The Bad Guys and the Good Guys in Petroleum Microbiology

Microorganisms make up 15 of the 24 subdivisions of life on earth—the animal kingdom occupies just one. With so much diversity, it is not surprising that microbes can even be found in high-pressure, hot, anaerobic oil wells. Until recently, the effects—both undesirable and beneficial—of these organisms on reservoirs were largely ignored. This attitude is gradually changing, however, and bacteria are now being harnessed to improve recovery.

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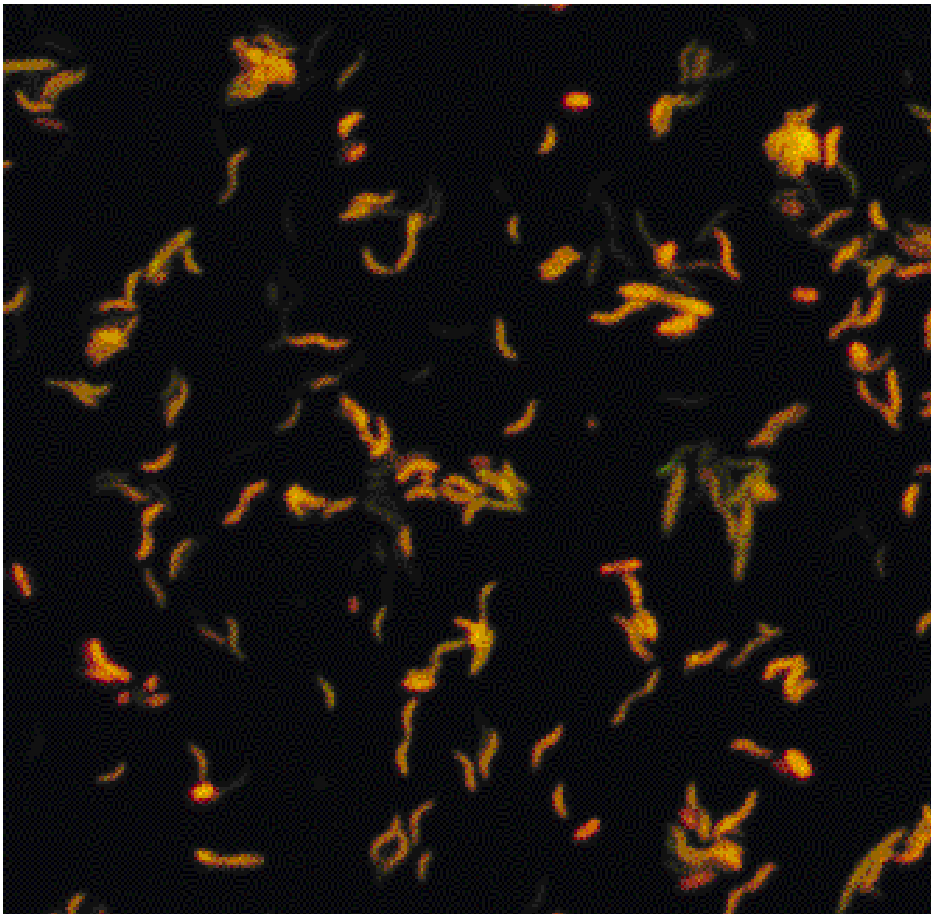

Bacteria: diverse and adaptable.

There is more diversity among microorganisms such as bacteria than there is in the range of life from artichokes to zebras. Bacteria have successfully colonized virtually every environment on earth because they can rapidly adapt to changing conditions, and use a large and varied number of nutrients to generate energy. However, until relatively recently, the environments of many petroleum reservoirs were considered too hostile for bacterial growth due to low availability of water, and high temperatures, pressures and salinities (*above*).[1]

Despite pioneering work during the 1930s and 40s in the USA by Claude Zobell, demonstrating a rich population of bacteria in water produced from shallow hydrocarbon reservoirs, the possibility of bacteria existing in larger, deep reservoirs was largely ignored. The start of North Sea production in the 1960s led to the realization that bacteria could produce hydrogen sulfide [H_2S] as a waste product and cause reservoir souring.

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1. For further background reading on this topic:
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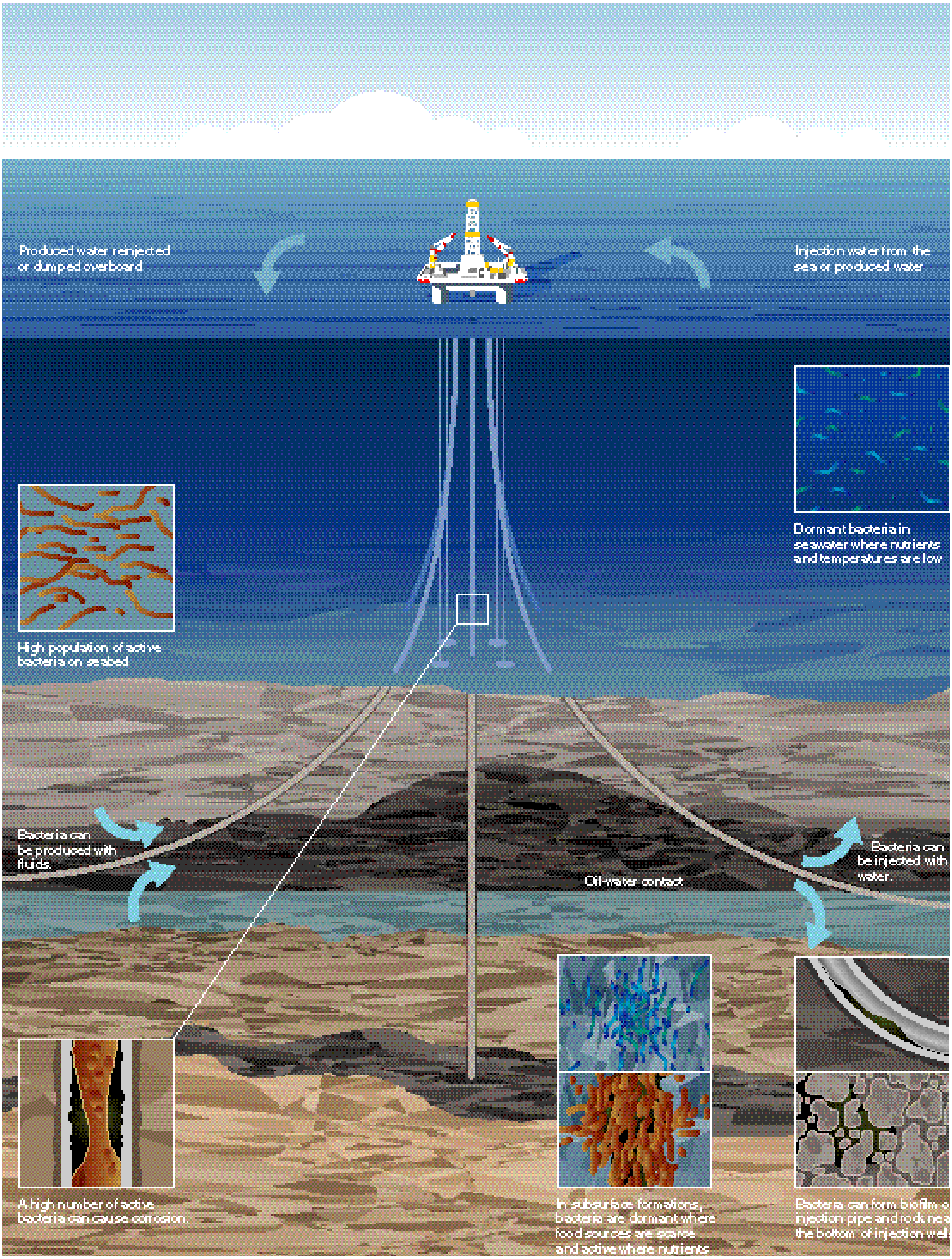
   Campbell A: "Reservoir Biogenics and its Application to Improved Oil Recovery," *Emerging Technology Status Review*. Edinburgh, Scotland: Petroleum Science and Technology Institute (PSTI), October 1996.

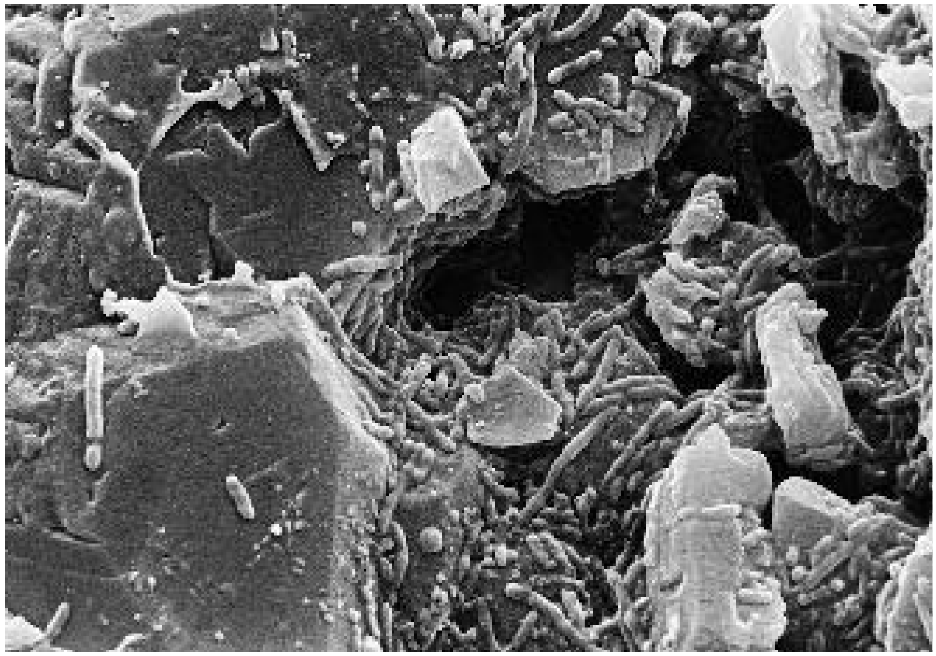


Produced water reinjected
or dumped overboard
Injection water from the
sea or produced water
Dormant bacteria in
seawater where nutrients
and temperatures are low
High population of active
bacteria on seabed
Bacteria can
be produced with
fluids.
Bacteria can
be injected with
water.
Oil-water contact
A high number of active
bacteria can cause corrosion.
In subsurface formations,
bacteria are dormant where
food sources are scarce
and active where nutrients
Bacteria can form biofilm o
injection pipe and rock nea
the bottom of injection well

A better understanding of subsurface microbiology from research programs—such as the British Geological Survey and US Department of Energy Deep Microbiology Subsurface Program—now shows that microorganisms can grow in temperatures above 125°C [257°F], at pH values of 1 to 11, in the presence or absence of oxygen, and in up to 30% sodium chloride [NaCl] solutions. As this knowledge develops, microbiologists are turning their attention to petroleum reservoirs as a habitat for microorganisms (*previous page*). This article examines how bacteria affect oil production by dividing them into two groups—the "bad guys" and the "good guys."

The bad guys are those groups of bacteria that use sulfur-based compounds present in seawater—and sometimes in formation or aquifer waters—as part of their energy chain, and use the simple carbon compounds that are present in formations as food. Waste from this growth includes hydrogen sulfide, which is poisonous to humans, and corrosive to tubulars and topside tanks. Other detrimental microorganism grow profusely around the wellbore region—in mud filter cake and the formation—blocking rock pores and reducing permeability; still others break down and render ineffective chemicals that are added to facilitate production operations and increase wellbore life.

On the other hand, good microorganisms are those helpful bacteria which, during their growth, produce useful compounds that improve oil recovery—for example, solvents, acids, gases, surfactants and biopolymers. It is these bacteria and their byproducts that can be used constructively in reservoirs. Petroleum microbiologists try to find ways of suppressing bad bacteria while encouraging growth of good microbes.



Electron micrograph of a biofilm inside rock. The blocking of pores by bacteria can clearly be seen.

The World of Petroleum Microbiology

Bacteria carry out all their life functions within a single cell. Nevertheless, their huge diversity ensures ubiquity. Bacteria are found virtually everywhere: in the air we breathe, the food we consume and on everything we touch; and they thrive in the most extreme habitats—hot springs, arid deserts, subterranean vents, aquifers, salty lakes and salt deposits. Microorganisms have a remarkable ability to survive adverse conditions and remain in a dormant state waiting for favorable growth conditions. Many microbiologists believe that this dormancy could last for thousands of years.

To date, most petroleum microbiological work has centered on waterflooded reservoirs that offer a cooled, oxygen-free, saline environment, which meets the environmental requirements of many different groups of bacteria. And bacteria certainly do grow in these conditions, thriving when nutrients—including reservoir chemicals or seawater—are available, and entering dormant states when food is scarce. Resuscitation from dormancy is rapid—perhaps taking two days after months of inactivity.

Most bacteria have a natural tendency to grow attached to rock surfaces rather than free-floating in the liquid phase. In a petroleum reservoir, bacteria may attach to the rock, start to grow and then produce exopolymers—sugars—that help them attach to each other and rock surfaces. Such growth is termed a biofilm and offers the advantages of protection from biocides while encouraging the bacteria to interact to best use nutrients and other resources (*above*).

Bacteria that are introduced to reservoirs through waterflooding will flow over preexisting biofilms; some bacteria will attach themselves to these biofilms and grow. From time to time, some bacteria detach from the biofilm and move with the liquid flow or by their own motility and colonize other areas deeper in the reservoir.

Complete analysis of all potential food sources supporting bacterial growth is still in progress. However, analysis of formation water from many reservoirs has demonstrated the presence of short-chain fatty acids—such as acetate, propionate and butyrate—that may be utilized by some bacteria to provide energy.

Possible locations of microorganisms. Active and dormant bacteria are found throughout the oil and gas production cycle, at and below the surface, on- and offshore, and in shallow zones as well as deep, hot, high-pressure reservoirs.

Biofilm-dwelling bacteria coating rock surfaces and pore spaces not only use external nutrients from formation fluids, but also utilize chemicals from other dead and dying parts of the biofilm by breaking them down with enzymes to release essential nutrients, which are then recycled. This process occurs to a significant degree in many biofilms, ensuring that energy sources entering, or already present in, a reservoir are used efficiently and economically several times over by many different opportunistic bacteria.

Environmental microbiologists have demonstrated that bacteria exist in—and may have originated from—the Earth's subsurface.[2] In carrying out this work, many problems were encountered obtaining subsurface fluid samples and rock cores that contain bacterial cells from the target environmental niche alone.

Drilling equipment carries chemical, mineralogical and biological material throughout the borehole, contaminating otherwise pristine environments and making it difficult for microbiologists to obtain genuine samples at a specific depth in sediments or rock cores. However, technology is now available to obtain cores in presterilized sleeves, sealed for examination in sterile conditions at surface. Methods for checking the integrity of these cores have also been developed—for example, fluorescent marker beads included in drilling muds can indicate contamination if they show up in the core.

There are several ways of determining the microbial content of cores. Direct observation of core material using microscopic techniques can show cells associated with rock pore spaces. Cell cultures from subsurface environments are possible by enriching portions of rock that have been crushed aseptically and then mixing these with liquid nutrient to see what grows. However, this method does not necessarily result in growth of representative organisms—merely those that could grow in the enriched media provided. Today, molecular techniques are employed to relate the genetic material found in recovered bacteria cells with well-documented organisms or with genetic material that is associated with specific, well-characterized functions.

Obtaining uncontaminated fluid samples at depth also poses problems, and much research and development have gone into devising equipment that will capture and hold separate sterile fluid samples from different depths. Extremely deep samples may require slow decompression to reduce the risk of physically damaging bacterial cells. There has been little evidence, however, in the scientific literature supporting the existence of genuinely barophilic organisms—those that actively require high pressure—so cultures of cells obtained from great depth need not be maintained at pressure.

One of the biggest issues facing subsurface sampling is the expense of drilling. Inevitably, petroleum reservoir microbiologists often have to be content with samples derived from produced fluids. These contain a mixture of oil, formation waters, and injection fluids plus all the added reservoir chemical treatments—many of which are used to mitigate the effects of microbial activity in the reservoir.

Introducing the Bad Guys

The most notorious villains on the reservoir scene are sulfate-reducing bacteria (SRB), which have relatively simple requirements for growth and energy generation—sulfate and carbon. Seawater contains about 2800 ppm sulfate and formation waters may contain up to 2000 ppm short-chain fatty acids.[3] Given suitable conditions, with no oxygen and favorable temperatures, the cocktail recipe is simple: inject seawater, and expect sulfide souring.

Although it has been known for many decades that SRB are active in shallow wells, the existence of significant bacterial populations in deep, hot, high-pressure oil formations was not considered until souring became economically significant. Today, the association of the onset of reservoir souring with commencement of seawater injection in previously "sweet" fields is all too apparent and is largely due to SRB activity.

As a group, reservoir SRB have a wide range of temperature tolerances, and their origin has been the subject of much debate. It is likely that thermophilic bacteria (tSRB)—those most active between 55 and 70°C [129 and 158°F] or higher—have always been present in the hot, deep subsurface environment, existing in porous rock matrices and maintaining viable populations using nutrients from deep aquifers and degraded hydrocarbons.

Work carried out by researchers at the Hatherly Laboratories, University of Exeter, England, demonstrated that living tSRB have been recovered from open North Sea waters at 10 to 16°C [50 to 60°F]. Thermophilic SRB are most likely brought to surface during production operations and introduced into the sea when separated fluids are dumped. These tSRB are extremely hardy and many of them are able to survive prolonged periods of starvation in seawater at both surface and reservoir temperatures. Given the resilience of these organisms, it is possible that they may subsequently be reinjected into another reservoir where they may also grow if conditions are favorable.

Starved SRB can exist by just surviving at a very low metabolic level, waiting for the right conditions in order to revitalize. During this dormancy, SRB tend to be smaller than their growing counterparts and may travel greater distances through the rock matrix pores during waterfloods. Starved SRB are less susceptible to standard reservoir biocide treatments than actively growing populations, making them particularly difficult to treat effectively. The consequences of flushing these bacteria to the surface during oil recovery and then later reintroducing them during waterflooding are potentially grave.

In cooler areas of the oil production process—such as surface equipment—the majority of SRB are mesophilic bacteria (mSRB) that prefer temperatures of 20 to 40°C [68 to 104°F]. Since they are not well

2. Long PE, Onstott TC, Fredrickson JK, Stevens TO, Gao G, Bjorstad BN, Boone, DR, Griffiths R, Hallett RB and Lorenz JC: "Origin of Subsurface Microorganisms: Evidence from a Volcanic Thermal Aureole," presented at the International Symposium on Subsurface Microbiology, Davos, Switzerland, September 15-21, 1996.
3. Biofilms in oil reservoirs frequently contain mixtures of different groups of bacteria, including SRB. Some of the organisms are involved in processes that complement the sulfate reduction activity of SRB by slowly reoxidizing the reduced sulfur products, thus completing the natural cycling of sulfur in the environment.

suited for long-term survival in deep formations and are often associated with corrosion processes occurring in topside facilities, the origin of this group of SRB is still being debated. The most likely source is seawater. With the advent of seawater injection to aid secondary recovery, it is likely that mSRB enter with the waterflood and attach either at injection wellheads or, if formation residence times are short, they are carried through the formation to production wellheads, where they again attach to the metal, creating corrosion cells and copious amounts of H_2S. Once established, these bacteria are difficult to eradicate since cells deep in the protective biofilm survive treatments with biocides that cannot penetrate the outer slime layers.

In addition to souring reservoirs, bacterial biofilms may also plug formations. As the biofilm increases in depth and maturity, it covers a greater surface area, bridging pore spaces and reducing fluid flow in and around rock pores. Deep in a rock matrix this can reduce waterflooding efficiency and divert flow. If this happens near injection inlets, it may have serious consequences, diverting the flood front away from the target zone.

Incoming seawater carries the sulfate necessary for SRB energy generation and low levels of carbon sources. Because the injection zone is the place where potential new nutrients enter the reservoir, it is also the area where most microbial growth is likely to be found. Injection profiles may quickly be disrupted in this way.

Chemicals, such as biocides, are periodically injected as slug doses in an intermittent treatment program. While these doses might inhibit bacterial growth at the injection well, chemical concentration is not maintained throughout the formation, and therefore some reservoir zones receive reduced levels of biocide, to which bacteria are not susceptible.

Reservoir managers also need to be aware of the ability of indigenous bacteria to utilize not only natural energy sources available in a formation, but also injected energy sources. Year after year, many production chemicals are pumped downhole on a continual basis, giving bacteria ample opportunity to adapt and possibly use some part of the reservoir treatment for nutrition. Furthermore, some chemicals—such as surfactants—act on rock surfaces, releasing attached organic material. If this material is oil, mobilization is good news. But if chemicals release part of the biofilm that may then travel deeper into the formation, reattach and grow, this is bad news.

Bacteria can also produce enzymes that are detrimental. These enzymes may degrade treating chemicals such as polymers on the surface. In this case, if a bactericide is used too late, it may kill only the bacteria, leaving the enzyme to wreak havoc in oil and gas producing operations.

Microbial Enhanced Oil Recovery Projects

Project	Mink Unit Pilot NIPER[1]	Phoenix Pilot NIPER	SE Vasser Vertz Sand Pilot University of Oklahoma	Phillips Petroleum Co.
Year Initiated	1987	1990	1991	1991
Oil Field	Delaware-Childers	Chelsea-Alluwe	SE Vasser Vertz Sand unit	North Burbank unit
Formation	Bartlesville sandstone	Bartlesville sandstone	Vertz sandstone	Burbank sandstone
Permeability, md	90	16	60 to 181	50
Salinity, %	<0.05%	2.9	11 to 19	10
Depth, m	200	122	550	884
Waterflood	Yes	Yes	Yes	Yes
Injection Wells	4 out of 21 treated	19	5 treated	1 treated
Producing Wells	15	47	19	4 active
Oil Viscosity, cp	7	6	2.9	3
Microorganisms Used	*Clostridium*, *Bacillus*	*Clostridium*, *Bacillus*	Indigenous	Indigenous
Microbial Products Produced	Surfactants, acids and gases	Surfactants, acids and gases	Gases and biomass	Biopolymer and biomass
Nutrients	Molasses (cane)	Molasses (cane)	Molasses and ammonium nitrate	N_2, phosphorus, carbon sequential injection —Phillips patent
Test Length	2.5 years	1.5 years	262 days	In progress
Shut-in	12 days	2 days	2 shut-ins (30 days and 14 days)	
Pre-MEOR[2] Oil Production	0.4 B/D per well	1 B/D per well	No oil production in pilot wells before nutrient injection	
Post-MEOR Oil Production	13% improvement in unit	1.2 B/D per well	83 barrels produced January 1992 to June 1992	
WOR[3]	WOR decreased 35% in wells near treated injectors			
Comments	WOR in off-pattern wells increased	Oil production improved by 20% through May 1993	Permeability modification was achieved; tertiary oil produced from watered out well	Permeability modification test has shown positive results in pressure fall-off tests

1. NIPER—National Institute for Petroleum and Energy Research 2. MEOR—Microbial Enhanced Oil Recovery 3. WOR—Water/Oil Ratio

Microbial Enhanced Oil Recovery Projects (continued)

Project	Institute of Microbiology, Russian Academy of Sciences and the Tatar Oil Research and Design Institute	Institute of Microbiology, Russian Academy of Sciences and the Tatar Oil Research and Design Institute	Institute of Microbiology, Russian Academy of Sciences and the Tatar Oil Research and Design Institute	USSR
Year Initiated	1987	1988	1988	1982
Oil Field	Romashkino field, Sarmanovskaya area	Romashkino field, Zay-Karatayskaya area	Romashkino field, Aznakaevskaya area	Bondyuzhskoe
Formation				Upper Devonian
Permeability, md	500	500	500	500
Salinity, %	0.25 to 4.0	0.25 to 4.0	0.25 to 4.0	16
Depth, m	1500 to 1700	1500 to 1700	1500 to 1700	1500 to 1700
Waterflood	Yes	Yes	Yes	Yes
Injection Wells	3	1	2	1
Production Wells	6	2	5	6
Oil Viscosity, cp				
Microorganisms Used	Indigenous	Indigenous	Indigenous	
Microbial Products Produced	Surfactants, acids and gases	Surfactants, acids and gases	Surfactants, acids and gases	Methane
Nutrients	Nitrogen, oxygen and phosphorus	Nitrogen, oxygen and phosphorus	Nitrogen, oxygen and phosphorus	
Test Length				36 months
Shut-in				
Pre-MEOR[2] Oil Production				
Post-MEOR Oil Production	106 B/D increase	33 B/D increase	166 B/D increase	
WOR[3]	85%	40%	95%	
Comments	43% increase	10% increase	46% increase	Oil >20 to 100% increase, water <20 to 30% increase

2. MEOR—Microbial Enhanced Oil Recovery   3. WOR—Water/Oil Ratio

Project	Institute of Biology of the Romanian Academy	Institute of Biology of the Romanian Academy	Institute of Biology of the Romanian Academy	Institute of Biology of the Romanian Academy
Year Initiated	1987	1990	1989	1990
Oil Field	Caldararu	Caldararu	Bragadiru	Bragadiru
Formation				
Permeability, md	245 to 248	245 to 248	150 to 300	150 to 300
Salinity, %	0.4 to 0.45	0.4 to 0.45	0.3 to 0.06	0.3 to 0.06
Depth, m	750 to 800	750 to 800	780	780
Waterflood	Yes	Yes	Yes	Yes
Injection Wells	2	1	1 treated	1 treated
Production. Wells				
Oil Viscosity, cp	26	26	9	9
Microorganisms Used	*Clostridium*, *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Mycobacterium*, *Micrococcus*, *Enterobacteriaceae*	*Clostridium*, *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Mycobacterium*, *Micrococcus*, *Enterobacteriaceae*	*Clostridium*, *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Mycobacterium*, *Micrococcus*, *Enterobacteriaceae*	*Clostridium*, *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Mycobacterium*, *Micrococcus*, *Enterobacteriaceae*
Microbial Products Produced	Surfactants, gases, acids, solvents and biopolymers	Surfactants, gases, acids, solvents and biopolymers	Surfactants, gases, acids, solvents and biopolymers	Surfactants, gases, acids, solvents and biopolymers
Nutrients	Molasses	Molasses	Molasses	Molasses
Test Length	4 years	4 years	4 years	4 years
Shut-in		2 to 3 weeks		2 to 3 weeks
Pre-MEOR[2] Oil Production	2.2 B/D per well	0.7 B/D per well	9.5 B/D per well	1.5 B/D per well
Post-MEOR Oil Production	9.6 B/D per well	2.2 B/D per well	21.5 B/D per well	7.4 B/D per well
WOR[3]				
Comments	Microbial flooding recovery	Cyclic microbial recovery (wellbore cleanup)	Microbial flooding recovery	Cyclic microbial recovery (wellbore cleanup)

2. MEOR—Microbial Enhanced Oil Recovery   3. WOR—Water/Oil Ratio

There Are Also Good Guys

No one should doubt the usefulness of bacteria. They yield many beneficial products, including pharmaceuticals (such as antibiotics), food and drink (cheese and beer), and they degrade human pollution. They are also responsible for nutrient cycling and soil fertility. In reservoirs, some indigenous groups of bacteria use nutrients that are present to produce byproducts that may enhance oil recovery. During growth, bacteria generate acids, surfactants, solvents, biopolymers and gases, all of which are commonly injected into reservoirs as chemicals to improve oil and gas recovery.

The types of bacteria used to improve oil recovery are frequently isolated from reservoirs in the first place. When reintroduced into the reservoir, it is assumed that these bacteria are best able to survive and outcompete other bacteria present. In some cases, specific nutrients may be pumped into the reservoir to support the bacteria so that their growth and byproducts may improve oil mobility. The introduction of bacteria generally follows initial laboratory investigation to optimize microbial growth and indicate the most suitable food nutrient package. The bacteria are then transported to the field site and injected into the reservoir.

With some applications, the nutrients are injected together with the bacteria so growth can begin quickly. However, with other field applications, it is desirable to drive the bacteria deeper into the formation before growth commences so the nutrients are introduced after injection of the bacteria, and microbial treatment may be followed by a shut-in period to allow the bacteria to grow before the reservoir is reopened. There are believed to be dozens of different types of bacteria in most reservoirs, and efforts are centered on identifying the desirable bacterium and determining a nutrient for it. In some proposed applications, only a nutrient targeted at desirable in-situ bacteria is injected.

Many projects that harness bacteria have been carried out around the world (see "Microbial Enhanced Oil Recovery Projects," *page 21, previous page and below*). For instance, surfactant-producing bacteria may be used in a microbial enhanced oil recovery (MEOR) project to reduce interfacial tensions between the oil and rock, and the aqueous phase, releasing oil from capillary pressure. The introduction of surfactant-producing bacteria or stimulation of indigenous bacteria that may permeate and grow throughout the reservoir is an attractive MEOR strategy, offering more extensive coverage and better cost-effectiveness than traditional injection of chemical surfactants. The bacterial production of surfactants has been successfully demonstrated in numerous field applications from Russia to the UK and the USA.

Gaseous waste from bacterial growth includes carbon dioxide, methane and hydrogen. The encouragement of bacterial growth and subsequent gas production increases reservoir pressure and enlivens dead oil. Carbon dioxide also dissolves in oil, aiding its physical displacement. The bacterial production of gases has been used in field applications in Bulgaria, Poland and the Czech Republic.

Acids produced by bacteria—such as acetic and lactic acid—assist oil recovery by dissolving carbonate rocks, increasing porosity and permeability. This has been demonstrated in simulated reservoir conditions and within the reservoir, although, like many of the microbial techniques, it is frequently a combination of methods, for example both acid and gas production, that assists recovery.[4]

Project	Alpha Environmental	Archaeus Technology Group Limited, United Kingdom	Research Institute of Exploration and Development, Daqing Petroleum Administration Bureau, Hailung Jang, China
Year Initiated	1987	1991	1990
Oil Field	West Geff	Lidsey field, southern England	Daqing Oil field
Formation	Aux Vases sandstone		
Permeability, md	5 to 165	0.62 to 4.38	405 to 932
Salinity, %			0.7
Depth, m	799	1173	1151 to 1171
Waterflood	Yes	No	
Injection Wells	2	1	2 treated
Production Wells	7	1	2 used for test
Oil Viscosity, cp			58.9
Microorganisms Used	Mixed Culture	Acetic acid producers	*Bacillus licheniformis*, *Pseudomonas aeruginosa*, *Xanthomonas campestris*, 5GA (similar to *Bacteroides*)
Microbial Products Produced		Acids	Acids, organic solvents, gases and alcohols
Nutrients	Catalyst, fertilizer	Carbohydrates	Molasses, sugar, crude oil and trace minerals
Test Length	12 months	30 days	18 months
Shut-in		7 days	40 and 64 days
Pre-MEOR[2] Oil Production	10 to 12 B/D	40 B/D per well	26 and 56 B/D per well
Post-MEOR Oil Production		50 to 60 B/D per well	41 and 126 to 185 B/D per well
WOR[3]		45% water cut	
Comments	40% increase in oil production	Carbonate reservoir, microbial hydraulic acid fracturing	Single-well stimulation appears to be successful

2. MEOR—Microbial Enhanced Oil Recovery 3. WOR—Water/Oil Ratio

Bacteria samples, before (left) **and after** (right) **producing exopolymer.**

In the laboratory, the bacterium *Clostridium tyrobutyricum,* isolated from a reservoir and growing anaerobically in a medium containing 6% molasses, produces high levels of organic acids—11,400 mg/L butyric acid with 3200 mg/L ethanol and butanol—plus 350 mg/L of carbon dioxide (80%) and hydrogen (20%). These products can suppress SRB growth and enhance methane-generating bacteria—methanogens.[5]

In a field study in the Russian Romashkino reservoir of porous carbonate rock, 107 cells per ml of *Clostridium tyrobutyricum* were inoculated into the reservoir, which had been primed with 2% by weight of molasses fed through the injector wells, gradually increasing the molasses concentration. Metabolic products suppressed the growth of SRB, and high levels of methane were produced. The well was shut in for seven months and on recommencing injection, the fluids were switched gradually from waterflood to molasses solution. Generation of methane, carbon dioxide and hydrogen increased the gas/oil ratio from about 4 m^3 gas/m^3 oil at the start to 8.5 m^3 gas/m^3 oil. Over two years, the rate of oil production was virtually doubled.

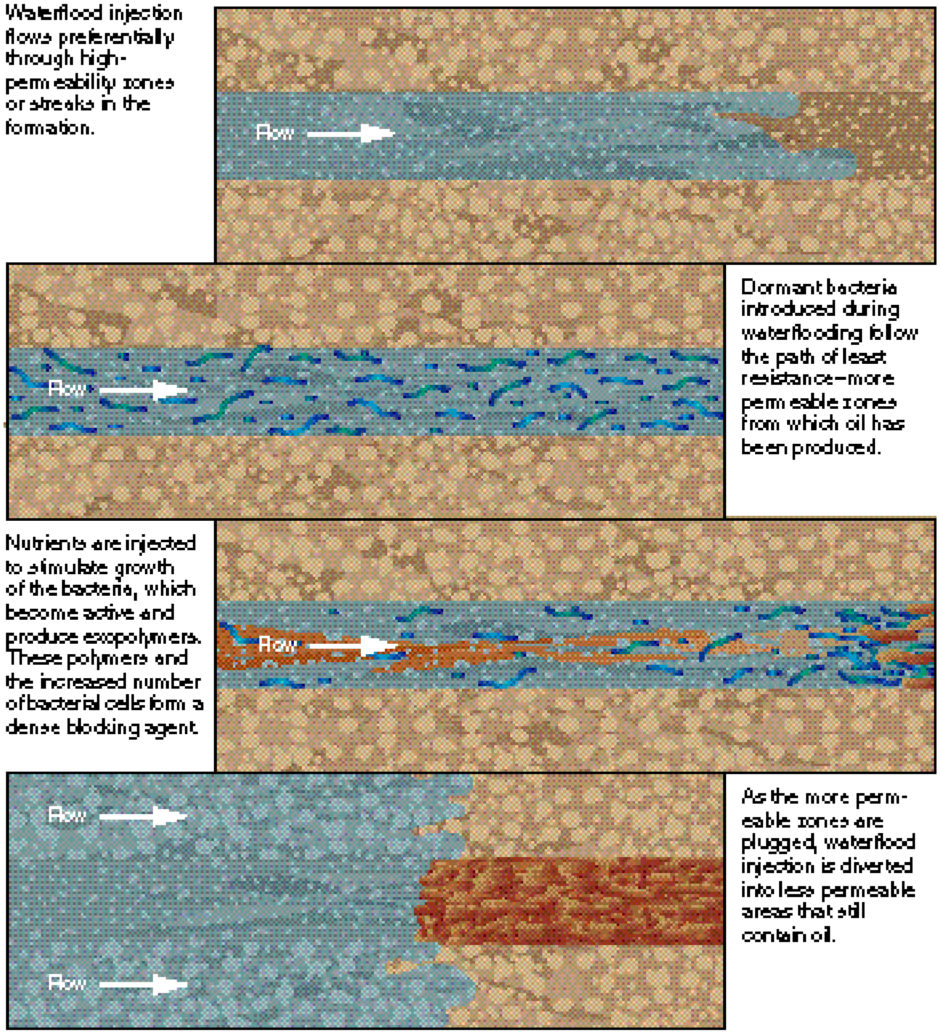
Additionally, some bacteria produce copious quantities of exopolymer during growth (*above*). This combination of an increase in the number of bacterial cells and production of these polymers can provide a dense physical blocking agent or plug that can effectively impede flow within reservoirs.

This effect may be employed positively. When exopolymer-producing bacteria are introduced into the reservoir during waterflooding, they follow the path of least resistance and are carried to the highest permeability zones where little additional oil remains. Some of the bacteria injected into the reservoir will attach to the high-permeability rock. Then, when a suitable nutrient is injected, the bacteria produces exopolymers that block this zone. Thus, bacteria may be used as a cost-effective, environmentally friendly, blocking agent, which subsequently diverts the waterflood into less permeable zones that still contain oil, but no blocking bacteria (*next page*). In a similar manner, bacteria that produce, or behave as, surfactants can cause emulsions in watered-out zones, improving sweep and recovery efficiency.

When microbial flow diversion is considered for a reservoir, the candidate bacteria may either be extracted from produced fluids or be specific exopolymer producers that are known to survive at the particular reservoir temperatures and conditions. Work at the University of Exeter has resulted in several bacteria cultures that may be used to divert waterflooding. For this microbiological method—Selectively Induced Flow Technique (SIFT)—to work optimally, however, reservoir data currently not readily available are required.

Ideally, a sterile sample of fluid is needed from each reservoir zone to perform the full range of analyses for anions, cations and hydrocarbon derivatives to discover what the potential nutrients for the bacteria might be. The products of bacterial activity such as polymers, acids and gases should also be detectable. Full details of key parameters—for example pH, redox, dissolved gases, temperature, salinity, fluid flow rates, pressure, and geology—are needed for each zone to help determine how bacteria will behave downhole.

4. Moses V, Brown BJ, Burton CC, Gralla DS and Cornelius C: "Microbial Hydraulic Acid Fracturing," in *Proceedings of the 1992 US Department of Energy International Conference on Microbial Enhancement of Oil Recovery*, Upton, New York, USA, September 7-11, 1992: 207-229.
5. Wagner M, Lungerhausen D, Murtada H and Rosenthal G: "Development and Application of a New Biotechnology of the Molasses In-Situ Method: Detailed Evaluation for Selected Wells In the Romashkino Carbonate Reservoir," in *Proceedings of the 5th US Department of Energy International Conference on Microbial Enhanced Oil Recovery and Related Technology for Solving Environmental Problems*, Dallas, Texas, USA, September 11-14, 1995: 153-173.



□**Microbial flow diversion scheme.**

Future Reservoir Bacteria "Farming"

There are other potential good guys—bacteria that help control SRB. The SRB in reservoirs do not live alone, but exist in communities with other groups of bacteria. Many of these groups interact by providing growth requirements for their neighbors, with some groups even living off the waste of others. Looking to the future, it is possible to envisage a situation whereby beneficial bacteria are farmed to control detrimental bacteria through their growth and activities.

Research by Mike McInerney and colleagues at the University of Oklahoma, Norman, USA, has demonstrated that a bacterium called *Thiobacillus* can mitigate the growth effects of some SRB. Their studies showed that as the SRB grew, they produced hydrogen sulfide, but the *Thiobacillus* kept sulfide levels low by converting it to sulfate. For this scheme to work, nitrate must be added to the reservoir. In this manner it is possible to control reservoir souring by manipulating the ecology of the bacteria residing there. This promising technology has been studied only in the laboratory at temperatures no greater than 30°C [86°F]. It would be necessary to ascertain whether this technique would be successful at the higher temperatures and more extreme conditions found in hydrocarbon reservoirs.

Given time, all microbial communities will adapt to the prevailing conditions, making efficient use of all available energy sources.[6] An open system, such as an oil reservoir, is in a state of constant flux with different populations of bacteria dominating the zones that most suit their energy requirements, and temperature and chemical preferences. It is impossible to achieve a state of sterility within a reservoir. However, given good data collection and management practices, it will be possible to create a balance that enhances production and economical reservoir management. It is this promise that is expanding the role of microbiologists in reservoir management.

—CF

6. For additional information on these topics:

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