REPORT

DOE/ET/27146--10

FLOW OF PARTICLE SUSPENSIONS THROUGH POROUS MEDIA

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PREPARED BY

DR. O. J. VETTER, DR. V. KANDARPA AND
A. HAROUAKA

VETER RESEARCH

3189C AIRWAY AVE. - COSTA MESA - CALIFORNIA 92626

SUBMITTED TO

AC03-79ET 27146

UNITED STATES DEPARTMENT OF ENERGY
DIVISION OF GEOTHERMAL ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISTRIBUTION LIST:

A. ADDUCI	6 COPIES
DOE TECH INFORMATION CENTER	1 COPY
OFFICE OF CALIFORNIA PATENT COUNCIL	1 COPY
DR. O.J. VETTER, VR	1 COPY
DR. V. KANDARPA, VR	1 COPY
DR. A. HAROUKA, VR	1 COPY
VR FILE	8 COPIES

DATE OF ISSUANCE: JUNE 22, 1982

VR REPORT NO: 82-06-22

SIGNATURE(S):

Officer Vetter
Vincent L...

ASIA/ASUN/ATC/...

TABLE OF CONTENTS

	<u>PAGE</u>
PREAMBLE.....	1
1.0 ABSTRACT.....	2
2.0 CONCLUSIONS.....	2
3.0 RECOMMENDATIONS.....	4
4.0 INTRODUCTION.....	5
5.0 OBJECTIVES OF THE STUDY.....	6
6.0 LITERATURE REVIEW.....	7
7.0 METHODS AND PROCEDURES USED IN THE PRESENT STUDY.....	13
7.1 DESCRIPTION OF FLOW APPARATUS.....	13
7.2 EXPERIMENTAL PROCEDURES.....	14
7.2.2 SLURRY PREPARATION.....	14
7.2.3 FLOW EXPERIMENTS.....	14
7.2.4 EXAMINATION OF THE CORES.....	15
8.0 EXPERIMENTAL RESULTS.....	15
8.1 PARTICLE SIZE DISTRIBUTION MEASUREMENT DATA.....	15
8.2 RESULTS OF FLOW EXPERIMENTS USING CHROME OXIDE PARTICLES.....	17
8.2.1 PARTICLE SIZE EFFECTS.....	17
8.2.2 PARTICLE CHARGE EFFECTS.....	18
8.2.3 FLOW RATE EFFECTS.....	18
8.3 RESULTS OF FLOW EXPERIMENTS USING BLENDED CERIUM OXIDE PARTICLES.....	19
8.3.1 FLOW RATE EFFECTS.....	19
8.3.2 PARTICLE CONCENTRATION EFFECTS.....	19

8.4	RESULTS EXPERIMENTS WITH CORES IN TANDEM.....	19
9.0	DISCUSSION OF RESULTS.....	20
9.1	PARTICLE SIZE RELATED EFFECTS ON FORMATION DAMAGE.....	20
9.2	EFFECT OF FLOW RATE ON FORMATION DAMAGE.....	21
9.3	EFFECT OF PARTICLE CONCENTRATION ON FORMATION DAMAGE.....	22
9.4	LABORATORY VERSUS RESERVOIR CONDITIONS.....	22
9.4.1	FLOW RATE.....	23
10.0	IMPLICATIONS OF THE STUDY.....	24
10.1	FILTRATION.....	24
10.2	PARTICLE SIZE DISTRIBUTION MEASUREMENTS.....	24
10.3	FLOW RATE.....	24
	REFERENCES.....	24

TABLES

FIGURES

PREAMBLE

The United States Department of Energy, Division of Geothermal Energy (DOE/DGE) awarded Vetter Research (VR) a contract to perform research related to injection and reinjection problems in geothermal operations. This contract (No. DE-AC03-79ET27146) is entitled: "Injection, Injectivity and Injectability in Geothermal Operations". The present report is one of the deliverables under this contract and is concerned with the "Flow of Particle Suspensions Through Porous Media".

1.0 ABSTRACT

The movement of particle suspensions through porous media and subsequent damage to the formation in oilfield and geothermal injection operations is well recognized. Most of the literature on this subject is limited to particles (or fines) having an equivalent spherical diameter of 2 microns and larger. Particles smaller than 2 microns and, specifically, submicron suspensions are generally believed, if considered at all, to have the ability to move away from the wellbore and to reach locations in the reservoir where their impact on fluid flow is practically nil.

A new attempt is made to study the mechanisms of particle invasions into porous media. This report describes the following subjects:

1. A critical survey of the literature indicating that the mechanism of particle invasions is not known in sufficient detail. Earlier studies published in the open literature used assumptions that either cannot be substantiated or are internally inconsistent with the proposed mechanisms.
2. The pros and cons of existing particle measuring devices are briefly described in the report. Results from a new laboratory study on particle characterizations are given.
3. The results of the laboratory studies on the flow of particle suspensions through porous media (up to 200 md) are discussed. The effects of flow rate and particle concentrations on the amount of damage (i.e., permeability impairment) and depth of penetration (from core inlet towards outlet) are particularly emphasized.
4. Filter methods (e.g., using millipore filter) cannot be used to determine particle invasions into porous medium. Any predictions of the injection problems based on millipore (or any other filter) measurements are useless and should be discarded.

2.0 CONCLUSIONS

1. Submicron particles can generate a damage within the porous medium whereas particles having a critical minimum size can not invade the porous medium. Thus, submicron particle can generate damage collars within the reservoir around the wellbore whereas large particles will not cause any damage inside the reservoir.
2. The depth of particle penetration inside the core is related to the flow rate for a given size and concentration of particles. The higher the flow rate, the greater is the depth of penetration of the particles

inside the core at a given particle size. Essentially, submicron particle distributions with a median size of about 0.7 micron are completely retained by Berea sandstone cores (up to 200 md) and do not break through at rates varying from 1.0 to 10.0 ml/min.

3. Particles having a size distribution with a median of approximately 0.5 micron are observed to pass through Berea sandstone cores (up to 200 md). Permeability damage for a given concentration of these particles appears to be inversely related to the flow rate. The lower the flow rate the higher seems to be the permeability damage.
4. For cores mounted in tandem, a filter cake was observed on the injection face of each core segment at various flow rates. This suggests that similar cakes would form at fractures inside the reservoir around injection wells. It also means that core flow test experiments using cores mounted in tandem are suspicious at best if the data are related to particle movements.
5. A new technique has been developed to determine the location of particles that are retained in a porous medium. This technique is based on the backscattered electron detector feature of a scanning electron microscope.
6. Submicron particles at a given concentration and size distribution can be completely filtered out by a 5.0 micron millipore filter while they break through two Berea sandstone cores (up to 200 md) mounted separately but in tandem. This means that filter data cannot be compared with or related to core data as commonly suggested in the literature or as done in routine field operations.
7. An optimum degree of particle filtration prior to injection of liquids should be determined by site-specific conditions. This optimum degree of filtration depends on:
 - a) Injection rate after filtration.
 - b) Characteristics of particles suspended in the liquid prior to and after filtration.
 - c) Physical and chemical characteristics of the reservoir rock accepting the filtered brine.
8. Damage collars inside the formation can be generated by invasion of submicron particles. However, the precise mechanism of this damage collar formation is not clear and

seems to be far more complex than suggested in the sparse literature references on the subject.

3.0 RECOMMENDATIONS

In this section we describe the major recommendations based upon the information obtained through this investigation.

1. Prior to any reinjection operation, the following factors must be thoroughly analyzed:
 - a. Skin around the wellbore.
 - b. Pertinent formation or reservoir characteristics.
 - c. Brine or brines to be reinjected.
2. High permeability Berea sandstone cores (e.g., 300 md and larger) should be used to reproduce most of the flow experiments described in the present report. Only low permeability cores (up to 200 md) were used in this present study.
3. Further investigation is needed to assess the impact of particle charges on the plugging mechanism of porous media by very small particles. It is suggested that these particle charges are the major contributing factors to generating damage collars within the reservoir.
4. We do not know of a single particle size analyzer which would accurately measure a submicron particle size distribution (below approximately 0.8 micron) in a given geothermal brine, without altering significantly that brine. Particle analyzers are available for the characterization of particles larger than 0.8 micron.
5. For a given reinjection operation, the optimum degree of brine filtration should be determined through relevant field and/or laboratory experiments.
6. The plugging mechanisms of porous media may be due to several factors, many of which, are barely known. The interaction of all these factors makes any generalization of the damage mechanism through particle invasion rather hazardous. Each injection operation should be considered individually, through laboratory experiments and, whenever feasible, through a pilot test.

4.0 INTRODUCTION

Reinjection of a heat-depleted geothermal brine into a reservoir is subject to several conditions and give rise to some operational problems. One of these problems involve the damage to the porous medium (formation rock) by suspended particles in the reinjected brine. Formation damage generated by particle suspensions flowing through porous media can seriously impede or even prevent any injection process, whether the injection is for pressure maintenance or heat mining or simply for brine disposal.

Many attempts were made by different investigators to explain the mechanisms of particle flow through porous media. Even though the problem is far from being solved, there are some points of agreement among various investigators regarding the importance of various factors such as flow rate, size, etc., on these mechanisms. Most of the literature on this subject considers particles having an equivalent circular diameter of 2 microns and larger. Particles smaller than 2 microns and, specifically, submicron particle suspensions are generally believed to have the ability to move away from the wellbore and reach locations in the reservoir where their impact on fluid flow is practically nil.

This assumption is very hard to verify, even in the laboratory, mainly because of the difficulties of characterizing submicron particles. The characterization of the submicron particles is extremely difficult because of the lack of available instrumentation that can operate at low size range and at low concentrations.

The present report is a summary of the problems and some solutions associated with the flow of particle suspensions through porous media. The following gives a list of the general topics addressed in this report:

1. A critical literature survey on the mechanisms of particle invasion into porous media is given. The literature search indicates that these mechanisms are not known in sufficient detail. Earlier studies used assumptions which cannot be substantiated by new experiments. Furthermore some of these earlier assumptions and the proposed mechanisms are internally inconsistent. In essence, much of this earlier work is questionable because of a lack of (a) properly defined parameters governing the particle invasion and (b) precisely measured values of some critical variables.
2. The difficulties associated with the characterization of submicron particles is described. Results from various particle characterization studies in the laboratory are also given.

3. Results of experiments conducted at Vetter Research on the flow of particle suspensions (essentially submicron in size) through porous media are given. The effects of particle concentrations and fluid flow rates on the amount of damage (i.e., permeability impairment) and depth of penetration are particularly emphasized.
4. An attempt is made to develop criteria for a brine to be suitable for reinjection from the particulate point of view.

5.0 OBJECTIVES OF THE STUDY

Formation damage and injectivity impairment subsequent to brine injection into a geothermal formation can be due to one or a combination of the following factors:

1. Fines contained in the injection fluid.
2. Scale formation due to chemical incompatibility between injected brine and the formation water.
3. Effects of temperature differences between injection and formation brines.
4. Chemical instability of the injected brine prior to reinjection and under reservoir conditions.
5. Characteristics of the formation itself.

While the damage to porous media due to the flow of fines suspended in an injection brine is well recognized, the degree and location of this damage is still under investigation. The plugging mechanism of suspended particles in a carrier fluid attempting to flow through a porous medium will depend on (a) the characteristics of the particles (size, shape, charge, etc.), (b) the characteristics of the formation (pore size, porosity, permeability, etc.) and (c) the nature of the interaction between the particles and the various reservoir materials. To understand the importance of some of these parameters on the plugging mechanism, the following objectives were chosen for this report:

1. To review the literature on particle flow through porous media. More specifically, the literature on formation impairment due to the flow of particle suspensions during brine injection had to be reviewed.
2. To review methods available for characterizing the size and eventually the shape of the particles and to apply

these methods to specific particle types in laboratory experiments.

3. To identify the mechanisms of plugging the porous medium by particle suspensions through experimental investigations.
4. To develop criteria for a brine to be suitable for injection from the particulate point of view.

6.0 LITERATURE REVIEW:

There are many studies in the literature related to formation damage by particles suspended in flowing fluids. This subject is rather complex and as such no unified model explaining all the aspects of formation damage is presently available. In this section, the existing literature on the subject is critically reviewed.

Donaldson et al. [1] made a significant contribution to the mechanism of the flow of particles through porous media using laboratory flow experiments and a statistical interpretation of their experimental results. They conducted some experiments by flowing silica particle suspensions through three types of core plugs. The specific core plugs used in their experiments were taken from Berea, Noxie and Cleveland sandstone. They determined the particle size distribution of the suspension using the particle counter (ElZone) made by the Particle Data Inc. In their studies they determined the pore size distributions of the cores by capillary pressure curve measured by the centrifuge method (air-brine system). Figure 1 shows the volume percent pore size distributions of the three cores used by Donaldson et al [1]. This figure is reproduced here from the work of Donaldson et al [1]. Figure 1 shows the lowest value of the pore size to be approximately 0.5 micron and the highest pore size value close to 40 microns. The accuracies near the extreme values of the pore size distribution shown in Figure 1 are questionable because of the limitations of experimental procedures used [1]. For example, the values at the lower end are affected by the two phase systems used in the capillary pressure measurement and at the larger sizes by the inaccuracies in measuring low capillary pressures. We believe that mercury injection is a better method for determining pore size distribution than that used by Donaldson et al [1].

Donaldson et al [1] have developed a random walk model for particulate migration using Poiseuille's equation to interpret their experimental results. For the development of their model, the following points were assumed:

1. Particles are perfectly spherical.
2. The final bridging process is attributed to the cake only.
3. The probability for a particle of diameter, D_p , entering any capillary is subject to two conditions:
 - a. D_p smaller than pore diameter
 - b. Maximum flow rate in a capillary

Both of the above assumptions are questionable. In calculating the probability for a particle entering a capillary, the cross section of the pore channel is assumed to be circular and the particles are assumed to be spherical. Neither of these assumptions is true. For example, needle shaped particles with equivalent spherical radii smaller than a given pore radius might not get through a pore. On the other hand, needle shaped particles with an "equivalent" spherical radii greater than a given pore radius might get through. This is, because, certain needle shaped particles can have an extremely small radius of the cross sectional area which can be smaller than the pore radius.

The second assumption needed for calculating the probability, namely, the maximum flow rate in a capillary, is also questionable. This assumption is particularly doubtful in situations involving dispersion phenomena in a single phase flow and wettability phenomena associated with multiphase flow. Moreover, Poiseuille's equation can give only a very rough approximation of the flow through porous media.

Additional studies on the flow of particle suspensions through porous media were performed by Davidson [2]. Davidson used alundum cores with a mean pore diameter of 90 microns, a permeability of 14 darcies and a porosity of 35%. The particle suspension is made with silica flour having a particle size distribution characterized by a median size of 3 microns with a 12 microns upper bound. Based on the experimental results, Davidson developed a pore plugging mechanism that estimates the pore velocity required to achieve a so-called "non-retaining bed" by taking into account gravitational, surface and lift forces. A major finding of this work is that the velocity required to prevent deposition is inversely related to the particle size which is in contradiction with the results of Donaldson et al [1] as well as some of our own observations. We believe that Davidson's conclusion is acceptable only under the specific conditions of his experimental procedure.

Using his experimental results and his model, Davidson [2] estimated that for an injection rate of 65 bbl/D/ft, the particle invasion will be 40 wellbore radii. He also estimated that a two to one formation impairment will take place in excess of 20 years at a concentration of 10 ppm suspended solids in the injection brine. It is hard to find any concrete evidence to support these

statements, which are presented as a "specific estimate of field performance for respective particle and pore diameters of 2 and 20 microns". A rate of 65 bbl/D/ft is assumed to prevent silica particles from plugging pores at the face of the wellbore, specifically, if 2 micron particles are entering 20 micron pores.

Many questions can be raised in using the model suggested by Davidson [2]. Is the 2 microns given in his publication a medium, an upper or a lower bound? Also, is the 40 wellbore radius invasion the maximum depth of penetration? About the extent of formation damage, Davidson does not say if the "two to one impairment" will occur at the wellbore, 40 wellbore radius away from the wellbore or somewhere in between. Is it simply a combination of all the locations mentioned above?

Gruesbeck and Collins [3] attempted to explain the abnormal decline in productivity of producing wells in terms of the movement of naturally occurring fines in porous media. They made a rather questionable hypothesis on the interrelationship of the flow velocity and the rate of entrainment. They assume that there exists a critical velocity, or flow rate, below which entrainment of fines does not occur and above which the rate of entrainment increases linearly with flow rate. Having this critical velocity or flow rate, one could easily locate the radius of damage around a wellbore in an ideal reservoir. Based on this concept, Gruesbeck and Collins [3] estimated that for a well producing at about 670 bbl/d/ft, fines would be entrained within an outer radius of 33 cm for a single-phase flow (of white oil) at connate water saturation and out to a radius of 1.6 m, with two-phase flow of water and oil. However, these estimates are valid only if their original hypothesis is correct. No basis for the hypothesis is presented in the paper [3]. Based on the critical velocity hypothesis, they [3] further reported that the entrainment and redeposition of fines is restricted to the near wellbore region. This statement is very hard to verify, except maybe for an ideal reservoir with a radial velocity proportional to the reciprocal of the radius of damage.

Muecke [4] presented an interesting qualitative analysis of fines movement through unconsolidated sand. This paper concentrated on the effect of single and multiphase flow of fines movement through porous media. The results are based essentially on a visual observation using a microscope. Some of the major findings of this study are summarized below:

1. Most formation fines are not clays. On a weight percent basis, Muecke reported that the composition of the fines are as follows:

Clay fines represent	11%
Quartz fines represent	39%
Other minerals represent	18%
Amorphous materials represent	32%

2. Particles will move only if the phase that wets them is moving.

Muecke [4] pointed out (a) the existence of bridging phenomena and (b) the difficulties of establishing properly defined criteria for bridging. As particles start piling up at or inside a pore entry (bridging), the sizes and concentrations of the retained particles will change continuously until the pressure buildup is high enough to break up the bridge. The bridging will occur again, with ever changing particle sizes and concentrations until an equilibrium is reached. This equilibrium could lead to either a completely plugged pore or one with partially narrowed flow paths allowing only a restricted flow through the core. Muecke raised the following question which many investigators, including ourselves, are trying to answer: What is the depth of penetration of the moving fines? Or in other words, what is the location of the damage due to particles invasion if the damaging particles are injected into the porous medium?

Abrams [5] work was concentrated on minimizing formation impairment due to drilling mud. He used an unconsolidated sand in an apparatus simulating radial flow. The permeability of the unconsolidated sand used was between 4 and 6 darcies which is rather common around an open hole where a multitude of micro fractures are present. In order to estimate the location and size of the particles causing the impairment, Abrams drilled cores from the sand body used in the experiments to obtain samples. Particle size distributions were analyzed using a Coulter counter. The particles flowing through the sandpack were silica particles. The author himself reported the quality of the data were poor.

Abrams approach is analogous to "gravel packing" of a well during the drilling phase because one of the purposes of a mud or a drilling fluid is to prevent formation fluids from entering the wellbore during the drilling phase. This "desired" formation damage or plugging is obtained by forming a mud cake at the sandface. It is very difficult to quantify invasion from the standpoint of formation damage and penetration away from the wellbore. For injection wells, reliable well tests could quantify the extent (unfortunately not the location) of the permeability impairment from formation damage due to drilling fluid. Reliable tests will give an idea as to what remedial methods could be tried to stimulate such a damaged well.

McCune [6] described an on-site testing apparatus for determining water quality standards required for a water flooding. McCune's approach was to filter the injection brine down to 0.45 micron "absolute". At this level of filtration, he attributed all permeability losses to chemical interactions, such as rock sensitivity to pH, salinity changes and precipitation of solids from the water. After one adds scale inhibitors, modifies the pH or changes the salinity of the brine to achieve the correct brine

injectibility (i.e., stable permeability of the formation rock), then the filter permeability (or filter pore size) is increased until plugging of the filter occurs. This method should give the proper and required filter pore size at a given filtration rate prior to reinjection of the brine according to McCune [6]. We found this approach convenient as long as the results it provides are taken as general guidelines only. The author himself [6] recognized that membrane filters have characteristics different from those of the formation being flooded. That is, particles which are retained by a filter on the surface could penetrate the formation under wellbore conditions for a given pore size distribution. On the other hand, particles which are not retained by a filter may be retained by the formation. An interesting feature of the test apparatus described [6] is that core tests could be run at high temperatures. McCune's paper is somewhat an update of an earlier one presented by Jordan et al. [7].

The work of Jordan et al [7] dealt with an offshore sea-water injection project where the brine was filtered through 0.45 micron filters prior to injection. Even after filtering, Jordan et al. found that "colloidal-size" iron particles were the primary plugging agents. This is the first evidence we found in the literature emphasizing the impact of submicron particles on formation impairment. Even McCune, whose work was apparently heavily inspired by the work of Jordan et al [7] does not stress the impact of submicron particles on plugging.—Moreover, he implies that at a filtration down to 0.45 micron all permeability losses are attributed to chemical reactions. This is in contradiction with what Jordan et al [7] stated about iron particles. Most probably, McCune was well aware of the impact of submicron particles on formation damage, but his major concern was the economics of water treatment. He suggested that a degree of plugging of an injector could be accepted sometimes as an economic compromise with reduction in the rate of injection. This is a reasonable argument as long as we know or can quantify the degree of damage attributable to a given particle size range, specifically submicron particles. However, we cannot measure particle sizes with any meaningful accuracy because the particle measurement devices currently available on the market have a lower bound of about 0.8 micron [13]. This sheds some additional doubt on the results and conclusion of the previously published work. Even the methods based on scanning electron microscopy and filtration cannot offer possible ways of accurately measuring submicron particles. For example, with a scanning electron microscope the fact that a brine sample has to be dried and the residue has to be coated under vacuum, makes it very difficult to reliably measure submicron particle sizes. If we cannot determine a representative submicron particle size distribution under the prevailing technology, we cannot say much about the amount of these particles in a given brine either. Of course, filtration through various grades of filters can be used to determine submicron sizes. However, as mentioned earlier, membrane filters have characteristics greatly different from those of the formation rock being considered. We

also found that submicron metallic oxide particles in a concentration high enough to be optically examined will not pass through a millipore filter with a "particle size to a filter pore size" ratio between one to two and one to five.

Todd et al. [8] worked on the impairment of permeability in core plugs resulting from water injection. This was a part of a global review of the problems of sea water injection in the North Sea. Some of the data presented in this paper [8] are reproduced in Table 1. The first row of this Table 1 gives a particle size classification between 0 and 2 microns using a Coulter counter which has a very limited resolution in that range and becomes, therefore, an unreliable instrument. Also, the particle concentration used in these studies makes it very difficult to achieve a material balance on particles (a) forming the cake, (b) settling inside the core and (c) breaking through the porous medium (not to mention other factors such as formation fines breaking through).

Figure 2 shows a "typical" particle size distribution in sea water [8]. In Figure 2 the smallest particle size reported seems to be 0.8 micron. There are about 60,000 particles per sample volume with a size of 0.8 micron while there are only about 300 particles per sample volume with a size of 2 microns. Todd et al [8], quoting other investigators, mentioned the existence of ever increasing number of particles at the low size range. However, their reported data (see Figure 2) cover a size range from 0.8 micron and up, while the material balance presented in their paper specifies a size range from 0 micron and up. We believe that Todd et al. as well as many other investigators, may have overlooked the size range from 0 to 0.8 micron, mainly because of the difficulty to characterize this size range. Todd et al. used a scanning electron microscope with an energy dispersive analyser to identify particles deposited inside a core. We believe that the backscattered electron detector feature of the scanning electron microscope is more suited to detect particles inside a core, especially in the submicron size range as long as the average atomic number of the particles considered is higher than that of the porous medium.

The method proposed by Barkman and Davidson [9] for water quality measurements and injectivity impairment, in spite of its many limitations [10], is probably the most widely used. The method consists of separating impairment from suspended solids into four mechanisms:

1. Wellbore narrowing (cake formation).
2. Invasion of particles into the porous matrix of the reservoir.
3. Wellbore fill up by settling.

4. Perforation plugging at slots or holes in the liner.

In the case of perforation plugging, Barkman and Davidson reported that "plugging is expected unless the suspended solids are so small that they can be transported through the rock matrix, or unless fractures exist which will allow the solids to bypass the perforations". Some of the questions to be asked here are: How small is "so small" and what about the effects of concentration of particles, the flow rate and the differential pressure on particle penetration into the rock?

In the case of invasion, Barkman and Davidson reported that if particles in the injection fluid can be transported to great distances from the wellbore, deposition will occur in a region of low pressure gradient, and the rate of impairment will be small. Here again, what is meant by great distances? In determining the "water quality ratio" Barkman and Davidson acknowledge the difficulty in interpreting filtration data due to "small" particles which invade and plug the porous structure of the filter medium. Experiments in our laboratory showed that submicron particles can be retained by a five micron filter but did break through two Berea sandstone cores (permeability of approximately 100 md) mounted in tandem within two separate in-line core holders.

It is apparent from the literature survey presented so far that there are many gaps in the area of submicron particle characterization as well as on the mechanism of flow of particle suspensions through porous media. Much more detailed work is needed before a unified model for formation damage by suspended particles can be formulated.

7.0 METHODS AND PROCEDURES USED IN THE PRESENT STUDY

The various experimental procedures and experimental apparatus used in the present study are described in this section.

7.1 DESCRIPTION OF FLOW APPARATUS

The apparatus used in all our experiments to study the flow of particle suspensions through porous media is shown schematically in Figure 3. An HPLC pump is linked by a 1/8 inch tubing to a slurry vessel which is sitting on an electrical Corning stirrer. A magnetic stirring bar and a free floating lucite piston are inside the slurry vessel as shown in Figure 3. A safety check valve is mounted between inlets of the core holder and the slurry vessel while the transducer is set between the core holder inlet and the slurry vessel outlet. An Eldex universal fraction collector is used downstream of the core holder. A pressure vessel and a gas bottle to simulate overburden pressure complete the set-up shown in solid lines in Figure 3. The dashed lines show a vacuum pump and a water container to evacuate and saturate the mounted cores. More details about the core holder are shown schematically in Figure 4.

7.2 EXPERIMENTAL PROCEDURES

The major experimental procedures in the present work are described in this section.

7.2.1 CORE PREPARATION

Core plugs are cut to 1.0 inch diameter and 1.5 to 2 inches long from Berea sandstone blocks. The core plugs are fired at 500°C for about 3.0 hours to desynthesize the clays. After measuring the porosity, a dry core is tied up to the two metal ends of a core holder. This is accomplished (see Figure 4), first with a teflon tape, then with a teflon shrink tube sleeve. The annulus of the core holder is filled with water and pressurized to about 1000 psi to simulate overburden. The core is evacuated for 1.0 hour (from the outlet end of the core holder) and then saturated with deaerated and deionized water. Once the core is saturated, the base permeability is measured.

7.2.2 SLURRY PREPARATION

A given weight of particles corresponding to the particle concentration desired is placed in an ultrasonic bath for 3 minutes and then diluted with deaerated and deionized water. The slurry vessel is then filled with this solution. A free floating lucite piston is placed on top of the solution. The slurry is stirred throughout the experiment. Most of the particles used in this study were provided as dispersions in deaerated and deionized water. A few experiments are performed with particle suspensions in deaerated NaCl solutions.

7.2.3 FLOW EXPERIMENTS

The flow experiments were conducted as described below. A given particle suspension is pumped through a core previously evacuated and saturated with deaerated and deionized water. The flow experiments are performed at constant flow rates. The pressure required to pump this suspension is monitored continuously as a function of time. An increase in pressure indicates a decrease in permeability due to particles plugging (cake and invasion) the porous medium being flooded. Output samples are collected by an automatic fraction collector.

The flow experiments are continued until the pressure buildup across a core goes up to 500 psi with a 1000 psi overburden as a first step, and then to 850 psi with an overburden of 1200 psi. For each experiment about 200 pore volumes are flowed through the core.

7.2.4 EXAMINATION OF THE CORES

At the end of each flow experiment, the core is unmounted and dried. Then, it is examined visually and through a microscope, then broken in order to generate cross sectional areas parallel to the inlet and outlet faces. These core sections are again examined optically with a microscope before breaking them one more time; this time, along the length of the core. After the final examination of these fragments, one half of the core (full length) is coated under vacuum with gold-palladium alloy for the analyses through various features of a scanning electron microscope. Our main objective is to determine the depth of penetration and distribution of particles inside a core. This is achieved through a backscattering electron detector.

8.0 EXPERIMENTAL RESULTS

There are many possible parameters that contribute to the plugging of a porous medium. The following are some of these parameters:

1. Porous medium properties: pore size, permeability, porosity, etc.
2. Particle size and concentration
3. Particle charge
4. Flow rate
5. Particle density and shape

To represent the porous media, Berea sandstone cores in the 100 to 200 md range permeability and 21% porosity were used. As mentioned earlier in this report, all the cores are fired prior to the flow experiments. To represent the particles in the suspension, submicron particles made from chromium oxide and blended cerium oxide are used. The results of the flow experiments, particle size distribution and SEM observations are presented in this section.

8.1 PARTICLE SIZE DISTRIBUTION MEASUREMENT DATA

The majority of the particles used in the present investigation have been supplied by the Leco Corporation. The type of materials and the size have been supplied with the product. Numerous attempts were made to determine the compositions and the particle size distributions of the slurries used. Tables 2 and 3 show the compositions of chromium oxide and blended cerium oxide, respectively, as analyzed by SEM and energy dispersive x-ray analysis.

Although the determination of the type of these materials is relatively easy, an accurate particle size distribution measurement is very difficult to achieve, especially in the submicron range.

Several particle analyzers were used in our laboratory [13]:

1. Particle Data Inc., Particle Counter:

Basically, this device measures electrical resistivities, thereby requiring that the solution being analyzed have a certain salinity. In order to perform a particle size distribution measurement in the submicron range with any meaningful accuracy, the coincidence errors should be minimized [13]. This narrows considerably the utility of this particle counter as far as our present investigation is concerned. Tables 4 through 6 give the particle size distribution of the particles used in the present study. These data are also represented graphically in Figures 5 through 7.

2. Micropure Systems, Inc., MCM-1100A:

This particle counter could theoretically measure particles down to 0.3 microns. However, we were unable to get an accurate submicron particle size distribution measurement using the instrument. The calibration curve for this device was, in fact, extrapolated to most of its suitable submicron range.

3. Sedimentation:

Low concentrations of chromium and cerium oxides reported to be 0.05 micron (and less in size) were put in two separate burettes and allowed to settle. According to Stoke's Law, particles with a 0.05 micron diameter would settle at a rate of about 0.5 mm a day. The problem we encountered here is that particles cling to the inner surface of the burette, making the reading of the interphase very difficult. Also, the effect of particle concentrations on the sedimentation is believed to have some detrimental impacts on the reliability of this method.

4. Filtration:

Solutions of chromium and cerium oxides in concentration barely high enough to be optically visible were run through different size millipore filters. The chromium as well as the cerium oxides are, at least to the naked eye, completely filtered out. During the filtration process, all the particles seemed to have been attached to the filters.

5. SEM:

Eventhough the particle size distribution can be determined only qualitatively by SEM methods, Figures 8 through 11 do give a good idea not only about the size of the particles but also about their shapes. One has to bear in mind that for a sample to be analyzed by SEM, it has to be coated under vacuum, usually with a gold-palladium alloy. This sample preparation process would result in giving larger values to the particles than the values in the original suspension.

Our conclusion, so far, is that eventhough the exact size distributions could not be determined by the available techniques, it can be stated that most of the fines used in this investigation (listed by the manufacturer as 0.05 micron and less) are of submicron size but larger than 0.05 micron. To substantiate this conclusion, a chromium oxide sample was given to Micron Data Laboratories for analysis. Figure 12 shows the distribution obtained by them. The particle size analyzer used by Micron Data was a Micromeritics Sedigraph. The solution analyzed was prepared in the following manner: The original slurry is dried and redispersed in a hydrocarbon solvent having a specific gravity of 0.7575 g/ml and a viscosity of 1.409 cp. The question here is: can we accept the particle size distribution determined by Micron Data as being that of the original slurry we submitted? We believe that the original slurry under constant stirring before being injected into a core plug and after being dispersed in an ultrasonic bath had a particle size distribution smaller than that reported by Micron Data Laboratories (See Figure 12).

8.2 RESULTS OF FLOW EXPERIMENTS USING CHROME OXIDE PARTICLES

The results related to the flow experiments using chrome oxide particle suspensions are described in this section.

8.2.1 PARTICLE SIZE EFFECTS

Figure 13 shows the pressure buildup across a core as a function of the number of pore volumes injected for various sized particles. Figure 14 shows the permeability impairment calculated from the pressure buildup shown in Figure 13. A new method [14], based on the backscattering electron detector feature of the SEM has been developed. This method is used in determining the particle size distribution in the core. Table 7 shows the distribution of the particles imbeded in a core section, broken along its length. This distribution is represented by the ratio of chromium to silicon concentration. The numbers in the table represent this ratio.

From Table 7, the depth of penetration of the chrome oxide particles is calculated to be 21.5 mm.

Table 8 shows a partial distribution of particles that invaded a core from another similar experiment.

8.2.2 PARTICLE CHARGE EFFECTS

A few flow experiments are conducted by external additions to the chrome oxide particle slurry. These external additions are as follows:

1. 10 g/l of sodium chloride
2. A Cationic surfactant
3. An anionic surfactant

The purpose of these tests are two-fold, namely, (1) to determine if the chrome oxide particles are electrically charged and (2) to determine the effect of electrical charge (if any) on the plugging mechanism in porous media. Figure 15 shows the results of these flow experiments. In this figure, the permeability impairment as a function of the number of pore volumes injected is shown for the three cases. More work is needed before we will be able to determine the exact impact of particle charges on the plugging mechanisms of porous media. Chrome oxide particles are believed to be anionic even though this may not be true at the lower size range. Also, the surfactant effect on the core itself is probably more important than on the particles.

8.2.3 FLOW RATE EFFECTS

One of the most important effects investigated in the present study is the effect of flow rate on the plugging mechanisms of porous media. Table 9 shows the pressure buildup and the resulting permeability impairments for different flow rates. Figure 16 through Figure 18 show the pressure buildup and permeability impairments as a function of pore volumes injected at various flow rates. The data given in Table 9 (see also Figures 16, 17 and 18) clearly show that flow rate is an important parameter in discussing the flow of suspended particles through porous media. Figure 19 is a plot of the maximum depth of penetration of chrome oxide particles versus flow rate. These maximum depths of penetration are determined using our newly developed technique based on SEM. For flow rates up to 10 ml/min, the chrome oxide particles are completely filtered out by the Berea sandstone cores in the 100 md permeability range.

8.3 RESULTS OF FLOW EXPERIMENTS USING BLENDED CERIUM OXIDE PARTICLES

The results related to the flow experiments using blended cerium oxide particle suspensions are described in this section.

8.3.1 FLOW RATE EFFECTS

Contrary to the behavior observed for chrome oxide particles, the blended cerium oxide particles are found to break through Berea sandstone cores, at all flow rates between 2 and 10 ml/min. Tables 10 and 11 show pressure buildup and permeability impairment at various flow rates, while Figure 20 through Figure 24 show the corresponding pressure buildup and permeability impairment as a function of pore volumes injected. Here, permeability impairment is found to be inversely related to the flow rate. This is contrary to the results described with chromium oxide (see Section 8.2.3). This is believed to be a very important result as we will see later in this report. Blended cerium oxide particles are smaller than chrome oxide particles.

8.3.2 PARTICLE CONCENTRATION EFFECTS

Figure 25 shows the impact of particles concentration on permeability impairment. From this figure, it appears that for the size range investigated, no difference was observed between the damage created by a concentration of 250 mg/l slurry and that created with a concentration of 500 mg/l. Table 12 shows the amount of deposition at the inlet face and inside a core, as determined by SEM. Table 12 along with Tables 7 and 8 show that even for a relatively homogeneous rock material such as Berea sandstone, the amount of particle deposition or retention is different along the length of the core. The particle deposition is random in locations perpendicular to the flow path. This leads us to believe that there is no such thing as a uniform skin. The distribution of particles deposited at the end of the test appears to be similar for chrome oxide and blended cerium oxide. However, the amount of cake formed with blended cerium oxide is less than that with chrome oxide. Another interesting result is shown in Tables 13 and 14 where a mixture of 50-50 percent by weight of chrome and blended cerium oxides was run through core number 48. This mixture was completely filtered out. On the other hand, individual experiments using the blended cerium oxide particles showed a break through whereas the chrome oxide particles did no break through. A comparison of the amount of deposition of both oxides at a given location may be done by comparing Tables 13 and 14.

8.4 RESULTS EXPERIMENTS WITH CORES IN TANDEM

Some flow experiments are conducted by mounting two cores in series. The flow output from the first core serves as an input for

the second core. Two (or more) cores used in this manner are called cores in tandem. The results of this type of experiment are as follows:

1. Filtration:

The blended cerium oxide suspension, once breaking through the first core, should be able to go through the second core without any further deposition (i.e. no cake should form on the second core). However, we found a relatively thick cake at the inlet face of the second cores as well as deposition inside these second cores. We conclude from these observations that there is no such thing as a "non-retaining bed". In other words, if a reinjected brine is filtered down to the lowest particle size which is technologically feasible to date, particles will still be deposited in the rock matrix if its permeability is on the order of 100 and even 200 md.

2. Fractures:

A Berea sandstone core plug had been sawn into two pieces, having approximately the same length. Both pieces were mounted in the same core holder. The blended cerium oxide suspension was used to flood the two plugs, all the other conditions being kept similar to the one core flow experiments. We found a significant cake at the inlet face of the second plug. The particle breaking through the second plug didn't seem to have any different characteristics than those breaking through a single core plug. The results of this experiment suggest that the same cakes would occur at fractures within the formation. Whether the formation is microcracked or widely fractured with bilinear flow any injection of suspended particles will lead to cake formation somewhat similar to what we have observed in the laboratory and described briefly in this section.

9.0 DISCUSSION OF RESULTS

The purpose of this section is to review and discuss the major findings of this investigation. All the experimental results obtained at Vetter Research are used in this discussion.

9.1 PARTICLE SIZE RELATED EFFECTS ON FORMATION DAMAGE

The results of the experiments reported in section 8.0 clearly show that even submicron particles can create severe damage to porous media with a permeability on the order of 100 md. From the qualitative point of view, the statement above is generally well

recognized. The controversy remains on the quantification of the damage or permeability impairment due to the invasion by submicron particles. The main problem in quantifying the damage is generated as a result of the extreme difficulties in determining the particle size distributions in the submicron range.

Summarizing, we can state that we do know that submicron particles can create a severe damage to the formation rock. However, it is still very difficult or even impossible to determine the particle size distribution in a given brine if the particle sizes are in the submicron range.

Filtration methods as a means of measuring the concentration of suspended solids offer numerous problems as outlined below:

1. A very large filtering surface is required before one can effectively filter (in the submicron range) even at very low concentrations.
2. The pertinent filter characteristics are greatly different from the formation characteristics. Thus, filter methods should not be utilized to determine a formation damage due to particle invasion.

9.2 EFFECT OF FLOW RATE ON FORMATION DAMAGE

The flow rate has a large effect on the flow of particle suspensions through porous media. For chrome oxide particles the depth of penetration inside a core is directly related to the flow rate. The higher the flow rate the deeper will be the penetration. While for blended cerium oxide particles (which are smaller than chrome oxide particles) the permeability impairment is inversely related to the flow rate, i.e., the higher the flow rate the less permeability impairment occurs. This leads us to believe that the well publicized critical velocity (or flow rate) below which particle entrainment (or particle movement) will not occur is strongly dependent on the particle size distribution in the suspension.

The Berea sandstone cores used in our laboratory experiments, have an average pore size diameter of about 7 microns. The chrome oxide particles have a median size of .7 microns (See Figure 12). It follows that for ratios of a median pore size to a median particle size of 10 to 1, the depth of penetration inside a core as a function of flow rate will be as given in Figure 19. On the other hand, for ratios higher than 10 to 1, particles will breakthrough at any rate between 2 and 10 ml/min. The lower the flow rate, the more deposition can be expected.

What does all that mean for actual downhole conditions in a well? On a 10 to 1 (and smaller) average pore size to particle size ratio

the particle invasion will be limited to the vicinity of a wellbore. For higher ratios, particles invasion will be much deeper in the formation. Thus, extremely small particles in a suspension can penetrate deep into porous formation and eventually create damage at locations far removed from the wellbore. In other words, even when filtering a brine down to a very low particle size the remaining solids can create a permanent formation damage. If the filtration is kept at or below the cut mentioned above (a 10 to 1 average pore size to particle size ratio), the damage will be limited to the vicinity of a wellbore, where the injectivity potential of a well could be restored.

9.3 EFFECT OF PARTICLE CONCENTRATION ON FORMATION DAMAGE

The majority of the flow experiments done within the framework of this report had a particle concentration of 500 mg/l. This high concentration was used for many reasons. For example, it is much easier to monitor the particle size at this high concentration. Also, a high concentration will generate the cake effect within a shorter time than a low concentration.

The slurry volume can be handled by a small vessel thereby, allowing a continuous stirring without disturbing the slurry during a given flow experiment. Eventhough more work is needed it may be stated here that the effect of concentration on the permeability impairment is directly related to the number of pore volumes injected and, hence, to time. This conclusion is based on the following experiments and observations. A 0.5 g/l of a blended cerium oxide suspension was diluted with 11.3 liter of deionized water and run through a Berea sandstone core for several hours (1 pore volume equals 5 ml). The resulting pressure buildup at the end of this run was practically the same as the pressure buildup measured during a subsequent flow experiment. During this new experiment a 0.5 g/l of a blended cerium oxide suspension was diluted in 2 liters of deionized water and run through a similar Berea sandstone core. In this experiment (using 11.3 liter of deionized water), the final pressure buildup was practically the same as in the previous flow experiment (using only 2 liters).

9.4 LABORATORY VERSUS RESERVOIR CONDITIONS

The injectivity potential of a well or a reservoir is usually determined through well testing. A skin analysis as shown below may allow us to estimate the degree of damage (Sd).

$$ST = \frac{h}{hc} (Sd + Sp) + SC + SQ$$

Where

ST= Total skin,

Sd= Skin due to formation damage,

h = Net pay,
 hc= Completed interval,
 Sc= Skin due to completion [15],
 Sp= Skin due to perforation [16],
 SQ= Skin due to well deviation [17],

However, the above equation does not consider the location of the damaged zone. Tracers may locate high permeability streaks and/or permeability anisotropy, while a log analysis will help in determining rock formation characteristics close to the wellbore. Simulation will use the elements or techniques mentioned above to forecast the injectivity potential and the number of wells required for a given reservoir.

9.4.1 FLOW RATE

The velocity

$$\frac{Q}{\phi A} = \frac{Q}{2\pi\phi r_w h}$$

decreases very rapidly with increasing distance from the wellbore.

Where

Q= flow rate
 ϕ = formation porosity
 r_w = wellbore radius
 h= net pay

Under laboratory conditions, the fluid velocity across a core sample is constant (steady state). The results from laboratory flow experiments can be related to actual field conditions through use of some simplifications. This would thereby, allow us to get a good estimate of the degree of damage and more importantly, its location.

It is well known that stimulating a well with the damage at a few inches away from the wellbore is much easier than if the damage is 2 feet away from the wellbore. For the time being we have no way of knowing if a formation damage is occurring at the vicinity of a wellbore or way deep inside the formation. The skin damage as determined by well testing is a rather rough estimation of the actual formation damage. The procedures of well testing assume the skin damage to be uniform around a wellbore. This is not true, not only from the standpoint of common heterogeneities around a wellbore but, also, for a typically homogeneous formation as Berea sandstone. We have shown in Tables 7, 8, 12, 13 and 14 that the rate of particles deposition is different even along the length of a core plug. Moreover, for brines having a particle size distribution similar to the chrome oxide one, the skin damage will decrease with increasing distance from the wellbore. While for brines with a particle size distribution similar to the blended cerium oxide one, skin damage will increase as we get away from the wellbore. In other words, chrome oxide type particles will settle

penetrate deeper into the formation.

10.0 IMPLICATIONS OF THE STUDY

This investigation showed that major problems exist with brine reinjection from the particulates point of view.

10.1 FILTRATION

Brine filtration before injection can be a tricky operation. An elaborate filtration down to 1.0 microns, per se, may be more harmful to the formation being flooded than a less elaborate filtration. This will depend on the brine or brines available and on the formation being flooded. A 10 to 1 pore size to particle size ratio is a good cut between formation damage around a wellbore and deeper inside the reservoir. The concentration of particles present in a brine and leading to a ratio higher than 10 to 1 (particle to pore sizes), along with the rate of injection required, should determine the optimum level of filtration.

10.2 PARTICLE SIZE DISTRIBUTION MEASUREMENTS

Particles having a size of 1.0 micron can be determined quite accurately. Even on-line measurements can be done at that size range. The question related to particle size distribution measurements in the submicron range is yet to be solved. None of the particle size analyzers available to date [13] are satisfactory in determining submicron particle size distributions.

10.3 FLOW RATE

Injection rate has a strong effect on formation damage. In a homogeneous reservoir, flow velocity will decrease rapidly as the injected brine gets away from the wellbore, inside the formation. Actually, in perforations or in heterogeneities around the well (natural as well as induced), the flow velocity will increase as the brine gets away from a wellbore. In geothermal reinjection operations, the injection rate is usually constrained. In other words, we have a given volume of heat depleted brine that has to be reinjected using the minimum number of injection wells. In other words, for a given reinjection operation, the injection rate is pretty much fixed. Based on the brine available and the reservoir characteristics to be flooded, an optimum filtration can be determined.

REFERENCES

1. Donaldson, E.C. et al., "Particle Transport in Sandstones", SPE 6905, presented at the 52nd Annual Fall Meeting of the SPE, October 9-12, 1977, Denver, Colorado.
2. Davidson, D.H., "Invasion and Impairment of Formations by

Particulates", SPE 8210, presented at the 54th Annual Fall Meeting of the SPE, September 23-26, 1979, Las Vegas, Nevada.

3. Gruesbeck, C. and Collins, R.E., "Entrainment and Deposition of Fine Particles in Porous Media", SPE 8430, presented at the 54th Annual Fall Meeting of the SPE, September 23-26, 1979, Las Vegas, Nevada.
4. Muecke, T.W., "Formation Fines and Factors Controlling Their Movement in Porous Media", Journal of Petroleum Technology, pp 144-150, February 1979.
5. Abrams, A., "Mud Design to Minimize Rock Impairment due to Particle Invasion", Journal of Petroleum Technology, pp 586-592, May 1977.
6. McCune, C.C., "On-Site Testing to Define Injection-Water Quality Requirements", Journal of Petroleum Technology, pp 17-24, January 1977.
7. Jordan, C.A. et al., "The Bay Marchand Pressure Maintenance Project-Unique Challenges of an Offshore Sea Water Injection System", Journal of Petroleum Technology, pp 389-396, April 1969.
8. Todd, A.C. et al., "Review of Permeability Damage Studies and Related North Sea Water Injection", SPE 7883, prepared for SPE International Symposium on Oilfield and Geothermal Chemistry, Dallas, Texas, January 22-24, 1979.
9. Barkman, J.H. and Davidson, D.H., "Measuring Water Quality and Predicting Well Impairment", Journal of Petroleum Technology, pp 865-873, July 1972.
10. Vetter, O.J. and Chrichlow, H.B., "Injection, Injectivity and Injectability in Geothermal Operations: Problems and Possible Solutions", DOE/DGE Report under Contract No. ET-79-C03-2044.
11. Collins, R.E., "Flow of Fluids Through Porous Materials", 1976, The Petroleum Publishing Company, Tulsa, Oklahoma.
12. DeWiest, R.J.M., "Flow Through Porous Media", 1969, Academic Press, New York and London.
13. Vetter, O.J. and Kandarpa, V., "Particle Characterization for Geothermal Operations", DOE/DGE Report under Contract No. DE-AC03-79ET27146.
14. Kandarpa, V. and Sparrow, J.T., "A Useful Technique to Study Particle Invasion in Porous Media by Backscattered Electron Imaging", SPE 10134, presented at the 56th Annual

Fall Meeting of the SPE, October 5-7, 1981, San Antonio, Texas.

15. Hong, K.C., "Productivity of Perforated Completion in Formations With or Without Damage", Journal of Petroleum Technology, pp 1027-1038, August 1975.
16. Brons, F. and Marking, V.E., "The Effect of Restricted Fluid Entry on Well Productivity", SPE paper, presented at the 34th Annual Fall Meeting of the SPE, October 4-7, 1959, Dallas, Texas.
17. Cinco, H., Miller, F.G. and Ramey, H.J., "Unsteady State Pressure Distribution Created by a Directionally Drilled Well", SPE 5131, presented at the 49th Annual Fall Meeting of the SPE, October 6-9, 1974, Houston, Texas.

TABLE 1
DISTRIBUTION OF INJECTED SOLIDS IN LOCHALINE [8]
SANDSTONE CORES

INITIAL PERMEABILITY K_i (MD)	PARTICLE SIZE CLASSIFICATION	PERMEABILITY AFTER 6000 PORE VOLUMES $\% K_i$	PROPORTION OF SOLIDS INJECTED (7)		
			IN FILTER CAKE	DEPOSITED THROUGH CORE	PASSED THROUGH CORE
982	0-2	72	7	74	19
984	2-3	23	20	65	16
874	3-4	7	73	13	14
927	5-8	7	74	12	14

TABLE 2

COMPOSITION OF THE CHROME OXIDE SOLUTION

SPECTRUM

FEB. 24, 1982

ACCELERATING VOLTAGE

20.0 KEV

INCIDENCE ANGLE

45.0 DEGREES

EFFECTIVE TAKE-OFF ANGLE

90.0 DEGREES

STANDARDLESS EDS ANALYSIS
(ZAF CORRECTIONS VIA MAGIC V)

ELEMENT & LINE	K-RATIO	WEIGHT PERCENT	PRECISION 2 SIGMA	OXIDE FORMULA	OXIDE PERCENT
AL KA	0.0099	1.15	0.04	AL2O3	2.17
SI KA	0.0061	0.58	0.03	SiO2	1.23
CR KA	0.9819	65.95	0.39	CR2O3	96.39
FE KA	0.0021	0.16	0.02	FeO	0.20
O *		32.16			
TOTAL					100.00

* DETERMINED BY STOICHIOMETRY

TABLE 3

COMPOSITION OF THE BLENDED
CERIUM OXIDE SOLUTION

SPECTRUM

FEB. 24, 1982

ACCELERATING VOLTAGE 20.0 KEV
INCIDENCE ANGLE 45.0 DEGREES
EFFECTIVE TAKE-OFF ANGLE 90.0 DEGREES

STANDARDLESS EDS ANALYSIS
(ZAF CORRECTIONS VIA MAGIC V)

ELEMENT & LINE	K-RATIO	WEIGHT PERCENT	PRECISION 2 SIGMA	OXIDE FORMULA	OXIDE PERCENT
AL KA	0.0542	7.96	0.37	AL2O3	15.03
SI KA	0.0530	6.24	0.31	SiO2	13.35
CL KA	0.0058	0.45	0.07	CL	0.45
CA KA	0.0199	1.14	0.12	CAD	1.59
FE KA	0.0369	2.42	0.28	FeO	3.12
LA LA	0.2956	20.36	1.00	LA2O3	23.88
CE LA	0.5346	36.35	1.36	CE2O3	42.58
O *		25.08			
TOTAL					100.00

* DETERMINED BY STOICHIOMETRY

TABLE 4

PARTICLE SIZE DISTRIBUTION
ELZONE
(Chromium Oxide)

CHNL	SIZE	COUNT	CHNL	SIZE	COUNT	CHNL	SIZE	COUNT
23	.72	364	50	1.84	1129	77	4.70	9
24	.75	347	51	1.91	1108	78	4.86	6
25	.77	347	52	1.97	1062	79	5.03	4
26	.80	370	53	2.04	990	80	5.21	2
27	.83	368	54	2.12	901	81	5.39	1
28	.86	382	55	2.19	801	82	5.58	0
29	.89	397	56	2.27	696	83	5.78	0
30	.92	414	57	2.35	592	84	5.98	0
31	.95	437	58	2.43	492	85	6.20	0
32	.99	458	59	2.52	400	86	6.41	0
33	1.02	480	60	2.60	319	87	6.64	0
34	1.06	504	61	2.70	251	88	6.87	0
35	1.10	532	62	2.79	195	89	7.12	0
36	1.13	569	63	2.89	151	90	7.37	0
37	1.17	614	64	2.99	118	91	7.63	0
38	1.22	666	65	3.10	93	92	7.90	0
39	1.26	719	66	3.21	74	93	8.18	0
40	1.30	772	67	3.32	60	94	8.46	0
41	1.35	825	68	3.44	49	95	8.76	0
42	1.40	876	69	3.56	41	96	9.07	0
43	1.45	926	70	3.68	34	97	9.39	0
44	1.50	974	71	3.81	29	98	9.72	0
45	1.55	1016	72	3.95	24	99	10.06	0
46	1.60	1053	73	4.09	20	100	10.42	0
47	1.66	1084	74	4.23	17	101	10.79	0
48	1.72	1109	75	4.38	14	102	11.17	0
49	1.78	1127	76	4.54	12	103	11.56	1

COUNT MODE = 1.84 MEDIAN = 1.60 MICRONS AND LARGER
 GEOMETRIC COUNT MEAN = 1.54 +/- .85 (42.23%) SKEWNESS = -.47
 ARITHMETIC COUNT MEAN = 1.64 +/- .58 (35.20%) SKEWNESS = -.36

TABLE 5

PARTICLE SIZE DISTRIBUTION
ELZONE
(Blended Cerium Oxide)

CHNL	SIZE	COUNT	CHNL	SIZE	COUNT	CHNL	SIZE	COUNT
18	.61	198	46	1.60	260	74	4.23	0
19	.63	31	47	1.66	210	75	4.38	0
20	.65	308	48	1.72	164	76	4.54	1
21	.67	634	49	1.78	134	77	4.70	1
22	.70	796	50	1.84	93	78	4.86	0
23	.72	916	51	1.91	73	79	5.03	2
24	.75	837	52	1.97	67	80	5.21	0
25	.77	897	53	2.04	57	81	5.39	0
26	.80	789	54	2.12	38	82	5.58	0
27	.83	810	55	2.19	25	83	5.78	0
28	.86	831	56	2.27	26	84	5.98	0
29	.89	949	57	2.35	18	85	6.20	1
30	.92	823	58	2.43	15	86	6.41	1
31	.95	881	59	2.52	12	87	6.64	0
32	.99	804	60	2.60	7	88	6.87	0
33	1.02	787	61	2.70	6	89	7.12	1
34	1.06	796	62	2.79	8	90	7.37	3
35	1.10	792	63	2.89	10	91	7.63	0
36	1.13	770	64	2.99	0	92	7.90	1
37	1.17	769	65	3.10	1	93	8.18	2
38	1.22	736	66	3.21	1	94	8.46	0
39	1.26	680	67	3.32	5	95	8.76	0
40	1.30	699	68	3.44	4	96	9.07	1
41	1.35	642	69	3.56	3	97	9.39	0
42	1.40	533	70	3.68	0	98	9.72	0
43	1.45	470	71	3.81	0	99	10.06	0
44	1.50	395	72	3.95	2	100	10.42	0
45	1.55	300	73	4.09	2	101	10.79	0

COUNT MODE = .89 MEDIAN = .99 MICRONS AND LARGER

GEOMETRIC COUNT MEAN = 1.01 +/- .33 (32.95%) SKEWNESS = .37

ARITHMETIC COUNT MEAN = 1.08 +/- .37 (34.86%) SKWENESS = .46

TABLE 6

PARTICLE SIZE DISTRIBUTION
ELZONE
(Chromium and Cerium Oxide)
(50% each, by weight)

CHNL	SIZE	COUNT	CHNL	SIZE	COUNT	CHNL	SIZE	COUNT
18	.53	190	49	1.55	827	80	4.54	1
19	.55	329	50	1.60	759	81	4.70	2
20	.57	149	51	1.66	681	82	4.86	1
21	.59	556	52	1.72	679	83	5.03	0
22	.61	720	53	1.78	643	84	5.21	0
23	.63	729	54	1.84	559	85	5.39	0
24	.65	712	55	1.91	491	86	5.58	1
25	.67	720	56	1.97	454	87	5.78	0
26	.70	686	57	2.04	375	88	5.98	2
27	.72	704	58	2.12	321	89	6.20	1
28	.75	706	59	2.19	300	90	6.41	0
29	.77	733	60	2.27	222	91	6.64	0
30	.80	708	61	2.35	217	92	6.87	0
31	.83	698	62	2.43	161	93	7.12	0
32	.86	691	63	2.52	142	94	7.37	1
33	.89	717	64	2.60	94	95	7.63	1
34	.92	687	65	2.70	78	96	7.90	0
35	.95	750	66	2.79	50	97	8.18	0
36	.99	778	67	2.89	40	98	8.46	0
37	1.02	812	68	2.99	29	99	8.76	0
38	1.06	777	69	3.10	35	100	9.07	1
39	1.10	781	70	3.21	22	101	9.39	0
40	1.13	800	71	3.32	16	102	9.72	1
41	1.17	874	72	3.44	16	103	10.06	0
42	1.22	897	73	3.56	5	104	10.42	0
43	1.26	900	74	3.68	7	105	10.79	1
44	1.30	923	75	3.81	5	106	11.17	0
45	1.35	841	76	3.95	0	107	11.56	0
46	1.40	851	77	4.09	10	108	11.97	0
47	1.45	824	78	4.23	1	109	12.39	0
48	1.50	812	79	4.38	5	110	12.83	1

COUNT MODE = 1.30 MEDIAN = 1.13 MICRONS AND LARGER

GEOMETRIC COUNT MEAN = 1.12 +/- .56 (49.51%) SKEWNESS = -.33

ARITHMETIC COUNT MEAN = 1.22 +/- .52 (42.89%) SKEWNESS = -.16

TABLE 7
CHROMIUM VERSUS SILICON RATIO

0.137	-	-	.029	-	-	-	-	-	-	-
0.172	0.091	0.038	0.059	0.038	-	.040	.025	.030	.026	.030
0.214	0.210	0.257	0.121	0.113	0.26	.026	.026	.028	.027	.027
0.491	0.324	0.246	0.155	0.182	.029	.026	.025	.034	.031	.026
0.366	0.282	0.224	0.132	0.160	0.036	.032	.027	.034	.036	.027
0.474	0.305	0.240	0.186	0.164	.055	.035	.034	.034	.033	.027
0.523	0.241	0.284	0.138	0.201	.081	.034	.036	.030	.029	-
0.428	0.364	0.354	0.189	0.188	.099	.049	.037	.031	.029	-
0.379	0.458	0.284	0.284	0.165	.073	.068	.028	.028	.029	.029
0.438	0.331	0.349	0.177	0.184	0.160	.079	.033	.030	.027	.026
0.834	0.307	0.328	0.156	0.111	0.080	.063	.033	.031	.026	.025
1.001	0.283	0.321	0.174	0.254	.059	.047	.030	.028	.026	.036
1.091	0.281	0.270	0.157	0.309	.061	.046	.025	.026	.024	.027
2.145	0.504	0.238	0.155	0.289	.057	.050	.026	.025	-	.026
0.676	0.442	0.341	0.104	0.310	.049	.049	-	-	-	-

FLOW
RATE
→

CHROMIUM VERSUS SILICON RATIO

0.724	0.570	0.299	0.187	0.087	0.081	0.056

TABLE 9

MEASURED PERMEABILITY DAMAGE FOR VARIOUS FLOW RATES

(Chromium Oxide Particles)

<u>Core Sample A</u>				<u>Core Sample B</u>		<u>Core Sample C</u>	
Flow Rate = 3cc/mn				Flow Rate = 6cc/mn		Flow Rate = 9cc/mn	
Time (mn)	*ΔP	**Kw/Kwi	ΔP	Kw/Kwi	ΔP	Kw/Kwi	
15					88	0.48	
30	7	1.0	35	0.43	142	0.30	
45					245	0.18	
60	10	0.7	138	0.11	395	0.11	
75					450	0.10	
90	22	0.32	300	0.05	465	0.09	
105					500	0.09	
120	47	0.15	385	0.04	730	0.06	
150	65	0.12	480	0.03			
180	88	0.08	500	0.02			
-							
330	500	0.01					

*ΔP = pressure difference across the core in psi

**Kw/Kwi = ratio of permeability at time t to initial permeability

TABLE 10

MEASURED PERMEABILITY DAMAGE FOR VARIOUS FLOW RATES

(Cerium Oxide Particles)

<u>Core Sample D</u>			<u>Core Sample E</u>		<u>Core Sample F</u>	
Flow Rate = 8cc/mn			Flow Rate = 5cc/mn		Flow Rate = 7cc/mn	
Time (mn)	*ΔP	**Kw/Kwi	ΔP	Kw/Kwi	ΔP	Kw/Kwi
15			13	.73	15	.75
30	9	.89	15	.62	17	.66
45			19	.49	20	.56
60	11	.72	24	.39	28	.40
75			29	.32	36	.31
90	21	.39	33	.28	46	.24
120	58	.14	48	.19	67	.17
-						
150					80	.14
-						
240			69	.14		
-						
300	97	.09				
-						
390	112	.06				

*ΔP = pressure difference across the core in psi

**Kw/Kwi = ratio of permeability at time t to initial permeability

TABLE 11

MEASURED PERMEABILITY DAMAGE FOR TWO
DIFFERENT FLOW RATES

(Cerium Oxide Particles)

<u>Core Sample G</u>			<u>Core Sample H</u>	
Flow Rate = 9cc/mn			Flow Rate = 10cc/mn	
Time (mn)	* ΔP	**Kw/Kwi	ΔP	Kw/Kwi
15	22	.81	32	.94
30	28	.63	38	.79
45			45	0.67
60	11	0.72	53	0.57
45	33	.54	45	.67
60	39	.46	53	.57
90	48	.37	62	.48
105	54	.33		
120	57	.31	65	.46

* ΔP = pressure difference across the core in psi

**Kw/Kwi = ratio of permeability at time t to initial permeability

TABLE 12

CERIUM VERSUS SILICON RATIO

	0.487	0.493	0.356	0.159	0.164	0.151	0.114	0.114	0.091	0.094	0.064	0.053	0.045	-

FLOW
RATE
→

TABLE 13

CHROMIUM VERSUS SILICON RATIO

FLOW
RATE

1.158	0.203	0.147	0.104	0.066	0.036	0.024
0.849	0.333	0.176	0.098	0.060	0.035	0.021
1.790	0.304	2.85	0.076	0.049	0.030	0.022

FIGURE 1

Fig. 3 - Volume percent pore size distributions measured with 1% brine and diiodomethane.

FIGURE 2

Fig. 12 - Permeability reduction in sandstone systems resulting from injected North Sea water

Fig. 13 - Particle size analysis of sea water before and after core

Fig. 14 - Barkman and Davidson plot of constant pressure plugging test

FLOW APPARATUS

FIGURE 3

CORE HOLDER

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

SAMPLE IDENTIFICATION

S.G. OF SOLID

S.G. OF LIQUID

VISCOSITY OF LIQUID

SYSTEM TEMPERATURE

Cr_2O_3 - Slurry (aqueous)

5.04

g/ccm

WEIGHT OF SAMPLE ANALYZED

0.3

grams

SEDIMENTATION LIQUID TYPE

SEDISPERSE-AB

SEDIMENTATION LIQUID VOLUME

30

ml

DURATION OF ULTRASONIC DISPERSION WITH SIMULTANEOUS STIRRING

60

MINUTES

DATE 5-18-1981

ANALYSIS BY RH

CONSTANT 165

STARTING DIAMETER 50 MICRONS

FIGURE 12

MICRON DATA LABORATORIES, 25672 Tatadro Circle, Mission Viejo, CA 92675

Phone (714) 586-4611

REPRODUCING CHARTS
MICRON DATA LABORATORIES
MISSION VIEJO, CALIFORNIA

No. GC-19944

FIGURE 13

FIGURE 14

FIGURE 15

FIGURE 16

FIGURE 17

FIGURE 18

FIGURE 19

FIGURE 20

FIGURE 21

FIGURE 22

FIGURE 23

FIGURE 24

FIGURE 25