Bakken Production Optimization Program

EERC
UND UNIVERSITY OF NORTH DAKOTA

ROD GUIDE ANALYSES

Final Report

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Members of the Bakken Production Optimization Program

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PREFACE

This work was performed within the Bakken Production Optimization Program, a consortium comprising the Energy & Environmental Research Center (EERC), the North Dakota Industrial Commission, and several of the largest oil producers in North Dakota. Funding to complete a 3-year, $117 million project was provided to accomplish a wide range of projects focused on improving Bakken system oil recovery while simultaneously reducing its environmental footprint. The program was designed to accomplish the following:

- Maximize oil production from Bakken and Three Forks wells by employing an "all of the above" approach
  - Perform reservoir characterization
    - Develop data sets to determine whether the oil of the second and third benches in the Three Forks Formation should be considered separate and unique from those of the first bench
    - Predict future reservoir sweet spot areas
  - Improve drilling/stimulation/completion/production techniques and sequences
    - Determine optimal well spacing for development in the Middle Bakken and first, second, and third benches of the Three Forks
- Optimize wellsite surface operations
  - Reduce operating costs
  - Reduce development and operations impacts to surrounding landowners
  - Reduce demands on surrounding infrastructure and water resources

Activities of this program are directed by member interests. All tasks completed within the program necessarily are widely applicable to all consortium members and affect most members equally. This is the case with the study topic reported within this document. Premature failure of plastic sucker rod guides ubiquitous throughout the Williston Basin likely impacts, or will impact, all consortium members. It is within this context that the EERC offers this report.

For more information on the Bakken Production Optimization Program or to investigate membership in the program, please contact John Harju at jharju@undeerc.org or at (701) 777-5157. Members of the program receive the following benefits:

- Participation in direction of program activities and foci
- Early insight into program results and data
- Participation in technical forums held among program members

Bakken Production Optimization Program

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ROD GUIDE ANALYSES

INTRODUCTION

North Dakota wellsite operators have reported a number of premature failures of plastic rod guides. The failures have most often occurred in green-colored guides that were being pilot-tested by a reputable rod guide manufacturer. It was reported to the Energy & Environmental Research Center (EERC) that the standard rod guide used by multiple operators is black and made of polyphthalamide (PPA). The rod guide manufacturer stated that the green material is also PPA. Operators have reported that the black guides have an expected lifetime of several years in Bakken operations, but many of the green guides have failed by crumbling, sometimes into a green mud, in time frames of less than a year.

As part of the Bakken Production Optimization Program, the EERC was asked to analyze the green and black materials to determine whether they are made of the same material and to provide suggestions on how to specify materials or molding methods to increase guide lifetimes. The EERC was also asked to perform the same analyses on three types of guides made by two alternate rod guide manufacturers. Select analyses were chosen only to determine differences in composition and some physical properties of the materials. These analyses were not designed to determine the likely relative performances or lifetimes of the materials in field use (1).

BACKGROUND

Plastics are materials composed of resins (polymers) and additives. The additives are used to improve the performance of the material such as increasing strength, adding color, resisting erosion, and reducing degradation by sunlight. Two types of plastics are often used in engineering applications: thermosets and thermoplastics. Thermoset resins like epoxy or phenolic resin start as a liquid that is polymerized with the addition of a curing compound. Thermosets soften upon heating but tend to decompose rather than melt so they cannot be reformed by melting the way that thermoplastics can. However, their maximum use temperatures are usually higher than for thermoplastics. In contrast, thermoplastics soften upon heating and then regain their original properties when cooled. This property allows many of the thermoplastics to be molded by heating to soften the material, then forcing it into a mold for shaping. Thermoplastics have good chemical resistance, except to strong oxidizing acids or aromatic organic compounds. The maximum use temperature and resistance to environmental damage are largely determined by the composition of the molecular chains, the length of the chains, the degree of their interlinking, and the extent to which they crystallize. Higher-temperature thermoplastics are usually used to make rod guides because they possess good chemical resistance and higher strength at downhole temperatures. Common thermoplastics used to make rod guides are PPA, polyphenylene sulfide (PPS), and polyether ether ketone (PEEK).

PPAs are a type of polyamide plastic such as nylon, but PPAs contain aromatic rings in their backbones that give them high mechanical strength and thermal resistance (2). The raw PPA useby the rod guide producer is purchased from a plastics source manufacturer. The plastics sourcemanufacturer calls the product Amodel® resin. Amodel PPA resins are described in source manufacturer literature (1) as follows:

> *PPA resin technology can produce a wide range of polymers that include both semicrystalline and amorphous resins. Since 1991, several base polymer formulations have been commercialized to meet specific industry needs. All of the commercial Amodel products are semicrystalline. The semicrystalline grades of Amodel PPA resins have excellent mechanical properties, outstanding dimensional stability, exceptional elevated thermal performance, and good processing characteristics. Amodel resins bridge the cost/performance gap between the high-volume, moderate-performance engineering resins, such as thermoplastic polyesters and aliphatic nylons, and the low-volume, high-cost specialty thermoplastics, such as PEEK.*

Thermoplastics are often divided into two classes: amorphous and semicrystalline. One of the major differences between amorphous and semicrystalline polymers is the way their properties change in response to changes in temperature. When the temperature is raised, the modulus (stiffness) of amorphous polymers generally decreases slowly until the glass transition temperature (T_g) is reached. At temperatures above the T_g, the modulus decreases rapidly. Therefore, amorphous thermoplastics are rarely used at temperatures higher than their glass transition temperature. In the case of semicrystalline polymers, the modulus also gradually decreases with increasing temperature. At or near the glass transition temperature, the modulus decreases rapidly to a lower but still useful level. Continuing to increase the temperature causes the modulus to remain at or near this new level (the crystalline plateau) until the melting point temperature (T_m) is reached. At T_m, the modulus decreases rapidly again.

Semicrystalline polymers are often used at temperatures above their glass transition temperatures, but below their melting points, particularly when they are modified with glass fibers and/or mineral fillers. When semicrystalline polymers are processed, the amount of crystallinity can be affected by processing conditions. For example, Amodel A-1000 PPA-based products require mold surface temperatures of at least 135°C (275°F) for development of the maximum amount of crystallinity during injection molding. Products based on Amodel A-4000 or A-6000 base resin will give high crystallinity at mold temperatures of about 80°C (176°F).

Above the T_m, a semicrystalline polymer melts, changing from the solid state to the liquid state. The thermal capability of a semicrystalline polymer is defined to a large extent by its T_g and T_m, as these values indicate the temperature ranges where the polymer has high stiffness (below T_g), moderate stiffness (between T_g and T_m), or no useful stiffness (above T_m).

Amodel PPA resins are typically combined with reinforcements, fillers, impact modifiers, flame retardants, colorants, and other additives to achieve a wide range of performance profiles. Currently, the family contains over 100 commercial grades. The base polymers are translucent white because of crystallinity, and the natural color of a specific product will vary depending on the additives used. Most grades are available in natural and black. Other colors can often be provided.

TESTING METHODS

Specific analyses performed on the rod guides were suggested by subject matter experts (3) and are summarized in the table below.

Analyses Performed on Rod Guides

Material Property	Analysis Type	Specific Measurement
Relative Crystallinity	Polarized optical microscopy of thin sections	Quantify area of microspherules relative to the area of amorphous material
	Quantitative x-ray diffraction (XRD)	Determine ratio of volume of crystalline to amorphous regions
Glass Transition and Melting Temperatures	Differential scanning calorimetry (DSC)	Measure heat flow into or out of the sample as a function of sample temperature
	Thermogravimetric analysis (TGA)	Determine weight changes in sample during heating (water loss, offgassing, and change in mass due to combustion)
Differences in Type of Plastic	DSC	
	Fourier transform infrared (FTIR) spectroscopy	Compare spectroscopic signatures of multiple samples
Size and Composition of Inorganic Additives	Scanning electron microscopy (SEM)	
Tensile Properties	Tensile properties tester	Determine ultimate strength and Young's modulus

The EERC has several types of analytical equipment that can be used to analyze the makeup and some physical properties of plastics (as well as other materials). The specific analyses performed on the rod guides were suggested in a book on failure analyses of polymers (3). In order to determine the relative crystallinity of the PPA in the guides, two methods were used. In polarized optical microscopy of thin sections, the crystallites often appear as microspherules. Therefore, this type of microscopy was used to take digital pictures of thin sections of each of the guides. The data were then analyzed to quantify the area of microspherules in an image relative to the area of amorphous material. Quantitative XRD was used as a second method for determining the ratio of the volumes of crystalline to amorphous regions. In XRD analysis, a beam of x-rays is directed into a powdered sample of the plastic. If the beam encounters a crystalline region, the x-rays are diffracted back out of the sample, where they are detected. The angle of diffraction is used to determine the type of crystalline material that is present.

The glass transition (T_g) and melting temperatures (T_m) of the plastics were determined using DSC. These analyses were performed in the Coatings and Polymeric Materials Laboratory at North Dakota State University. DSC measures the heat flow into or out of a sample as a function of the sample temperature. Exothermic reactions such as crystallization show as a peak in the data, endothermic reactions such as melting show as a dip, and changes in specific heat such as occurs across T_g show as a change in slope. DSC tests use only a very small sample of the material, typically 5–10 milligrams, which is filed from a larger piece. The filings were heated at a rate of 20°C/min to 385°C, then cooled at 20°C/min to just above room temperature, and then reheated at 20°C/min to 385°C again. The reheat is used to determine T_g because after the sample melts during the first heating cycle, it ends up as a small disk that is in much better contact with the instrument temperature sensors than the initial filings. In addition, an exotherm can occur around T_g because of crystallization of the PPA if it is not already fully crystallized, which can obscure the indication of T_g. By first heating to melt the plastic and then slowly cooling, we assure that it is fully crystallized during the reheat.

In conjunction with DSC analyses, TGA was used to determine temperatures and amounts of weight changes in the sample during heating. The data are shown as sample weight as a percentage of the original weight as it is heated at 10°C/min. These data indicate whether or not a change in weight occurred at a DSC endotherm to determine if the endotherm was due to a phase change such as melting, which would not have any associated weight loss, or if it was due to evaporation of a portion of the sample, which would show weight loss. TGA was also used to determine how much absorbed water was in the samples and how much ash formed during combustion of the sample, which directly indicates the percentage of the plastic that is reinforcing or filler material.

Differences in the type of plastic used in each of the rod guides were determined both by DSC and FTIR spectroscopy. The FTIR tests were also performed at NDSU. In FTIR analysis, a beam of IR light is shown on the sample that absorbs some wavelengths depending on the molecular structures that are present. The wavelengths and amounts of infrared light that are reflected are then detected, and molecular composition of the plastic is determined from the wavelengths that were absorbed. Unfortunately, the laboratory does not have a computerized database of IR spectra for plastics, so firm identification of the type of plastic from the spectra was not possible. However, the comparisons of the spectra can reveal whether two plastics are the same or different.

The size and composition of inorganic additives in the plastics were determined by SEM. In SEM, a beam of electrons is focused on the surface of a polished piece of the plastic. When the beams hit an inorganic particle such as a filler or glass fiber that has a higher average atomic weight than that of the plastic, the electrons are scattered backwards and detected. By scanning the electron beam back and forth across the surface, an image showing the distribution, size, and shape of the inorganic particles is developed. The composition of the particles is determined by focusing the electron beam on individual particles. The interaction between the electrons and the atoms in the inorganic particles causes x-rays to be emitted from the particle, which are then detected and quantified as functions of the wavelengths of the x-rays. Since each element emits x-rays of specific wavelengths, the percentage of each element in the particle can be quantified based on the area under the peak on a plot of numbers of x-rays detected versus wavelength.

Tensile properties of the plastics were determined by cutting thin sections into dog bone-shaped pieces, clamping the ends of the test specimens in the test rig, and then pulling them apart while measuring the stress on the sample as a function of the strain in the samples. These tests were done at a rate of 1 mm/s while the samples were held at 125°C. The tensile properties of ultimate strength and ratio of the stress applied to the elongation produced (Young's modulus) were determined using this test.

RESULTS AND DISCUSSION

Baseline Green and Black Guides

Figure 1 shows examples of the green and black rod guides offered for the analyses. As can be seen more clearly in the green guide, the resin is injected into the mold at the center of one vane that is wider at the top than at the bottom. Along the surface of the injection vane, structures known as flow lines can be seen from the variations in the color. The dull surface finish of the guides indicates that they were likely molded well below the melting temperature of the Amodel resin, a method known as cold molding.

Figure 2 shows a thin cross section of each of the two rod guides. These cross sections were taken near the ends of each of the guides, away from the injection point, and show considerable but similar porosity in each of the green and black plastics. It should be noted that some of the pores in the green guide have filled with the polishing compound and appear black rather than white. The pores are approximately 1 mm in diameter and relatively smooth-walled, which indicates that they are probably caused by entrapped gas and are not due to lack of sintering of the plastic particles. The trapped gas could either come from air trapped between the plastic particles or from moisture that was absorbed by the plastic particles before molding.

Figure 3 shows an SEM image of a cross section of a vane in the green (top) and black (bottom) guides. The images were made using backscatter imaging, in which darker areas are composed of lower-atomic-number elements such as plastic, and the light areas are composed of higher-atomic-number elements such as silicate glass. The round white areas are cross sections of glass reinforcing fibers, the smaller white particles are pieces of glass or inorganic filler materials, and the black areas are empty pores within the plastic. The composition of the glass fibers in the black guide is essentially the same, with very small variations that are likely due to uncertainties in the measurement method. The green guide also contains small amounts of fine calcium silicate particles between the glass fibers, which may be a mineral filler. However, an analysis of the ash left after combustion of the green material also shows microscopic regions of iron-rich material, indicating either that the iron was very finely dispersed and not visible in these SEM images or that it was in larger discrete particles that were not analyzed just because they were widely distributed. The black guide images show much less of the filler material. The increased level of filler material and the presence of iron in the ash of the green guide are significant differences between the two guide materials. TGA data indicate that the green material leaves 46% ash after combustion, and the black material leaves 35% ash.

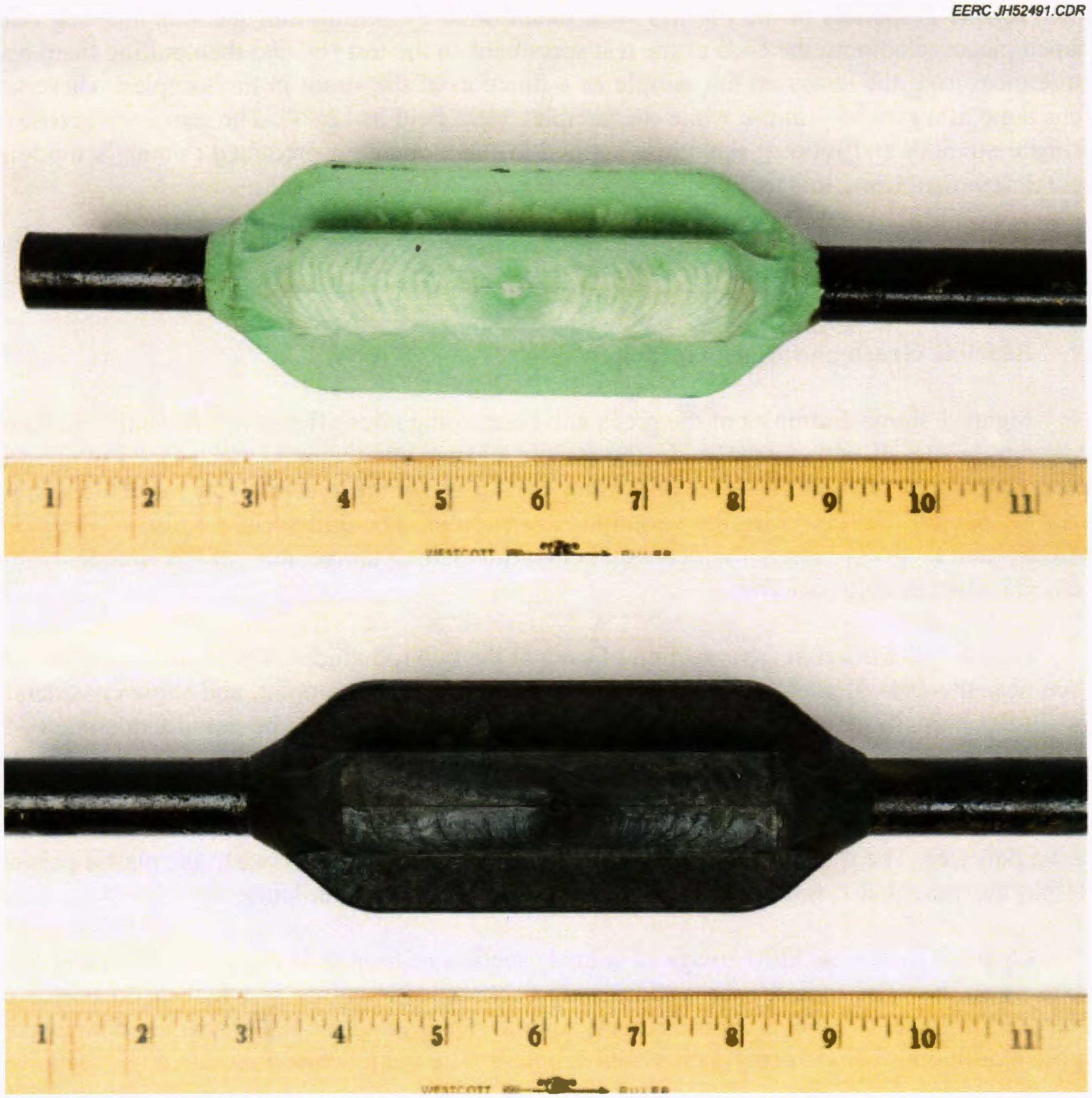

Figure 1. Baseline green and black rod guides.

Figure 4 shows the DSC data for each rod guide. The top graph is for the green guide, and the bottom graph is for the black guide. As can be seen from the graphs, during the first heating of each sample, there is an exotherm caused by partial crystallization of the polymer near the T_g for both plastics, possibly indicating that they were not fully crystallized when made. As the material heats further, an endotherm occurs when the material melts. During cooling, an exotherm occurs because of partial crystallization of the PPA. Then when the sample is reheated, a slight shift in slope occurs at T_g. No exotherm occurs in the reheat because of crystallization near T_g because the material was fully crystallized while cooling from the melt that formed near the end of the first heating cycle.

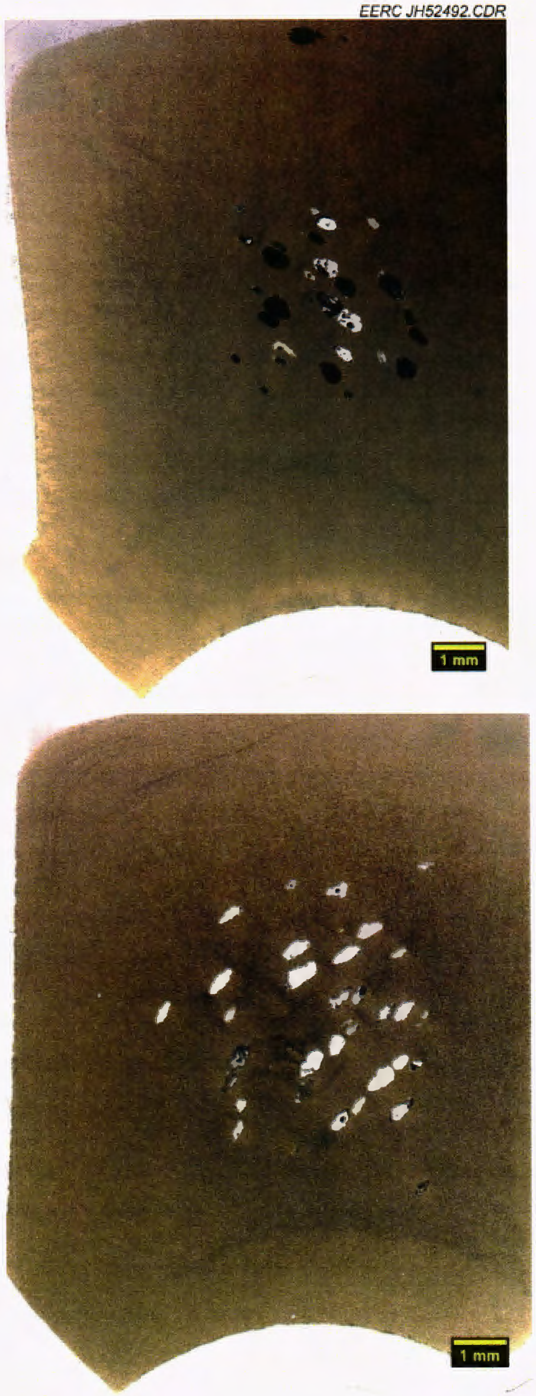

Figure 2. Thin cross sections of single vanes from the green (top) and black (bottom) guides showing extensive but similar rounded porosity.

The T_m for the green guide is 291°C, and its T_g is 86°C, while for the black, the T_m is 301°C and the T_g is 113°C. These differences are significant. In addition, the temperatures and shapes of the crystallization event during cooling are significantly different. The differences indicate that the green and black guides are made from different plastics. The resin manufacturer has told the EERC preliminary data from measurements of the viscosities of the plastics indicate that the black plastic is Amodel resin but the green plastic is likely Amodel mixed with other resins or additives.

XRD was used to determine the degree of crystallinity of the two plastics as well as any crystalline inorganic material that may have been used as fillers in the plastics. XRD does not detect amorphous plastic or inorganic glass. Figure 5 shows the x-ray diffractograms for the two plastics presented on one graph for comparison. The broad peaks in the data are known as amorphous humps and do not indicate crystalline material. Several sharp peaks can be seen in the line for the green guide, but no sharp peaks can be seen in the line for the black guide. This indicates that there is crystalline material in the green guide but not in the black guide. However, identification of the peaks in the green guide data indicates that the crystalline material is all inorganic, primarily calcium silicate, calcium iron silicate, and calcium carbonate. The lack of crystalline polymer peaks indicates that the plastic material in both guides contains very little crystalline polymer.

Figure 6 shows the FTIR spectra for the green and black guides. The data for the green guide are the green line and for the black guide the black line. The graph indicates the percent reflectance of the infrared light from the surface of the materials as functions of the wave number of the light, which is the number of waves of light per centimeter. The wave number is the inverse of the wavelength of the light. For the most part, the data are similar until the wave number reaches 1100/cm. Below that, the spectra show different positions for peaks and valleys, indicating that the plastics are somewhat different. As noted previously, because of the lack of a computerized database, it is not possible to identify the specific differences between the plastics. It may be that the green contains PPA mixed with another plastic or additive.

The tensile strain-versus-stress curves for the green and black guides are given in Figure 7. The curves are averages from the tests of four samples for the green guide and two samples for the black guide. The graph shows that the material in the black guide has an ultimate tensile strength significantly higher than that of the green guide at 125°C. The resin manufacturer reports a tensile strength for its 33% glass fiber-filled resins at 125°C of about 110 MPa (2), so the lower ultimate strength found (30 MPa) during these analyses is likely due to the pores in the material cut from the guides. The average Young's modulus, or ratio of stress to strain, was approximately 0.9 GPa for the green and 2 GPa for the black material, whereas the resin manufacturer lists moduli of between 7 and 9 GPa for three different glass fiber-reinforced PPAs at 125°C (2). The pores also caused significant variations in the curves between individual samples as the number of pores varied from sample to sample.

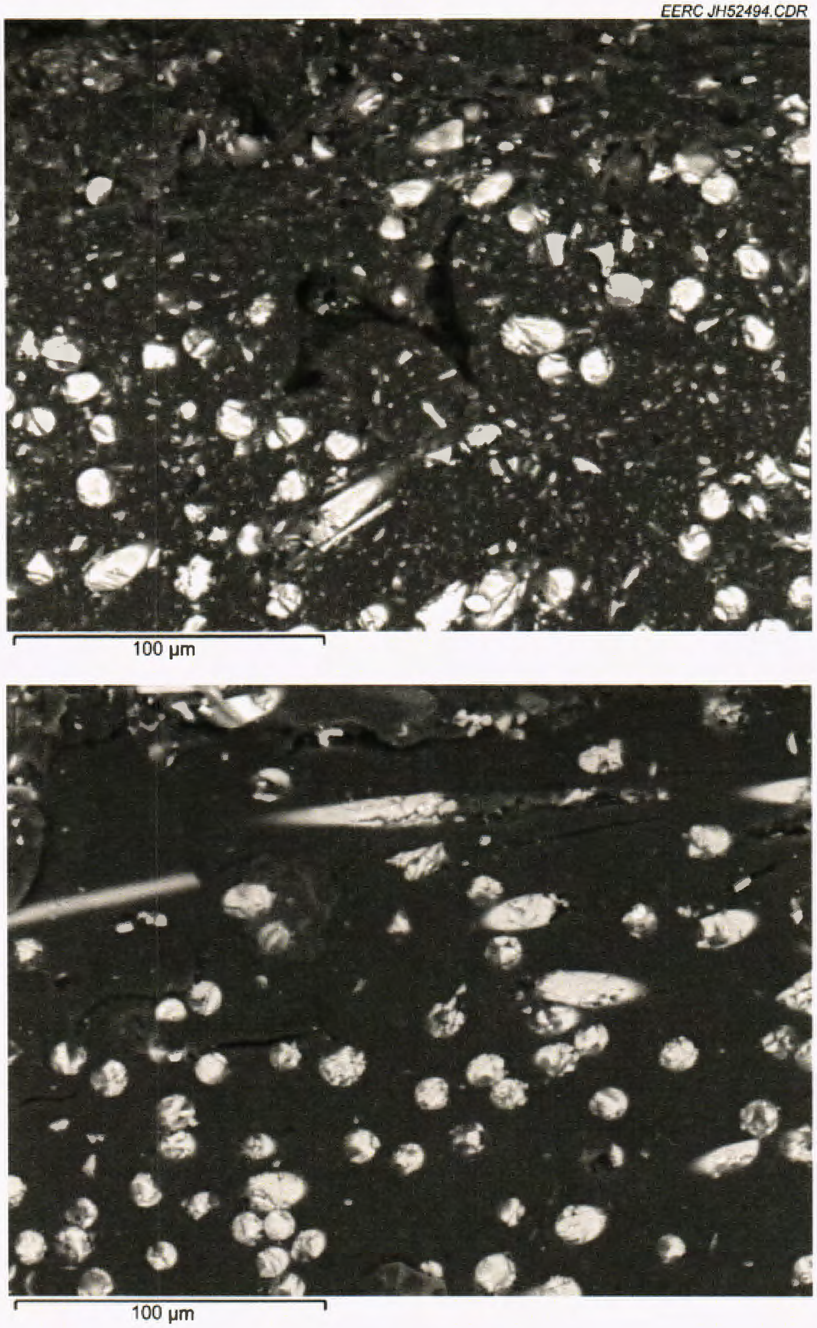

Figure 3. SEM images of polished cross sections of the green (top) and black (bottom) guide materials.

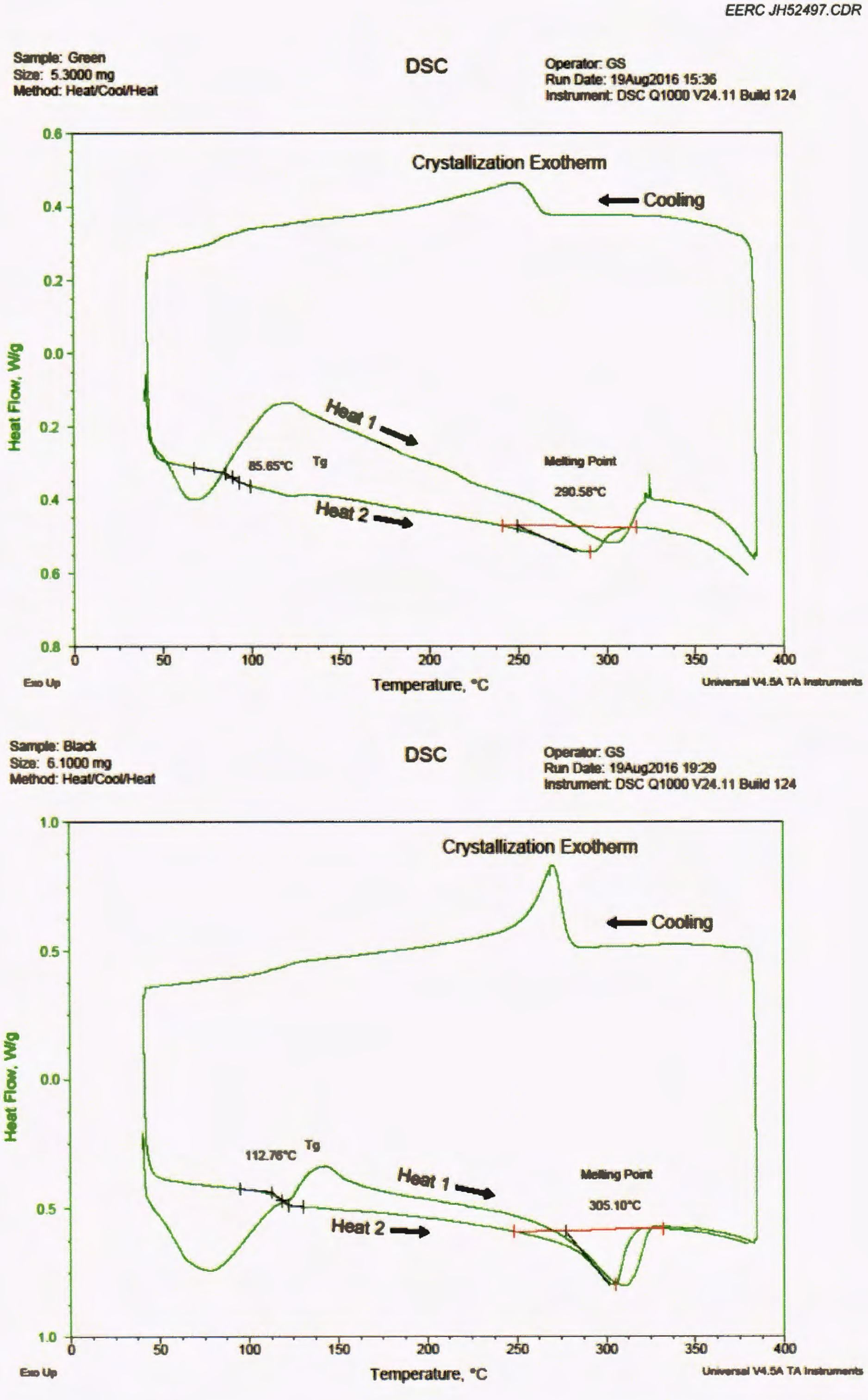

Figure 4. DSC graphs for the green guide (top) and black guide (bottom).

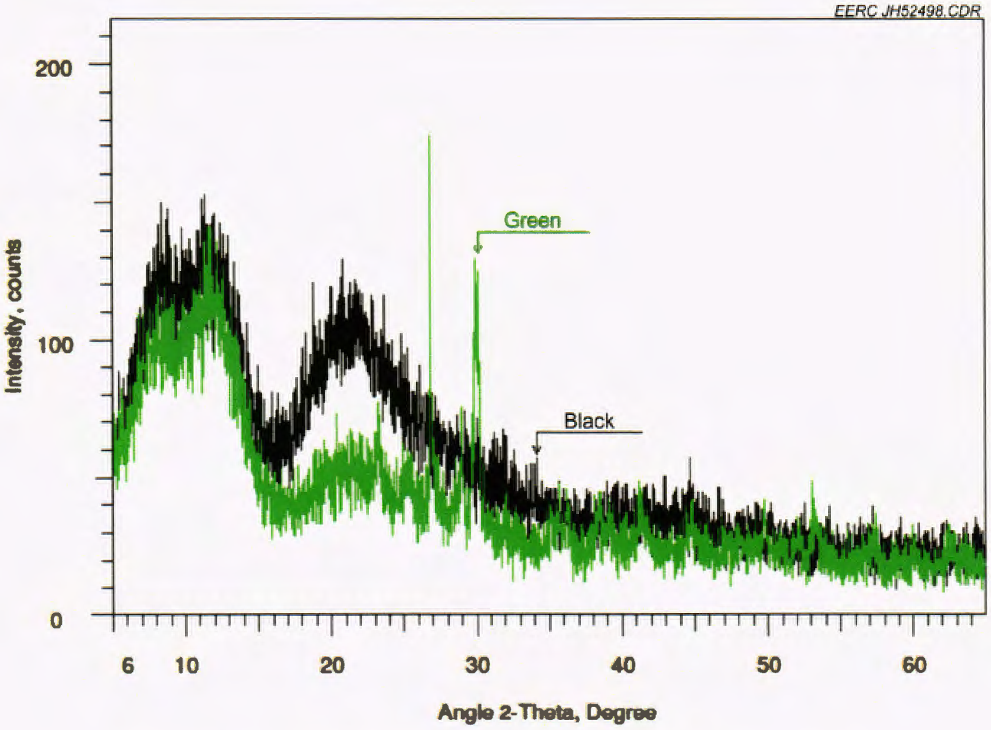

Figure 5. X-ray diffractograms for the green and black guides.

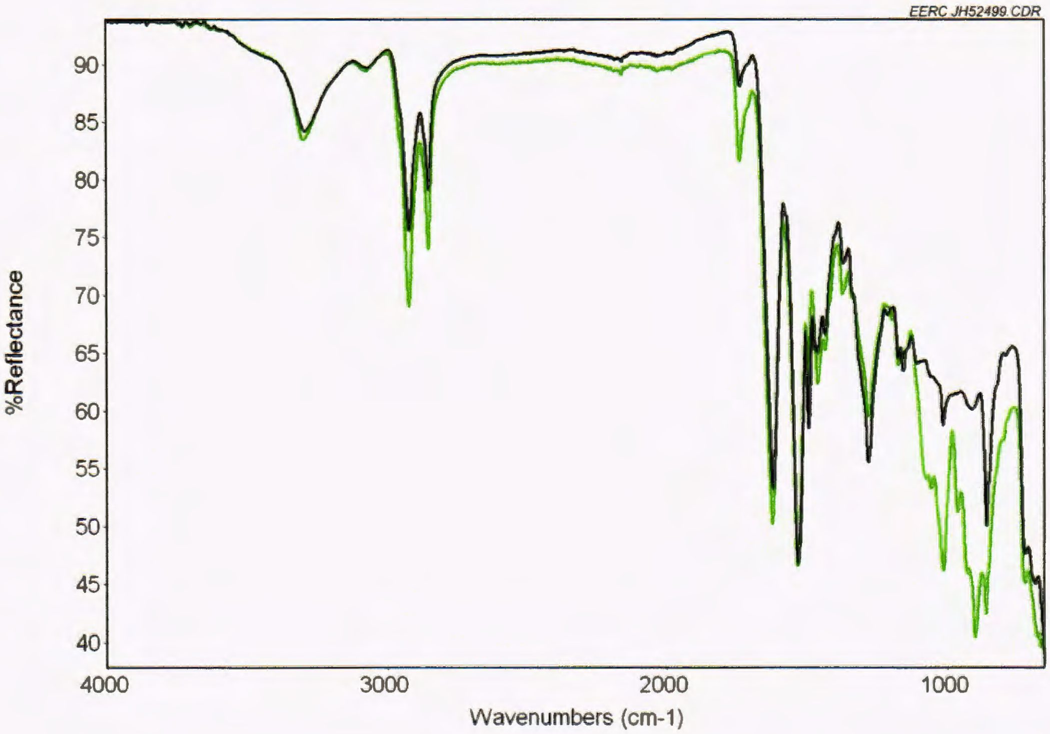

Figure 6. FTIR spectra for the green and black guides.

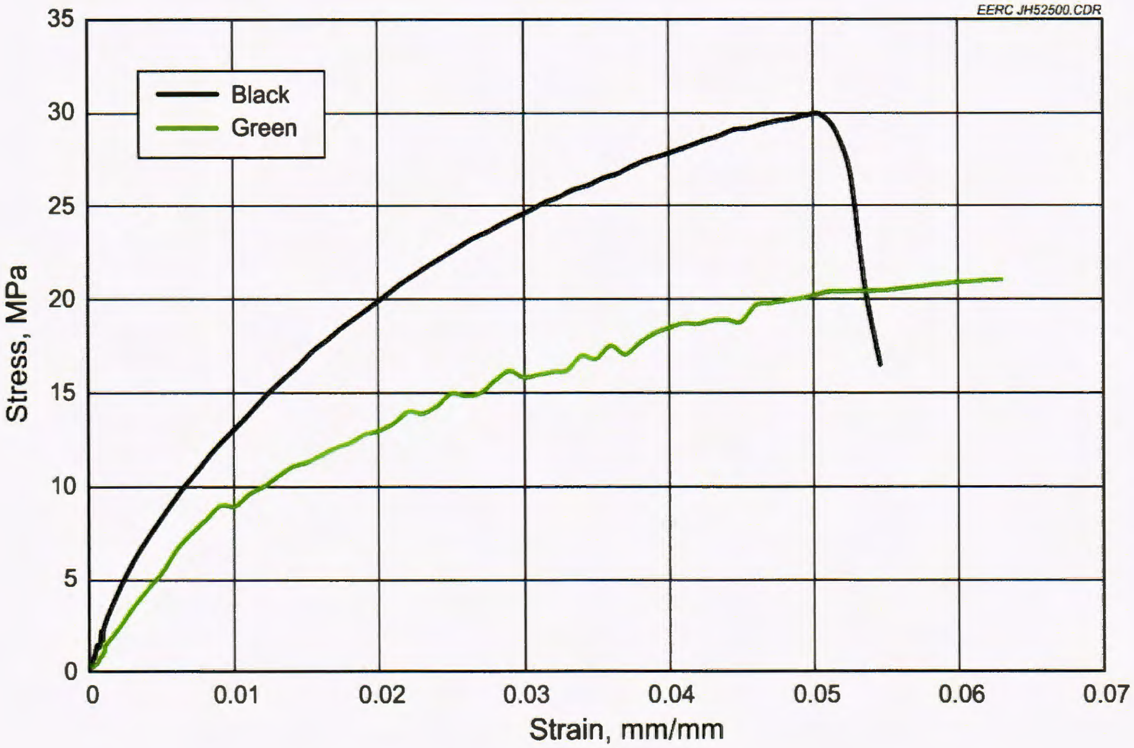

Figure 7. Average tensile test data for the green and black guide materials.

Changes in Green and Black Guides Due to Downhole Use

Pieces of green and black guides were removed from sucker rods by the operator and sent to the EERC for testing to determine what changes had occurred during exposure in active wells. The guides were usually removed by inserting a screwdriver in an existing crack in the guides and then hitting the screwdriver with a hammer. Figure 8 shows two views of a broken-off, used green guide. The top view shows the outer surface of the guide, and the bottom view shows the interior of the guide. As can be seen in the outer surface, particles of sand or proppant had become embedded in the guide vanes. The inner surface shows orange/brown deposits inside the vane, indicating that brine had penetrated into the guide along a relatively smooth and flat plane in the middle of one of the vanes. SEM analyses indicate that the deposits are made primarily of sodium chloride, with some potassium, calcium, and iron. The smoothness of the orange/brown areas indicates that environmental stress cracking (ESC) had occurred in the material along that plane. The green portion of the break exhibits a surface roughness typical of a standard mechanical fracture, indicating that ESC had not yet occurred all the way through the vane. It is notable that the ESC occurred from the inside (next to the rod) moving toward the outside, rather than starting at the outside and moving in toward the rod, although more used rod guides would need to be examined to determine whether that is a common occurrence.

ESC is not a chemical reaction between the fluid and polymer. Instead, the fluid diffuses in through a weak zone and reduces the cohesive forces between the polymer chains. It occurs more rapidly in structures that are under tensile stress and only in the amorphous portion of the polymer, not in the crystalline portion. ESC can be increased either by sorption or desorption of liquid, such as when a polymer absorbs moisture from the air and then the moisture is pulled out of the polymer by the brine (3) through osmotic pressure. ESC is known to occur in polyamides that are exposed to brines but occurs more readily when the solution is saturated in divalent cation salts like $CaCl_2$, as compared to NaCl saturation (4).

Figure 9 shows a used black guide. The photograph of the outside of the guide (top) shows cracks transverse to the axis on one vane. The transverse cracks are of similar size and shape to the flow lines that are visible in the new guide shown in Figure 1. These cracks do not appear on the other vanes, just as the flow lines do not appear on the other vanes on new guides. Flow lines form as the injected plastic cools in contact with the mold, causing it to become more viscous. More plastic then flows up to contact the mold from below until it also cools, and then the process repeats. A simplified view of how flow lines form in the injection vane of the rod guides is shown in Figure 10.

These cracks did not appear on the used green guide, but smaller pieces from the green guide were analyzed, resulting in the possibility that the injection vane may have not been included, or the cracks may not have formed in the green guide. In addition, the left piece in the photograph of the interior of the black guide (Figure 9) shows similar salt penetration into the plane down the middle of the vane on the opposite side of the injection port. Like the green guide, this indicates ESC along that plane. ESC likely occurred because of weakness along that line caused by the presence of a weld or knit line.

Knit lines form when plastic flows around an object, such as the sucker rod, during molding. As the plastic is injected, it must flow around the rod and then flow back together on the opposite side of the rod. A simplified version of the process is shown in Figure 11. At the knit line, the reinforcing glass fibers and polymer chains often will not bridge the two sides of the flow sufficiently, thus creating a weak zone in the middle of the vane opposite to the injection port.

In order to increase the strength of the knit line and reduce the formation of flow lines and pores, several changes in the molding procedure can be made. These include drying the resin before injection; increasing the temperature, pressure, and hold time of the plastic; and increasing the temperature of the mold. However, determining which process variable to change and by how much can be a difficult task because changing one variable to increase knit line strength may cause other problems in the molding process. Resin manufacturer representatives have indicated that they will travel to the molding site free of charge to review procedures with the rod guide manufacturer to reduce the formation of the pores and flow lines and increase the strength of the knit lines in the rod guides. These changes would also likely increase the crystallinity of the guides, making them more erosion-resistant, but possibly at the cost of a reduction in toughness (resistance to breaking as a result of a sharp impact).

Figure 8. Used green rod guide.

Graphs from the DSC analyses of the used green and black guides showed shapes similar to those of the unused guides, except similar shifts in T_g and T_m. The T_g of the used green guide increased from 86°C in the unused guide to 99°C in the used guide, whereas the T_g of the black guide increased from 112° to 123°C. The increase in T_g indicates that the polymer chains increased their attraction to each other, possibly through the loss of a plasticizer (such as water) or because of an increase in molecular weight. These changes could occur by being held at high temperatures for extended periods or through dehydration in the brine.

Figure 9. Used black guide.

T_m also changed, but in the opposite direction. It dropped from 291°C in the unused green guide to 276°C in the used green guide and from 305° to 298°C in the black guides. However, a drop in T_m usually indicates a drop in molecular weight, the opposite of what would cause an increase in T_g. Therefore, additional testing is required to determine why these temperature changes occurred in the used samples. Optical microscopy and XRD analyses of the used guides did not show any increased crystallization of the polymers due to exposure. However, tensile testing of the used black guides showed significant drops in tensile strength of the material due to exposure downhole, as seen in Figure 12.

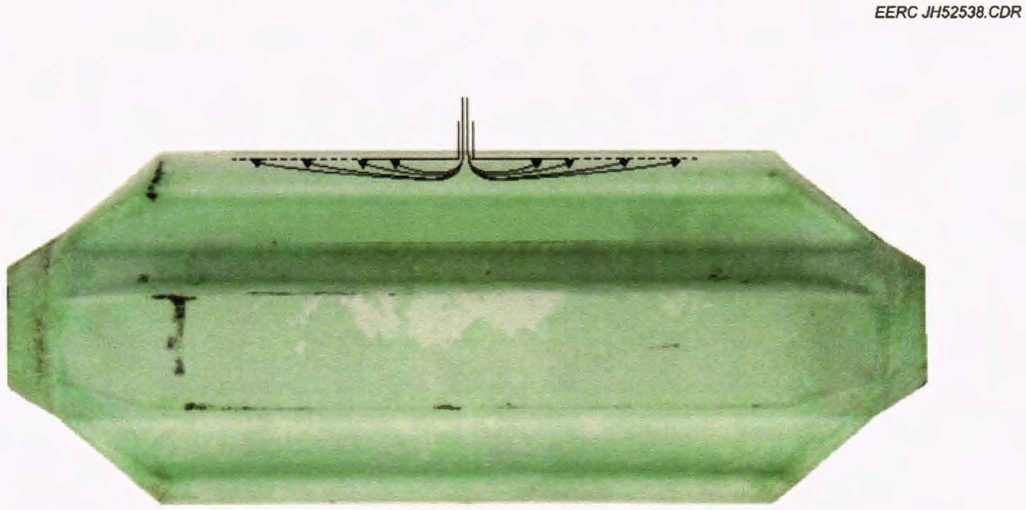

Figure 10. Simplified view of how flow lines form in the injection vane of the rod guides.

Figure 11. Simplified view of the formation of a knit line during injection molding.

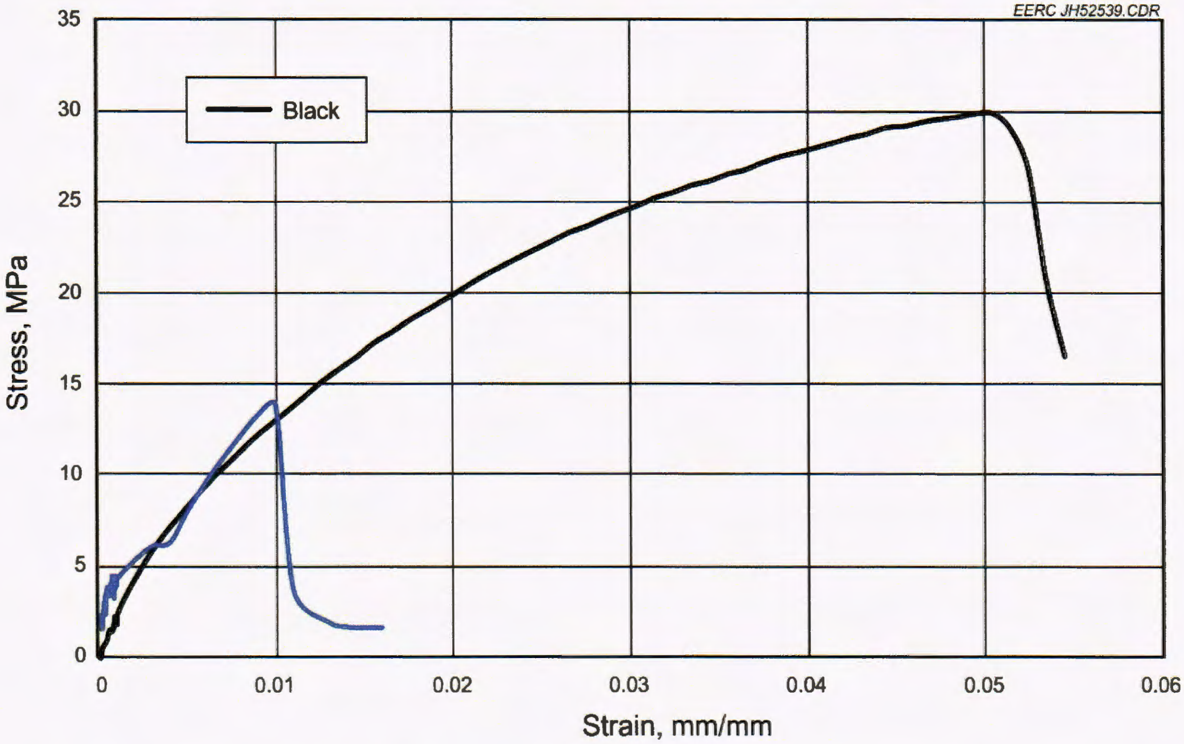

Figure 12. Average tensile test data for the new (black line) and used (blue line) black guide materials.

The data for the used material is an average from only two samples because two other samples broke while clamping the samples in the test machine. Tensile tests of the used green material could not be performed because of the limited amount of sample that was available.

Analyses of the Alternate Manufacturer Rod Guides

In addition to the analyses of the new and used green and black baseline guides, the EERC was asked to perform similar analyses of a "Stealth XL" guide and two types of "MP" guides. Stealth XL guide is shown in Figure 13. It has a dull surface similar to the baseline black rod guide, indicating that it was likely molded at a relatively low temperature compared to the melting temperature of the plastic. Also like the baseline guide, it exhibits flow lines along the surface of the injection vane but not on the surfaces of the other vanes. Optical microscopy shows that like the baseline guides, the plastic in the thick vanes is porous.

The DSC data for the Stealth XL are shown in Figure 14. The data are essentially identical to those for the baseline black guide shown in Figure 4. T_g and T_m for the Stealth XL are within 1 degree of the values for the baseline black guide. These similarities, and the differences with the data for the baseline green guide, reinforce the evidence that the baseline black and green guides

Figure 13. Stealth XL.

are made from different plastics. XRD, ash content, and SEM analyses were all very similar between the Stealth XL and the baseline black guide, indicating that they are made of essentially the same material and likely molded in a very similar fashion, although the tensile strength and Young's modulus for the Stealth XL were about 20% lower than for the baseline black material.

In contrast, the alternate MP guides were very different from any of the other guides analyzed. Figure 15 shows the two MP guides. EERC analyses indicate that they are essentially the same; therefore, when discussing the analytical data, only the analyses of one of the guides will be discussed, except for the tensile data. As can be seen in the figure, the MP guides are very shiny compared to the other guides in this study, indicating that they were molded with a fully liquid polymer. They also do not show any flow lines. The Web site for the guides (5) indicates that they contain less glass fiber than most other guides, they contain a proprietary mineral filler, and they are made of a proprietary polymer.

Figure 16 shows a cross section of one of the vanes in an MP guide. As can be seen, no porosity is evident even though the vanes are of a thickness similar to the other guides studied. An SEM image of a polished cross section of an MP guide is shown in Figure 17. Energy-dispersive x-ray spectroscopy shows that the glass fibers have an average composition of 28% Si, 15% Ca, 8% Al, 2% Mg, 1% Na, 2% Fe, less than 1% each for other metals, and 46% O. This composition is essentially the same as for the glass fibers seen in the other guides. In addition, analyses of the

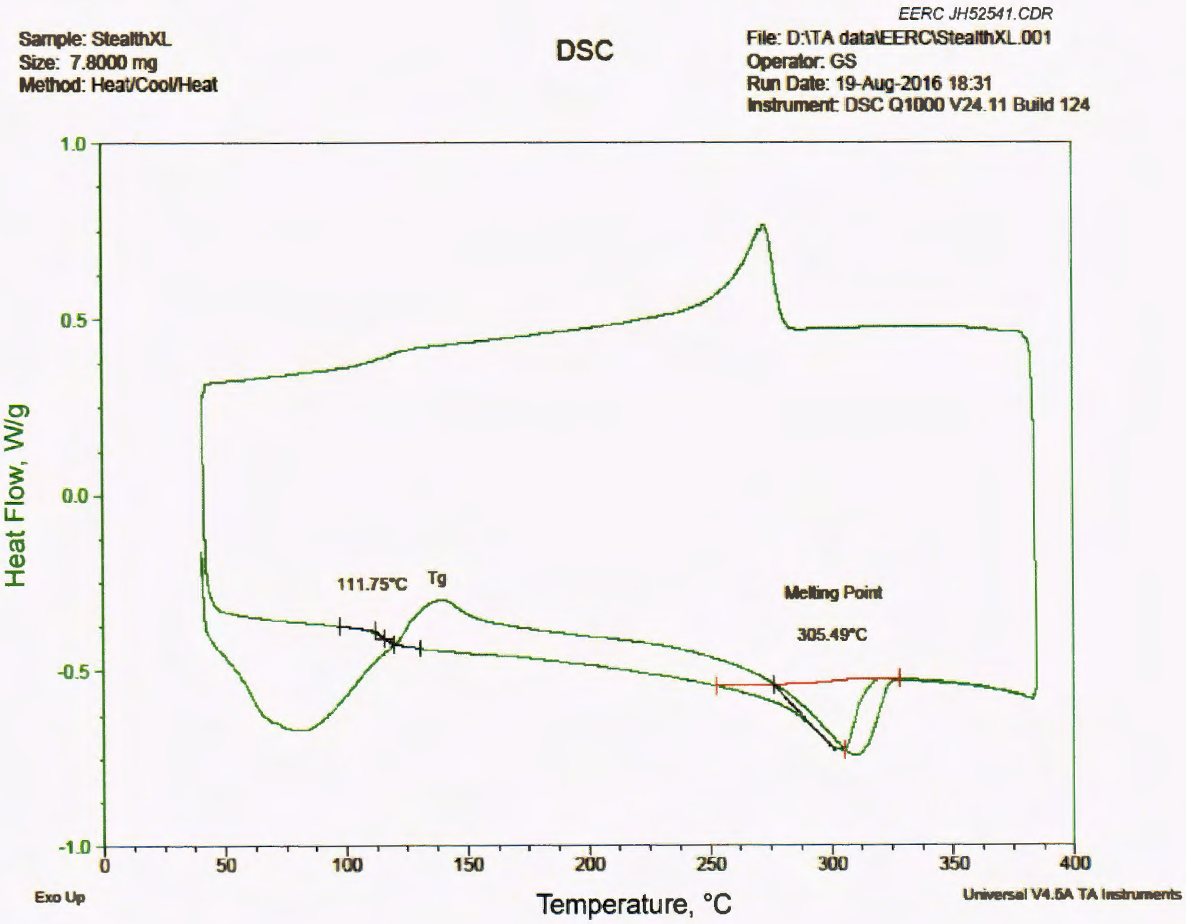

Figure 14. DSC graph for the Stealth XL rod guide material.

plastic between the glass fibers show that there is likely a very fine filler not easily visible which contains Si, Al, Ca, and zinc (Zn). The ash content of the MP guides is similar to that of the baseline green guide at around 50%.

Figure 18 shows the DSC graph for the MP guide. The data indicate that there is no T_g or T_m during heating and no crystallization peak during cooling. This indicates that the material is not thermoplastic such as PPA, PPS, or PEEK, but is more likely a thermosetting polymer. FTIR analysis indicates that the material is similar to a phenolic resin. XRD does not indicate any crystalline polymer present. When preparing samples for analyses, it was found that these guides were more easily abraded than the any of the other guides tested. Also, an odor of ammonia was detected when they were abraded which could possibly indicate that they are made from an epoxy rather than phenolic resin (6).

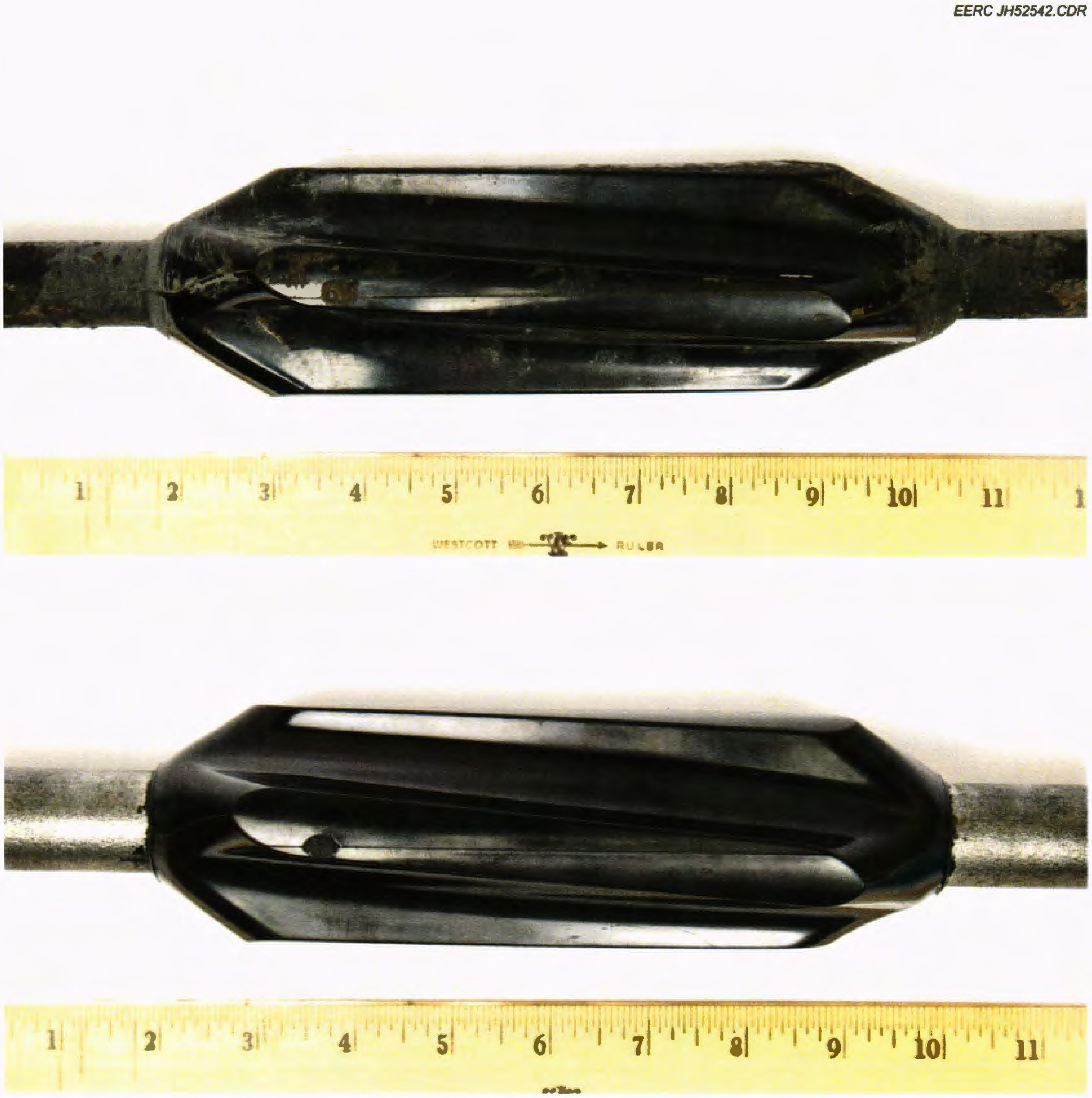

Figure 15. MP guides, older version on top and newer version on bottom.

CONCLUSIONS

DSC and FTIR analyses indicate that the baseline green and black guides are made out of different types of plastics. Resin manufacturer representatives have told the EERC that the DSC data and preliminary data from measurements of the viscosities of the plastics indicate that the black plastic is Amodel resin but the green plastic is likely Amodel mixed with other resins or additives. FTIR data indicate many similar molecular structures to the Amodel resin but different enough that the green plastic is likely blended with other resins or additives. TGA analyses indicate

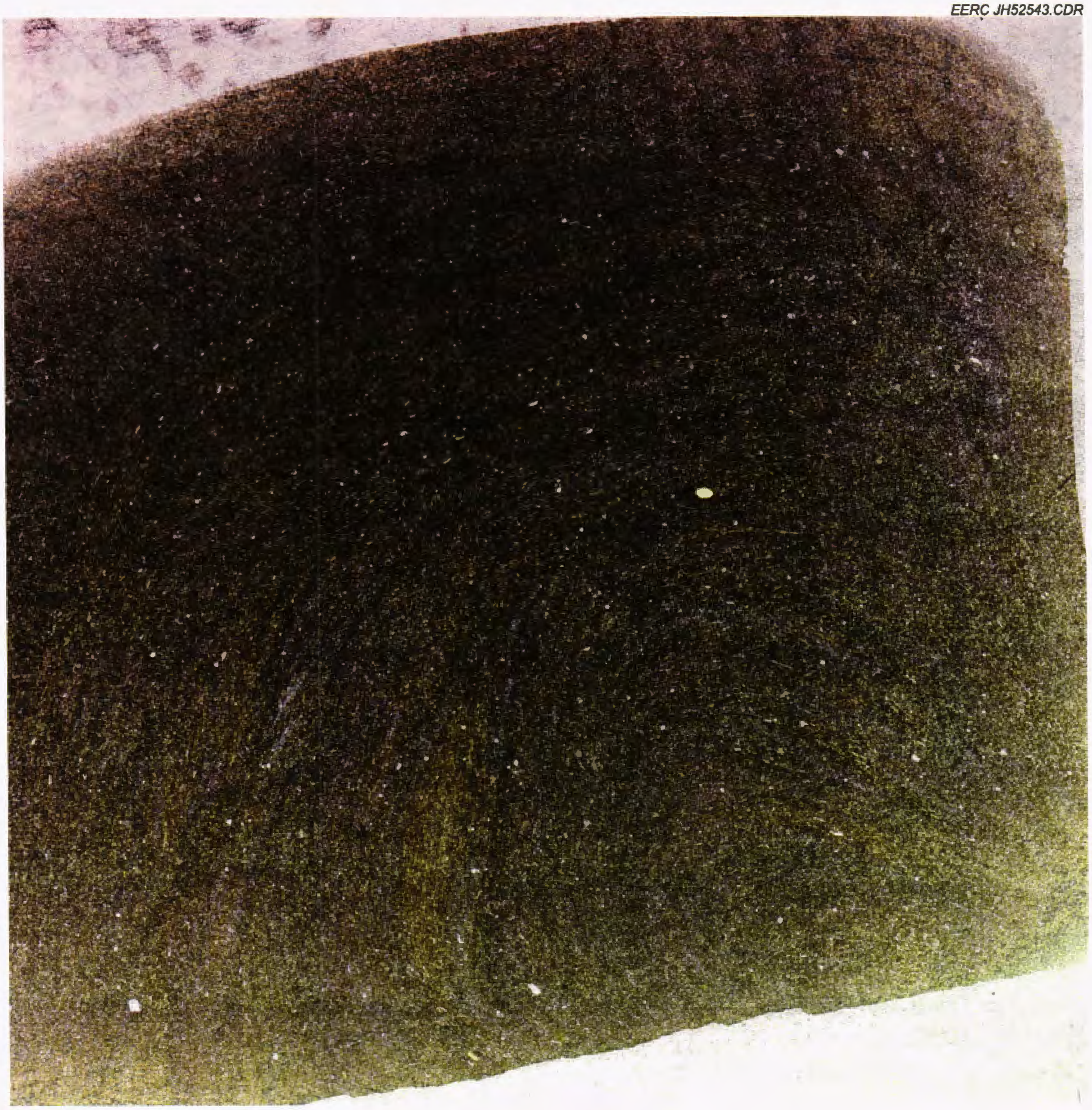

Figure 16. Optical microscope image of a thin section of an MP guide.

that the green guide contains significantly more reinforcing or filler than the black guides. Tensile testing shows that the black guides are significantly stronger than the green guides, but both are much weaker than shown in data for reinforced Amodel resins from the resin manufacturer, likely because of their high porosity. The material in the black guide that had been exposed to downhole conditions was only one-half as strong as the new material.

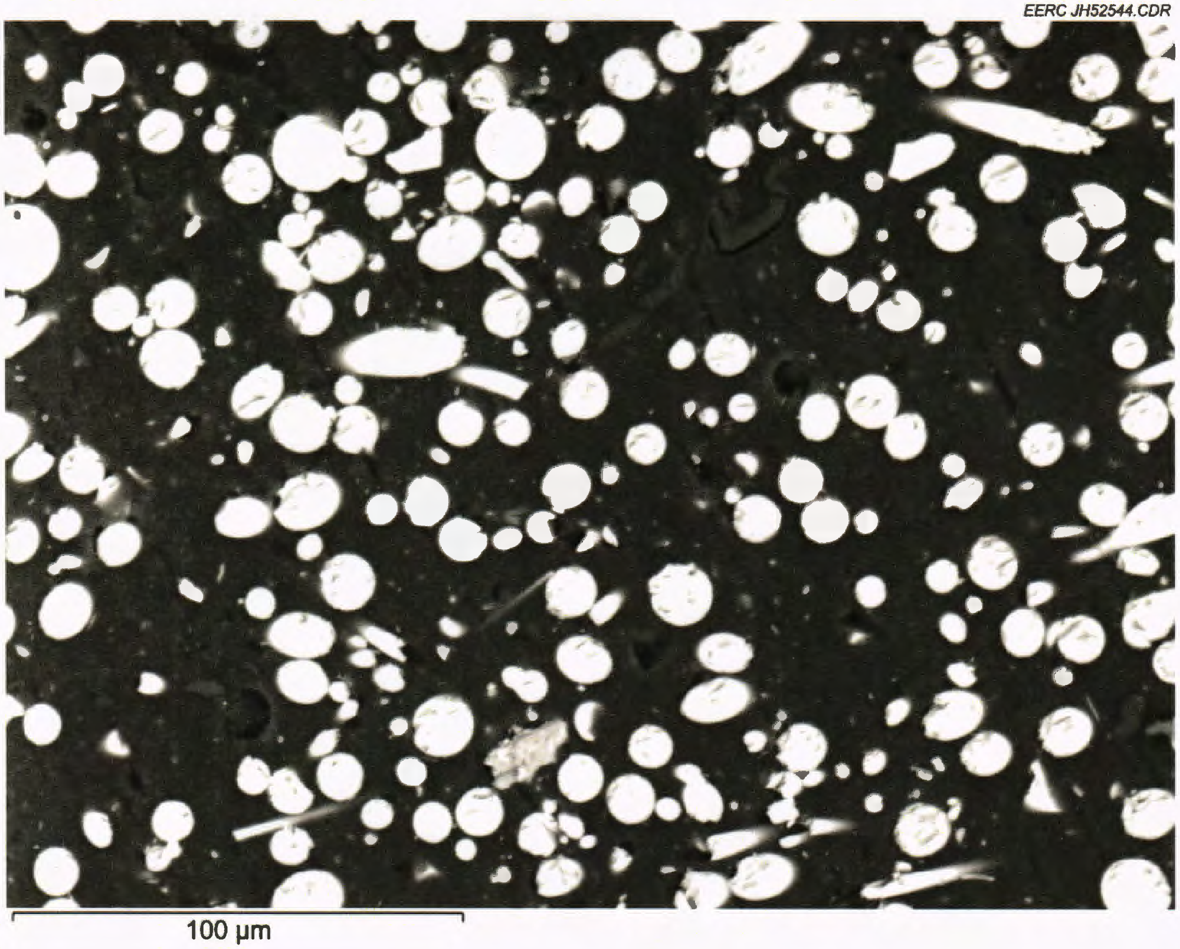

Figure 17. SEM image of a cross section of an MP guide.

The black and green guides both exhibit dull surfaces, indicating that they are molded at lower temperatures than the melting point of the resin. Optical microscopy and XRD analyses did not detect any crystallinity in either guide.

Both show significant flow lines on the erodible surface of the vane into which the plastic is injected. The used black guides were cracked along these flow lines. Similar cracks were not seen on the used green guide; however, only a portion of a used green guide was obtained for analysis, and it may have come from a sucker rod that experienced significantly different conditions than the black guide.

Both types of guides showed environmental stress cracking along what is likely the knit line along the center length of the vane opposite to the injection vane. It is likely that these types of guide failures could be reduced by altering the molding process variables. These include drying the resin before injection; increasing the temperature, pressure, and hold time of the plastic; and increasing the temperature of the mold. These changes would also likely increase the crystallinity

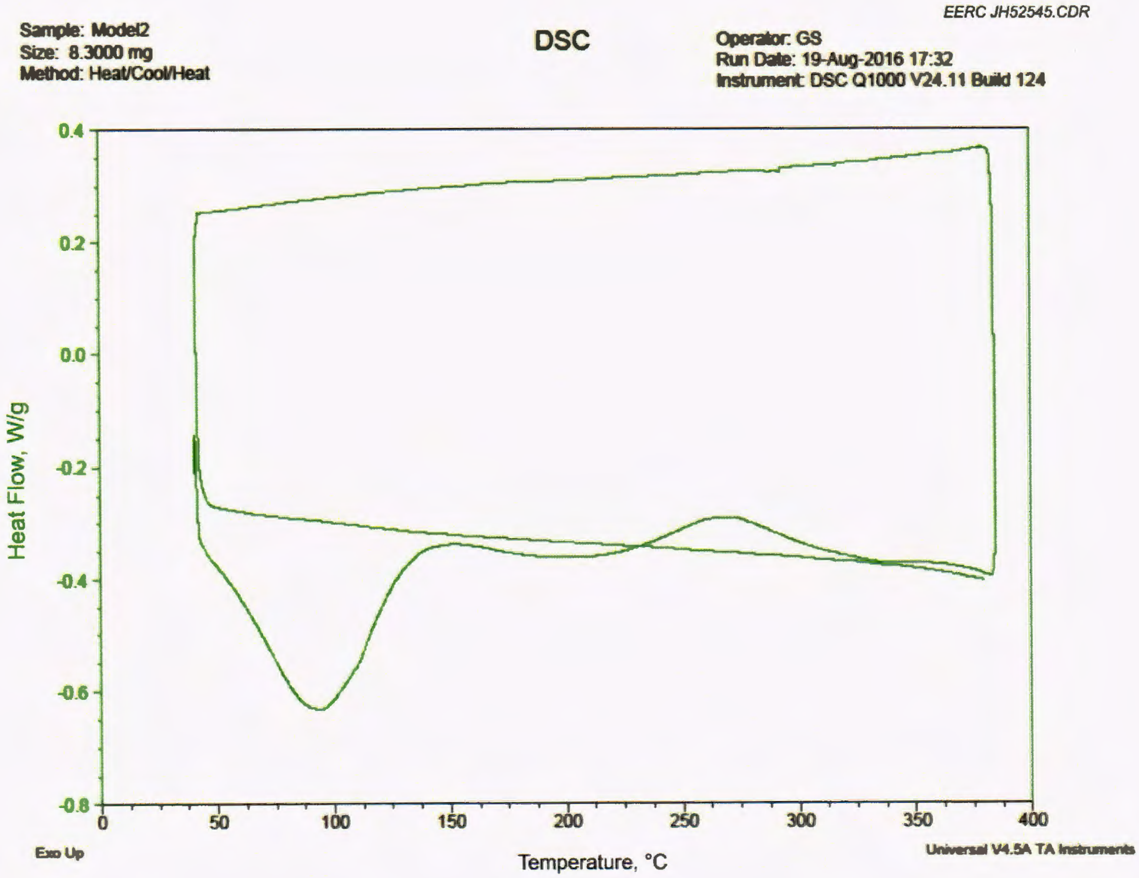

Figure 18. DSC graph for the MP rod guide material.

of the guides, making them more erosion- and corrosion-resistant, but possibly at the cost of a reduction in toughness. However, determining which process variable to change and by how much can be a difficult task because changing one variable to increase knit line strength may cause other problems in the molding process. The EERC suggests that the rod guide manufacturer work with the resin supplier to develop the best set of process variables for molding the guides to reduce the failure rates.

Analyses of the Stealth XL guide showed that it is very similar to the baseline black guide. It is composed of the same resin and appears to have been molded in a similar fashion as well because the thick vanes are similarly porous and there are flow lines on the erodible surface of the injection vane. It will likely fail in ways similar to the baseline rod guide, and failure rates could likely be improved using changes to process variables similar to the baseline rod guide.

In contrast, the MP guides are shiny and do not show flow lines, indicating that they were molded as a liquid. They also do not contain any obvious porosity. DSC analyses indicate that they are made from a thermosetting resin rather than thermoplastic. FTIR indicates that they may be made from a phenolic resin, but an ammonia odor that was produced when abrading the samples indicates that they may have been made from an epoxy resin. They likely would not crack or suffer ESC in manners similar to the current Amodel guides. However, when preparing samples for analyses, it was found that these guides were more easily abraded than the Amodel guides.

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INDUSTRIAL COMMISSION OF NORTH DAKOTA

Doug Burgum	Wayne Stenehjem	Doug Goehring
Governor	Attorney General	Agriculture Commissioner

Memorandum

TO: Robyn Loumer

FR: Karlene Fine
Executive Director and Secretary

DT: February 27, 2017

RE: **OGRC GRANT PAYMENT**

Please have a check(s) prepared in the following amount to the entity(s) listed below as per their contract.

UND - EERC	$200,450
ATTN: GRANTS & CONTRACTS OFFICE	
G-030-060 PROGRAM DETERMINE UNIQUENESS OF THREE FORKS	
PO BOX 7036	
GRAND FORKS, ND 58202-7036	(Final Payment)
For work done: Final Payment	

Please pay from the 2015-2017 biennium. If you have any questions, please call. Please forward the check(s) to the appropriate person(s) and make a copy for my files.

Thanks. KF

Shirley —
Please process final payment of $200,450.00.
This will close the file on this project.
Linda [illegible]
Karlene

I have the electronic copies of these reports.

Karlene K. Fine, Executive Director and S
State Capitol, 14th Floor - 600 E Boulevard Ave Dept 405 -
E-Mail: kfine@nd.gov
Phone: (701) 328-3722 FAX: (701) 3
www.nd.gov

EERC
Energy & Environmental Research Center®
Putting Research into Practice

University of North Dakota
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www.undeerc.org

January 30, 2017

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
State Capitol, 14th Floor
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Final Report Entitled "Bakken Production Optimization Program"
Contract No. G-030-060; EERC Fund 18776

Please find enclosed the subject Energy & Environmental Research Center report.

Thank you for your support of this project. It has been a pleasure working with you. If you have any comments or questions regarding the report, feel free to contact me by phone at (701) 777-5157 or by e-mail at jharju@undeerc.org.

Sincerely,

Jay C Almlie
FOR JAH

John A. Harju
Vice President for Strategic Partnerships

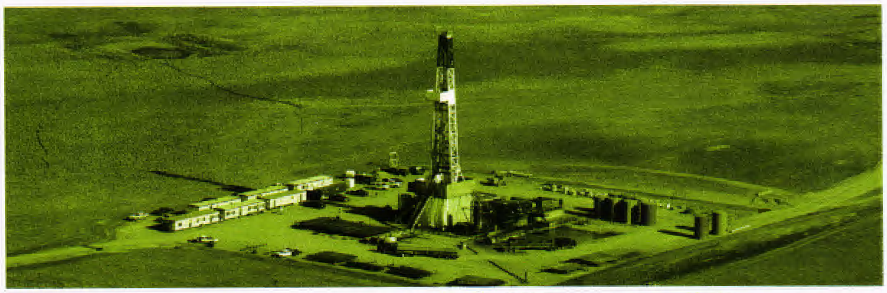
JAH/rlo

Enclosure

Bakken Production Optimization Program

FINAL REPORT

Years 1–3 (2013–2016)



EERC

UND UNIVERSITY OF NORTH DAKOTA

FINAL REPORT SUMMARY FOR "BAKKEN PRODUCTION OPTIMIZATION PROGRAM" INDUSTRIAL COMMISSION OF NORTH DAKOTA CONTRACT NO. G-030-060

In June 2013, a consortium comprising the Energy & Environmental Research Center (EERC), Continental Resources, Inc. (Continental) and several of the largest oil producers in the state was awarded North Dakota Oil and Gas Research Program (OGRP) funding to complete a 3-year, $117 million project with the goal of improving Bakken system oil recovery while simultaneously reducing its environmental footprint. This program was referred to as the Bakken Production Optimization Program (BPOP).

BPOP was a premier public–private partnership harnessing the best minds in North Dakota and in industry. BPOP demonstrated how effective a public–private partnership can be. It demonstrated that researchers, state lawmakers, state regulators, and industry can work together for positive results for shareholders and taxpayers alike. Significant achievements directly attributable to this program have made measurable, positive impacts to how the business of oil and gas exploration and production is accomplished in North Dakota.

BPOP conducted focused research in the areas of hydrocarbon utilization, water management, waste management, systems failure analysis, site logistics, spills remediation, and land reclamation. The centerpiece of BPOP was a massive project conducted by Continental to determine optimal well spacing within the Bakken. A small sampling of concrete examples of these impacts includes the following:

- Continental's Hawkinson Project, completed within BPOP, determined that the Bakken and Three Forks Formations represent unique and distinct reserves, which has enormous implications for current estimates of recoverable resources.
- BPOP facilitated a science-based process to determine if a change in rules regarding state drill spacing unit (DSU) setbacks was prudent, then supported state regulators in adopting the required changes. More oil will now be extracted from each DSU as a result of program efforts to justify a change in rules regarding the minimum distance between a well bore and the boundaries of each DSU.
- BPOP led an analysis of gas-flaring trends, and helped industry and the state of North Dakota determine appropriate flared gas reduction goals over a period of years. Program efforts to address flaring reduction resulted in new rules on flaring that were defined collaboratively, with industry and state interests working together.
- BPOP researchers provided science-based support to state regulators and industry during a critical discussion on how to best manage radiological waste associated with oil exploration and development.
- BPOP coordinated discussions with state regulators and industry groups on the topic of best practices for remediation of brine spills associated with oil development. BPOP then completed a best practices remediation manual with these groups.

The final report on this program summarizes BPOP achievements at the end of the original 3-year contract. The program continues as BPOP 2.0 during the period of November 2016 – October 2019. Many of the efforts begun under BPOP 1.0 will continue under BPOP 2.0.

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ACKNOWLEDGMENTS

The EERC would like to thank all state and industry program members for their active participation in this program. Without active engagement from all members, this program would not have been able to accomplish the numerous tangible, high-impact results described in this final report. Although the EERC led this effort, it could not have achieved success alone. The successes of this program were made possible only by enthusiastic participation of member companies and state agencies.

The EERC would specifically like to thank the following companies and North Dakota State agencies:

- ConocoPhillips Company
- Continental Resources, Inc.
- Hess Corporation
- Hitachi Data Systems
- Marathon Oil Corporation
- North Dakota Industrial Commission
- Nuverra Environmental Solutions, Inc.
- Oasis Petroleum Inc.
- Oil & Gas Research Council
- SM Energy Company
- Whiting Petroleum Corporation
- XTO Energy Inc.

Additionally, the program received extensive support, collaboration, and cooperation from the North Dakota Petroleum Council.

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Bakken Production Optimization Program

EERC
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BAKKEN PRODUCTION OPTIMIZATION PROGRAM

Final Report, Years 1–3 (2013–2016)

INTRODUCTION

In June 2013, a consortium comprising the Energy & Environmental Research Center (EERC); Continental Resources, Inc. (Continental); and several of the largest oil producers in the state was awarded North Dakota Oil and Gas Research Program funding to complete the 3-year, $117 million Bakken Production Optimization Program (BPOP), with the goal of improving Bakken system oil recovery while simultaneously reducing its environmental footprint. The program was designed to accomplish the following:

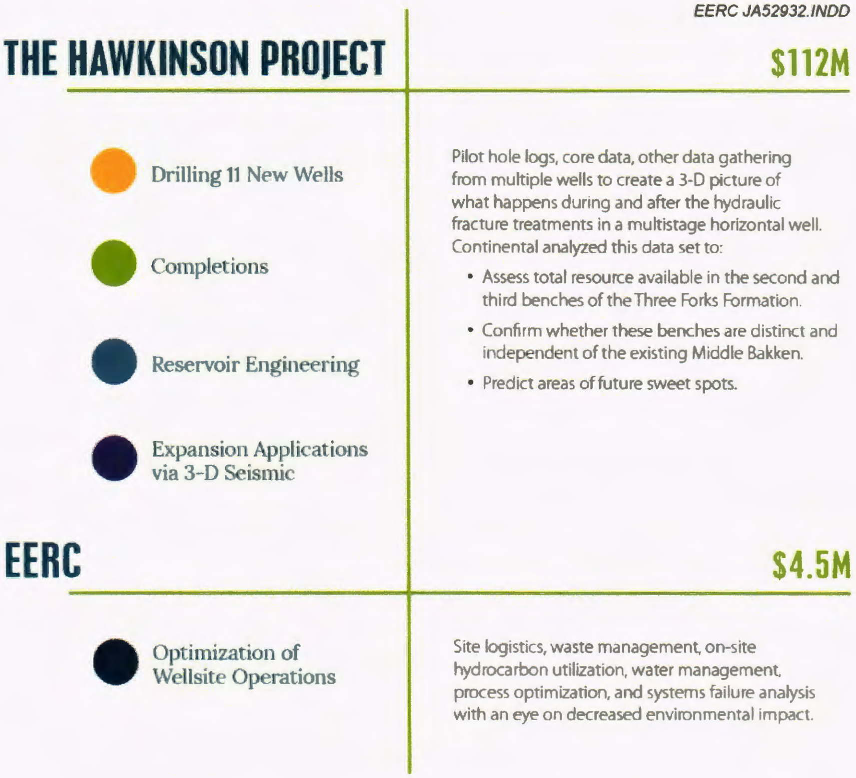
- Maximize oil production from Bakken and Three Forks wells by employing an "all of the above" approach
  - Perform reservoir characterization
    - Develop data sets to determine whether the oil of the second and third benches in the Three Forks Formation should be considered separate and unique from those of the first bench
    - Predict future reservoir sweet spot areas
  - Improve drilling/stimulation/completion/production techniques and sequences
    - Determine optimal well spacing for development in the Middle Bakken and first, second, and third benches of the Three Forks
- Optimize wellsite surface operations
  - Reduce operating costs
  - Reduce development and operations impacts to surrounding landowners
  - Reduce demands on surrounding infrastructure and water resources

BPOP comprised two major work segments. Continental was responsible for planning and execution of the Hawkinson Project, and the EERC led a number of activities under the umbrella of "optimization of wellsite operations," both of which are detailed in Figure 1.

BPOP was a premier public–private partnership harnessing North Dakota research scientists and industry to maximize productivity of the Bakken oil play while simultaneously reducing its environmental footprint. BPOP has demonstrated how effective a public–private partnership can be and that researchers, state lawmakers, state regulators, and industry can work together for positive results for shareholders and taxpayers alike.

Significant achievements directly attributable to this program have made measurable, positive impacts to how the business of oil and gas exploration and production is accomplished in North Dakota. The following is a small sampling of concrete examples of these impacts:

- The Hawkinson Project, completed within BPOP, determined that the Bakken and Three Forks Formations represent unique and distinct reserves, which has enormous implications for current estimates of recoverable resources.
- BPOP facilitated a science-based process to determine if a change in rules regarding state drill spacing unit (DSU) setbacks was prudent, then supported state regulators in adopting the required changes. More oil will now be



EERC JA52932.INDD

THE HAWKINSON PROJECT **$112M**

- ● Drilling 11 New Wells
- ● Completions
- ● Reservoir Engineering
- ● Expansion Applications via 3-D Seismic

Pilot hole logs, core data, other data gathering from multiple wells to create a 3-D picture of what happens during and after the hydraulic fracture treatments in a multistage horizontal well. Continental analyzed this data set to:

- Assess total resource available in the second and third benches of the Three Forks Formation.
- Confirm whether these benches are distinct and independent of the existing Middle Bakken.
- Predict areas of future sweet spots.

EERC **$4.5M**

- ● Optimization of Wellsite Operations

Site logistics, waste management, on-site hydrocarbon utilization, water management, process optimization, and systems failure analysis with an eye on decreased environmental impact.

Figure 1. Overview of Bakken Production Optimization Program.

extracted from each DSU as a result of program efforts to justify a change in rules regarding the minimum distance between a well bore and the boundaries of each DSU.

- BPOP led an analysis of gas-flaring trends and helped industry and the state of North Dakota determine appropriate flared gas reduction goals over a period of years. Program efforts to address flaring reduction resulted in new rules on flaring that were defined collaboratively, with industry and state interests working together.
- BPOP researchers provided science-based support to state regulators and industry during a critical discussion on how to best manage naturally occurring radioactive waste associated with oil production.
- BPOP coordinated discussions with state regulators and industry groups on the topic of best practices for remediation of brine spills associated with oil development. BPOP then completed a best practices remediation manual in conjuction with these groups.

This report, summarizing BPOP achievements at the end of the original 3-year contract, was produced as a final report on the first 3 years of the program. The program continues as BPOP 2.0 during the period spanning from November 2016 to October 2019. Many of the efforts begun under BPOP 1.0 will continue under BPOP 2.0. This summary is intended for public distribution and is intended to highlight the important work of this public–private partnership in advancing North Dakota's economic and environmental interests directly related to exploration and production of oil from the Bakken and Three Forks Formations.

A comprehensive list of BPOP products is presented in Appendix A.

RESULTS AND DISCUSSION

PROJECT MANAGEMENT

MEMBERSHIP

The North Dakota Industrial Commission (NDIC) committed $8.0 million in matching funds over 3 years to support a consortium of industry partners conducting research focused on improving the efficiency and reducing the environmental footprint of oil production in North Dakota. The EERC, along with original partners Continental, Marathon Oil Corporation (Marathon), and Whiting Petroleum Corporation (Whiting), then sought and obtained additional member commitments from organizations interested in participation in this consortium.

This was a member-driven program with the goal of providing solutions to nonconfidential wellsite productivity issues affecting all Bakken producers. Employing a consortium approach for these issues minimized corporate financial and staffing input, made solutions available to consortium companies without dedicating staff resources, and partnered with the state of North Dakota to ensure transparency and continued cooperative efforts to assist producers in getting the most out of wellsite economics.

Additional membership participation was solicited in the following categories:

- $100,000 per year for producers with 150 wells or more
- $50,000 per year for producers with fewer than 150 wells
- $25,000 per year for service companies

Program member benefits included:

- Ability to guide research efforts to issues highest on individual company priority lists.
- Rapid information sharing among consortium members.
- Engagement with professional researchers focused on high-priority wellsite productivity issues.

Membership in this consortium-facilitated program is shown in Figure 2.

Figure 2. BPOP consortium partners.

AWARDS

In October 2014, the EERC received the Interstate Oil and Gas Compact Commission's 2014 Stewardship Award in the Environmental Partnership category for its BPOP work, as shown in Figure 3. The EERC accepted this award on behalf of its state and industry partners. The unique business environment present in North Dakota, combined with a state government eager to responsibly develop mineral resources, has enabled collaboration among highly competitive companies in a world-class shale play. This collaboration, in turn, has enabled BPOP to achieve the results discussed in this report.


EERC JA53039.PSD

Figure 3. IOGCC Stewardship Award.

OUTREACH

FACT SHEETS

Seven fact sheets were created to educate and inform stakeholders on key Bakken headline issues from 2013 to 2015. The fact sheets , shown in Figure 4, are science-based and written for public consumption.

These fact sheets were distributed widely by the EERC, by state agencies such as the Department of Mineral Resources, and by the North Dakota Petroleum Council (NDPC).

- **FLARING –** The flaring fact sheet explains what associated gas is, why flaring occurs, how flaring is regulated, and what North Dakota is doing to reduce flaring.


EERC JA52935.CDR

Figure 4. BakkenSmart fact sheet series.

- **WATER –** The water fact sheet explains how water is used in oil and gas production, where producers obtain freshwater for operations, options available for water treatment and reuse, and water-handling costs.
- **NORM –** The NORM fact sheet explains what naturally occurring radioactive material is, what radiation is in layperson's terms, what levels of radioactivity are hazardous, how NORM is regulated in North Dakota, and how NORM waste is disposed of safely.
- **SPILLS –** The spills fact sheet explains the types of spills associated with oil and gas production, what happens when a spill occurs, and how spills are cleaned up and provides an objective perspective on spill statistics.
- **RECLAMATION –** The reclamation fact sheet explains the reclamation process, parties typically involved in a reclamation project, how disturbed areas are reclaimed, and how spill sites are reclaimed.
- **HYDRAULIC FRACTURING –** The hydraulic fracturing fact sheet explains fundamental aspects of hydraulic fracturing,and dispels misinformation frequently and erroneously reported.
- **FUGITIVE EMISSIONS –** The fugitive emissions fact sheet explains the nature of fugitive emissions, factors driving regulatory interest in this topic, the measurement of fugitive emissions, and regulation of fugitive emissions.

- **BAKKEN FLARES AND SATELLITE IMAGES –** The Bakken flares and satellite images fact sheet explains the science behind satellite images, how visible light and other radiant emissions (heat sources) can be represented in these images, and the contribution flaring makes relative to other sources of light and heat.

CONFERENCE PRESENTATIONS

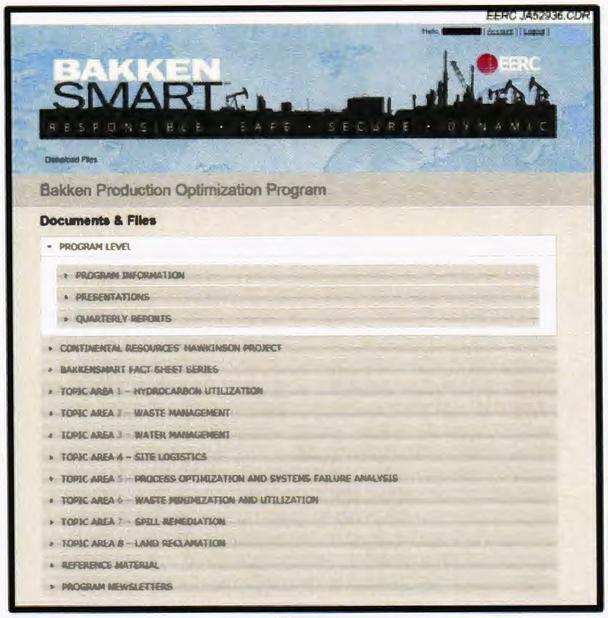
Results of BPOP activities were presented at nearly two dozen conferences and forums in the United States and Canada, highlighting the value of this unique state/industry consortium. The presentations also demonstrated North Dakota's leadership in developing unconventional shale resources.

PRESENTATIONS TO STATE AND FEDERAL GOVERNMENT

EERC staff also regularly briefed state and federal government agencies on program results, ensuring a truly engaged state member of the consortia-based program. The federal briefings demonstrated North Dakota government's leadership in shale development practices and policies to such agencies as the U.S. Department of Energy. During the 3-year program, over three dozen BPOP briefings were given to such state institutions as NDIC, the Oil & Gas Research Program, the Department of Mineral Resources, the Energy Development and Transmission Interim Legislative Committee, the EmPower Commission, the North Dakota Department of Health (NDDH), and others.

MEMBERS-ONLY WEB SITE

To facilitate rapid transfer of information and broad dissemination of program products to all program members, the EERC created a members-only, password-protected Web site (Figure 5). This Web site was used to store and make available each and every major product of the program. Members were encouraged to create a log-in account on the site to gain access to the latest program developments and deep reporting of results from program activities. At project end, over 120 program product documents are available for download to program members on this Web site.



Bakken Production Optimization Program

Documents & Files

- PROGRAM LEVEL
  - PROGRAM INFORMATION
  - PRESENTATIONS
  - QUARTERLY REPORTS
- CONTINENTAL RESOURCES' HAWKINSON PROJECT
- BAKKENSMART FACT SHEET SERIES
- TOPIC AREA 1 – HYDROCARBON UTILIZATION
- TOPIC AREA 2 – WASTE MANAGEMENT
- TOPIC AREA 3 – WATER MANAGEMENT
- TOPIC AREA 4 – SITE LOGISTICS
- TOPIC AREA 5 – PROCESS OPTIMIZATION AND SYSTEMS FAILURE ANALYSIS
- TOPIC AREA 6 – WASTE MINIMIZATION AND UTILIZATION
- TOPIC AREA 7 – SPILL REMEDIATION
- TOPIC AREA 8 – LAND RECLAMATION
- REFERENCE MATERIAL
- PROGRAM NEWSLETTERS

Figure 5. Members-only Web site.

MEMBER NEWSLETTERS

To keep all program members apprised of significant program developments and to encourage deep industry engagement in all facets of program activities, the EERC published electronic newsletters periodically. A partial example is shown in Figure 6. These newsletters served to extend engagement in BPOP activities within the organizational structures of member companies, beyond the senior management engaged largely through the contracting and invoicing processes, and beyond the senior technical leads who typically attended BPOP meetings. Electronic newsletters were delivered to over 200 industry contacts each time a newsletter was completed.

EERC JA52937.CDR

BAKKEN SMART

RESPONSIBLE • SAFE • SECURE • DYNAMIC

Bakken Production Optimization Program Newsletter

In This Issue

Your Program, Your Investment

- Third Program Update Meeting Scheduled
- Hydrocarbon Utilization
  - Flaring Reduction
  - Crude Oil Volatility
- Waste Management
  - TENORM Disposal Rules Released in North Dakota
- Water Management
  - Bakken Water Opportunities Assessment
- Spill Remediation and Land Reclamation
  - Saltwater Spills Task Force
- BakkenSMART Fact Sheet Series

Program Partners

Third Program Update Meeting Scheduled

Figure 6. Sample BPOP Newsletter to members.

PLATFORM FOR TECHNICAL INDUSTRY FORUMS

Oil and gas industry research consortia are often faced with challenges with respect to the open exchange of information and ideas. This is partly because of the competitive nature of petroleum exploration and resource development and partly due to regulatory limitations imposed by the U.S. Securities and Exchange Commission. In some instances, dialogue amongst participants can even be hampered by the need to avoid potential violations of federal antitrust laws. One of BPOP's greatest successes was its ability to serve as a platform for open technical exchanges during hosted industry forums. BPOP specifically targeted these open exchanges in its effort to elicit earnest conversation on issues affecting all producers. The EERC then utilized information gleaned from these exchanges to develop new approaches to issues experienced broadly by industry on its quest to optimize Bakken production.

The EERC was told by multiple BPOP member companies that previous industry forums had not met this level of success in facilitating open technical discussion. It was this feature of the program that enabled BPOP to serve as a platform for one of the most significant results of the program – the changes to prior state rules on setbacks from DSU boundaries.

SETBACKS

The state of North Dakota currently imposes setback rules on DSU for Bakken–Three Forks oil production. These rules exist to allow efficient resource development within a DSU while protecting the correlative rights of resource owners in adjacent DSUs. Prior setback rules stipulated that the total depth (TD) of a horizontal wellbore in the Bakken–Three Forks petroleum system should not penetrate within 200 ft of a DSU boundary (200-ft setback), as described in Figure 7.

EERC JA52938.CDR

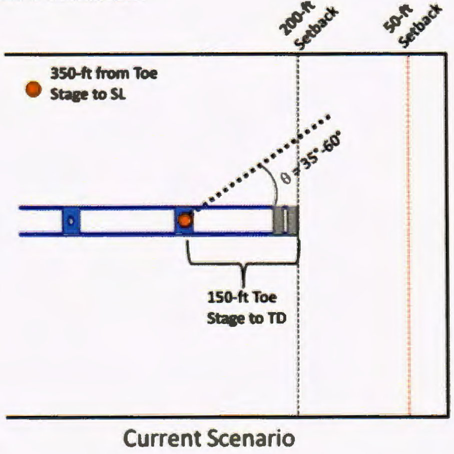


Figure 7. Well toe setback diagram.

A variety of opinions existed about the 200-ft setback and its ability to properly balance the needs of efficient development and correlative rights.

To help better describe the impact of the 200-ft setback rule, several operators that are members of BPOP each performed an agreed suite of representative simulation cases and presented their results in a common format for the benefit of interested parties. The EERC functioned to ensure the simulations were conducted on comparable assumptions – acting as a facilitator.

These simulations resulted in a variety of opinions on recommendations for modifications to existing setback rules enforced by the state of North Dakota. In November 2016, industry and the EERC presented their case to NDIC for consideration. In December, the NDIC modified the rules as follows:

- Noncemented well heels shall be no closer than 150 ft from the DSU boundary.
- In openhole completions, the well toe shall be no closer than 150 ft from the DSU boundary.
- In cemented casing or liner completions, the well toe shall be no closer than 50 ft, unless the well is to be hydraulically fractured through the casing shoe; in that case, the distance limit becomes 150 ft.
- In external casing packer completions, the well toe shall be no closer than 100 ft from the DSU boundary.

It has been openly stated by industry representatives that without the collaboratory guidance provided by BPOP and BPOP's refereeing, this significant change in DSU setbacks would not have happened. These changes, supported by collaborative science, will now allow operators and the state of North Dakota to maximize the extraction of recoverable resources without undue risk to correlative rights.

An estimate of the return on investment of NDIC funds via the Oil & Gas Research Program was calculated. An anticipated increase in tax revenue is based on average per-well production increases resulting from the new rule, as modeled by four large North Dakota oil and gas producers. This anticipated increase in tax revenue is estimated to be approximately $1.27 billion.

ENVIRONMENTAL PEER GROUP

At the direction of BPOP members, the EERC was able to serve as a technical resource to the Environmental Peer Group, an industry working group of company environmental experts who meet on a quarterly basis to discuss issues common to participating entities. These meetings focus on current and future headline issues such as TENORM (technologically enhanced naturally occurring radioactive material) disposal, saltwater spill remediation, drill cuttings disposal, gas-flaring mitigation, surface process design, fugitive emissions, etc. These topics so closely mirrored the topics studied by the EERC within the confines of BPOP, that BPOP member companies leading the Environmental Peer Group asked the EERC to begin attending these meetings regularly.

EERC staff were able to support these meetings, providing relevant scientific insight on various topics. EERC staff were also tasked by BPOP members via these meetings with assisting efforts on various environmental challenges. This proved to be a valuable addition to BPOP tasks and kept the program tightly focused on issues being managed in real time, on the ground by BPOP members.

NDPC TASK FORCES

Also at the direction of BPOP members, the EERC was able to provide robust technical and scientific support to multiple task forces organized by NDPC. EERC staff were asked to provide ongoing, substantial support to the following NDPC task forces:

- Flaring Task Force
- NORM Task Force
- Saltwater Spills Task Force

EERC support for these task forces is described more specifically elsewhere in this report.

CONTINENTAL'S HAWKINSON PROJECT

The Hawkinson Project, executed by Continental in four phases as described in Figure 8, was a research project aimed at significantly increasing total production and production rates from North Dakota oil wells where oil reserves of the second and third benches of the Three Forks Formation, located just below the Bakken oil formation, are being explored. This research has the potential to result in significantly increased production from the Bakken–

Three Forks system and decreased production costs to producers.

The Hawkinson Project area has already proved productive for the Middle Bakken and first, second, and third benches of the Three Forks zones. The Bakken Formation immediately overlies the Three Forks Formation. This stratigraphic relationship, combined with geochemical similarities of the respective formation fluids, has led many in the Williston Basin to theorize that the Three Forks zone is in communication with the oil-producing middle member of the Bakken. As a result, petroleum resource estimations have typically summed the two together. However, Continental had previously proved that these formations are indeed separate in its evaluation of the Middle Bakken and first bench of the Three Forks with the Mathistad Project.

Figure 8. Summary of Hawkinson Project phases.

The upper three benches of the Three Forks Formation have recently shown great promise as potentially prolific oil-producing zones in North Dakota. The second bench of the Three Forks zone had an initial production rate of 1140 barrels of oil equivalent a day in the Continental-operated Charlotte 2-22H well. The Charlotte 3-22H had an initial production rate of 953 barrels of oil equivalent a day from the third bench of the Three Forks.

Before the completion of this project, the stratigraphic interval used by the North Dakota Oil and Gas Division to define the Bakken Pool included the Sanish zone in most North Dakota oil fields. The result of this approach was that production information specific to the Sanish was limited, making a definitive determination of the uniqueness of the different benches of the Three Forks–Sanish play difficult. Acquiring new data focused on demonstrating that the different benches in the Three Forks are separate from the Bakken has now provided the state of North Dakota and the oil industry in the state with new insight that can be used to:

1. Develop realistic assessments and estimates of the first three benches of the Three Forks oil reserves.
2. Design and implement effective and efficient E&P (exploration and production) strategies for defining and developing an emerging second and third bench Three Forks play in North Dakota.

The streamlined development schedule provided the opportunity to collect a data set unique in its scope and quality. During the stimulations, Continental collected bottomhole pressure (BHP) data in three existing "parent" wells and microseismic data. Stimulation fluids were tagged with chemical tracers. Produced fluids were sampled, and the concentration of these chemical tracers was recorded. Subsequently, pulse tests were conducted.

The microseismic data set collected was uniquely comprehensive and carefully designed to ensure high quality. Continental recorded treatment of 283 stages among ten wellbores extending across the entire 1- by 2-square-mile unit in this project. Comparatively, most microseismic projects usually include only a single treatment wellbore and record the stimulation of only five to 40 stages.

The diverse and multidisciplined data set was analyzed with a variety of methods. Where appropriate, data from one source were integrated with data from another to improve analyses. Where possible, results from prior analyses were incorporated into subsequent ones. Where different analyses used different data to analyze the same property, results were reconciled. The variety of available data allowed a unique opportunity to compare and reconcile multiple analyses. Industry firsts accomplished by the Hawkinson Project are shown below.

DRILLING

- Drilled sequentially 11 long laterals in four formations within a single unit
- Four cemented liners, seven openhole packers

COMPLETIONS

- Completed 11 wells sequentially
- Tractored longest lateral USIT (ultrasonic imaging tool) runs (>21,000 ft MD)
- 63 days' continuous, 24/7, microseismic recording field operations

MICROSEISMIC

- Historically largest to date in the industry
- Ten treatment wells sequentially monitored
- 283 stimulated stages recorded
- 171 tool monitoring days
- Longest laterals with three monitoring wells (>21,000 ft MD)
- Most footage of tractored tools in a single project (microseismic >270,000 ft; USIT >40,000 ft)
- Longest lateral footage pulling ten geophone shuttles (>21,000 ft MD)
- Highest BHT (bottomhole temperature) project designed with three monitor wells (266°F)
- ~1,200,000 microseismic event picks generated
- 3-D full elastic modeling to design microseismic data collection
- Measured, via VSP (vertical seismic profiling), and applied "Q" to the microseismic data

The subsurface portion of the work resulted in a one-of-a-kind effort to give a 3-D picture of what happens during and after hydraulic fracture treatments in multistage horizontal wells in the Middle Bakken as well as the first, second, and third benches of the Three Forks Formation. This had not been previously attempted. Examples of analysis results are shown in Figure 9.

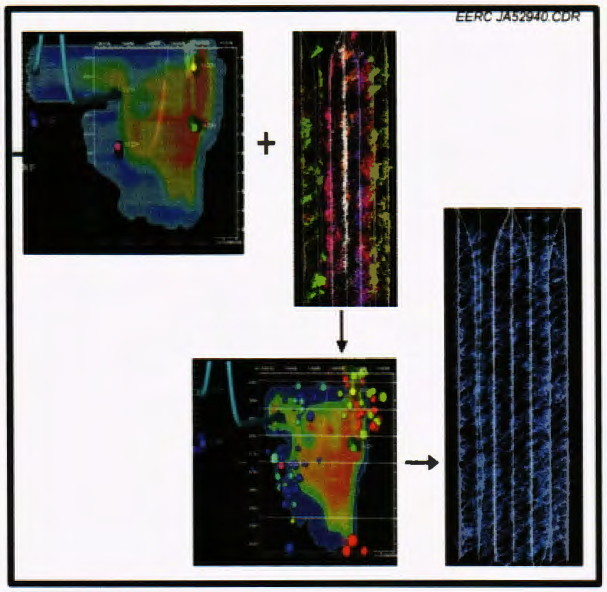


Figure 9. Reservoir insights resulting from Hawkinson data analysis.

This activity provided previously unknown information regarding potential Bakken development, helping to determine the optimal number of wellbores that need to be placed in each zone for proper development. Knowing the appropriate number of wellbores needed will help the industry know how many wells will ultimately need to be drilled in spacing units in North Dakota in the Bakken Pool.

The potential economic impact of understanding the number of wells needed to be drilled in the future for primary development alone will lend confidence to the effort to build infrastructure in the region and will develop estimates for potential oil industry employment over the long term.

Conclusions:

- The Bakken and Three Forks Formations represent unique and distinct reserves, even in an area with a high degree of natural tectonic fracturing.
- Producers must drill on a denser spacing than 1320 ft within the same formation to maximize production from the DSU.
- 200-ft heel/toe setbacks result in uncaptured resources.
- Significant undrained resources remain along section lines.
- Fracture asymmetry results from pressure depletion and induced stresses.
- Stimulations are well-contained within the Bakken petroleum system.
- Maximum positive curvature is the seismic attribute best-suited to predict well performance.

EERC OPTIMIZATION OF WELLSITE OPERATIONS ACTIVITIES

The EERC conducted multiple parallel activities to advance the goal of optimization of wellsite operations. These activities were driven by the common needs program members. In general, BPOP addressed the headline issues of 2013–2016. Flaring reduction, TENORM disposal, and saltwater spills all became focus areas of the program. Opportunities for improved water use and handling were also addressed within program activities.

The goal of this phase of BPOP was to explore wellsite optimization approaches that have potential to reduce wellsite costs, improve wellsite production, reduce wellsite development and operation impacts to surrounding landowners, and decrease demands on surrounding infrastructure and water sources.

Following is a summary of major activities in which BPOP was engaged during the 2013–2016 period of performance.

HYDROCARBON UTILIZATION

FLARING REDUCTION

Flaring Task Force

The EERC supported NDPC's Flaring Task Force at the direction of BPOP membership. As the Flaring Task Force formulated a multistage plan to decrease flaring rates, BPOP provided statiscal flaring analyses that served as the foundation for these plans. The BPOP team presented the resulting plan to Governor Dalrymple in January 2014. This plan was eventually endorsed by Governor Dalrymple and is now integral to regulations enforced by the North Dakota Department of Mineral Resources. The plan approved by NDIC included associated gas capture targets as follows:

Gas Capture Deadline	Gas Capture Target, *% flared max.*
October 2014	74% *(less than 26% flared)*
January 2015	77% *(less than 23% flared)*
April 2016	80% *(less than 20% flared)*
November 2016	85% *(less than 15% flared)*
October 2018	88% *(less than 12% flared)*
November 2020	91% *(less than 9% flared)*

Flaring Database

The EERC supported BPOP membership in their efforts to implement technologies and practices to utilize stranded wellhead gas and reduce gas-flaring volumes by creating a database containing 65+ technologies that claim to utilize wellhead gas economically for beneficial purposes. This database continues to add technologies and is used by industry to screen potential solutions to stranded gas challenges. Figure 10 shows a screen capture of the database. The database can be examined at www.undeerc.org/Flaring_Solutions/.

Flaring Solutions Technology – Search

Figure 10. Flaring Solutions Technology Database.

The database entries were solicited and refereed by EERC staff. Industry continues to utilize this database to gather information on possible solutions to flaring at wellsites not yet served by gas gathering pipelines or where gathering capacity is insufficient to capture all of the produced gas.

PRODUCED FLUIDS CHARACTERIZATION

In support of wide-ranging activities associated with BPOP tasks, the EERC assembled all known physical and chemical property data pertaining to Bakken Formation produced fluids – crude oil, associated gas, and produced water. These data were be used in the holistic, "system of systems" approach toward which BPOP turned at the end of the program, as the EERC anticipated a BPOP 2.0. Within this produced fluids characterization activity, the EERC developed and populated a GIS (geographic information systems)-compatible database to compile all existing data available to EERC staff. This included public information housed at the North Dakota Department of Mineral Resources, public information housed at the U.S. Geological Survey (USGS), data developed via other EERC projects and programs, and data provided to EERC staff by industry.

The data set currently contains data from 943 produced water samples, 507 crude oil samples, and 718 associated gas samples. With sufficient data entered into the database, the EERC then began a preliminary evaluation of spatial and temporal data to identify potential data gaps that could be filled during BPOP 2.0 activities. An example of analysis results is shown in Figure 11. Preliminary results of this evaluation indicate that the data gaps of highest priority include:

- Specific temporal data on fluid composition on individual wells.
- Additional compositional information (e.g., aliphatic content, aromatic content, light ends content, water chemistry).

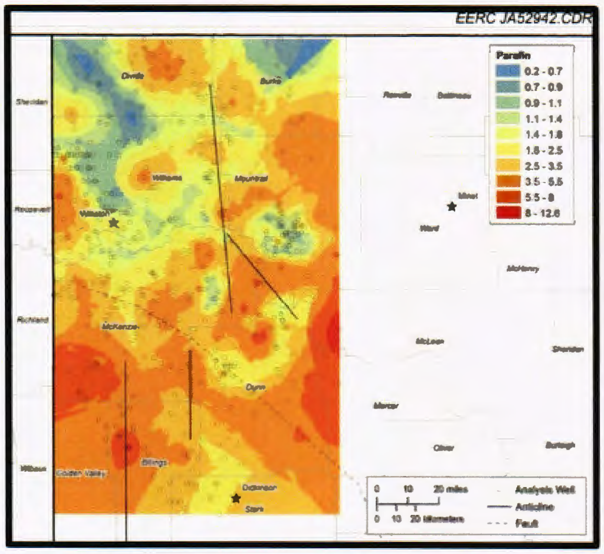


Figure 11. Example of maps created using preliminary results of produced fluids database development.

This work also resulted in recommendations regarding future sampling efforts. Downhole sampling must maintain downhole conditions (pressure, temperature) to obtain accurate compositional and PVT (pressure, volume, temperature) analyses. This means that a more methodical approach to sampling must be promoted within BPOP 2.0 activities. For produced fluid samples taken at the separator at the wellsite, BPOP 2.0 activities must strive to attain accurate separator flow rate measurements and stability in separation conditions to achieve accurate determination of reservoir phase behavior from the recombined fluids.

INVESTIGATION OF OIL COMPOSITIONAL ANALYSIS FOR SOURCE DETERMINATION

The EERC analyzed a limited set of 43 samples of Upper, Lower, and Middle Bakken rock to begin to explore the hypothesis that aromatic/aliphatic tracers can be used to better understand oil transport and oil sources within the reservoir system, thus potentially impacting the estimates of recoverable reserves.

The ratios of aromatic to aliphatic hydrocarbons in rock samples from nine well locations were consistently fourfold to tenfold higher in the 20 upper and lower shale samples than in all of the 23 Three Forks and Middle Bakken rock samples tested, as shown in Figure 12. The aromatic/aliphatic ratios in Three Forks and Middle Bakken samples were all similar to that of a typical produced Bakken crude oil, while the ratios from upper and lower shales averaged seven times as high. Aromatic/aliphatic ratios from upper and lower shales corresponded to shale maturity maps, with the higher ratios affiliated with less mature zones.

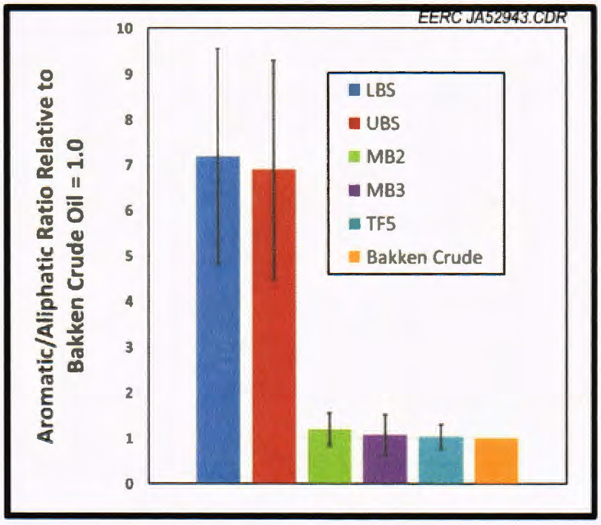


Figure 12. Data showing distinct differences in aromatic/aliphatic ratios from various portions of Bakken/Three Forks System.

These results suggest that aromatic/aliphatic tracers could be useful for better understanding oil transport and sources in the reservoir, allow better well management (e.g., by determining the relative contributions of the shales and Middle Bakken to produced oil), and support the development of more accurate recoverable reserves estimates for the Bakken petroleum system. These results also provide strong indication that further investigations of this hypothesis are justified.

INVESTIGATION OF RICH GAS FOR ENHANCED OIL RECOVERY (EOR)

The advent of horizontal drilling and hydraulic fracturing unlocked unconventional reserves such as those in the Bakken Formation. It is critically important to now investigate the next revolutionary advancement in oil production. This next advancement might be the application of EOR techniques to increase the amount of oil currently recoverable from the tight shale formations. Rich gas may be a prime candidate for an EOR working fluid for many reasons. Capture and production of natural gas in the Bakken play is resulting in increasing concern over what options are available to utilize excess ethane that must be removed from the gas stream to meet downstream and/or interstate pipeline natural gas specifications. In essence, the cost of transporting Bakken ethane to potential users exceeds its commercial value. The purpose of these investigations was to perform initial laboratory experiments to determine the potential for utilizing ethane as an injectant for EOR in the Bakken.

Three laboratory methods for investigating EOR using CO_2 were performed using ethane as the injected fluid. These three experiments were:

1. Measuring the multiple-contact minimum miscibility pressure (MMP) of ethane (as compared to CO_2) at Bakken reservoir temperature of 230°F (110°C), including the effect of associated methane in each fluid.
2. Collecting and analyzing the Bakken crude oil hydrocarbons that are mobilized into an upper "miscible" phase.
3. Exposing rock samples collected from a Bakken well to ethane to determine the rate of crude oil recovery from untreated Bakken rocks.

Each of these experiments had previously been performed using CO_2, which allowed a direct comparison of the relative capabilities of ethane and CO_2 as potential EOR fluids. Figure 13 summarizes this comparison.

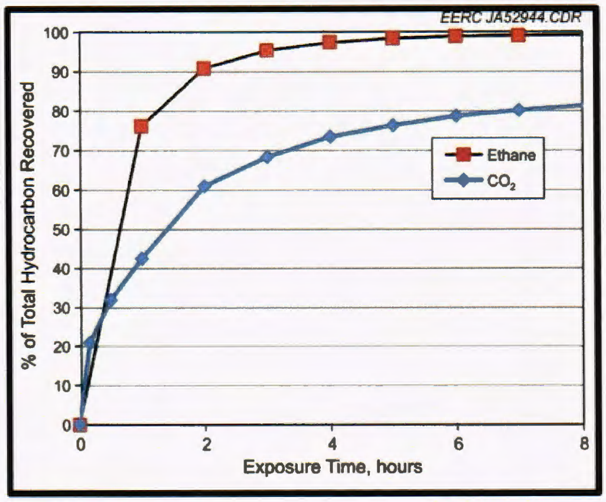


Figure 13. Comparing EOR potential for CO_2 and ethane.

All three laboratory studies support the conclusion that ethane is an excellent candidate EOR fluid for achieving lower crude oil MMPs, for more efficiently mobilizing crude oil hydrocarbons into the mobile "miscible" phase, and (based on initial results) for recovering crude oil hydrocarbons from Bakken rock samples. However, it is important to note that these lab experiments only mimic some of the processes necessary to achieve EOR from the actual reservoir and that substantial laboratory research into EOR mechanisms, model development, and pilot-scale tests will be needed to exploit the use of EOR fluids in tight/fractured plays like the Bakken. It is also important to note that neither ethane nor CO_2 is currently available in sufficient quantities to satisfy demand if these approaches were to be broadly applied. This is the focus of research continuing in BPOP 2.0.

SIMULATION OF ETHANE FLOODING IN CONVENTIONAL RESOURCES

There are many depleted conventional reservoirs and developing unconventional reservoirs in the Williston Basin. Production from many of the conventional reservoirs are stagnant after primary depletion or waterflooding without carrying out EOR operations, despite the fact that numerous field demonstrations have shown that CO_2 flooding can be an effective and economically attractive EOR method. The EERC MMP experiments described in the prior section have shown that ethane can also produce desirable EOR effects.

With this knowledge, BPOP researchers at the EERC conducted reservoir simulations to investigate ethane flooding in a conventional reservoir using an existing history-matched reservoir simulation of a CO_2 EOR project. In this study, typical conventional reservoir conditions were selected to investigate the EOR performance of CO_2 compared to ethane.

Utilizing a tuned, nine-component PVT model, a numerical simulation for a representative conventional reservoir was selected to investigate ethane EOR performance. The simulation model was history-matched to production data including primary depletion, waterflooding, and CO_2 flooding stages to ensure the model was able to reliably represent reservoir performance.

Results showed that miscible flooding is more easily attainable for ethane than for CO_2 in the reservoir conditions (see Figure 14). Results also showed that ethane maintains miscibility, even with limited processing and reinjection of produced gas from the field. The oil recovery performance from ethane injection is better than from CO_2 in all simulation cases studied. Considering the availability of ethane in the Williston Basin area, ethane EOR may be a good candidate for conventional reservoirs in the basin and could potentially aid in commoditizing ethane-rich natural gas resources in the region.

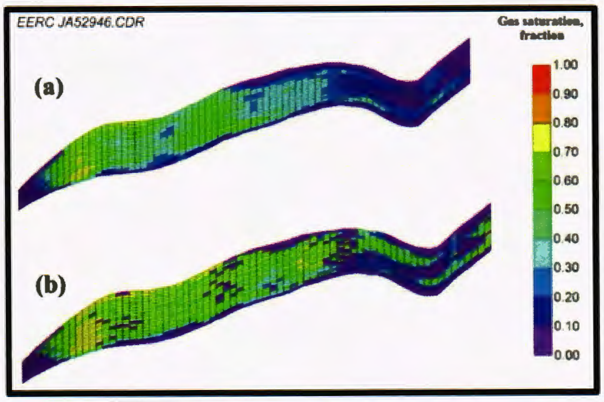


Figure 14. Snapshot of verical sweep performance of CO_2 and ethane after 42 years of flooding.

SURFACE FACILITIES PROCESS MODEL DEVELOPMENT

To facilitate a "system of systems" approach to optimizing production from the Bakken system, the EERC began development of a surface facilities process model (summarized in Figure 15). Having a detailed understanding of this step in the production cycle is important since wellsite operations are a central to many production concerns including crude oil vapor pressure, natural gas and natural gas liquids recovery, and storage tank vapor generation rates.

In development of this model, EERC staff worked with a BPOP member to identify "typical" wellsite process design parameters and performance data for each unit of process equipment. The initial static, or steady-state, model was created using Aspen HYSYS® process simulation software. Trends predicted by the static model were validated by comparing them to field observations from the member company. During discussion of the steady-state model's applicability, it was determined that a dynamic model was needed to accurately capture the non-steady-state behavior of actual wellsite operations. This dynamic model, created using VMGSim Dynamics™ software, is being used to assist in BPOP efforts to determine the impacts to crude oil composition, crude oil volatility, gas flaring, and produced water flow volumes as reservoir changes drive changes in process unit operations. Ultimately, this model will be employed to predict operational issues arising from changes in well fluid production rates and compositions. This model may prove beneficial in helping BPOP member companies alter wellsite process designs to accommodate evolving knowledge of fluids production from the Bakken–Three Forks petroleum system. The model may also be used to predict changes in flare performance, crude oil quality, and produced water disposal quantities during periods of process upsets.

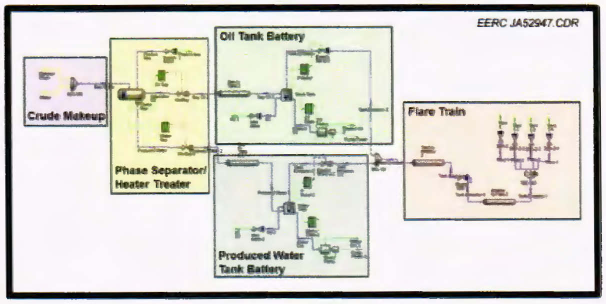


Figure 15. Reconfigurable facility process model.

The EERC also hopes to employ this model to develop an understanding of implications of a variety of alternative production strategies, including new completions techniques and EOR.

DECLINE CURVE ANALYSIS

The EERC analyzed hydraulic fracturing and other trends within the Bakken petroleum system during the period from 2006 into the first half of 2016. This period of the Bakken's development included a transition to a low-oil-price environment, which spurred experimentation with hydraulic fracturing parameters away from conventional values. Explored parameters included number of fracture stages, amount of proppant injected, and volume of fluid used for fracturing. Distinct subcategories of fracture conditions were identified and analyzed for their impact on water use, and oil and water production.

The EERC completed a preliminary investigation using Arps' decline curve analysis to determine if basinwide production trends and performance drivers could be identified for the Bakken Formation. Differences in performance have been identified, and more in depth analysis using more advanced decline curve analyses may improve understanding of Bakken current and future production performance. The main objectives were to select a representative and diverse sample set from producing Bakken wells, analyze, and then inspect their production performance by different groups (county, vintage, stage spacing, and proppant amount) in order to understand the influence if any of these factors on initial production, overall performance, and estimated ultimate recovery using decline curve analysis.

A data set consisting of 200 Bakken wells producing from McKenzie, Williams, Mountrail, and Dunn Counties within North Dakota was used to evaluate production performance in this study. The results of this analysis showed that:

- A majority of the selected wells are in boundary-dominated flow.
- When the oldest wells are compared to the most recent wells, results of analysis by well vintage indicate that advances in drilling and completion technologies over the years have not only increased estimated ultimate recovery (EUR) but have also speeded up oil recovery from the reservoir. Older wells that were identified as underperforming could be restimulated to improve their production performance. Oil production performance improved with decreasing spacing between fracture stages.
- With respect to proppant loading, there was a general direct trend of increasing peak oil rate with higher amounts of the proppant used per stage to complete the well. However, the same trend was not reflected in estimating the ultimate oil recovery.
- Based on the limited number of wells and their relatively short operating history, the estimated well operating life required to attain an abandonment oil rate of 5 stb/d will range from a minimum of 30 years to as high as 48 years.

Gas production from the same data set of wells was also analyzed in similar ways:

- McKenzie and Williams Counties are likely to have wells with peak gas production rates 75% to 100% higher than rates for Dunn and Mountrail Counties.
- In general, peak gas production and estimated ultimate recovery, gas (EURg) are expected to increase as the distance between stages decreases.
- While increasing proppant loading tended to increase the peak gas production rate, no firm trend was established between proppant loading and EURg.

The gas production rate corresponding to the abandonment oil rate is estimated to be in the range of 4.5 to 7.5 Mscfd.

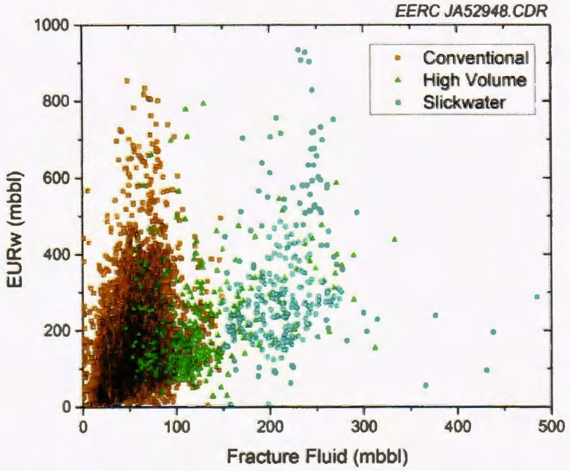


Figure 16. Comparing EURw with injected fracture fluid volume.

With respect to water production, more aggressively fractured wells produced more water; however, Figure 16 reveals little to no correlation between the amount of fluid used for fracturing and the total estimated quantity of produced water on an individual well basis. For the Bakken well population as a whole, new wells in 2015 required approximately 0.7 bbl of fracture fluid per stb of total estimated oil recovery. These wells also produced approximately 1.1 bbl of total estimated water recovery per stb of total estimated oil recovery. Trends within the well population subcategories suggest that these summary ratios could decrease slightly in the future.

WASTE MANAGEMENT

TENORM WASTE DISPOSAL

NORM Task Force

BPOP representatives served as subject matter experts and advisors to the NDPC NORM Task Force and to state interests throughout 2013–2015. During that period, the topic of TENORM was in the headlines regularly. Illegal dumping of filter socks from oilfield operations was casting a negative light on the state and the industry. BPOP was able to provide expert analysis on draft TENORM disposal regulations proposed by NDDH in 2014. BPOP personnel provided public testimony before the North Dakota Legislature's Energy Development and Transmission Committee and during three public hearings held by NDDH to solicit public comments on the proposed TENORM in-state disposal rules.

NORM Primer

The NORM Primer (Figure 17) was produced to provide the reader with a brief, highly readable summary of the breadth of radiation science behind NORM regulations. Because radiation is one of the most complex topics in physics and because biological damage due to radiation is an inexact science, it is impossible to reduce the volume of knowledge in radiation physics to a single booklet. Therefore, this booklet was meant to provide the reader with enough information to begin asking pertinent questions. It served as a mechanism to ensure that industry and state interests were speaking with commonality on facts.

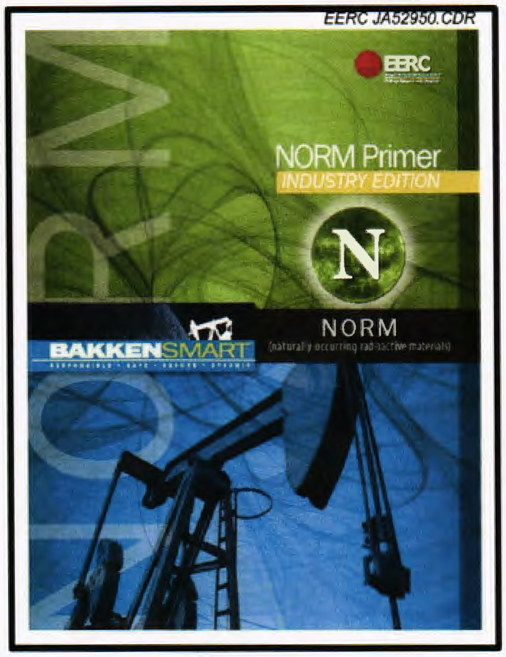


Figure 17. NORM Primer cover page.

TENORM Analysis of Drill Cuttings, Produced Water, and Flowback Water

The EERC coordinated a TENORM sampling effort among several oil producers of the NDPC NORM Task Force. Fifty samples of drill cuttings, produced water, and flowback water were analyzed for radium content (isotopes Ra-226 and Ra-228). The results (Figure 18) of this survey were shared with industry and NDDH. The EERC also supported the NORM Task Force in interpretation of the results. This work was completed in support of comments written by industry in response to NDDH's release of a draft of its new rules for in-state TENORM disposal.

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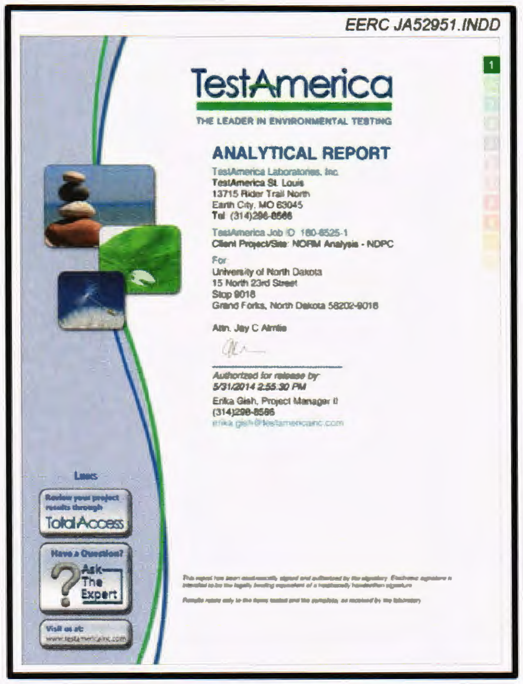

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ANALYTICAL REPORT

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TestAmerica Job ID: 160-8525-1
Client Project/Site: NORM Analysis - NDPC

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Grand Forks, North Dakota 58202-9018

Attn: Jay C Almlie

Authorized for release by:
5/31/2014 2:55:30 PM

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Figure 18. TENORM Sampling Analysis Report cover page.

WATER MANAGEMENT

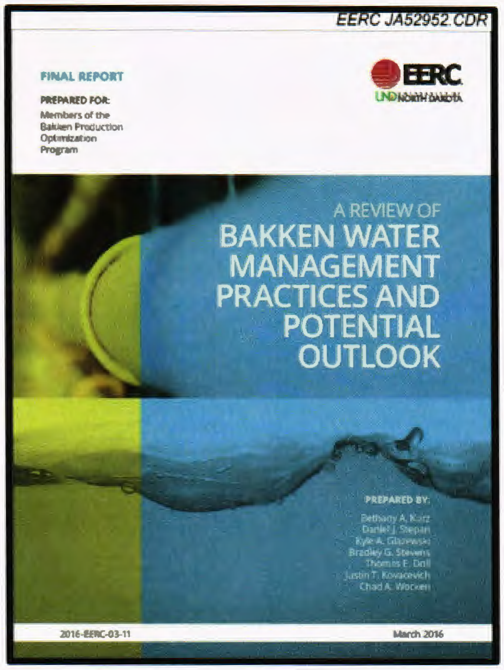
BAKKEN WATER MANAGEMENT PRACTICES AND POTENTIAL OUTLOOK

As a product of water management activities within BPOP, the EERC completed a comprehensive assessment of water management practices in the state. This report (shown in Figure 19) provided a summary of water use and handling trends in the Bakken, an estimation of future water supply demand and disposal needs, an overview of potential treatment technologies, considerations for recycling and reuse, a summary of the implications of the report findings for our partners, and recommendations for future work.

The report can be used by industry to identify potential freshwater resources and produced water disposal opportunities. It can be used by regulators to calibrate an understanding of anticipated trends in water demands for the oil and gas industry. It can be used as an outreach tool to legislators and the general public to help all concerned parties gain an understanding of the true needs of industry for water resources and compare those needs against needs from other sectors of North Dakota's economy.

This report can be downloaded at: www.undeerc.org/Bakken/Water-Study.aspx.

EERC JA52952.CDR



FINAL REPORT

PREPARED FOR:
Members of the
Bakken Production
Optimization
Program

A REVIEW OF
BAKKEN WATER MANAGEMENT PRACTICES AND POTENTIAL OUTLOOK

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2016-EERC-03-11

March 2016

Figure 19. Water Management Practices cover page.

DAKOTA SANDSTONE CAPACITY MODELING

The increase in oil and gas production in North Dakota due to Bakken petroleum system development has resulted in a threefold increase in produced water generation over the past decade. As of 2015, nearly 440 million barrels of water were disposed of in North Dakota's saltwater disposal (SWD) wells. This trend is expected to increase in the coming decades with the continued extraction of oil and gas from the Bakken. As of 2015, 94 vol% of all SWD occurred within the Inyan Kara Formation of the Dakota Group.

Because of industry's current reliance on the Inyan Kara as a SWD target, an effort is under way through BPOP to evaluate the disposal capacity of the Inyan Kara and to identify locations where additional disposal may be optimal or problematic based upon geologic characteristics, injection rates, and proximity to existing SWD wells. A reservoir simulation model was developed to enable the assessment of current and potential future SWD scenarios in a portion of western North Dakota with a high concentration of SWD wells. The areal extent of the model encompasses most of McKenzie County and a portion of northwestern Dunn County, as shown in Figure 20. A preliminary validation of the model has been completed, and initial simulation results have been produced that will allow for full model calibration.

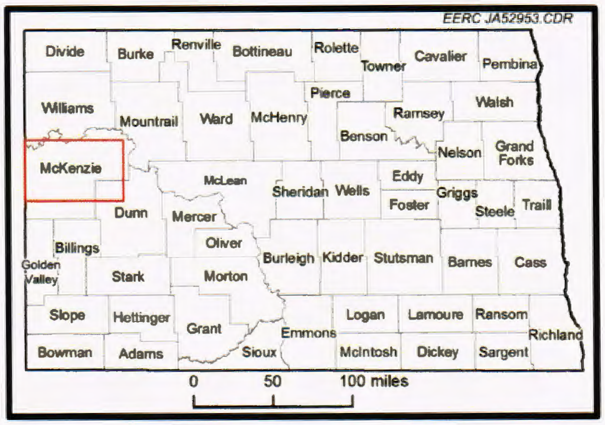


Figure 20. Initial focus area of Dakota Sandstone modeling.

This effort will continue under BPOP 2.0 and will focus on improving the model calibration through refined history matching of the predicted wellhead pressure with the field-reported data for each well. This will entail modification of the reservoir properties and adjustment of the individual SWD well characteristics.

FAILURE ANALYSES

SUCKER ROD GUIDE PREMATURE DETERIORATION

North Dakota wellsite operators have reported a number of premature failures of plastic rod guides. The failures have most often occurred in green-colored guides that were being pilot-tested by a reputable rod guide manufacturer. It was reported to the EERC that the standard rod guide used by multiple operators is black and made of polyphthalamide (PPA). The two types of rod guides are shown in Figure 21. The rod guide manufacturer stated that the green material is also PPA. Operators have reported that the black guides have an expected lifetime of several years in Bakken operations, but many of the green guides have failed by crumbling, sometimes into a green mud, in time frames of less than a year.

Figure 21. Types of sucker rod guides analyzed.

The EERC was asked by BPOP members to analyze the green and black materials to determine whether they are made of the same material and to provide suggestions on how to specify materials or molding methods to increase guide lifetimes. The EERC was also asked to perform the same analyses on three types of guides made by two alternate rod guide manufacturers. Select analyses were chosen only to determine differences in composition and some physical properties of the materials. These analyses were not designed to determine the likely relative performances or lifetimes of the materials in field use.

Differential scanning calorimetry (DSC) and Fourier transform infrared (FTIR) analyses indicate that the baseline green and black guides provided to the EERC were made out of different types of plastics. Resin manufacturer representatives have informed the

EERC that the DSC data and preliminary data from measurements of the viscosities of the plastics indicate that the black plastic is a known resin, but the green plastic is likely mixed with other resins or additives. FTIR data seem to corroborate this assessment. Thermogravimetric analysis (TGA) indicates that the green guide contains significantly more reinforcing or filler than the black guides. Tensile testing shows that the black guides are significantly stronger than the green guides, but both are much weaker than shown in manufacturer data for reinforced material made of the known resins, likely because of high porosity measured by the EERC. The material in the black guide that had been exposed to downhole conditions was only one-half as strong as unused material.

SPILL REMEDIATION AND LAND RECLAMATION

SALTWATER SPILLS TASK FORCE SUPPORT

BPOP provided subject matter expertise to NDPC's Saltwater Spills Task Force during 2014–2016. BPOP also enlisted the assistance of North Dakota State University's (NDSU's) Range Science, Soil Science, and Agricultural Extension Programs to ensure that all remediation and reclamation efforts for industry and the state were grounded in valid soil science. It is through this partnership with the EERC, NDSU, the Saltwater Spills Task Force, and industry at large that the Spills Cleanup Primer and the Remediation Resource Manual were created.

SPILLS PRIMER

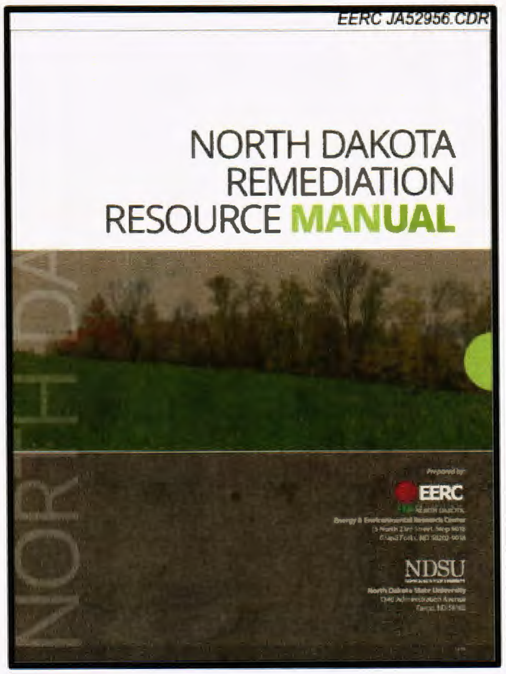
The Spills Cleanup Primer (Figure 22) is intended to provide the reader with a fundamental understanding of hydrocarbon and brine spills from oil and gas production and the related remediation and reclamation of these spills. As oil and gas production in the Williston Basin has increased, the number and volume of spills have also increased; however, when normalized by actual volumes produced, spill rates have actually decreased. The primer is designed to inform the reader on spills, how spills are regulated, what measures are taken to minimize their impacts, and how spills are cleaned up. Material presented in this document regarding techniques, processes, and technologies to address spills is intended to be informational only. Actual performance of spill-related activities will vary.

Figure 22. Spills Primer cover page.

NORTH DAKOTA REMEDIATION RESOURCE MANUAL

BPOP and the Saltwater Spills Task Force collaborated to create a field guide to aid those involved in the remediation and reclamation of sites impacted by oilfield-related spills. This field guide is shown in Figure 23. Remediation information included in this document is for spills limited to soil impacts and does not address remediation related to groundwater impacts. In addition, the information is specific to the execution of these activities in North Dakota and may not be wholly applicable to other areas of the country.

This document is organized as an instruction manual, with distinct sections for different topics such as soil types, spill evaluation, and determining when no further actions are necessary. This manual is based on practical, reproducible, and field-friendly procedures. Users can reference individual sections specific to their needs without having to read the entire document.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NORTH DAKOTA
REMEDIATION
RESOURCE MANUAL

EERC

NDSU

Figure 23. North Dakota Remediation Resource Manual cover page.

MEMBERSHIP AND FINANCIAL INFORMATION

BPOP was sponsored by the NDIC Oil and Gas Research Council, Continental, and a consortium of Bakken producers and service companies. As shown in Table 1, the originally proposed budget for this program was $115,784,500. As the program progressed, the EERC estimated that an additional $1,050,000 would be attained from industry partners beyond what was originally planned (from $1.2M to $2.25M); the EERC was able to secure $2,025,000.

Continental's expected in-kind contribution was $106,030,000. Continental ultimately reported in-kind contributions of $99,166,805 which represents approximately $6.9 million less than what was projected at the beginning of the project. This differential is largely attributed to actual expenditures coming in slightly lower than original estimates. The differential amounts to a 6.4% variance, which may be considered within expectations for a project of this magnitude.

Table 1 enumerates the evolution of the budget over the course of the program's execution.

Cash contributions from industry totaling $2,025,000 were as follows:

- $300,000 each from Marathon, SM Energy Company, ConocoPhillips, XTO Energy, and Hess Corporation for a total of $1,500,000.
- $200,000 each from Whiting and Oasis Petroleum North America for a total of $400,000.
- $75,000 from Nuverra Environmental Solutions.
- $50,000 from Hitachi Data Systems.

Expenses to date by funding source are listed in Table 2.

Table 1. BPOP – Budget Evolution

	Proposed Budget*	**Expected Budget**	**Final Budget**	**Variance from Original Budget**
NDIC** – Cash	$8,554,500	$8,554,500	$8,554,500	0%
Industry – Cash	$1,200,000	$2,250,000	$2,025,000	69%
Continental – In-Kind	$106,030,000	$106,030,000	$99,166,805	-6%
	$115,784,500	**$116,834,500**	**$109,746,305**	**-5%**
NDIC Share	7%	7%	8%	
Industry Share	93%	93%	92%	

* EERC Proposals 2013-0176 and 2014-0118.
** Includes $6.26M subcontract to Continental.

Table 2. BPOP – Expenses to Date

	Funding Source		
	NDIC	**Industry**	**Total**
EERC*	$2,293,500	$2,022,488	$4,315,988
Continental – Subcontract	$6,260,000		$6,260,000
Continental – In-Kind		$99,166,805	$99,166,805
Total	**$8,553,500**	**$100,189,293**	**$109,742,793**

*As of the date of this report, not all expenses have posted, therefore actual expenses are an estimate.

CONCLUSION

BPOP represents a successful, award-winning collaboration between the state of North Dakota and its petroleum industry. The work performed within BPOP has achieved the stated goals of maximizing Bakken production while simultaneously minimizing the environmental impact of production activities. The collaborative work completed within the program has demonstrated a new mode of mutually beneficial cooperation between state and industry players to responsibly and productively maximize development of unconventional resources.

At the time of this report, the state of North Dakota has opted to extend this successful program for an additional 3 years. Marathon and Liberty Resources LLC have signed on as anchoring industry partners, while the EERC continues to solicit additional, substantial partners interested in leveraging their corporate research power with this collaborative state–industry framework.