REPORT

PARTICLE CHARACTERIZATION FOR GEOTHERMAL OPERATIONS

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SUBMITTED TO

UNITED STATES DEPARTMENT OF ENERGY
DIVISION OF GEOTHERMAL ENERGY

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DATE OF ISSUANCE:

JANUARY 6, 1981

VR REPORT NO:

81-01-06

SIGNATURE(S):

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VR

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PREAMBLE

"Injection, Injectivity and Injectibility in Geothermal Operations" is the topic of a research contract awarded to Vetter Research (VR) by the US Department of Energy/Division of Geothermal Energy (Contract No.DE/AC03-79ET27146). This present report is one of the deliverables under this contract and is concerned with Major Task A: "Conduct a Particle Determination, Clean-up and Monitoring". In this report we describe our evaluation of several different methods to determine critical particle characteristics to find the best method(s) in the laboratory. In order to maintain continuity of our reporting under this contract, the scope of this present report is somewhat expanded beyond the original task on the subject.

1.0 ABSTRACT

Suspended particles can play a key role in geothermal operations. Characterization of these particles must be done through measurements and monitoring. This characterization is an important aspect of this present contract.

The particle characteristics include not only their size, size distribution, concentration, shape and shape distribution but also their complex material qualities such as optical, electrical, sound reflecting, surface and other properties. Some of these characteristics are important for measuring or monitoring of the particles; others are critical for particle invasions into porous media and the resulting formation damage.

The present report is a detailed summary of an ongoing evaluation of existing particle measuring methodology with emphasis on (a) adapting of existing methods in geothermal operations and (b) further development of existing instrumentation for field use. Presently, there exists no commercially available single instrument capable of measuring critical particle characteristics under the hostile conditions of a geothermal operation. Among the numerous advertised instruments, three have been selected for further testing in the field and laboratory. Hopefully, these instruments may become useful for limited applications. These three instruments are (1) Microtrac, an instrument based on optical forward scattering, (2) El Zone, an instrument based on electrical conductivity changes and (3) Micropure, an instrument based on ultrasonic scattering. Two more optical instruments, namely, Prototron and Differential I, seem to be of potential value for geothermal operations but have not been selected for further field studies.

The report describes in detail the various instruments and methods used and/or suggested for particle characterization. Theoretical and practical aspects of particle characterizations are outlined. A plan for further laboratory and field experiments is outlined. The instrumentations to be selected after some additional lab and field tests will be used in the studies on (a) formation damage through particle invasion and (b) characterizing and monitoring of particle suspensions in geothermal operations.

2.0 CONCLUSIONS

The following conclusions have been made on the characterizing, measuring and monitoring of particles that are suspended in liquids such as the geothermal fluids:

2.1 GENERAL CONCLUSIONS:

1. A complete description or characterization of particles is essential for geothermal operations both from the point of view of measuring their properties as well as in describing the flow of particle suspensions through porous media. This problem is generally underestimated or grossly neglected and may be one of the main reasons for the slow development of geothermal resources in the United States where reinjection is mandatory.

2. Particle measurements in the laboratory do not pose major measuring problems. Many types of instruments can be used satisfactorily to describe a number of critical particle characteristics in the laboratory. The ease of these laboratory measurements has lead many people to believe that measurements in geothermal operations do not pose a problem.
3. Finding a convenient and/or appropriate technique for measuring critical particle characteristics in the laboratory does not solve the problem of the determination of critical particle characteristics in a geothermal installation. Laboratory and field methods may be quite different and may be based on different principles.
4. The principal problem regarding particle measurements in geothermal operations is the dynamic nature of the particles themselves. That is, in the flowing geothermal fluid, the sizes and size distributions, shapes, surface properties, chemical nature, etc., of the particles are constantly changing. Most of the commercial instrumentation for particle characterization require that a sample be taken before the particle measurements can be made. The particle characteristics in the sample may be quite different from those in the in-line fluid. The only methods for instantaneous in-line measurement of potential value seem to be those based on the technique of utilizing ultrasonic scattering methods. This method, however, needs further development. Light scattering methods could become valuable if the necessary optical windows can be kept clean of scale and can withstand the hostile environment encountered within geothermal fluids.

2.2 CONCLUSIONS REGARDING BASIC CONCEPTS OF PARTICLE CHARACTERIZATION

1. There are many different ways of characterizing particles in suspensions; some through their geometry, some through the material of the particles and some through the chemical, physical and surface properties of the particles. Actual measurements based on different principles may not yield the same information describing a given particle characteristic. This means, different methods may give quite different values for the same particle property.
2. Particle size is one of the main descriptive properties and its specification depends very much on the geometry of the particle. The measured particle size depends very much on the measurement technique used. For example, the electrical methods determine the particle size through the volume of the particle whereas the light obscuration techniques use its projected area to determine the size. Both methods have principal shortcomings and may measure different sizes of a given particle. This may become critically important for monitoring particles in actual geothermal field operations.
3. Monosized particles and particles made up of single type of materials

do generally not occur in geothermal operations. That is, the particles in a suspension are statistical in nature. As a result, the characterization of particles in suspensions, particularly their size, have to be treated using statistical distribution functions and parameters describing these distributions.

4. The description of particle shape can only be considered qualitatively. Several attempts have been made to describe various shape factors quantitatively in the literature. The pertinency of these shape descriptions for the particle plugging of porous media is not clear and needs to be investigated. Shape factors may or may not be critical for proper particle monitoring in geothermal operations.
5. There are several properties other than the size, size distribution and shape (which are geometrical properties) that need to be considered. For example, particle populations and concentrations are two of the properties which are important both from the particle measurement point of view as well as for the treatment of flow of suspensions through porous media. Both the particle population and concentration represent the amount of "particle material" in the suspension. Both of these are difficult to measure and to evaluate.
6. The surface properties of particles can be considered as some of the most important properties of particles in the particle plugging of porous media. This behavior arises from the interfacial reactions between the particles and the surface of the porous medium. This is contrary to many conventional considerations about the causes for particle plugging and the resulting formation damage.
7. The interrelation between the surface property of particles and the plugging of porous medium needs to be investigated. This may be one of the most important factors in the understanding of formation damage experienced in geothermal injection systems. The generation of damage collars around injection wells may be more related to the surface properties of particles than to other plugging mechanisms.

2.3 CONCLUSIONS RELATED TO MEASURING DEVICES

1. Most measuring techniques use secondary properties to determine particle characteristics. If those secondary properties and their relation to the desired particle characteristics are not well known, the measurements will yield wrong or misleading information. This is the major shortcoming of all particle measurements. For example, the optical properties such as the refractive index and opacity of the particles are important from the point of view of measurements using optical methods. These properties are usually not known, thus constituting critical limitations of optical methods for the determination of particle characteristics in geothermal brines.
2. There are many physical principles that can be used in sensing and measuring particles. However, only a very limited number of these

seem to be useful for the measurement of particles in liquids.

3. There are several severe operating requirements for the purpose of monitoring or measuring of particles in-line, especially in high temperature geothermal systems.
4. There is no commercially available single instrument which is capable of measuring critical particle characteristics under the conditions one encounters in geothermal operations.
5. The methods based on electrical measurements are highly sensitive and are capable of high resolution. They are capable of measuring a wide range of sizes. However, the complete range of sizes cannot be made in a single step. These methods seem to be extremely useful for particle characterization in geothermal operations. Special techniques need to be developed in order to utilize this technique for geothermal field applications. Further evaluations under this contract will utilize one of this type of instruments, namely, the El Zone (manufactured by Particle Data).
6. The optical methods are useful for a rapid determination of particle size distributions.
7. Many different commercial instruments based on optical methods are available for particle characterization. However, only three of these instruments were considered to be useful for this work. These three are the Differential I, Prototran Particle Counter, and Microtrac. Only the Microtrac was considered for further evaluations under this contract.
8. The Microtrac particle counter (manufactured by Leeds and Northrup) seems to offer some possibilities for in-line particle size measurement through the use of side-streams from geothermal operations. Its actual utilization needs to be tested as a particle field monitor. Its bulkiness and difficulty of required alignment are major handicaps of this instrument.
9. The technique based on the scattering of ultrasonic waves by particles seems to offer good possibilities for application as a real in-line particle monitor. Its commercial application is relatively new. An instrument based on this principle is manufactured by Micropure, Inc and has been field tested by us at the Mercer 2 site in Imperial. Initial experiments failed to deliver the expected results. The instrument needs to be altered and adapted for geothermal applications. Development work with this method seems to be of considerable potential value and is in progress.

3.0 INTRODUCTION

In the Phase I report on the injectivity problems and possible solutions, it has been emphasized that the suspended particles in geothermal operations can cause a number of operating problems in a geothermal field [1]. We believe

that the lack of appropriate measurements and monitoring methods to determine the critical characteristics of suspended particles poses one of the most important hurdles for a rapid and economic development of the geothermal industry. It seems obvious that the injectability of a heat-depleted geothermal brine depends to a large degree upon the type of particles suspended in this brine. Plugging of reinjection wells and formation damage by particle invasion seem to be critical parameters for the projected life of an injection system. However, it does not seem to be clear how the particles suspended in geothermal brines will cause the feared damage collars within the reservoir around the reinjection wells. Any critical investigation of the true damage mechanism must include a thorough characterization of the suspended particles. For that reason alone, an elaborate study of particles suspended in heat-depleted geothermal brine is strongly warranted at this present time. In addition, some scale is formed within geothermal installations due to impingement of particles. This type of scale formation also warrants a thorough investigation of particle characteristics in geothermal operations.

These suspended particles either exist in the produced brines or are formed through precipitation reactions during various geothermal operations. It has also been emphasized [1] that presently existing methodology and instrumentation for particle determinations have not been thoroughly evaluated for today's geothermal operations. There seems to be a strong need for a thorough review of the pertinent particle characteristics and their determination through various existing or potentially valuable measuring methods.

We also outlined in the Phase I report [1] that it may be extremely difficult to determine the pertinent particle parameters because of the thermodynamic instability of geothermal brines. As the geothermal fluids flow within the field installations or the reservoir, even small changes of pressure and temperature may cause a rapid change of the particle parameters as a function of time. For example, the size and population of certain particles in a flow line under high pressure and/or temperature may not be the same as the size and population of the particles in a sample collected from this flow line. Therefore, any measurement of particle parameters in a sample may or may not result in collecting the proper and pertinent information on the critical particle characteristics describing the suspensions within the flowing system. This thermodynamic instability of the suspended particles and the geothermal fluids would require (a) instantaneous and (b) in-line measurements. To our knowledge, no such instrumentation exists today despite some claims to the contrary. Most of these false or exaggerated claims ignore the problems caused by (a) the dynamic nature of particles suspended in geothermal brine and (b) the hostile environment generated by the thermodynamic conditions in these flowing brines. Considerable development work may be necessary before a useful and reliable particle characterization becomes available for field use.

What is needed is a thorough evaluation of existing particle measuring methods and instrumentation with emphasis on possible (a) adaption of presently existing methods and instruments and (b) further development of measuring devices. The first part of our evaluation is given in this report.

4.0 OBJECTIVES OF THE PRESENT REPORT

The present report is a partial summary of the work done during the first six months on Task 1 of Phase II of the contract on injectivity. This Task 1 consists of four subtasks:

1. Determination of various particle parameters.
2. Monitoring of suspended particles.
3. Removal of particles from process streams.
4. Effects of suspended particles on fluid flow in equipment and porous media.

This present report is concerned only with the determination of various particle parameters. Below, we list the major items described in this report.

1. A critical review of the physical principles used in determining the particle size parameters.
2. A critical review of the commercial instruments based on the useful physical principles.
3. A study of the suitability of specific instrumentation having high resolution for determining particle sizes.
4. A study of the suitability of specific instrumentation for in-line applications.
5. A study of the feasibility of specific instrumentation to be useful for particle shape determination.
6. A study of the definitions of various particle parameters and their implications and usefulness for geothermal applications.

Based on our evaluations, four commercial instruments have been found to offer some possibility for application in geothermal operations. These four instruments are (1) the El Zone particle counter, (2) the Microtrac particle counter, (3) Differential I, a differential angle laser light beam scattering device and (4) the Prototron particle counter. Two of these four instruments are presently being used and will be further evaluated in all studies of the remainder of the Phase II contract. These two instruments are (1) an El Zone particle counter and (2) a Microtrac particle counter. The other two instruments are presently not considered for various reasons. These reasons are explained in the body of this report (Section 7.0). An additional type of instrumentation, which is based on ultrasonic scattering, is planned to be utilized for monitoring during future work under this contract. This instrument is manufactured by Micropure. Preliminary field experiments with a prototype instrument of this kind have not yielded proper and desired data.

However, the reasons for the failure of this instrument in the field were determined. Altered and, hopefully, more suitable probes are presently being made. These altered probes may allow us to overcome the shortcomings of the original instruments. All these instruments are described in later sections of this report.

5.0 PARTICLE CHARACTERIZATION OR MEASUREMENTS FOR GEOTHERMAL OPERATIONS

A complete description of a particle suspension in aqueous medium is essential to study the particle plugging effects on a porous medium and to design equipment for an efficient particle removal from the geothermal brines before brine reinjection.

5.1 PRINCIPAL PROBLEMS ENCOUNTERED DURING PARTICLE CHARACTERIZATIONS IN GEOTHERMAL BRINE

Below we describe some of the problems which are of principal nature and also related to the highly specific situation regarding the particle characterization in geothermal operations.

5.1.1 LABORATORY VS. FIELD MEASUREMENTS

Geothermal brines will cool down as their heat content is utilized or exploited. This cooling process causes a definite thermodynamic instability of the brines. This instability, in turn, is the cause for the precipitation of salts, i.e., for the formation of particles which have to be characterized for a large number of reasons. As the particles form due to the brine instability, this instability may still be changing,, thus causing not only the formation of constantly changing types of particles (i.e., particles consisting of different chemical species) but also constantly changing the geometry of the forming or already formed particles. This highly dynamic process of particle formation and particle alteration in a flowing geothermal brine causes numerous problems for a useful determination of the critical particles properties.

One could try to perform particle measurements by simulating geothermal field conditions in the laboratory. Attempts to simulate some of the complex precipitation reactions have been made [2]. However, the authors of this present report do not believe that particle characterization performed in simulating laboratory experiments will have much relevance to the particles found in actual geothermal field installations. We do not believe that the hostile environment inherent to geothermal field operations can be simulated in the laboratory. Too many variables lead to the formation of particles and their critical properties in a flowing geothermal brine to be duplicated in laboratory experiments. Therefore, we strongly believe that any actual characterization of these particles must be based on methods developed and proven in real field experiments. A limited number of laboratory experiments can be performed to support the field experiments. However, we would like to warn that particle characterizations related to geothermal brines which are not based on actual field experiments may prove to be of absolutely no value to the geothermal industry.

5.1.2 PARTICLE MEASUREMENTS VS. PARTICLE MONITORING

An operator of a geothermal field would like to determine as frequently as technically and economically feasible all the particle characteristics which are critical for his daily field operations. Preferably, he would like to obtain and record all measurements critical for his field operations through in-line measurements of the actual particle properties. Assuming precise and instantaneous determinations of these critical particle properties are not possible (see Section 6.0), the operator will be looking for substitute, in-line instrumentation which will allow him to monitor those particle properties or related phenomena which are most important for him to maintain his daily operations. Some kind of in-line monitors would be acceptable if these in-line monitors would allow an instantaneous indication of changing particle properties as a brine quality control measure.

5.1.3 SAMPLING VS. IN-LINE MEASUREMENTS

Assuming that there is no reliable or useful in-line instrumentation for particle measurements or monitoring, samples may have to be collected and the critical particle properties may have to be measured in these samples by using instrumentation and/or methods which are not adaptable for in-line operations. This method of particle characterization in samples collected in a geothermal installation is filled with "pitfalls for the unwary". As mentioned earlier, the thermodynamics of the sample suspension will be, most likely, quite different from those of the in-line fluid. Because of the effects of the thermodynamics on the particles themselves, all measurements within the collected sample may be quite irrelevant and may be non-representative for the particles within the line. Furthermore, additional uncertainties are caused by (a) the problems of collecting representative samples in a flowing suspension and (b) the time delays between sample collection and actual measurements.

5.1.4 PROBLEMS CAUSED BY PARTICLE BOUNDARIES

The particle suspension can be characterized by the properties of the particles in the suspension assuming the particle boundaries are rigidly defined and the particle properties (including its boundaries) are sufficiently distinguishable from the liquid properties (including its boundaries). These preconditions related to the particle boundaries are necessary for a successful particle characterization and may or may not exist in geothermal brines. Some of the particles (e.g. galena or argentite particles) may have boundaries which are very discrete and, therefore, rather easy to define and to determine. Other particles, e.g. the silica particles, may exhibit far more complex boundary conditions.

The center part of a formed silica particle may be silica already polymerized to various and fairly high degrees. The particle shells, layers or portions outward from this center part may be polymerizing silica having still a fairly low but also varying degree of polymerization. The most outward shell layer or portion of a particle may consist of a liquid phase with strongly oriented water and monomeric silicic acid molecules (or ion) bordering on the liquid phase.

Measuring the critical characteristics of this type of a particle may be nearly impossible because of the boundary problems. By boundary problems we mean (a) the lack of sharp and defineable boundaries in a particle of this nature and (b) the changing consistency and/or composition throughout the particle. In this present section we assume that the above described boundary preconditons are met, i.e., no boundary problems exist, thus allowing us to describe the various characteristics which are essential for the measurement of particles and for predicting the behavior of particles in porous medium. The chemical composition or nature of the particles and the density of the particle material are not considered in this present report. However, in future reports on the subject of particle characterization, we will attempt to include the chemical nature of the particles.

Particles may be characterized by parameters or characteristics describing the chemical nature of the particles, the physical properties and various statistical parameters. Table 1 summarizes the various ways of characterizing particles in an aqueous suspension. The primary and secondary particle properties are described in the subsequent sections.

5.2 CONCEPTUAL PROBLEMS REGARDING PARTICLE CHARACTERIZATIONS

No matter what kind of particles have to be characterized in any type of aqueous suspension, there are still some problems related to the basic concepts of particle characterization. These conceptual problems lead to quite a confusion among geothermal field personnel and should be identified. An attempt to identify this type of problem is described in the following paragraphs.

5.2.1 PARTICLE SIZE

It can be very difficult to describe the size of any thing or body if it has a very complex geometry. Suspended particles found in geothermal fluids can have very complex geometries. Therefore, describing the size of any suspended particle can pose a real problem. To illustrate the problem of determining the particle size we would like to describe a few examples: For a spherical, homogeneous particle, the characteristic size parameter would be its diameter, i.e., no real size determining problem exists. For some other regular shaped particles, more than one size dimension may be necessary to describe the critical size of a given particle. On the other hand, particles of irregular shapes may have to be characterized through their volume or other equivalent measurable parameters, i.e., it may become impossible to describe these particles by a simple size determination. These other parameters may be converted later to an "equivalent or effective diameter". For example, if a particular method of measuring particles gives the volume of a particle, then the concept of the "equivalent spherical diameter" may be used. The equivalent spherical diameter of a particle may be defined as the diameter of a sphere having the same volume as the particle.

There are various definitions that are being used in the literature to describe the size parameter of particles. These various definitions have their origin in the techniques used in the mesurement of particles. The different definitions of particle sizes are described in Table 2.

None of these particle size definitions may be relevant for our objective to study formation damage through particle invasion. A determination of the particle "size" without simultaneously determining the "shape" of the particles (see below) may be meaningless for investigating of a number of different damage mechanisms.

5.2.2 PARTICLE SIZE DISTRIBUTION

Particle size distribution is the relationship between the size of the particles and the quantity of particles corresponding to that size. A distribution of particle sizes is always present in aqueous particle suspensions such as geothermal liquids. Therefore, an understanding of the distribution of particles is essential when one studies the plugging of a porous formation through particle invasion.

Once a particle size distribution in a suspension is known or measured, one can quantitatively determine the characteristic parameters (mean diameter, standard deviation, maximum diameter, etc.) that are useful in interpreting particle plugging experiments assuming the particles exhibit a rather simple shape (see below).

Particle size distributions may be presented in analytical form, in tabular form or as histograms. The analytical forms are extremely useful as they are easily adaptable in quantifying the particle plugging tendencies and in modeling the particle invasion of a porous medium. Several empirical forms of the particle size distribution functions are generally used and are summarized in Table 3.

There are three important parameters that can be used in describing the particle size distribution. They are the Mode, the Median and the Mean. These distribution parameters are defined below:

1. The Mode of a particle size distribution is the size corresponding to the peak on the size distribution curve and is the most commonly used parameter. This mode describes the size of the particle having the highest concentration of all particles present.
2. The Median of a particle distribution is the size at which half the amount of particles are larger and the other half smaller than this size.
3. The Mean of a particle size distribution is the average size of all particles in a given suspension.

5.2.3 DEFINITIONS OF PARTICLE SHAPE PARAMETERS

A host of particle shapes are possible in a suspension. A quantitative description of these particle parameter is extremely difficult. In the literature, several qualitative terms have been used to describe particle shapes. These terms are summarized in Table 4. These qualitative terms are not useful if one wants to describe quantitatively the effect of particle

shape on the plugging of porous medium by particles.

Heywood approached the subject of particle shape systematically [3-4]. Attempts will be made in the present study to incorporate these ideas in the subtask dealing with the effect of particle shape on the plugging of porous medium by particles. As a prelude to the future study on this topic, Heywood's approach to particle shapes is described in this section.

The word "shape" refers to two distinct characteristics - namely, (1) the degree to which the particle approaches a definite geometrical form (e.g., sphere or cube) and (2) the relative proportions of the particle which distinguishes one particle from another having the same form. In general, particles may be characterized by the surface area and the volume. The surface area is proportional to the square of some characteristic dimension and the volume is proportional to the cube of a similar characteristic dimension. The constants of proportionality depend upon the dimension chosen to characterize the particles. As an example, consider the projected area diameter (d_a) as defined in Table 2. Then, we can simply state that

$$\text{Surface Area: } S = \alpha_s d_a^2 = \pi d_s^2 = x_s^2 \quad (1)$$

and

$$\text{Volume: } V = \alpha_v d_a^3 = (\pi/6) d_v^3 = x_v^3 \quad (2)$$

where:

α_s	= Surface shape coefficient
d_a	= Projected area diameter
d_s	= Surface diameter
x_s	= Size factor including the surface shape coefficient
α_v	= Volume shape coefficient
d_v	= Volume diameter
x_v	= Size factor including the volume shape coefficient

For the cases where three mutually perpendicular dimensions of a particle are available, Heywood defined two ratios, namely

$$\text{The elongation ratio: } N = L/B \quad (3)$$

and

$$\text{The flakiness ratio: } M = B/T \quad (4)$$

where "L" equals the length, defined as the distance between any two parallel planes which are perpendicular to the planes defining thickness "T"

and breadth "B" and are tangential to opposite sides of the particle. The breadth is defined as the minimum distance between two parallel planes which are perpendicular to the planes defining the thickness and are tangential to opposite sides of the particle. "T" equals the thickness, defined as the minimum distance between two parallel planes which are tangential to opposite surfaces of the particle, one plane being the plane of maximum stability.

The above semi-quantitative description of particle shapes can usefully be utilized in describing (at least qualitatively) the effect of particle shape on the damage caused by particle invasion into porous media. Such studies are planned to be undertaken during the latter part of the present contract.

5.2.4 OTHER PARTICLE PARAMETERS

There are at least four particle properties other than the ones mentioned in the previous sections that are important from the point of view of particle measurements and/or for the investigation of the plugging effects caused by particles. These parameters are as follows:

1. The population or concentration of particles.
2. The surface properties of particles.
3. The electrical properties of particles.
4. The optical properties of the particles.

5.2.4.1 PARTICLE POPULATION AND CONCENTRATION

The parameter which characterizes the amount of particles in a suspension is one of the most important quantities necessary in the study of particle invasion in a porous medium. There are three ways of expressing this parameter, namely, (1) particle population expressed as the number of particles, (2) the particle population expressed as the volume of the particles, and (3) the particle population expressed as the mass of the particles per volume or weight unit of geothermal brine. These different ways of expressing this parameter are defined below:

1. The particle population of a suspension may be expressed as the total number of particles in a unit volume or unit mass of the suspension. In this definition, the particles are counted irrespective of their size or chemical nature. As mentioned in future sections, the methods based on the flow of electrolytes through orifices are suitable for such counting procedure without elaborate calibrations.
2. The particle population of a suspension may also be expressed as the total volume of particles in unit volume or unit mass of suspension. In this definition, the particle volume is counted irrespective of the chemical nature of the particles. The electrical sensing methods again are suitable for the measurement of this type of parameter and

this type of measurement is useful when a broad distribution of a particle size is present. This parameter describing the particle population is used in most of the presently conducted investigations.

3. Another parameter that represents the particle content in a suspension is the particle concentration. The particle concentration in a suspension may be expressed as the total mass of suspended particles in a unit volume or mass of suspension. The determination of this type of parameter can only be accomplished by independent density measurements. However, this parameter is useful in the preparation of predetermined suspensions for the flow experiments. These carefully prepared suspensions are used for instrument calibrations.

In general, the quantity of particles in a suspension is an extremely important parameter in studying the plugging of the porous medium by particles.

5.2.4.2 SURFACE PROPERTIES OF PARTICLES

The surface properties of particles include two different aspects of particles and at the present time they can be stated only in qualitative terminology. These are described in this section.

One aspect of the surface property arises in the case of suspensions of extremely small particles (e.g., smaller than 0.05 microns). In the flow of such suspensions, the interaction between the surfaces of the porous medium and the fine particles in the suspension may interact through surface forces. The origin of these surface forces may result through electrostatic or dipole interactions. However, the details describing such surface forces are difficult to determine experimentally. As a result, it is convenient to treat these surface forces through the phenomenological parameters such as surface tension. In other words, the particles may tend to adhere to the solid surface of the porous medium and eventually may plug the formation, even if these particles are much smaller than the pore throats within the porous medium. This type of situation may exist in the case of flow of clay fines through the porous formation. The second aspect of the surface properties arises due to the "physical" surface boundary of the particle itself. Two extreme cases of the "physical" surfaces boundaries are: (1) the well-defined solid boundary of the particles separating it from the liquid as in the case of particles consisting of sulfates, carbonates, heavy metal sulfides, etc., and (2) the "fuzzy or transitional" boundary between the particles and the liquid as one finds in the case of the polymeric growth of amorphous silica particles as mentioned earlier. The plugging effects of these two kinds of properties need further investigation.

5.2.4.3 ELECTRICAL PROPERTIES OF PARTICLES

As mentioned in a future section, the measurement of electrical capacitance changes in the flowing electrolytes through an orifice due to particles suspended in them offers a powerful way of measuring particle sizes. It may be suspected that the electrical or magnetic properties of the particles may

cause difficulties in the measurement of particle sizes by such methods. The evidence from the literature so far seems to indicate that such effects may be insignificant and, therefore, are not considered at present in this report.

5.2.4.4 OPTICAL PROPERTIES OF PARTICLES

The optical properties of particles are important and their nature should be known prior to the use of optical methods in the determination of particle sizes. The two most important optical parameters that are needed are, (1) the refractive index and (2) opacity of the particles. The refractive index becomes important in those optical methods that use the scattered light above an angle of scattering of 5° . The opacity of the particles become important in those optical methods which use light obscuration or attenuation principles.

5.2.5 RELEVANCE OF VARIOUS PARAMETERS FOR PARTICLE MEASUREMENTS

The important particle properties that need to be measured in the present study are the size, size distribution and the shape. The criteria for the selection of particle measuring devices depend on the nature and properties of both the particles and the fluid of the system under consideration. From the point of view of particles, such parameters as the size of the particle itself, the refractive index or opacity (or dielectric constant) of the particle and the mechanical stability or friability of the particle becomes important. From the point of view of the fluids, such properties as the conductivity, the refractive index and the color of the fluids become important. On the other hand, from the point of view of the particle-fluid system, such properties as the solubility of the particle in the fluid, other chemical reactions between the particle and the fluids and the relative refractive index of the solid particles with respect to the fluid become also important. The relative importance of each of the above mentioned properties depends upon the actual method of measuring the particles.

6.0 MEASUREMENT OF PARTICLE PARAMETERS

The measurement of particle size and size distribution depends upon well known principles. However, all the principles are not suitable in the determination of the particles in aqueous medium. In addition, most of the methods known so far are not easily adaptable for in-line measurements of particle characteristics. Thus, the selection of instruments for measuring particle sizes or simply for monitoring of particles of given sizes in geothermal operations requires an understanding of the physical principles involved in the particle measuring instrumentation. This section briefly reviews the various physical principles that are generally useful for particle measurement.

6.1 PHYSICAL PRINCIPLES USED TO SENSE AND SIZE PARTICLES

The various physical principles that are presently used by various investigators are listed below:

1. Image replication and analysis
2. Electrical resistance change
3. Light scattering
4. Light obscuration
5. Light diffraction
6. Beta ray attenuation
7. X-ray absorption
8. Acoustic interference
9. Ultrasonic attenuation
10. Ultrasonic scattering
11. Differential air classification
12. Hydrocyclone separation
13. Pulsating gas flow
14. Pressure drop in a nozzle
15. Hot wire anemometry
16. Impact and momentum measurement
17. Magnetic flux variations
18. Electrostatic ion capture
19. Glow discharge perturbation
20. Automatic sieve methods
21. Sedimentation
22. Correlation techniques
23. Microscopy

Many of these physical principles mentioned above are not suitable for the measurement of all types of particle systems. In order to discuss the suitability of these methods, the particle systems may be classified into three categories. They are as follows:

1. Solid particles in air
2. Bulk powders or scales formed by particle adherence
3. Solid particles in liquids

Table 5 gives the list of methods that seem to be suitable for in-line particle characterizations. The emphasis of this report is placed on the measurement techniques suitable for liquid systems because our main concern of the present work is the characterization of solid particles in aqueous fluids.

Several commercial producers of instruments have utilized some of these physical principles mentioned. They have manufactured commercial measuring instruments for sizing particles. Table 6 gives a partial source listing of the various instruments along with pertinent information on the size limitation of each of the instruments.

There are many instruments commercially available for adaptation in determining particle size distribution in a liquid medium (see Section 6.2). However, all the methods are not readily adaptable to the measurement of particles in an in-line operation. There are several requirements that should be satisfied for an instrument to be useful as an in-line instrument. The characteristics of the instruments for in-line particle measurements are listed below.

1. It must operate automatically and continuously under preset instructions.
2. The response time of the instruments from observation to readout must be short, i.e., nearly instantaneous.
3. It must be accurate and precise.
4. It must have the capability of detecting and measuring a wide spectrum of particle sizes and distributions.
5. It should have the capability to look at the shape factor.
6. It must be operational with high and low particle concentrations.
7. Instruments and sensors must be robust, corrosion and erosion resistant.
8. It must not disturb the flow pattern of the particulate and fluid phase.
9. It should have the capability to study the changes in the particle size distribution with time.

In our opinion, there is no single instrument commercially available at the present time that can satisfy all the characteristics mentioned above.

6.2 BRIEF DESCRIPTION OF THE TECHNIQUES THAT MAY OFFER POSSIBILITIES FOR IN-LINE GEOTHERMAL APPLICATIONS

Table 5 gives a list of the methods of measuring particles which offer possibilities for in-line measurements in geothermal systems. None of the methods satisfy all the stringent requirements necessary for in-line measurements or monitoring of particles in geothermal operations. A few of the techniques that show possibilities are briefly reviewed in this section.

6.2.1 ELECTRICAL RESISTANCE CHANGE

This method has application in the rapid sizing of particles in electrically conducting liquids. This method is based on the modulation of electrical current due to changes in electrical conductivity caused by passage of particles through a small aperture between two electrodes. The method relies on the assumption that the modulated pulse is proportional to the particle volume.

As indicated in Table 6 there are several companies which manufacture instruments based on the electrical method. Two of the most popular ones are the TA II system, manufactured by Coulter Electronics, Inc., and the El Zone particle counter manufactured by Particle Data, Inc. In the present work, the method based on electrical measurement is chosen for further evaluation and utilization under this contract and is described in detail in a future section. (Section 7.1).

6.2.2 LIGHT SCATTERING

The instruments based on light scattering find their use in both gaseous systems and liquid suspensions. The method is based on the light scattering property of particles. The intensity of scattered light by particles as a function of angle is related to the particle characteristics. The light scattering methods are employed in several commercial instruments as shown in Table 6. Three instruments based on the optical scattering principles have been chosen for further evaluation and use, and are described in future section (Section 7.2).

6.2.3 LIGHT OBSCURATION

The method based on light obscuration is useful for gaseous and liquid suspensions. The principle of the method is based on the light blockage by particles. The operating principle of the method is described in the next paragraph.

A small sample of fluid passes through a small rectangular passage past a window. A beam of light is allowed to pass through the window and is detected by a photoelectric detector. Any particle passing through the window interrupts a portion of the light beam according to its size. This causes a momentary reduction in the photoelectric signal which is used in determining the particle size.

The light obscuration technique is an extremely useful technique for determining the particle size distribution in a suspension. However, this method is very restricted in the sense that it is useful only to extremely small volumes of samples at low particle concentrations directed to the observation point.

6.2.4 BETA RAY AND X-RAY ATTENUATION

The methods based on beta-ray and x-ray attenuation are useful for liquid suspensions. The methods is based on separating particles of various sizes by means of centrifugal force applied to the system and measuring the beta ray or x-ray absorption by passing the rays through the system. These methods are not suitable for application to the present work, as they require elaborate mechanical forces such as centrifugal force to be applied to the suspension.

6.2.5 ULTRASONIC ATTENUATION

The method based on ultrasonic attenuation is suitable for liquid suspensions. However, the smallest particles that are detected by this technique are 60 microns. Therefore, it is not useful for geothermal application where the suspended particles are expected to be much finer.

6.2.6 ULTRASONIC SCATTERING

The method based on ultrasonic scattering, a relatively new technique, may offer quite a few possibilities as a particle monitor and will be tested for field application. The method is based on the dependence of the scattering intensity of ultrasonic waves on small-sized particles. This technique is described further in a future section.

7.0 SELECTED INSTRUMENTS TO BE USED FOR GEOTHERMAL APPLICATIONS

As mentioned in the previous sections many methods exist for particle size determination in liquids. However, all the methods are not suitable for operation in situations where in-line particle measurement or particle monitoring is needed. In this section, three of the physical principles that may offer methods for geothermal application are reviewed in some detail. Also, some specific instruments for this purpose are evaluated. A summary of the plans for particle monitoring system design to be applicable for field use is given. The physical principles that seem to offer the best possibilities are as follows:

1. Electrical conductivity changes
2. Optical methods
3. Ultrasonic methods

7.1 METHODS BASED ON ELECTRICAL CONDUCTIVITY CHANGES

There are several instruments in the market which are based on electrical conductivity changes [5-16]. However, two of the most popular instruments are (1) the Coulter Counter, which is manufactured by Coulter Electronics, Inc., and (2) the El Zone Particle counter, which is manufactured by Particle Data Inc. Both these instruments are based on the same physical principles. These instruments are based on the modulation of electrical current due to changes in conductivity caused by the passage of particles through a small gate between two chambers. In applying the method, the suspension to be analyzed is made to pass through a small orifice. As each particle passes through the orifice it displaces its own volume of electrolyte and thereby changes the resistance across the orifice. This change in resistance is converted into a voltage pulse with an amplitude proportional to the particle volume. The voltage pulses are counted and converted to particle size with a calibration arrangement.

The main advantages of the electrical methods are the following:

1. The method is very rapid. That is, the complete particle size distribution in a suspension can be determined within a matter of seconds or minutes.
2. The method has a high resolution. The El Zone particle counter that is being used at Vetter Research has a resolution of about 0.2 microns.
3. The method covers a wide range of particle sizes. The El Zone particle counter is capable of measuring particles as small as 0.2 microns to as large as 600 microns.
4. The results obtained have a high degree of reproducibility.
5. In a limited manner, the El Zone particle counter can be adopted for in-line measurements. The limitations are the temperature, pressure and sample volume.
6. The electrical methods, in principle, can be used to obtain some qualitative information about particle shapes through the monitoring of shapes of voltage pulses generated by the system. Much further work is needed in this direction before any conclusions can be made regarding the measurement of particle shapes.
7. The electrical method is adoptable for further improvements. One of the immediate improvements that is contemplated at the present time is the adaptation of the system to compare particle distribution of a flowing suspension at different locations and times through use of a stationary main instrument within a geothermal operation. The main limitation for this method is the distance between the sampling points and the measuring station. The farther any station is located from the instrument the longer would be the sample lines. The other method would be to have a number of measuring cells with short sample lines. Each of these cells is connected to the microprocessor-based main station. Again, the distance between measuring cell and main

station could pose problems. Signal transmission through long cables could result in electrical noise problems which reduce the sensitivity of the instrumentation.

There are several disadvantages to the electrical method. They are as follows:

1. The electrical method is based on the assumption that the voltage pulse generated when the particle passes through the orifice is proportional to the particle volume. However, this linear relationship breaks down as the particles become non-spherical. The more non-spherical the particles, the greater the error in particle size measurement.
2. Coincidence errors due to multiple particles arise and correction for coincidence errors is possible only in dilute solutions. The coincidence errors are those errors which are caused by counting small multiple particles as a large single particle.
3. The particle size range that can be measured in a single measurement of a given suspension is narrow even though the overall capability of the instrument covers a wide range. The El Zone particle counter has a measurement capability range of 2% to 50% of the size of the orifice. That is for an orifice of 95 microns diameter, the sizes of particles that can be measured in a single measurement in a given suspension range only from 2 microns to 47 microns. However, this range can be increased through use of additional orifice sizes.
4. For the actual application in geothermal operations, small side streams of the samples have to be taken from the main flow and passed through an orifice. The immediate implications of this requirement are: (a) the side stream and the orifice disturb the original flow and may alter the particle size distribution; (b) the sample itself may not completely be representative of the original flowing system; (c) the change in the thermodynamic conditions may actually cause growth of particles to sizes larger than the orifice itself and plug the orifice; (d) the particles may break due to frailty upon passage through a small orifice.
5. As the particles grow in an aqueous system, the electrical resistivity of the fluid is changing constantly and it may result in calibration difficulties. However, this effect is considered minor for high TDS brines.
6. The orifice may be plugged by larger particles and thereby end the test rapidly.
7. Geothermal brines as those encountered in recent field testing in the Imperial Valley, California, are thermodynamically extremely unstable and can cause numerous measuring problems. Sodium chloride can precipitate during the measuring due to evaporation of water. Oxygen

from the air can penetrate the sample thus causing the precipitation of iron (III) hydroxide. These secondary precipitations do strongly interfere with the actual particle measurements in the field. These problems were circumvented at later stages of the field test work by adding small amounts of a diluted hydrazine solution to the sample. This work will be described in a future report on the subject.

8. The instrument requires a constant attention of trained operators. The instrument operation is not routine.

In spite of the several disadvantages and limitations, the El Zone particle counter has been chosen as one of the particle counting instruments for evaluation and use during the performance of the present work. The instrument is being used in all the laboratory experiments connected with the flow of particle suspensions through porous media. The instrument is also being utilized in some of the geothermal field experiments conducted by Vetter Research. Some of the results from these various tests will be described in detail in the next report on the subject.

7.2 METHODS BASED ON OPTICAL MEASUREMENTS

The optical methods of particle measurement utilize the interaction of light with particles [17-33]. There is much information that is available on the optical properties of particles from the work of Rayleigh, Debye, Mie, Van de Hulst, Kerker and Hodgkinson [17]. Almost all of the theoretical work is done on the interaction of light with particles using homogeneous spheres. The exception to this is the Rayleigh-Debye approximation which gives a semi-quantitative result for arbitrary shapes of particles. This approximation used in particle shape determination is based on two stringent requirements. They are as follows:

1. The refractive index difference between the particles and its surrounding medium is very small and
2. The total phase shift of a wave passing through particles is very small.

As we will outline below, these stringent requirements are not necessarily met in geothermal brines.

7.2.1 BASIC THEORY OF OPTICAL INTERACTION WITH PARTICLES

When a particle is illuminated by light, a certain amount of energy is removed from the incident beam by absorption and scattering. The sum of these two effects is called the extinction and is expressed by the extinction coefficient (E) which is the ratio of the absorbed and scattered light flux to the incident light flux. The extinction modifies one or more of the incident light parameters, namely the amplitude, the polarization and the phase. Four optical phenomena are involved here, namely the diffraction, reflection,

refraction and absorption. The contribution of the individual phenomena to the light-scattering varies with particle size, optical properties of the particle, optical properties of the medium, the scattering angle and the wavelength of the incident light.

Three regions of light interaction with particles can be distinguished, namely Rayleigh, Mie and the large particle region. These three regions are briefly described in the next sections.

7.2.1.1 RAYLEIGH REGION

Extremely small particles exhibit Rayleigh scattering. In this region, the scattered intensity is proportional to the square of the particle volume and is characterized by the two lobes formed symmetrically about 90° as shown in Figure 1.

7.2.1.2 RAYLEIGH - GANS REGION

As the particle size increases, the energy distribution changes so that the forward scattering lobe increases and the backward scattering lobe decreases as shown in Figure 2. The angular energy distribution depends only upon the particle size and not on the optical properties or shape.

7.2.1.3 MIE REGION

The Mie region is characterized by the formation of additional scattering lobes due to interference between the three scattering components, namely, the diffraction, the reflection and the refraction. In principle, the angular positions of the maxima and minima can be used to determine the particle size. However, the intensity of the scattered light is an extremely complicated function of the scattering angle, the refractive index and the size parameter.

7.2.1.4 LARGE PARTICLE REGION

In the large particle region, the scattering is dominated by the diffraction of light passing near their surface and most of the scattered energy is being directed forward. This region represents the most useful region from the point of view of particle measurement for geothermal application.

Four different types of measurements are generally made. They are as follows:

1. Forward scattering
2. Near-forward scattering
3. Right-angle scattering
4. Differential scattering

1. FORWARD SCATTERING

This type of instrument utilizes the forward lobe of the scattered light and it is well-suited to particles smaller than 5 microns diameter. In this region the scattered light intensity is not dependent upon the particle shape and the refractive index and absorption of the particles.

2. NEAR-FORWARD SCATTERING

This method takes advantage of the fact that the angular energy distribution of the scattered light for low scattering angles is a function of the particle size. However, the scattered light is dependent upon both the refractive index and the absorption of the particles. The effect of the refractive index can be eliminated by taking the ratio of the light intensity at two different angles. However, the effect of the light absorption by particles is still important.

3. RIGHT ANGLE SCATTERING

For right angle scattering, the difference in absorption among various particles is eliminated. However, at this angle of scattering, the shape and the refractive index of the particle become extremely important.

4. DIFFERENTIAL LIGHT SCATTERING

In general the main disadvantage of the optical methods based on light scattering by particles as mentioned above is that the intensity of scattered light is a function of several variables. This disadvantage can in principle be eliminated by measurement of scattered intensity as a function of scattering angle. Commercial instruments based on the measurement of scattered intensity as a function of angle from particle suspension are available.

7.2.2 DETAILS ON SPECIFIC COMMERCIAL INSTRUMENTS BASED ON OPTICAL METHODS

Three commercial instruments based on optical methods have been chosen as possible candidates for consideration in geothermal operations. These three commercial instruments are as follows:

1. DIFFERENTIAL I, which is manufactured by Science Spectrum, Inc.
2. PROTOTRON PARTICLE COUNTER, which is manufactured by Spectrex Corp.
3. MICROTRAC PARTICLE COUNTER, which is manufactured by Leeds and Northrup Corporation.

7.2.2.1 DIFFERENTIAL I

The Differential I is based on the measurement of the scattered light intensity from a particle suspension as a function of the angle of scattering. This scattered light intensity pattern as a function of angle (also called the differential scattered light intensities) contains a wealth of information about a particle suspension. The differential light pattern, in principle, can be converted to a determination of the particle size, shape, structure and particle size distribution of the suspension. However, Differential I cannot be readily adopted for actual application in geothermal operations without considerable R&D work on its use. It should be mentioned, however, that this method can offer a potentially powerful technique if a considerable amount of research and development on the design of in-line operations and on the interpretation of the differential scattering intensity is made.

The quantitative interpretation of the differential light scattering pattern is highly complex and there is no unique way of obtaining the exact information on the characteristics of the suspension from the complex pattern. The complexity of the differential light scattering becomes even more severe when polysized particles are present in the suspension. This is illustrated in Figure 3 where the differential scattering pattern of polysized particles are shown for various particle size distributions.

The differential scattering pattern is a function of the particle size, refractive indices, the state of polarization of the incident light, wavelength of the incident light and particle shape. The work by Wyatt [24] shows that all these parameters are important in the interpretation of the differential scattering intensity.

As seen from the figure, the major effect associated with the presence of a distribution of sizes is the smoothing out of the scattering pattern that would be associated with particles of identical sizes. This complication would increase further if multi-particle agglomerations are present. At least theoretically, different particle size distributions can give the same differential scattering patterns. In other words, a particular differential scattering pattern could be interpreted by more than one different distinct particle size distributions.

From the above discussion, it becomes obvious that the differential scattering method of Differential I may not offer a unique method useful for geothermal applications at the present time. However, a considerable R & D effort on the instrumentation and interpretation techniques can open new possibilities for this instrumentation in the future. Differential I is not being used in our present research effort on geothermal injection problems and solutions.

7.2.2.2 PROTOTRON PARTICLE COUNTER

The Prototron Particle Counter is based on the analysis of the near scattered light of a scanning laser beam scattered by a particle suspension. The instrument uses a one milliwatt helium-neon laser. The beam from the laser is spatially filtered and focused to form a small but well defined illuminated volume within the liquid to be inspected. The laser beam is rotated so that the illuminated region rotates in a circle at a constant speed. As this

scanning laser beam moves across the particle suspension, some light from the beam will be scattered by the particle suspension. The scattered beam is collected by a secondary lens system and the collected light intensity is measured by a photodetector. The direct beam is absorbed by an absorbent target at the center of the secondary lens. Since the intensity of the scattered beam is proportional to the square of the particle radius for large particles, the pulse height of the scattered light is proportional to the particle size. In the Prototron particle counting system, the photodetector is electronically controlled to reject pulses of certain height and smaller. That is, a threshold setting on the electronics enables one to detect the particles larger than a certain size. By changing this threshold setting, a quasi particle size distribution curve can be generated. The use of a microprocessor in conjunction with the Prototron Particle Counter enables one to determine the distribution curve automatically.

The Prototron Particle Counter is an independent particle counting system. This instrument can be adopted to in-line monitoring for particles in the range of 1 to 100 micron in geothermal fluids of relatively low concentration. This instrument has been used in some of the geothermal operations by other investigators (Battelle PNL). In the execution of the present work, this instrument will not be evaluated in the field, as the basic principle behind this instrument and the Microtrac are very similar.

7.2.2.3 MICROTRAC PARTICLE COUNTER

The Microtrac Particle Counter works on the principle of low-angle forward light scattering. Small particles in the path of the incident light beam scatter the light in a definite way. The intensity of the light scattered by particles is directly related to their size. The size of the scattered lobe, however, is inversely related to particle size. The detecting system uses a rotating optical filter with 13 windows at different radial distances from its center. The light intensity passing through each of these windows is measured by a photodetector. Each window receives light from a certain size range of particles and the intensity of light passing through a certain window gives the relative number of particles of that size range.

The principles of operation of the Microtrac Particle Counter and the Prototron Particle Counter are very similar. The details in obtaining the particle size distribution in these two methods are quite different. The Microtrac Particle Counter is being used in the laboratory studies and will be used in future field operations as part of the geothermal injection studies. The main advantages of this system are as follows:

1. It gives the particle size distribution accurately and rapidly without elaborate interpretation problems as in the case of Differential I.
2. Because of the low angle scattering region chosen, the scattered light intensity is independent of the optical properties of the scattering particles.
3. The operation of the instrument is simple and does not require

elaborate training.

4. In a limited manner, the instrument is easily adaptable to in-line measurement with a limited amount of development work.

The Mirotrac has a built-in facility to perform in-line measurement of particle size distribution. However, it cannot handle the observation through large pipes. A side stream has to be taken through a 1/2" pipe from the main pipe systems. Such a set-up is being designed for the purpose of monitoring the reinjection brine for a future field operation.

7.3 METHOD BASED ON THE SCATTERING OF ULTRASONIC WAVES

The instruments based on ultrasonic waves have not been considered originally under this contract for the purpose of measuring particle size distribution in liquid suspensions. However, recently it was felt that the instruments based on the scattering of ultrasonic waves by particles may offer a possible monitoring device for particles without disturbing the flowing geothermal fluids. This would offer a great advantage over other particle measuring devices. For this purpose the Micropure Submicron Particle Detection System manufactured by Micropure Systems, Inc., was selected to be tested under actual geothermal field conditions on a trial basis.

The Micropure Particle Detection System is based on the Rayleigh scattering of waves by small particles having sizes smaller than the acoustic wavelength. The theory of operation of this particle system is similar to the optical wave scattering described in the previous section.

The operation of the Micropure system consists of sending a focussed ultrasonic pulse through the steel walls into the flowing fluid and detecting the scattered pulses to determine the characteristics of these pulses. The characteristics of the scattered pulses, in principle, carry information about the nature, size and concentration of the particles in the system. The main disadvantage of this system is that the signal characteristics of the scattered pulses cannot easily be resolved if (a) the particle system contains many particles or (b) many layers of scale exist inside the pipe.

The first attempt to use this instrument for measuring particle characteristics through the pipe walls failed for a number of reasons:

1. The probe made by Micropure for field experiments in a 10" pipe was not properly mounted. The plastic mount used by Micropure for this probe failed above 250°F.
2. Too many particles were found in the lower temperature system (below 250°F), thus preventing us from obtaining a useable resolution of the scattered pulses.
3. Pulse reflections from the scale layers inside the pipe caused further confusion regarding the evaluation of the signals from the

scattered pulses.

We still think that this method offers the best chances for measuring and monitoring suspended particles in geothermal systems. Presently, we are planning to construct three more probes to further evaluate this system in the field.

8.0 FUTURE PLAN TO COMPLETE THE PRESENT TASK

As described in the earlier sections, two major particle measuring systems are being used as an aid in the execution of the present task. In addition, various probes for ultrasonic scattering devices are being designed. The complete work plan of this task is described in this section.

Following is a list of the laboratory and field experiments to be performed as part of the present task:

1. Flow tests to determine the damage caused by suspended particles to the porous media
2. Study of the growth of particles in unstable brines
3. Studying of the effectiveness of flocculants.

The work plan on each of these substances is described below.

8.1 FLOW EXPERIMENTS WITH PARTICLES

The objective of this set of experiments is to study the flow of "non-reactive" particle suspensions through various porous media and to obtain the criteria for brine injection in geothermal operations from a suspended-particle viewpoint. Three types of particles are being utilized for this purpose:

1. "Spherically symmetric" particles of various size distributions in the range of 0.05 to 100 micron are one of the choices. For this purpose particles of glass spheres, cerium oxide and chromium oxide are being utilized. The glass spheres are chosen for their availability in well characterized size distributions. The cerium oxide and chromium oxide particles are chosen because of the ease in locating them in core samples that are used in flow tests with such particles. It has been found that particles contain elements having atomic weights larger than silicon (the major elemental constituent of the Berea cores being used) can be easily recognized by use of back scattered electrons in the scanning electron microscope (SEM). This direct observation of the plugged cores will be extremely useful in ascertaining the plugging mechanism of cores by particle invasion.

Preliminary core plugging tests using this method gave very encouraging results. The cores have been plugged with particles and, then, were broken and examined under the SEM using an electron back-scattering mode. Such micrographs will allow us to obtain some basic information about the plugging mechanism in porous media.

2. Needle shaped particles having "equivalent" size distribution of some of the above distributions will also be utilized in the flow experiments. At the present, it is planned to use particles containing the pyroxene and amphibol group of minerals. These minerals are chosen as they are known to form needle shaped particles upon grinding. A considerable effort will have to be made to obtain particles of appropriate distributions. This work is presently in progress.
3. In addition, randomly shaped particles of germanium oxide will also be used in the final stages of the laboratory experiments. The germanium oxide particles are chosen as part of the study to simulate the invasion of silica particles in porous medium. The back scattering technique mentioned earlier is also useful in locating the germanium oxide particles in the silica background of the porous cores using SEM techniques.

Berea core samples of three different permeabilities (a range of 10 millidarcies to 500 millidarcies) are being utilized in all the flow tests. The flow tests using a combination of the three sets of cores and the above particle systems should give sufficient information to arrive at specific mechanisms for plugging of porous medium by particle invasion.

The particle suspensions are being prepared with a given size distribution in "particle free" deionized water. The uniformity of the suspension will be maintained through a constant stirring of the suspension by means of a magnetic stirrer. The particle suspension is pumped from the particle suspension system through the Berea core samples by means of a floating piston. The floating piston is moved at a constant velocity by pumping deionized water at a constant rate by means of an HPLC pump. The pressure is being monitored constantly at the input end of the core sample. Also, the differential pressure across the cores are monitored to allow Darcy's law calculations related to the core plugging by particles.

The particle size distribution of the suspension entering and leaving the Berea cores is being measured by means of particle counter. Initially, samples are collected manually at regular intervals. At the end of each test, the cross-sections of core samples broken out of the entire core are examined by SEM to investigate the plugging mechanism of the particles.

All the experiments in this category are to be conducted at room temperature. The ultimate aim of this set of experiments is to develop criteria for injection in terms of the physical characteristics of the particles and the porous media. The temperature of the core under flowing conditions is irrelevant for these experiments as long as the temperature remains constant.

8.2 STUDY OF THE PARTICLE GROWTH IN THERMODYNAMICALLY UNSTABLE BRINES

The final objective for all particle characteristics are the measurements and determinations in the field. Laboratory measurements are required only (a) to establish the methodology for field measurements and (b) to characterize the particles used in the laboratory study. The basic difference between field and laboratory measurements must be seen in the stability and accessibility of the particles as mentioned in a previous section of this report (see Section 5.1.1).

These field measurements cannot be replaced or duplicated by laboratory measurements. There seems to be no feasible way to generate the same particles formed in simulating laboratory experiments. Therefore, actual field measurements of particle characteristics are vital for this present study.

A number of various field measurements have been performed during recent well testing in the Imperial Valley. The results obtained so far are too sparse to allow us a complete evaluation of these particle measurements. It is planned to continue the measurements of the particle characteristics in the field using various measuring devices and techniques.

Presently, the following field experiments are planned for the near future:

1. Attempt to measure various types of particles with the El Zone instrument at MCR's Mercer 2 site.
2. Simultaneously with the above measurements, use the Microtrac instrument for similar measurements.
3. At the same time, attempts will be made to use two different prototypes of ultrasonic scattering probes manufactured for Vetter Research by Micropure.
4. Concurrently with all of the above measurements, we will also perform constant pressure filtration experiments. This technique is believed to allow life time predictions for injection wells [1].

After performing the above field experiments, we will attempt to correlate the data from all four types of measurements. The actual field measurements should be completed by the end of January 1981. The evaluation of these experiments will be included in a report to be issued in March 1981.

8.3 STUDY OF FLOCCULANT EFFECTIVENESS IN GEOTHERMAL OPERATIONS

Flocculants may turn out to be of extreme importance for geothermal operations. Suspended solids may be flocced with the aid of chemical, thus decreasing effectively required time and required investment cost for solid removal processes and equipment. The determination of the effectiveness of

various types of flocculants poses a severe problem unless the particle removal process can be monitored in a technically and economically feasible way. This required monitoring of the pertinent particle properties during flocculation is an important part of the present study.

Screening of numerous flocculants for geothermal applications must be done in the field utilizing proper particle characterization methods. As part of the present contract, some detailed study of the removal of suspended solids through flocculants is planned to be undertaken in our ongoing geothermal well test program.

Various flocculants will be added to the geothermal brines and their effects on the particle characteristics will be determined. Without proper particle measuring or monitoring devices, this task cannot be completed. Laboratory experiments to study flocculating processes do not seem to be feasible for reasons outlined in this report (see problems related to simulating geothermal brine properties, Section 5.1.1). Preliminary field experiments using a number of flocculants showed gross effects which are very encouraging. These preliminary results warrant a further and more detailed study of this flocculation process using proper particle measuring devices.

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TABLE 1

PARTICLE CHARACTERISTICS IN
AQUEOUS SUSPENSION

- 1) PROPERTIES OF THE PARTICLE MATERIAL
 - a) Chemical Composition of the Particle
 - b) Density of the Particle Material
- 2) PRIMARY PARTICLE PROPERTIES
 - a) Particle Size Parameters
 - b) Particle Shape Parameters
 - c) Particle Size Distribution
 - d) Particle Concentration
- 3) SECONDARY PARTICLE PROPERTIES
 - a) Optical Properties
 - b) Electrical Properties
 - c) Surface Properties

TABLE 2

DEFINITIONS OF PARTICLE SIZE

<u>NAME</u>	<u>SYMBOL</u>	<u>DEFINITION</u>
<u>1. Equivalent Sphere Diameter</u>		
a. Volume Diameter	d_v	Diameter of a sphere having the same volume as the particle.
b. Surface Diameter	d_s	Diameter of a sphere having the same surface as the particle.
c. Surface to Volume Diameter	d_{sv}	Diameter of a sphere having the same external surface to volume ratio as a sphere.
d. Drag Diameter	d_d	Diameter of a sphere having the same resistance to motion as the particle in a fluid of the same viscosity and the same velocity.
e. Free-Falling Diameter	d_f	Diameter of a sphere having the same density and the same free-falling speed as the particle in a fluid of the same density and viscosity.
f. Stoke's Diameter	d_{st}	The free-falling diameter of a particle in the laminar flow region ($Re \leq 0.2$). Here Re represents the Reynold's number.
g. Sieve Diameter	d_{si}	The width of the minimum square aperture through which the particle will pass.
<u>2. Equivalent Circle Diameters</u>		
h. Projected Area Diameter	d_a	Diameter of a circle having the same area as the projected area of the particle resting in a stable position.
i. Projected Area Diameter	d_p	Diameter of a circle having the same area as the projected area of the particle in random orientation.

j. Perimeter Diameter

d_c

Diameter of a circle having the same perimeter as the projected outline of the particle.

3. Statistical Diameter

k. Feret's Diameter

d_F

The mean value of the distance between pairs of parallel tangents to the projected outline of the particle.

l. Martin's Diameter

d_M

The mean chord length of the projected outline of the particle.

m. Shear Diameter

d_{sh}

Particle width obtained with an image shearing eyepiece.

n. Maximum Chord
Diameter

d_{ch}

Maximum length of a line limited by the contour of the particle.

TABLE 3

PARTICLE DISTRIBUTION FUNCTIONS

<u>DISTRIBUTION</u>	<u>FUNCTIONAL FORM</u>	<u>COMMENTS</u>
1. NORMAL DISTRIBUTION	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp -(x-x_a)^2/2 \sigma^2$	Rarely fits the actual distribution
2. LOG-NORMAL DISTRIBUTION	$f(x) = \frac{1}{\ln\sigma_g \sqrt{2\pi}} \exp-(\ln x - \ln x_a)^2/2\ln^2 \sigma_g$	Commonly used in particle size work
3. ROSIN-RAMMLER DISTRIBUTION	$F(x) = \exp -(x/x_R)^n$	Widely used in particle size work
4. HARRIS'S THREE PARAMETER DISTRIBUTION	$F(x) = 1-(x/x_0)^s$	Very versatile distribution function

NOMENCLATURE

- $f(x)$ = The particle size distribution function, which represents the frequency of occurrence of particles having a size of units.
- x_g = Arithmetic mean size.
- σ = Standard deviation of the particle sizes.
- x_g = Geometric mean size.
- σ_g = Geometric deviation factor, which by convention is defined as the ratio of the size at 84% frequency of occurrence to the size at 50% frequency of occurrence.
- $F(x)$ = Cumulative fraction over size, .
- x_R = A constant, which is a measure of the particle size range.
- n = A constant characteristic of the particle material.
- x_0 = The maximum size of the particles.
- s = An empirical constant characterizing the given particles.

TABLE 4

QUALITATIVE DEFINITION OF PARTICLE SHAPE

<u>NAME</u>	<u>DESCRIPTION</u>
Acicular	Needle-shaped
Angular	Sharp-edged or having roughly polyhedral shape
Crystalline	Freely developed in a fluid medium of geometrical shape
Dendrite	Having a branched crystalline shape
Fibrous	Regularly or irregularly thread-like
Flakey	Plate-like
Granular	Having approximately an equidimensional irregular shape
Irregular	Lacking any symmetry
Modular	Having rounded, irregular shape
Spherical	Global shape

TABLE 5

METHODS OF MEASURING PARTICLES IN-LINE IN
VARIOUS PARTICLE SYSTEMS

1. SOLID PARTICLES IN GAS

- a. Light Scattering
- b. Light Obscuration
- c. Acoustic Interference
- d. Pressure Drop in a Nozzle
- e. Impact and Momentum Measurement
- f. Electrostatic Capture
- g. Magnetic Flux Variation Measurement

2. SOLID PARTICLES IN LIQUIDS

- a. Electrical Resistance Change
- b. Light Scattering
- c. Light Obscuration
- d. X-Ray Absorption
- e. Beta Ray Attenuation
- f. Ultrasonic Attenuation
- g. Ultrasonic Scattering

TABLE 6

COMMERCIAL INSTRUMENTS FOR PARTICLE SIZE
ANALYSIS IN SUSPENSIONS

<u>METHOD</u>	<u>SIZE RANGE</u> (MICRONS)	<u>MANUFACTURER</u>
1. SIEVING	37-1000	1. LA Pine Scientific Co., Chicago, ILL. 2. Albert & Co. D6580 Ibar-Oberstein 1 West Germany
2. SEDIMENTATION (GRAVITY)	2-100	1. Pola Laboratory Supplies, Inc. New York, NY 2. Micromeretics Instrument Corp. 800 Goshen Springs Road Norcroft, GA. 3. Saratorius Werke GMBH, D-34 Gottingen West Germany
3. SEDIMENTATION	0.01-10	1. Mines Safety Appliances Co. 201 Braddock Avenue Pittsburgh, PA.
4. ELUTRIATION	5-100	1. Griffin & George Ltd. Wembley, Middlesex
5. MICROSCOPY	0.8-150	1. IMANCO 40 Robert Pitt Drive Monsey, NY. 2. Millipore Corp. Ashby Road Bedford, MA.
6. ELECTRICAL RESISTANCE	0.2-500	1. Coulter Electronics 590 West 20th Street Hialeah, FL. 2. Particle Data, Inc. 111 Hahn Street Elmhurst, ILL.

7. LIGHT OBSCURATION	2-100	1. Hiac 141 Spring Street Claremont, CA.
8. LIGHT EXTINCTION/ SCATTERING	2-100	1. Procedyne Corp. 221 Somerset Street New Brunswick, NJ.
9. LIGHT EXTINCTION/ TOTAL SCATTERER	5-400	1. Royco Instruments Co. 141 Jefferson Menlo Park, CA.
10. NEAR FORWARD SCATTERING	2-200	1. Leeds & Northrup Co. 6950 Bryan Dairy Road Largo, FL. 2. Spectrex Corp. 3594 Haven Avenue Redwood City, CA.
11. DIFFERENTIAL SCATTERING	0.3-400	1. Science Spectrum Inc. 1216 State Street P.O. Box 3003 Santa Barbara, CA.
12. ULTRASONIC SCATTERING	0.3-100	1. Micropure Inc. P.O. Box 914 Providence, RI.

FIGURE 1

POLAR LIGHT- SCATTERING DIAGRAM FOR THE RAYLEIGH REGION

FIGURE 2

POLAR LIGHT - SCATTERING DIAGRAM FOR RAYLEIGH-GANS REGION

FIGURE 3

EFFECT OF PARTICLE SIZE DISTRIBUTION ON THE DIFFERENTIAL SCATTERING PATTERN