Investigation of Storage-Well Damage Mechanisms

V. Yeager (vyeager@halnet.com; 405-251-3845)
F. Behenna (405-251-2101)
M. Blauch (mblauch@halnet.com; 405-251-3496)
Halliburton Energy Services
P.O. Box 1431
Duncan, OK 73536-0428

S. Foh (sfoh@gri.org; 773-399-8302)
Gas Research Institute
8600 West Bryn Mawr
Chicago, IL 60631

Introduction

In the more than 350 U.S. storage reservoirs that represent over 14,000 individual wells, most gas-storage operators experience an average loss in deliverability of 5% over time. This decline rate based on reported American Gas Association (A.G.A.) deliverability capacity, translates to approximately 3 Bcf/D each year for the entire industry. Estimates of spending to recover or replace this lost deliverability have been set at $100 million per year. These expenditures include both drilling and stimulation/remediation. However, drilling is the more costly method of retaining or recovering this loss, and as the demand for storage increases, the need to improve and maintain deliverability in existing wells also increases.[1,2]

Two problems exist regarding the cost of recovery and replacement of deliverability. First, a significant portion of this money is expended without a clear understanding of the damage being addressed. Second, while operators may understand the various mechanisms of damage that could account for the loss, they have no diagnostic approach available that will help them determine which mechanism is responsible for the loss in a specific circumstance. Therefore, the choice and design of remedial and preventive measures is ineffective.[3]

Objectives

This research effort is targeted at producing a fundamental understanding of the formation-damage mechanisms responsible for deliverability loss and their cause-effect relationships to deliverability loss in a broad spectrum of gas-storage fields and reservoirs. This project will provide 1) definitions of the mechanisms responsible for loss of deliverability in storage wells, 2) an outline of testing procedures that operators can use to deduce the type of damage mechanism, and 3) the basis for identifying procedures to prevent or remove damage.

Approach

The technical approach to problem-solving for the investigation of storage well damage mechanisms consists of the following three major task categories:

Task 1—selecting candidates
Task 2—determining the damage mechanisms
Task 3—writing the final report

Figures 1 and 2 illustrate the structure of the overall technical approach.

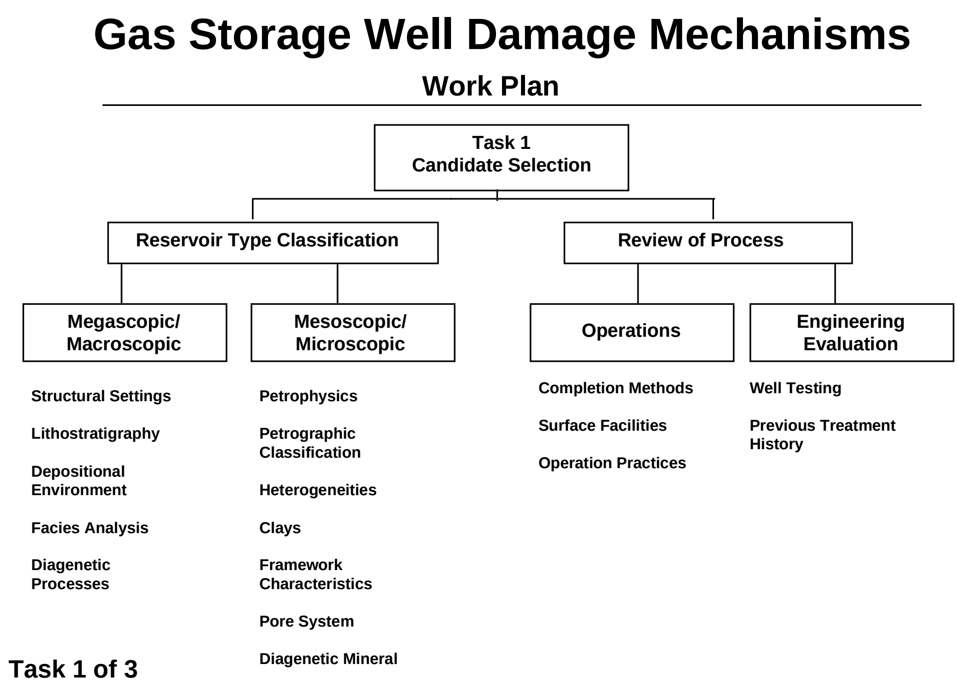

Figure 1—Selecting Candidates

The approach to Task 1 involves integrating information and expertise designed to select candidates based on reservoir type characterization, deliverability loss assessment, and well history/well records review. The objective of this task is to use existing data and classification of reservoir types outlined in the Maurer Engineering study (reservoir types R1 through R12) and document the magnitude of deliverability losses within fields operated by the cooperating companies.[1]

The second phase of this study will focus on 12 reservoirs. Nine of these reservoirs are located in the Northeast U.S., as are the majority of the U.S. gas storage reservoirs. Two of the reservoirs are located in the midcontinent region, and the final one is a west coast reservoir. Candidates include both cased and openhole completions, average permeabilities from 20 to 700 md, a temperature range of 60 to 185°F, depths of 1,260 to 7,700 ft, geologic ages from Cambrian to Miocene/Tertiary, wells from 20 to 100 years old, and fields with maximum deliverabilities ranging from 10 Mcf to 1 Bcf. There were 11 sandstone and one carbonate reservoir. Of the 11 sandstone reservoirs, one is an aquifer-driven reservoir, and one has both oil and gas as its original contents.

The technical approach strategy for Task 2 involves applying the outlined strategy for determining the mechanisms responsible for loss of deliverability over time in the identified gas storage study wells. The damage mechanisms will be determined based on the following three-stage approach: 1) quantifying the degree of existing damage, 2) diagnosing the existing downhole damage mechanisms, and 3) performing specifically designed mechanistic formation damage studies.

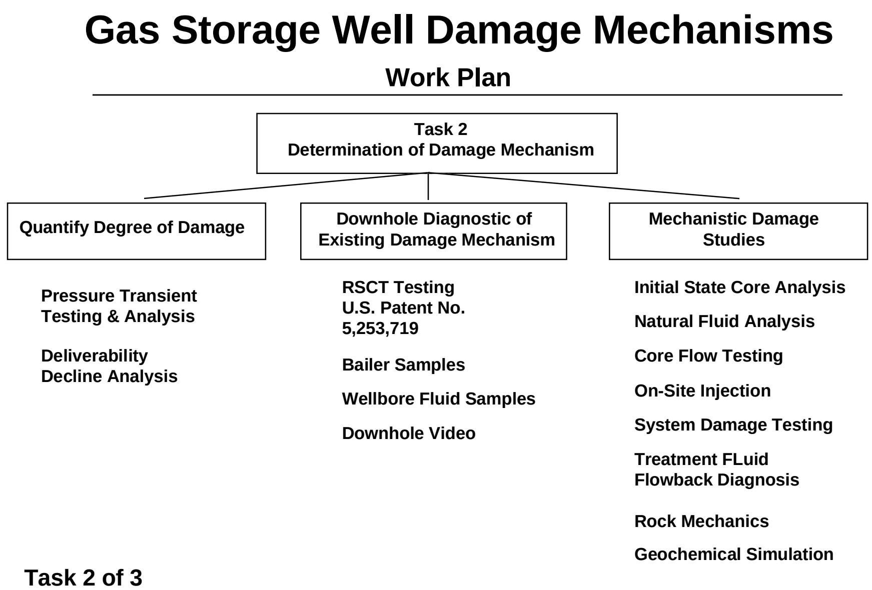

Figure 2—Determining Damage Mechanisms

Identification of mechanisms is based on the evaluation and field-testing of 33 wells from 12 reservoirs. The 12 reservoirs are selected as a representative cross section based on a statistical analysis of existing storage database information. Areas of statistical analysis include trap and drive mechanisms, geologic parameters, formation parameters, and completion types.

Downhole diagnostic field results for the 33 selected wells include 1) well-test analysis to determine quantitatively if damage existed, 2) downhole video to observe the wellbore and formation areas, 3) physical sampling in the form of downhole liquids and solids, and 4) rotary sidewall core samples of the wellbore face as a “biopsy” of the storage formation. Techniques for collecting and analyzing the physical samples are targeted at preserving the damage and allowing emphasis to be placed on specific areas where damage is most likely to occur, such as the surface of the sidewall core, oxidation of solids, etc.

Before all other downhole diagnostic testing and sampling runs, a downhole video run is made that evaluates the morphology, nature, and distribution of any potentially damaging deposition that may be present, such as salt bridges, scale deposition, or organic buildup on the wellbore surface in openhole completions or in the vicinity of perforations in perforated completions. The video analysis also allows for flow-distribution analysis that supplements interpretation of the well-test results and evaluates the flow efficiency, plugging of perforation tunnels, evidence of sand production, and determination of fluid levels that may interfere with well-test analysis.

Identifying a baseline from which to measure the degree of damage is the first step toward proper identification of the damage mechanisms being analyzed. Identifying this baseline is accomplished by conducting pressure transient analysis tests to measure formation kh and skin on each of the study wells.

Bailer samples are taken to sample any bottomhole solids and fluids accumulated in the wellbore through the application of a downhole bailer. For cased-hole completions, these samples are the only physical samples available.

U.S. Patent 5,253,719 describes the primary damage diagnostic method for damage existing in the openhole completed gas storage wells.[4] The patent describes a method for evaluating the type and extent of formation damage that involves acquiring core samples from the wellbore wall in the zone of interest and evaluating those core samples to determine what, if any, formation damage exists. In the preferred mode of the patent process, core samples are acquired through the use of a rotary sidewall coring tool. This tool can drill core plugs perpendicular to the borehole wall. After correlating and gamma ray positioning at the desired core point, a backup arm is extended to decentralize the tool and hold the tool securely against the formation. A diamond bit rotating at 2,000 rev/min cuts a $^{15}/_{16}$ x 1 ¾-in. sample from the formation, and telemetry from the tool allows the operator to monitor the coring process continuously. After the sample has been cut, a slight vertical movement of the bit breaks the core sample from the formation. The sample is withdrawn into the tool and the core is ejected into a receiver tube. The tool is then ready for the next selected core point. Up to 30 core samples can be cut on one trip in the well. During drainage studies, sidewall samples must be carefully handled so that "face" material is not removed, separated, or otherwise damaged before analysis.

Results

The seven damage mechanisms found in gas storage wells include 1) bacteria, 2) inorganic precipitates, 3) production chemical/organic residues, 4) drilling/injection particulate plugging, 5) mechanical obstructions, 6) relative permeability effects, and 7) sanding/unconsolidation.

Bacteria

Wellhead tests of fluids from bailer samples indicated sulfate-reducing bacteria and in some cases, acid-producing bacteria in 7 of the 12 study reservoirs. Sulfate-reducing bacteria favor an anaerobic (oxygen-free) environment. They can coexist with iron-reducing bacteria (which is not tested for in this study), and even small amounts of oils and grease will provide nutrients for growth. Stagnant water and low-flow conditions such as those encountered in the bottom of the wellbore are ideal for bacterial growth.[5]

Figure 3 shows a binocular-microscopy photograph taken at the wellhead that shows the abundance of the bacteria present in the fluid along with sodium chloride crystals and iron-containing particles.

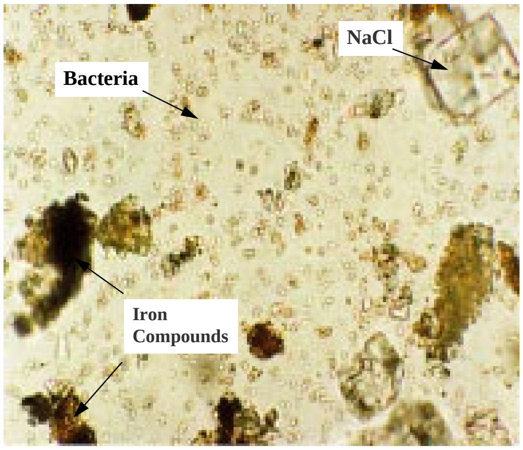

Figure 3—Bacteria at the Wellhead

Inorganic Precipitates

Inorganic precipitates found in the bailer samples and on the faces of the rotary sidewall cores were many and varied. In most cases, crystals were very well defined and often included quartz fragments and organic materials. The crystals effectively blocked entrance into and out of the natural formation permeability.

The precipitated compounds, including such iron compounds as iron oxides, iron carbonate (siderite) (Figure 4), and iron sulfides (Figure 5), and were present in 6 of the 11 sandstone reservoirs. The presence of these compounds along with elemental sulfur is often a key to (and occurs in association with) the sulfate-reducing bacteria already discussed. Iron serves as a good electron acceptor for bacteria in the metabolism of sulfates. Of the water samples obtained, 85% had wellhead pH and Eh (reduction/oxidation potentials) values in the range for the formation of iron sulfides and carbonates.

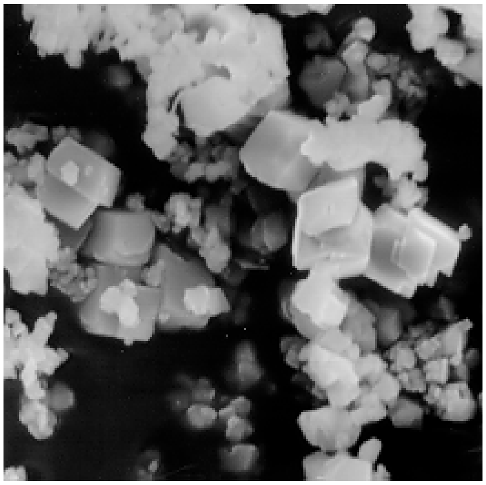

Figure 4—Siderite Crystals

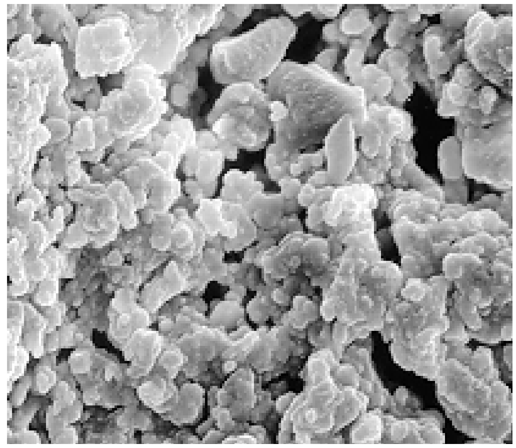

Figure 5—Layer of Iron Sulfide

Four of the sandstone reservoirs and the carbonate reservoir contained salts such as sodium chloride and/or calcium chloride (Figure 6). Calcium carbonate (Figure 7) was present in five sandstone reservoirs (three of which did not contain the salts) and the carbonate formation. Calcium and/or barium sulfate were present in about half of the sandstone formations and the carbonate. The most significant deposits of barium sulfate were found in the aquifer-study reservoir.

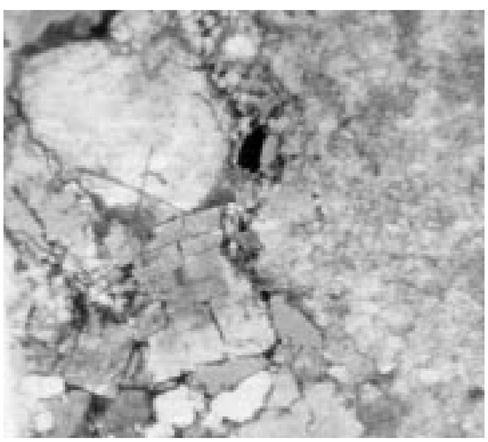

Figure 6—Salt (Sodium Chloride)

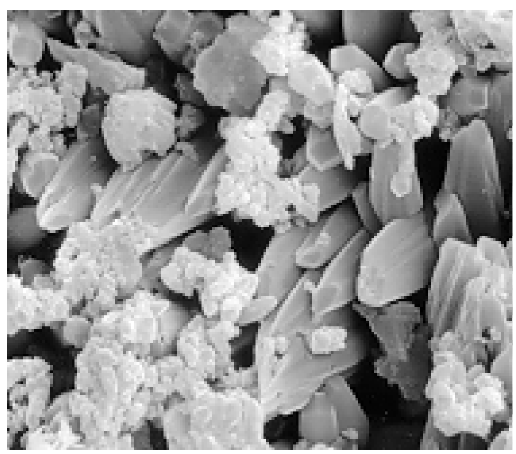

Figure 7—Calcium Carbonate

The presence of inorganic precipitates is undoubtedly influenced by 1) the type and quantity of fluids injected and withdrawn from the formation, 2) operating procedures, 3) presence of bacteria, and 4) reservoir characteristics such as temperature and pressure.

Production Chemicals/Organic Residues

Trace or very small amounts of hydrocarbon oils, ester compounds, and/or isobutylene materials were found during the organic extraction of many of the solids and the rotary sidewall cores. In a few samples, these materials were seen (with petrographic and scanning electron microscopes) as a dark layer along the wellbore face (Figure 8) or as substances lining/plugging pore throats (Figure 9). Based on baseline sampling of compressor oils, bacteriacides, and corrosion inhibitors, these organic residues are assumed to be the result of compressor or lubricating oils and/or various production chemicals.

Figure 8—Organic Layer on Formation Face (left)

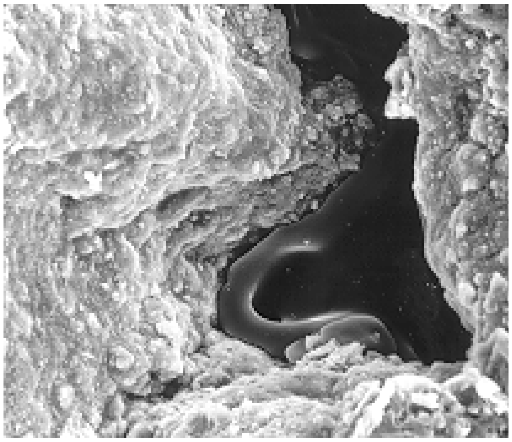

Figure 9—Organic Residue Lining Pore Throat

Drilling/Injection Particulate Plugging

Surfaces of most of the sidewall cores had some degree of very fine material adhering to them. This layer of material generally contains silica even in the carbonate formation, and in many cases, it is incorporated into or encapsulated in a geochemical precipitate or a hydrocarbon residue. This material is not present at depth in the cored samples, indicating that it came from the outside. The material is therefore a product of drilling and/or the injection process. Figure 10 is a cross-sectional view of a sidewall core shown through a scanning electron microscope (SEM). This 20- to 30-micron thick layer of debris is made up of calcium and iron scale along with shards of quartz.

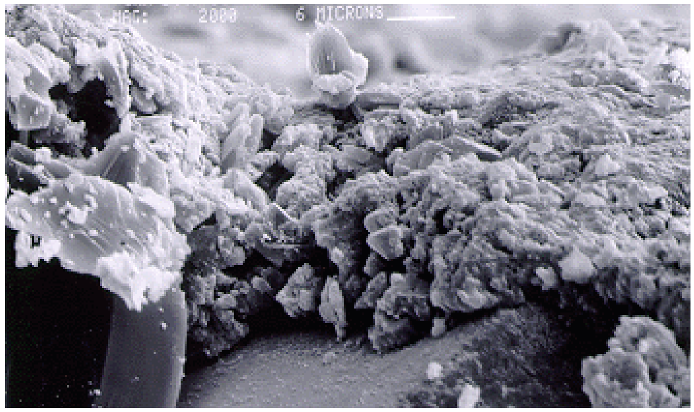

Figure 10—Particulate Layer at Surface of Sidewall Sample

Mechanical Obstructions, Relative Permeability Effects, and Sanding/ Unconsolidation

Three other potential damage mechanisms were present in the isolated study wells. The first mechanism is a physical obstruction, such as a threaded metal connection or other “fish” that can mechanically influence the deliverability of a well. These types of obstructions are often hard to deduce because 1) they may be mistaken for fill with wireline and 2) their influence may be sporadic if they are free to move up and down within the wellbore.

Relative permeability effects were a damage mechanism in at least three different cases within this study. This mechanism was an expected effect in the first case because the original contents of the reservoir included both oil and gas. The oil had become more viscous and had developed a heavier API gravity with time. The second relative permeability case was a high-permeability formation into which oil has been injected and had penetrated a significant distance because of the large pore structure. The final case in which relative permeability was a factor was one in which fluid (either water or water/oil) was standing in the wellbore and actually covered the interval during withdrawal. The source of fluid was not always known, although in several instances, downhole video did indicate fluid being produced from the interval (both openhole and perforated completions) where little or no fluid came to surface and no fluid was expected on entry.

Sanding or unconsolidation was the result of a very soft or friable formation. Little or no cementing material was present to keep the formation together. During withdrawal, the pressure drop was sufficient to pull sand into the wellbore. Significant amounts of solids, just as with the fluids, decreased deliverability.

Depth of Damage

In 9 of the 12 study reservoirs, the damage observed, regardless of the damage mechanism, was less than 0.25 in. deep. In two of the other three reservoir rocks, all of which had average permeabilities greater than 200 md, the depth of damage was less than 0.75 in. Only in the highest-permeability formation (750 md average permeability) was the depth of damage greater than the 1.5-in. core length field of investigation.

Application/Benefits

Operators in the gas-storage industry will have immediate use for the findings of this study. The conclusions relating to damage mechanisms apply to the overall storage population because the mechanisms are based on representative candidates. Guidelines for candidate well selection processes and various strategies and diagnostic test procedures that may be used to determine damage based on the reservoir and available information can be drawn from this work. Finally, identification of parameters that may influence the damage mechanism as well as some preventive and remedial conclusions are also possible from this work. This work will also be the foundation on which later efforts may build to develop and evaluate preventive and remedial technologies and methods.

Figure 11 identifies the first benefit to the storage industry, the money that could be saved if the overall average decline in deliverability was reduced for the entire industry from 5%. Depending on the cost of gas, a reduction in this decline would translate into millions of dollars per year of additional gas that could be delivered.

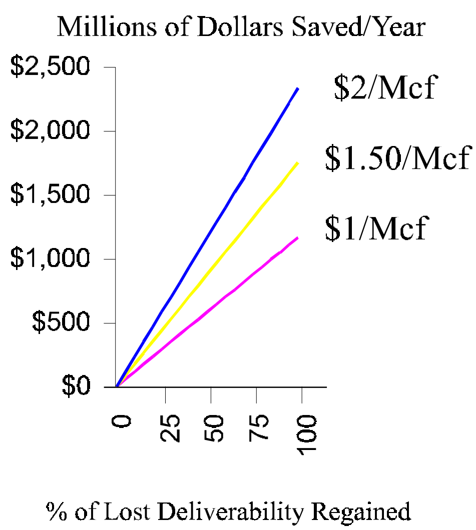

Figure 11—Savings to Gas-Storage Industry

In addition, the Maurer Engineering study indicated that “the industry total annual expenditures are approximately $100 million,” which is the cost of the deliverability enhancement expenditure required to offset the reported decline. The majority of this expenditure is being used for infill/replacement drilling (approximately $66 million), which is the most effective replacement technique, and also the most costly. Better identification of the damage mechanisms can result in more effective use of less expensive production-enhancement techniques. Understanding the damage mechanisms also aids in developing preventive measures, which should reduce the slope of the overall decline curve.

Cost savings and benefits should also come with the injection cycles in the form of additional gas stored, lower injection pressures, and compressor expenditures, etc.

Overall, identification of the damage mechanisms involved in the injection and recovery of gas in storage wells should lead to both additional revenues in the form of additional deliverability and lower expenditures for day-to-day operations and remedial enhancement/damage removal.

Future Activities

Future work will compare the overall data from the study wells and will present the general conclusions and recommendations that can be drawn based on these data. The similarities and differences of the data will be analyzed with respect to geologic parameters, completion and operations practices, etc.

The final report for this project will then be assembled to describe the different damage mechanisms (with specific reservoirs as examples), discuss the methodology for determining that damage, and provide conclusions and recommendations for prevention and remediation.

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