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**GEOHERMAL FRACTURE STIMULATION
TECHNOLOGY**

Volume 4. Proppant Analysis at Geothermal
Conditions

By
Maurer Engineering

January 1981

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Republic Geothermal, Inc.
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VOLUME IV
PROPPANT ANALYSIS AT GEOHERMAL CONDITIONS
January 1981

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GEOHERMAL RESERVOIR WELL STIMULATION PROGRAM

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I. SUMMARY AND CONCLUSIONS

Crushing and degradation mechanisms of proppants are examined in this report to characterize proppants and assess their usability in geothermal wells. Short-term tests can tell the physical strength of a proppant, but long-term tests are required to ascertain any interrelated chemical effects. Degradation of proppants is measured as a loss in permeability and can be correlated to temperature, time, and closure stress.

Sand is a common proppant which is strongly affected by higher temperature and closure stress. Even at low stress levels, sand degrades in brine or hot water with long-term exposure. Most geothermal waters and their pH levels can also be detrimental to sand.

There are some proppants with desirable properties at geothermal conditions. These are resistant to the crushing loads or closure stress in geothermal wells and will not react or dissolve in high temperature brines. While there are limits to these proppants, which are covered in this report, an unqualified list of possible geothermal proppants is listed below:

- Aluminum Oxide
- Garnet
- Resin-coated Proppants
- Sintered Bauxite

II. INTRODUCTION

Proppants need to be thoroughly analyzed as to their possible use in geothermal stimulation activities. They have a long and varied history in oil and gas technology, but they have only been subjected to much lower temperatures. Proppants tested for geothermal use include all currently used proppants and any new materials that might have potential for either high temperature or high closure stress.

The purpose of this study is to define the limits of the various proppants and present viable proppants that can retain fracture conductivity at the extremely high downhole temperatures.

In Volume I¹ of this series (prepared for the Geothermal Reservoir Well Stimulation Program), the use and testing of proppants in oil and gas wells is reported which, in general, is for low temperature operations. The few higher temperature tests that are reported show that glass beads (in brine) are extremely temperature sensitive, and in fact, unstable at downhole conditions. This fact alone raises suspicion that sand and other proppants may not withstand the higher temperatures of the hydrothermal, geothermal wells.

In Volume II² of the same series, a specially built proppant tester, built by MEI, is described and used to test proppants at downhole conditions comparable to geothermal conditions. Available proppants are tested and reported at the higher geothermal temperatures. Temperature effects on sand are quantified for the first time; however, Volume II tests are physical in nature and neglect possible time effects that might be caused by chemical interactions of the fluids and proppants. All tests reported in Volume II last less than 4 hours and are defined as short-term tests.

Volume III³ reports on the high temperature effects on fracturing fluids while this report, Volume IV, starts where Volume II leaves off and reports on the result of longer term testing on proppants. Here, the breakdown mechanisms of proppants are quantified and examined after exposure to high temperature and closure stress for long-term periods. Test times are varied from 4 hours to 30 days and, if high temperature proppant degradation in brine does occur, it is generally measured after 50-hour exposures at downhole conditions. For the purposes of this report, the standard "long-term test" is defined as a 50-hour test.

III. PROPPANT ANALYSIS

To evaluate proppants, they must be exposed and kept at downhole conditions long enough for degradation to take place. In the lab this is difficult since the practical time scale for examination and the limits of our test systems are measured in days. The weak points of most high temperature test systems are the elastomer seals, and these can fail unpredictably after a few days. Some of the long-term chemical effects may require weeks, months, or years. However, dynamic geothermal well effects are stimulated very well in the triaxial loaded test cell that can continually be monitored to measure permeability as a function of time. While some of the long-term chemical effects cannot be measured, the combination effects of closure stress, proppant cracking and silica dissolution can be modeled.

There are many tests that can be performed on proppants, but one of the best is to measure the dynamic permeability of the proppant as it changes with increasing temperature and closure stress. Using an actual field brine or frac fluid, a permeability is measured essentially at downhole conditions and any change of permeability indicates particle failure, crushing, or movement of fines. Other tests include visual and scanning electron photomicrographs of the test samples to see how proppants break apart and why. The type of proppant fracture and failure is examined from fragments and the area of fracture initiation on the proppant is measured and quantified. Sieve analysis is performed on the broken or crushed proppants to find the relative amount of crushed material. Also, detailed grain strength measurements of individual particles are made to understand the onset of crushing. Combined effects of the hot brine and high closure stresses are looked at on sand and silica surfaces from the standpoint of silica solubility (or dissolution) as a function of temperature and exposed surface area.

Combined effects need to be assessed because of the different structures and properties of the available proppants for geothermal use. A good understanding of all these mechanisms should allow us to choose an optimum proppant based on the exact environment of the particular geothermal field.

IV. PROPPANT DEGRADATION

A. Long-Term Proppant Tests

In the MEI proppant tester, shown in the Appendix, long-term permeability measurements (50-hour tests) are taken with a linear flow cell that approximates downhole temperature and closure stress. The temperature range of the tests is from 350 to 500°F (177 to 260°C) where closure stress is varied from 2,500 to 10,000 psi. In general, proppants are classed either as reactive (thermal or chemical degrading) or as nonreactive. Almost all of the reactive proppants are unsuitable as geothermal proppants mainly because of the high temperature or usual pH conditions of the brine. Some of the nonreactive proppants will degrade at higher closure stresses (brittle degradation) but will not react or degrade when exposed to a high temperature brine. Table 1 lists most of the available reactive and nonreactive proppants with subclasses of degrading and nondegrading proppants.

TABLE 1.
REACTIVE & NONREACTIVE PROPPANTS

Reactive	Nonreactive	
Thermal or Chemical Degradation	Brittle Degradation	Nondegrading
<ul style="list-style-type: none">• Sand• Glass Beads• Walnut Hulls• Steel• Aluminum• Plastic Pellets• Fiberglass Reinforced Nylon	<ul style="list-style-type: none">• Hematite• Garnet	<ul style="list-style-type: none">• Aluminum Oxide• Corundum• Resin-coated Particles• Sintered Bauxite

The proppants that are not reactive and do not degrade under normal geothermal conditions are the best choices for geothermal proppants; however, under certain circumstances a proppant, like garnet, may be suitable if closure stress remains low. At extremely low geothermal temperature and stress, sand may be used in special circumstances.

In the first series of tests, the resin-coated proppants, sintered bauxite, and Ottawa and Brady sand were compared at 350°F (177°C). The closure stress was held constant at 5,000 psi for the 50-hour tests. While the resin-coated particles and sintered bauxite were not affected, both types of sand continued to degrade during the test period. Longer term tests were then attempted with sand but model plugging became a problem. Upon completion of the 50-hour tests, an examination of the remaining particles showed no change with the resin-coated material or sintered bauxite, but both sands contained over 30 percent fines and were obviously not suitable as proppants. Figure 1 shows these results, where dynamic permeability loss with time indicates crushing, degradation, or movement of fines.

Figure 2 shows permeability retention at a lower closure stress of 2,500 psi but at a higher temperature of 500°F (260°C). In Figure 2, of the two main frac sands, Ottawa and Brady sand, only Ottawa sand was tested since it was felt that combined effects of high temperature and brine would affect most sands similarly. Also reported are the resin-coated particles, sintered bauxite, and a 50/50 mixture of the resin-coated sand and sintered bauxite. The sand again degrades, but not quite as severely as the Ottawa sand at the higher closure stress of 5,000 psi and 500°F. Our conclusions here are that the chemical interactions or silica dissolution in a 50-hour test are very strongly dependent on the amount of exposed area of the sand. With higher closure stress, there is more crushing and microcracks formed by the applied physical stress. In the case of the higher closure stress tests, surface area and the number of microcracks are orders of

magnitude greater than at the lower closure stress. With this complex of cracks and fractures in each grain and a high physical load on the remaining grains, progressive degradation and failure cause a steady loss of permeability while the proppant and the crushed pieces are contained within the triaxially loaded test cell at geothermal conditions.

Figure 1. Permeability Retention Under Closure Stress

Figure 2. Permeability Retention Under Closure Stress

B. Photomicrographs

Some of the effects of high temperature and high closure stress on proppants are clearly illustrated in the photomicrographs taken before and after testing at in situ geothermal conditions. The Ottawa and Brady sands are seen in Figures 3 and 4, respectively. The upper pictures show and characterize them as rounded pieces of almost pure crystalline quartz (SiO_2) in the untested state, but after testing (lower pictures) over 30 percent of the original sand has been powdered into fines. Most of the fracture-conductivity is permanently lost. If used in a fracturing treatment, damaged fracture conductivity may result.

Figure 5 shows a photomicrograph of glass beads before and after testing. In the upper picture, glass beads can be seen as perfect spheres. They are usually amorphous in structure and have a high solubility in elevated temperature brines. For this reason they are extremely sensitive to high temperature brines and fail catastrophically under closure stress and temperature (see lower photo in Figure 5).

Figure 6 shows sintered bauxite¹¹ before and after testing. These round particles are made by sintering many small pieces together. Essentially the bauxite is aluminum oxide with small quantities of other minerals. It is a very hard particle commonly used as an abrasive. While some particles crack (see lower photo in Figure 6), the percentage of broken pieces is small at 10,000 psi closure stress. Compared to sand or glass beads, the broken fragments are many times larger. The main attractiveness of sintered bauxite for geothermal wells is its nonreactivity in high temperature brine; however, its main drawback is its high cost.

Before

After

Figure 3. Ottawa Sand

Before

After

Figure 4. Brady Sand

Before

After

Figure 5. Glass Beads

Before

After

Figure 6. Sintered Bauxite

Figure 7 shows a resin-coated sand before and after testing. This material retains some of the advantages of sand without the drawbacks. A thin uncured resin-coating is put onto Ottawa sand (upper photo of Figure 7). These particles are injected into the created fracture of the geothermal well. The high temperature causes the phenolic formaldehyde resin to "thermoset." When this occurs in the fracture, a cohesive permeable sandstone (coated by resin) is formed in place (lower photo of Figure 7). After curing, the resin coating becomes "Bakelite" and is inert in geothermal fluids to well over 600°F. An additional benefit of a composite material is that it is not crushed under high closure stress. The resin forms cushion-like pads between every sand grain and prevents cracking. At extreme closure stress not found in geothermal wells, some of the resin-coated sand can crack, but because of the bonding between the resin coating and the sand grain, no small mobile fines are found and large fragments remain in position.

Before

After

Figure 7. Resin-coated Sand

C. Scanning Electron Micrographs

More technical details and some of the effects of degradation can be seen by the scanning electron microscope.* These micrographs can begin to quantify the breakdown loads and effects on the various proppants. The contact areas between grains can be clearly seen in Figure 8; and with the loads concentrated at these points, this is where degradation starts. Glass beads, because of their almost perfect roundness, have minimum contact areas. When they reach their strength limit, the beads begin to fail (or "pop"), and as the load is transferred to other whole beads, they also fail in a progressive manner. The particle sizes after failure are very small and these particles are generally called fines.

Figure 8. Contact Areas on Proppants

*Scanning Electron Microscope pictures were taken by John Sparrow of Vetter Research on test samples furnished by Maurer Engineering.

Sand has slightly larger contact areas because of many flat spots on the rounded material. Failure is instigated at the small contact areas of brittle materials, but it is less spontaneous or as progressive as the glass beads. Figures 9 and 10 show several views of the contact area in cross section and a more highly magnified view of the countless number of cracks radiating away from the initial contact point. Where large chunks of SiO_2 have broken off, smooth planes similar to "flint marks" are easily seen. Sand fractures are sometimes classified as "conchoidal fractures." The immense amount of fresh SiO_2 surface exposed by these cracks helps to accelerate any chemical attack or dissolution of the sand which the physical crushing has started. It appears that both stress and dissolution contribute to proppant degradation as long as unsaturated fluid is available to dissolve some of the cracked silica surfaces and to sharpen the tiny cracks.

With sintered bauxite the contact areas are slightly larger because of slight surface deformation. Figure 11 shows the small particles that make up the sintered bauxite, and Figure 12 shows some of the broken pieces. Breakage seems to start near previously unreported blisters on the bauxite and also on some of the bauxite material that is hollow (see Figure 12e). Broken pieces are few in number and, in general, fairly large ($>1/10$ original diameter).

Figure 13 shows the resin-coated sand in a cohesive mass. Where it could be found, failure mechanisms started with a crack in the resin cushion between grains. Figure 14 shows the fully cured resin-coated material with a perfect pendular ring or plastic pad between grains. The interesting aspect here is the diameter of the relatively large contact area between grains ($\sim 40\%$ of grain diameter). This accounts for this material's high strength. When a cracked grain is found, it is usually being held in place by the resin, and because of the good coupling of the resin to the sand surface, cracked pieces are quite large.

Figure 9. Brittle Failure of Sand

Figure 10a.

Figure 10b.

Figure 10. Sand Particle Failure

Figure 10c.

Figure 10d.

Figure 10 (Continued). Sand Particle Failure

Figure 11. Sintered Bauxite Particles

Figure 12a.

Figure 12b.

Figure 12. Sintered Bauxite Degradation

Figure 12c.

Figure 12d.

Figure 12 (continued). Sintered Bauxite Degradation

Figure 12e.

Figure 12f.

Figure 12 (continued). Sintered Bauxite Degradation

Figure 13a.

Figure 13b.

Figure 13. Failure Mechanisms of Resin-coated Sand

Figure 13c.

Figure 13 (continued). Failure Mechanisms of Resin-coated Sand

Figure 14. Large Contact Areas on Resin-coated Materials

D. Crushing and Physical Tests

The strength of a proppant and the retention of its strength at geothermal conditions is important. For this reason tests on many proppants were carried out by using a measured crush load on one particle divided by the proppant diameter squared (L/D^2). A system to do this at elevated temperatures in oil was built earlier in the GRWSP program; however, it was found that the proppants degraded much more severely and realistically in brine than oil. Since this was an open system, hot brine would flash to steam or be turned into steam at any realistic temperature. If it is possible in the future to enclose the single grain tester inside a pressure chamber, more realistic physical tests will be made. Table 2 gives the room temperature values of the physical strengths of most of the proppants. While most proppants would degrade at the higher temperatures (i.e., sand and glass beads), the bauxite particles are not affected and the resin-coated materials become stronger and more resilient to crushing because their coating becomes more pliable and spreads the crushing load to a larger area on each grain.

TABLE 2.
APPROXIMATE PHYSICAL STRENGTH OF A SINGLE GRAIN

<u>Proppant Type</u>	<u>L/D^2(psi)</u>	<u>Conditions</u>
Ottawa Sand	14,000	All tests in air at room temperature
Resin-coated Sand--uncured, i.e., Super Sand	20,000	"
Resin-coated Sand--cured, i.e., Super Sand	28,800	"
Glass Beads 56,000	"	"
Resin-coated Glass Beads--uncured, i.e., Super Beads	62,000	"
Resin-coated Glass Beads--cured, i.e., Super Beads	64,800	"
Sintered Bauxite	21,000	"
Resin-coated Bauxite--uncured, i.e., Super Bauxite	60,000	"

One other test, the API standard crush test,⁴ tests 40 grams or more proppant at various closure stresses. A close fitting piston is lowered into a steel cup, and closure stress and/or temperature can be applied. The material is screened before and after each test and the fines are carefully weighed. If the fines content exceed 8% at any test condition, the proppant is considered to be degrading or crushing and is not recommended for hydraulic fracturing. Even though these tests are run at ambient conditions, we can see that the percent fines is a very good indication of the condition of the proppant. Figure 15 shows that resin-coated sand and sintered bauxite are crush resistant out to very high closure stress much above the generally reported stresses in geothermal wells. Figure 16 shows the percent of uncrushed material for sand and resin-coated sand. Table 3 compares the percent of fines created at varied closure stress for sand, glass beads, resin-coated proppants, and sintered bauxite.

Figure 15. Crushing of Proppants in API Crush Cell, Test 1

CRUSHING OF PROPPANTS IN API CRUSH CELL

- Sample Size = 125 Grams
- Performed at Room Temperature

Figure 16. Crushing of Proppants in API Crush Cell, Test 2

TABLE NO. 3

API FRAC SAND CRUSH RESISTANCE TEST

PROPPANT TYPE	STRESS (PSI)	% FINES	CONDITIONS
20/40 Ottawa	3,000	2.48	125 gram sample, dry @ room temp.
	5,000	6.40	"
	7,000	15.13	"
	10,000	34.08	"
	12,000	35.64	"
40/60 Ottawa	3,000	1.44	"
	5,000	4.08	"
	7,000	8.68	"
	10,000	23.56	"
20/40 Resin-Coated Sand uncured, i.e., Super Sand	3,000	0.80	"
	5,000	1.60	
	7,000	5.64	
	10,000	11.20	
	12,000	12.24	
20/40 Resin-Coated Sand cured, i.e., Super Sand	7,000	0.64	"
	10,000	4.80	
	12,000	6.80	
20/40 Glass Beads	3,000	0.60	"
	5,000	0.72	
	7,000	3.20	
	10,000	22.12	
20/40 Resin-Coated Glass Beads - uncured, i.e., Super Beads	5,000	0.56	
	7,000	1.00	
	10,000	5.92	
20/40 Sintered Bauxite	7,000	0.10	"
	10,000	0.60	
	12,000	1.44	

E. Silica Dissolution

Silica dissolves in water in two possible forms, molecularly dispersed and colloidal.⁵ Hydration of the silica gives the following reaction.

Tests run by Reed⁶ show that gravel packs (or proppant packs) at 260°C would be quickly dissolved by high temperature brines or steam. At a pH of 11, a cubic meter of water will dissolve up to 3.6 kilograms of quartz sand. In fracturing, most of our fluids will generally have a lower pH, but the above example shows that this problem should be carefully considered. Fracturing fluids injected into a geothermal reservoir are not silica saturated and therefore can attack the proppant and/or the formation itself. For example, Figure 17 shows the effect of temperature upon the dissolution of quartz and amorphous silica in pure water. In Figure 18 the dissolution effect of hot brine flowing through Boise and Berea sandstone is presented.

Different sandstones show different rates and amounts of dissolution depending on their clay content and other constituents. Table 4 shows typical mineral and chemical compositions of sandstones. Sandstones are described as clastic, detrital or fragmental rocks in which at least 50 percent of the grain sizes lie between 1/16 and 2 mm. The grains have been compacted and cemented. Exact mineral makeup depends on the parent rocks from which the fragments are derived. Shape and size of the grains vary as to the degree of chemical weathering and how the grain was transported.

Many of the geothermal resources are produced from sandstone formations and will be more susceptible to silica dissolution than the other metamorphic geothermal resources. Silica dissolution on the

exposed fracture face of a sandstone formation may be significant if exposed to unsaturated brine and high temperatures. Silica dissolution of the proppant can be more important since the proppant is under a great deal of stress. If cracks occur within the proppant, then the hot brine will penetrate into the particle. If sand is the proppant, our tests show that degradation of the sand is caused, in part, by the closure stress, but silica dissolution may sharpen the generated cracks and hasten the degradation process. This is evident by our 50-hour test data shown in Figures 1 and 2.

Figure 17. Effect of Temperature on Quartz and Amorphous Silica Solubility in Pure Water⁶

Figure 18. Boise and Berea Sandstone Dissolution During Flow of Neutral 1 N NaCl versus Temperature and Flow Rate⁶

TABLE 4
MINERALOGICAL AND CHEMICAL COMPOSITION OF SANDSTONES⁸

<u>Mineral</u>	<u>Chemical Composition</u>	<u>Remarks</u>
Quartz	SiO_2	Principal constituent
Muscovite	$\text{KAl}_2(\text{OH})_2(\text{AlSi}_3\text{O}_{10})$	Common constituent
Albite	$\text{Na}(\text{AlSi}_3\text{O}_8)$	Feldspars
Microcline	$\text{K}(\text{AlSi}_3\text{O}_8)$	
Perthite	(Microcline and Albite)	
Orthoclase	$(\text{K}, \text{Na})\text{AlSi}_3\text{O}_8$	
Glauconite	$\text{KMg}(\text{Fe}, \text{Al})(\text{SiO}_3)_6 \cdot 3\text{H}_2\text{O}$	Occasionally important constituent. Marine sand
Greenalite	$\text{Fe}_3\text{Al}_2\text{Si}_2\text{O}_{10} \cdot 3\text{H}_2\text{O}$	Associated with iron formations
Stilpnomelane	$\text{H}_2(\text{Mg}, \text{Fe})\text{Al}_2\text{SiO}_7$	
Minnesotaite	(iron rich hydrous magnesium silicate)	
Zircon	ZrSiO_4	Accessory and Heavy minerals
Garnet	(Ca, Mg, Fe, Mn, Al silicate)	
Rutile	TiO_2	
Magnetite	Fe_3O_4	
Leucoxene	(Secondary Ti mineral)	
Tourmaline	(Complex boron aluminum silicates of Na, Mg, Fe, Li, Mn, Ca)	
Apatite	$3\text{Ca}_3(\text{PO}_4)_2\text{CaF}_2$	
Monazite	$(\text{Ce}, \text{La}, \text{Nd}, \text{Pr}, \text{Th})\text{PO}_4$	
Biotite	$\text{K}_2(\text{Mg}, \text{Fe})_2(\text{OH})_2(\text{AlSi}_3\text{O}_{10})$	
Chlorite	$\text{Mg}_3(\text{Si}_4\text{O}_{10}(\text{OH})_2(\text{OH})_6$	
Kyanite	Al_2SiO_5	

TABLE 4 (Continued)

<u>Mineral</u>	<u>Chemical Composition</u>	<u>Remarks</u>
Staurolite	$2\text{Al}_2\text{SiO}_5 \cdot \text{Fe}(\text{OH})_2$	Metamorphic minerals
Andalusite	Al_2SiO_5	
Sillimanite	Al_2SiO_5	
Hornblende	$(\text{Ca}, \text{Na}, \text{K})_{2-3} (\text{Mg}, \text{Fe}^{2+}, \text{Fe}^{3+}, \text{Al})_5 (\text{SiAl})_8 \text{O}_{22} (\text{OH})_2$	
Pyroxenes	(Metasilicates of Fe, Mg, Ca, Na, Al, Ti, Mn, Cr)	
Sphene(Titanite)	CaTiSiO_5	Less Abundant
Olivine	$(\text{Mg}, \text{Fe})_2\text{SiO}_4$	
Cementing material or matrix in sandstones are usually calcium carbonate (CaCO_3), Silica (SiO_2) and ferric oxide (Fe_2O_3).		

A scanning electron microscope picture (Figure 19) of one sand grain shows that many cracks are caused by crushing a sand grain. As unsaturated silica water invades these cracks, further cracking occurs and more fines are generated which lower the overall permeability and effectiveness of sand as a proppant.

Figure 19a.

Figure 19b.

Figure 19. Multiple Brittle Cracks in Sand After Testing

F. Salinity Effects

To generalize the use of proppants for any geothermal stimulation treatment, they must work and not be sensitive to any salinity changes or amounts of salinity. MEI ran tests in distilled water, 2,000 ppm NaCl, and 100,000 ppm NaCl brine. Taking into account normal data scatter, no significant differences were found in short-term tests using the three different salinities on Ottawa sand, resin-coated sand or sintered bauxite. Figure 20 shows the Ottawa sand data with the three different salinities of brines tested at 350°F. Tests were also run of two brine concentrations at 500°F, and only normal data scatter was found. However, varying the length of the tests or the time factor drastically changed results with any brine. This fact suggested the longer term test series.

The silica content of the water could not be varied; however, there may be a significant effect on unsaturated versus saturated test fluids. Silica scaling and plugging of the MEI test system resulted when silica saturation was added to the test brines. To prevent this and take repeatable data, the entire system must be modified so as to remain at the downhole test temperature throughout the test period.

Figure 20a. Permeability Retention Under Closure Stress

Figure 20b. Permeability Retention Under Closure Stress

Figure 20c. Permeability Retention Under Closure Stress

V. GEOTHERMAL PROPPANT SYSTEMS

Since we have shown that silica proppants are not effective as proppants in geothermal stimulation treatments, we need to look at other proppants which will work. One requirement is the inertness of the material in high temperature brine. Many minerals can be considered as proppants if they have formed under high temperature conditions and are stable. These mineral crystals also need to be plentiful, easily sieved and inexpensive.

Garnets

One such alternative is garnet which comprises a mineral group of the form $A_3B_2(SiO_4)_3$ where "A" may be calcium, magnesium, ferrous iron or manganese; and "B" may be aluminum, ferric iron, titanium or chromium. It remains inert in hot brine; however, it will crush under high closure stress since it is brittle. Figure 21 shows the high temperature behavior of an Idaho Garnet.

Sintered Bauxite

A bauxite material,¹¹ a mixture of aluminum hydroxides made by sintering microspheres of bauxite together, has been found to be quite good in resisting crush loads in high temperature brines. Its specific gravity is 3.6 to 3.8, and it approaches Al_2O_3 in hardness. Many of the tests presented so far show the sintered bauxite to work well. Figure 22 shows the permeability retention of the sintered bauxite at geothermal conditions and there is no apparent degradation.

Figure 21. Permeability Retention vs Closure Stress

Figure 22. Permeability Retention Under Closure Stress

Corundum and Other Minerals

Another possible geothermal proppant is corundum (Al_2O_3) which is now widely used as an abrasive. It has a slightly higher specific gravity than sintered bauxite of 4.02 and is very hard. A possible advantage of the corundum might be a lower cost than the sintered bauxite. Other possible crystal systems that could be tested are cordierite ($\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$), tremolite [$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$], zircon (ZrSiO_4), andalusite (Al_2SiO_5), olivine [$(\text{Mg},\text{Fe})_2\text{SiO}_4$], tourmaline (complex silicate of boron and aluminum), and other minerals. Hematite, Fe_2O_3 , the principal ore of iron, may also be of use, but the available sample was sintered from many small particles, and their cohesiveness was insufficient to hold the larger particle together at realistic closure stresses.

Resin-coated Particles⁹

Another alternative to the minerals and materials mentioned above is the addition of an inexpensive but inert coating on sand or other materials. If there are no holes in this thin coating, then dissolution is prevented. The resultant coating deforms and spreads any crushing load evenly to prevent brittle behavior, failure, and flow back. Resin-coated materials are cohesive in the fracture and do not interfere with production operation. They have been thoroughly tested at high temperatures, are reasonably priced and available in large quantities. The resin-coated materials use a phenolic formaldehyde one-step resin that remains stable at temperatures above 300°C . These materials work best in hot brines commonly found in geothermal wells. Figure 23 shows the permeability retention of the resin-coated sand at geothermal conditions. In Figure 23, the 10/20, 20/40, and 40/60 mesh resin-coated proppants are shown at elevated temperatures and with varying closure stress. These proppants have been tested by Exxon⁹ and others¹⁰ for up to 90 days with no permeability degradation.

For deeper wells, materials other than coated sand may be required. Figure 24 compares the permeability of resin-coated bauxite at all elevated temperatures to that of the resin-coated sand. Because of different packing factors and slightly higher particle strength, the absolute permeability always tests slightly higher with the resin-coated bauxite material.

Figure 23. Super Sand Permeability (Resin-coated Sand)

Figure 24. Permeability Retention vs Closure Stress

VI. REFERENCES

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VII. APPENDIX

MEI Geothermal Proppant Test System

During 1979 and 1980, Maurer Engineering designed and built a new proppant test system to use at actual geothermal conditions. Figure A-1 shows a schematic of the system. It is capable of 50 tons of closure stress (10,000 psi on a 10-in² cell) and temperatures of up to 550°F. Any normal frac fluid system can be tested. Normal geothermal brine systems which are silica saturated fluids cannot be tested at present.

The unique aspect of this tester is the high temperature elastomer seals on the test cell. The high temperature EPDM elastomers were recommended by other Department of Energy projects and allowed most of the 50-hour tests to be conducted without seal failure. In several cases, 350°F tests of 15 to 30 days have been completed with the EPDM seals.

GEOHERMAL PROPPANT TESTER

Figure A-1