CHARACTERIZATION OF CONDITIONS OF NATURAL GAS STORAGE RESERVOIRS AND DESIGN AND DEMONSTRATION OF REMEDIAL TECHNIQUES FOR DAMAGE MECHANISMS FOUND THEREIN

ANNUAL TECHNICAL PROGRESS REPORT

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ABSTRACT

There are four primary goals of contract DE-FG26-99FT40703:

1) We seek to better understand how and why two damage mechanisms, 1) inorganic precipitants, and 2) hydrocarbons and organic residues, occur at the reservoir/wellbore interface in gas storage wells.
2) We plan on testing potential prevention and remediation strategies related to these two damage mechanisms in the laboratory.
3) We expect to demonstrate in the field, cost-effective prevention and remediation strategies that laboratory testing deems viable.
4) We will investigate new technology for the gas storage industry that will provide operators with a cost effective method to reduce non-darcy turbulent flow effects on flow rate.

For the above damage mechanisms, our research efforts will demonstrate the diagnostic technique for determining the damage mechanisms associated with lost deliverability as well as demonstrate and evaluate the remedial techniques in the laboratory setting and in actual gas storage reservoirs.

We plan on accomplishing the above goals by performing extensive lab analyses of rotary sidewall cores taken from at least two wells, testing potential remediation strategies in the lab, and demonstrating in the field the applicability of the proposed remediation treatments.

The benefits from this work will be quantified from this study and extrapolated to the entire storage industry. The technology and project results will be transferred to the industry through DOE dissemination and through the industry service companies that work on gas storage wells.

Achieving these goals will enable the underground gas storage industry to more cost-effectively mitigate declining deliverability in their storage fields.

Work completed to date includes the following:

1) Solicited potential participants from the gas storage industry.
2) Selected one participant experiencing damage from inorganic precipitates.
3) Developed laboratory testing procedures.
4) Collected cores from National Fuel Gas' Summit #1527 Well.
5) Analyzed cores from National Fuel Gas' Summit #1527 Well.
6) Began investigating methods to remove damage identified in Summit #1527 cores.
7) Began investigating methods to reduce non-darcy turbulent effects

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INTRODUCTION

The gas storage industry uses over 400 reservoirs and 17,000 wells to store and withdrawal gas. It is thus a significant contributor to gas supply in the United States. It is generally accepted that many gas storage wells show a loss of deliverability each year due to numerous damage mechanisms.

This problem has been studied previously (GRI/DOE studies by Mauer, Halliburton, and Schlumberger Holditch - Reservoir Technology Consulting Services). These studies estimated that up to one hundred million dollars are spent each year to recover or replace lost deliverability. The expenditures include both drilling new wells and stimulating/remediating existing wells. The American Gas Association estimates a deliverability loss of approximately 3.2 Bscf/D per year in the storage industry.

Thus, there is a great potential for restoring the capability of existing wells that are not being treated, for reducing the cost of deliverability enhancement by reducing the number of infill/replacement wells, for reducing remediation costs, and/or developing technology to mitigate or eliminate damage from occurring.

The GRI/DOE Halliburton study identified the primary mechanisms that may be responsible for loss of deliverability over time in gas storage wells. They defined testing procedures in storage wells and in the laboratory to identify potential damage mechanisms. The Halliburton study found eight major categories of potential damage mechanisms. The study discussed, in general, the possible reactions that need to occur to create the damage, but the study did not address the exact cause of damage or the most likely period of damage, i.e., during the injection or withdrawal cycle, how to prevent or mitigate the damage, and/or how to eliminate the damage from occurring in the future.

Thus, this contract serves to expand the effort Halliburton started and compliments the current GRI gas storage project. We expect to identify the exact damage mechanism and the optimal remedial, mitigative, and/or preventative measure both by laboratory testing and field application. The long-term effectiveness of the remediation treatment will be quantified based on damage mechanism and geochemical environment. A benefits study will extrapolate the results to the entire U.S. storage industry. The commercialization aspects of the diagnostic and remediation procedures will also be determined in the study.

EXECUTIVE SUMMARY

The gas storage industry is a significant contributor to gas supply in the United States. The American Gas Association estimates that deliverability losses of approximately 3.2 Bscf/D per year occur in the storage industry due to numerous damage mechanisms. Previous studies estimate that up to one hundred million dollars are spent each year to recover or replace this lost deliverability. Thus, there is a great potential for restoring deliverability in existing wells, reducing deliverability enhancement costs and/or developing technology to mitigate or eliminate damage from occurring.

Prior studies have identified the primary mechanisms that may be responsible for deliverability loss in gas storage wells, and defined procedures to identify potential damage mechanisms. Although these studies discussed, in general, the possible reactions that need to occur to create the damage, they did not address the exact cause of the damage, determine when it occurs (injection or withdrawal) cycle, or determine how to prevent or mitigate the damage.

This research serves to expand prior efforts to identify the specific damage mechanism and the optimal remedial, mitigative, and/or preventative measure both by laboratory testing and field application.

There are four primary goals of contract DE-FG26-99FT40703:

1) We seek to better understand how and why two damage mechanisms, 1) inorganic precipitants, and 2) hydrocarbons and organic residues, occur at the reservoir/wellbore interface in gas storage wells.
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For the above damage mechanisms, we will demonstrate the diagnostic technique for determining the damage mechanisms and evaluate the remedial techniques in the laboratory as well as in actual gas storage reservoirs. We will accomplish this by performing extensive lab analyses of rotary sidewall cores, testing potential remediation strategies in the lab, and demonstrating the applicability of the remediation treatments in the field. Achieving the above goals will enable the underground gas storage industry to more cost-effectively mitigate declining deliverability in their storage fields.

The work we have completed to date includes the following:

1) Solicited potential participants from the gas storage industry.
2) Selected one participant experiencing damage from inorganic precipitates.
3) Developed laboratory testing procedures.
4) Collected cores from National Fuel Gas' Summit #1527 Well.
5) Analyzed cores from National Fuel Gas' Summit #1527 Well.
6) Began investigating methods to remove damage identified in Summit #1527 cores.
7) Began investigating methods to reduce non-darcy turbulent effects.

EXPERIMENTAL

The protocol for lab analysis of rotary sidewall cores was finalized by Dr. Phil Halleck. Dr. Halleck is a Professor of Petroleum and Natural Gas Engineering at Penn State. He will direct the laboratory investigations of the cores. The protocol, as well as the rationale for the various procedures is outlined below.

The sidewall coring program requires four sidewall cores from each well, plus samples of formation rock in its original condition. The objectives of testing performed on each core are summarized below, as well as the procedure employed to perform the stated testing

Core #1:

Objective - Damage Characterization

Slab the core lengthwise with a diamond saw, and perform the following analyses on the first half of core #1:

- Solvent Extract
- Gas Chromatograph Mass Spectrometer (GCMS) analysis on organics from this half to determine compounds present
- Prepare thin section
- Perform Scanning Electron Microscopy/Energy Dispersive X-Ray Analysis (SEM/EDAX) to map texture and identify inorganic scale elements
- Examine with petrographic microscope for mineralogy and texture

These tests are designed to identify the presence of various mineral scales and organic compounds in the pore structure and on the surface of the core. Solvent extraction using appropriate solvents in Soxlet apparati will dissolve any organic material and condense it into a separate container for analysis. The amount of organic material extracted from a given volume of rock allows determination of how much pore space was occupied by the organic material. The GCMS, or gas chromatograph mass spectrometer, is used to separate the various components of the resulting mixture and determine their molecular weights and thus their composition. These data are useful in determining the source of the material as native organic liquids, compressor oil, production chemical, or reaction products of one of these with other chemical agents. If necessary, carbon isotope analysis is available to assist in determining the age of the organics.

The thin section will be used primarily for SEM (scanning electron microscope) and EDX (energy dispersive X-ray) analysis. These will provide a microscopic view of the pore structure of the rock as well as maps of the distribution of the specific elements composing any inorganic precipitates. The result is determination of the distribution of scale minerals in the pore structure, which will assist in determining the scale's affect on permeability. These data will be supplemented with bulk analysis of cation and anion composition as described below. Thin sections will also be used for standard petrographic examination of the rock's texture, mineralogy and pore structure.

Data from the sidewall core will be compared with a rock sample in its original condition. This is necessary both to evaluate the geochemical environment and to quantify how much of each mineral has been deposited by storage and production operations and how much may have been originally present.

Perform the following on the second half of core #1:

- Perform gas permeability measurement on the half core
- Slice second half crosswise in 1/4-in increments
- Retest permeability after taking each slice
- Solvent extract each 1/4-inch increment
- Perform X-Ray Diffraction (XRD) analysis on each increment
- Perform Inductively Coupled Plasma (ICP) and ion chromatographic analyses on each increment
- Perform Total Organic Carbon (TOC) measurement on liquids from each increment

These tests are designed to further identify the nature of any inorganic and organic materials on and in the formation rock, and to provide a course map of the severity of potential plugging. The gas permeability tests give the average permeability of the core as each slice of material is removed. The change in permeability after taking each slice allows determination of the permeability of the slice, thus obtaining a course map of permeability as a function of distance from the sand face. Analyzing each slice separately for the presence of organic and inorganic plugging materials allows the amounts of these compounds to be mapped as a function of distance from the sand face. XRD, or X-ray diffraction analysis, is used to identify the presence of specific minerals present in the rock. These are identified by their crystal structures as revealed by their diffraction patterns. Interpretation is assisted by knowledge of the cations and anions present. These data come from the EDX measurements described above and from ICP (Inductively Coupled Plasma) spectrophotometer analysis of cations. This test is performed by dissolving the mineral phases in appropriate acids to form a solution. The solution is ionized in a plasma and the light emissions analyzed to determine the amounts of specific cations present. Ion chromatography is used to separate and quantify anions such as CO3-2, HCO3-, and SO4-2. TOC (or total organic carbon) measurements on each slice will determine how much organic material is present, again, as a function of distance from the sand face.

Core #2:

Objective - Relation of permeability damage to observed plugging mechanisms.

- Perform gas permeability on entire core in both directions
- Solvent extract entire core
- Retest permeability

Cores #3 and #4:

Objective – Evaluation of remediation techniques.

- Perform gas perm on entire core in both directions
- Treat core with selected remedial method
- Acidization
- Miscible solvent
- Heat/Pressure
- Mechanical removal of the sandface
- Re-measure gas permeability
- Several cycles of treatment may be possible
- If appropriate, evaluate post-treatment sample as for core #1

These tests are designed to determine the effectiveness of treatments that might be applied in the field. A special vessel will be fabricated to apply these treatments in a manner consistent with the downhole environment. Acids or miscible solvents will be injected into the sandface of the core. The core itself will be backed by additional formation rock so that spent acids and solvents are pushed through the core and into the backing rock. The spent treatment fluids will be recovered back though the test core to simulate actual down-hole processes. After completion of each treatment, gas permeability will be remeasured to determine the effects of the treatment. Due account will be taken of relative permeability effects.

Scrapings/Other non-core samples:

Objective: Evaluate lower-cost testing alternatives.

- Obtain samples from perforations and/or wellbore wall
- Extract hydrocarbons
- Perform GCMS to determine hydrocarbons present
- Perform XRD on inorganic material
- Perform cation/anion analysis on same material

These tests are designed to evaluate the effectiveness of lower-cost testing alternatives. The sidewall cores required for the above tests are quite expensive and simpler, more cost effective methods of determining the damage mechanisms are required. The intent of these tests is to evaluate whether cheaper, but less well-defined samples can be used to obtain the same information. The tests described have the same purpose as those run on sidewall core, except that permeability itself is not measured and distribution of damage away from the sand face is not obtained. The results of these tests will be compared with those from the sidewall cores.

Wellbore Liquids and Formation Liquids Analysis:

Objective: Supplement mineralogical/chemical data obtained from formation mineralogy and pore fluid analyses

- Perform ICP and ion chromatographic analyses on well water
- Obtain total ion content and Ph to define environment

The intent of these tests is to supplement the mineralogical and chemical data obtained from formation mineralogy and pore fluid analyses. The combined data, plus historical records of production chemicals and previous remediation treatments used, form the basis for characterizing the geochemical environment. These data are needed to establish the precipitation reactions and phase behavior involved in depositing the observed scale. The intent is to go beyond remediation to develop operating procedures that prevent re-occurrence of permeability damage.

Dr. Halleck had coordinated the design, construction, and calibration of the equipment required for the above testing. In addition, test runs are planned on non-study cores to iron out operational, procedural, and/or technical problems prior to testing the study cores.

RESULTS AND DISCUSSION

Several of the subtasks associated with Task #1 (Table 1) in our proposal have been completed. Data and reports from several previous GRI, DOE, FETC, and other industry studies have been reviewed where pertinent. Specifically, GRI/DOE studies by Mauer, Halliburton, ARI, and other authors related to damage mechanism identification protocol, identification and estimation of damage levels in storage wells, frequency and success of remediation treatments used in the storage industry and novel stimulation techniques have been reviewed.

TABLE 1: SUMMARY OF TASKS AND SUBTASKS

Task	Task Description
1	Select and characterize a study set of damage mechanisms in the natural gas storage geologic/geochemical environment.
2	Develop conceptual strategies to mitigate or eliminate the selected damage mechanisms.
3	Design and perform laboratory scale studies to evaluate conceptual strategies with selection and refining of promising strategies.
4	Budget Period I Report

In addition, we have selected the first geochemical/geological environment to study. Namely NFG's Well #1527 in the Summit Field, located near Erie, PA. This well is completed in the Oriskany sand, was part of a previous Halliburton damage mechanism study, and has been subject to testing and sampling over the last several years.

Historical and operational data related to NFG's Summit 1527 study well has been collected and reviewed. This information includes past pressure transient testing results, backpressure testing results, results of analyses of wellbore fluids and pipeline solids, past stimulation information, and information included in the Halliburton report.

Plans to collect rotary sidewall cores from this well in early summer of 2000 were made. However, due to operational problems in the field and poor weather conditions, this work was cancelled several times. Finally, in October 2000, rotary sidewall cores were collected from Summit 1527 Well, and transported to Penn State for analysis.

We have started the investigation of wellbore damage due to non-darcy flow. To date we have reviewed non-darcy flow theory to identify which parameters significantly affect the non-darcy flow component of wellbore damage. We also performed a preliminary study to investigate the relative impact these parameters have on deliverability, and estimated the potential increases in deliverability that result when these parameters are altered.

The Forcheimer Equation can be written as shown in **Eqn 1**, where P is pressure, x is the coordinate in the flow direction, u is viscosity, v is average velocity, k is permeability, β is the turbulence or beta factor, and ρ is fluid density.

$$\frac{\partial P}{\partial x} = \frac{uv}{k} + \beta\rho v^2 \qquad \textbf{Eqn 1}$$

The turbulence factor, β can be approximated as shown in **Eqn 2** below:

$$\beta = \frac{2.23x10^{10}}{k^{1.201}} \qquad \textbf{Eqn 2}$$

As is evident from **Eqn 1**, the non-darcy flow component of pressure drop for fluid flow in porous media, $\beta\rho v^2$, is a function of the turbulence factor (which is permeability-dependent) , the velocity of the fluid, and the density of the fluid. The implication of these relationships suggests that there are at least four practical ways we can reduce the pressure drop due to non-darcy flow.

First, we could increase the effective permeability of the reservoir (thus reducing the beta-factor). Since most of the pressure drop occurs in the near-wellbore region, increasing the near-wellbore permeability may prove practical in carbonate formations, where "wormholes" from acidizing would increase the permeability. This option could alternatively be considered an increase in the effective wellbore radius, which would have similar effects.

Second, we could decrease the velocity of the fluids in the near-wellbore region by increasing the radius of the wellbore. This could be accomplished by underreaming in an open hole completion, and by milling and underreaming in a cased hole completion.

Third, we could decrease the velocity of the fluids in the near-wellbore region by increasing the shots per foot in a cased hole completion. This would reduce convergence of fluid flow into a limited flow area in the near-wellbore region, thus effectively reducing the velocity of the fluid through the porous media.

Fourth, in partially completed wells (i.e., wells that are not drilled completely through the reservoir), deepening the well through the entire reservoir would also reduce convergence of fluid flow in the near-wellbore region. As in the case of increasing the perforation shot density, the result would be to reduce the velocity of the fluid in the porous media.

Based on preliminary NODAL analysis sensitivity studies, we estimate that deliverability increases on the order of 50% are possible by successfully addressing the non-darcy flow issues discussed above.

Further work is planned in this area to more precisely identify the potential increases of each option discussed above. In addition, practical methods of implementing field procedures to realize these theoretical improvements will be studied.

Technology transfer is underway. Numerous meetings with operators, consultants, and DOE have occurred, and several presentations have been made in the normal industry forums (Society of Petroleum Engineers, American Gas Association, Independent Oil & Gas Association, etc.), outlining our intent and approach in an effort to secure additional participation in the project.

CONCLUSIONS

The following preliminary conclusions can be drawn at this point:

1) Penn State has developed the laboratory testing protocol for the analysis of rotary sidewall cores collected from the study wells.
2) Construction of lab equipment for the analysis of rotary sidewall cores collected from the study wells has been completed.
3) The coring of National Fuel Gas Well 1527 in the Summit field has been completed.
4) Analysis of cores from Summit 1527 Well should be completed in November 2000.
5) Our investigations suggest that there are practical ways to reduce the non-darcy skin damage in gas storage wells.
6) Implementation of the methods identified (to date) to reduce non-darcy flow in storage wells is expected to result in deliverability increases on the order of 50% in wells with damage caused by non-darcy flow.

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