When and Where Relative Permeability Modification Water-Shutoff Treatments Can Be Successfully Applied

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Summary

This paper provides guidance on when and where relative-permeability-modification/disproportionate-permeability-reduction (RPM/DPR) water-shutoff (WSO) treatments can be successfully applied for use in either oil or gas production wells. When properly designed and executed, these treatments can be successfully applied to a limited range of oilfield excessive-water-production problems. When these treatments are applicable, they may be placed using bullhead injection (not requiring mechanical zone isolation)—a very favorable feature. However, there are a substantial number of limitations and possible pitfalls relating to the successful application of RPM/DPR WSO treatments. First-time application by an inexperienced operator should be considered a somewhat high-risk undertaking. In order to successfully treat unfractured production wells (i.e., radial flow through matrix rock into the well) that are fully drawn down, the oil and water zones should not be in pressure communication and the oil-producing zone(s) must be producing at 100% oil cut (dry oil). When treating unfractured and multizoned production wells that are not fully drawn down, the well's long-term oil-production rate can be increased if the post-treatment drawdown is increased substantially. Treatments that promote short-term (transient) decreased water/oil ratios can, in principle, be applied to many unfractured production wells (that are not totally watered out) in matrix-rock reservoirs. However, these latter treatments must be custom designed and engineered on a well-by-well basis. Furthermore, for most wells, the performance and the economics of such transient WSO treatments are generally marginal. An attractive application of RPM/DPR WSO treatments is the use of robust pore-filling gels in the matrix reservoir rock that is adjacent to a fracture(s) when oil and water is being co-produced into the treated fracture.

Introduction

RPM is a property that is exploited during certain oilfield WSO treatments, and a property whereby many water-soluble polymers and aqueous polymer gels reduce the permeability to water flow to a greater extent than to oil or gas flow. These are some of the many illustrative literature references (Sandiford 1964; White et al. 1973; Sparlin 1976; Weaver 1978; VanLandingham 1979; Schneider 1982; Kohler et al. 1983; Dunlap et al. 1986; Dovan and Hutchins 1994; Seright 1995; Stanley et al. 1997; Faber et al. 1998; Eoff et al. 2003a; Ligthelm 2001; Morgan et al. 2002; Di Lullo and Rae 2002; Eoff et al. 2003b; Kume 2003; Seright 2006a; Pietrak et al. 2005) that discuss the RPM phenomenon. RPM WSO treatments are applicable to both oil and gas production wells.

RPM is also referred to as disproportionate permeability reduction (DPR). Some practitioners reserve the term "DPR" for relatively strong polymer gels that impart a large degree of disproportionate permeability reduction and a large reduction in water permeability. These practitioners reserve the term "RPM" for systems such as solutions of water-soluble polymers or relatively "weak" gels that impart more subtle disproportionate permeability reductions and more subtle reductions in water permeability. However, in this paper, the terms RPM and DPR will be considered synonyms. At times in the literature, DPR and RPM have also been referred to as "selective-permeability reduction" and "selective-permeability blocking."

In this paper, the term "WSO treatment" refers to a chemical treatment that is applied (to an oil or gas producing reservoir) to either reduce or totally shutoff water production from a well.

Historically, RPM/DPR is a phenomenon that was believed limited to fluid flow in matrix-rock porous media. More recently, it has been reported that certain relatively strong WSO gels impart RPM/DPR to fluid flow within gel-filled fractures (Sydansk et al. 2005). However, because such relatively strong gels also significantly reduce the permeability to oil flow in fractures, these gels are better characterized as total shutoff gels than as RPM/DPR WSO gels.

DPR is only of value for water-shutoff treatments applied to production wells. DPR has little, or no, value for application from the injection-well side.

A distinction that has not been made clearly in the past is RPM/DPR WSO treatments that promote long-term ("permanent") vs. short-term (transient) WSO. In this paper, "long-term" means months to years and hopefully for the economic life of the treated well, and "short-term" or "transient" means hours up to a month or two (often hours to days). Long-term and short-term RPM/DPR WSO treatments will be discussed and differentiated in this paper. This distinction helps to explain some of the historically disappointing field results of these treatments.

The objectives of this paper are as follows. First, we will outline when, where, and how RPM/DPR WSO treatments can be successfully applied. Second, issues, potential pitfalls, and limitations relating to the successful application of RPM/DPR WSO treatments will be reviewed.

Background

Historical Review. The ability of acrylamide polymers to impart RPM/DPR to water and oil flow in porous media was recognized as early as 1964 by Sandiford and 1973 by White et al. The mechanism(s) by which numerous water-soluble polymers and aqueous gels impart RPM and DPR has been the subject of a number of investigations (Zaitoun and Kohler 1988; Dawe and Zhang 1994; Liang et al. 1995; Barreau et al. 1997; Thompson and Fogler 1997; Nilsson et al. 1998; Mennella et al. 1998; Zitha et al. 1999; Al-Sharji et al. 1999; Elmkies et al. 2001; Stavland and Nilsson 2001; Grattoni et al. 2001; Seright et al. 2002; Willhite et al. 2002). More recently, a plausible mechanism was proposed that explains how chromium(III)-carboxylate/acrylamide-polymer (CC/AP) gels impart DPR (Seright et al. 2006). A detailed discussion of the mechanism by which water-soluble polymers and aqueous polymer gels impart RPM/DPR is beyond the scope of this paper.

Historically, a large number of ineffective, underperforming, and/or disappointing RPM/DPR water-shutoff treatments were applied by the petroleum industry (Eoff et al. 2003a; Ligthelm 2001; Pietrak et al. 2005; Gludicellie and Truchetet 1993; Stavland et al. 1998; Zaitoun et al. 1999; Mennella et al. 2001; Botermans et al. 2001; Kabir 2001; Kalfayan and Dawson 2004). This paper will

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provide insight into the reasons for the historically uninspiring field-success rate for RPM/DPR WSO treatments.

Why RPM/DPR WSO Treatments Are Attractive. The reason that there is so much active interest in the petroleum industry regarding bullheadable DPR water-shutoff treatments is that they normally do not require the use of mechanical zone isolation during treatment-fluid placement. In contrast, when applied to wells of matrix-rock reservoirs involving radial flow, conventional (relatively strong and total-fluid-shutoff) polymer-gel WSO treatments normally require the use of mechanical-zone isolation during treatment placement (Seright et al. 2003). Mechanical-zone isolation often requires costly workover operations. In addition, the use of mechanical-zone isolation during water-shutoff-treatment placement is normally not feasible when the well possesses a slotted-liner or gravel-pack completion or when the well involves a subsea tieback flow line. Presently, RPM/DPR WSO treatments are a technology that is in vogue within the industry, and many individuals and organizations are attempting to develop and exploit these treatments.

RPM/DPR Does Occur. When numerous of the early RPM/DPR WSO treatments did not perform as well as expected, a number of oil-industry professionals questioned whether RPM/DPR actually occurs. As it turns out, it does as is supported and indicated by essentially all of the literature references of this paper. Thus, the challenge is to learn when, where, and how RPM/DPR can be successfully employed in WSO treatments. Addressing this challenge will be the focus of the remainder of this paper.

Ideal RPM/DPR WSO Treatments

As used in this paper, "ideal" RPM/DPR WSO treatment means the following: First, an ideal RPM/DPR WSO treatment does not reduce oil permeability at all in the volume of matrix-reservoir rock where it is placed. Second, in the field setting, an ideal RPM/DPR WSO treatment does not promote any reduction in the post-treatment oil-production rate.

In this paper, when considering polymer-alone and weak-gel WSO treatments in unfractured reservoirs, we will, for the most part, discuss ideal RPM/DPR WSO treatments. Unfortunately, an ideal RPM/DPR WSO technology does not yet exist commercially. When an operator is considering the application of a RPM/DPR WSO treatment that does impart some permeability reduction to oil flow in the treated reservoir volume, he or she must factor this into the treatment design and the expected treatment performance.

The application of a nonideal RPM/DPR WSO treatment could be an attractive business venture for an operator, for example, for a treatment that reduced oil production by only 5%, but reduced water production by 90%.

Additionally, an ideal RPM/DPR WSO treatment does not wash out with time and is not back produced in the field setting.

When and Where Applicable

Matrix-Reservoir-Rock Radial-Flow Vertical Wells. In this section, we assume gravity effects are negligible and assume the application of an "ideal" RPM/DPR WSO technology. An ideal RPM/DPR WSO treatment imparts no permeability reduction to oil or gas flow, but imparts a relatively large permeability reduction to water flow in the treated reservoir volume. This section of the paper is limited to discussion of RPM/DPR WSO treatments of unfractured production wells (radial flow through matrix rock or sand).

Fully Drawn Down Wells. If a well is fully drawn down before a treatment, we normally expect it to remain so after the treatment (so long as the treatment is not applied over fracture pressure). We assume here that the production conditions and equipment are the same before and after the treatment. The following discussion is specifically targeted at oil-producing wells, but the same general arguments also hold for gas-producing wells.

When a well is fully drawn down, the application of a RPM/DPR WSO treatment (alone) provides no opportunity to increase the post-treatment oil-production rate.

Long-Term WSO. In this subsection, we discuss when and where long-term (months to years) RPM/DPR WSO treatments can be successfully applied to production wells in matrix-rock reservoirs where flow is radial into the wellbore. Alternatively, by "long-term," we mean the target longevity of the treatment life is the economic life of the treated well—the ideal longevity goal for any highly effective and durable WSO treatment. By "successful" WSO treatments, we mean treatments that reduce the water production rate, while not simultaneously reducing the pre-treatment oil-production rate.

- Single oil-producing zone (geological strata or formation): RPM/DPR WSO treatments are <u>not</u> applicable. RPM/DPR WSO treatments are of no practical value [for providing long-term (e.g., years of) water shutoff] when applied to a single zone (relatively homogeneous) reservoir that is producing at a high water cut. As shown in **Fig. 1,** this is because after the treated well is put back on production, a relative-permeability water block will form just beyond the outermost penetration of the treatment (Eoff et al. 2003a; Ligthelm 2001; Gludicellie and Truchetet 1993; Stavland et al. 1998; Kalfayan and Dawson 2004; Seright et al. 2003).

  The relative-permeability water block occurs because after the RPM/DPR WSO treatment, water and oil in the far wellbore region continue to flow to the well at the originally produced water/oil ratio (WOR). When this oil/water fluid stream reaches the outer radial penetration of the treatment, the water flow is impeded, whereas no permeability reduction and impediment (for an ideal treatment) is encountered by the oil flow. Thus, with time, the water saturation builds up just beyond the treatment material (polymer or gel). As the water saturation builds up, the relative permeability to oil flow is reduced. As a result, the oil permeability is also reduced in this volume. In this paper, the term "water-block problem" refers to this treatment-induced reduced oil relative permeability and the consequential reduction in oil productivity from the treated zone.

  The best that anyone can do in this single oil-producing-zone situation over the long term is to end up with the final/equilibrium water cut being the same as the pre-treatment water cut, but the well producing at lower production rate (Eoff et al 2003a; Ligthelm 2001; Gludicellie and Truchetet 1993; Stavland et al. 1998; Kalfayan and Dawson 2004 and Seright et al. 2003). This is a lose/lose result. The WOR ratio is not reduced, and the oil-production rate is reduced. In the proceeding discussion, the single zone was considered to be homogeneous; however, from a practical point of view, this argument normally still holds if the single oil-producing zone is mildly or somewhat heterogeneous. Stated another way, RPM/DPR WSO treatments are of no value for promoting long-term WSO within any single, isolated oil-producing zone that is nearly watered out.
- Multiple producing intervals in the reservoir.
  - Crossflow exists between reservoir zones/strata. RPM/DPR WSO treatments are not applicable (Pietrak et al. 2005). By crossflow, we mean that the various reservoir

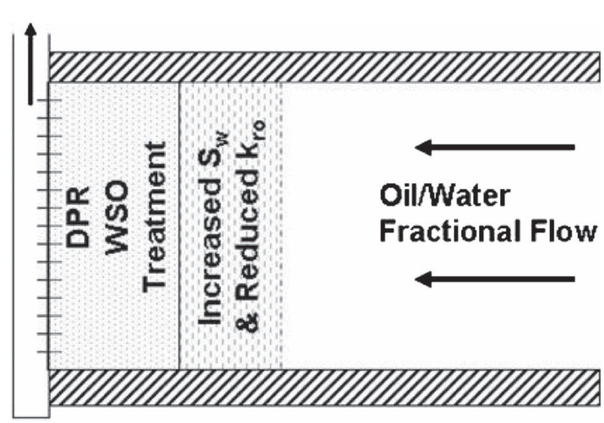

Fig. 1—DPR WSO treatment applied to a single formation (strata) producing at an O/W fractional flow.

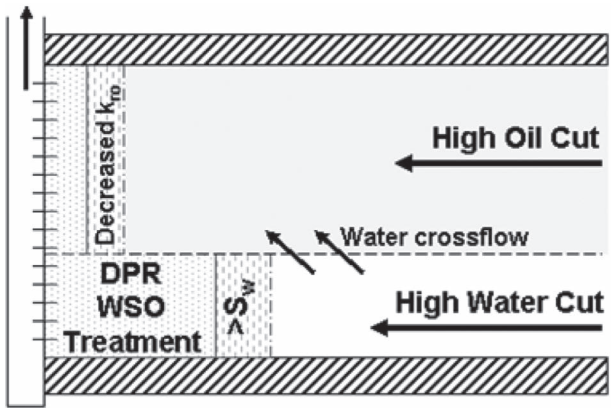

Fig. 2—DPR WSO treatment applied to a reservoir having a water and a high-oil-cut producing strata with crossflow.

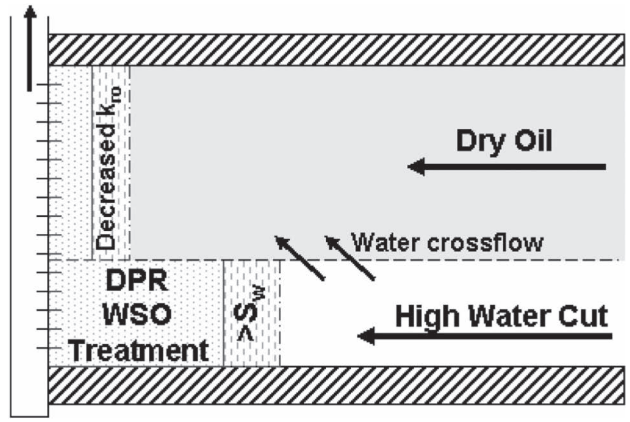

Fig. 3—DPR WSO treatment applied to a reservoir having a water and a dry-oil producing strata with crossflow.

geological strata within the producing reservoir are in vertical pressure and fluid communication (e.g., continuous impermeable shale barriers do not exist between the reservoir geological strata). Stated another way, a finite k_v exists across the reservoir intervals in question. In view of the previous discussion under the "Single oil-producing zone" bullet item, what is a little less obvious is that for the same basic reason when producing from matrix-rock reservoirs in the radial-flow mode, RPM/DPR WSO treatments are not effective at promoting long-term water shutoff/reduction anytime crossflow exists between the oil- and water-producing zones. This is shown in **Figs. 2 and 3.** The phenomenon depicted in Figs. 2 and 3 will also occur if the water-producing interval overlies the oil-producing interval. The situation depicted in Figs. 2 and 3 is not representative of water coning because the lower zone in the figures is implicitly of much higher permeability than the upper zone, and operators do not normally perforate below the oil/water contact.

– Crossflow between reservoir zones/strata does not exist.
  + Oil zone(s) is producing at 100% oil cut (dry oil): RPM/DPR WSO treatments are applicable. As shown in **Fig. 4,** this favorable result occurs because no water-block problem forms in the oil-producing zone(s). This is a type of excessive water-production problem that is amenable to successful RPM/DPR WSO treatments (for wells that are fully drawn down) (Zaitoun et al. 1999; Mennella et al. 2001; Botermans et al. 2001; Kalfayan and Dawson 2004). To maintain this favorable result, the oil-producing zone(s) must continue to produce dry oil for the economic life of the treatment.
  + Oil zone(s) producing at a finite (intermediate) water cut: Long-term RPM/DPR WSO treatments are not applicable. This problem degenerates to the problem of a series of isolated oil-producing zones producing at a finite water cut and the associated gel-treatment-induced water-block problem (as discussed previously).

    As previously mentioned, any treatment cannot change the steady state fractional flow from a given zone. If a zone produces at an intermediate water cut (e.g., 20% water and 80% oil) before treatment, the water cut must have the same value after treatment (Liang et al. 1993). Thus, if polymer or gel enters and causes a two-fold loss of water productivity from this zone, it must also cause a two-fold loss of oil productivity.

    As a caveat, circumstances may exist where some loss of oil productivity may be acceptable if dramatic reductions in productivity can be achieved from other prolific water-producing zones (e.g., the bottom zone in Fig. 4).

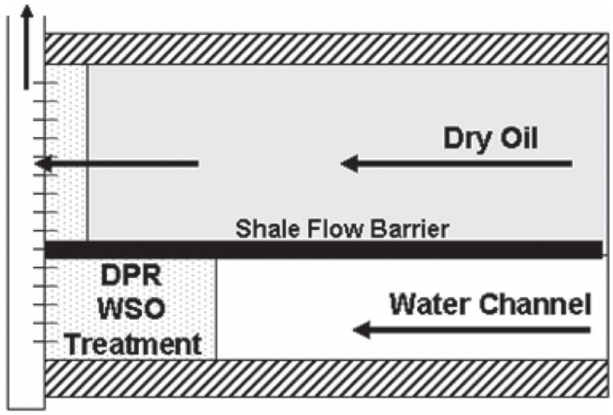

Fig. 4—DPR WSO treatment applied to a reservoir having a water and a dry-oil producing strata with no crossflow.

• Water coning through unfractured matrix rock: RPM/DPR WSO treatments are generally not applicable. For justification of this assertion, see Zaitoun et al (1999), Mennella et al. (2001), Liang et al. (1993) and Seright et al. (1993). Except under rare circumstances, RPM/DPR WSO treatments can only delay (normally for a relatively short period of time) the water from coning around the emplaced treatment (Liang et al. 1993; Seright et al. 1993).

Short-Term WSO. In this subsection, we discuss when and where short-term ("transient") RPM/DPR WSO treatments can be applied with some success to production wells in matrix-rock (unfractured) reservoirs where radial flow is occurring. By "short-term," we mean treatments that promote WSO for hours to a month or two (but often hours to days).

• Single (homogeneous or nearly homogeneous) oil-producing zone: Short-term RPM/DPR WSO treatments can possibly be applicable. Short-term RPM/DPR WSO treatments, in theory, can be applied with some success (Ligthelm 2001) because immediately after treatment placement and during initial post-treatment production, oil can "readily" pass through the gel-treated matrix-rock volume (for an ideal treatment), while simultaneously water production is significantly impaired. However, the post-treatment production rate in the oil zones will decrease to an equilibrium level as the water block is established at a point just beyond the outer radial penetration of the treatment material. As a result, favorable long-term WSO will not result. The economics of applying RPM/DPR treatments that impart short-term/transient WSO are often marginal, and these are relatively high-risk WSO treatments, where each treatment needs to be custom designed, evaluated, and engineered. The treatment design and expected performance needs to be carefully evaluated in terms of both technical and economic considerations. Refer to Fig. 1 when considering this particular problem.
• Crossflow between reservoir zones/strata does not exist:
  – Oil zone(s) producing at 100% oil cut: Short-term RPM/

DPR WSO treatments are applicable. However, in this case, the RPM/DPR treatment will also promote *long-term* WSO, which is a more favorable outcome.
  - Oil zone(s) producing at a finite water cut: Short-term RPM/DPR WSO treatments can possibly be applicable. This problem degenerates to the problem of a series of isolated oil-producing zones producing at a finite water cut and to a version of the problem described in the first bullet item of this subsection. That is, a series of isolated producing intervals, as depicted in Fig. 1, where the zones overlay one another.
- Crossflow exists between the oil- and water-producing zones with the oil-producing zone(s) either producing at 100% oil cut or at a finite water cut: *Short-term RPM/DPR WSO treatments can possibly be applicable*. This is because, following the application of a RPM/DPR WSO treatment, it takes a finite period of time for the water block to establish itself just outside of the treatment penetration radius in the oil-producing zone(s). Beginning with first post-treatment production, the oil production rate in the oil-producing zones will be decreasing to an equilibrium level as the water block is established. This can be seen by carefully studying Figs. 2 and 3. The economics of applying RPM/DPR treatments that impart short-term/transient WSO are often marginal, and these are relatively high-risk WSO treatments. Each of these treatments needs to be custom designed and engineered. The treatment design and expected performance needs to be carefully evaluated in terms of both technical and economic considerations.

Wells Not Fully Drawn Down. Production wells that are not fully drawn down before application of a RPM/DPR WSO treatment often experience increased drawdown pressure after application of the WSO treatment. The ability to increase drawdown pressure provides the means to possibly increase the oil-production rate after the WSO treatment. For a RPM/DPR WSO treatment to increase the oil-production rate, the treatment must "significantly" increase the drawdown pressure. By significantly increasing the post-treatment drawdown pressure, we mean that in the Darcy radial-flow equation, the magnitude of the post-treatment drawdown pressure increase exceeds the magnitude of the loss of the overall effective permeability to oil flow—that is, oil permeability lost because of treatment-induced damage to oil flow in the treated reservoir volume and/or any treatment-induced water-block problem(s). To generate an increased oil-production rate, the effect of the increased drawdown pressure must exceed the effect of the loss in the well's productivity resulting from treatment-induced loss of oil permeability and resulting from the formation of any treatment-induced water block.

This can be quantitatively seen by considering Darcy's radial-flow equation,

$$q_o = (\Delta p \cdot k_o)\,(h/[141.2 \cdot \mu \cdot \ln\{r_e/r_w\}]), \qquad (1)$$

where q_o is the oil production rate in B/D, Δp is differential pressure in psi, k_o is the effective permeability (in md) for oil flow from the *entire* producing interval, h is the total height of the producing interval, μ is oil viscosity in cp, r_e is the external drainage radius in ft, and r_w is the wellbore radius in ft. In Eq. 1, Δp and k_o are the two key variables of interest. The other variables on the right side of Eq. 1 are fixed. Oil production will only increase if the magnitude of the increased drawdown pressure exceeds the magnitude of the loss of oil flow capacity caused by the treatment.

Viewed in another way, treatment-induced increased drawdown pressure in a treated well provides a countervailing phenomenon to help, or possibly fully offset, RPM/DPR WSO treatment-induced damage to oil permeability in the treated reservoir volume (for a "nonideal" WSO treatment) and/or treatment-induced water-block problems.

Single Oil-Producing Zone. RPM/DPR WSO treatments are not applicable. Under all post-treatment drawdown-pressure conditions, single (homogeneous or nearly homogeneous) oil-producing zones cannot be successfully treated with long-term RPM/DPR WSO treatments due to the water-block problem (previously discussed) that occurs outside the outer radial penetration of the WSO treatment.

Multiple Zones With, or Without, Crossflow, and With, or Without, the Oil Zone(s) Producing at 100% Oil Cut. RPM/DPR WSO treatments can possibly be applicable. The technical and economic applicability, in this instance, of a RPM/DPR WSO treatment to wells that are not fully drawn down must be evaluated on a well-by-well basis.

Treatments Exploiting Gravity Effects. RPM/DPR WSO treatments that exploit gravity effects in matrix-rock reservoirs may be beyond the primary scope of this paper. However, there have been a few isolated instances where aqueous-gel RPM/DPR WSO treatments were based on the exploitation of the gravity concept. **Fig. 5** shows how capitalizing on gravity might be exploited. For the sake of completeness, this subject is briefly covered in this subsection.

We emphasize the difference between the case considered here (Fig. 5) and conventional 3D coning. In normal 3D coning in matrix rock, the absolute permeability of the underlying aquifer is typically about the same as in the hydrocarbon zone. For the case in Fig. 5, the water zone is much more permeable than the overlying hydrocarbon zone.

For a RPM/DPR WSO treatment to exploit gravity effects, the water-producing interval, must be located at the bottom of the producing interval and there must be good pressure and fluid communication (good k_v) between the oil and water producing zones.

The successful application of RPM/DPR WSO treatments that exploit gravity effects are favored by:

- High permeability producing intervals.
- Long gel onset times.
- Low oil viscosity.
- High density contrast between the treatment fluid and the oil.
- Thick hydrocarbon-producing zones.

However, in this instance, the use of an appropriate classical "total shutoff" WSO gel would work just as well, if not better. Also, a plug-back operation (e.g., sand-back plug) within the wellbore is operationally less complex, usually less costly for this application, and often nearly as effective.

Matrix-Reservoir-Rock Radial-Flow Horizontal Wells.

Coning in Matrix Rock. RPM/DPR long-term WSO treatments are not applicable. Such WSO treatments are not applicable to water coning into a horizontal well for basically the same set of general reasons that WSO treatments cannot be effectively applied to promote long-term WSO when the excessive water production is coning into a vertical well producing from a matrix-rock reservoir (Zaitoun et al. 1999; Mennella et al. 2001; Liang et al. 1993; Seright et al. 1993). That is, any such WSO treatment will only delay the water coning.

Fractured Wells.

Hydraulically Fractured Production Wells. When production wells are hydraulically fractured, the fracture often unintentionally

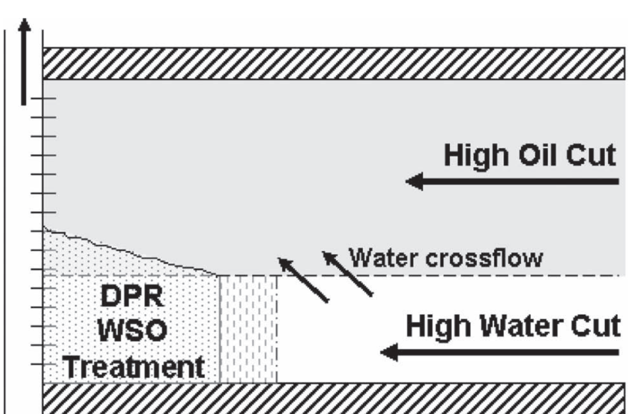

Fig. 5—A gravity-exploiting DPR WSO treatment.

breaks into water zones, causing substantially increased water production. RPM/DPR gel WSO treatments (involving robust, relatively strong, and pore-filling polymer gels) have significant potential to correct this problem. These gel WSO treatments rely on the ability of these gels to be placed in the rock matrix adjacent to the fractures and to reduce permeability to water flow much more than that to hydrocarbon flow (i.e., DPR). An engineering-based method has been developed for designing and sizing gelant treatments in hydraulically fractured production wells (Seright et al. 1998; Seright, *Reservoir*).

These gel WSO treatments permit the use of gel that reduces the permeability to oil flow significantly (greater than a factor of two) within the reservoir volume where the gel is placed, as well as pore-filling, robust, relatively strong, and more classical polymer gels.

In these matrix-rock treatments, the gelant fluid (gel fluid in which no gelation has yet occurred) flows along the fracture and leaks off a short, predictable distance into the matrix rock of all the zones (water, oil, and gas). Success for such a treatment requires that the gel reduce permeability to water much more than that to hydrocarbon (oil or gas) in the treated matrix rock **(Fig. 6).** The ability of the gel to reduce water entry into the fracture is determined by the product of gelant leakoff distance (from the fracture face) and the residual resistance factor (permeability reduction factor) provided by the gel. For example, consider the case where the gelant leaks off 0.2 ft into both water and oil zones, and in the gel-contacted rock, permeabilities to water and oil are reduced by factors of 50,000 and 50, respectively. In this case, the gel adds, effectively, only the equivalent of 10 ft of additional rock that the oil must flow through to enter the fracture (i.e., 0.2 ft × 50 rrf). In contrast, for the water zone, the water must flow through the equivalent of 10,000 ft of additional rock to enter the fracture (i.e., 0.2 ft × 50,000 rrf). Thus, in this circumstance, the gel can substantially reduce water production without significantly affecting oil productivity.

In this method, fluid entry into the fracture is controlled by the gel in rock next to the fracture (Seright et al. 1998; Seright, *Reservoir*). Ideally, fracture conductivity should not be reduced significantly, because it allows a conductive path for hydrocarbon flow into the wellbore. To some extent, gravity segregation of the gelant (between placement and gelation) will mitigate damage to the fracture when the excessive water production originates from an underlying aquifer. However, to minimize fracture damage, an oil or water post-flush could be used to displace gelant from the fracture.

From a rigorous viewpoint, the method assumes that impermeable barriers (e.g., shale or calcite) separate adjacent zones (Seright et al. 1998). However, the method should frequently provide acceptable results even if crossflow can occur between the water-bearing and oil-bearing zones. For example, consider the case where oil lies on top of water in a single formation (i.e., a common situation where coning becomes a problem). Previous work (Liang et al. 1993; Seright et al. 1993) showed that gravity alone can retard water influx into oil zones much more effectively when the water must "cusp" to a linear pressure sink (i.e., a vertical fracture or a horizontal well) than when the water "cones" to a point pressure sink (i.e., a partially-penetrating vertical well). For the type of gel treatment that we are proposing for application in hydraulic fractures, in many cases, gravity may be sufficient to minimize water invasion into the hydrocarbon zone of a single formation. Of course, the degree of water invasion (coning) into hydrocarbon zones increases with increased production rate, pressure drawdown, vertical permeability, and hydrocarbon viscosity, and decreases with increased water-hydrocarbon density difference and oil-column thickness (Liang et al. 1993; Seright et al. 1993). If water invades too far into the hydrocarbon zone, a water block could form that reduces hydrocarbon productivity.

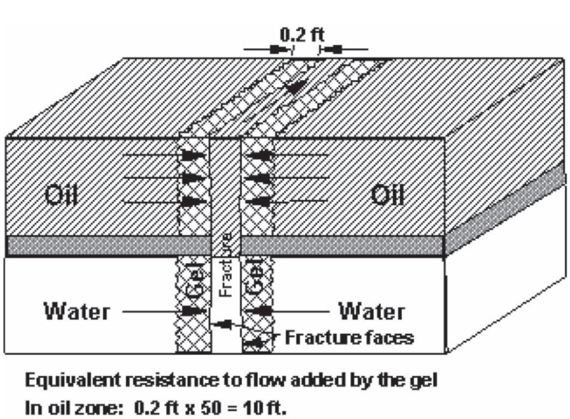

Fig. 6—Use of DPR to inhibit water entry into a fracture or fracture system.

To use this procedure to reduce water production from a hydraulic fracture, field data are needed, coupled with results from two simple laboratory experiments (Seright et al. 1998). The needed field data include: fluid production rates before the gel treatment, downhole static and flowing pressures before the gel treatment, permeabilities, porosities, and thickness of the relevant zones, water and oil viscosities at reservoir temperature, and well spacing or distance between wells. These parameters are often available during conventional gel treatments. The downhole pressure drops are critically important for this method. They must be reasonably current and measured specifically for the well to be treated.

Use of the procedure also requires oil and water residual resistance factors from laboratory core experiments (Seright et al. 1998; Seright, *Reservoir*). These experiments must be conducted using the gelant, oil, brine, rock, and temperature that are representative of the intended application. In the absence of laboratory oil and water residual resistance factors, the model can use field data to back-calculate these values in-situ after a gel treatment. This information may be useful when designing similar treatments in nearby wells. For cases where residual resistance factors are calculated from field data, three parameters (from a similar, previous gelant treatment) are required in addition to the five items listed in the previous paragraph. These three parameters are: fluid production rates after the gel treatment, accurate downhole static and flowing pressures after the gel treatment, and the volume of gelant injected.

Naturally Fractured Production Wells. The previously discussed concepts have also been applied to applications in more complex naturally-fractured vertical wells where fractures connect to a water source, although additional work is needed is this area (Marin et al. 2002; Al-Dhafeeri et al. 2005).

Horizontal Wells With Fractures That Lead to an Aquifer. Horizontal wells often intersect fractures that lead to an aquifer. Field cases exist where a partially formed or fully formed (mature) gel of the classical type was extruded down the length of the well and into a fracture (Lane and Seright 2000; Lane and Sanders 1995). Classical fracture-problem gels are relatively "strong" and total-fluid-flow-shutoff gels. Seright et al. (2003) discusses a strong gel application for this excessive water-production problem. Because the formed gel cannot enter the porous rock, it causes no significant damage to hydrocarbon-productive zones. However, when extruding through the water-producing fracture, the gel dehydrates (concentrates). When the well is returned to production, the concentrated gel remains in the fracture (if the treatment is designed correctly) and prevents water from entering the well from the underlying aquifer.

An alternative to the previous approach could exploit DPR. Instead of a formed gel, gelant (gel fluid in which no gelation has yet occurred) could flow down the horizontal well and into the offending fracture, leaking off into porous rock during the entire placement procedure. When the gelant sets up in the porous rock next to the fracture within the aquifer, the gel effectively encapsulates the fracture and greatly restricts water entry. In contrast, although gelant has entered hydrocarbon-productive zones along the well, the DPR effect (if properly designed and sized) could allow hydrocarbon to enter the well with limited loss of productivity.

TABLE 1—GUIDELINES – WHEN & WHERE IDEAL RPM/DPR WSO TREATMENTS ARE APPLICABLE

Guideline	Applicable
• Matrix-reservoir-rock radial-flow vertical wells	
➢ Fully drawn down wells	
▪ Long-term WSO	
⅄ Single homogeneous oil-producing zone	No
⅄ Multiple zones	
♦ Cross flow exists	No
♦ No crossflow exists	
▫ Oil zone(s) producing at 100% oil cut	Yes
▫ Oil zone(s) producing at a finite-water cut	No
▪ Short-term WSO	
⅄ Single homogeneous oil-producing zone	Possibly
⅄ Multiple zones	Possibly
➢ Wells not fully drawn down	
▪ Long-term WSO	
⅄ Single oil-producing zone	No
⅄ Multiple zones	
♦ Oil zone(s) producing at 100% oil cut	Yes
♦ Oil zone(s) producing at a finite water cut	Depends*
▪ Short-term WSO	
⅄ Single homogeneous oil-producing zone	Possibly
⅄ Multiple zones	Possibly
• Matrix-reservoir-rock radial-flow horizontal wells (long-term WSO)	
➢ Water coning	No
• Fractured wells	
➢ Vertical wells	
▪ Hydraulic fracture extending into a fracture	Yes
▪ Single natural-fracture problem	Yes
▪ Limited natural-fracture-network problem	Yes
▪ Extensive natural-fracture-network problem	Challenging
➢ Horizontal wells	
▪ Fracture(s) connected to an aquifer	Yes

* depends on drawdown pressure

Guidelines

Table 1 provides guidelines as to when and where RPM/DPR WSO treatments can be successfully applied, especially with regard to reservoir, geological, and production conditions.

The guidelines assume the application of an "ideal" RPM/DPR WSO treatment, where the treatment does not impart any significant reduction to oil permeability in the treated reservoir volume. If the treatment does reduce the permeability to oil flow in the treated reservoir volume, this must be factored in separately.

In Table 1, under the Applicable column, "Depends" means depending on whether the magnitude of the post-treatment drawdown pressure increase exceeds the magnitude of the loss of the overall effective permeability to oil flow occurring from the treated well.

Treatment Limitations and Potential Pitfalls

This section will briefly discuss a series of limitations and potential pitfalls that often apply to RPM/DPR WSO treatments.

Treatments for Matrix-Reservoir-Rock Radial-Flow Wells. Presently available RPM/DPR WSO treatments for application to wells in matrix-rock reservoirs producing under radial-flow conditions usually involve the use of water-soluble polymers alone or relatively weak polymer gels. The following treatment limitations and potential pitfalls pertain to RPM/DPR WSO treatments that are to be applied to wells of matrix-reservoir-rock reservoirs producing under radial-flow conditions.

Oil Permeability Always Reduced. To date, all known commercial RPM/DPR WSO treatment technologies for this application reduce the permeability to oil flow to some degree in the treated reservoir volume (Botermans et al. 2001). The goal of these WSO treatments should be to not reduce the permeability to oil flow by a factor exceeding two (Ligthelm 2001; Seright 2006a, Seright 2006b).

However, for the sake of completeness, it should be noted that Dovan and Hutchins (1994) discuss a laboratory study of gel and polymer-alone use for WSO purposes in gas wells. In this paper during certain instances, the gas permeability was observed to be fully maintained, or to increase somewhat, following application of the WSO treatment. However, these laboratory studies were not of just classical RPM/DPR WSO treatments, but treatments that additionally involved the sequential injection of gas slugs during the WSO treatment fluid placement.

Permeability Dependence. For adsorbing polymers and weak gels, residual resistance factors increase with decreasing permeability (Zaitoun and Kohler 1988; Seright 1993; Seright 1992; Vela et al. 1976; Jennings et al 1971; Hirasaki and Pope 1974). In other words, these materials damage low-permeability rock more than high-permeability rock. Depending on the magnitude of this effect, these polymers and gels can harm production flow profiles in wells (Liang et al 1993; Seright, *Reservoir*; Seright 1988).

This phenomenon is counterproductive for RPM/DPR WSO treatments because adsorbing polymers and weak gels often reduce the flow capacity more in the low-permeability oil-producing zones than in the high-permeability water-producing zones/channels. This is the opposite of what is desired of a WSO treatment.

Limited Permeability Range of Applicability. All presently available RPM/DPR WSO treatment technologies have a limited range of absolute permeability over which they are applicable (Pietrak et al. 2005; Mennella et al. 2001; Kalfayan and Dawson 2004). This is especially true for the polymer-alone RPM/DPR WSO technologies. Because operators often underestimate the permeability of their water-producing reservoir channels (Sydansk and Southwell 2000), this has proven historically to be an especially acute problem and the explanation for many field failures of RPM/DPR WSO treatments. Thus, it is critical that the operator correctly estimate the permeability of his or her water-producing channels and/or reservoir water flow paths if he or she is considering the application of a RPM/DPR WSO treatment.

Erratic Performance. The performance of currently available RPM/DPR WSO treatment technologies, in both the laboratory and field setting, has proven to be quite erratic (Pietrak et al 2005; Kalfayan and Dawson 2004; Seright 2006b). This is true even for the same treatment applied two or more times under "identical" conditions in the "same" core material in the laboratory or the same treatment applied in the same field to highly similar wells. Erratic behavior and performance is more acute for those RPM/DPR treatments that are meant to promote short-term/transient WSO. This limitation reduces the attractiveness of RPM/DPR WSO treatments and increases the uncertainty when applying such treatments in an oil or gas field.

Variability of residual resistance factors may be an inherent flaw for adsorbed polymers and weak gels. Permeability reduction by adsorbed polymers can be strongly influenced by mineralogy of the rock. In turn, rock mineralogy typically exhibits significant variations locally within a porous medium. Consequently, these mineralogical variations could lead to wide variations in performance for adsorbing polymers.

Weak gels are typically suspensions of gel particles—not a continuous three-dimensional gel structiure (Seright 1992; Seright 1993; Seright and Martin 1993). These particle suspensions have a particle size distribution—they are not monodisperse. Pores and pore throats within a rock also have a size distribution. Since the particles reduce permeability by lodging in pore throats, the ratio of particle size to pore-throat size is important in determining residual resistance factors for these suspensions. Variations in particle size distribution (especially resulting from unknown or uncontrolled particle generation) and variations in pore-throat size distribution (resulting from normal geologic processes) may cause wide variations in WSO performance for weak gels.

Back Production and Washout. Another significant limitation and potential concern and pitfall for RPM/DPR WSO treatments is the tendency of the emplaced WSO material (for many such treatment technologies) to be back produced and washout, especially when placed in the high-differential-pressure region adjacent to a radial-flow production well. In addition, this is especially true for RPM/DPR WSO treatment technologies that are based on the use of water-soluble polymers alone, where the WSO mechanism involves the adsorption of the polymer onto pore walls and/or in pore-throat constrictions. This can also be a serious problem for RPM/DPR WSO technologies that are based on the use of weak polymer gels. Use of pore-filling RPM/DPR WSO gels may mitigate this problem (Seright 2006b).

Slow Restoration of Oil Permeability. The slow clean up (restoration) of oil permeability in treated matrix porous media, as is exhibited by numerous RPM/DPR WSO systems, could possibly prove to be problematic and a limitation (Seright 2006b).

A simple mobility-ratio model was developed to predict cleanup times for both fractured and unfractured wells after a gel treatment (Seright 2006b). The time to restore productivity to a gel-treated oil zone was similar for radial vs. linear flow, varied with the cube of distance of gel penetration, varied inversely with pressure drawdown, varied inversely with the k_w at S_{or} in the gel-treated region, and was not sensitive to the final k_o at S_{wr}. Although k_o at S_{wr} (after gel placement) had no effect on the cleanup time, it strongly affected how much of the original oil productivity was ultimately regained.

Treatments for Fractured Wells. To follow is a brief listing and discussion of limitations of RPM/DPR WSO treatments where the treatment material is placed in the matrix rock that is adjacent to the treated fractures.

Size of the Fracture System. RPM/DPR WSO treatments can be used effectively to treat water production that emanates from finite-volume hydraulic fractures that extend out of zone into an aquifer or water strata (Seright et al. 1998). Also, these WSO treatments have been successfully applied to natural fracture networks of limited extent and size (Marin et al. 2002).

However, the successful application of these WSO treatments to extensive fracture networks is more challenging for two reasons. First, as further discussed in the next section, obtaining a uniform depth of gel placement into the matrix-reservoir rock (adjacent to the treated fracture) becomes more challenging as the size of the fracture network increases. Second, for RPM/DPR WSO treatments that are to be placed to any significant depth in the matrix rock, the treatment volume and cost may become prohibitive as the size of the fracture network increases beyond some critical value.

Obtaining Uniform Depth of Treatment Placement. As the size of the fracture(s) or fracture network increases, it becomes more difficult to obtain uniform depth of placement of the RPM/DPR WSO treatment material into the matrix rock that is adjacent to the fracture(s). There are two major factors contributing to this problem. First, for large volume treatments that take a long time to inject (many hours to days), the fracture faces nearer the wellbore experience more contact time with the injected-treatment fluid, and thus will experience deeper penetration of the treatment fluid into the matrix rock. Second, and especially in fractures having significant aperture widths (e.g., greater or equal to 1 mm), significant gravity effects may occur during aqueous treatment-fluid placement where the aqueous treatment fluid may segregate to the lower portion of the fracture. Of course, this could prove to be an advantage if water is being produced from the lower portion of the fracture, and oil is being produced from the upper portion.

Question of the Water Source. When considering the application of a RPM/DPR WSO treatment involving placing the gel into the matrix rock that is adjacent to the water-producing fracture(s), the source of the water production is an important issue. If water is being coproduced with oil from the matrix reservoir rock into a fracture or fracture system, this is a good gel WSO scheme. However, if the majority of the oil is produced into the fracture or fracture system from the matrix reservoir rock, but the majority of the water is produced through the fracture from a source far from the wellbore, this is not a good gel WSO scheme.

Discussion

RPM/DPR WSO Treatments of Gas Wells. Although this paper has implicitly emphasized the application of RPM/DPR WSO treatments to oil production wells, these treatments are also very applicable to gas production wells. Seright (1995) describes a number of gels that impart disproportionately large permeability reductions to water flow, relative to oil and gas flow. We feel that the application of RPM/DPR WSO treatments is nearly equally applicable to both oil and gas production wells and that the application of RPM/DPR WSO treatments to gas production wells has been, to date, under exploited.

Determine or Deduce the Water-Production Problem. It is imperative that an operator correctly deduce the source and nature of the excessive and unnecessary water-production problem before considering, designing, and implementing a RPM/DPR WSO treatment.

Need for Custom Engineering. If a RPM/DPR WSO treatment is to be applied in a new field for the first time, the WSO treatment must be custom designed and engineered. Under these circumstances, RPM/DPR WSO jobs are not routine, low-risk, "cookie cutter" treatments. Operators, who are not experienced with the application of RPM/DPR WSO treatments, should proceed with caution when considering applying such a treatment.

Fractional Flow. For treatments that are to be placed in fully drawn down radial-flow wells of matrix-rock reservoirs, oil/water fractional flow in any given geological strata (zone) is a serious challenge to presently available RPM/DPR treatments that are intended to promote long-term WSO (Pietrak et al. 2005). This is because of the water-block problem that occurs just beyond the outer radial penetration of the RPM/DPR treatment (Eoff et al. 2003a; Ligthelm 2001; Gludicellie and Truchetet 1993; Stavland et al. 1998; Kalfayan and Dawson 2004; Seright et al. 2003). After treatment placement, the fractional flow in the far-wellbore region remains unchanged. At the outer radial penetration of the RPM/DPR treatment, water flow is impeded, water saturation builds up at this point, the relative permeability to oil is reduced, and oil production is thus impeded.

As a result, RPM/DPR treatments that are intended to promote long-term WSO are not applicable to a single-zone reservoir.

In the case of a multizoned reservoir, where the water-producing zone is not in fluid and pressure communication with the other zones and the well is fully drawn down, RPM/DPR treatments will cause a loss in oil-production rate from zones that have a finite fractional flow (i.e., not 100% oil cut) because of the water-block problem (Eoff et al. 2003a; Ligthelm 2001; Gludicellie and Truchetet 1993; Stavland et al. 1998; Kalfayan and Dawson 2004; Seright et al. 2003). In this case, RPM/DPR WSO treatments are of dubious value unless in the case of wells that are not fully drawn down, the post-treatment drawdown pressure can be substantially increased and incremental oil production can possibly be obtained from the other strata resulting from increased drawdown pressure.

For a zone that is producing at a high-water cut and fluid crossflow can occur into adjacent zones, the resultant water-block problem will cause detrimental water crossflow as depicted in Fig. 2.

Water Crossflow. After treating matrix-rock reservoirs with a RPM/DPR long-term WSO treatment and where water crossflow can occur between the water- and oil-producing zones, water crossflow into oil-producing strata can be problematic, especially when the drawdown pressure on the producing formation after the treatment is not, or cannot be, significantly increased.

As can be seen by studying Fig. 3, this can prove to be especially troublesome when the oil cut is 100% in the oil-producing zone. In this case, water crossflow creates a detrimental water-block in the original dry-oil-producing zone.

Drawdown Pressure. For unfractured production wells (i.e., radial flow from matrix rock) that are not fully drawn down before a treatment, the magnitude of the increase in the drawdown pressure after a RPM/DPR long-term WSO treatment has major implications. If the post-treatment drawdown pressure is not significantly increased, then unless oil is produced at 100% oil cut (dry oil) from isolated strata, RPM/DPR WSO treatments are unable to promote increased oil-production rates and/or substantially compensate for any treatment-induced loss in oil productivity.

Stated another way, any treatment-promoted increased oil-production rate is proportional to the increase in the post-treatment drawdown pressure (beyond a critical value that is related to the treatment-induced loss in oil productivity).

The implication of this observation is that applying RPM/DPR WSO treatments to wells that are not fully drawn down holds the possibility (if a whole set of conditions can be met) to increase the oil-production rate following the treatment. On the other hand, if the treated wells are initially fully drawn down and all the oil production is produced at finite fractional flow, some oil-production rate will always be lost when applying a RPM/DPR WSO treatment.

For wells that are not fully drawn down, post-treatment increased drawdown pressure provides a countervailing phenomenon to help, or possibly fully, mitigate oil productivity losses caused by oil permeability damage in the treated reservoir volume and/or any water-block problems that may be caused by the RPM/DPR WSO treatment.

DPR and Reduction in Water-Producing Rate Do Not Necessarily Correlate. For unfractured production wells, some oilfield personnel have naively believed that the degree of water-permeability reduction in the treated reservoir volume will be directly proportional to the degree of reduction in the water-production rate that results from a RPM/DPR WSO treatment. This is not true for two reasons.

First, the post-treatment water-production rate is dictated by the average overall permeability of the producing interval. After a RPM/DPR long-term WSO treatment, the composite permeability of the producing zone averages two volumes that are in series flow—namely, the bulk of the untreated intermediate- and far-wellbore volume of the producing interval and the near-wellbore volume containing the WSO treatment material. Consequently, the final overall reduction in water permeability of the producing interval is less than the permeability reduction imparted in the near-wellbore-treated reservoir volume. However, because we are dealing with radial flow in these instances, this is often a second-order effect and consideration.

Second (and more importantly for unfractured radial-flow wells of matrix-rock reservoirs that are treated with a RPM/DPR long-term WSO treatment and wells that are fully drawn down before and after the treatment), the following applies. The treatment-induced water-block problem (discussed earlier), which occurs just beyond the outer-radial penetration of the WSO treatment material when fractional oil/water flow is occurring in the producing interval, will cause the well's post-treatment reduction in the water-production rate to be less than the treatment-induced reduction in water permeability imparted in the treated reservoir volume. This is because the water block causes an overall reduction of the production rate for the treated well. This is not an issue when the oil is being produced at 100% oil cut (dry oil) from geological strata that are not in fluid and pressure communication with the other strata of the producing interval.

Issue of Possibly Shutting Off Oil Production. Compared to conventional total-fluid-shutoff polymer-gel WSO treatments, some oilfield professionals assert that RPM/DPR WSO treatments present little risk of shutting off (totally) oil production if the treatment is inadvertently placed in the oil-producing interval of a vertical well.

If mistakenly placed in the oil-producing strata, numerous conventional polymer-gel WSO treatment are capable of essentially totally shutting off oil production.

The concern, in this regard, with RPM/DPR WSO treatments is that a number of oilfield operators infer that such treatments are not likely going to damage oil production. There are two reasons that this inference is not necessarily correct. First, many presently available RPM/DPR WSO treatments do reduce oil permeability to a significant extent in the treated matrix-rock reservoir volume. Second, and possibly more importantly, the treatment-induced water-block problem (described earlier) will often cause reduction of the post-treatment oil-production rate in wells that were initially fully drawn down (Eoff et al. 2003a; Ligthelm 2001; Gludicellie and Truchetet 1993; Stavland et al. 1998; Kalfayan and Dawson 2004; Seright et al. 2003).

Slow Treatment Cleanup. There is a second water-block problem that can adversely affect the performance of RPM/DPR WSO treatments in unfractured production wells. This problem involves the water of an aqueous-based RPM/DPR WSO treatment that invades the near-wellbore oil-producing zone during treatment injection and placement (Ligthelm 2001; Zaitoun et al. 1999; Botermans et al. 2001). This problem is especially noticeable when the oil zone is producing dry oil. The problem here is the slow cleanup of the injected-treatment water from the oil-producing zone and the associated transient post-treatment reduction in the oil-production rate of the zone in question. As long as the oil-producing zone was at residual water saturation prior to the treatment and there are no clay-sensitivity issues, this oil-productivity cleanup and water-block problem usually lasts only for a relatively short duration.

The primary difference between the water-block phenomenon resulting from the injected aqueous-treatment fluid and any RPM/DPR-WSO-treatment-induced water-block problems is the cause of the water block. The water block resulting from injecting an aqueous-WSO treatment fluid into an oil zone is caused by the water of the injected treatment fluid. The RPM/DPR-WSO-treatment-induced water block is caused by the treatment-induced water-block problem, where this problem occurs just beyond the radial penetration of the treatment material. The cleanup mechanism and rules for these two "different" water-block problems are similar.

The cleanup problem involving the injection of the aqueous-based RPM/DPR WSO fluid into an oil zone was not previously discussed in the Treatment Limitations section for two reasons. First, this is a potential problem that must be accounted for during any aqueous-based treatment that is injected for any reason into an oil zone of a matrix-rock radial-flow well. Second, this problem can often be effectively managed and mitigated through the use of conventional petroleum engineering practices. Productivity damage caused by relative permeability issues when an aqueous treatment fluid is injected into an oil-producing zone of a matrix-rock well can be mitigated, reduced, and/or greatly shortened in duration by either incorporating an appropriate surfactant or mutual solvent into the overall treatment design or injecting a post-treatment stimulation fluid containing an appropriate surfactant or mutual solvent.

Mobile Oil. Any operator considering the application of a RPM/DPR WSO treatment (or any WSO treatment) needs to realize that an oilfield WSO treatment can only be successfully applied to a production well if there is an economically sufficient volume of moveable-oil saturation in the reservoir surrounding the treated well. This is one of the first considerations that an operator should address when contemplating a WSO treatment.

Wettability. Wettability of the reservoir rock is another factor that an operator needs to consider before application of a RPM/DPR WSO treatment if the WSO mechanism is based on adsorption of polymers or weak gel particles onto the pore wall surfaces of the reservoir rock. RPM/DPR WSO treatments that are based on the adsorption of polymers onto pore walls reportedly often perform less well in oil-wet reservoirs (Pietrak et al 2005; Elmkies et al 2001; Mennella et al. 2001; Kalfayan and Dawson 2004).

Deviated Well. Previously in this paper, we discussed the applicability of RPM/DPR WSO treatments for treating excess water-production problems occurring in vertical and horizontal wells. What happens if the well to be treated is deviated somewhere between vertical and horizontal? If the well is near vertical (within 15°), then it can normally be considered to be a vertical well. Likewise, if the well is near horizontal (within 15°), then it can normally be considered to be a horizontal well. If a deviated well is intermediate to the previously discussed ranges, then good engineering and geological judgment needs to be exercised in how to classify the well and how to design an effective RPM/DPR WSO treatment for such a well.

Historical Performance. The relatively poor performance historically of RPM/DPR WSO treatments has resulted from the following combination of factors:

1. Over expectations of operators regarding RPM/DPR (Pietrak et al. 2005).
2. Over selling of RPM/DPR WSO treatments by oilfield service companies.
3. Failure to recognize the limitations and constraints of RPM/DPR WSO treatments (as discussed in this paper).

Treatment Risk Factor. For reasons discussed in this paper, the application of a RPM/DPR WSO treatment for the first time in a new field by an inexperienced operator should not be considered to be a low-risk undertaking.

Treatments Can Be Bullheaded. The primary reason why bullheadable RPM/DPR WSO treatments are of high interest is that they are one of the few options presently available to treat excessive water-production problems in matrix-rock reservoirs where mechanical-zone isolation is not possible or practical during treatment fluid placement.

Treatment Development and Exploitation Activity. At the time of the writing of this paper, laboratory studies, development, and exploitation of RPM/DPR WSO treatments were actively being pursued by numerous petroleum-industry-sponsored research and development efforts.

What Is Needed. A desired "next generation" matrix-rock RPM/DPR (water selective) WSO technology (Botermans et al. 2001) would have the following properties:

- Greatly reduce (or, more desirable yet, totally eliminate) water permeability during "high" water-cut flow (i.e., provide water residual resistance factors that reliably exceed 100, and preferably exceed 1,000).
- Totally inactivate (become nonfunctional) during "high" oil-cut flow—at a minimum, consistently provide oil residual resistance factors that are reliably less than two (and preferably near unity).
- Possess a controllable set point between "low" and "high" water-cut flow where the WSO functionality would be activated.
- Be able to promote effective long-term (i.e., years to decades) WSO.

Extensive efforts are underway to fulfill some of these requirements. Seright (2006a) reports several formulations where gels provided water residual resistance factors greater than 2,000 and ultimate oil residual resistance factors of 2 or less. These results provide hope that gels that can be found that successfully and reliably treat either fractured or unfractured production wells without zone isolation.

We also note work by IFP and Delft U. in determining permeability reduction values at intermediate water saturations and fractional flows, particularly for adsorbing polymers (Kohler et al. 1983; Zaitoun and Kohler 1988; Barreau et al. 1997; Zitha et al. 1999). Additional work of this type is needed for other gels (especially pore-filling gels) if extensive RPM/DPR WSO applications are to be applied in hydrocarbon zones that produce at intermediate fractional flows.

Conclusions

1. When properly designed and executed and when they function downhole as intended, polymer-gel or polymer-alone RPM/DPR WSO treatments can be successfully applied to a limited range of excessive-water-production problems occurring in either oil or gas production wells.
2. When a treatable excessive-water-production problem occurs, RPM/DPR WSO treatments can be applied using bullhead injection (not requiring the use of mechanical zone isolation).
3. When treating an excessive-water-production problem in a matrix-rock reservoir where the water is being produced radially into the production well and the well is fully drawn down, the only situation where a RPM/DPR WSO treatment can render long-term WSO, without reducing the pre-treatment hydrocarbon (oil or gas) rate, is when the hydrocarbon and water producing zones are not in fluid and pressure communication and the hydrocarbon zone(s) is producing at 100% cut (i.e., dry oil) and will continue to do so for the economic life of the WSO treatment.
4. When a multizoned unfractured production well (radial-flow through matrix rock) suffers from excessive water production and the well is not fully drawn down prior to the application of a RPM/DPR treatment that is applied for long-term WSO, the

oil production rate can possibly be increased if the post-treatment drawdown pressure can be "substantially" increased (as defined in the paper).

5. RPM/DPR WSO treatments, which provide short-term (transient) decreased WOR, can be, in theory, applied to most production wells (that are not totally watered out) in matrix rock reservoirs where radial flow is occurring. However, each of these treatments must be custom designed and engineered on a well-by-well basis. Furthermore, for most wells and associated excessive water production problems, the performance and the economics of such transient WSO treatments are, at best, marginal.
6. A potentially attractive application of RPM/DPR WSO treatments is the use and placement, in certain instances, of pore-filling and relatively robust gels in the matrix rock that is adjacent to a water-producing fracture(s).
7. There are a substantial number of limitations and possible pitfalls to the successful application of RPM/DPR WSO treatments, and their application for the first time by an inexperienced operator should not be considered a low-risk undertaking.

Nomenclature

h = height, ft [m]
k_o = permeability to oil, md [μm^2]
k_v = vertical permeability, md [μm^2]
q_o = oil flow rate, BPD [m^3/d]
r_e = drainage radius, ft [m]
r_w = wellbore radius, ft [m]
rrf = residual resistance factor
Δp = pressure drop, psi [kPa]
μ = viscosity, cp [Pa·s]
CC/AP = chromium(III)-carboxylate/acrylamide-polymer

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SI Metric Conversion Factors

cp × 1.0*	E−03	=	Pa·s
ft × 3.048*	E−01	=	m
in. × 2.54*	E+00	=	cm
md × 9.869 233	E−04	=	μm^2
psi × 6.894 757	E+00	=	kPa

*Conversion is exact.

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