Chapter 1

Introduction

1-1. Purpose

a. This engineer pamphlet (EP) provides geotechnical, chemical, microbial, and operational guidance for U.S. Army Corps of Engineers (USACE) elements in identifying aspects of ground water extraction wells, injection wells, and treatment systems that have led to failures at contaminated ground water sites. The nature of these systems can involve extensive biologically and chemically induced fouling. This fouling often becomes magnified by the mechanisms used to manage the contaminants within the ground water systems. These guidelines are a compilation of specific problems that have been identified in each of several categories, along with a technical discussion of their diagnoses and solutions.

b. This EP provides the multidisciplinary guidance needed to:

(1) Sustain the performance of ground water remediation systems

(2) Apply cost-effective maintenance management that will prevent or at least delay the need for costly and substantial, radical rehabilitation of these systems as long as possible.

c. This EP will provide:

(1) Background and rationale for well problems.

(2) Demonstrated prevention and remedial methods for these wells.

(3) Specific guidance practices for applying solutions.

d. This background and associated recommendations are based on the experiences and applied research conducted by USACE, its contractors, and other experienced parties.

e. The USACE and the programs it oversees in ground water rehabilitation have the responsibility to ensure that the project’s mission, to clean up impacted ground water as defined by risk analysis or legal maximum contaminant levels (MCL), is carried out where this is technically feasible. Extraction and injection well systems are essential integral parts of these efforts on many sites. It is the management’s responsibility to ensure that well systems installed continue to function at the optimal level.

1-2. Applicability

This EP applies to all USACE Commands having Civil Works and/or Military Programs HTRW project responsibilities.

1-3. References

Required and related publications are listed in Appendix A.

1-4. Distribution Statement

Approved for public release; distribution is unlimited.

1-5. Safety

Personal safety is the top priority in any operations on USACE sites. The guidance in this EPis provided with safety in mind. However, users of this pamphlet are responsible for following the requirements of EM 385-1-1 and ER 385-1-92.

1-6. Scope and Application

a. Scope. This EP is concerned with the rehabilitation of ground water extraction and/or injection wells on ground water remediation sites. The EP addresses the rehabilitation of these systems, that is, the actions taken to restore any well, or group of wells after there has been a substantial loss of performance or water quality problems associated with well deterioration. Also, it has to be recognized that monitoring wells (for either HTRW or preventive monitoring) may also become impacted and may no longer be able to provide reliable samples for water quality analysis. The scope of this EP is limited to the impact of plugging and clogging events and the methods of rehabilitation.

(1) Performance. This EP will emphasize the role of rehabilitation (based on good quality data and practice) in cleaning and restoring extraction and/or injection wells to an acceptable performance and in extending the life span of the project. It is assumed that wells on contaminated ground water sites will operate under conditions that often promote rapid well performance deterioration and they need to be to be monitored with a program designed to prevent problems before total failure occurs.

(2) Effects of past design and maintenance. The EPalso addresses situations where installation operators are required to maintain well systems that were not optimally designed in the first place. In studying the operating challenges of such systems, it has become apparent that some rehabilitation practices for HTRW site well systems are ineffective, and obsolete processes are being followed that do not reflect modern understanding of microbial and geochemical processes. This EP is intended to provide guidance to update rehabilitation processes, taking into consideration modern understandings to improve overall well effectiveness.

b. Application. The specific application of and adherence to these guidelines must be tailored to each project function, the contaminants of concern, the adopted treatment solution, local geohydrologic properties, geotechnical judgment, available resources, applicable regulatory requirements, policy and guidance, public concerns, and remediation goals.

1-7. Terminology

Communication between regulatory, oversight, owner, and contractor personnel involved in the rehabilitation of an HTRW site is important both before and during rehabilitation of the site. Communication is complicated by the involvement of numerous technical disciplines and regulatory agencies, and it is imperative that the descriptive language used during discussions be compatible. Likewise, the practices of well design, construction, and maintenance and rehabilitation also have specific terminology and usages. This EP promotes an interdisciplinary approach to well-system rehabilitation that works to enhance system performance. The reader is assumed to be a technically competent person who may not be familiar with all specific terminology usages, but has a general but not thorough knowledge of ground water and well-system construction. Therefore, a wide range of definitions will be supplied to promote clarity.

(1) EM 1110-1-4000 provides definitions for terms in the following topical areas: drilling and well installation/ drilling plan, field activity (FA) guide, field drilling organization (FDO), geotechnical data quality management, HTRW identification, well redevelopment / rehabilitation guidelines, screened interval determination, and also site safety and health plan (SSHP).

(2) Additional industry (e.g., National Groundwater Association, American Water Works Association (AWWA) Research Foundation, American Society for Testing and Materials (ASTM)) and international sources of definitions were used in preparation of this pamphlet. Several relevant documents provide lists of definitions specific to the O&M of wells, particularly Borch, Smith, and Noble (1993), Cullimore (1993), Driscoll (1986), Helweg, Scott, and Scalmanini (1983),

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Smith (1992), and Alford and Cullimore (1999). ASTM Standard Guides cited herein (e.g., D 5978, Standard Guide for Maintenance and Rehabilitation of Ground-Water Monitoring Wells) also provide definitions of specific terms used.

(3) Some technical terms have come to be commonly used in specific ways in well maintenance activities and are frequently used in this pamphlet. Most of these relate to causes of problems and are listed in the glossary (Appendix B) along with other relevant terms.

1-8 Basis

This EP has been designed to allow the user to develop a suitable protocol for the rehabilitation of extraction and injection wells at HTRW sites under the management of the USACE. There are several factors that impact the selection of the most appropriate rehabilitation option. This selection will be influenced by many factors that would relate not only to the ground water containment and remediation involving the wells but also the local environmental conditions at the site. As a result of these various parameters no one standard treatment can be advocated for all of these wells on contaminated ground water sites. This EPaddresses the potential form of compromise that can occur in these wells and then the management practices that can be effectively used to achieve a successful rehabilitation.

Chapter 2

Problem Delineation

2-1 Background Issues

Sites that require ground water remediation consist of three basic systems; a ground water extraction system, a treatment facility and a discharge system. Typically the extraction system consists of one or more wells (vertical or horizontal) while the discharge system is comprised of wells, trenches or discharge to a surface water body. The treatment plants are not discussed in this EP except to indicate how they can fundamentally change the chemistry of the discharge water and the effects this might have on the injection wells. Injection and extraction wells form one of the major methods through which contamination can be contained within the impacted site and remediated through the removal of the specific chemicals of concern. In essence this approach interrupts the normal ground water flows by extracting ground water usually to the surface where a treatment is performed as a part of the remediation process. Ground water that passes through the process can be injected back into the ground. The systems have on the whole one or two goals: 1) to contain the contaminated plume within a specific geographical boundary or 2) to clean up the contaminated ground water to an acceptable standard.

Understandably a large part of the focus is on hydraulic control of the plume and ensuring that the discharge (to a well or surface water) meets the required standards. In this environment the wells are often not considered as part of the operations and maintenance of the treatment plant. However, factors such as plugging or clogging of the porous media through which the treated ground water cycles during the treatment process may not have had the same priority for attention.

As a result, the long-term impacts that clogging and/or plugging may have on the efficiency of the treatment facility have not been so clearly addressed. It is a prime objective in this EP to set out the guidelines to be employed to monitor the hydraulic efficiency of wells. The plant operators often do not understand the factors that impact well performance and the significance of the data gathered to monitor well performance. The issues of O & M practices for wells are captured in EP 1110-1-27 (Operation and Maintenance of Extraction and Injection Wells at HTRW Sites).

Even sites that have functional O & M programs will have a general well deterioration with time and the wells will have to be rehabilitated and redeveloped periodically over the life of the treatment system. More often the sites that have the need to rehabilitate wells have little or no proactive maintenance of the wells. The site manager or the plant operator will call in a contractor on an ad hoc basis to find a solution to the performance problems. In many cases by the time that the wells show significant deterioration, the biological or chemical plugging is far along in stages of development and requires radical rehabilitation becomes a probable outcome.

2-2 Factors influencing plugging and clogging

The next section addresses the basic factors that can influence the fouling by some combination of plugging and clogging.

Responses to performance failures by these wells operate at two levels involving either (1) a radical rehabilitation (where the losses are very significant) or (2) a preventative maintenance (where losses are marginal but threatening). The latter case is addressed in EP 1110-1-27.

a. Injection and extraction wells simply inject water into the ground or extract water from the ground. For many different reasons these wells can fail to perform at the expected levels for which they were designed. Traditionally it was thought that much of this failure was due to structural and/or geochemical factors. Today we recognize that most of problems are the result of microbial activity and associated chemical precipitation. A functional diagram of the process through which the wells are operated is given in Figure 2-1. The prime objective is to curtail releases of chemicals of concern to the environment. In some instances, water is extracted from the ground and then injected into the ground to help maintain hydraulic control of the plume.

b. We can classify the methods that reestablish the operating condition of wells under the general headings of redevelopment and rehabilitation. Redevelopment is the term used when it is thought that the original development of the well was not thorough enough. Consequently the well began to fail because of this poor development and so a redevelopment is applied to recover the well. Often biofouling is involved in this failure. Rehabilitation is the term used to describe a condition where the well has been subjected to severe post-development fouling and that the treatment to be applied must return the well to its original state followed by redevelopment to meet its designed criteria.

c. Sustainability is another term that recently has become established in the field of well maintenance. The concept requires accepting that the well is inevitably going to become subject to biofouling and geochemical challenges that to some extent can be predicted and can be treated successfully.The application of preventative maintenance to control these conditions can extend the life of the well and therefore make it sustainable. If the well is monitored (to determine the state of geochemical clogging and biological fouling) and treated periodically to control the occurrence of these events, then the life span of the well can be significantly extended.

d. Only in the last fifteen years that it has been recognized that these ground water remediation sites are subjected to a range of microbiological challenges that can both help and hinder the planned tasks. There are two major impacts. One of these receives an increasing amount of attention since the remediation process can be enhanced by these microbial activities. Such increases may relate to a natural attenuation through which the natural microflora adapts to cause degradation, accumulation and/or occlusion (plugging) of the ground water media. These events (Figure 2-2) could act to reduce (by biodegradation), concentrate (by bioaccumulation) or restrict movement (by bioplugging). This pamphlet addresses the practical aspects of rehabilitating wells impacted by undesirable side effects of the impact of the contaminants.

e. This pamphlet provides some of the present rehabilitation processes and the technologies involved for wells at ground water remediation sites. It is recognized that this area of technology is in a state of dynamic flux and, consequently, it can be expected that new technologies and approaches will be developed beyond those discussed in the pamphlet. A universal problem still to be fully recognized is the nature and effects of the biological activity that occurs during the

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IN-SITU
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Figure 2-1. Diagrammatic presentation is shown of the common ground water cycles (arrows) to control contaminants (C) using above-ground (upper diagram) and *in-situ* (lower diagram) treatment. Ground water cycles out of the ground level (GL) through extraction wells (E) and returns through injection wells (I). In the upper diagram, the contaminated ground water is removed (red arrows) in a treatment facility (TF). Either air stripping (upper arrow), sorption and accumulation (left arrow) or degradation (right arrow) may then remove the contaminant. The treated ground water is then injected back into the ground to pass through the contaminated zone again and recover further contaminants. The in-situ (lower) diagram illustrates the application of a treatment (shown as nutrients as green arrows and N) that is injected into the ground water and impact on the contaminants causing degradation.

2-2

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extraction and injection operations. This biological activity is primarily attached to the surfaces, occupying the voids in the porous media, growing as biofilms (Figure 2-3) and interfering in many ways with the designed operation of the wells.

2-3 Rehabilitation Challenges for Remediation Wells

For the setting where contaminated ground water is extracted, treated and then injected back into the formation, the **method** of treatment becomes critical to the impact that the injected product water will have upon its return to the formation.

It can be expected that the treatment will significantly change at least some of the biological, chemical and physical characteristics of the water in a manner that could cause a reactive form of fouling to occur around the injection wells. For example, elevating the oxidation-reduction potential (ORP) from a reductive to an oxidative state during the above-ground treatment would be likely to cause, upon injection, an intense biofouling to build up around the reaction front where the ORP reverses again from an oxidative to a reductive state. Other changes in pH or chemistry could also lead to chemical precipitation in the reaction zone where the treated water and the native ground water mix.

In the circumstances where there is an in-situ treatment between the extraction and the injection wells it can normally be expected to involve some form of in-ground covert or applied treatment. The net effect would again be changes in the localized environment that could lead to some form of fouling. For example, the injection of nutrients, gases, acids, bases and redox modifiers would all tend to have impacts on the *in-situ* biological activity. There are, however, fundamental differences when the wells are placed vertically or horizontally.

FORMS OF BIOLOGICAL IMPACTS IN WELLS

C

D

F

E

C

C C

C C
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C
BIOACCUMULATION
BIODEGRADATION
C
C
C
C
C
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C
BIOPLUGGING
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C

Figure 2-2 Diagrammatic presentation of the impact of biodegradation (upper), bioaccumulation (middle) and bioplugging (lower) on the movement of a contaminant (C) through ground water (arrows). Biodegradation converts the contaminant to daughter products (displayed as D, E and F), bioaccumulation causes the contaminant to concentrate within the fouled zone (shaded area) while bioplugging (P) prevents ground water flow causing the contaminant to concentrate in front of the plugged zone.

Vertical wells will have a relatively small lateral area of impact but would extend deeper into the formation. The net effect of this would be for the zone of influence to be a vertical cylinder around the well distorted to some extent by the pathways of ground water flow. Horizontal wells have the reverse characteristics in which in which there would be a large lateral area of impact over a relatively short vertical profile (Figure 2-4). These differences have very major potential impacts on the site locations where biofouling will occur. Rehabilitation of horizontal wells is therefore likely to involve a need to penetrate the media around the well to much greater distances but over a relatively shallow vertical profile. For vertical wells, the biofouling is likely to be tighter around the wells but with a deeper vertical profile. Consequently, very fundamental decisions as to what the manner for rehabilitating of a well will be affected by the well's configuration (either vertical or horizontal).

Figure 2-3. Schematic presentation shows the growth and form of a biofilm. The upper diagram shows how a cell (C) becomes attracted to a surface so that the cell attaches (CA). Cell will now reproduce to form a colonial growth (COL). This growth expands on the surface as a bacterial slime (BS) within which various bacterial species grow together in various communities.

Hydraulic conduits pass through this slime to create water pathways (WP) through the biofilm along hydraulic conduits (HC).
The slime forms the site for accumulating various inorganic as well as organic materials.

2-4

Figure 2-4. Presentation of theoretical extension of biofouling around a vertical well (left as VW) and twinned horizontal wells (right as HW) in which the near- or at- surface lateral fouling potential is displayed at ground level (GL) for the vertical (GFPV) and the horizontal (GFPH) well. The extension of the fouling at depth is displayed around the wells (vertical as DFPV, horizontal as DFPH). Shaded regions reflect the theoretical interpretation of the relative scale and density of the fouling associated with the wells.

SURFACE
COL
WP
WP
HC
HC

C
CA
BS
WP

SURFACE
VERTICALWELL
GL
GL
GL
GFPV
DFPV
DFPH
D
E
P
T
H
DE
P
T
H
DE
PTH
GFPH
HORIZONTALWELL

HBI

It is often too late to rehabilitate a well when you first see a significant change in the pumping rate. For example, consider that many horizontal wells have a very significant excess capacity built into design. Therefore a 500 foot long with an eight inch diameter screen in sand mat be capable of producing 1000 GPM, but it is only pumped at 20 GPM that is only 2% of the total capacity of the well. Therefore over 90% of the flow paths would have to become clogged before the water production of the well is affected. Anytime more than 50% of the pores are blocked off then it is difficult, or impossible, to recover the original well hydraulics.

2-4. Causes of Well Problems

a. Well problems can be categorized into four broad problem areas:

- Structural or mechanical failure due to natural stresses exceeding the designed capacity of the equipment;
- Clogging due to geochemical impacts dominated by physical and/or chemical factors
- Plugging due to the infestation of the well and/or the surrounding environment with excessive levels of biological activity.
- Corrosion related to microbial activity impacting screen integrity

Corrosion is lumped in with plugging since, on most occasions, the corrosive processes follow the generation of a biofilm that would commonly be contributing to a biological plugging process.

b. Structural or mechanical failures exist either because of a failure to design and/or install the wells properly, or because the wells were impacted by some shifting in the soils and/or the geological strata in the region. This group of problems is most likely to be well-specific event and not involve either clogging or plugging. Improper development, poor design of filter packs or screens or over pumping can cause physical clogging of extraction wells. Problems in the treatment processes can cause physical clogging of injection wells.

c. Geochemical clogging is driven by a mixture of materials created by chemical interactions that occur in the void spaces around the well and by materials such as clays, silts and sands that clog the voids as they move towards the well with the ground water flow. It was historically thought that clogging was the major cause of well fouling and that it commonly involved an oxidative precipitation of chemicals, in particular ferric iron and carbonates, into insoluble accumulates. Changes in physical conditions in the well caused by turbulence often affects CO_2 and/or O_2 leading to mineral precipitation. Sand, silts and clays were thought to accumulate to cause the clogging. Presently it is recognized that many events previously characterized as geochemical clogging have been recognized as biologically driven plugging events.

d. Biological plugging can start with the initial growth of biofilms at sites where the growth restricts ground water into the borehole. This initial growth matures and hardens through the process of bioaccumulation particularly of iron and other metallic cations, and through the synthesis of crystalline structures usually based on carbonates. At the same time as this maturation occurs, there is an entrapment of clays, silts and sands that add bulk to the volume and the mass. This entrapment then increases the losses in ground water flow through the infested region.

e. Treatment and successful rehabilitation involves applying a treatment that removes the clogged or plugged regions of any biofilms, accumulates, and trapped materials so that the void volume becomes fully available for ground water flow.

This chapter examines the data that can determine whether the well is impacted by some form of physical well failure, geochemical clogging or biological plugging. Interpretation of the baseline data, the historical data (see chapter 4) and the observed impact data (chapter 5) leads to development of an effective remediation treatment strategy.

2-5 Pump Test Data

The original performance of the extraction / injection wells once developed represents the ability of the wells to perform. Data relating to this original performance therefore gives the optimal performance characteristics for each well.

Over time this performance can become compromised by a combination of geochemical, biological and mechanical events.

To attempt rehabilitation therefore it is essential to have a clear goal to return the well to its original specifications. Therefore it is important to have at hand not only the original pump test data but also any subsequent test data to determine the manner

in which the well has been failing. Failure may also be linked to mechanical problems and so all equipment pamphlets and specifications need to be kept at-hand for reference purposes.

2-6. Extraction versus Injection Wells: Differences

a. The two types of wells are broadly grouped as extraction and injection wells. There are some elementary differences in the operation of these two types of wells even though each have similar structures and penetrate from the surface into, commonly, a saturated part of the ground water that may, or may not, be in the zone impacted by the contamination event.

Each of these two types of wells has a very different impact on the environment and the form, function and nature of the microbial events that will, almost inevitably, cluster around the wells.

b. Extraction wells resemble the typical water well in that the fluids are removed, commonly by pumping, from the surrounding ground water systems. These fluids may be comprised of mixtures of the contaminant of concern and the diluting ground water. The contaminants may be present as a distinctive layer (usually floating on the water), an emulsion, or as biocolloidal structures dispersed or dissolved in the water. Pumping will affect the movement of the contaminants depending upon the hydraulic movement through the aquifer, any pack material, and screen slots. Once in the well, the contaminants must be pumped out of the well via the pump screens, through the impellers and finally out through a collection pipe. This hydraulic movement may bypass any floating contaminant and will reflect the chemistry and biology of the ground water exiting the more porous layers in the aquifer.

c. Along this hydraulic flow channel into the extraction well, a series of environments are created that generally shift from a reductive to an oxidative nature due to the impact of the contaminant as it moves towards the well. It is at these sites that a number of microbial events are created in sequence. One prime factor inherent in these events is that biofilms are generated and attach to the surfaces of the porous media and begin to occupy an increasing part of the void volume in that porous medium. The net effect is that the biofilms grow within the void volume leaving fewer voids available for ground water flow. Atypical consequence of the biofilms is reduced hydraulic conductivity and a loss of specific capacity in the extraction well (Figure 2-5).

d. As the contaminated ground water moves towards the extraction well, there are a variety of microbial events that occur in sequence along the reduction-oxidation gradient. Their impacts are addressed in Section 2-4 and 2-5 and involve a full range of effects from partial to complete biodegradation to bioaccumulation and relocation. It should be noted that monitoring and extraction wells could suffer from similar forms of biofouling. In either event, the occurrence of this biofouling can mean that samples taken from ground water in an extraction or monitoring well may not necessarily reflect the true level of contaminants found within groundwater approaching the well. Physiochemical changes in the well bore can induce rapid geochemical precipitation if the ground water is nearly saturated with carbonates or other salts. Injection wells are usually used to return treated ground water to the aquifer. The characteristics of this ground water are changed from the original ground water as a result of the treatment. These changes are likely to be radical shifts in the redox (ORP) potential particularly if the treatment involved some form of aerated and/or oxidative processes. It is also likely that there would have been some chemical additives aimed at either stimulating the desired microbial activity or removing the undesirable chemicals from the ground water. As a result, injection wells create a very different environment in the recharged zone around the well. It can commonly be expected that there would be an enhanced level of microbial activity in, and around, an injection well (Figure 2-6) as a result of the stimulation of biofilm formation and microbial activities. The net effect of this form of biofouling would be increased resistance to the injected flows resulting in increased power demands and higher pressures required to meet the specified requirements for the rates of injection.

f. Extraction wells differ from injection wells primarily in the nature of the focal sites of biofouling. Extraction wells tend to create a gradually increasing gradient of microbial activity and biofouling problems moving towards the well.
On the other hand injection wells can cause radically localized microbial activity depending upon the nature of the treated

ground water returned into the ground. The extraction wells because of radial flow geometry concentrate more and more water and contaminants in an ever-decreasing cylinder as the ground water approaches the well bore. On the other hand, the flow in the injection well starts at the well bore surface assuming proper screen and filter pack design) and tries to expand to larger cylinders as the treated water moves outward.

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C
C
B
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A
A

Figure 2-5. Effect of biofilm formation is shown on water movement (arrows) through porous media. The media is represented to the left as a throat between two particles (shaded). Biofouling is shown progressively developing in the throat through: A - Pristine condition (upper), B - starts of fouling (center), and C – severe encrustation causing total plugging (lower). Graphs to the right show the impact on specific capacity (vertical axis, SC) versus time (horizontal axis, T). Arrows to the left designate the state of the plugging (blue – no fouling, light brown – fouling, and dark brown – plugged). The down pointing arrow in the lower diagram shows the point of plugging.

Figure 2-6. Photograph illustrates the forms of bacterial biofouling occurring in a 4” horizontal injection well impacted by highly oxidative nutrient-rich waters injected back into the formation. The bacterially-formed complex thread-like structures cause severe plugging in the screen slots and the surrounding media.

2-7. Flow Volume Changes

a. Both extraction and injection wells will be subjected to flow volume changes as the biofilms grow within and occupy a significant percentage of the void volumes in the porous media. This loss in available void volume due to the growth of biofilms means that both the transmissible water volume entering (in the case of an extraction well) and leaving (in the case of an injection well) will decline significantly. The impact of decreased void volumes would result in significant reductions in the flow volumes under standard pumping procedures accompanied by a loss in the specific capacity for the well. The configuration of the well in the vertical or horizontal position will have a major impact not only on the mode of extraction, particularly where lateral mobile plumes such as solvents or hydrocarbons, but will also have a different aspect ratio for the slot area to the influenced volume.

For horizontal wells the concept of the zone of influence is often measured as a distance rather than being considered as a radius. These influences of a horizontal well are dependent upon many factors including soil type(s) present along the screened interval, radius of the well, operating conditions (i.e., pressure and flow), depth of the well below grade, well construction materials, and filter pack, relationship of the well to the water table and its range of fluctuation. Other factors also important are type/nature of contaminants present, distribution of concentration of contaminants, the configuration of the wells (horizontal or vertical) within the ground water remediation site as well as a large number of other factors.

Biofouling may tend to occur as long lateral growths affecting much of the length of the horizontal well while for vertical wells, there is a greater likelihood that the biofouling will concentrate within specific depth zones and form as radial growths around the well in addition to fouling up the water column itself. In summary, a horizontal well is more likely to become biofouled along a considerable part of its length while the vertical well is likely to have a more focused site of biofouling that is usually associated with the sites where the contamination is concentrated down the vertical profile.

Another important factor, however, is the slot size and distribution along the screened interval. Horizontal wells are very prone to biofouling along considerable lengths particularly where the environmental conditions are more conducive to microbial growth. It should be recognized that the smaller slot sizes are likely to become plugged by microbial biofouling but much of the biofouling will occur in the porous media away from the screen slots and the well itself. It is these growths that make rehabilitation difficult.

b. Much of the biofouling is caused by the formation of biofilms. These growths commonly undergo cyclic stages of biofilm growth followed by sloughing and compaction. Flow volume changes can be impacted by these harmonic shifts during the maturation of the biofilms. In laboratory studies, it has generally been found that the cyclic form of biofilm growth does affect the product flow volumes out of, or into the well. Where the loss in volume flow is linear in nature then there is a greater probability that the losses are a result of a geochemical event or some shift in the availability of ground water to, or from, the well.

2-8 Biofouling and the Impact of Biofilms

Biofilm is the name given to bacterial growths occurring over surfaces commonly as a continuous coating. This coating often begins slime-like but often matures into more complex structures that are amorphous

or crystalline encrustations,
nodules, tubercles or exotic growths extending out into the water. As the biofilms mature, they occupy void spaces within
porous media that can drastically change the hydraulic characteristics of the water flow. Avertical section through a maturing
biofilm illustrates the nature of the biofilm in Figure 2-7 as shown. Most of the biofilm is comprised of bound water that is
held in place by strands of polymers produced by the resident microorganisms. Rehabilitation has to involve, where biofilms
are present, some **method** for disrupting and dispersing these polymers before the microbial cells can be attacked. Application
of chemicals during rehabilitation can be improved if the resultant reaction is able to penetrate down the water conduits into
the biofilms. The chemicals attack the microbial cells that disperse in clusters that commonly involve several species.
Chemicals entering primarily though these water conduits may also become entrapped within the polymeric webs and
accumulate or become neutralized.
In rehabilitation, the state of maturation of a biofilm is critical to the form or treatment to be applied. Identification
of the nature of the biofilm may become critical to the selection of the rehabilitation procedure. The stages of maturation are
shown in Figure 2-7. Young biofilms begin with a very high water content, relatively large volume and are unstable.

Maturing biofilms have gradually reducing water content and increasing content of accumulates. This can include metallic
ions with iron oxides and hydroxides often dominating under oxidative conditions. Carbonates (such as calcite) may also
accumulate generally as crystalline structures synthesized by the microbes within the biofilm. Under reductive conditions,
it is various metallic sulfides that accumulate, particularly iron sulfide. Organic materials can also accumulate but are also
likely to be degraded (if not recalcitrant). If they are recalcitrant it means that the conditions present do not support the
degradation of the organics and so they therefore accumulate. In a matured biofilm, the bioaccumulation in the biofilm will
reach a saturated state with bound water and organics reduced to lower levels. At this stage the biofilm becomes an encrustation
and rehabilitation must focus on the destruction of the elements dominating that relatively dormant mass. Iron content under
some oxidative conditions can be as high as 30% to 36% of the dry weight mass while the organic content can fall to less
than 1.0%.

2-9 Considerations in Selecting a Rehabilitation Strategy

In developing a rehabilitation strategy, the treatment has to account for the nature of any biofouling that causes
process problems and attacks the various components in the biofilms. Physical treatments require

agitation and commonly include changing the pH and temperature. Chemical treatments are applied to be destructive to the incumbent structures such as the polymers and various recalcitrant materials and can be toxic to the microbial cells. These various strategies can be applied through a blending of different physical and chemical treatments applicable to the biofouling conditions experienced.

Figure 2-7, Maturation of a Biofilm is depicted in three stages from young (upper) through to maturing (middle) to mature in the form of an encrustation (lower). Young biofilms are bound by a polymeric (POLY) matrix with a diffuse surface (DS) and many water conduits (WC) through the matrix. As the biofilm matures it accumulates materials (AM), develops a more hardened surface (HS) and the water channels becomes more restricted (WCR). In the encrusted biofilm, plate-like (PL) forms develop that are often iron or calcite rich; the surface hardens becoming even more and durable (SE) with many fractures (FR).

1

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YOUNG

DS

WC

POLY

2. MATURING

WCR

AM

HS

PLM

3. ENCRUSTATION

FR

FR

SE

PL

Geochemical events relate to physical and chemical events that accumulate materials within the void spaces and, more particularly, in the voids of the porous media thus severely restricting hydraulic flows. It used to be thought that ground water was an essentially sterile environment and that any interference with water flows and volumes were a result of some physical-chemical interaction within the ground water and/or siltation within the voids. The chemistry in these events was generally considered to be associated with the oxidative deposition of encrustations formed as a result of physical and chemical interactions that occurred in the ground water. Interaction of the microbiological factors and the chemical factors in these environments is not clearly understood. However, it has become very clear is that ground water is biological active.

Flow volume changes are relatively simple to measure but difficult to explain. Clearly, in the rehabilitation of a well, it is essential to understand the nature of the causes involved in the changes in flow volumes since the application of a treatment should address, and target, the causes of the problem. Each well should be considered to have its own unique environment with differences occurring in wells only a few feet apart. This uniqueness means that it may not be effective to make an assumption that blanketing a well field with a specific treatment package will resolve all the fouling problems in every well in the field.

2-10 Drawdown Changes

a. A vertical well has a head within the water column that will be stable and reflect the neighboring water table when the well is at rest. Pumping extraction wells can cause excessive drawdown of the water level when the volume of water entering the well cannot keep up with the pumping demand at the static head pressures of the well. Pumping fluids into injection wells has a reverse effect on the static head. The water level rises in the column as a result of the greater volume of fluids entering the well compared to the amount that can leave the well through the slots and or directly into the porous media of the aquifer. Horizontal wells function differently because all of the screen slots cover a range of depth equivalent to the width of the screens. Hydraulic efficiency in this case would be based on a narrow range of aquifer depth with biofouling likely to extend along the entire length of the screen. Evidence of this occurring may be the presence of gas blankets along the upper quadrant of the wells where gases are collecting but are unable to escape through the slots or be degraded. These events can best be examined by video logging the well.

b. Changes in the elevation of water levels in piezometers sited within the normal zone of influence during active pumping of the well can reflect the losses in permeability in the surrounding media that have resulted from geochemical and/or biological activities. In vertical extraction wells, this would mean that the drawdown would become greater until the pumping action was impaired by the water level reaching the pump itself. For horizontal extraction wells, there would be a loss in ability to extract water under constant pumping conditions. The reverse is true for injection wells. In vertical injection wells, the same losses in permeability would cause the water to rise in the borehole. If the well were capped then the impact would be seen in greater pressures needing to be applied in order to inject the specified volume of fluids into the well.
Horizontal injection wells would show similar increases in back-pressure resistance that would lower the efficiency with which water could be injected through the well.

c. Operation of wells is more difficult when there is a lateral plume floating on the ground water at a depth occupied by the well screens. For a vertical well, this would mean that plume might be focusing biological activity over the depths where the plume is having a significant influence. Drawdown data, under these circumstances, may become difficult to obtain. Drawdown measurements may be further exacerbated by biological degradation and smearing of these contaminants at the interface. For horizontal wells a condition could be reached where considerable lengths of the screens may be impacted. This would theoretically increase the ability to remove the contents of the plume but also increase the potential for severe plugging along large lengths of the well.

2-11 Biological, Chemical and Physical Changes of the Well and Plant Components

a. While the performance changes described in Sections 2-7 and 2-10 are relatively easy to determine, the changes that may occur concurrently in the well relating to the biological, chemical and physical parameters tend to be more difficult to determine. These parameters all are interlinked in a manner that may cause several parameters to shift as a result of the change in one critical parameter. Standard practice has been to concentrate on the well performance data to determine whether a well is functioning effectively usually with respect to approved management of the contamination. As a result

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only a limited body of information may be collected that can be used to determine changes in the biological and chemical parameters and even the hydraulic performance of the wells. The root problem with these monitoring procedures rests in the fact that the biological activities involved can be localized, can be located away from the well screens and can exhibit a natural variation often associated with the maturation cycles involved during the growth.

b. There has been a tendency to rely on simple inorganic chemistry to determine the “health” of a well. Chemistry data were often limited to a range of metallic ions including sodium, potassium, calcium, magnesium and iron, chloride ions, sulfate ions, and a broad sweep of the total dissolved solids using conductivity. This type of analysis was slanted toward determining the origin of the ground water and its hardness rather than determining the likelihood of biological and/or chemical challenges to the performance characteristics of the well.

c. Addressing biofouling/performance problems in both extraction and injection wells is made complex by a set of factors that interact to make interpretation more experiential than scientific. In this section these various factors will be addressed in a logical order. This order covers the reliability of the sampling procedures to obtain meaningful data through to the critical biological, chemical and physical parameters that can influence the performance of the wells. This engineering pamphlet presents a management pathway that involves the experiential knowledge and understanding of the site staff as much as the need to follow a preordained pathway without consideration to local conditions that could make each well unique in the manner that they are treated.

d. Performance is often designated as compromised when the hydraulic conductivity within the porous media around the well becomes severely curtailed by a growth of biofilms with, or without, associated encrustations that biologically plug off the well. Geochemical clogging can also cause this loss in conductivity and, under many circumstances; it can be a combination of both biological plugging and chemical clogging. On contaminated ground water sites, the prime concern is the control of the contaminants by the extraction and/or injection wells with relatively little or no attention paid to the basic hydraulic performance of the well. This engineering pamphlet provides a guidance document to ensure the rehabilitation and long-term management of these wells.

e. Examining the available historical performance data for a well is the first step in the diagnosis of the likely cause(s) of performance losses. There is a common tendency for many wells to exhibit erratic forms of decline in performance. This variability, particularly during periods of erratic and sharp declines, can be used to determine whether the failure is biological plugging, geochemical clogging, or some combination of these two events. Biological plugging usually causes more variations associated with the nature of the biofilms growth cycle. In general, the bacterial activity associated with biological plugging can become significant before there are losses in performance by the well due to an increase in aggressivity of the particular bacterial consortia infesting the well site. Where geochemical clogging dominates, the bacterial activity does not precede the decrease in production but follows later. Variability in the slope of the decline is also less where a geochemical clogging is dominating the losses in production.

f. Beyond the primary indicators of the cause for production losses, there is the more detailed assessment that is inherently essential for the rehabilitation of the wells to assure acceptable performance. After an unacceptable loss in production, a two-phase reaction program needs to be instituted.

- The first phase would be a rehabilitation treatment to return the well to an acceptable level of performance.
- The second phase would be to set up an ongoing preventative maintenance that will assure that, with a minimum of treatment applications and effective monitoring, the well remains within an acceptable range of performance.

g. The first step to conduct a complete visual inspection includes camera logging of the borehole, screens and any formation material that may be visible. Often this visual inspection gives an indication of the state of the water column in the well, the degree of biofouling present, and the form and nature of any encrustations and crystalline deposits. This inspection may reveal design or mechanical failures, i.e., intrusions of fines into the well, broken or damaged screen, etc. A camera log that gives images identical to the initial well development log (i.e., pristine and new looking) does not mean that changes have not occurred. It may mean that any biological and/or chemical activity causing problems cannot be observed from the borehole itself because these events are happening back in the pack or further out into the formation. Some of the characteristic forms of biological growths that can be observed during camera logging are show in Figure 2-8. Careful

comparisons have to be made with the past and present video borehole logs while noting any changes. Acomprehensive list of symptoms is given in Section 3.7 below.

h. Historical records can reveal significant shifts in specific parameters that can be used to give an indication of fouling. Functioning wells are likely to be biologically compromised to some extent during their operational life. Some of these impacts may even result in a positive event. An example of this is that biofouling, as it forms and matures, may often act like a biological filter and remove chemicals from the ground water that have a potential value to the microbial consortia growing in the various biofilms. During this phase, the chemistry of the groundwater may shift significantly to reflect the activity of these microorganisms. For example ground water with an iron concentration of 1.4 ppm may enter an extraction well and lose most of the iron through bioaccumulation. If an order of magnitude reduction occurs then the ground water pumped from the well may contain only 0.14 ppm total iron. However, once the biofilms mature then the total iron concentration held as accumulates now ranges from 20 to 36% by dried weight of the encrustations. As the iron levels rise, there is a reduced stability in the biofilms and some of the iron shears away with the collapsing biofilms. This iron re-enters the water in a biocolloidal form to elevate the total iron level in the influent to the plant. It is therefore quite common to see the total iron concentrations in the product suddenly rise in an erratic manner to as much as ten times the original total iron concentration (14.0 ppm). Low iron values in a ground water sample do not mean necessarily that the water has a low iron content but simply that any iron that was in the ground water could have been significantly removed through bioaccumulation into the biofilms forming the plugging.

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Figure 2-8. Nine forms of typical biological growth sometimes seen when camera-logging wells. These are: (1) well snow which are particles in almost a gel-like state; (2) calcite stalks; (3) slime-like globular structures; (4) nodules or tubercles; (5) encrustations; (6) loosely attached slime which easily detach and float through the water; (7) threads; (8) ill-defined fragile clumps of slime that extend out into the water; and (9) concretious arches that can extend right across the screen's diameter.

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i. Injection wells with a high total iron content (in excess of 0.5 mg/L) in the water can expect to generate an ongoing maintenance concern since the iron is moving from the borehole through the limited well screen surface leading outwards into the formation can generate very significant localized plugging. This plugging can lead to rapid losses in hydraulic conductivity, rising injection pressures to achieve targeted flows, and a radically shortened operating cycle.

j. Historically, iron is the most well known chemical parameter that causes well clogging problems including losses in production and deterioration of water quality. This failure in production used to be considered to be mainly a chemically driven event. It was thought that the oxidative conditions created a chemical precipitation of the iron into large masses of ferric oxides and hydroxides perhaps with some carbonates. These structures commonly resulted in encrustations that were hard and brittle with very porous structures. It is important to recognize that some primary features inherent in the failures of wells are biological in origin.

k. Formerly scientific research emphasized the chemical and physical factors more than biological in well fouling. Recent research and field experience demonstrates that the impacts on a well are primarily driven by biological events. In a semi-saturated environment, the microbial activity tends to be dominated by the molds (fungi). For conditions where there are plumes of organics floating on the ground water beneath the vadose layer, the fungi may play a major role in their accumulation and degradation, Figure 2-9. Volatile materials escaping from the water into the soil's atmosphere in the vadose zone may also be bioaccumulated and biodegraded by these fungal growths.

l. In the ground water saturated zones, there is likely to be significant oxidation-reduction potentials (ORP) formed between the more oxidized conditions (commonly above and also around boreholes) and the reduced conditions (commonly back in the aquifer formations). This shift in the ORP from an oxidative to a reductive state is referred to as the redox front. This front is likely to be dominated by various species of bacteria growing in communities known as consortia. The exact nature of the consortia growing at a specific site will be dependent in part on the ORP at the site. Commonly, the dominant microorganisms shift from oxidative through the redox front to reductive in the following sequence: IRB, MCB (methane consuming bacteria), HAB, SLYM, DN, and SRB, MPB (methane producing bacteria) with the HAB, SLYM and DN dominating at the redox front. Both DN and MPB can produce gases (nitrogen or methane, respectively) causing temporary foam blocking off of the porous media. This can result in sudden (often short-lived) losses in flow.

FS

SS

PL

PR

WT

SSM

SAQ

FGZ

VOS

FS

FM

WT

Figure 2-9. Fungi influence on the activity of wells. The fungi grow (left diagram) in a vertical profile above the water table (WT) above the saturated aquifer (SAQ) in the semi-saturated media (SSM) well below the soil's surface (SS) where the plant leaves (PL) and plant roots grow (PR). Usually there would be a small but sufficient concentration of oxygen to support the growth of fungi in the zone (FGZ) at the lower edge of the vadose zone. Inserted to the right is a close up of the fungal growth that takes the form of a fungal mat (FM) from which fungal spores (FS) are generated. Volatile organic substances (VOS) emitted from the water table can become sorbed and utilized by these fungal growths as nutrients.

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m. Since the microbiology interacts with the chemistry and the physical states of both horizontal and vertical wells, it is often difficult to obtain a comprehensive answer to these sudden partial or complete failures. It could be argued that a comprehensive database is essential. It could also be argued that for many of the existing wells such an argument makes no sense since the data was not historically gathered and the cost of its acquisition could be seriously questioned. On this basis, the remaining chapters in the EP focus more upon expediency, experience, and the exercise of a

reactive management rather than generate a set of regulatory rules that have to be strictly followed. Chapter 3 deals primarily with the available and desired base line data while Chapter 4 places this information into a historical setting so that decisions can be made.
Chapters 5 through 8 set the decision tree in place to allow the well to be effectively treated and return to acceptable operating conditions. Chapters 9 and 10 outline the steps of selecting and applying a treatment while Chapter 11 addresses health and safety concerns. Chapter 12 forms a checklist to ensure that all of the steps in the treatment process have been effectively followed and that a preventative maintenance (PM) program ensues. Without a post-treatment preventive maintenance program, the well problems can reoccur and exhibit the same decline in performance.

Chapter 3

Baseline Data Requirements and Interpretation

3-1 General

Commonly the data collected at ground water remediation sites is to ensure that the remedy is working as designed (containment or capture). There is little emphasis on individual wells outside of water elevations and pumping/injection rates. However, reference points are needed when a well is exhibiting signs of failure. To presume that all wells within the same well field exhibit the same characteristics can lead to an attitude that a blanket treatment should be equally effective when applied to all of the wells within a field. In reality, each well has some unique characteristics because of location, variations in construction, distribution of contaminants and the nature of the biological activity within that particular site.
Given that each well does possess at least some unique properties, each well should be considered independently and the most effective management practices determined on a case-by-case basis. Under these circumstances, baseline data is required for each well. While some comparisons with other wells can inevitably be made, the treatment strategy for each well should be an independent decision. Analysis of the baseline data, therefore, forms an essential part of the development and operational management of the well through rehabilitation and subsequent preventative maintenance. Chapter 3 addresses the baseline information from pump tests, variations in the specific capacity, and various logging, chemical, and biological analytical data.

3-2 Causes of Well Problems

a. Cause summary. Remediation well-system problems have a number of identified causes (Driscoll 1986; Borch, Smith, and Noble 1993; Smith 1995; Alford and Cullimore 1999; Cullimore, 2000a) that often work together to produce conditions encountered in the wells. Further information can be obtained from DG 1110-1-1 and Table 2-1 in EP 1110-1-27 that summarizes the main problems often associated with wells on contaminated ground water sites.

Table 3-1. Parameters Useful in Well Rehabilitation

3-1

Test Types

Parameters Obtained

Hydraulic testing

Flow and drawdown forspecific capacity (water level rise in injection wells).

Total amount of pumping time and quantity pumped per year.

Periodic step-tests for well and pump efficiency.

Power and fuel consumption for pump efficiency.

Physiochemical parameters (for changes due to deterioration)

Total and ferric iron, and total manganese (and other metals as indicated).

Important anions as identified, including sulfides, sulfates, carbonates, and bicarbonates.

pH, conductivity, and redox potential where possible (instrument readings may be replaced by checking ratios of Fe (total) to Fe 2+ (soluble).

Turbidity or total suspended solids calculation of product water.

Physicochemical parameters (for changes due to deterioration)

Calculation of corrosion/encrustation potential is using a consistent **method**.

Microbial

Total Fe/Mn-related bacteria, sulfate-reducing bacteria,slime-forming bacteria and other microbial types that are of concern

Visual/physical

Pump and other equipment inspection for deterioration

Borehole TV for casing and screen deterioration.

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b. Symptom determination. In many cases, symptoms of well deterioration may not be apparent until well performance has become severely and obviously impaired, unless the results of system water and quality and performance monitoring are compared over time to establish trends. Such problems can be prevented by rehabilitation and controlled afterwards by effective PREVENTATIVE MAINTENANCE, but to do so requires valid information on the environment, hydrology, and material performance of the well systems produced by information collected to form a basis for reactive monitoring

3-3 Pump Test Data

a. General Statement. Reliable, valid tests are critical to both injection and extraction well assessment when deciding the need to rehabilitate and institute a preventative maintenance program. Such assessment and management is enhanced by a history of valid well data over time, back to installation if possible. Valid results depend on a reproducible test design, appropriate performance reporting, and interpretation. In practice, it can be expected that the reporting of data interpretations will lag behind the actual performance of the well. Deterioration of performance standards will not be recognized immediately allowing further degeneration of the conditions in the well. This pamphlet briefly reviews types of pumping tests and how these can be used to assess pump, well, and pumped-formation (aquifer) parameters. It describes minimum valid baseline data to be reported, including:

- Minimum data standards for tests.
- Minimum data for individual water level measurements (not just final levels), pumping rates, sand (particulate) or colloidal content, and information on conditions that would affect results.
- How to determine adequate testing intervals.

b. Data collection.

(1) Accurate discharge flow data are needed for any pumping test. All devices should be calibrated prior to installation, and at regular intervals to ensure proper operation. Flow measurement devices suitable for pumping tests include:

- Orifice weirs: Driscoll (1986) provides a detailed description of the necessary elements of the construction and use of an orifice weir.
- Mechanical flow meters.
- Sonic-based flow meters available that is accurate and well adapted to this application.

(2) Equally important are accurate time and water level measurements throughout the test reported in convenient units for analytical input. If there is the potential for water cascading down the screen in the well during the test, fit the well with a drawdown (stilling) tube to shield the water level probe from the cascading water and ensure accurate water level measurements. Finally, the data must be recorded on a sheet specifically structured to record and organize pumping test data. Directly measuring system gauge pressure is essential in evaluating pump performance and useful in making field decisions on tests of relatively unknown wells or pumps. Water levels in the surrounding network of wells are required to complement data from the pumped well.

c. Step-drawdown tests. Step-drawdown tests are a hydraulic testing tool for assessing well performance. When properly conducted and analyzed, these tests provide data on specific capacity, well and aquifer losses, well efficiency, and drawdown..

(1) Conducting and analyzing step-drawdown tests are treated in detail in Kruseman and de Ridder (1994). For porous medium aquifers, the Hantush-Bierschenk **method** of analysis is employed, which is relatively straightforward. For

fractured rock aquifers, Rorabaugh’s **method** may be required, which is less straightforward. A computer application to solve Rorabaugh’s **method**, such as FASTEP (Labadie and Helweg 1975), may be useful. Examples are referenced in EP 1110-1-27 in Appendix D as Plate D-2 (example step drawdown plot). Plates D-3 and D-4 provide an analysis of the step-drawdown test charted in Plate D-2 to determine well and aquifer loss.

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(2) The step-drawdown test is useful to:

- Determine characteristics about both the well and the aquifer simultaneously (aquifer and well loss).
- Extrapolate or interpolate the performance of the well at various discharge rates, using measured data points as a reference.
- Determine the operating characteristics of the well pump used.

(3) If performed immediately after a well is constructed, the step-drawdown test provides an estimate of the efficiency of the well, the effectiveness of the well development phase of the well construction, and the baseline well and pumps performance for comparison in the future. Well design criteria and assumptions can also be tested and adjusted as needed Improper or incomplete well development may affect the test results.

(4) For step-test data to be useful in calculating well, pump, and aquifer performance parameters:

- Data must be accurately gathered, collected at standard intervals of decreasing frequency, as recommended (Helweg, Scott, and Noble (1983), and Driscoll, 1986).
- Each step must be of a sufficient length of time for either the water level decline to stabilize or the decline trend to be established on a semi-log plot of drawdown versus time
- The effects of interference (such as other wells starting and stopping) must be factored into the analysis.

(5) Contaminated sites may impose restrictions on optimal step testing methodology. For example, a five-step test with pressure measurement is recommended to determine pump wear. However, pumping contaminated ground water requires collection and disposal of the fluid. Perfecting the gathering of pump wear data from a three-step test, and learning to extrapolate from short steps may be a necessary compromise in methodology (Driscoll, 1986).

d. Constant rate and slug tests. Constant rate pumping tests and slug tests are employed predominantly to determine aquifer characteristics, that is, transmissivity, hydraulic conductivity, and storage coefficient. Their utility in well rehabilitation is less direct than with step-drawdown tests, but data derived from these tests can be used in preliminary calculations of expected well hydraulic parameters.

(1) Constant-rate pumping tests.

(a) With knowledge of aquifer characteristics, the theoretical drawdown in the aquifer at the well screen for a given discharge rate can be calculated and compared with the observed drawdown at the same rate, yielding the well efficiency at that rate. As a constant rate test approaches steady state, the final specific capacity at the discharge rate can be calculated.

Neither the constant-rate nor the slug test can provide the means for predicting the well loss and the well efficiency that occurs over a range of discharge rates.

(b) The constant rate test is conducted similarly to the step-drawdown test. Accurate discharge, water level, and time measurements are essential. Again, Kruseman and de Ridder (1994) provide an in-depth discussion of conducting and analyzing these tests. Computer applications are available to aid in the analysis of constant rate tests. Boulding (1995) provides a useful conceptual review of pumping test software that can be updated by research into current products.

(2) Slug tests. A slug test is also used to determine aquifer characteristics.

(a) Descriptions of procedures and methods of analysis are provided in Kruseman and de Ridder (1994), Bouwer and Rice (1976), Hvorslev (1951), and ASTM D 4044, D 4050, and D 4104. The computer applications available to aid in the analysis of constant rate tests, such as AQUITEST (Walton 1996), can also provide analysis of slug tests. Because of the small volumes of water involved and the short time span over which the test occurs, pressure transducers and digital data logging are generally employed. Pressure transducers are submerged in the well and register the pressure of the column of water overlying them. Water-level changes are detected as changes in pressure as the height of the overlying water column increases or decreases. The data logger can be programmed to sample and record data from the transducer at required time intervals. This feature of digital data logging is most useful when conducting slug tests in high-permeability sediments where many water level measurements will be required over a span of seconds as the water level rapidly recovers.

(b) As with constant rate pumping test data, calculations of aquifer characteristics based on slug test data can be used for estimation of theoretical well mounding in injection wells.

3-4. Specific Capacity Data

a. Specific capacity is a term used to express the productivity of a well, and is defined as Q/s, where Q is the discharge rate and s is the drawdown in the well (Driscoll 1986). The observed drawdown in the well is a function of aquifer and well loss; therefore, Q/s is a term incorporating both aquifer and well performance. Step-drawdown tests described in Section 3-3 provide a means of separating the aquifer and well loss components.

b. Q/s calculations, using water-level change and well pumping data, are used to assess pumping well performance and results of development and redevelopment (Helweg, Scott, and Scalmanini 1983; Driscoll 1986; Borch, Smith, and Noble 1993). The data that need to be collected (Q and s in pumping wells) are simple to obtain and the calculations simple to make. Specific capacity is a relatively sensitive indicator of hydraulic performance change in wells. Making valid calculations in turn depends on reliable data collection. Appropriate actions in response to changing values depend on setting action levels that permit a response before performance is seriously impaired.

c. To determine Q/s for a well, accurate static water level, pumping water-level, and discharge rate data are needed. Since the water table or potentiometric surface varies seasonally and with outside stresses, a deeper pumping water level for a given discharge rate may not reflect a change in the well performance. Therefore, some means will be required to determine the variation in the static water level, e.g., an observation well outside the influence of the pumping well or static water levels obtained when the well is not pumped. The former **method** is the only way to efficiently monitor specific capacity in an active treatment system since we cannot shut down the pump and wait hours for the water level to equilibrate.

d. Static and pumping water levels can be affected by oscillations caused by the pump, cascading water, the water level probe becoming entangled in wiring and pump column, and operator error.

(1) Many problems can be avoided by installing a stilling (drawdown) tube in the well. Also, clearly establishing the “measuring point” (MP) of the well from which all measurement are taken and informing all personnel who will be collecting data of the MP will avoid many problems. The discharge rate can vary in response to system backpressure and changes in pump performance, and therefore cannot be assumed to be constant. Backpressure should be measured along with water levels when determining Q/s. The flow meter used to measure the discharge rate is also subject to error as it wears or clogs.

(2) It is desirable that a baseline Q/s be determined at the intended discharge rate when a well is constructed (assuming the efficiency of the well is acceptable). Subsequent measurements of the drawdown in the well and discharge rate and recalculation of Q/s will provide an indication of the ongoing performance of the well (Borch , Smith, and Noble, 1993; Howsam, P., Misstears, B., and Jones, C. 1995).

e. Of the many tests applied to determine the production capabilities of a well, the specific capacity is most commonly used. The reason is basically that the specific capacity reflects the ability of the well to produce water by the average amount of volume generated per unit distance of drawdown. In this formulation, it can be considered that the larger the volumes per unit of draw down, the greater the production. In an extraction well, the effect of fouling is to restrict the flow of ground water into the well causing the specific capacity to drop. This would be a signal that the well is failing and in need of rehabilitation. Horizontal wells present more difficulty in determining the specific capacity. Essentially in these wells there is an intrinsic hydraulic capacity designed into the well system. Losses in this capacity would similarly restrict the flow and declining efficiencies would result including an increasing pump pressure, longer operating times to achieve the same flow volume and greater variability in the water quality and contaminant chemistry due to the fouling events. While most of these tests apply to vertical wells, ongoing references to horizontal wells will be added where appropriate.

f. It is normally assumed that the original specific capacity taken when the well was first developed can be used for future comparisons. It is expected that the specific capacity will fall progressively and in conjunction with the fouling whether it is predominantly geochemical clogging or biological plugging. If the failure is structural in nature then a much sharper decline in specific capacity is likely to occur.

g. Under ideal circumstances, any loss in specific capacity must be viewed as a serious problem that could impact the designed efficiency of the site. Effective preventative maintenance scenarios call for keeping the well at or close to the original specific capacity with treatments applied on a routine basis as a preventative maintenance practice. If the well is suffering from fouling, there are identifying stages in the severity of the event listed in this EP. Generally, the critical ranges are losses of between 5% and 15% in the specific capacity, and losses of between 40% and 60% in specific capacity. The first range (5% to 15%) represents a significant impact that can normally be overcome by effective treatments followed by preventative maintenance. Once the specific capacity drops into the second range (40% to 60%), recovery may not be possible. There can be dramatic failures in wells that have 40% to 60% losses in the specific capacity since the geochemical clogging and/or biological plugging now rapidly occludes the remaining ground water pathways into the well.

h. Injection wells follow a different plugging history than extraction wells since water is being injected into the ground and displacing the resident ground water in the aquifer. The critical pathway is the movement of the injected water through the borehole into the surrounding media. The injected water has to pass outwards through the screen slots (where they are used) and into the relatively small volume of porous media surrounding the borehole. Quite often the water injected into the natural ground water has very different chemical and biological properties. A relatively small volume of the voids near the well is subjected to a maximum amount of disruption that can lead to biological plugging and/or geochemical clogging events becoming focused within this relatively small volume. Abroad range of biological, chemical and physical interactions could occur. Where the injected water is oxidative, redox fronts are likely to establish in the entrance void spaces and cause rapid conductivity losses.

i. Since injection wells function opposite to extraction wells, an evaluation of their performance using specific capacity requires a different perspective. The injection well can be shut down and a specific capacity obtained by conventional borehole pumping to determine draw down and the pumping rate. From this data the specific capacity can be derived. In practice, it may be more convenient to monitor the relationship between injected volumes and the pressures created to achieve that injected flow. As the borehole fouls and loses conductivity, there would need to be a greater amount of applied pressure during injection to achieve the needed injection volumes. Under fouling conditions, it can be expected that the pressure/volume ratio will rise. This would be a reflection of the loss in specific capacity and the onset of significant plugging/clogging; therefore, it is very important to monitor the characteristics (e.g., pressure changes, electrical power consumption, running time) to determine whether the well is fouling. However, for a more representative baseline, it is recommended that potable water is used in an ‘injection step test’ to measure the changes in the water table and pressure with the volume of water added.

3-5. Development Data

a. Historically, little attention is paid to the impact of well development on the subsequent performance of the well. Development has been centered on achieving an acceptable performance from the well with a deliverable output of water. The term development is primarily used to describe a set of primarily physical treatments that causes the aquifer, packs, and screen to become physically developed to a maximum porosity (void space) to allow delivery of a consistent and reliable volume of water. Robust well development should be performed immediately after installation for removal of drilling fluid solids and natural fines, and to complete the subsidence of the gravel pack where more material can be added to bring the pack up to the specified elevation. This concept is the basis for all vertical and horizontal water wells and is equally applicable to injection and extraction wells. With extraction wells, there is an ongoing flushing action that continues to develop towards the well. Injection well flow is outward from the well which means the flushing action of the injected water moves away from the well forcing any materials present back into the formation. With both injection and extraction wells, effective development is essential to attain a maximum porosity and to achieve effective movement of fluids into, and out of, the wells.

b. Data collected during development are critical in documenting how effectively the well was developed. This forms one part of the historical information that would be integrated with data described in Sections 3.6 through 3.12 to build up a comprehensive detailing of the history of the well. Improper or inadequate well development is one of the most common contributors to poor well performance and fouling. It is desirable to obtain the oringinal field notes of the geologist or engineer who was on site during development.

3-6. Well Construction

a. “As constructed” well construction records are used in well maintenance to provide a basis for the comparison of past and present conditions and for use in other relevant calculations. As a minimum, diagrams shall contain the following information:

- an accurate geographic location,
- the precise designation used by the project,
- accurate depth, diameter (including different components), casing and screen material type, screen slot size and screen length for the well,
- filter pack type, particle size and dimension,
- grout type and dimensions, and
- bentonite seal type and dimensions
- well equipment descriptions and dates drilled and developed.

ER 1110-345-700 provides general guidance for plan components. EM 1110-1-4000 provides general guidance on well construction documentation.

3-7. Biofouling Potential

a. Additional information for a contaminated site should include the nature of the contamination the wells are pumping together with information on the various chemicals, physical and biological steps designed as a part of the containment/treatment system. Each of these steps is likely to have an influence on the potential for a geochemical or biological problem in the wells. The nature of these possible interactions is a site-specific event and only generalities can be included in this EP. It is recommended that biologists as wells as geohydrologists, geologists and engineers be involved in the development of both an assessment of biofouling potential and routine preventative maintenance program. These participants should be familiar with both clogging and plugging events in wells. Such evaluations should, ideally, be applied to both new and existing sites with extraction and injection wells. Some of the major factors evident at the design stage that are likely to cause fouling problems include total organic carbon, metallic cations, phosphorus and nitrogen. Radioactive materials present in the ground or treated waters do not automatically mean that there is no potential for biological fouling because of the potentially toxic/mutagenic effects. Radiation emitted from these materials can create a destabilization of water with the generation of a shifting ORP that can focus biological activity and stimulate plugging.

b. While these are a few generic examples of the influence of water quality on the assessment for plugging and clogging, it is necessary to conduct an evaluation of this potential during the design stage (to enact an appropriate preventative maintenance protocol).

3-7. Construction Boring Log

a. Boring logs include precise geographic location and boring identification (with cross-reference to subsequent well designations), accurate formation descriptions (including sediment and rock descriptions provided according to uniform accepted standards with accurate depths), and particle size descriptions of water-producing/accepting zones.

b. A lithologic log is a record of the character, depths, and thickness of geologic materials encountered by the drill as the borehole is advanced, with emphasis given to hydraulic properties of the materials. Lithologic logs should be recorded and maintained by qualified oversight personnel, using standard engineering or geologic terminology. EM 1110-1-4000 provides guidance on sample logging, the data to be recorded, and examples of forms used to record the data.

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(1) The lithologic/boring log should contain as a minimum.

- The depth at which recognizable geologic changes occur should be logged along with the depths from which samples are collected and described.
- A description of cutting samples collected at every change of geologic materials and at 1- to 1 -m (3.28- to 33-ft) intervals, and 100 percent logging for the screened interval in either the pilot or the final boring.
- Changes in drilling action, that is, penetration rate, fluid loss, drilling noise, etc.

(2) Descriptions of unconsolidated sediments should note dominant grain size, sorting, and estimate of the relative percentages of sizes according to the Unified Soil Classification System (USCS) procedures and those described in ASTM 421 and 422. Grain shape and rounding are useful for estimating hydraulic properties. Color related to degree of weathering and oxidation-reduction is useful in determining degree of saturation. Descriptions of consolidated bedrock should note degree of cementation, induration, and fracturing. The depth at which saturated conditions occur should be noted. Changes in drilling fluid properties (gains or losses of fluids, changing specific gravity, etc.) should be noted, as they provide

information on water-bearing zones.

3-9 Video Borehole Log

a. Color borehole TV survey videotapes are an essential component of the historical information base for recording changes occurring in the condition of a well. These should be taken critical times such as immediately after well construction and also at intrusive service intervals such as during preventive maintenance (prior to, and following the treatment to determine effectiveness) and as a diagnostic tool in the determination of the efficiency of well rehabilitation. These tapes may be consolidated showing important well features over the years, but each should be labeled by well identification and dated, then stored properly in an accessible location.

b. It is recommended that any survey should follow a standard protocol that allows an easy comparison of imagery. This should include ensuring that the date, time and position are always displayed together with the camera lens position in relation to the well screens. This latter function is particularly important in horizontal wells where the fouling events may occur laterally. For example, gas pockets would tend to collect on the upper arc of the screen where the media beyond the screen is fouled, and microbial encrustations may be localized over an arc of the screen that is consistent. This data also enables the user to locate particular regions in the well and determine whether a preventive maintenance or rehabilitation treatment has been effective at reducing or eliminating these growths or clogs within the body of the well. It should be remembered that the presence of a pristine screen and borehole does not mean that the well is not fouled but that there is no visible evidence of fouling within the well. There would only be visible evidence where the fouling has become intrusive in the well. (see Figure 3-1)

Figure 3-1. Illustration of a camera view looking down/along a screened section of four boreholes showing different locations of fouling (shaded areas in and around the well) resulting from intrusive fouling. Upper left (1) shows the fouling almost totally blocking off the water column with the water inside colored. Upper right (2) shows a gradually fouling as an even growth in from the screens. Lower left (3) shows minor but distinct visible evidence of fouling through limited regions of the screen, and lower right (4) shows all of the fouling mass back from the screen itself and therefore not visible even though the well would be fouling. The water inside the well would also be discolored with events 2 and 3 shown above.

1
2
3
4

3-10. Ground Water Geochemistry

a. There are two broad classes of chemicals associated with ground water remediation sites. First there are the contaminants that are being removed and second the native constituents. The contaminants can be either organic or inorganic while the native constituents are predominantly inorganic. The potentially adverse human health effects, of course, drive the remediation. However, it is often the native geochemistry that contributes to the demise of the well either by forming chemical precipitates (carbonates and sulfates, e.g.) or causing accelerated rates of corrosion, plugging, bioaccumulation and well failure.

Contaminants may be toxic to biota (commonly limited to animals and plants but excluding the microbial kingdom). In the microbial kingdom there are different protective safeguards in place than those found in animals and plants since the polymers and bound water that make up the bulk of the biofilms create an effective barrier too many contaminants. Inorganic contaminants similarly may not pose such a risk to the microbial kingdom since this material may be bioaccumulated within the biofilms and present little or no restrictions to the growth of the microbes contained within the biofilms

b Once biofilms have adapted to, and are growing, in regions exposed to contaminants there would be increases in the biomass. With that increase come losses in free void volume and a greater risk of plugging. At the same time as the biofilms are thickening due to growth, the conditions within the depths of these biofilms become more reductive increasing the potential for acidic- and hydrogen sulfide- driven forms of corrosion. These corrosive processes can then lead to serious pitting, lateral fracturing and destruction of metal and concrete structures such as mild steel casing, pumps, screens and grouts.

c. Radioactive wastes pose a major hazard to the biota due, in part, to the emission of radiation and partly to the chemical properties of many of these wastes. When this exposure occurs in, and around, a well the impact on the microbial communities is likely to be less extreme because of the “protection” afforded by the polymers and metals bioaccumulated in the biofilms. Here, the polymers restrict the diffusion of the radioactive wastes towards the incumbent microbes with the biofilm. At the same time, the metal accumulated within the polymeric matrices around the cells shield the microbial cells to some extent from the radiation. The combination of these effects means that microorganisms (normally one to two orders of magnitude more resistant to the effects of radiation) are even more able to endure apparent lethal doses of radiation.

Plugging, corrosion and bioaccumulation can therefore occur under conditions that humans might consider “sterile”.

d. Intense interaction exists between the geochemistry of the ground water and the biological components infesting the wells. It can be seen in Table 3-2 that the likelihood of these materials in the ground water being tested frequently can vary with the state of maturation of the biofouling in the wells. The challenge is, in part, to be able to collect a water sample that reflects these events where bioaccumulation and biodegradation would at least temporarily (former) or permanently (latter) take the chemicals out of the water and into the biofilms growing in and around the well.

e. The geochemistry of extraction and injection wells is complex in large part due to the changes induced by pumping. The radial geometry of pumping and the cone of depression cause the water to flow through a constricted volume into the well screen. Thus all of the contaminants and native inorganics flow through the small area of the well bore and screen. The dewatering of the cone of depression alters the redox regime in the vicinity of the well bore especially if the well is screened across the water table. Both of these conditions change the environment for bacteria to grow in. Conversely if an injection well is part of the treatment system the chemistry of the water injected has been significantly changed in most cases by the treatment system. The contaminants have been removed, but the treatment process alters the pH and/or the ORP. This also means that the injected water will not match the geochemistry of the native ground water and that the zone where they mix is a potential zone of precipitation.

Notes: N.A, - not affected by that state of biofouling; Low - the concentrations are reduced more than 20% as a result of accumulation within the biofouling; Variable - there is instability in the concentrations in the production water because of variability in accumulation and releases (due to sloughing) of the chemical(s) in the biofilms; High - means that higher chemical concentrations (> 20% above background recharge water levels)are emerging in the production water in the sloughing materials from the biofouling than is currently entering into the zones of biofouling around the well (recharge water).

Chemical	Young	Maturing	Biofouled
Iron	Low	Variable	High
Manganese	Low	Low - Variable	Variable – High
Total organics	Low	Low	Variable
Hydrocarbon fuels			

High
High
Medium - Low
Recalcitrant
organics
Low
Low
Low – Variable
Total Nitrogen
Low
Low
Low – Variable
Total Phosphorus
Very Low
Low
Low – Variable
Sulfate
NA
NA
NA – Low
Cationic
radionuclides
Low
Medium
High
Anionic
radionuclides
Low
Low
Medium
Toxic organics
Low
Medium - Variable
High – Variable
Hazardous wastes
Low
Variable
Variable
Chloride
NA
NA
NA
Calcium
NA
NA

NA – Low
Magnesium
NA
NA
NA

Table 3-2. Expected Concentrations in Ground Water of Various Chemicals of Concern during the Biofouling of Extraction and Injection Wells

Maturation State of Biofouled Wells

3-11. Biological Assay Data

a. Of all of the data to be generated in connection with water wells it is the biological data that is perhaps the most difficult to obtain in a meaningful manner. An extraction well essentially draws ground water to the borehole and so the biological activity tends to be driven by the microorganisms moving in with the flow supplemented by those microorganisms that may have entered the borehole during the construction and development of the well. Injection wells pump water into the well thus displacing the ground water and introducing the microorganisms present in the injected water into the well environment. In an injection well this would mean that any microbial growth and biofouling might be more affected by surface microbial contamination/infestations from injection well operations.

Beyond this major difference in the likely source of microbial biofouling, the environment in and around the borehole and the manner in which the wells are operated are more likely to influence the types of microbial problems that may develop.

b. To conduct a biological assay, there is a need to get a general evaluation of the levels of bacterial aggressivity in the ground water and, in the case of injection wells, of the water being injected into the ground. The simplest manner to get a first level evaluation of this aggressivity is to use the biological activity reaction tests (BART) in which time lag (to the observation of the first recognizable reaction) forms the critical criterion. It is possible to use this time lag to determine how aggressive the bacteria are on the basis that the shorter the time lag the more aggressive the populations of detected bacteria are. Conversely the longer the time lag then the less aggressive the bacteria are Time lags are measured as the time delay from setting up the test to the first appearance of a visible reaction generated by the bacteria. The units used commonly are days and the time lag represents the days of delay.

c. There is a wide range of bacteria that can become aggressive in the wells. The full range of bacterial groups (consortia) includes the following by group name, acronym and the culture medium used to detect the bacteria:

- Iron Related Bacteria (IRB) Winogradsky’s medium;
- Sulfate Reducing Bacteria (SRB) Postgate’s medium;
- Slime Forming Bacteria (SLYM) Glucose Peptone medium;

- Heterotrophic Aerobic Bacteria (HAB) Sugar Peptone medium;
- Algae (ALGE) Bold's medium;
- Fluorescent Pseudomonads (FLOR) Peptone base medium;
- Denitrifying Bacteria (DN) Nitrate Peptone medium;
- Nitrifying Bacteria (N) Ammonium salts medium

Of these bacteria, the groups most commonly investigated are:

- IRB (associated with iron concretions plugging up the wells),
- SRB (associated with anaerobic conditions with the production of hydrogen sulfides and iron sulfides with black waters and slimes produced),
- SLYM (sensitive to the broadest range of bacteria that can occur in wells)

Where a well is being compromised by organic loadings under aerobic conditions, there are likely to be aggressive loadings of heterotrophic bacteria and the HAB test should also be used. If the injection well is recovering water from an aerobic biodegradation facility, there is likely to be an aggressive pseudomonad population and the FLOR test should be used. Many of these bacteria often dominate the aerobic degradation of a wide range of organics including hydrocarbons (such as JP4, diesel, gasoline) and solvents. At the same time, Pseudomonads can also cause biofouling in the wells. The activity of these bacteria can be measured by their aggressivity when samples are tested. This can be measured as being high, medium or low depending upon the time lag observed during testing. These relationships between aggressivity of the different consortia of bacteria (as low, medium or high) are shown in Table 3-3 for the various states of maturation of a well.

Table 3-3, The likely aggressivity of the five most common consortia of bacteria (left hand column) at the four stages of maturation in a plugging well (going from young, column 2 to plugged in column 4)

Consortium	**Young**	**Maturing**	**Biofouled**	**Plugged**
IRB	Low	High	High	Medium
SRB	Very Low	Low	Medium	High
HAB	High	High	Medium	

Low
SLYM
Medium
High
Medium
Medium
DN
Low
Medium
Medium
Low

As a well undergoes biofouling towards a total plugging, the probability of a successful rehabilitation falls and the consortia of bacteria causing the plugging frequently changes. This can mean that a treatment effective against one consortial group of bacteria may be less effective against another group. Table 3-3 above ascribes the aggressivity of the bacteria in water samples likely to be collected immediately downstream of the site of biofouling. The designation in this table is defined below and does not relate to the aggressivity of the bacteria inherent within the biofouling biofilms but only the probability of detecting the bacteria in the discharge water.

- Low meaning that the bacterial aggressivity is less likely to be detected at that stage even though the bacteria may be very aggressive in the biofouling,
- Medium meaning that there is a reasonable probability that the bacterial consortia will be in the produced water if present and aggressive in the biofouled well,
- High means there is a high probability that if the bacteria are active at the biofouled sites then they will be detected with a high level of aggressivity.

Chapter 4

Extraction/Injection and Draw Down Results

4-1. General

a. In order to develop a well rehabilitation program that will be effective on each well treated, there is a need for a complete historical record of the well. This data can often help us focus our rehabilitation efforts and can indicate areas of design, construction, or operation/maintenance that are contributing to well failure. One of the early symptoms of failure is often the inability to efficiently inject or extract water from the wells because of either a physical (geochemical) clogging or a biological plugging occurring in and around the well. To interpret these events, one of the most convenient approaches is to monitor (and record) the changes in the pumping characteristics of the well. These changes can range from shifts in specific capacity, injection/discharge pressures, increases in draw down and length of pumping times to achieve a specific production goal.

b. It is relatively common for remediation wells to operate at less than the maximum capacity of the formation to accept or produce water. As a result there is a probability that the very early stages in well failures may not be recognized since these partial failures may not be sufficiently significant to affect the observed performance. For example, if a well is over designed so that is capable of pumping 50 % more than the design capacity, and there is a 25 % blockage of the formation, there will be little or no effect on the pumping rate for this well. It would take more than a 33 % effect to cause the pumping rate to decrease below design capacity. Consequently, when failures do occur they can occur very rapidly. Thus even minor losses in performance can, in an historical context, have more serious consequences. This chapter focuses on the generation of historical data and the manner in which this data can be used to determine the long-term operational viability of the well.

4-2. Mapping Local and regional Changes in Water Levels

a. In general, the impact of operating injection and extraction wells will be reflected in changes in ground water levels for the affected regions. The most common means of monitoring the cone of influence is through the use of piezometers positioned at various points within the region influenced by the operation of these wells. The function of these piezometers is discussed below with respect to the operation and management of the injection and extraction wells .

b. Piezometers verify the changes in water levels associated with the activity going on in the borehole. In an injection well, it can be expected that the water levels in the surrounding formation may tend to mound (rise) where the injected water volume exceeds the capacity of the formation to accept that water. This acceptance capacity may decline where there is a significant amount of geochemical clogging and/or biological fouling. The decline in capacity would mean higher mounding which would spread to a larger sphere of influence. A contour map of the water levels generated by piezometer data around the injection well (and site wide) during injection should indicate the extent of this event and can be used as an indicator to adjust a treatment strategy.

c. Extraction wells remove ground water from the surrounding formations normally lowering the water table in the piezometers surrounding the well. The draw down in the well itself will be reflected through the cone of depression in the piezometers. Ageochemical clogging and/or a biological plugging could distort the shape of the draw down curve. Distortions in the curve will be a reflection of the location of the clogging/plugging problem. A problem close to the well should bring a sharply angled cone of depression reflecting the inability of the ground water to penetrate through the occluded zone to the well. In the event that the clogging /plugging problem is further away from the well, the cone of depression would be much steeper inside of the occluded zone but much shallower outside (Figure 4-1). Piezometers positioned inside the occluded zone would thus have similar and very significantly increased draw downs while the piezometers outside the zone should exhibit reduced draw downs related to the distance these piezometers are from the occluded zone itself.

d. One problem rarely addressed is the biofouling of piezometers. Like wells, piezometers can also be impacted by biological plugging that can affect the sensitivity of the piezometer to changes in the water table. In most circumstances this would mean that the piezometer would take a longer time to adjust to changes in the water table as a result of demands created by the well. In very severe conditions, the piezometer may become so impaired that the sensitivity to the shifts in the water table is reduced to an extent that the readings become of little value. The very passive nature of a piezometer as simply a monitoring tool set away from the activity in the wells has led to a state of mind developing that piezometers could not foul. In reality, piezometers could become fouled and fail.

4-3 Evaluation of Fouling Events in Monitoring Wells

a. Monitoring wells, like piezometers, are relatively simple vertical boreholes of narrow dimension installed in the ground strategically set around the injection and extraction wells to monitor chemical levels in the formations influenced by the activity of the wells. The passive nature of monitoring wells, like piezometers, also leads to a common belief that significant fouling will not occur during the operational life span of the site (Figure 4-2). Monitoring wells can become fouled as a result of the passive ground water flow and the pumping of a number of well volumes from the well to obtain representative water samples.

Figure 4-1 Vertical diagram through two piezometers (P1 distant from the well and P2 close to the well) around the extraction well (EW) showing ground level (GL), static water level (SWL) and the cone of depression (dotted blue line) under four conditions. Condition one in the upper left quadrant is a normal operation of pumping water from the well with the cone of depression being observed as having a small effect on the SWL in P1 (1) and a greater effect at P2 (2) with the maximum effect of the pumpage being observed in EW (3). The effect of plugging close to EW (shaded region) in upper right quadrant is shown as condition two. Here, the cone of depression becomes much steeper with little draw down in P1 (4) and P2 (5) but an exaggerated draw down (6) in EW due to the restricting effect that plugging has on the movement of water into the bore hole (7, blue arrows). Quadrant three lower left shows the impact of a piezometer P2 plugging (shaded) to impact on the cone of depression causing little draw down in P1 (8), reduced draw down in P2 (9) but no change in EW (10). This effect is caused by the restricted ability of water to move in, or out of, P2 (11) while movement of ground water in EW (12) is virtually unaffected. Quadrant four lower right shows the impact

of impermeable zones within
the formation (shaded) that are preventing the extraction of water from P1 (13) and P2 (14) while compensatory water flows from unaffected regions
around EW allow the draw down (15) to remain unaffected although the cone of depression (16) would be exaggerated around from the impacted
region (16) from the occluded zones (17) that could have been formed by clay lenses, dispersed biomass or low permeable regions in the formation.

P1
P1
P1
P1
P2
P2
P2
P2
EW
EW
EW
EW
1
8
13
4
2
9
14
5
3
10
15
6
7
7
11
16
12
17
GL
GL
SWL
SWL
(2)
(3)
(4)

Figure 4-2. Diagram of the possible impacts of biofouling in a monitoring well on the analytical value of a water sample take by standard methods
from the well. Quadrant one in the upper left shows a normal monitoring well (NMW) as a vertical section from ground level (GL) through the static
water level (SWL) in which the ground water sample (GWS) is extracted through the well as a water sample (WS).

Where biofouling is occurring as a zone (BZ) around the well then it will become biofouled (BMW) so that the water sample (BWS) taken from this zone is likely to be affected by the activities in the BZ. Biofouling can also lead to the bioaccumulation of chemicals such as heavy metals and recalcitrant organics and the monitoring well (AMW, lower left quadrant three) will generate water samples (AWS) that will, on occasions, include some of these accumulates when they sheer away from the attached biofouling (BAZ) into the ground water as suspended or dissolved accumulates (GWA) generating a water sample (AWS) sometimes high in these accumulates. Where a monitoring well plugs (PMW, lower right quadrant four) then the ground water flow will be diverted (DGW) around the plugged zone (PZ) so that the water sample would be difficult to even obtain on occasions because of the occlusions (OWS) associated with the plugging.

b. Fouling may be viewed to be more likely to be the result of biological fouling due to the changes in the environment brought about by the installation of the piezometer rather than a geochemical clogging since the ground water flow would be relatively passive. The nature of biological fouling of a monitoring well is likely to be significant in a three distinct ways:

(1) The development of biofouling would lead to an enhanced bioaccumulation, which could entrap chemicals of concern. Where bioaccumulation occurs, the water samples drawn from the monitoring well would show anomalous, usually lowered concentrations.

(2) The generation of biofilms within the voids around the well would restrict water flows causing the well to be less responsive to changes in the contaminant levels that would be occurring during the operation of the injection and extraction wells nearby.

(3) Water quality parameters will change as a result of the biofouling. This would be reflected in increased turbidity, more reductive ORP (redox) and a more aggressive bacterial population. This would be important at sites where monitored natural attenuation is part of the selected remedy.

Such events are more likely to occur where the ground water has higher levels of organics and or metals. In extreme cases, such as when there is a floating plume of NAPL then the impact on the level of biofouling could be very significant.

c. Piezometers and monitoring wells that are showing symptoms indicating biofouling should be treated in a similar manner to the rehabilitation and preventative maintenance of wells. These issues are addressed in Chapters 6 and 7.

GL
GL
SWL
SWL
(1)
(2)
(3)
NMW
WS
GWS
BMW
BWS
BZ

4-4 Geologic Regime

a. Geologic maps and cross-sections provide information on the influence of stratification, particle gradations, and geochemical types on well performance and degradation, and how effective original well designs were. Design flaws, such as poorly graded filter packs in variable stratified aquifers can be identified. Expected well treatment problems such as overdeveloping clay lenses can be predicted.

b. Well systems are often designed based on too little geologic site information. Some wells are designed for a generic site condition, sometimes based on a single boring, instead of well-specific data. Reviewing historical files can suggest problems when multiple wells on a site have identical depths, screen slot sizes, and filter packs. Results include screens and filter packs that are too fine or too coarse for the formation material and generally poor hydraulic efficiency.

c. Interpretations of geologic data over time may be distorted or simplified; it is recommended that original field notes be preserved for reference. Good data collection and analysis save operational money in the long term by aiding good well design that improves the capability of facility operators to maintain well systems. It is important that facilities maintain an archive that remains available and accessible despite management changes for use by future technical oversight or advising personnel.

4-5. Maintenance Logs for Individual Wells

a. Purpose. In order to design a successful well rehabilitation program it is critical to know what type of maintenance has been performed at each well in the past. This includes data on chemical or physical treatment in the well bore itself, pump maintenance and/or replacement, flow meter or pressure gauge maintenance, etc. While many ground water treatment systems perform little or no regular maintenance of the wells until performance declines. This leads to a series of ad hoc measures that should also be include in the well history.

b. File elements. Section 2-10 in EP 1110-1-27 reviews the major file elements for well system maintenance. While general site information such as piezometer maps can be held centrally, files should be kept for individual wells to record their specific O&M histories.

c. Information recorded at well site. As an onsite backup, brief basic information on the well should be kept within the casing or casing protection sleeve or structure. This information should include:

☐
Dimensions of the entire well (depth), casing (length) and screen (length, location, type, and slot sizes), and filter pack (length, thickness, and particle sieve sizes).

☐
Material construction of each well.

☐
Pump and power information.

☐
Information on any inserts downhole.

☐
Last service date and information on how to obtain more detailed records.

d. Off-site backup information. Files and video tapes kept at the project site should be duplicated at an off-site location that will continue to be available to site O&M personnel perpetually, regardless of changes in project management or service provider firms.

e. Types of records needed. Essential information includes:

(1) Physical locations and as-built descriptions of the wells and their equipment (including any later modifications), the geographic location of each well should include reference to fixed landmarks as well as precise geographical coordinates such as provided by a geographical positioning system (GPS) for use in plotting using geographical information systems (GIS).

(2) Lithologic log of the well as constructed, well drilling, construction, and development logs, and any other logging data (caliper, gamma-gamma, etc.). Logs must be completely labeled with dates, depths, and borehole site identification. Copies of interpretation reports should be included in the file.

(3) Records of pumping tests and geophysical structure, borehole flow meter, etc., tests of the completed well over time.

(4) Pumping, static water levels and pumping/injection, by date and time of day.

(5) Dates of replacement of components, manufacturer and type of component, if known, and length of service, if known. Itemized invoices with costs should be included. Photos or videotapes should be made of deteriorated components for future reference, including descriptions. Copies of product owner operation and service literature should be included along with documentation of any contractor service personnel.

(6) Electrical power and pump mechanical information.

(7) Water quality data from wellhead samples, plus biofilm collector results, listed by date. Labs and costs should be tracked, and should include reports analyzing water quality data.

(8) Electrical, power and pump mechanical (submittal literature, shop drawings, and nameplate) information.

(9) Details of well rehabilitation activities, including dates, diagnosis, if any, treatment methods, results, time involved and any relevant contractor information.

4-6. Downtime History

a. Injection and extraction wells do not operate continuously but are subject to idle periods as a result of both routine operational maintenance and exceeding the capacity of the related treatment and discharge facility. This downtime is not a time when the wells are totally inactive since there remains a considerable level of intrinsic biological and chemical activity associated with the natural flows of ground water through the well’s environments. One effect of these downtimes is that a different environment develops around the wells that could cause a shifting in the biological activity in, and around, the well primarily as a result of the shifting redox conditions shift and the flow rates change. It is therefore important to track the length of the times that wells are down.

b. Functional failures may also cause an extended downtime until the problem is addressed either by effective treatment or a correction to a mechanical problem. Even a mechanical problem may be a the result of a geochemical and/or biological impact on the functioning of the well. As a result it is very important to determine the length of down time events and their frequency and relate these events to the performance of the wells and changes in the operational parameters being observed after an extended down time.

c. In summary, an increase in the occurrence of significant down times compared to active times for a well is an indication that the well is in a progressive failure mode due to some form of fouling. Efforts should be made to determine the origin of the fouling and address the problem directly in an appropriate manner. Sudden failures of the well leading to enforced down times of considerable length require immediate attention and the cause needs to be determined and rectified.

If the enforced down time occurs suddenly without any previous shifts in the relationship of active down times then there is a significant probability of a major structural and/or mechanical failure. If the active down times have been gradually changing with shorter active and longer down times then the problem should be treated as a potential geochemical clogging and/or biological plugging problem. Evaluations of the data for the specific capacity draw down, biological and chemical parameters may resolve the cause.

Chapter 5

Impact on Wells and Plant

5-1. Invasive or Fouling Bacteria

a. There is a potentially wide range of bacteria that can become involved in the fouling of injection and extraction wells. This lack of oxygen around the wells severely restricts or eliminates members of the animal kingdom including the protozoa and also the molds. Where oxygen is present the aerobic (oxygen requiring bacteria) rapidly uses it aggressively.

In these environments the bacteria tend not to grow freely in the water but as biofilms attached to solid surfaces within the porous media and the well. Within the biofilms there are normally communities of bacterial species known as consortia that perform in a variety of ways. Descriptions of the various types of bacterial consortia can be found in Cullimore (1999) and Cullimore (2000a and b) but the major bacterial consortia are described briefly below. In the classification of the bacterial genera involved there are now two approaches. In the first approach, molecular analysis of the RNA16S is used to identify with precision individual bacterial cultures isolated from the environment. Commonly this involves a selective approach in which a single bacterial culture is identified while the remaining species present are ignored. While a widely practiced art in microbiology today this identification has little place in a complex consortial-rich community that may involve hundreds of different strains of bacteria in a complex interdependent “web” of life. In the second approach, the bacteria are identified at the consortial level. This is called the “lumper” approach as opposed to the “splitters”. In the complex world surrounding a well, the “lumper” approach is probably the more all embracing and of greater diagnostic value.

b. There are a number of major bacterial consortia that on occasions can play critical roles in the fouling of wells. They are described briefly in turn below referencing some of the major genera recognized to be particularly significant.

c. Iron-related bacteria (IRB-) are recognizable because of their innate ability to bioaccumulate iron under oxidative conditions in the ferric form primarily as oxides and hydroxides. As biofilms rich in IRB grow the amount of iron accumulates into the percentile range often reaching as high as 20 to 35% of the dried weight. These ferric salts give the growths a color ranging through orange to red and brown and frequently the growths harden into encrustations, dome-like nodules, wedge-shaped nodules or simply flake-like rust. Bacterial genera often associated with IRB infestations include:

- *Gallionella* (a bacterium that generates a ribbon-like tail that is easily recognized microscopically).
- *Sphearotilus* and *Leptothrix* (both genera where the cells grow within a slime tube usually on the outside edge of biofilms)
- *Pseudomonas* (a heterotrophic aerobic bacteria genus that has the ability to degrade a range of organics and also generate polymeric-rich slimes). They tend to be slow growing growths near or on the oxidative side of the redox front and can be difficult to treat due to protection afforded by the iron-rich coatings.

d. Sulfate-reducing bacteria (SRB) traditionally were thought to only grow in sulfate-rich reductive environments but they have also been found cloistered in aerobic consortia as well. The principle effect of SRB is to generate hydrogen sulfide as a product of growth. This product can have a number of effects ranging from odor (“rotten” egg), taste, the generation of black slimes and the initiation of electrolytic corrosion. This latter effect causes a myriad of problems from the corrosion of pumps, fittings and casing materials to weakening of concrete and grouting. All of these effects can severely compromise the management of a site. In general, the SRB grow more deeply back in the formations and so are often more difficult to successfully treat. When a well has been successfully treated it is the SRB that tends to lose aggressivity the most quickly. The major genus most frequently associated with SRB biofouling is *Desulfovibrio*.

e. Heterotrophic-aerobic bacteria (HAB) often dominate in environments that are oxidative with a significant amount of degradable organic materials such as solvents or hydrocarbon fuels present. They usually grow most aggressively when oxygen is present although many can use nitrate as an alternate substrate to oxygen. Growths are also in biofilms and these tend to be white or pale yellow in color. A number of species generate fluorescent pigments that glow particularly in ultra-violet light. Of some concern is generation of a pale blue glow that indicates the species *Pseudomonas aeruginosa* some strains of which present a potential health risk as an opportunistic (nosocomial) pathogen. Species of *Pseudomonas* tend to routinely dominate these consortia with the genera *Micrococcus* and *Bacillus* also commonly present. Growths dominated by these bacteria can be disrupted relatively easily by effective treatments but, frequently, these bacteria will rapidly recolonize regions effectively treated to remove biofouling growths.

f. Slime forming bacteria (SLYM) differ from the HAB consortia in that they tend to generate much thicker layers of slime during growth that may range in color from white through yellow to orange and shades of gray. This latter color becomes evident under more reductive conditions and often when the bacterial genera involved includes enteric bacteria as well as species of *Pseudomonas*. There are usually more bacteria species involved in a SLYM consortium than a HAB and also these strains are generally also able to function under reductive conditions (in the absence of oxygen). SLYM consortia can therefore often be found in many of the biozones that form around a well and are often much more difficult to disrupt and disperse during treatment than HAB consortia.

g. Denitrifying bacteria (DN) function under anaerobic conditions and possess the unique ability to reduce nitrate essentially to dinitrogen gas. They tend to occur in organically rich (eutrophic) environments where nitrates (generated aerobically by nitrifying bacteria) are present. These DN consortia often dominate treated regions around wells that are reductive.

h. The consortial bacterial groups described above form the major microbial challenges involved in the fouling of injection and extraction wells. Their occurrence is influenced by the oxidation reduction potential in the local environment (Figure 5-1) and they can be recognized by the form of growth that may be seen by camera logging or direct sampling at the fouled site (Figuree 5-2). The nature of the treatment for it to be effective must take into account the forms and locations of the bacterial consortia causing the suspected or confirmed fouling of the wells.

Eh

G

IRB

SB

Figure 5-1. Diagrammatic presentation is shown of the manner in which the oxidation-reduction potential (oxidative at the top and reductive at the bottom) influences the type of bacterial consortia likely to be dominating and fouling the local environment. The vertical scale) shows the Eh (ORP) going from oxidative to reductive with the units set as millivolts. The stratification of biological activities is listed from oxidative to reductive as: growths of *Gallionella* (G), sheathed bacteria (SB) that are set into the biofilms (BF) with iron-rich (IRB) accumulations in the water on the oxidative side of the white to orange biofilms (WOB). Across the redox front on the reductive side are blackened biofilms (BB) due to activity of SRB. Under more reductive conditions denitrifying bacteria can produce nitrogen gas foams (DNF) while below that are the methane-producing bacteria (MPB) that can release copious amounts of methane.

Figure 5-2 Presentation of a vertical profile through vertical (left) and horizontal (right) injection (I) and extraction wells (E) in a vertical (upper) and plane (lower) view. The upper diagram shows from ground level (GL) down through the static water table (SW) showing the influence of operating the wells have on the table causing an up thrusting (UPI) of the water table around the injection well and a down ward (DNE) around the extracting well where the flow through the media (FM) is not adequate to maintain water supply to the extraction well. In the plane view below the two wells are set into the formation media. The colors represent the zonation from oxidative conditions (RED) graded to reductive conditions (BLUE) with the likely zone for biological activity at the redox front shaded vertically.

i. From examining these figures (5-1 and 5-2), it can be seen that the form of biological growth around injection and extraction wells can often be complex and fundamentally different over even relatively small distances. In developing a rehabilitation and preventative maintenance strategy, it becomes critical to consider where the maximum biological activity is likely to be in relation to the wells. For a rehabilitation to be successful it is important to ensure that these plugging forms of growth are dispersed. Successful rehabilitation does not mean that the treated formations are now “sterile” but it does mean that the hydraulic pathways that were plugged are now open again. It must be considered that microbial recolonization of the “treated” regions will start again usually very quickly. It is recommended because of the instability created by an effective treatment that post-treatment monitoring for the impacts on the biofouling communities be delayed for at least six weeks. Major considerations are summarized below:.

(1). It is inevitable that microbial fouling will occur around extraction and injection wells. The form of these infestations is going to vary but all will involve some attachment to surfaces where the biofilms grow, expand to form slimes, and then frequently harden. These growths therefore become robust and durable and can easily withstand the variations in pressures and flow associated with the enforced movement of water through the well.

I
E
GL
SWT
EWT
IWT
UPI
DNI
FM
VERTICALVIEW
PLANE VIEW

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(2). These microbes are predominantly bacteria in the saturated zones and molds in the vadose zones above. These microorganisms can cause a range of events to occur in the well environment. These include corrosion, biodegradation, gas biogenesis, acidic leaching, water retention and various forms of concretions. Relevant events are described in the glossary of terms.

(3). It is difficult to determine which microorganisms are dominating in a particular extraction or injection well since there are so many micro-environments within which these various microorganisms can flourish. In an injection well there is a high probability that bacteria infecting the well via the injected water initiate some of the fouling. However, extraction wells are probably most likely to be dominated by the natural bacterial flora that are already in the formations around the well and are stimulated by the changes in the environment associated with the installation and operation of the well.

(4). Whatever the circumstances it is unlikely that the microorganisms focusing within and around the well will remain passive given that the environments are in an active state when the wells are operating.

5-2. Attenuation and Degradation of, or by, Biological Constituents

a. Not all of the impacts of the microbial activity around wells are deleterious and during rehabilitation it can be expected that even the positive impacts of this activity will also be impacted. Attenuation, in this context, refers to the reducing the impact of contaminants through biological activity in and around the wells. This attenuation is primarily a result of components in ground water bioaccumulating within the biofilms. Such accumulates may continue to concentrate in some of the biofilms under favorable redox conditions and water passing out of the zone of influence of the well could have considerably lower values for these bioaccumulated wastes. However, in the rehabilitation or PM treatment of the well, these accumulates could be sufficiently disrupted where they are released and pumped out of the wells during the treatment and post-treatment phases. The result of these releases would be the discharge of sufficiently high levels of the contaminants, which would have to be treated or properly disposed.

b. Where the contaminant is predominantly organic, there is a potential for these organic compounds to become degraded through microbial activity within the biofilms forming within the impacted zones. Generally degradation under oxidative conditions tends to be more complete with carbon dioxide as a common terminal product. Under reductive conditions, such biodegradation pathways are fermentative and usually terminate with the production of at least some fatty acids (including volatile fatty acids). Under such reductive conditions the fatty acids now become prime substrates for the SRB and the methane-producing bacteria (MPB). Under less reductive conditions it is the SRB that usually dominate to generate black slimes while under more reductive conditions the MPB are more aggressive and are able to dominate generating copious quantities of methane.

5-3. Geochemical Changes

Geochemical changes are an inevitable and parallel event accompanying the fouling of wells. The major changes are likely to be primarily hydrological as the biofouling affects the water pathways through the geological media. Secondary impacts occur where these growths now develop into impermeable “lenses” and grow larger through the entrapment of colloids, silts, clays and sands as well as through the growth and maturation of the biofilms into plugging formations. Such activity can also cause localized “mounding” of ground water around the site due partly to this plugging and partly due to water “bound” within the plugging formations rising up into the vadose zones above. Coring can best monitor the impact of these effects and sampling from within and around the affected region.

5-4. Flow Rate Adjustments

a. Flow rates into, and out of, the wells will be influenced by biofouling occurring around the well screens and out into the formations. To achieve a constant volume of water flow through the well, adjustments will have to be made to meet the design criteria.

b. For injection wells, water is forced down into the formation through the vertical or horizontal borehole. For the vertical wells, it is unlikely that the water would flow out of the well uniformly but would move towards those regions closest to the flow or the most porous regions. This focusing of the flow also creates a condition where the associated turbulence, water pressure, and an alien-environment can cause accelerated aggressive microbial activity. There is a two-fold effect of this happening; radical plugging occurs and increased hydraulic resistance created by these plugging growths diverts the flows deeper in the borehole (Figure 5-3). This increase in resistance could now result in the need to apply more energy to achieve the same rates of injection through either increasing the pressure and/or the flow rates. Since the screened area through which the water has to pass into the formation may be relatively small (compared to a horizontal injection well), plugging conditions may severely limit the injectable volumes.

c. Horizontal injection wells generally have a much greater screened area at the given depth of injection that means that the plugging is less likely to become so focused and not as able to completely plug up the formation around the screens. A much slower increase of resistance to flow may be helped by the relocation of the plugging growths in response to the changing water flow patterns. The net effect may be that the horizontal injection well will take a longer time to reach a plugged state and would not involve a high-energy demand or adjustments to maintain flow.

Figure 5–3. Vertical section of an injection wells showing the changes in movement of water (arrows) during pumping. The progressive effect of biofouling (1, 2, 3 and 4 show progressive growths as shaded zones) around the screens (lateral line shading) using in quadrants 1 to 4. Growth initially forms within the zones where water is flowing actively out of the well. Once the well has plugged off, there is very little flow (dashed arrows ,4).

d. Extraction wells are doing the opposite of injection wells and are “pulling” water out of the aquifer formations. On some sites this water was injected into the ground at a planned distance as a part of the remediation strategy. Biofouling is likely to be back further in the transitional formations between the injection and the extraction wells. Commonly there would not be such a focusing of microbial growth close to the borehole unless the extraction well is removing contaminants (and particularly organics) either passively or through backpressure from the injected upstream water. Fouling and plugging in these wells is more likely to be dispersed and less likely to cause adjustments in the flow rates. In the event of the extraction of organics and particularly floating plumes of organics (such as fuel) the movement of these materials into the borehole can trigger intensive plugging events. These will often require not just adjustments to flow rates but also rehabilitation and careful management to minimize these impacts.

5-5. Permitting Requirement for Disposal Water

There are variations in the local, state and federal requirements for the disposal of waters that have been involved in the rehabilitation of a fouled well. The concerns range from the direct release of contaminants, treatment chemicals, and/or of their daughter products in the discharged water. The permitting requirements will vary from site to site, depending on the procedure used, the products and byproducts of the treatment, and the effectiveness of the rehabilitation treatment needed.

Evaluation of the permit requirements should be an essential early stage in any rehabilitation program. Careful attention should be paid to the predictable impact of the proposed rehabilitation scenario not just on the potential recovery of the well but also, and equally, on the downstream impact of the treatment itself. It is recommended that your Office of Counsel be consulted to determine whether there is a need for any permits before any field-based treatment is initiated.

5-6. Treatment Plant Capability to Handle Flow and Constituent Changes

Successful rehabilitation should control the form of fouling and/or any mechanical compromises, thereby increasing significantly the flow to and through a treatment plant over a short period of time, up to ten days after rehabilitation. Where treatment plants have been brought on-line significantly after the installation of the wells, the production by the wells could exceed the previous maximum experienced by the treatment plant especially if the wells were already partially fouled when the treatment plant went on-line. Successful rehabilitation would bring the well production closer to the real maximum that would have occurred before the wells were significantly compromised. In designing the rehabilitation sequences for wells, care should be given to the impact of sudden and significant increases in flow to the treatment plant that may exceed the capabilities of the plant. Staged rehabilitation may be required to ensure that the treatment plant would be able to handle the increased flow.

Given that the biofouling is generated at least in part through presence of sufficient organics as one of the primary drivers in the activities, then the effluents being generated from the treatment processes are likely to create an oxygen demand within the body of the environment receiving the product. The releasing of effluents with too high an oxygen demand is therefore likely to have a negative effect firstly upon the indigenous animals now competing for the oxygen, secondly on all organisms during periods when respiration using oxygen is the dominant function, and thirdly in a positive manner on the microorganisms that are either able to continue to function, or begin to function, in these oxygen depleted environments. Federal and state regulations are in force to limit effluent discharges commonly based upon the 5-day BOD (biochemical oxygen demand) test. These regulations ensure that the oxygen demand being created by the effluent does not exceed the capacity of the receiving bodies to support the fauna and flora already resident in those bodies. The 5-day BOD test has two significant limitations. First, the test examines only that fraction of the organics that are respirable by the organisms within the environment. Second, the test takes five days to complete which means that the data generated is aged and any management responses are delayed. In the management of the control of potential environmental impacts from such effluents, a faster test widely used to monitor the potential impact is the chemical oxygen demand (COD) test that forms a measurement of the total materials that can be chemically oxidized. This test therefore gives the maximum oxygen demand that would be created if all of the substrates within the samples were to be oxidized. COD therefore generates high oxygen demand data whereas the BOD is restricted to those substrates that were biologically respirable during the five days of the test period and would not include the more recalcitrant materials. In the practice of good environmental practices, it is important to assure that all liquid effluent discharges have a BOD that is acceptable to the state and federal regulations in force at the site and that the COD may provide an effective management tool to ensure reactive compliance.

Chapter 6

Evaluation of Treatment Alternatives

The discussion of treatment alternatives that follows is predicated upon having an experienced contractor apply the various technologies. Great care should be taken during the selection process to have contract language that requires a minimum of five years experience in applying well rehabilitation technologies and one year applying the present treatment **method**. Inexperienced contractors often do more harm tan good to wells and the contracting officer should aggressively check references from previous customers of each contractor. While cost is certainly an important factor in selecting a treatment option, it should not be the overriding factor. There are many inexpensive ways to rehabilitate wells that are unfortunately ineffective.

Care needs to be practices to ensure that any contractor selected to undertake a treatment has both the knowledge and experience to complete the task in a manner that would achieve the designated results. Selection needs to include an evaluation of the contractor’s record in performing similar tasks in the past, ability to understand the nature of the tasks to be performed, and have the necessary equipment and personnel to ensure that all of the stages in the treatment process assigned to the contractor can be completed with confidence. This would include the contractor having a thorough understanding of the regulations and the environmental implications associated with the treatment practices. Examination of the past records of the contractors should be an essential step in the selection process. This examination should include a full range of experiences from stellar successes to problematic treatments where unforeseeable circumstances led to failures. An acceptable contractor should be as willing to divulge these failures and learn from them as much to develop confidence from successes.

6-1 Introduction to Treatment Alternatives

As presented in previous chapters, no two wells will foul in exactly the same manner and a rehabilitation strategy, to be successful, must take into account the nature, location, and form of the fouling that is occurring in individual wells.

The industry sector involved in well rehabilitation has a natural bias towards the application of their recommended products and processes. Rehabilitation, unlike replacement, of all types of water wells remains a relatively young service industry and this has resulted in the limited number of viable options available and a limited database of independent verifications of the effectiveness of particular rehabilitation technologies. This chapter will be divided into two parts:

(1) A survey of the potential treatment applications that are currently in use.

(2) A discussion as to which of the potential technologies would be the most suitable for the particular problems in the injection and extraction wells of direct concern to the reader. This includes both the critical steps in diagnosing the problem, the selection and application of the treatment, and the formulation of post-treatment preventative maintenance.

6-2. Survey of Potential Treatment Applications

Rehabilitation treatments can often involve some combination of physical and/or chemical applications since the target is to control, and preferably remove, a form of fouling that is dynamic and involves different agencies. At this time, rehabilitation is focused on physical and chemical treatments because no biological treatment has yet been demonstrated as effective in the long term. In this survey, there are three major sections covering the applications ranging from the use of a single physical or chemical treatment to the blended treatments that involve both physical and chemical aspects.

Selection of a treatment option to achieve the successful rehabilitation of a well will be somewhat different when the problems originate from geochemical clogging sources rather than biological plugging. The treatments' relative effectiveness will be addressed for each of the potential fouling conditions.

6-3. Overview of Physical Treatments

Physical treatments can be divided into the following categories:

- Direct application of heat.
- Hydraulic surging and direct physical cleaning of the fouled sites.
- Shifting in position of the redox front.
- Application of electro-magnetic charges.

a. Direct application of heat. Since the discovery of the use of heat to control the biofouling (spoilage) of foodstuffs in the nineteenth century by sterilization (Nicholas Appert) and/or pasteurization (Louis Pasteur), heat has been widely used particularly in the medical, food and beverage industries to control biofouling/spoilage. All living organisms can only function within a set range of temperatures. Elevating the temperatures inhibits organisms and then is lethal once the temperature rises well above the normal range. In rehabilitation of biofouling, it was considered that simply raising the temperature by greater than 40 °C (104 °F) above the ambient background temperatures was normally sufficient to kill off the cells that do not have a heat-resistant form (e.g., spore). The advantage of applying heat to a well is that a thermal gradient will form and gradually move out around the well, penetrate the slimes and deposits as well as the porous media and eventually kill most of the microbes contained in that zone. This technique is a very effective **method** to reduce the microbial population, however, the impact on the slimes, deposits, and other plugging and clogging elements is often minimal.

Various techniques have been applied to heat wells as a means of controlling plugging including injected steam and hot water, the use of immersion heaters, and the use of chemicals that generate exothermic reaction when hydrated. A relatively small number of biofouled wells were found to be recoverable using this technique even when the temperatures reached as high as 85 °C (185 °F). The reason for the relatively poor performances observed was considered to be a combination of failure to disrupt and disperse the biofilms and other deposits along with the thermal coagulation of the slime (similar to the impact of boiling on the white of an egg). The application of heat has been found to be more effective when combined with chemical treatments since this additional heat also accelerates the rate of the chemical reaction causing shocking and disruption of the fouling material within the well.

While raising the temperature in the fouled zones in and around a well has been investigated, there have been some efforts to lower temperature in order the freeze the biofilms. It has been documented that when a biofilm freezes it will commonly detach and become disrupted. Because of the technical difficulties of freezing a fouled zone around a well, it has never been developed to a fully commercial verified technology. Similar to the blending of heat with chemicals acts to improve the effectiveness of rehabilitation, so blending low temperatures with chemical additives (such as carbon dioxide) can under some conditions prove to be effective for rehabilitation.

b. Hydraulic surging and direct physical cleaning of the fouled sites. Geochemical clogging often involves the siltation with fines (silts, sands and clays) within the voids in response to the water flow patterns through the voids. Where this is the principle problem, radically changing the water movement characteristics, usually by vigorous agitation within the borehole, can set up conditions that disrupt and disperse this material. Agitation can either push the material back out further into the formation or release the material into the borehole where it can be removed by techniques such as air lifting.

Biological plugging, when also present, tends to reduce the ability of physical surging to release the accumulated materials. This is principally due to the binding action of the polymeric slimes. In the event that the problems in the wells involves mainly a biological form of plugging then the hydraulic surging would be more effective after the plugging material has been shocked and at least partially dispersed. Once the material forming the biological plugging has been dispersed then surging can much more effectively remove the bulk of the biofouling within the treated zone.

In addition to surging, the direct action of brushing down the screens in a borehole is recommended where there is material in the form of encrustations, slimes or deposits that is adhering to the insides of the screen slots. Brushing utilizes a simple series of whip-like strokes to physically detach such materials that may then be removed by the hydraulic or air-lift surging of the well. Essentially the initial use of brushing will remove some of the more exposed materials from the well and open up fresh surfaces to the other treatments when they are applied.

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c. Shifting in position of the redox front. Microbiological activity in biofouling events tends to focus at the redox front (see section 2-11-l and 5-1 for specific examples). The redox front is formed as the interface between the reductive conditions (free of oxygen) and the oxidative conditions (where dissolved oxygen exists). On the reductive side of the front, organics tend to be incompletely degraded. These daughter products of partial degradation are however rapidly degraded under oxidative conditions. This results in a focusing of oxidative (aerobic) microbial activity at these fronts since there is an intense competition for the nutrients flowing from the reductive side of the front and oxygen flowing from the oxidative side. In laboratory experiments designed to deliberately biofoul porous media; it is common for the biofilm growths to concentrate around the redox front. Where the redox front is close to the well (as may be the case with many injection wells) then there is likely to be a significant increase in biomass close to the well. With the growth and maturation of this biological plugging, the specific capacity can become drastically reduced. It has been found that where the redox front sets up further back from the borehole, there is a larger amount of available surface area and void volumes within which the biofouling can grow. As a result there is a much slower impact on the specific capacity of the well. This does not mean that there is any smaller a biomass involved than where the redox front was close to the well but the biomass is more dispersed.

Some techniques deliberately involve, as a rehabilitation treatment, the relocation of the redox front further away from the well. This can be done by creating a larger oxidative zone in, and/or, around the borehole. A larger zone can be obtained by injecting aerated water down a number of satellite wells around the affected well, or by injecting the aerated water directly down the borehole often at rates equivalent to a significant part (e.g., one third) of the production of water from the well. In either case it is the expansion that occurs in the size of the oxidation zone around the well that drives the growth of fouling microbes further out into the formation. Forcing the redox front out could be compared to blowing up the “slime balloon” so that it is further away from the well and would take longer to have an effect. Thus, driving the redox front further back into the formation also increases the surface area of the front that would have to be severely fouled in order to affect the production characteristics of the well. The net effect is that the biological plugging moves outwards away from the well along with the redox front. This causes the plugging to become dispersed over the greater surface area and the specific capacity of the well is not as dramatically affected by the ongoing plugging of the well. It should be noted that clogging because of its geochemical nature would not be so affected unless it is also driven predominantly by chemical oxidation phenomena.

This technique of manipulating the redox front is more applicable to improve the sustainability of the water well by reducing the rate of observable biofouling rather than employing a rehabilitation technique on a challenging situation where the biological plugging is already deeply entrenched around the well. It should be noted that the acquisition of a larger oxidation zone through the inputs of oxygenated water into the well environment could enhance the overall level of aerobic microbial activity. Where this happens the discharged waters may carry a greater burden of more aggressive bacteria that have sloughed from the larger surface areas generated by the expanded redox front.

d. Application of electro-magnetically charged surfaces. Biofouling and the associated microbially initiated corrosion have been a major concern in all industries using steel structures and pipes. In the oil and gas sector these problems are catastrophic leading to major losses of product and many installations employ an active cathodic protection to the vulnerable surfaces. Corrosion, where it is microbially induced, involves a number of stages. The early stages relate to the attachment of microbes to the surfaces and the generation of expanding biofilms that cover significant amounts of the surface. The forms that the biofilms mature into are very much a factor of the local environment including the form and resident charges of any metals and concretes at the surfaces and their physical state (e.g., porous, embrittled, fractured). Growths may generate into nodules, tubercles, and encrustations and may be either iron- or calcite- rich. Corrosion is mostly initiated through the biofilm generating acids (acid producing bacteria) or hydrogen sulfide (sulfate reducing bacteria). When the latter gas is produced it initiates an electrolytic form of corrosion. Corrosion can cause a number of effects from pitting, lateral fracturing, dramatic losses in strength and mechanical failure.

To understand corrosion there is one golden rule and that is **the microbes are all negatively charged and therefore gravitate towards positive charges**. When cathodic protection is used to protect a surface from a microbial biofilm infestation, the surface contains an impressed negative charge that prevents successful attachment of microbial cells to the surfaces. At the same time an anodic (positively charged) surface is generated as a sacrificial point at which microbial attachment and subsequent growth and corrosion will occur at sites that have no consequence to the operation of the device. The art of cathodic protection is now widely practiced but has not been extended to the injection and extraction wells because of lack of experience, high operating costs, and uncertain benefits.

This use of cathodic and anodic charged surfaces and fields is now being subjected to investigation as a means of anodically focusing (AF) or cathodically disrupting (CD) a potential or actual site of biofouling. These processes are now patent pending (Alford, Cullimore, Monea and Johnston, 2003) and have potentially major implications for applications to wells as a means of manipulating the form, function and position of biofouling events. It is expected that the CD process may be very suitable for application as a part, or the whole, of a preventative maintenance treatment.

6-4. Overview of Chemical Treatments

There exists a broad spectrum of chemical treatments, some of which are target specific single chemical treatments while others involve applications using various blends of chemicals. For the purposes of this survey, the chemicals are separated into the following sections: disinfectants, acids, dispersants/penetrants, alkalis and chemical blends.

a. Disinfectants. Disinfection relates to the ability of a chemical to significantly reduce or eliminate the risk of infection arising from contaminated water. Chemicals are traditionally used to reduce health risks by suppressing or killing infectious microbial agents causing such diseases as cholera, dysentery, and typhoid. The perception that disinfectants are equally effective against all microorganisms is not necessarily the case. Traditionally, the effectiveness of disinfectants has been judged by their effectiveness against the enteric bacteria that includes the coliforms, *Escherichia coli* and the major infectious agents mentioned above. However, the focus in treating an extraction or injection well should be on disinfecting the well of the infestations of microbes causing problems to the “health” of the well. Unfortunately, the disinfectants effective against the enteric bacteria may not be effective at all against these biofouling agents. Chemical groups commonly used as disinfectants include the halogens, various benzene/phenol based compounds and ozone or peroxides. Of the halogens, it is the chlorine-based compounds that have been the most effective particularly at controlling the enteric bacteria including coliforms although both iodine- and bromine-compounds have been found to be effective under some circumstances. There is a vast array of benzene/phenol-based compounds available in the marketplace and many function to suppress microbial activity (bacteriostatic) rather than kill (bactericidal) in the low parts per million range. Ozone or peroxides are both commonly used disinfectants that rely for their effectiveness in creating such a strongly oxidative state often with hydroxyl radicals that together acts to very significantly reduce the microbial populations in the impacted environment.

To be effective, the disinfectant, as a minimum, has to reach the cell wall of the targeted microbial cell and either cause irreparable damage to the cell wall or enter the cell and create irreversible damage. In order to achieve either of these impacts, the disinfectant has to penetrate through the bound water zone held in place by a complex web of polymers (that form the biofilms). Cationic disinfectants are likely to get absorbed into this matrix and never make it to the cell. In a growing biofilm, much of the volume is composed of the polymeric matrices with, commonly, less than 0.1% of that volume actually made up of microbial cells. The dispersed nature of the cells within the matrix thus makes disinfection more difficult to achieve. Often a dispersant and penetrant is used concurrently in order to disperse these matrices and expose the cells to the action of the disinfectant. Given these limitations in effectiveness there are also significant differences in the activity of the various chemical disinfectant treatments when applied to wells. These are summarized below.

(1). Chlorine-based disinfectants include chlorine gas, chlorine dioxide and forms of hypochlorite. The first two forms are very powerful disinfectants but require judicious use because of their extreme levels of chemical activity. Generally chlorine gas use is restricted to carefully managed conditions while the chlorine dioxide can be applied more widely when used with an inhibitor to control the releases of the active chlorine dioxide. Most of the time it is the hypochlorites that are used either as the sodium salt (soluble) or the calcium salt (solid). Sodium hypochlorite is widely available in different strengths commonly ranging from 5 to 12.5% but degenerates significantly on storage. Application to a well site is convenient and low residual chlorine values in the low ppm range can control the enteric bacteria. However, sodium hypochlorite is not as effective against maturing biofilms and the impact may be limited to a compression of the slimes that does improve conductivity in the short run. Once the hypochlorite has been flushed through the system and the residual value is gone, there is often a rapid rebound that again restricts conductivity through the infested region. In some wells that have been subjected to hypochlorite treatments the short-term gain may only last from hours to a few weeks depending upon the severity of the fouling. Calcium hypochlorite has a much lower solubility and is often dispensed in a tablet or pellet form that dissolves slowly. There is some risk of these pellets/tablets hanging up and not dissolving completely causing concretions to form that could cause localized clogging. Chlorine gas is much more reactive and, along with chlorine dioxide, is generally more effective.

Over the past four decades, disinfection using chlorine-based chemicals has lost a lot of its advantages due to the generation of potentially health threatening trihalomethanes (THM) and possibly other compounds by interaction between the contaminants and the chlorine. In many states the use of these chemicals is severely restricted because of the risks posed by the THM products of the disinfection. There has been a swing to other disinfectants such as ozone and. Disinfection is only one part of a treatment protocol to rehabilitate and its effect may be severely limited to some of the enteric bacteria (and in particular the coliforms) but not to the vast majority of the bacteria that are causing the biofouling.

(2). Ozone has over the last two decades been increasingly promoted as a replacement for chlorine-based compounds to achieve disinfection. Ozone is a very powerful oxidizing agent that creates an environment lethal to many microbes. This condition is enhanced by the releases of hydroxyl radicals that can also act as bactericide. However the effectiveness of the ozone is limited by the lack of any residual disinfectant activity. Thus even when a massive ozonation of a well is conducted, once completed, there would be no residual antimicrobial activity. Localized impacts with ozonation on the microbial populations can be dramatic reducing the population often by more than four orders of magnitude. In an open system such as a well, the application of ozone would have a marked, but localized effect. The zone in which the microbial populations had been severely impacted would undergo a rapid recolonization by microbes moving in from outside the impact zone. These organisms would utilize the organic debris left from the treatment as a food source so that regrowth could be very fast.

(3). Peroxides are also oxidizing agents and are lethal to microorganisms. However peroxides are a normal byproduct of aerobic activity (respiration) and so microbes able to grow aerobically possess a biochemical protection mechanism. This is the possession of an enzyme system called catalase that rapidly breaks down the peroxides to water and oxygen. So universal is this enzyme that it is a part of a standard test to determine whether a bacteria is aerobic because it will usually be catalase positive. A good example of this in action is the application of hydrogen peroxide to an infected skin wound. Here the peroxide immediately erupts into foam caused by releases of oxygen through the action of the catalase. In practice, peroxides have been used in a blended chemical treatment but more rarely as a single chemical treatment.

Both ozone and peroxides create strongly oxidizing conditions with the releases of oxygen as a daughter product. The presence of this condition along with the presence of oxygen is likely to impact at least temporarily on the redox front moving it away from the treatment zone. At the same time the saturation of the region with oxygen as a product of the treatment along with the residual organic debris left over from the treatment impact can stimulate very significant aerobic microbial activity.

(4). While the previous chemicals described in section 6-4 are relatively specific and easy to chemically define, there are also a large group of benzene- and/or phenol- based chemicals that do have significant bactericidal properties. They have been widely employed in the health- and food- related industries, but none have yet become widely adopted in the treatment of biofouling in wells. Generally, these chemicals are broad-spectrum disinfectants that commonly focus on the enteric bacteria and/or the Gram-positive cocci.

In the treatment of wells, the selection of a disinfectant as the treatment agent implies that the main concern would be health-related and that the objective is not to effectively control the biofouling as such. In general, disinfectants have been designed to function most effectively on either flat relatively non-porous surfaces or in waters with a low to moderate turbidity. This effectiveness is compromised when attempting to disinfectant porous media with the surfaces coated and the void spaces filled with microbial biofilms. In most cases where disinfectants are used they are used in combination with other chemical agents (see sections 6-4-e, 6-5 and 6-7).

b. Acids. Acids are capable of breaking down both the polymers forming the slime and the matrices forming the microbial cell walls by a process called hydrolysis. In this process some of the bonds within the molecules are fractured causing the large molecules to collapse into fragments and so lead to the deconstruction of the biofilms and the death of the cells within those impacted structures. Hydrolysis usually becomes a significant event when the pH in the environment drops below 4.5 and can become extreme where the pH falls to less than 2.0. It should be remembered that dramatic as this may seem there are many microorganisms that can flourish in very acid pH conditions right down to a pH of 0.0. The effectiveness of an acid treatment is therefore partly dependent on the temporary pH swing created by the application of the acid. The temporary nature of the pH swing means that there would not be time for the acid-loving bacteria (acidophiles) to grow and become dominant. Effective pH swings from the ambient pH values should ideally be at least 3.5 pH units with greater than 5.0 pH units to achieve a maximum effect.

There are two major groups of acids, inorganic and organic. In general it is the inorganic group that can achieve the greater pH swings but it is the organic group that sometimes has a greater disinfectant activity level. It is more important to achieve a designed pH swing towards an acidic state rather than to apply a specific quantity of the chemical. The pH meter and the determination of the extent of the pH swing become a more important measure than the weight or volume of the selected chemical applied.

It is often necessary to achieve the required pH shift to combine organic and inorganic acids to reach the rehabilitation goal. This combination results in an optimal detergent and disinfection capability.

(1). Inorganic acids. Inorganic acids commonly used in the rehabilitation of wells include hydrochloric (muriatic), sulfamic, and phosphoric acid. Each of these acids plays a very different role when applied and need to be considered separately. A summary of the limitations and suitabilities of these chemicals is given in EP 1110-

1-27.

(a). Hydrochloric acid has been used in the water well industry for many years as a well cleaning chemical. Third strength hydrochloric acid is commonly known as muriatic acid and this term is often preferred since this form of the acid is known to be less corrosive than the concentrated and glacial forms of hydrochloric acid. The low pH generated by these acids is particularly effective against encrustations. Camera-logging the well before and after treatment with the acid can show dramatic improvements such as screen slots becoming freed from any forms of deposit or growth. There remains a risk that the acid may also begin to attack the metal (such as stainless steel) and some formulations include some additional chemicals to act as an inhibitor. Usually the inhibitor added is a gelatin-based material that is able to control the aggressivity of the acid to the metal surfaces. Some of these inhibitors are toxic and so caution should be exercised when using inhibited acids. It should also be recognized that if the treatment chemicals are not completely removed from the treated well then there could be two possible concerns. First, there is the effect of the residual nature of any toxic materials involved in the inhibitor. Second, the gelatin base applied with the inhibitor may act as an additional food substrate for the microorganisms recolonizing the impacted site.

In general, hydrochloric and muriatic acids have been widely used in the industry with a direct impact on the inner surfaces of the borehole and screens. When used as a single source chemical treatment, these acids have not been found to be able to penetrate deeply into the packs and formations around the well. Some newer rehabilitation treatments do still use hydrochloric acid but only as one component in a blended treatment train (see sections 6-4-d, 6-4-e and 6-7). Caution should be exercised when working with these acids since they are very corrosive and all safety guidelines should be observed.

(b). Sulfamic acid is often used as a less vigorous form of treatment. This chemical will not drop the pH as effectively as hydrochloric acid but it is much easier to handle and can be purchased in a dry form. This makes transportation and handling much safer but gloves, masks, goggles and effective ventilation should be used. Sulfamic has been found to be particularly effective against carbonate-rich scales and encrustations but remains less effective against biofouling particularly where these are rich in metals. It is common for sulfamic acid to be used in blended mixtures with other acids (see sections 6-4-e and 6-7).

(c). Another inorganic acid that has been widely used in the industry is phosphoric acid. It is effective against the various metal and mineral hydroxides and has been used widely to remove concretions and encrustations rich in these materials. It is, however, less effective against biofilms. There is a concern that treatments using phosphoric acid may tend to leave significant amounts of phosphate residues behind to stimulate microbial growth. Because of this risk of stimulating

the reoccurrence of biofouling with these residues, the use of phosphoric acid and phosphorus-based compounds is **NOT RECOMMENDED** as a part of a rehabilitation strategy for injection and extraction wells.

(2). Organic acids. The organic acids most commonly used include oxalic, acetic and hydroxyacetic (glycolic). A summary of the limitations and suitabilities of these chemicals is given in EP 1110-1-27.

(a). Of the organic acids, acetic acid has had a long history as a very effective biocide validated through the use of vinegar in the preservation of many foods. It has also been found to be very effective in the dispersing of biofilms. It is not as effective an acidizer as the inorganic acids described above and generally the pH can normally only be brought down to around 3.5. While acetic acid is widely available as a byproduct from many industries, it is strongly recommended that a food-grade or good industrial grade be applied. Some of the lower grades tend to have significant quantities of various metals and other compounds that might compromise the rehabilitation process. Acetic acid comes in various forms and concentrations ranging from 30% up to >85%. There are two distinct problems associated with acetic acid. First, the acetic acid tends to gel at temperatures below 55 ^{o}F making dispensing difficult if not impossible. Second, strong odors are given off from the acetic acid that can become repulsive to the workers and inhabitants of regions surrounding the treatment site.

To combat the fist concern, it is recommended that the acetic acid containers be kept at room temperature in regions where the ambient temperatures fall to less than 55 ^{o}F.

Acetic acid performs as both a disinfectant that is very effective against many bacteria and also as an acidizer. Consequently it is commonly used in the rehabilitation of wells. To improve the ability of acetic acid to act as an acidizer, sulfamic acid is often added to improve the ability to lower the pH down to less than 2.0 (see section 6-4-e). The odor problem can also prove to be challenging where the wells being treated are in a populated region.

An effective alternative to acetic acid is hydroxyacetic (glycolic) acid. Glycolic acid appears to be a stronger biocide than acetic acid. Glycolic acid has further advantages in that it requires less of a volume to be applied to lower the pH. In many ground waters, the nature of hydroxyacetic acid as a stronger acid means that it requires only 1/3 to ½ half of the volume to effectively treat a well in comparison to acetic acid. This advantage commonly more than offsets the increases in cost involved in using glycolic rather than acetic acid. Additional advantages for glycolic acid are that it odorless and safer to handle. The increases in the cost per volume of glycolic over acetic acid is therefore compensated through the stronger nature of glycolic as an acid, the odorless nature of the glycolic, its greater ability to act as a biocide, reduced risk for the operators handling the product and the lower volumes of the glycolic acid that need to be applied to achieve the designated pH shift.

(b). Other organic acids sometimes used are oxalic and citric acid. These acids are good acidizers in low-calcium waters and also act as chelators. However, both should be avoided in high calcium content (>125mg/L) waters where it can generate insoluble precipitates that may induce additional clogging causing the rehabilitation treatment to fail. Citric acid is widely recognized to inhibit the activities of many microorganisms and is a mainstay in the prevention of microbial spoilage in the beverage industry. However, citric acid does form a potential substrate for the growth of many bacteria in the sub-surface environment.

c. Dispersants / Penetrants. There is a wide range of compounds that have been generated as adjuncts to the detergent industry. These compounds fundamentally possess the ability to clean surfaces by a variety of mechanisms. These compounds are grouped according to the form of their effect on a biofouled region. Where the effect is for the compound to penetrate into the biofilms and cause a disruption of the structures, these compounds are known as penetrants. Penetrants would be used under conditions where there is known heavy biofouling and the purpose is to enter into and disrupt the biofilms causing them to break apart. They may also be used to break open a pathway along which other chemicals can enter into the biofouled region and have a significant impact. When the effect of the compound is to remove relatively thin layers from a surface, thus rendering that surface clean, the compounds are known as surfactants.

Detergent has been the name given to those chemicals that are effective in removing foreign materials primarily from various forms of fabric. The detergent group tends to act more like surfactants in that the action is essentially surface cleaning. There is a considerable functional overlap between these various chemicals that is further complicated by the fact

that these compounds may be anionic, cationic or neutral in their charge. The form of this charge clearly would influence the manner in which the chemical would function as a penetrant, surfactant, detergent or dispersant (PSDD).

In the marketplace, these chemicals have achieved considerable use as synergistic stimulators of other chemical activity (such as the effectiveness of pesticides and cleaning agents). This gives these products considerable value and their formulations and precise abilities are protected as commercially confidential. As a result the exact nature of the various chemicals in this group is often difficult to determine but their adjunct effects on various chemical processes is well recognized.

It is rare for a PSDD to be used as a sole treatment chemical since their addition is usually associated with improving the efficiency of some other chemical treatment. There is a growing group of PSDD that have additional functional ability that may allow them to be used as a sole treatment agent. For example, the dispersant CB-4, an anionic polymer, is not only an effective dispersant of biofilms at concentrations above 0.01% but is also biocidal at concentrations in excess of 0.5%.

Thus this compound has merit in the preventative maintenance phase since it is not only able to disperse biofilms but also able to kill many of the incumbent microorganisms. As research progresses, it is probable that there will be more use of the PSDD in the control of biofouling post-radical treatments.

d. Alkalis. Acid treatments have long been recognized as a suitable means for reducing the impact of clogging and plugging on wells. The use of alkaline treatments, taking the pH up, has not received the same recognition. While it is known that alkaline conditions, particularly above 9.5, is known to be inhibitory to many microorganisms, the impacts of raising the pH to a similar extent as it is lowered in acid treatments does not bring about the same degree of lethality. In other words, raising the pH from 7.5 (close to neutral) to greater than 11.5 (a 4 pH unit shift) does not yield the same dramatic reductions in microbial numbers as acid treatment would. The reason for this is twofold. First, as the pH goes higher the bound water (slime) polymeric matrices around the cells in the biofilms tend to thicken to provide additional protection from the pH impact. Second, this elevated pH can cause carbonate and metal precipitation and the formation of concretious structures that now also shield the surviving microbes.

As a result of the described limitations in the effects of alkaline treatments it has never been widely adopted by the industry. In laboratory studies, it has been noted that following of an acid treatment (to lower the pH) with an alkaline treatment (to raise the pH above the original pH of the water) can result in a pH shift of 7.0 or greater pH units. The additional pH-induced stress has been found in both laboratory and field studies to increase the effectiveness of the rehabilitation process on the wells. This combined treatment is referred to as the “flip-flop” treatment since it flips the pH one way and then flops it the other way.

The two alkalis commonly used for such treatments are sodium and potassium hydroxides and both are capable of raising the pH of the water up to as high as pH 11.5. The sodium form tends to be the more aggressive and should be used with extreme caution if there is a significant amount of clay in the formation materials around the wells. The sodium alkalis can cause the clay to swell causing flow into or out of the well to be partially or completely blocked. It should be remembered that if a “flip-flop” has been planned after an acid treatment, there should be a “buffer” of water injected into the well in order to keep the acidic and alkaline elements apart during the treatment. **Mixing acids and alkalis can cause eruptions or explosions. The volume of the buffering water between the two treatments should be a minimum equivalent to three well volumes**.

e. Selected Blended Mixtures of Chemicals. In the water well rehabilitation industry, the bulk of the chemical treatments are blended involving more than one active chemical ingredient. The exact formulations are commonly proprietary and cannot be easily obtained. It is recommended that the MSDS sheets be obtained and carefully examined for possible undesirable impacts. There is a range of typical combinations that are widely used. Many such formulations include a proprietary PSDD to facilitate the effectiveness of the treatment. The PSDD would be incorporated with one or two other chemicals in a solid or liquid form. Inhibitors to reduce the speed of a given reaction may also be included. The nature of the blended chemicals and the form of the treatment should closely follow the manufacturer’s guidelines in order to ensure the potential effectiveness of the treatment.

Typical combinations found in the marketplace include, but are limited to, the following broad groups:

- Organic acids with a PSDD
- Peroxides with inorganic acids and PSDD
- Inorganic acids with a pH color indicator to ensure an adequate drop in pH is achieved
- Inorganic acids with PSDD
- Disinfectants commonly with some pH modifier and PSDD

The proprietary nature of these blended products and the lack of comprehensive independent trials to determine the effectiveness of these products limits the validity of the recommendation of any particular product. In general there is a considerable variation in both the treatment costs and the validation/assurance procedures required for validating the products are actually effective. It is recommended that local chemical applications that have independently experienced good results from the application should be reviewed before deciding on the choice of an applicable product.

6-5. Overview of treatments blending chemical and physical methods

The varied nature of many fouling events involving growths and elements of clogging, from the borehole out into the formation, often involves the need to maximize treatment effectiveness by including a more comprehensive blend of both chemical and physical elements. While these technologies are generally more expensive to apply, they often can be more effective in controlling the fouling event. This may simply be because the disruption and dispersion of the fouling is more effectively tackled using a comprehensive blending of physical and chemical treatments. Of these blended forms of treatment, the following are in use: pressurized injection of carbon dioxide and blended chemical and heat treatments.

a. Pressurized injection of carbon dioxide. Carbon dioxide, like citric acid, has long been used in the beverage industry as chemicals that can suppress biological activity. While citric acid, as an organic acid treatment, has largely been discarded because of the secondary bacterial growths that can occur from feeding on the citric acid, carbon dioxide application has increased. The injection of carbon dioxide can act to inhibit and remove biofilms and biofouling from wells through freezing, the generation of carbonic acids, and a surge in pressures within the formation and well. When carbon dioxide is injected at very low temperatures into the biofouled zones in and around a well, the temperatures in those zones will also drop leading some of the bound water within the biofilms to freeze. As the ice crystals form within the biofilm they also form at the attachment sites of the biofilm to underpinning surfaces and this activity causes the biofilms to be lifted up from the attached surfaces and then be disrupted. The net effect is that the biofouling structures are shattered and dispersed into the freezing water within the voids. As the carbon dioxide reacts with the ground water, carbonic acids are formed that reduce the pH of the environment and also inhibit and kill many of the microorganisms that survived the disruption of the biofilms involved in the biofouling. Like the freezing, this action is also transient and will be neutralized as new ground water enters the treated zone. The third impact of pressurized carbon dioxide treatment is the application of significant pressures as the carbon dioxide is forced out into the formation. In general the microbial kingdom has a much greater tolerance of pressure changes than plants or animals and the types of pressures applied may not significantly increase the lethality inherent in the treatment.

Application of carbon dioxide can range from the simple act of dropping solid carbon dioxide pellets down the borehole to sophisticated patented application techniques in which large volumes of carbon dioxide are injected down the borehole under pressure. Like many other well rehabilitation treatments, this treatment also involves the movement of the treatment chemical out into the formation and is also likely to take the hydraulic lines of least resistance in moving away from the application site. Movement of the chemicals out into the formation would mean that the effectiveness of a treatment may be witnessed by carbon dioxide appearing at a well one hundred yards or more away from the treated well. In reality this may be a reflection of the probability that there was a pathway of least resistance between the treated well and the well where the carbon dioxide gas appeared. That does not necessarily mean that all of the biofouling around the treated well was removed but simply that a path had been established in the biofouling in the direction of the well now showing the presence of carbon dioxide. Field experience has shown that there have been successful treatments in consolidated wells in hard rock fed by fractures. Here, the limited pathways created by the fractures and open structures were the sites of the biofouling and the carbon dioxide came into contact with most, if not all, of the biofilms and deposits associated with losses in production for the well.

The application of freezing and pressures to a well does pose two possible risks. First, when water freezes into ice there is an expansion in the volume that could put additional pressures on the structures within the well leading to well structural failure. Second, the application of pressurized carbon dioxide down hole has to be done under carefully controlled conditions to ensure that either the injection apparatus is not forcibly expelled from the well or that the pressure does not collapse the installed well structure.

b. *Blended chemical and heat treatments,* the application of heat as a sole treatment to recover wells from biofouling has been attempted periodically over the last century. Practices through 1970 to 1985 showed that heat alone often not only killed off the majority of the microbial population but also caused a seemingly non-reversible coagulation of the biofilms creating a concretious plug that became almost impossible to control. In the last fifteen years attempts have been made to combine the clear advantages of heat to control the microbial populations with chemical techniques to not only prevent concretions from forming but also to aid in the effective removal of the various elements causing the fouling. USACE investigated a process combining heat and chemicals through the REMR Program at the Waterways Experiment Station in Vicksburg Mississippi in the 1980s and 1990s. Several publications detailing this research have been issued (Alford and Cullimore, 1999; Cullimore, 1993 & 2000). Acommercial patented application of heat and chemicals has been successfully applied to a number of USACE sites ranging from relief wells at levees and dams to injection and extraction wells at ground water remediation sites. The types of acids used and the heat generating equipment have evolved over time and the process was successfully used to rehabilitate extraction and injection wells at several CERCLA sites.

The value of combining heat with chemical strategies for the control and management of biofouling wells extends from two important well recognized phenomena. First, the application of heat to a microbial community should exceed the tolerance limits of the microorganisms to heat causing trauma and death. In the Nineteenth Century, Nicholas Appert and Louis Pasteur demonstrated how the application of heat could sterilize meat and reduce spoilage of beers and milk by pasteurization. For pasteurization, the effective temperature rises above ambient to achieve a significant reduction in microbial populations was at least 75°F. For sterilization, the commonly accepted temperature range to achieve this is 250 to 270°F.

Second, the application of heat is well understood to accelerate the rate of many chemical reactions following the laws of thermodynamics. For the application of heat to a well being subjected to chemical treatment, this would mean that as the kinetic energy of the molecules causing greater translational motion. For the well being treated this would mean that the addition of heat would increase speed up the chemical reactions causing faster reactions and accelerated diffusion. Blending heat in with chemical treatment involves the application of pasteurization rather than sterilization with the associated increases in the rates of associated chemical reactions.

The advantages of this combined strategy of heat and chemical application allows for a more complete impact of the biomass causing the biofouling than the use of heat without chemical supplementation or chemicals without the application of heat. However, no amount of chemical or physical effort will effectively rehabilitate a biofouled well unless a maximum effort is made to employ mechanical methods (such as air lifting and jetting) to remove the disrupted biomass from the wells both during and after treatment.

6-6. Rehabilitation Treatments Currently Commercially Available

This chapter presents some of the recognized technologies that have been successfully applied to rehabilitate extraction and injection wells. This document addresses the various treatment technologies in a generic manner discussing the advantages and disadvantages of each technology and indicates the conditions under which the technology is likely to be the most effective. It should be noted that some treatments are separated out by trademark names while others are grouped together since the prime mechanisms have a common origin.

Each sub-heading is divided into three distinct parts. The first part deals with the location of the manufacturer or principal agents who developed the technology. Reference can be made directly to these agencies for further information. In the second part, the manufacturer or principal service agent briefly describes the process technology giving some of the claimed advantages and application for their technology. In the final part there is a neutral commentary on the applicability of the technology and some of the recognized advantages and shortcomings inherent in the application of the technology to ground water remediation sites.

Based upon commercial information released and readily available the following four treatments applicable to injection and extraction wells have been included. These treatments have been included because there has been some field experience with the techniques described and at least under some circumstances, they have been found to be reasonably effective.

a. Aquafreed® Treatment

(1). Aquafreed® incorporates the controlled application of gaseous and liquid carbon dioxide (CO_2). Inquiries about Aquafreed® can be made to: Subsuface Technologies Inc., Rock Tavern, NY.

(2). The Aqua-Freed™ process (often called "freezing") employs the application of cold liquid and gaseous CO_2 for biofouling and encrustation removal. While "dry ice" (solid CO_2) has long been used as a well development tool in North America, control of dose and application has been a problem. The Aqua-Freed procedure (described in Mansuy, 1999) was developed as a way to provide the redevelopment effects of cryogenic CO_2 in a controlled manner.Atypical procedure is as follows:

(a) Install a packer to confine a desired interval in the well. Begin injection of CO_2 vapor at predetermined and controlled pressures.

(b) Begin controlled injection of liquefied CO_2 in pulses.

(c) Inject liquefied CO_2 at temperatures and pressures that "will encourage the liquid to change to CO_2 'snow'" (temp as low as -110F), freezing water in the formation around the well.

(d) Remove packer and thaw.

(e) Surge or airlift for final development. (This is crucial, as Mansuy, 1999 notes.)

(f) Some Aqua-Freed service providers will add a chemical rehabilitation step and additional redevelopment at this point as needed.

(3). This process is described by its developers as acting on the formation and encrustants in the wells through gas expansion and freezing and thawing, which dislodges deposits, and also through the formation of carbonic acid, acting under pressure. The carbonic acid solution is relatively high in concentration and, as a mild acid, can attack deposits. The thermal shock on bacteria and their biofilm networks probably has some benefit in dislodging biofouling.

The Aqua-Freed process has some other attractive features:

(a) The injectant is chemically reduced and not reactive with organic molecules.

(b) It does not work under high pressure, so that fracture opening is minimized.

(c) The material, compressed CO_2, is relatively safe to handle.

Problems identified are (at present):

(a) Possible structural damage to the well (based on discussion with service providers, probably a declining situation as they gain experience).

(b) The cold thermal shock is not nearly as effective as can be applied by heating the water.

(c) Kinetic force generated is readily dissipated in hydraulically highly conductive aquifers and is most likely confined to discrete channels.

(d) The poor thermal conductivity of lithological materials also will limit cold transmission to the immediate area of the well, based on studies of glacially influenced materials.

(e) If packers are not set properly, the CO_2 blows out up the casing and is wasted.

Its best use is probably in situations with significant encrustation immediately at the screen or borehole wall vicinity, removal of which will provide significant relief. Also, where chemical use is precluded, e.g., due to policy.

Casings must be firmly sealed into the formation with cement, unless the packer is used to isolate the casing. In its current form, it is probably best to be very cautious with bentonite-grouted wells, especially structurally weak monitoring

wells (although with time, use with these wells should be possible). One additional problem at present in recommending the process is a lack of objective, documented case histories of its effectiveness although short testimonials are available.

An AWWA Research Foundation draft report on well condition assessment and rehabilitation techniques for meeting output and quality goals planned for release in 2003 includes a variety of Aquafreed case history evaluations along with other treatment technologies.

b. Sonar-Jet®

(1). Sonar-Jet® incorporates the controlled detonation generation of kinetic and gas force for redevelopment.

Inquiries about Sonar-Jet® can be made to: Sonar-Jet® Water Well Redevelopers, Anaheim, CA.

(2). Improving the application of force in redevelopment is a crucial area of improvement. Among these are treatments based around detonating a shaped or charged wire, cord or device in wells. This cleaning approach has been in common use in the water and oil industry for several decades. These methods take advantage of the different elastic properties of the materials (screen and pipe, gravel back-fill and surroundings, deposits between formation and filter pack particles) to loosen deposits from well and aquifer and filter pack surfaces, affected by the detonation at differential frequencies.

Sonar-Jet® (Pat. #4,757,663) is among the best known of these. It employs two controlled physical actions working simultaneously:

(a) Amild "harmonic" (kinetic) frequency of shockwaves designed to gently loosen hardened mineral, bacterial or other types of deposits, such as gypsum, that are difficult to attack chemically.

(b) Pulsating, horizontally directed, gas pressure jets fluid at high velocity back and forth through the perforations to begin developing the aquifer.

In practice, the Sonar-Jet string specified is based upon well depth, diameter, standing water column depth, and the location of intake features, such as fractures, determined by video survey.

The EnerJet (Welenco, Bakersfield, CA) and **Shockblasting**® (**Berliner** Wasserbetriebe, Berlin, Germany) methods are similar devices (employing an explosive/implosive type of cleaning **method**). In both technologies, different strengths or grain sizes of detonating cord are used depending on the diameter, condition, and amount of encrustation on the casing.

There is a centralizer at the top and bottom of the string, plus a basket at the bottom to catch a sample of the encrustation and gravel that may enter the well during the cleaning process. A typical use of the system is as follows:

(a) Conduct borehole TV and review history and water chemistry, and determine that a hardened or entrenched deposit exists.
(b) Perform an initial bore cleaning
(c) Perform the Sonar-Jet or similar treatment.
(d) Follow immediately with a chemical and mechanical redevelopment step.
(e) Follow-up TV camera log, pump test and review.

The developers of the **Shockblasting method** also use it to detonate old brittle intake pipes (i.e. vitreous clay, plastic and similar materials, as well as strongly corroded steel filters) to ease installation of new, better-quality screens.

Screen installation is followed by mechanical redevelopment.

(3). Sonar-Jet or similar technologies have typically been considered optimal for near-well, hardened mineral deposits (gypsum, calcite, dolomite, etc.), and have been not so effective on soft, biofouling plugs, which can be forced outward into the formation by the kinetic force action. However, sometimes problems identified as biofouling actually have hydraulic impact through deposition of hard solids, such as iron sulfides, or impacted fines embedded in biofilm, in pore spaces and fractures, especially around persistently dewatered open borehole intakes, screens and filter packs.

c. Blended Chemical Heat Treatment (BCHT™)

BCHT (U.S. patented process) involves the combination of heat and a strategic application of various chemical combinations with the objective of obtaining a three-phased control of the biofouling. The concepts applied are elaborated below.

The **SHOCK** phase is designed to disturb the nature of the biofouling elements by the combined application of heat (to traumatize and kill many of the incumbent microbes) along with a disinfectant to further improve the lethality of the treatment. At the end of this phase it would be expected that most of the microbial cells would be minimally traumatized by heat and many killed by the disinfectant action. These effects are heightened by the use of an appropriate PSDD.

The objective of the next **DISRUPT** phase is to begin the process of destroying the integrity of the biofouling elements by disrupting the structural integrity. Maintaining the heat but now radically shifting the pH either upwards, downwards by at least 3 pH units or conducting a flip-flop to get a 7 pH unit shift achieves this. At the same time a PSDD is used to penetrate the collapsing structures and cause further disruption.

At the start of the final **DISPERSE** phase in the BCHT treatment the structures that created the biofouling are now shattered, occupying pore spaces in fractures, the well screen, the gravel pack, and the adjoining aquifer. The dispersion phase continues while the PSDD treatment further collapses structures and the temperature is allowed to decline. Pressure or air-lift surging is used to move the particles out of the well through the borehole or force the particle deeper into environment surrounding the well where there would be less direct impact on the future operation of the well.

Blending chemical and heat treatments therefore forms a structured approach to rehabilitation. The major features of this process is the constant application of heat during the first two phases to accelerate the chemical reactions while at the same time impacting negatively on the microbes involved in the plugging process. There are a number of scenarios that have been used for the application of heat ranging between:

- Premixing the chemicals into solution and then heating the mixture in a stainless steel boiler prior to discharge down the borehole.
- Heating the water using a conventional boiler and then mixing the chemicals into the hot water prior to discharge down the borehole.
- Heating the water down the borehole using injected steam, hot water or electrical immersion heaters and adding the chemicals directly to the borehole.

Of these three alternative approaches premix and then heat prior to injection has been shown to be the most efficient.

The last technique, heat down hole and add chemicals down hole, has been found to be the least efficient. It should be recognized that for all three scenarios there would be a condition where accelerated (heated) chemical reactions are occurring at the treatment site. To avoid interaction between the various parts of the chemical treatment train (e.g., acid with base, chlorine with acid), there should be an injection of hot water equivalent to at least three times the well volume in order to separate out and buffer antagonistic chemistries. Trained personnel using certified equipment should always perform treatments blending chemicals and heat.

BCHT, as a technology, has been under observation and analysis by the USACE add USACE references since 1989 and has been successfully applied to ground water remediation wells, to relief wells on levees and dams, to individual and community water wells, and to industrial high production wells. A generally accepted “rule-of-thumb” states that after a well loses 20% of the original specific capacity, maintenance or rehabilitation is required. As losses in specific capacity go from 20% to 40%, rehabilitation becomes more difficult and the well is approaching a point where greater losses may require abandonment. BCHT has been very effective at returning wells in unconsolidated formations back to original capacity when they have not declined by greater than 40%. Where wells have declined by more than 40%, BCHT has produced 30% to 50% improvement over the present original specific capacity. To date over 4,000 wells have been treated with approximately 90% achieving the objectives described above. After these improvements to the well and if the well is considered to meet site specifications, preventative maintenance practices should be determined immediately and should consider the conditions experienced at the well before and during the BCHT treatment. A maintenance program that is

followed diligently can help insure that the well performs adequately for the planned life of the facility. In some cases the well hydraulics will continue to improve and the time between maintenance cleanings can be lengthened.

6-7. Chemical Treatments - Traditional versus New

There has been a traditional attitude that treatment of any sort of geochemical or biological problem can be addressed by a single-source chemical treatment. In the medical industry this thinking has led to a very development of powerful chemicals designed to target specific problems. In ground water remediation, injection and extraction wells have been perceived to exhibit geochemical problems, but not serious biological problems. To address these problems, a range of chemical treatments have been developed over the years that, unfortunately, have been found through experience do not address all of the challenges of the injection and extraction wells. Diagnostic techniques were limited in their application and not designed to adequately determine the root causes of the symptoms observed. The uncertain nature of the chemical treatment in some cases coupled to the desire to replace wells rather than rehabilitate them has led to a poor understanding of the mechanisms involved. Traditional treatments, although practiced over the last fifty years, have not generated a level of confidence that they effectively addressed the problems. The new generation of treatments coming into the marketplace as verifiable technologies generally recognizes the broad spectrum of problems that can occur in wells. It is for this reason that most of the newer treatments accept the need to apply more than one chemical therapy and/or improve the effectiveness of a physical treatment process. At this time the quality assurance and quality control (QAQC) are not clearly specified and there is no base line compliance requirements. As the understanding of the nature of clogging and plugging in wells on contaminated ground water sites becomes better understood then QAQC compliance guidelines would become a part of the treatment practice. General points to consider are listed below in the election of a treatment option:

a. Chemical treatments of wells have been practiced for more than a century.While there are many different proprietary products in the marketplace, only limited attempts have been made to conduct an independent evaluation of these technologies. Any evaluation immediately faces the task of making comparisons in treatment effectiveness for a wide variety of products, each of which may function very effectively under some circumstance and fail to achieve any effects on others.

b. Traditional technologies have used some relatively simplistic approaches that involve a single chemical strategy designed to treat a particular problem such as iron encrustations, carbonates, slimes, and taste and odors problems. Typically, acids would be used to control carbonates and iron encrustations while disinfectants would be used to treat slimes, taste and odors problems. In the last thirty years there has been a movement to include various surfactants (also known as dispersants, penetrants, detergents and wetting agents) to improve penetration of the active chemicals. Modern products usually are blended mixtures that are claimed to have a greater effectiveness within a particular set of conditions. There remains a reluctance to increase the effectiveness of chemical treatments by heating the well up to accelerate the chemical action.

c. Chemical treatment in a preventive mode is a major aspect of maintenance of well and fluid system performance. ASTM D 5978, which addresses the maintenance of monitoring wells, does not recommend the use of chemicals, but redevelopment only. This restrictive guidance is not extended to extraction and injection wells on contaminated ground water sites, for which the responsible use of chemicals in preventive maintenance. Redevelopment is usually needed to improve the well’s effectiveness. Experience shows that chemical choices in well treatment are often made based on incomplete information or vendor sales literature. While information should not be dismissed if it comes from a commercial source (as vendors frequently seek to educate), it is crucial that personnel engaged in the planning of well system O&M seek expert advice and review publications. Publications specifically written for these types of sites are a necessity to become well acquainted with the features of chemical choices, both for effectiveness and safety.

d. This section provides a limited survey of some of the major suppliers of treatment products and services that have been found to be effective under some conditions. The vendor’s statement has been supplied by the purveyor of the product line and represents the domain of claims for the product. Acommentary is included that describes, on the basis of the claims, the most likely conditions under which treatment with the product is most likely to be successful.

Chapter 7

Completion of Rehabilitation

7-1. General

Historical records denoting changes in the specific capacity (Q/s), camera logs, and water quality parameters can be used to assess the status of any fouling occurring within the injection and extraction wells. There would be differences in the manner in which the data is obtained depending upon the nature of the individual well. Extraction wells would be easier to determine the Q/s since the normal hydraulic flow would be into the well during operations. For the injection well, the Q/s would be obtained using the flow into the well. The inward flow during Q/s testing may cause some realignment of any clogging and/or plugging materials in the well causing false data before the realignment has stabilized. It is recommended that ten well volumes be pumped into the well preceding any attempt to obtain a Q/s value in an injection well.

Often considerable fouling may occur within the well and the rate at which this is occurring can be determined by routine (e.g., annual) video-camera logging of the well. If the logging is standardized then a review of the images at specific depths and/or locations down the well can provide evidence of the rate of visible fouling. In addition the effect of rehabilitation and the rate of refouling of the system can be determined.

In comparing historical video-camera logs of the same well it is essential to ensure that a common measurement frame so that the position of the site in the well can be determined for each of the logs covering this section of the well. It is considered essential that the camera record a view directly into the screen and filter pack and it is preferred that the camera is equipped with a 360 degree panning lens, It is equally important to ensure that the camera travels slowly in a consistent manner each time the inspection is conducted. A fast rate of descent with the camera speeds up the survey but it can lead to difficulty in locating particular sites within the well and it can also dislodge some of the fouling material into the water. Where this happens and the material breaks up, visibility is obscured reducing the value of the video records. Speed of video-camera movement can be varied at the initiative of the operator if there is no evidence of any fouling (i.e., a clean borehole). In the event that there is evidence of fouling, the speed of the video-camera should be slowed to assure good clear images for the logged location. If cloudiness occurs in the water as a result of the knock down and dispersion of fouling materials, the camera’s movement should be stopped until the cloudiness has cleared. If the clouding will not clear then the camera should be slowly moved out of the zone. When video-camera logging, it is the horizontal wells, as opposed to vertical injection and extraction wells, that present some configuration challenges. In the horizontal wells, gravity plays a major role in the positioning of biofouling materials and products. Gases, for example, will tend to collect under the upper side of the borehole where the slots and the porous media beyond are plugged or clogged. This entrapped gas would be seen as a ribbon of gas rippling along the upper side of the well. Additionally growths may be seen hanging down rather like stalactites into the water while others may from complex growths involving calcite and or iron oxides and hydroxides (goethite). Careful note should be made of the positions of these growths and the occurrence of perched gas pockets so that after rehabilitation or PM, any regrowth of this biofouling can be recognized and positioned. An effective treatment should prevent regrowth at the same locations but rather the plugging events should again be random. Vertical wells tend to have stratified events at different depths down the well relating to the oxidation-reduction potential and the entry of various materials down the length of the vertical column. For example, a floating plume would appear focused on the surface of the water column and may have elements of biofouling growing above (on the walls of the casing), within the plume and/or below the floating plume in the water. If the floating plume is able to allow oxygen diffusion (e.g., diesel fuel) then this growth underneath the plume can become intense and obscure any images of the well’s walls at those depths. Further down in the well’s water column, evidence of growth may be evidenced by cloudiness, slimes, encrustations, nodules, tubercles and even crystalline calcite-like structures occurring at specific depths. These depths usually relate to the points where ground water is now, or has been (now plugged off by the growths), entering the wells through the screen slots or directly from the fractured or porous media. In some cases these slime-like growths can cross connect at a specific depth indicating a false well bottom. Often lightly tapping this “slime” floor with the camera can cause it to collapse. The position of this false floor can reflect the position of the redox front in the well. Where this is the case,

above the floor will be oxidative while beneath the floor will be reductive. On the reductive side there is likely to be accumulation of gases from biological activity including, but not specifically limited to, methane, carbon dioxide and nitrogen. When the “slime” floor is penetrated (for example by the camera) very often this entrapped gas may suddenly be released. This will be recognized through a series of large bubbles being easily recognized using the video-camera as they move up the well. Moving below the floor into the reductive zone, the conditions observed now reflect the reductive nature of the environment. The walls will tend to be blackened with sulfide and iron carbonate deposits and the growths (where observed) would have a gray or black color as either soft slimes or hardening encrustations. There is less stratification at these levels and the water is often less turbid.

Video-camera logging of the horizontal or vertical injection or extraction well gives a considerable amount of information about the structural integrity of the well but also the form of biofouling that may be occurring. By historically examining the various camera-logs it then becomes possible to get an appreciation of the sequences in which the various materials appeared to foul the well and determine the likelihood of these materials being biological in origin. If the materials are slime-like then there is a virtual certainty that they are microbial. Where the materials appear hardened but break up upon contact releasing clouds of colloidal (slime-like) particles than these are also microbial. Even hardened encrustations if they have softer zones within are likely to be microbial. Very hard crusts and crystalline materials would, at first examination, appear to be geochemical in origin, but on some occasions these are actually the products of microbial activity. This activity can be confirmed by taking a sample of the material and conducting IRB-, SRB-, SLYM- and HAB- BART tests on 0.5g of sample per test vial to which 15ml of sterile phosphate buffer solution has been added. To conduct the BART test, roll out the ball from inside the bottle into the inverted inner cap, add the 0.5g sample, add the 15ml of sterile phosphate buffer, and return the ball by dropping it from the cap into the vial (do not handle the ball). After screwing the cap back on, the test is started and should be observed daily for reactions. Moderate or High aggressivity would implicate those bacteria as components in the fouling process.

Direct evidence for the role of microbes in the losses in the Q/s for these wells can also be obtained by periodic direct sampling of the water in the injection and/or extraction wells. Care should be taken to assure that the sampling **method** is consistent and appropriate to the particular well from which the data was/is being collected. Changes in the sampling procedure can seriously affect the data compromising a historical comparison of the data. Sampling procedures are discussed in sections 2-11 and 3-10 and in the texts dealing with ground water microbiology (Cullimore, 1993 and 2000a). In historically reviewing the risks of biofouling using the BART testing technique, there are two key components for each bacterial group being evaluated: (1) shifts in the time lag, and (2) changes in the reaction patterns being reported.

Time lags are normally measured in days through daily observation of the tests. It should be noted that the manufacturer is now providing a micro-processor controlled testing apparatus that allows automatic reading of the test vials with an LCD display showing the time lag and the reaction patterns these are based on. This is called the HAB-BART™ test system incorporating a micro-processor controlled reader and should be available for routine use late in 2003. Generally where the time lag shortens significantly (by one day or more) then the bacterially induced fouling in the well is increasing. Examples of the use of the time lag to determine the aggressivity and possible populations of particular bacteria are given in Appendix C. This system provides a useful in-field, in-office or in-laboratory technique to determine the nature of the bacteria that may be linked to the biofouling of the injection and extraction wells.

Reaction pattern signatures (RPS) generated by the BART testers define the characteristics of the bacteria that are aggressive in the sample taken from the site. The RPS can be interpreted using the BART-SOFT™version 4.01 software. software. This program is available at no charge through the web site Examples of this use is given in Appendix C. This enables the data to be conveniently filed and used to generate an archival record of the state of the wells after rehabilitation.

7-2.

Assessment of Original Development Records

The need for rehabilitation could be a result of the original development of the well being faulty to an extent that the well did not reach its intended potential and requires a premature treatment. It is recommended that, in association with personnel familiar with injection and extraction wells in similar environments, all of the records relating to the original development of the well(s) be examined. This examination should be used to determine whether it is reasonable to conclude that the well was developed properly in the first instance and if the original Q/s values may be in error.Where well development

was incomplete, the Q/s recoveries recorded by effective rehabilitation may not be related to the original Q/s values logged for the well(s). An historical log, based on the first set of data in which there is confidence, may be appropriate to establish relative values.

7-3. Records of Rehabilitation

Rehabilitation of a well may be considered a success but this does not mean that the well is now immune to future deterioration caused by biofouling. Ideally the records for hydraulic efficiency should be kept should be kept from the day that the well was first developed. Declines in the specific capacity in such records would clearly indicate the potential for a long term deterioration of the well. Should these declines observed in the records be accompanied by changes in water quality through such indicators as increases in iron and/or manganese, fluctuations in turbidity and/or color and increases in the aggressivity of the bacteria through shortening time lags then a preventative maintenance or radical rehabilitation would need to be considered. Records need to include all aspects of the rehabilitation process through from the determination that the well was deteriorating through to confirmation, selection and application of the treatment to post-treatment confirmation of the effectiveness of the treatment. Important components in the records should be all video-camera logging in digital or tape form recording the status of the well including initial development as well as pre- (diagnostic) and post- (confirmatory) treatments. This now provides a growing history of the state of the well itself including structural concerns.

These records should also include a detailing of the precise nature of the rehabilitation treatment employed including not just the chemicals applied but also the methods of application of all stages in the treatment, surging and post-treatment activities. These records are crucial given that each well has distinct characteristics that may require the contractor to adjust the form and/or duration of the treatment. Contractors who have considerable experience in well rehabilitation often consider that the rehabilitation of a well is really more of an art than a science since ingrained experiences often dictate the precise approach to well rehabilitation. These experiences need to be recorded should rehabilitation need to be repeated on that well.

Associated with the treatment records there also needs to be maintained records on the hydraulic efficiency and water quality parameters not just to determine the effectiveness of the rehabilitation but also to provide an ability to determine which of these parameters can be used as an early warning for well deterioration. Examples of these early warnings could relate to significant declines in the specific capacity by greater than 5% and the increasing aggressivity of specific groups of bacteria that have been associated with the previous biofouling of the well. By implementing a preventative maintenance program that is triggered when these early signs are recognized. Here the level of treatment would be at a lower level than the rehabilitation strategies would require but sufficient to return the well to within an acceptable performance range. Such preventative maintenance treatments should be established to be undertaken as an automatic reaction to deteriorations in the wells performance and may significantly delay the need for another major well rehabilitation. Good record keeping and experienced interpretation of the data as it is gathered can therefore aid significantly to improve the sustainability of the well.

7-4.
Objective Criteria to Judge Completion of Rehabilitation

Post treatment testing after rehabilitation has to include hydrological, chemical and biological parameters that are relevant to the performance of the well. One important factor to be considered after what time frame following rehabilitation objective assessments of the effectiveness of the treatment can be determined? Given that the environment in and around a well is severely disrupted by the application of an effective treatment, there will follow a period of time during which the conditions in and around the well stabilizes. Biomass may continue to sheer and slough from the well from the peripheries of the treated zone around the well for a number of days. The impact of the treatment would frequently have caused destruction of large microbial communities with many of the cells killed by the treatment. Under these conditions even with effective removal of the dispersed biomass there would remain significant amount of organic materials remaining within the treated zone to allow surviving and/or invasive microorganisms to grow. Aconsequence of this is that an effective treatment may be followed by a massive microbial infestation of the treated zones. One effect of this is that some bacterial groups may become very aggressive and dominate. These bacteria form very loose structures which take two or more weeks to stabilize.

Any attempt to determine the post-treatment impacts of the treatment the sampling should occur after the reinfestation of the treated zones has occurred and stabilized. This will commonly take three to six weeks and so all post treatment water

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quality determinations should be restricted to at least six weeks after the completion of the treatment phase. At this time the well has now returned to a stable condition and the microbial and chemical parameters should have stabilized. Premature monitoring may lead to a lack of confidence in the effectiveness of the treatment. There is always a natural desire to determine as quickly as possible the effectiveness of a treatment applied to a well but caution should be taken since data gathered before six weeks may still be affected by the post-treatment equilibration that will be occurring in the well.

It is important to attempt to get the well back to as close to, or better than, when it first went into service by the rehabilitation of the well. The possibility that the well may perform better than the original specifications is based on the potential for some wells to have had inadequate development and been poorly characterized when the well was first put into service. Delays in bringing a well into service after its original development could mean that the data gathered would be from a well already suffering from some level of fouling. Characterization after this process has started would give a lower baseline value which means that a successful rehabilitation is likely to exceed those characteristics as the well returns to its true original performance capabilities. Claims that the well has returned to 140% of its original Q/s may therefore be as much a failure in the original data baseline as a highly successful recovery.

The criteria to determine the success of a treatment should include a careful judgment as to the value of the data being used to establish the baseline. Parameters to be considered should extend beyond the Q/s to shifts in the water quality that occur after the treatment. For the bacterial aspects of the fouling, it should be expected that the aggressivity should drop and be reflected through prolonged time lags. Minimally time lags should increase by at least one day with the longer the additional delay indicating the more successful the treatment. Taking water samples for this type of testing immediately after treatment is likely to give false data since there would be many bacterial survivors within the water that would tend to give periodically very short time lags and high aggressivity. It takes six to eight weeks for the bacteria in and around a well to stabilize as a part of a reforming biofouling. Until this happens the aggressivity cannot be reliably measured. As the time lags become stable, the RPS patterns also become constant indicating that the bacterial growth is now reinfecting the environment in and around the well.

Water quality characteristics tend to settle down more quickly than the bacterial once the redevelopment has been completed and is often recognized by the water suddenly shifting from a turbid, often colored form to crystal clear water.

The clear water indicates that much of the disrupted and dispersed materials have now been removed from the well by the selected development process. Water quality parameters (e.g., total organic carbon, phosphate, iron) can be affected by flow past the newly forming biofilms as each becomes accumulated in the biofilms. This newly forming biofouling is acting as a filter producing water with a much higher quality, continuing until the biofilms begin to either saturate or slough.

Saturation or sloughing can cause sudden and dramatic declines in water quality with products such as iron suddenly appearing in increasing quantities in the product water. Again, the industry has to recognize the unique nature of each well, the need for diligent robust monitoring, and the need for ongoing preventative maintenance programs even for wells that appear to present no problems in meeting the designed objectives.

7-5.

Unique Aspects of Rehabilitation in Contaminated Wells

Injection and extraction wells on contaminated sites present a number of unique problems in terms of rehabilitation. These problems extend from the fact that the wells were designed to limit offsite pollutant migration, while providing collection and treatment of the specific contaminants. Where these problems have an organic base, the organics can become a food source for the indigenous microbes at the site. The process of biofouling would inevitably be accelerated far beyond the rates normally encountered in water wells. Even where the organics are known to be toxic or carcinogenic, these effects may only be limited to some species in the biota (plants and animals) but not to all of the microorganisms at the site. The bacteria that are sensitive to the organics would either be killed off or protected by other more robust species within particular consortia. One aspect of injection and extraction wells is that it cannot be assumed that all microbial life is impacted negatively simply because the contamination is toxic, hazardous or radioactive. For radioactive contaminants, the ability of microbial consortia to create mutually protective matrices outside of the cells using such material as carbonates, sulfides and various forms of ferric oxides and hydroxides means that microbial growth can occur in regions commonly thought to be too extreme to allow life to continue.

For remediation wells, a rehabilitation procedure must work on deep-seated, robust/durable forms of biofouling while solving the problems inherent to controlling the hazardous nature of the discharged materials during and following a rehabilitation procedure whether it was successful or not. In planning to undertake the rehabilitation of a badly biofouled well that has excessive accumulates of contaminants, the operator should consider the consequences of the well treatment in terms of safe and effective handling of the discharges that are regulated as dangerous to the environment. Local, state and federal officials responsible for the regulation of discharges into the environment should be consulted and an effort should be made to effectively project the likely scale of the hazardous releases as a result of the rehabilitation. Experts knowledgeable about the potential impact of the various rehabilitation treatments on the types of discharges that may be released should be included in the planning. Documentation should be provided on the exact nature of the contamination, the nature of the geochemical, hydrological and physical environments within which the well(s) are placed, and also the nature of microbiological activity that has been observed or is suspected to be occurring.

7-6. Collection, Disposal and/or Treatment of Rehabilitation Water

There are a number of basic constraints that should be considered in the collection, handling and disposal of the discharges inevitably a part of a rehabilitation process. There are some processes that claim minimal discharges since the treatment is so effective that it drives the disrupted materials deep into the formation away from the well. Even if this were to be the case, the action of the extraction and the injection well would be to cause relocations to occur with the potential for covert discharges. In section 7-4, it is emphasized that there should be open discussions with the responsible regulating agency officials to ensure that all of the correct steps are being taken to rehabilitate the well with a minimal environmental impact.

a. Treatment of a well particularly involving the disruption and removal of the plugging biomass has an inherent concern. As the biomass is maturing within the well, there is an accumulation of potentially hazardous materials that will be removed from the well during the treatment process. These bioaccumulates can range from recalcitrant organics that have not yet been degraded daughter products of degradation, or inorganic materials such as cationic species of metals and radionuclides. In the maturation of the biological plugging, these materials gradually accumulate with only a relatively small fraction being periodically released into the water flow through the sheering of the biofilms. Such releases usually take the form of biocolloidal particles moving with the ground water flow.

b. The discharges from the successful treatment of a well can be expected to contain the bulk of these potentially hazardous materials that have been biologically filtered out of the well. For extraction wells, this process would happen as the ground water moves towards the well. For injection wells the entrapment would occur as the injected water moves away from the well. It can be expected that accumulates are likely to occur further away from an extraction well and closer to the injection well. Discharges after treatment should have different characteristics with injection wells having the most accumulate close to the well creating a heavier discharge at the beginning of the discharge. Extraction wells may have disrupted accumulates located at greater distances from the well, along the redox gradient, and may take longer to discharge all of the disrupted materials. There is also a higher probability for extraction wells that some of the accumulates may be too far back in the formation to be affected by the redevelopment treatment but these may be released later

Chapter 8

Cost Analysis

8-1 General

Once a well has begun to fail (i.e., no longer meets the operational criteria established), there is a choice between replacement and rehabilitation. Rehabilitation involves treating the well to remove the materials blocking the flow so that the well can again function in an acceptable manner. Replacement involves the closing down of the existing (failing) well and replacing it with a new installation. There is a relationship controlling this choice that is commonly based upon economics. If the rehabilitation costs begin to approach (e.g., greater than 30% of) the costs then replacement may be a better option than rehabilitation. If replacement is selected that does not mean that the problem has been resolved, but that the new installation would be expected to take a longer time before it becomes dysfunctional than a rehabilitated well. Appropriate preventative maintenance of either a rehabilitated or replacement well is essential to assure the effective use of the well. Local considerations may also weigh heavily on the decision. The unique nature of some of the aspects of each well the manner in which it interfaces with the surrounding environment as well as the manner of its construction means that there can be no hard and fast guidelines that can be applied to all wells particularly in undertaking a cost benefit analysis for each of the three potential decisions. These are:

a) To undertake no rehabilitation and accept eventual abandonment of the well and lose the contribution that was made by that well.

b) To rehabilitate the well to recover performance on the understanding that without preventative maintenance the wells performance could degenerate in a sudden and unpredictable manner.

c) Replace the well to recover the production performance that had been lost from the failing well.

These three options are commonly faced where wells are degenerating as a result of biofouling which may also be affecting the performance of the mechanical operation of the well. Where there has been a serious failure in the mechanical operation (such as through the fouling of the impellers of the pump) then this aspect can be resolved by the repair or replacement of the pump. This does not, however, address the broader concerns over the gradual relentless biofouling of the well that is continually reducing performance and will lead to the eventual abandonment of the well.

This chapter addresses the factors that will influence the choice between well rehabilitation (decision b above) or eventual well abandonment and replacement (decisions a accompanied by c). These factors will be affected by local conditions but do form a mechanism for electing to rehabilitate or abandon/replace a well. In this selection process, a cost-benefit analysis is an essential part of the process including the operating costs that may be affected in ways that may not be readily recognized. For example, biofouling could be affecting the drawdown causing the pump to have greater lift. Plugging or clogging in the well screen could also be causing the pump to work harder to draw the water into the well screen. One of the problems commonly with making the decision to rehabilitate or abandon is frequently the slow nature of the changes that are occurring often causes the operators to make a series of minor adjustments without considering the long term trends that these changes are a part of. Often times the window of opportunity of effective rehabilitation of a well has passed by before there is recognition that rehabilitation of the well is required.

Factors that are specifically important to the selection of well rehabilitation (decision b) or abandonment/replacement (decisions a and/or c) are given in Table 8-1. Each of these factors "_________?"

A. Comparisons of the specific capacity (Q/s) can give an indication of the degree of the degree of plugging / clogging with critical vales being when the % Q/s falls by more than 15%. Rehabilitation is commonly likely to be effective when the losses are relatively small (less than 40%). The greater the loss in Q/s from original then the smaller is the probability of returning the well to its original Q/s values. Wells that have lost >70% of their Q/s are unlikely to be rehabilitated back to their original Q/s.

B. During biofouling events in a well, it is common for iron to be accumulated in the biomass so that the concentrations in the product water are low. However, as the well becomes more biofouled, there is frequently spiking in the iron concentrations followed by consistently high iron in the water. The well is severely biofouled at this time and rehabilitation would be much more challenging.

C. Manganese generally accumulates further back in the reductive zones and so the occurrence of spikes and then consistent increases in manganese would indicate that the biomass on the reductive side of the redox front is becoming saturated and is now sloughing off surplus manganese. Generally this condition is likely to require more aggressive rehabilitation than a well showing increase in iron.

D. As the biomass associated destabilizes, iron would tend to be released more from the oxidative side and manganese more from the reductive side of the redox front. Shifts in the ration of iron to manganese could indicate the major site at which plugging is occurring around the redox front. Relatively higher iron values would indicate more oxidative focal sites for the biofouling while higher manganese would indicate more reductive and potentially deeper set sites.

E. Turbidity is a means of measuring the clarity of the water. It is common to find the turbidity of the water will significantly increase (generally erratically at first) as the well begins to significantly biofoul.

F. Total suspended solids indicate the amount of solid particulates in free suspension in the water. These particles would consist, in large part, of the products from the sloughing biomass that now becomes suspended in the water. When the amount of suspended solids in the water increases this could be considered as a significant part of the sloughing of the biofouling biomass in the well. If preventative maintenance or rehabilitation is not attempted then the level of suspended solids will continue to increase as the well fails.

Table 8-1

Factors important to the decisions concerning well rehabilitation

Factor (to be compared with original values)	**Suitable range for rehabilitation**	**Range favoring abandonment and replacement**	
Specific capacity, % of original Q/s	<85% ---60%--- >30%	<30% or failure to achieve designed minimal criteria	A
Iron concentration, ppm	Increases in ironinitially erratic but then >0.5 ppm	Increases iniron exceed 2 ppm frequently with spiking	B
Manganese concentration, ppm	Increases in manganese erratic by >0.1ppm	Increases in manganese >0.2 ppm often with spiking	C
Fe : Mn ratio	Ratio stablewithin ±20%	Ratio shifts >±40%	D

Turbidity,
Increases by 20 to 80%
Increases by >80% often
erratic
E
Total suspended
solids, ppm
Erratic increasesin TSS
values compared to original
TSS constantly exceeds
original values by >x10
F
ORP, Eh
Eh becomes more reductive
by >10 to <40 millivolts
Ehdrops by >50 millivolts to
become reductive
G
Video-camera
survey
>20 --- 60 ---<80% of the
production zone encrusted
>80% of production zone
biofouled, water verycloudy
H
Aggressivity, IRB-
BART, TL
Time lags shorten by >1 to
<2 days compared to original
Time lag falls to <2 days
consistently
I
Aggressivity,
SRB-BART, TL
Time lags shorten by >2 to
<4 days compared to original
Time lag falls to <2 days
periodically
J
Aggressivity,
SLYM-BART, TL
Time lags shortens to <2
days
Time lag falls to <18 hours
consistently
K
Aggressivity,
HAB-BART, TL
Time lags shorten by 30% to
60% from the original
Time lagfalls by >70% from

the original
L

G. A biofouling well would tend to have a greater biomass with a high biochemical oxygen demand. This would be reflected in the water tending to move from a more oxidative to reductive state that would be reflected in falling Eh values becoming more negative.

H. The limitation of video-camera surveying of the borehole is that the imagery relates to the water in the well and the forms of growth that may be witnessed on the walls and in the slots of the well. It does not give indication of any activity within the media beyond the sight through the slots. Often operators take the position that the video-camera log can define whether the well is biofouled or not. All the camera gives is information relating to the structural integrity of the well and the locations and form of any growths or precipitates attached to the walls and slots. One valuable role of the video-camera survey is to determine the effectiveness of an applied preventative maintenance or rehabilitation treatment particularly with respect to impacts on the growths and precipitates. Asuccessful treatment could be considered to be one that leaves the inner surfaces as clean as when they were first installed. While this is important it does not indicate that the biofouling within the well and its environment has been effectively controlled.

I. Iron related bacteria (IRB) become a major problem in waters that are relatively oxidative and have a high iron concentration. During the earlier phases of biofouling, the iron in the ground water can be filtered out by accumulation within the biomass. As the biomass matures, the accumulated iron exceeds the accumulative capacity and the surplus is released together with any sloughed material being released into the water. In the early phases of biofouling, the IRB are cloistered in the biomass and not necessarily detected at all in the product water. However when iron saturation and sloughing occurs then high populations of very aggressive IRB can be released into the water. In a severely (terminally) biofouled well the IRB populations can be excessively high indicating that rehabilitation may now be very difficult.

J. Sulfate reducing bacteria (SRB) tend to dominate under reductive conditions growing deep within the biomass associated with the biofouling. As the biomass grows it becomes less stable and there are releases of SRB in the product water. This means that the time lags become much shorter indicating the rehabilitation or preventative maintenance is required to control the biofouling. Amajor indicator of the state of the fouling is the reaction pattern observed for the SRB-BART. If the blackening begins at the top (BT reaction) then the SRB are shallow embedded in oxidative regions of the biomass and may be relatively easy to control. If, however, the reaction begins at the base (BB reaction) then the SRB are deeply entrenched in the reductive zones of the biofouling and therefore be more difficult to control.

K. Slime forming bacteria (SLYM) are the most ubiquitous of the various bacterial groups associated with biofouling and, as a result, are commonly the most aggressive giving the shortest time lags. Unfortunately these bacteria are opportunistic scavengers and can rapidly invade zones that have been treated and rehabilitated. While the SLYM bacteria TL can be used to determine the severity of biofouling in a well, the success of a treatment may not cause any losses in aggressivity for these bacteria. Reductions in aggressivity (increases in TL) are most likely to occur in the period of stabilization that follows the treatment and can last as long as six weeks.

L. Heterotrophic bacteria (HAB) tend to become dominant under conditions where there is high total organics in the ground water. Like the SLYM bacteria, the HAB also can be opportunistic scavengers and grow abundantly in treated wells. A useful signal of the form of the biofouling in a well is to examine the reaction pattern generating a positive reaction. Oxidative regions are usually dominated by aerobic heterotrophs that generate an UP reaction while reductive regions generally cause a DO reaction to be observed.

From Table 8-1 above, a number of factors can be used to determine whether a well may be rehabilitated or abandoned.

Each factor (from A to L) has to be considered separately and a decision to rehabilitate or abandon has to be made based upon each of the factors listed above and the likely nature of the biofouling that is occurring within the well. As a general "rule of thumb", the success of rehabilitation can be linked to the percentage of the original Q/s (specific capacity) of the well. In note A above, the ability to recover a well to original state declines rapidly from an 15% down to a 40% loss.

Confidence to recover wells that have lost between 40 and 70% of the specific capacity declines rapidly with an increasing probability of only a partial recovery as the losses get bigger. Once the losses exceed 60 to 70% of the Q/s then the potential to rehabilitate the well becomes simply one of stabilizing production with only minor gains in the specific capacity of the well. Additionally, a well that has been rehabilitated may return to original flows but remains much more vulnerable to biofouling. To assure maximum production from the rehabilitated well, a preventative maintenance program needs to be instituted immediately and continued diligently to prevent a resurgence of the biofouling.

Given that a well has been subjected to a selected rehabilitation procedure, the ideal scenario would be for the well to return to its original performance characteristics. However, a well that has been heavily biofouled is not likely, through the process of rehabilitation, to return completely to original specifications because of residual deep seated regions not completely impacted by the treatment. This would mean that only a partial recovery to original specifications would be obtained. Assessment of success in these circumstances therefore would be dependent upon the degree of recovery obtained and the cost-benefits that may be achieved through this partial recovery.

The challenge therefore becomes one of examining the factors and determining the cost benefit from the rehabilitation of the well as opposed to allowing the well to continue to degenerate until abandonment. Many of these considerations may be site-specific and relate also to any

8-2 Cost Benefit Analysis

In the capitalization and operational cost estimates, a number of assumptions are made concerning the wells. These assumptions relate commonly to a presumption that the wells will have an extended performance life span that would be adequate to meet the needs of the designed goals. Consequently, in order to ensure this assumption, there is often a large safety factor built in through designing a greater production capacity for the wells than would actually be required. This means that the wells can generate an adequate production to meet the demand for an extended period of time before problems associable with biofouling would become significant. However this extension in the performance comes at a cost. This cost is associated with two primary factors. First, the routine preventative maintenance of the wells is neglected as a routine procedure to assure that the wells continue to perform effectively. Second, when the wells do exhibit symptoms these are more radical and result in a more radical application of treatment with a lower probability of returning the wells to the original designed productions.

In performing a cost benefit analysis for the treatment of wells exhibiting production failures, there is a high probability that this analysis would be particularly challenging since there may have been a history of neglect through not performing routine preventative maintenance and reactive treatments at times when individual wells were developing significant symptoms. These symptoms are summarized in Table 8-1 above. The cost benefit decisions are influenced by local conditions and only broad guidelines are discussed below as they relate to specific conditions.

8-2-1 Economic impact of biofouling

Biofouling in a well may be divided into two broad impacts: (1) corrosion; and (2) plugging with associable water quality issues. Corrosion usually results in equipment failure (e.g. pumps, pipes) that requires replacement of the failed equipment.

This is already a normal part of maintenance activities. Plugging is more challenging to recognize since the progression of the biofouling is frequently slow and insidious. The first impact of a plugging event is on the costs of pumping water into, or out of, the well. In the case of an extraction well, the impact of the plugging is to cause a lower flow of water into the well causing the drawdown to increase. This reduces the water level during active pumping and so creates a smaller hydrostatic head. The pump now has to work harder in order to pump the same volume of water from the well. This means greater energy costs to bring the water into the well (through the zones of biofouling) coupled to the costs of a greater lift demanded of the pump to achieve that volume through put. In an injection well, the scenario is reversed in that the plugging. The reverse would occur in an injection well where the plugging within the well and its immediate environment would cause lower flow rates out of the well. The net effect of this would be the water level in the well would rise creating a greater hydrostatic head as a result of the pumped water into the well exceeding the wells ability to disperse the water through the plugging zone. In this circumstance the maintenance of the additional head of water in the well would reflect in higher energy costs to extract or inject the water out of, or into, the well. One symptom of plugging would therefore be an increasing energy burden to move the same volume of water. These economic costs have been addressed by Helweg, 1982 who proposed two equations to calculate this impact. Equation one forms a calculation of the kilowatts (KW) of power used based upon discharge in gallons per minute (Q), drawdown in feet (s), the static water level in feet (SWL), the overall efficiency of the “wire to water” of the pump and motor (e_o), efficiency of the motor (e_m), efficiency of the pump (e_p) at the present pumping rates being used while the factors 0.746 converts horsepower to kilowatts and 3,956 converts GPM-ft to horsepower. In equation one e_o is equal to (e_m) (ep).

$$KW = \frac{Q\,(s + SWL)\,(0.746)}{3956\,(e_o)} \quad \text{(Equation One)}$$

Equation two can now be used to calculate the total cost (TC) per day of power used where power used is calculated as KW using equation one and the cost of energy (C) in dollars per kilowatt hour.

$TC = KW * C$ (Equation Two)

Cost savings from the rehabilitation of a well suffering from plugging may be not be very significant (less than $1,000 per year, Cullimore 2000) but the improvements in the well performance coupled to reduced treatment costs associated with improved water quality may radically magnify the savings through reductions in water treatment costs. In the example given above (Cullimore, 2000) the final savings in the treatment costs for two wells approached $100,000 of which less than 1% was due to power savings and most was due to reduced treatment costs. Cost benefit analysis should therefore extend from direct power savings through to improvements in the well field, treatment plant operations and improvements in the efficiency that can be translated into lower operating costs and more predictable quality management.

To understand cost benefit analysis there is a need to determine the financial drivers that are controlling the wells and the manner in which these change as the wells degenerate as a result of biofouling. Pumping the water out of, or into, a well is primary economic driver since this activity is essential for the operation of the wells. Changes in the energy costs associated with this activity could be a reflection of plugging that would also cause changes in the costs associated with the treatment of the water. In both cases the energy and treatment costs can be expected to rise as plugging interferes with water flows into, or out of, the wells and the degenerating water quality increases the costs of treatment. It is therefore important, in addition to the routine testing activities associated with the parameters listed in table 8-1 to also monitor the operating costs of the wells and any associated treatments because these can be expected to rise as the plugging develops. Since each well includes unique circumstances created by its own environment and demands placed upon that well, only general economic considerations can be drawn. EP 1110-1-27 lists in Table 10-1 the approximate costs for the PM equipment for wells through a process of either purchasing or renting where appropriate. However for complexes of wells involving both injection and extraction wells the cost benefits are difficult to categorize since these are site-dependent and influenced by the local environmental conditions. Outcomes of these influences are listed in Table 8-1 and can have a very significant effect upon the selection of treatment procedures and the subsequent costs involved Typical cost-benefits for undertaking reactive rehabilitations (table 8-2) and preventative maintenance (table 8-3) are given below. Due diligence, persistent preventative maintenance and timely rehabilitation treatments are essential to assure the ongoing effective operation of the wells and neglect is the enemy. In times of budgetary restraint, cutting back on monitoring and preventative maintenance would appear attractive options to reduce costs.

Radical well treatment involves a more aggressive attempt to rehabilitate the well impacted by fouling. Table 8-2 gives the normal cost range per well (2003 $) for the rehabilitation treatment given that the treatment of a greater number of wells will bring the costs down per well through reduction in the mobilization / demobilization costs, the ability to purchase materials and chemicals at bulk rates and the more favorable terms that can be obtained for the renting of equipment. There are a range of radical treatment technologies that are available and four of the more commonly recognized treatments are listed by cost range for treating a small (100’, 6") medium (300’, 8") and large (1,000’, 12") well. BCHT is a patented treatment involving the use of heat to accelerate the chemistry of the reactions) and has been evaluated by the U.S. Army Corp of Engineers over the last twelve years. CO_2 injection involves the pressurized injection of carbon dioxide commonly in a gaseous or liquid form into the well with the major impact being created by the acidic daughter products of the carbon dioxide. Pulsed water jetting involves the application of water under pressure in a pulsing or continuous manner to impact on the fouling. Cold chemical treatments relying on the activity of the chemicals at the normal temperatures of the well has been the most commonly practiced traditional from of radical rehabilitation. These treatments involve a range of chemical options that may be applied as a single mixture of staged in a recommended sequence.

Four categorizations for PM treatments are listed but these costs also include the necessary monitoring to determine the relative state of the well compared to the historical data generated for that well. Disinfection includes such chemicals and blends that are claimed to primarily be biocidal and function thought disinfectant activity. Acidization involves the application of chemicals that generate acidic conditions that may be effective against carbonates and the organisms considered to be biofouling the well. Pulsed water jetting relies upon the generation of violent hydraulic forces either continuously or through pulsing in a manner to disrupt and disperse the fouling. There are also a range of proprietary blends of chemicals that are claimed to include a variety of treatment effects including some combination of biocide, penetrant, dispersant and pH amendment.

8-3. Cost Effectiveness of Rehabilitation versus Replacement

Cost comparisons between rehabilitation and replacement give us an indication of which is the more reasonable option. In general, the more costly and complicated the well is, then the more likely that rehabilitation will be found to be the more cost effective of the alternatives. Conversely, shallow and simple wells that are cheaper to replace are likely by analysis to

Radical Treatment	**depth(ft)**	**diameter(")**	**Normal cost range per well**
BCHT	100	6	$2,000 to $5,000
BCHT	300	8	$4,000 to $6,000
BCHT	1,000	12	$8,000 to $14,000
CO_2 injection	100	6	$6,000 to $10,000
CO_2 injection	300	8	$8,000 to $16,000
CO_2 injection	1,000	12	$12,000 to $24,000
Pulsed water jetting	100	6	$1,000 to $4,000
Pulsed water jetting	300	8	$2,500 to $5,000
Pulsed water jetting	1,000	12	$6,000 to $10,000
Cold chemical			

	100	6	$1,000 to $3,000
Cold chemical	300	8	$2,000 to $ 5,000
Cold chemical	1,000	12	$4,000 to $10,000

Table 8-2, Approximate Costs of Radical Well Rehabilitation

PM Treatment	**depth (ft)**	**diameter (")**	**Normal cost range per well**
Disinfection	100	6	$500 to $2,000
Disinfection	300	8	$1,000 to $3,000
Disinfection	1,000	12	$2,000 to $4,000
Acidization	100	6	$500 to $1,000
Acidization	300	8	$1,000 to $2,000
Acidization	1,000	12	$4,000 to $6,000
Pulsed water jetting	100	6	$1,000 to $2,000
Pulsed water jetting	300		

		8	$1,000 to $3,000
Pulsed water jetting	1,000	12	$2,000 to $8,000
Blended cold chemical	100	6	$500 to $2,000
Blended cold chemical	300	8	$1,000 to $ 3,000
Blended cold chemical	1,000	12	$2,000 to $6,000

Preventative maintenance is given in table 8-3 based upon the annual costs for a selected well that is recognized to be subjected to fouling and is in a condition that does not require radical rehabilitation.

Table 8-3. Approximate Costs for Annual Preventative Maintenance Program

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favor the election of replacement over rehabilitation. Site-specific conditions can cause the comparison to shift in either direction.

Prior to carrying out cost comparison analyses we need to first ascertain that the particular well(s) under discussion are still required in these locations. There may be an opportunity to install a replacement well in a more suitable location after an optimization study or hydrogeologic evaluation using operational data that was unavailable when the system was first installed.

One very important aspect of the evaluation of the potential value of rehabilitating an well is economic. This chapter addresses these issues in three stages: (1) establish the range of costs involved in a successful rehabilitation presuming that the problems with the well were correctly diagnosed; (2) calculate the cost savings derived from improved well efficiency; and (3) describe the decision pathway between the cost-effectiveness of rehabilitation as compared to abandonment and/or replacement. This latter alternative also should address the impact of the abandonment of the well on the operations of the site considering the replacement option.

8-3-1. Replacement cost projections.

In the determination of the replacement costs, it is not appropriate to simply establish the costs associated with the

installation of a complete injection and/or extraction well at the site since this is only one part of the total costs of replacement.
Other factors that have to be considered include well abandonment, removal and disposal of associated pipes and equipment,
and connection to the treatment plant (plumbing, electrical, telemetry, etc.).
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