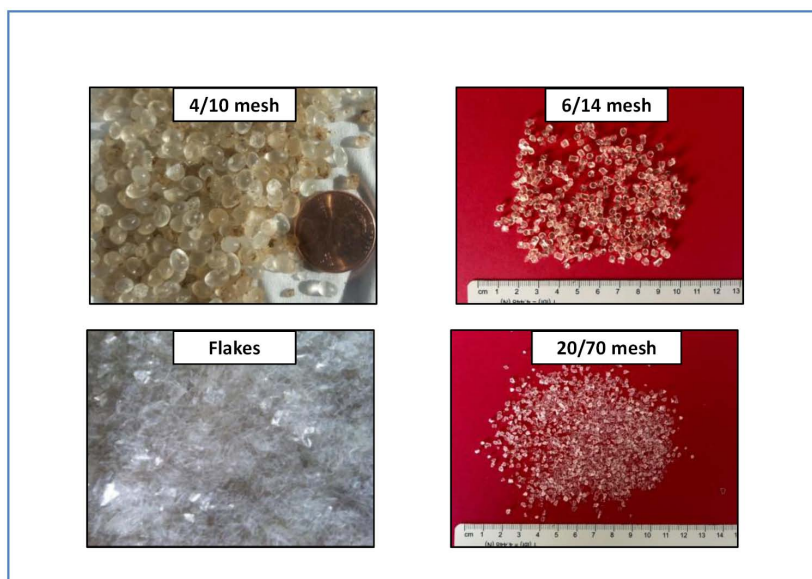


Figure 4—Shape and size of commercially available PLA diverting agents

Particulate diverting agents come in a variety of chemical compositions. Selecting the most appropriate type for a particular treatment depends primarily upon the fluids to be injected, formation fluids to be produced, average treatment temperature and bottomhole static temperature (BHST). The differential pressure that will be placed across the diverter pack is arguably important – more so in hydraulic fracturing applications compared to matrix acidizing applications. The basic desire is that the diverting agents be relatively insoluble in the treatment fluids and dissolve readily (or biodegrade) in the produced or injected fluids. Table 2 summarizes the chemical and physical properties of traditional particulate diverting agents.

Table 2—Properties of traditional diverting agents

Type	Melting Point (°F)	Specific Gravity*	Bulk Density (lb/ft ³)	Solubility in Kerosene* (lbs/bbl)	Solubility in Fresh Water* (lbs/bbl)	Solubility in Saturated Salt Water* (lbs/bbl)
Rock salt	1,472	2.164	92.5	nil	112	nil
Benzoic acid	253	1.316	43.3	6	0.75	0.25
Naphthalene	176	1.145	43.3	42	nil	nil
Wax beads	140-200	0.81-0.92	24.3-27.7	70	nil	nil
Oil soluble resin	280	1.062	32.0	highly**	nil	nil

* Specific gravity and solubilities measured at 75°F

** Solubility in oil varies based upon the substrate material.

Biodegradable diverting agents do not dissolve in treatment or produced fluids. Instead, they degrade, or more appropriately, undergo chemical decomposition. There are several polymeric materials that are gradually degraded by water through a process known as hydrolysis. In this process, water attacks the polymer at certain bond sites and causes the material to cleave. Polymers such as polyanhydrides, polyesters, polyorthoethers, polylactones, polyamides, and polyurethanes are such materials. As an example, when the polyester material known as polyglycolide is hydrolyzed, it degrades into glycolic acid. PLA will degrade to lactic acid, an environmentally benign material. In both cases, the degradation is permanent and the degradation products will not re-solidify on cooling. Both polymers are degraded in water from a very competent solid material into a liquid solution. By controlling the polymerization process, these materials can be manufactured to be quite pliable or very rigid solids. The rate of degradation will depend on the material used, fluid it is in contact with, and temperature.

Step 1: Choosing the most appropriate base material

The most critical step in the diversion process is to select the most appropriate base material. This sounds obvious, but it warrants a brief discussion. Primary selection criteria includes: a) limited solubility in the treatment fluid, b) solubility in the produced fluids, and c) a melting point higher than the treatment temperature. Refer to Table 2 for properties of traditional particulate diverting agents. Rock salt should be pumped in a salt solution to avoid prematurely dissolving the salt particles thereby decreasing the diverting effectiveness. Benzoic acid, while it does have the ability to sublime in dry gas wells, has a much lower solubility in liquid hydrocarbons than does naphthalene, wax beads or oil soluble resins. Combined with a higher melting point, benzoic acid as a diverting agent takes longer to clean-up than does naphthalene, wax beads or oil soluble resins. The key to removing any of the traditional diverting agents is fluid contact. If a perforation is totally packed off, and no fluid flows through or by the perforation, the cleanup times can be extremely long.

The beauty of PLA as a diverting agent is that it biodegrades as a function of temperature. The presence and type of fluid may accelerate the dissolution, but is not fundamentally required. Commercially available PLA diverting agents provide good blocking and sealing when applied to the well and also degrade across a wide temperature range to a monomer species that will be non-damaging to hydrocarbon bearing formations. [Figure 5](#) shows the repeating polymer unit of PLA, the structure of the degradation product, lactic acid, and summarizes the favorable properties of PLA. Lactic acid, known as milk acid, is similar in strength to formic acid which is commonly used as a preservative and antibacterial agent in livestock feed.

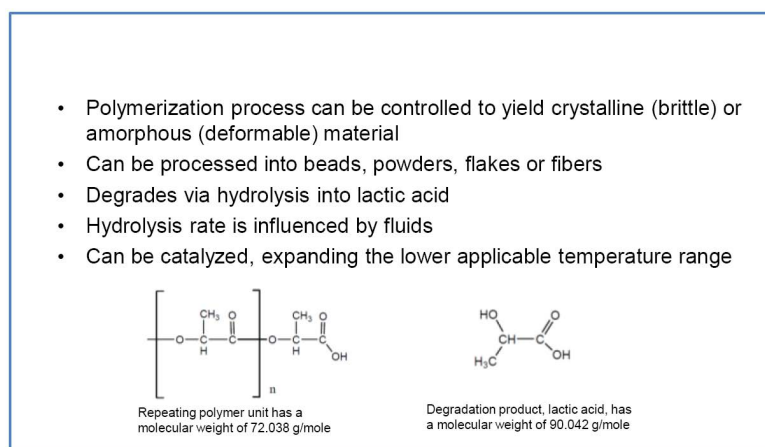


Figure 5—Self-degrading PLA diversion particulates

As mentioned previously, contact with fluid is not necessarily required for the degradation of PLA. Figure 6 shows the degradation of PLA at 250 °F in a high pressure, high temperature, sight cell developed by Munoz (2003). The initial pack of PLA crystals is at a height of 50 cm³. After 8 hours, the pack height is reduced by half. At 24 hours, only 10 cm³ remains and at 48 hours, the PLA is totally degraded.

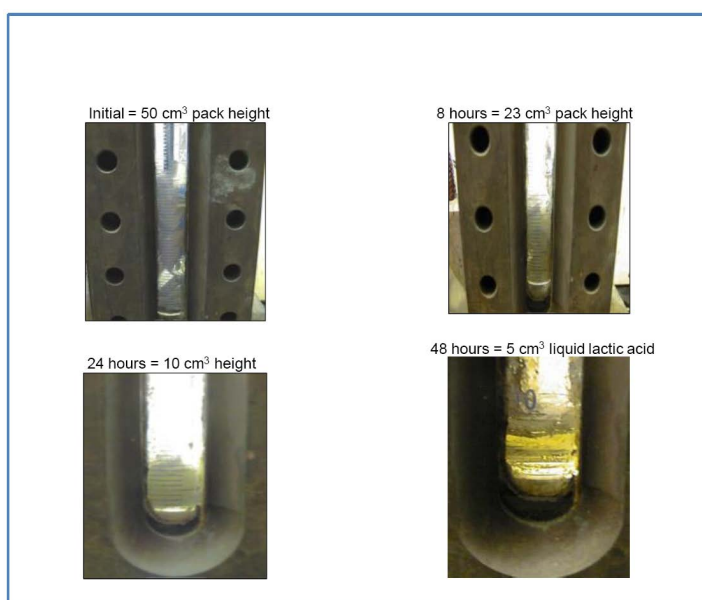


Figure 6—Degradation of PLA at 250°F, no water present

PLA has diversion application in wells with bottomhole temperatures ranging from 180 to 320 °F. Possibly higher temperatures if sufficient cool down occurs during treatment. [Tang \(2014\)](#) describes several

possible degradation accelerators which could expand the application of PLA to lower temperatures. Figure 7 shows the degradation rate of PLA in fresh water at various temperatures. This data was extracted from several recent SPE papers by Madsen (2015), Schneider (2015), Rondon (2016) and Heaton (2016). At 245 °F, 100% degradation occurs in less than 10 hours. A slight decrease in temperature to 230 °F, increased the degradation time to slightly over a day. At 194 °F and below, the degradation rate is 10 days or greater.

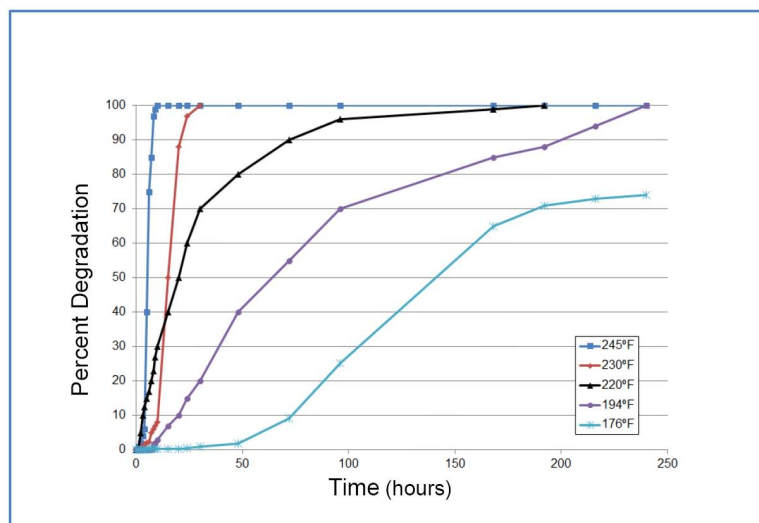


Figure 7—Degradation of PLA in fresh water at various temperatures

Figure 8 compares the degradation rate of PLA in fresh water and 15% salt water. At 194 °F, changing the solute to 15% salt water decreases the degradation time from 10 days to 3 days. An increase in degradation due to the addition of salt is also evident at 176 °F. Even at 10 days, however, the percent of the PLA degraded was less than 80% in both fresh water and salt water. The increase in degradation rate due to salt is attractive in plays such as the Bakken which produces high salinity brine. The catalyzing effect of brine, however, is not sufficient to allow rapid decomposition in the case of a pre-mature screen-out during hydraulic fracturing applications.

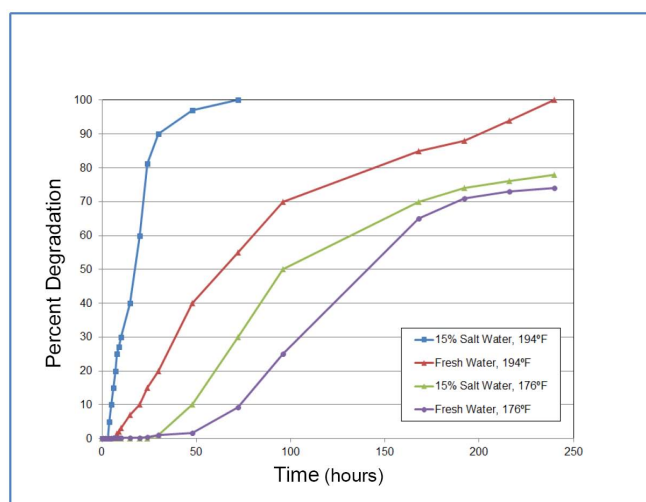


Figure 8—Degradation of PLA in fresh water and 15% salt water

Figure 9 compares the degradation rate of PLA in various acid and brine systems at 220 °F. This data was generated using a very accurate gravimetric method documented by Frost (2007). Live acid solutions

such as 15% HCl, 28% HCl and 15% HCl+9% Formic result in very rapid degradation: 5 hours or less. The addition of 9% Formic acid to the 15% HCl acid did not increase the degradation rate significantly. An interesting observation is the difference in degradation rate in 2% KCl compared to 5% NH_4Cl . Not only is the amount of salt in solution important, but composition of the individual ions has an effect. Data is also presented for the three acid solutions, spent on calcium carbonate. At 24 hours, the amount of degradation can vary from 30% to 60% depending upon the composition of the salt solution. This data illustrates the importance of performing degradation tests in the actual treatment fluid to be used and representative field brine in order to confirm degradation rates prior to field applications.

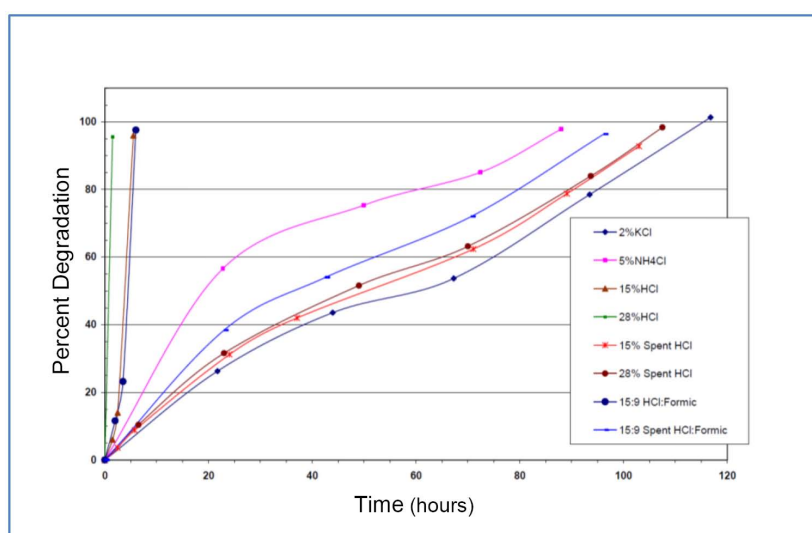


Figure 9—Degradation of PLA at 220°F in various fluids

Step 2: Choosing the correct particle size distribution

As mentioned previously, the broader the particle size distribution of a diverting agent, the better. This is because particles which are poorly sorted have lower permeability than comparable size particles which are well sorted. Wentworth (1922) introduced this concept when he described the grades and classes of clastic sediments. It is also important to size the particles properly so that they filter out, rather than invading into, the formation or proppant pack. Saucier (1974) and Abrams (1977) provided guidelines which can be applied to PLA diverting agents packing off on the various proppant sizes commonly used in hydraulic fracturing applications. Saucier's rules were developed for gravel pack applications, therefore, can be used to select the appropriate particle sizes to bridge on the proppant pack. We simply substitute the diversion particle sizes for the unconsolidated sand size and substitute proppant particles sizes for the gravel pack sand size. Abrams' rule can then be used to size the smallest of particles which function to seal in the pore throats of the larger particles. An illustration of the process follows.

Figure 10 compares the Wentworth particle size classification for clastic rocks to the US sieve classification used for gravel pack and proppant agents.

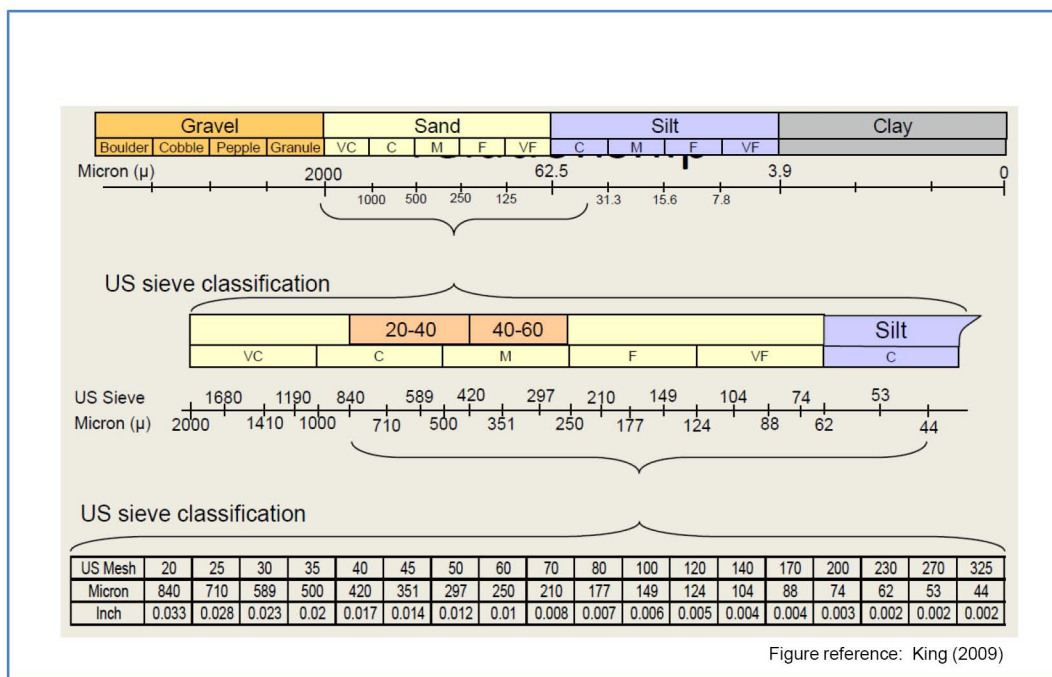


Figure 10—Wentworth particle size classifications

Table 3 contains a typical sieve size distribution for 20/40 Northern White Sand (NWS) determined by averaging the results of testing with 15 field sample taken from a recent fracturing treatment.

Table 3—Average sieve analysis from 15 field samples of 20/40 NWS

US Series Mesh Size	Sieve Opening (inch)	Sieve Opening (mm)	% Retained	Cumulative %	Weighted Average Particle Size
16	0.0469	1.190	0.4	0.4	0.005
20	0.0331	0.840	1.2	1.6	0.010
25	0.0280	0.710	23.2	24.8	0.165
30	0.0232	0.589	24.8	49.6	0.146
35	0.0197	0.500	30.2	79.8	0.151
40	0.0165	0.420	18.4	98.2	0.077
50	0.0117	0.297	1.1	99.3	0.003
70	0.0083	0.210	0.7	100.0	0.001
pan					

Average Particle Size, Frac Sand (mm) FS_{ave} 0.559

Median Particle Size, Frac Sand (mm) FS_{50} 0.589

From the amount of proppant retained on each screen, we can use the average US sieve size to calculate the median particle diameter of the proppant pack. Using median particle size of the frac sand (FS_{50}) as the starting point, we can apply Saucier's and Abrams' rules to determine the appropriate mesh sizes for the coarse, medium, and fine particulate diverting agents. This is illustrated in Figure 11.

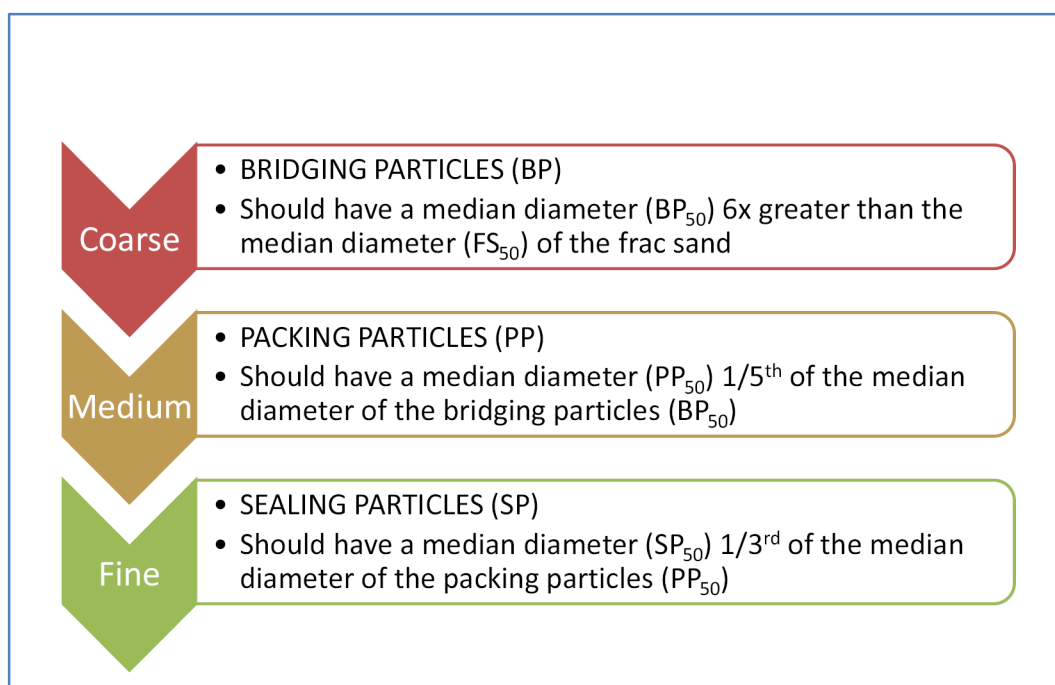


Figure 11—Selecting the appropriate diverter particle size distribution

The coarse particulates, which are intended to bridge on the proppant pack, should have a median diameter (BP_{50}) six times greater than the median diameter of the frac sand (FS_{50}). When using 20/40 NWS, the coarse diverting agents should have a median diameter of 3.534 mm which is equivalent to 5/6 mesh.

To determine the appropriate size for the medium particulates which are designed to pack off on the coarser particles, we again use Saucier's guidelines which state that the packing particles should have a median diameter (PP_{50}) $1/5^{\text{th}}$ that of the bridging particles (BP_{50}). Dividing BP_{50} by 5 yields a median diameter of 0.736 mm which is equivalent to 20/25 mesh.

Finally, to determine the appropriate size for the fine particles, we use Abrams' rule which says that a particle will seal in the pore throat of a larger material if it is $1/3^{\text{rd}}$ the median diameter (SP_{50}) of the larger material (PP_{50}). Multiplying BP_{50} by $1/3$ yields a medium diameter of 0.258 which is equivalent to 50/60 mesh.

This process can be applied to different proppant sizes. Table 4 summarizes the recommended diverter particle sizes (bridging, packing and sealing) for various proppant sizes. Reviewing Figure 2, shown earlier in this paper, one can see that it is possible to blend two commercially available PLA diverting agents and achieve the distribution required to divert on the most commonly used proppant mesh sizes of 20/40, 30/50 and 40/70.

Table 4—Recommended diverter particle sizes

Proppant at Wellbore	Bridging Particles	Packing Particles	Sealing Particles
20/40	5/6	20/25	50/60
30/50	7/8	30/35	80/100
40/70	10/12	40/45	100/120

Step 3: Determine the amount of PLA required per stage or per perforation

There are three basic considerations for determining how to properly deploy a diverting agent: 1) the carrier fluid, 2) the concentration of diverter in the carrier fluid and 3) the total amount of diverter used. It is common to refer to each cycle of diversion as a "pill" or "drop". Table 5 provides guidelines for traditional diverting agents. These guidelines were assembled from various technical publications provided by BJ Services (1997) and Halliburton (2005 and 2008). Because traditional gelling agents have been used for many years, the guidelines are well established and are surprisingly consistent from company to company.

Table 5—Traditional diverter guidelines for various applications

Type	Applications	On Perforations	In Perforations (lbs per perforation)	Open Hole Formations (lbs per ft ²)
Rock salt	HCl and non-HF Acid Treatments	16 lbs @ 1 lb/gal	0.5 to 2	5
Benzoic Acid	Gas, Oil, Injection Wells	9 lbs @ 0.5 lb/gal	0.25 to 1	2.5
Naphthalene	Oil Wells Only	8 lbs @ 0.5 lb/gal	0.25 to 1	2.5
Wax beads	Oil Wells Only	n/a*	0.25 to 0.5	1.0 to 2.0
Oil soluble resin	Oil Wells Only	n/a*	0.25 to 0.5	1.0 to 3.0
Foam	Preferably in higher permeability gas wells	n/a*	60 to 80 Quality	60 to 80 Quality
Ball Sealers	Sinkers - Vertical Wells	200% excess	n/a	n/a
	Neutral density or floaters - Vertical wells	50% excess	n/a	n/a
	Mixed density - Horizontal wells	no excess	n/a	n/a

* Insufficient strength to hold pressure on perforations.

The carrier fluid is an important consideration in with traditional diverting agents. It should have its specific gravity and viscosity adjusted to maintain a uniform dispersion of the bridging agent. The strongest bridge is achieved with carrier fluids having the minimum viscosity for maintaining a uniform dispersion of the bridging agent. The lower viscosity lets the carrier fluid continue to flow through the bridge for a slightly longer time and deposit more of the packing and sealing particulates for a stronger, less permeable diverter pack. At low rates, as in matrix acidizing, the density of the carrier fluid needs to be balanced with the specific gravity of the particulates. In hydraulic fracturing applications, the pump rates are usually high enough to prevent settling of the particles.

Traditional bridging agents are run at relatively low concentrations of 0.5 to 1 lbs per gallon (ppg) for diversion in perforations. In openhole applications or in vuggy formations, the traditional bridging agents are run at concentrations as high as 5 to 10 ppg.

No such general rules of thumb have been developed for PLA diverting agents. In fact, some pumping service companies consider the make-up of the diverter-fluid proprietary and prefer to charge on a pill or per drop basis. Multiple papers are available describing the "engineered workflow process" but nearly all refer to specific case histories, rather than providing general guidelines. Arguably placing diverters in horizontal well hydraulic fracturing operations is complicated. Nicely illustrating this point, Francisco (2016) presented the results of dynamic modelling based upon the combined physics of fluid flow and particle deposition in the diversion process.

The three keys to properly deploying PLA diverting materials are: a) determining the mass required per stage or per perforation, b) determining the appropriate slurry concentration to deliver the diverter pill, and the c) appropriate injection rate to seat the pill. There are, of course, many operational issues relating how

to configure the blending and high pressure pumping equipment on location. The operational aspects are beyond the scope of this paper. Reviewing the papers referenced earlier, there is a wide range of PLA slurry concentrations being applied, typically varying from 1 to 6 ppg. It is most likely that the slurry concentrations used are more closely related to the blending and pumping configurations than to any type of engineered work flow.

In attempt to develop guidelines for the amount of PLA diverter material required for operations in the Williston Basin, 6 different pumping services companies were asked for recommendations based upon their experience in the basin. For open hole completions, the recommendations ranged from 0.25 to 4.1 lbs/perforation. For cemented laterals, the recommendations ranged from 0.2 to 2.7 lbs/perforation. Although the absolute values of the recommendations varied from company to company, all but one company indicated that open hole completions require an additional 20-35% diverting agent, compared to cemented completions.

One way to determine historical amount of diverter used for a given area is to data mine FracFocus. Using the correct search parameters, and performing a mass balance, it is possible to calculate the total amount of PLA diverting agent used in a given well. Combining the total amount of diverter used in a well with completion parameters obtained from reporting required by the North Dakota Industrial Commission (NDIC) allows the determination of typical diverter usage for various wellbore configurations. While the data reported to the NDIC is not granular enough to determine the amount of PLA used per perforation, it is sufficient to determine the average mass used per stage for a given well.

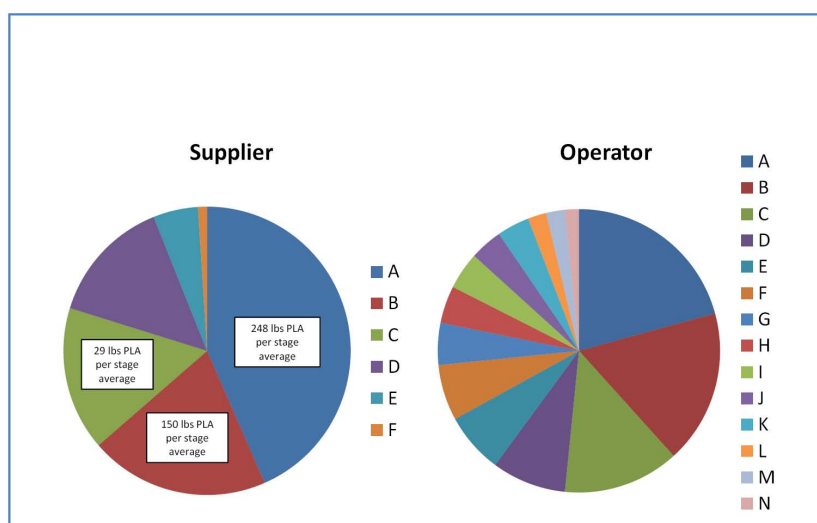
A series of key words was developed to allow FracFocus to be data mined for the Williston Basin. Key words included service companies, chemical manufactures, product names, chemical classes, molecular formulas, chemical names, and product descriptions. In total, 56 key words were assembled. Oddly enough, the key word which received the most hits was the name, not the CAS number itself. Given the complexity of the specific chemical name for PLA: 1,4-Dioxane-2,5-dione, 3,6-dimethyl-, (3R-cis)-, polymer with (3S-cis)-3,6-dimethyl-1,4-dioxane-2,5-dione and trans-3,6-dimethyl-1,4-dioxane-2,5-dione, (3R,6R)-3,6-dimethyl-1,4-dioxane-2,5-dione, polymer with rel-(3R,6S)-3,6-dimethyl-1,4-dioxane-2,5-dione and (3S,6S)-3,6-dimethyl-1,4-dioxane-2,5-dione; it is highly possible that some wells utilizing PLA were not identified due to typographical errors when the FracFocus reports were filed.

An iterative process was used where we data mined FracFocus, performed a quality control check on the well set, compared to wells which we were certain used PLA diverter, updated the key words and performed the search a second, then third time. Once the wells were identified, mass balance calculations were performed with the FracFocus fluid component data and the total mass of PLA used in each well was estimated. The calculations were compared to wells where the PLA mass was known and found to be an acceptable estimate. The result was a set of 170 Williston Basin wells completed through the end of the 1st half of 2016. Table 6 contains a high level summary of the findings.

Table 6—FracFocus data mining of PLA diverter in the Williston Basin

Number of wells		170
Number of operators		14
Number of suppliers		6
Completion parameters (average)		
	Lateral length (ft)	9,328
	Normalized proppant (lb/ft)	577
	Normalized fluid (bbl/ft)	13
	Stage spacing (ft)	285
PLA per well (average) - lbs/well		5,643
	OH swell packer wells	10,621
	Cemented laterals	4,577
	Middle Bakken wells	6,427
	Three Forks wells	4,978
PLA per stage (average) - lbs/stage		203
	OH swell packer wells	375
	Cemented laterals	162
	Middle Bakken wells	239
	Three Forks wells	165

In the data set, there are 14 operators and 6 PLA suppliers represented. See Figure 12 for an illustration of the percentage of each supplier and operator, by well count. The top 3 suppliers represented slightly more than 75% of the PLA diverter sales and the top 6 operators represented slightly less than 75% of the deployment of PLA. For the top 3 suppliers, the average PLA per well is included in Figure 12. It can be seen that there is a significant variation in the amount of product used by each of the suppliers.

**Figure 12—PLA suppliers and operator usage by well count percentage (FracFocus - Williston Basin)**

The average completion parameters for the 170 wells are representative of what is typical in the basin. The bulk of the wells were 2-mile laterals (9,328 ft horizontal sections) with normalized proppant and fluid

volumes of 577 lbs/ft and 13 bbl/ft. Stage spacing averaged 285 feet which represents completions consisting of 30 to 40 stages per well in most cases. This data set is representative of typical enhanced completions in the Williston Basin with 90% of the wells completed in the last 2 years, as can be seen in Figure 13.

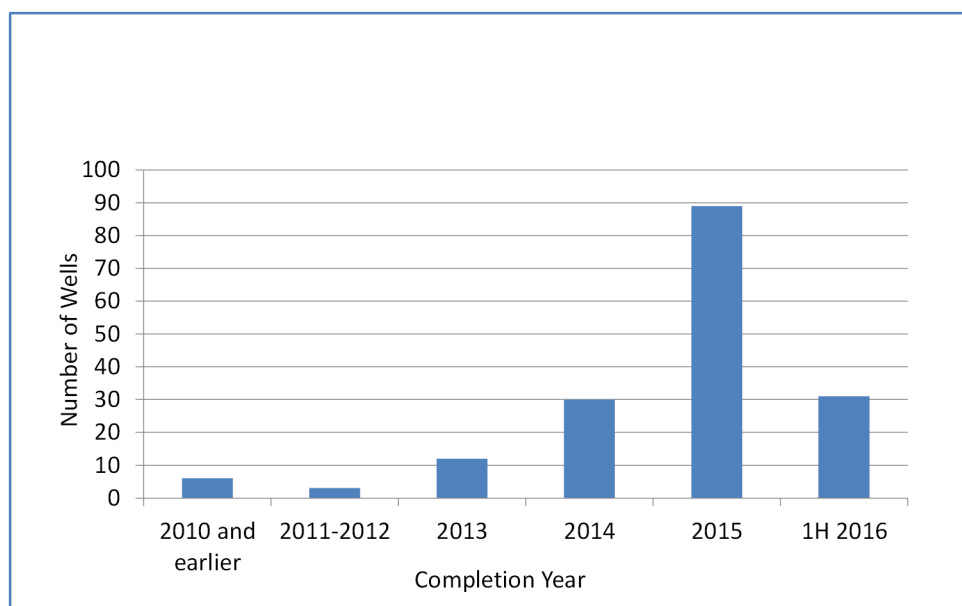


Figure 13—Williston Basin wells identified as using PLA diverting agents

Reviewing the average amount of PLA used per well and per stage, a couple significant trends were observed. First, larger amounts of PLA are used in the Middle Bakken wells compared to Three Forks wells. On a per well basis, 30% more PLA was used Middle Bakken wells. On a per stage basis, 45% more PLA was used in Middle Bakken wells. The service companies' recommendations did not account for different formations; however, our experience in 13 wells indicates similar pressure responses can be achieved in the Three Forks with smaller PLA diverter pills.

The second observation with the FracFocus data set is that open hole completions used 2.3x more PLA than cemented laterals. This was true on both a per well and per stage basis. The service companies recommended 1.25x to 1.5x PLA for open hole wells, less of a different than the FracFocus data set indicated. Our experience with open hole completions agrees with the FracFocus data set.

Figure 14 illustrates the difference in average PLA requirements for the two different well completion methods, separately for the Middle Bakken and Three Forks wells. Two general guidelines should be considered when planning diversion with PLA in the Williston Basin: more material will be required in open hole completions compared to cemented laterals and less material will be required in Three Forks wells. Referring back to Figure 12, the amount of PLA required can vary from supplier to supplier: from less than 1 lb/perf to as much as 10 lbs/perf based upon well conditions. How the PLA is delivered also varies from supplier to supplier, with the PLA content of the slurries typically ranging from 1 to 6 ppg of PLA material.

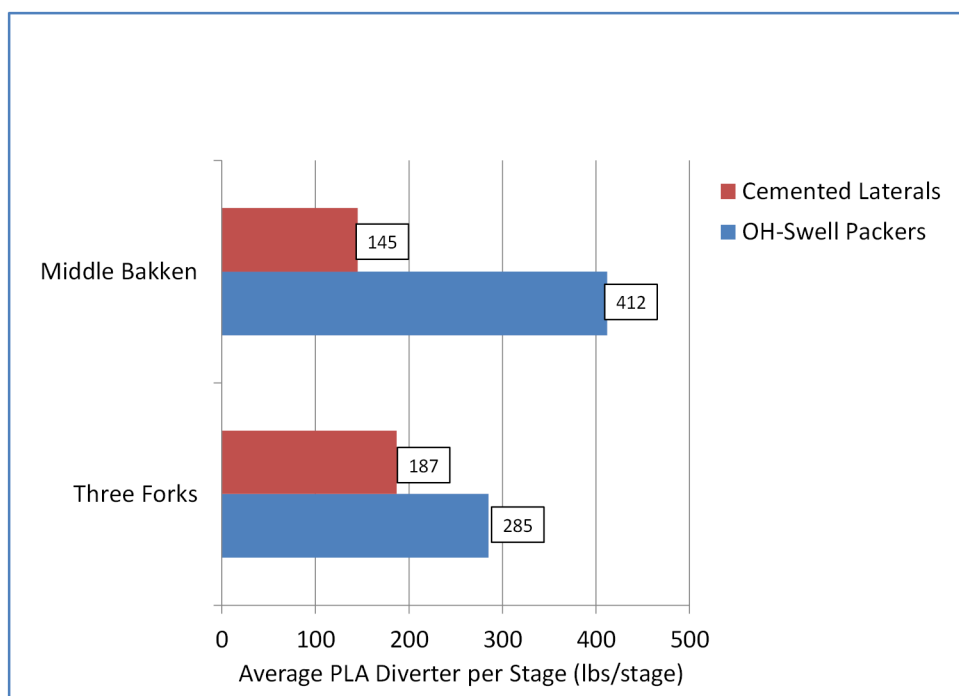


Figure 14—Average PLA used per stage (FracFocus-Williston Basin)

Step 4: Monitoring the injection well

With so much variation in diverter requirements from well-to-well, monitoring of the treatment is critical for real-time optimization of the diversion process. High end techniques such as microseismic monitoring and combination Distributed Temperature Survey/ Distributed Acoustic Surveys (DTS/DAS) provide the most definitive method of evaluating fluid distribution during stimulation. These techniques, however, require months of preplanning and add significant expense to a completion. In addition, while they provide qualitative evaluation during the execution of the treatment, it can take weeks for the final processed reports to be completed.

Post-treatment evaluations of diverter performance can be made with DTS/DAS, production logging and flow back of chemical tracers used in the different stages pumped into a well. This data is valuable but does not provide any guidance during the treatment.

While not definitive, the least expensive and most common way to monitor diversion effectiveness is to evaluate the pressure responses during pumping and changes in fracture gradients throughout the stimulation treatment. There are three responses that should be observed: 1) overall trend in treating pressures at constant rate, 2) increase in instantaneous pumping pressures as the diverter enters the perforations and 3) increase in net pressure from the beginning to end of the treatment.

Figure 15 shows a single stimulation stage in well #1 which incorporated multi-cycle diversion. The treatment plot shows the surface and bottomhole pressures along with the treatment rate and proppant concentrations as a function of time. Diverter pills entering the perforations are marked by the flags 67-70. In this example, there is no significant diverter response when the diverter hits the perforations, but there is a trend of increasing bottomhole treating pressure. Rondon (2016) proposed a method of overlaying curves before and after each diverter will. While this is useful in many cases, a simple line through the data, as shown in Figure 15, can be used real-time during the execution of the treatment to determine if the subsequent pills in a given stage need to be increased or decreased. In this particular case, the amount of PLA diverter in each pill was 50, 50, 75 and 75 lbs. The completion was an uncemented lateral utilizing swell packers between the stages. There are 6x 1-ft perforation clusters in this stage, shot at 6 shots per foot (spf).

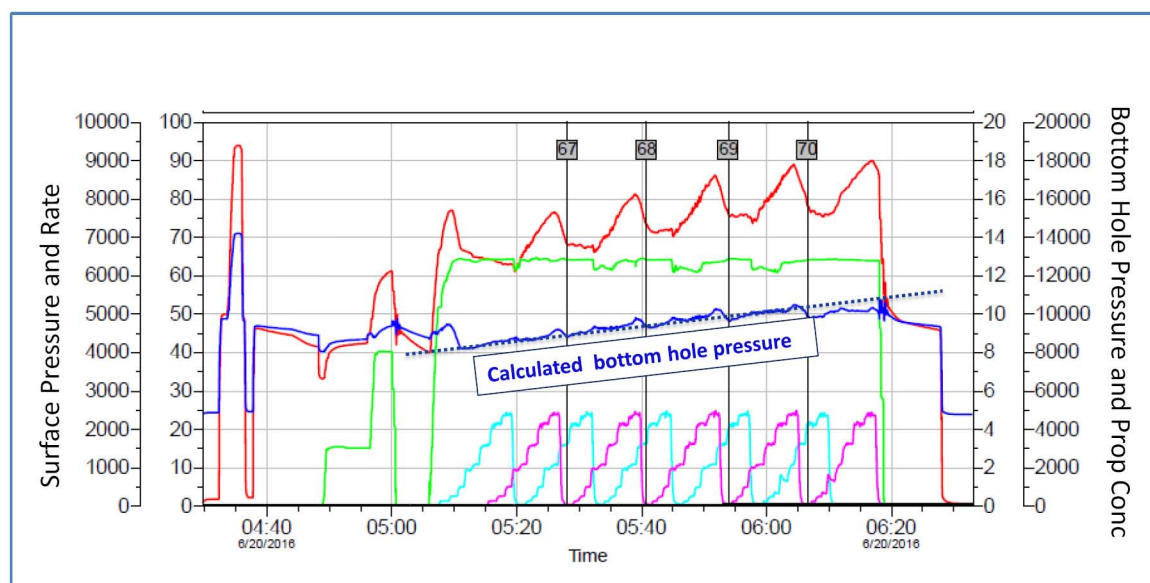


Figure 15—Multi-cycle diversion stimulation stage in well #1

In Figure 15, the red curve is the well treating pressure (scale 0 – 10,000 psi), green curve is the the slurry pump rate (scale 0 – 100 BPM), blue curve is the calculated bottom hole pressure (scale 0 – 20,000 psi), and turquoise and magenta curves represent the surface and bottom hole proppant concentrations (0 – 20 ppg), respectively.

The second method used to estimate diverter effectiveness is to look for instantaneous pressure increases as the diverter enters the formation. Figure 16 shows a stimulation stage in well #2 which incorporated dual-cycle diversion. This well was also completed with an uncemented liner using swell packers for isolation. The stage was perforated with 7x 1-ft perforation clusters shot at 6 spf. In this case a single, 12 lb PLA pill resulted in a pressure increase of 743 psi when hitting the perforations.

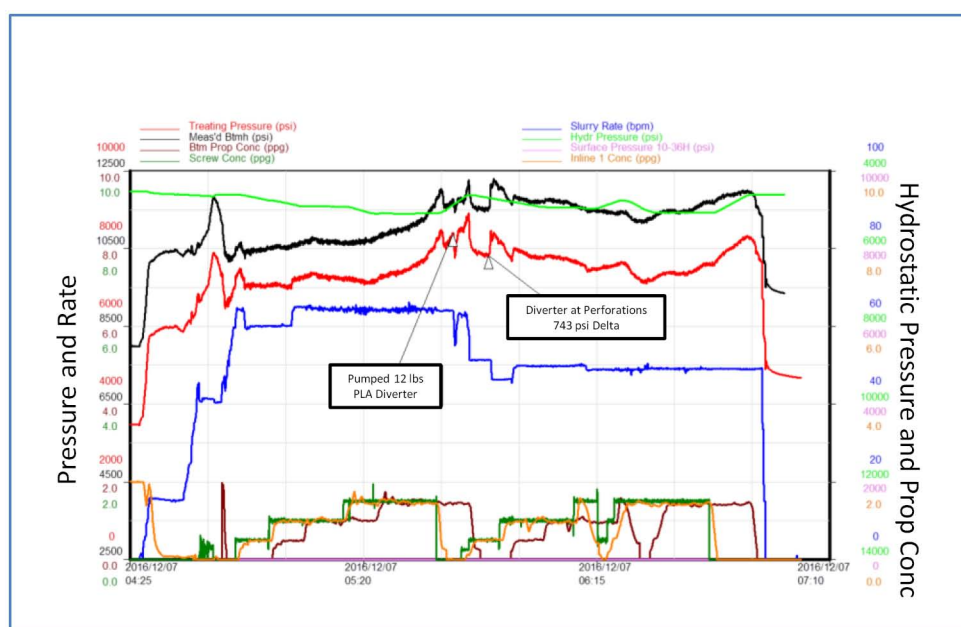


Figure 16—Dual-cycle diversion stimulation stage in well #2

The third common method used to estimate diverter effectiveness is to look for an increase in net pressure from the beginning to the end of the stimulation treatment. Figure 17 shows a stage in well #3 incorporating multi-cycle diversion. Once again, this well is completed with an uncemented lateral using swell packers for isolation. The stage was perforated with 5x 1-ft perforation clusters shot at 6 spf. In this particular case, the amount of PLA diverter in each pill was 5, 10, 15, and 15 lbs. In this case, the bottomhole treating pressure trend (blue dashed line) is flat. There is, however, a notable increase in the instantaneous shut-in pressure (ISIP) at the end of the job compared to the ISIP at the beginning of the job. The ISIPs increased (red dashed line) from 4,016 psi to 4,233 psi for a net pressure increase of 217 psi.

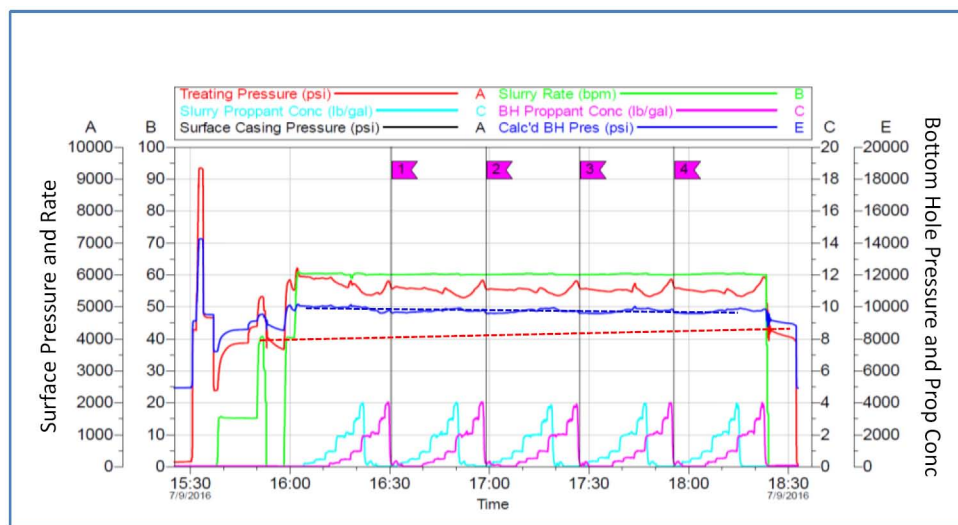


Figure 17—Multi-cycle diversion stimulation stage in well #3

These three examples illustrate that indications of successful diversion can be variable from well to well. In reality, there can be significant variations from stage to stage in the same well. What amount of pressure response should we use for success criteria? Achieving diversion success will, of course, vary based upon reservoir and completion parameters. As a starting point, the guidelines proposed by Rondon (2016) as success criteria are considered reasonable for Williston Basin wells:

- An overall constant increase in bottomhole treating pressure throughout the stage
- An instantaneous reaction to the diverter hitting the perforations of at least 500 psi
- A net pressure increase, or Δ ISIP, of 50 psi or more

Step 5: Monitoring the offset wells

The observation of positive pressure responses due to diverter pills deployed in wells being stimulated does not, unfortunately, guarantee that the diverters are working. It gives us a good feeling, but not positive proof. Figure 18 shows the control panel used in conjunction with an existing production monitoring system which allows offset wells to be monitored real-time, in the data van, as a stimulation treatment progresses. In this application, CygNet Vision software was used to display SCADA data received from pressure transducers installed in the wellheads of offset wells. The system was initially set up to monitor 4 primary and 6 secondary offset wells. Data was transmitted every 30 seconds and pre-set alarms, test and email notifications were established to alert the completion engineer of any interference (frac hits) between the stimulated and offset wells. Data can be viewed on an adjustable time scale and exported as needed. All data is stored on the company's production server.

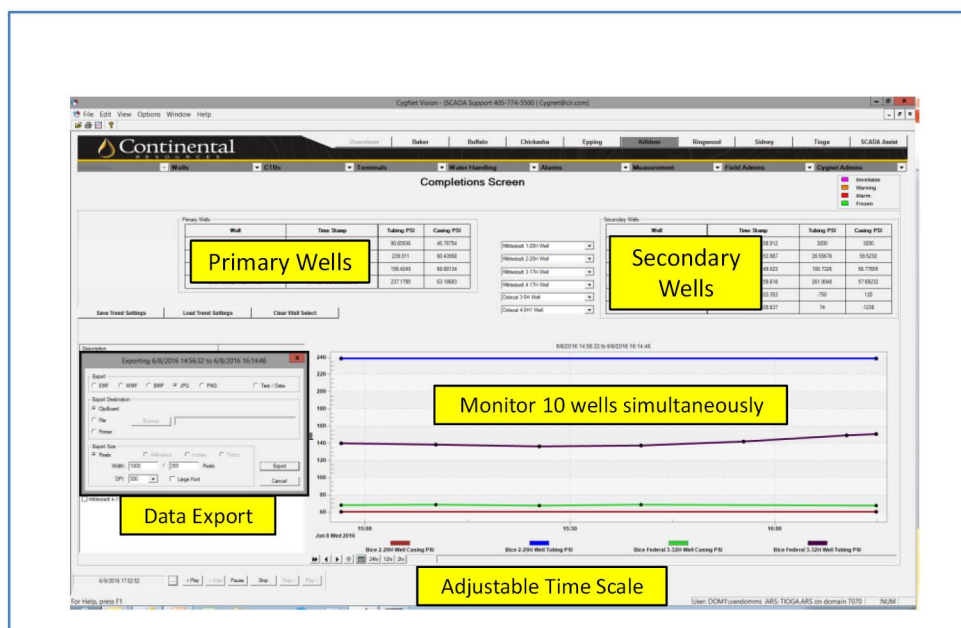


Figure 18—Offset well monitoring via CygNet set-up for well #1

Figure 19 shows the expanded well monitoring screen during two of the stages from well #3. In this case, there are 3 offset wells being monitored, each represented by a different color. Annotations have been added to show when the diverter pills hit the perforations during the two stages. The vertical lines indicate the start of each stimulation stage. Throughout this time frame, there is no interference with the blue well. The decrease in pressure after the peak in each of the wells corresponds to the end of pumping in well #3. Pressure in the offset wells declines during the down period between stimulations.

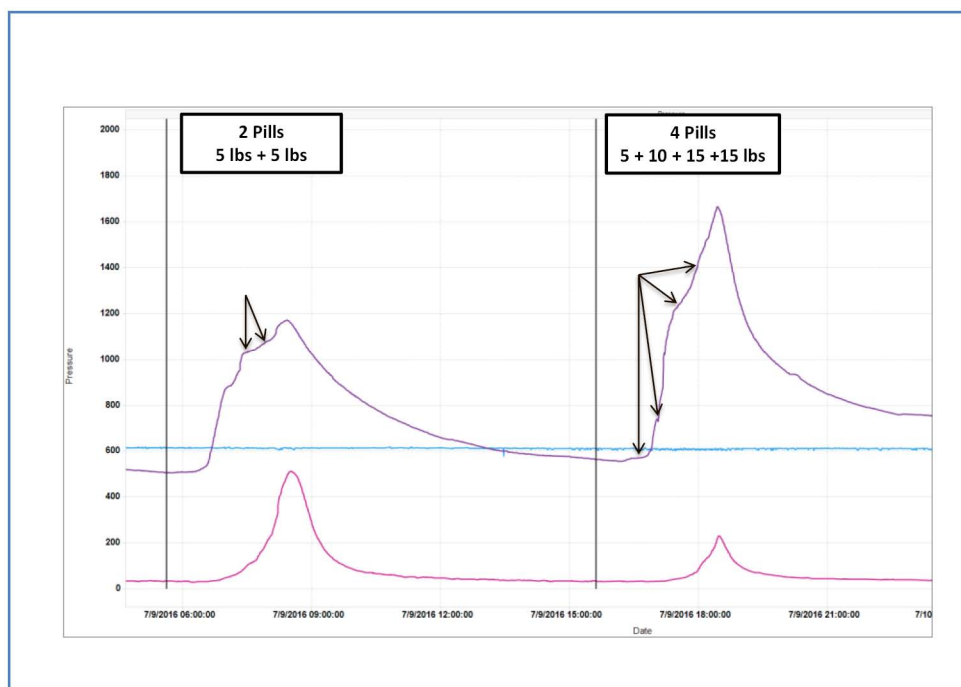


Figure 19—Offset well monitoring of diverter stages for well #3

Both the red and purple wells show interference, with the purple well (which was at a closer spacing) being hit harder and sooner. Two small PLA diverter pills of 5 lbs each were used on the first stage. It is interesting to note that was almost immediate pressure responses in the purple well when the diverter pills hit the perforations of the well #3. Diversion was more aggressive in the second stage; 4 pills of PLA 5, 10, 15 and 15 lbs. In this case, there is an observable change in slope of the purple offset well when each of the pills hits the perforations of well #3. In addition, the pressure response in well #3 has been decreased. The really interesting observation is that the second stage in Figure 19 is corresponds to the pumping of the stage in Figure 17, which did not show positive pressure responses in the injection well when the diverter hit the perforations.

Conclusions

- The degradation rate of PLA varies based upon temperature and fluid contact from several hours to several days. Degradation tests should be performed with treatment fluids and representative field brines to confirm degradation rates.
- Well established gravel pack rules can be applied to allow calculation of the most appropriate diversion particle size distribution for a given application. The particle size distribution should be confirmed with laboratory testing and verified with field application.
- As a starting point, a diverter designed to divert on various proppant sizes might contain the following particles:
 1. 20/40 Proppant: a mixture of 5/6 mesh, 20/25 mesh and 50/60 mesh particles
 2. 30/50 Proppant: a mixture of 7/8 mesh, 30/35 mesh and 80/100 mesh particles
 3. 40/70 Proppant: a mixture of 10/12 mesh, 40/45 mesh and 100/120 mesh particles
- The amount of PLA diverting agent required per stage varies based upon the well completion, formation properties, and supplier. Uncemented laterals require greater amounts of diverter. In the Williston Basin, the Three Forks formation responds to less amounts of diverter when compared to the Middle Bakken.
 1. As a starting point, use 0.8 to 1 lb/perf on earlier stages
 2. Be prepared to work up to 5 lb/perf for cemented laterals, and
 3. Possibly up to 10 lb/perf for uncemented laterals
- Data mining FracFocus is a method to determine historical diverting practices in a given Basin.
- Surface pumping pressures are used to evaluate the effectiveness of a diverter, but can sometimes be misleading. As a starting point, the following guidelines are proposed as success criteria:
 1. An overall constant increase in bottomhole treating pressure throughout the stage
 2. An instantaneous reaction to the diverter hitting the perforations of at least 500 psi
 3. A net pressure increase, or Δ ISIP, of 50 psi or more
- Monitoring offset wells during stimulation treatments can provide valuable information on the diverter performance.

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