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**THERMAL STRESS FRACTURING OF
MAGMA SIMULANT MATERIALS**

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ABSTRACT

Direct contact heat exchanger concepts for the extraction of energy from magma chambers are being studied as part of the DOE-funded Magma Energy Research Program at Sandia National Laboratories. These concepts require the solidification of molten material by a coolant circulated through a borehole drilled into the magma and subsequent fracture of the solid either as a natural consequence of thermal stress or by deliberate design (intentional flaws, high pressure, etc.). This report summarizes the results of several thermal stress fracturing experiments performed in the laboratory and compares the results with an analysis developed for use as a predictive tool. Information gained from this test series has been the basis for additional work now under way to simulate magma melt solidification processes.

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INTRODUCTION

Direct contact heat exchanger concepts for the extraction of energy from magma chambers are being studied as part of the DOE-funded Magma Energy Research Program at Sandia National Laboratories. These concepts require the solidification of molten material by a coolant circulated through a borehole drilled into the magma and subsequent fracture of the solid either as a natural consequence of thermal stress or by deliberate design (intentional flaws, high pressure, etc.). A field experiment to investigate a direct contact heat exchanger concept was conducted in the Kilauea Iki Lava Lake in 1981, Dunn, Ref. [1]. It showed that the effective heat transfer surface area was an order of magnitude greater than the borehole surface area, presumably a result of fracturing in the solidified lava around the borehole. An analysis has been developed, Longcope, Ref. [2], which predicts specific features of the fracturing around a borehole; including geometry of the fracture pattern, new surface area of the fractures, and gap widths of the fractures. For the test at Kilauea Iki, Ref [1], this model indicates new fracture surface area at least an order of magnitude greater than the borehole area, which agrees qualitatively with the measured results.

An experimental effort was initiated in June 1985 to study thermal stress fracturing in magmatic materials and simulants and

to develop information with which the theoretical fracturing model of Ref [2] could be evaluated. The predominant test material was manufactured glass, which simulates obsidian. Since it is possible that either obsidian (fast cooling) or crystallized granitic material (slow cooling) may form around the borehole, a few samples of these natural materials were tested as well. Thick-walled glass cylinders were fabricated and tested by heating the outer surface and cooling the axial borehole. This effort was later extended to thin-walled cylinders and to edge-cooled thin plates. The thin plates are intended to represent a vertical half-section through the borehole and surrounding solid magma. An effort was also made to determine a number of material properties (see Appendix B) pertinent to the thermal fracturing of the tested materials and necessary for the theoretical analysis.

Results of the various experiments are compared, both qualitatively and quantitatively, to predictions of the theory. For the comparisons involving the glass plate experiments, the analysis of Ref. [2] was extended to account for unstable initial crack growth by using the APES fracture mechanics code, Gifford, Ref [3].

THEORETICAL MODEL

Theoretical analyses and results describing lava fracturing from Ref. [2] are summarized in the following discussion.

Thermal Stresses in Unfractured, Solid Magma. In developing a theory of magma fracture during cooling it is assumed that the zone of interest consists of two regions--a long, hollow circular solid cylinder which behaves as a brittle, elastic material and a surrounding liquid as shown in Figure 1. Density changes which may occur on solidification are neglected since the solidifying magma is surrounded by liquid. The overburden pressure is neglected, which restricts the analysis to shallow depths, including the Kilauea field experiment and other laboratory experiments discussed in the following. The analysis of Ref. [1] considers the overburden pressure and shows that tensile stresses remain high to significant depths. As in Ref. [1] steady state heat conduction in the radial direction is assumed and the corresponding temperature gradient is defined by:

$$T = -\Delta T + \frac{\Delta T}{\ln b/a} \ln r/a \quad (1)$$

$$\Delta T = T_o - T_i$$

where T is the change in temperature from the solidification temperature T_o , assumed to exist at the outer surface $r = b$ of the cylinder, and T_i is the inner surface temperature.

Solutions for the thermal stresses in a long, hollow, circular cylinder with free ends are given in Refs [2,4].

Figure 1. Conceptual Solidification Geometry

Nominal parameter values for the basaltic lava of the field experiment of Ref [1] are $\alpha = 9 \times 10^{-6} \text{ (C)}^{-1}$, $E = 5 \times 10^4 \text{ MPa}$, $\nu = 0.25$, $Y = 10 \text{ MPa}$, $T_1 = 400\text{C}$, and $T_0 = 750\text{C}$, where α is the coefficient of thermal expansion, E is Young's modulus, ν is Poisson's ratio and Y is the tensile strength. Using Eq. (1) and these values in the solutions for the thermal stresses shows the maximum tensile stresses are $\sigma_\theta = \sigma_z = 105 \text{ MPa}$ in the circumferential and axial directions, respectively, at $r = a$, in a thin cylinder. Since these stresses are much greater than the tensile strength, it is expected that both horizontal (r, θ plane) and radial (r, z) fractures will occur.

Growth of Fractured Region. As solidification continues, it is expected that the fractured region will grow. Because of symmetry, it is assumed that the fractured region will be confined to a cylinder of outer radius c , where $a < c < b$. The radius, c , is determined by requiring that the peak thermoelastic tensile stresses at $r=c$ in an unfractured outer cylinder ($c < r < b$) be the tensile strength, Y . Figure 2 shows that the outer radius of the fractured region c increases with increasing outer radius of the solidified region b . The difference in the dashed line and the solid line in Figure 2 represents the thickness of the outer cylinder of unfractured, solidified magma and shows that the fractures extend relatively close to the outer boundary of the solid for $b/a \sim 15$.

Figure 2. Growth of Fractured Region Versus Growth of Solidified Region.

Independence of Horizontal and Vertical Fractures. Magnitudes of σ_r and σ_θ in an annular plate ($\sigma_z=0$) are smaller by the factor $1-\nu$ than in a long cylinder with the same a , b , and radial temperature distribution Eq. (1). This indicates that horizontal fracturing only weakly affects σ_r and σ_θ and will not eliminate radial fracturing. Similarly an elasticity solution shows σ_z in a long, hollow, slit (rz plane) cylinder is smaller by the factor $1-\nu$ than σ_z in an unslit cylinder of the same dimensions. This indicates that vertical fracturing will not significantly reduce the σ_z tensile stresses. Thus it is expected that both vertical and horizontal fractures will form relatively independently of one another in the solidified magma.

Vertical Fracturing. The high σ_θ tensile stresses will initiate a vertical fracture which will lie in a plane defined by the z axis and a radial direction. For reasons given in Ref. [2] it is expected that a vertical fracture will grow in finite increments and during each increment of growth will propagate to the outer boundary of the solid region. According to Ref. [4] for the temperature distribution given by Eq. (1) such a through vertical fracture will reduce the σ_θ and σ_r stresses to zero in either a long cylinder or in an annular plate. Thus only one vertical fracture will occur and it will reduce the σ_r tensile stress to zero so that no cylindrical fractures will form.

Horizontal Fracturing. Spacing of the horizontal fractures is estimated through an energy balance like that of Griffith, discussed in Knott, Ref. [6] in which the decrease in strain energy resulting from extension of the fractures is equated to the energy required to rupture solidified magma. The horizontal fracture front is shown at $r=c$ in Figure 3 which represents the overall fracture geometry. Strain energy states across $r=c$ are estimated by assuming the cracks are smeared. In the region just outside $r=c$, the average stresses are $\sigma_z=Y$, $\sigma_r=\sigma_\theta=0$, since it is expected that a vertical crack will have previously advanced beyond $r=c$. Inside $r=c$, the average stresses are $\sigma_z=\sigma_r=\sigma_\theta=0$. The strain energy U change when the horizontal fractures extend a distance Δc is:

$$U = \frac{\pi c l \Delta c Y^2}{E} \quad (2)$$

where l is an arbitrary axial length which includes many horizontal fractures. The fracture energy required to extend n cracks a distance Δc is:

$$U_f = \frac{2\pi n c \Delta c (1-\nu^2) K_{IC}^2}{E} \quad (3)$$

SECTION AA

Figure 3. Geometry of Fracturing in Solidified Magma

where K_{IC} is the plane strain critical stress intensity factor. Equating these energy changes and using $n=l/d$, where d is the spacing of the horizontal fractures gives:

$$d = \frac{2(1-\nu^2) K_{IC}^2}{Y^2} \quad (4)$$

This indicates that the horizontal fracture spacing is independent of distance c . Using the previously given nominal parameter values and $K_{IC} = 0.75 \text{ MPa-m}^{1/2}$, a nominal value for glass and for basaltic obsidian gives:

$$d = 1.1 \text{ cm.}$$

as a nominal value for the horizontal fracture spacing near the borehole of Ref. [1].

Gap Width of a Horizontal Fracture. Since the fractured region contains horizontal fractures and a vertical fracture, the average stress state is $\sigma_z = \sigma_r = \sigma_\theta = 0$. Using these stresses in Hookes' law with temperature effects, Ref. [4], gives for the axial strain

$$\epsilon_z = \alpha T \quad (5)$$

and the gap width, w , is

$$w = -d \alpha T \quad (6)$$

Using the previous nominal values for these parameters, a nominal value for the gap width at the borehole surface, $r=a$, is:

$$w = 0.08 \text{ mm}$$

Estimates of fracture gap widths are required for analysis of fluid flow in the fractures.

TEST PHILOSOPHY

The experimental program philosophy dictated limited testing to obtain consistent results which could then be qualitatively compared with theoretical predictions.

Readily available, well-characterized glasses were chosen as magmatic simulants in this test program because properties were well defined and compositions similar to those predicted for magma are available. A limited number of geologic materials were also tested for comparison with the simulants.

THICK-WALL CYLINDERS

Experimental Procedures. Cylinders (6.35 cm OD x 10.16 cm L) were cast, annealed, and axially cored (1.27 cm dia) using a well characterized Sandia "S" glass (alumino silicate, see Appendix B, Page 48). The cylinders were inspected with polarized light to verify that annealing to a relatively stress-free state had indeed occurred.

Testing the cylinders required a vertical tube furnace with appropriate fixturing and a perforated wand of 304 SS tubing that carried the coolant (house air at ~ 0.61 MPa and at a flow rate of ~ 5.6 m³/hr) into the borehole. Tests were performed with the entire cylinder at initial temperatures of 400C and 200C and

the borehole cooled via the wand. More severe rubbing of the cylinder occurred at the higher temperature due to the greater thermal stress. The cooling interval (varying from 2-6 min) with airflow into the borehole was also a factor in the extent of the rubbing. Developing a method to determine an accurate inner wall temperature was found to be very time consuming early in the scoping test effort. Therefore, air cooling parameters (pressure, flow, time) were kept as uniform as possible from sample to sample.

Several successful tests to initiate and then alternately halt and propagate cracks were performed with the cylinders by cooling and then not cooling the borehole.

One additional test was performed with a Coso obsidian cylinder cored from natural obsidian. This cylinder (5.7 cm OD x 6.35 cm L) was heated and air cooled through the axial borehole as were the previous samples. Heating to 680C was necessary to crack this natural material.

Test Results and Comparisons with Theory. In general several approximately parallel horizontal fracture planes occurred as the glass cylinders were cooled. The horizontal planes were vertically connected by primary cracks located at approximately 120° intervals as viewed from the cylinder end face. Secondary interconnecting cracks occurred as cooling progressed. The cracks were sufficiently irregular to cause the rubble to stay intact as

Figure 4(a). Typical Thick-Wall Cylinder Fractured at 200C

Figure 4(b). End View of Typical Thick-Wall Cylinder

a cylinder, even though many cracks extended to the O.D. of the test sample. Figure 4 (a) and (b) are photographs of a typical fractured thick-wall cylinder.

The results of the thick-wall glass cylinder experiments were in qualitative agreement with the predicted fracture geometry. In accordance with the theory, both horizontal and vertical fractures were produced and no cylindrical fractures occurred. At both temperatures there were substantially more horizontal than vertical fractures. There was an average of two or three vertical fractures whereas theory predicts the equivalent of one vertical fracture. This difference could be the result of either of two conditions which do not match the theory. (1) The theory predicts that a vertical crack will propagate into a "thin" cylindrical shell of solid magma whereas the test cylinders were thick-walled and (2) the cooling produced a transient temperature distribution with zero thermal stress in an outer region of the cylinder while the theory assumed a steady-state temperature distribution in the cylinder.

The Coso test specimen was sectioned for visual examination and the fracture network originating at the borehole was similar to the simulant glass cylinders.

THIN-WALL CYLINDERS

Experimental Procedures. These cylinders were cut to length from commercially supplied soda-lime (Type 0080) drawn and annealed glass tubing having a wall thickness of nominally 1.25 mm. Two different diameters (5.08 cm OD and 2.54 cm OD) were used for the test and all cylinders were 25.4 cm in length. The cylinder end faces were ground with 240 grit material to eliminate major flaws acquired during cutting and to obtain a surface having a known distribution of flaws with an average depth of 0.031 mm.

The test setup for these thin-wall samples was the same as discussed previously for thick wall cylinders.

Test Results and Comparisons with Theory. A very limited amount of cracking occurred in these samples although the extent of the crack pattern increased as initial temperature increased (330C→480C). In general, more horizontal cracks occurred than vertical cracks. The larger diameter samples exhibited a more regular horizontal crack spacing than did the smaller diameter samples.

Due to the thin wall sections, the samples did not stay intact when rubbing occurred so extreme care was required to perform post-test reconstruction of the samples by gluing the fragments

Figure 5. Illustration of a Typical 2.54 cm Diameter Thin-Wall Cylinder Fractured at 475C

into place before any visual analysis could be made. Figure 5 illustrates a typical thin-wall sample.

The thin-walled glass tubes that were tested are believed to approximate the geometry of the solid, unfractured magma during solidification. The 2.54 cm and 5.08 cm diameter glass tubes, initially at temperatures of 330C to 480C and cooled by air at 20C were more difficult to fracture than the thick-walled glass cylinders, as expected from thermal stress analysis. The stress analysis indicated that a steady-state temperature difference of 180C across the wall of either diameter tube would be sufficient to produce cracking. Axisymmetric air cooling uniform over the length of the tubes was not sufficient to produce cracking; however, axially localized cooling did produce cracking. Usually the equivalent of one or two vertical fractures were produced, which are fewer than those in the thick-walled cylinders and are in better agreement with the single crack predicted by theory.

THIN PLATES

Experimental Procedures. These samples represented a borehole half section. The primary test material used to prepare these test specimens was common soda-lime (Type 0080) window glass approximately 2.29 mm in thickness. A few 6.35 mm plates were also tested. Typical test samples were 10.16 cm x 25.4 cm, but varied slightly, generally maintaining a length to width ratio >

2:1. Edge surfaces were prepared with 240 grit material as previously described.

The test setup is very simple, requiring a convection furnace and a water bath (~20C) with stepped fixtures that permit a pre-heated glass plate to be quickly immersed on edge to a controlled depth and then withdrawn after an appropriate cooling period. Glass samples were tested at various temperatures ranging from 65 to 305C with immersion times of 2 seconds and 60 seconds.

Another test was performed with glass plates to determine if cracks could be propagated continuously if the moving crack tip were maintained at the water line. This is analogous to a high heat transfer rate in an actual borehole.

Additional cracking experiments were performed with Sandia "S" glass plates slabbed from a cast, annealed billet. The plates were 5.08 cm W x 11.43 cm L x 0.280 cm T and cooled on a long edge. Several "S" glass plates were deliberately heated to 600°C to form a crystalline phase in the material simulating a granitic structure resulting from slow natural cooling of geologic material.

A limited number of samples cut from natural geologic material (obsidians and granitic materials) were also tested. Due to the natural cooling fractures already present, the slabs were cut from the parent material in approximately 0.6 cm thickness to maintain

overall structural integrity. These samples were not cut into rectangular shapes but rather were used as rough squares or semicircular shapes. One straight edge was prepared on each specimen by cutting and then grinding to a 240 grit finish. Both Coso and Panum Crater rhyolitic obsidians were tested (Coso at 250C and Panum Crater at 340C), as well as Obsidian Dome core (granitic - 536 m depth) at 250C and 340C.

Test Results and Comparisons with Theory. The most extensive and repeatable set of experiments involved fracturing glass plates at temperatures from 100 to 300C by edge cooling in water at 20C.

These simulated the horizontal fracturing which would be evident in a vertical cross section through the axis of symmetry of magma solidifying around a borehole. If a vertical fracture had occurred in the magma, σ_{θ} would be zero and this would match the zero stresses normal to the plate surfaces.

Typical cracking patterns are shown in Figure 6. These figures are retouched (for clarity) copier images taken directly from the samples. It is apparent that the fracture pattern changes radically as greater thermal stress is applied. The crack spacing along the cooled edge was very repeatable from sample to sample as long as the same thermal conditions were applied. The regularity of the cracks and the extension of alternate cracks with distance from the cooled edge is remarkable. Figure 7 is an

Figure 6. Fracturing of 10 cm x 25 cm x 3.17 mm Glass Plates at Various Temperatures

305C

Figure 7. Dynamic Cooling and Resulting Crack Propagation
at 305C

example of a plate cracked across its width by immersing the plate progressively further, maintaining the crack tip at the waterline. It shows that the fracture spacing is approximately uniform with depth.

A consistent, qualitative feature of the fracturing was that the spacing of the fractures increased significantly with distance from the cooled edge, in agreement with the experiment by Geyer and Nemat-Nasser [7]. A theory developed by Oranratnachai and Nemat-Nasser [8] can explain this by showing that a system of quasistatically growing cracks may be unstable, with alternate cracks stopping while the others continue to grow. This instability depends on the thermal stress gradient ahead of the crack tips with more steeply declining gradients (toward compressive stresses) enhancing stability. The theory developed herein predicts a uniform crack spacing, independent of depth. This does not agree with the edge-cooled plate experiments; however, the stress field in the plates near the crack tips does not have the steeply declining gradient predicted for the stress field in the solidifying magma. The plates which were deeply submerged to produce localized thermal stresses near the crack tips showed a system of cracks with approximately uniform spacing from the plate edge to the final crack tips; Figure 7.

By a development similar to that leading to Eq. (4) it can be shown that the spacing of the fractures in the glass plates is

also represented by that equation. Since Eq. (4) is based on the assumption that the extension of fractures completely reduces the thermal strain energy to zero when some actually remains, it is expected that the theory will provide a lower bound on the spacing between fractures. A comparison is made with the minimum average fracture spacing which always occurred at the cooled edges of the plates. It was observed that the crack growth from the edges was initially dynamic for a short distance (a few mm) and then continued slowly or quasistatically. The theory, Eq. (4), assumes slowly growing cracks and it is necessary to modify it to account for the initial unstable growth of the edge flaws, as detailed in Appendix A. A one-dimensional transient heat conduction analysis is performed and the corresponding time-dependent temperature distributions and thermal stresses are determined. The fracture mechanics code APES, Ref. [3], is used to determine when an average edge flaw will begin to grow and at what length it will arrest. It is assumed that the thermal strain energy existing at the time the flaw begins unstable growth is completely relieved in the plate up to the depth of the crack tip at arrest. Equating this energy to the fracture energy required by an unknown number of cracks determines the crack spacing.

A typical experiment (No. 20) involved a 0.635 cm thick plate initially heated to 150C and edge-cooled in water at 23C. Initial flaws of average depth 0.031 mm are calculated to propagate to a length of 0.230 mm. Using this final length in the energy balance

gave an edge fracture spacing of 0.69 mm while the measured average spacing is 9.3 mm. The glass plate experiments at the other temperatures also showed edge fracture spacings that were considerably larger than the theoretical lower bound spacings. According to Eq. (6), if the actual fracture spacing d is considerably larger than that predicted, then the crack width w will also be larger by the same factor.

One explanation for the difference between theory and experiment is that the tensile stress field near the plate edge could have penetrated to much greater depth than predicted by the one-dimensional theory because of side cooling, since the plates were submerged to a depth of a few millimeters. In the experiment analyzed, the average depth of the shortest cracks is 1.9 mm which approximates the submerged depth and is much larger than the predicted arrest depth of 0.23 mm for flaws driven by edge-cooling only. Another explanation is that convective heat losses from the sides of the plates to the air significantly affected the thermal stress profile.

The plates of Coso obsidian and crystallized granitic material from beneath Obsidian Dome represent two forms of geologic material which have been solidified by relatively rapid and slow cooling, respectively. Either or both of these may form when magma is solidified during energy extraction in the direct contact heat exchanger concept.

Measured average edge fracture spacing in plates of the crystallized granitic material initially at 250C and 350C were 1.0 cm and 2.5 cm, respectively, as compared with a spacing of 0.39 cm given by Eq. (4). The values used in Eq. (4) are $Y = 25$ MPa, $K_{IC} = 1.2 \text{ MPa-m}^{1/2}$ and $\nu = 0.2$. These values of Y and K_{IC} are mean values from laboratory tests, Appendix B, and the extremes about the means are $\pm 30\%$ and $\pm 15\%$, respectively. In these tests the fractures were observed to grow slowly on initial cooling. The theoretical lower bound spacing is closer to the test results than for the glass plates.

The plane strain critical stress intensity factor for Coso obsidian was determined, Appendix B, to be $K_{IC} = 0.71 \text{ MPa-m}^{1/2}$. This value and the values for other relevant parameters are nominally the same as that for glass Table I, which indicates that glass can be used as a simulant for studying thermal fracturing of obsidian. In the two plates of Coso obsidian initially at 250C, the average fracture spacing was 1.5 cm at a depth of 1 cm from the edge which is comparable to the spacing in the glass plates at the same initial temperature. Shorter cracks in the obsidian plates were not visible post-test, but may have closed up after the tests. These results suggest that the fracturing in glass approximates that in obsidian.

At a distance from the cooled edges of 1 cm, the fracture spacing in two plates of granitic material averaged 2.2 cm. This

spacing is greater than that in the obsidian plates. The theory also indicates that the fracture spacing in the granitic plates should be greater than in the obsidian plates. There is uncertainty as to whether obsidian or granitic solid material will form around a borehole, but these experimental results and the theoretical results indicate that the assumption of obsidian would give an estimate of the minimum spacing of horizontal fractures.

**Table 1. Comparison of Glass, Obsidian, and Crystallized Granitic
Magma Properties**

	K_{IC} (MPa-m ^{1/2})	σ (MPa)	α (in/in/C)	E (MPa)	δ (m ² /s)
Glass	0.75 [9]	51	9x10 ⁻⁶ [10]	6.9x10 ⁴ [10]	0.030x10 ⁻⁵ [11]
Coso Obsidian	0.71	54	5x10 ⁻⁶	7.0x10 ⁴ [12]	
Obsidian Dome Crystallized Granitic Magma	1.2	25	16x10 ⁻⁶		0.06x10 ⁻⁵

[] - References

K_{IC} - Plane strain critical stress intensity factor

σ - Tensile strength

α - Coefficient of thermal expansion

E - Young's modulus

δ - Diffusivity

In summary, comparable test temperatures and immersion times produced overall crack patterns and spacings very similar to the window glass samples. Fracture tests on these plates yielded patterns that were regular in initial crack spacing, but had propagated in circuitous fashion between crystals. Each cracked with a different fracture spacing as expected, but the regularity and alternate extension of fractures was very similar to the laboratory glasses.

DELIBERATELY FLAWED SAMPLES

This test series was initiated with the goal of obtaining some information pertaining to fracture control. The rubble column geometry surrounding a borehole is expected to directly influence energy extraction efficiencies in direct contact heat exchangers. Test samples were prepared in several geometries with deliberately emplaced flaws expected to act as mechanical stress risers during thermal testing.

Experimental Procedures. Several thick-wall "S" glass cylinders were cast and annealed with an integral, axial 304 SS tube (1.27 cm OD x 1.52 mm wall). A control set (2) were cast with a standard piece of tubing, two were cast with tubing having circumferential ribs (0.5 mm x 0.5 mm) spaced 1.27 cm apart on the tube O.D., and two were cast with tubing having four longitudinal fins (0.8 mm x 3.17 mm x 10.16 cm) welded to the tube O.D. Each

of these cylinders was heated in a convection oven (160C and 250C), insulated and then removed to a test stand where city water was connected to flow through the central tube. This cooling technique, as expected, was more severe than air cooling and produced fracturing in all of the samples, the extent depending on the initial temperature.

Thin plates were also prepared for testing as previously described, except randomly spaced notches were formed in the ground edge by using a 0.3 mm wide diamond wafering saw to form a flaw approximately 0.3 mm x 0.7 mm.

Test Results. The cylindrical glass samples with the smooth O.D. 304 SS tubing produced random fractures similar to those in previous thick-wall cylinders that were air-cooled. The samples having circumferential ribs exhibited primary horizontal fractures generally corresponding to the rib location. The longitudinally ribbed samples, however, had only one primary vertical fracture corresponding to a rib location.

Test results with the deliberately flawed thin plates indicated that if flaws are available to the thermally stressed region, fractures originate at the nearest deliberate flaw and not in the unflawed region. If an excess of flaws is present, the fracture stress is selective in only using the flaws needed to relieve the stress. Also, a uniform fracture pattern can be

Figure 8. Deliberately Flawed Test Sample at 65C

initiated at lower thermal stresses if a pre-existing flaw pattern is present. Figure 8 illustrates a typical flawed plate.

These results are encouraging and indicate that some measure of fracture control may be feasible using relatively passive techniques in forming direct contact heat exchangers in a magma chamber at depth.

CONCLUSIONS

Although these thermal stress fracturing experiments were by intent qualitative, consistency was found in duplicate tests within a material set and also between material sets. The results reinforce the model's predictions that rubble matrices for direct contact heat exchangers can be formed at depth in a magma chamber if the appropriate thermal stresses can be applied.

Specific points to be made in conclusion are:

- (1) Thermal gradients predicted during energy extraction from solidified magma are sufficient to cause fracturing of the solidified material.
- (2) Predicted general fracture geometry consisting of horizontal and vertical fractures but no cylindrical fractures agrees qualitatively with results of thick and thin-walled glass cylinder tests.

- (3) Theory and material properties data indicate that glass can simulate thermal fracturing in obsidian and this is supported by the similar fracture patterns in plates of laboratory glass and Coso obsidian.
- (4) The energy balance theory provides a lower bound on fracture spacing in the plates of glass and magmatic materials tested; however, the theoretical values of 0.69 mm and 3.9 mm were substantially smaller than the average spacings of 9.3 mm and 18 mm measured in the glass and granitic plates, respectively. Initial fracture growth instabilities were observed in the glass plate tests and may account substantially for the difference in theoretical and observed spacing.
- (5) Observed fracture spacings were moderately greater in the crystallized, granitic plates than in the obsidian plates. Both experimental and theoretical results indicate the assumption of obsidian formation around a cooled borehole would lead to a minimum estimate of vertical spacing of the horizontal fractures.
- (6) The difference in fracture spacings observed in the deep immersion and edge-cooled glass plate tests suggests that the spacing depends on the method of cooling and the associated stress gradient near the fracture tips. This

indicates a need to simulate the solidification process in fracture studies.

- (7) Some measure of fracture control was demonstrated through deliberate flaw placement in both thick-wall cylinders and thin plates.

Results of these experiments and correlation with theory have been the impetus for future melt solidification experiments now being planned. Initially the melt solidification samples will weigh ~5kg with an aspect ratio of ~4:1. However, larger facilities are available at SNLA for scaling up the experiments if the theoretical structural and thermal models dictate the need.

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The authors wish to make special mention of the contribution to this work by the Supervision and Staff of the Glass Formulation and Fabrication Laboratory, Organization 7471. Special melts of natural geological material as well as laboratory glasses and many thermal property measurements were performed in timely support of the experiments.

Also, the suggestions made by T. Y. Chu, Organization 6242 and C. E. Hickox, Organization 1513 regarding test methods and other experiment considerations are appreciated.

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APPENDIX A

CALCULATION OF INITIAL, UNSTABLE CRACK GROWTH IN EDGE-COOLED GLASS PLATES

The initial crack growth instability observed in the edge-cooled glass plates was studied with the finite-element code APES, Ref. [3], using the model shown in Figure A1. The temperature difference for 1-D transient heat conduction in the plate cooled along one edge ($x=0$) and insulated on the sides is

$$T = - \Delta T \left(1 - \operatorname{erf} \frac{x}{2\sqrt{\delta t}} \right) \quad (A1)$$

where ΔT is the difference in the initial plate temperature and the water bath temperature, δ is the thermal diffusivity and t is time since cooling started. Temperature differences give by Eq. (A1) with $\Delta T = 150\text{C} - 23\text{C} = 127\text{C}$, $\delta = .030 \times 10^{-5} \text{m}^2/\text{s}$, and $t = 0.0240 \text{ sec.}$ were used in the finite-element analysis representing experiment 20. The value of t is the time at which calculated thermal stresses would cause a single edge flaw of length 0.031 mm to begin propagating. This flaw size was selected as a reasonable average flaw size for the edge which was ground with 240 grit material. Plates with the same edge condition at 100C experienced only 3 fractures and an analysis of those tests indicated the maximum edge flaw depth was 0.060 mm.

Figure A1. Finite element model to compute the stress intensity factor K_I at the tip of a single crack in an edge-cooled glass plate.

With the temperature distribution fixed, the plane strain stress intensity, K_I , at the tips of cracks of different lengths was calculated with APES to produce the curve shown in Fig. A2. This curve indicates that an initial flaw of length $a_0 = 0.031$ mm will grow unstably until it reaches the length $a_1 = 0.230$ mm at which K_I falls below the critical value of $0.75 \text{ MPa-m}^{1/2}$ for glass. This calculation neglects inertia effects produced by the rapidly growing crack. Although the calculation is for a single crack, it is assumed that a_1 approximates the length at which a collection of edge cracks will stop growing in unstable fashion.

The thermal strain energy existing in a strip of the plate between $x = 0$ and $x = a_1$ is

$$U = \sqrt{\delta t} \, h l E \alpha^2 (\Delta T)^2 S$$

$$S = \int_0^\Phi (1 - \text{erf} z)^2 dz \quad , \quad (A2)$$

$$\Phi = \frac{a_1}{2\sqrt{\delta t}}$$

where h is the plate thickness and l is the plate length. The fracture energy required to extend n fractures a distance a_1 is

$$U_f = \frac{n h a_1 K_{IC}^2 (1 - \nu^2)}{E} \quad (A3)$$

Figure A2. Stress intensity factor versus crack length for the thermal stress field at 0.0240 sec. after immersion.

Equating Eq. (A2) and Eq. (A3), and using $n = l/d$ determines the fracture spacing

$$d = \frac{2(1-\nu^2)K_{IC}^2 \phi}{(E\alpha\Delta T)^2 S} \quad (A4)$$

Using the values $\nu = 0.25$, $K_{IC} = 0.75 \text{ MPa-m}^{1/2}$, $E = 69 \times 10^3 \text{ MPa}$, $\alpha = 9 \times 10^{-6} (\text{C})^{-1}$, $\Delta T = 127\text{C}$ gives $\phi = 1.35$, $S = .330$, and $d = 0.69 \text{ mm}$. S was calculated numerically.

APPENDIX B

THERMAL/MECHANICAL TEST DATA

A limited set of basic properties data was obtained for the simulant glasses and geologic materials used in the thermal stress fracturing experiments. The following text is comprised of that auxiliary data in memoranda supplied to the authors by those performing the tests. A summary matrix for the tests and materials precedes the set of memoranda.

MATERIAL PROPERTIES TEST SUMMARY

MATERIAL	THERMAL TESTS						MECHANICAL TESTS	
	DTA	ΔL	T_C	THERM DIFF.	SPECIFIC HEAT	TGA	TENSILE STRENGTH	FRACTURE TOUGHNESS
COSO OBSIDIAN	•	•	•	⊙	•	•	•	•
GLASS CREEK OBSIDIAN	•							
PANUM CRATER OBSIDIAN		•						
OBSIDIAN DOME GRANITE	•		•	•	•		•	•
SANDIA "S" GLASS								
GLASSY	•		(D)		(D)		(D)	(D)
CRYSTALLIZED	(L)	(L)	(L)		(D)		(D)	(D)
SODA-LIME GLASS	•	(L)	(L)				(L)	
SYNTHETIC RHYOLITES								
MOD 1	•							
MOD 2	•	•	•	•	•		•	•
MOD 3	•		•	•	•		•	•
FUSED SILICA								•

• COMPLETED

⊙ UNDERWAY

(D) PRIVATE COMMUNICATION FROM DEVELOPER/PATENT HOLDER H. L. MCCOLLISTER - SNLA, ORG 7471

(L) AVAILABLE FROM PREVIOUSLY CITED LITERATURE

GLASS MELT DATA SHEET

Glass Formulation: S-188- Melt No. _____ Date 2-14-85Intials: _____ Intended Use: MD ProductionRequester: P.R. Wengert

Furnace No. _____

Batch Size 900 to 1000gD.R.

Finished Product (Weight %)	BATCH CALCULATIONS				
	Original Compound	Grams Used	Compound Yielded	% Yield	Weight Yielded
73.0	SiO ₂	657 ✓	SiO ₂	100%	657
2.5	Li ₂ PO ₄	36.7 ✓	P ₂ O ₅	61.3	22.5
1.5			Li ₂ O	38.7	13.5
11.8	Li ₂ CO ₃	262.9 ✓	Li ₂ O	40.4	106.2
1.8	H ₂ BO ₃	28.8 ✓	B ₂ O ₃	56.3	16.2
4.8	K ₂ CO ₃	63.4 ✓	K ₂ O	68.2	43.2
9.6	Al ₂ O ₃	41.4 ✓	Al ₂ O ₃	100	41.4
					900 g approx
Calcine @ 325°C for 1HR					
Load in Bldg 864					
Transport cooled melt to Bldg 894 & melt & stir over <u>note</u>					

Glass Characterization: Samples

TYPE OF SAMPLE

DTA

Thermal Expansion

No other analysis

REQUIRED

☒☒ Yes ☐ No☐ Yes ☐ No☐ Yes ☐ No

QUANTITY

SAMPLE SIZE

Other 0.25" dia preforms

LINEAR THERMAL EXPANSION TEST

Date: 11-29-85 Run No: 1
 Mill No: 04-2 Sample No: 1
 Sample Description: OBSTIDIAN COKE GRANITE CORE-1700' 170-21 (1)
 Sample Length: .8949 Inches
 Furnace No: 1 Furnace Atmosphere: Air
 Heating Rate: 5 Deg. C per Min.
 Magnification: 10000 X
 Reference Material: Fused Silica
 Requester: S. HEMPLE
 Reference Length: 1.0000 Inches
 Operator: Chirigos

HEAT TREATMENT SCHEDULE

COEFFICIENT OF LINEAR THERMAL EXPANSION FROM 20.0 DEG C TO

	DEG C	INCHES IN/IN/DEG C	ALPHA
1	200.0	0.00133	94.19E-7
2	300.0	0.00008	274.1E-7
3	500.0	0.00016	197.0E-7
4	800.0	0.01023	192.0E-7
5	700.0	0.01100	190.0E-7

Table 1. Report of Fracture Stress and Fracture Toughness Test Data
Analysis Support Lab

Materials Tested: Fused Silica, Rhyolite Mode 2 and 3,
Coso-obsidian, and Obsidian Dome
Granitic Core
Consultants: B. Wemple
Test Conditions: Ambient Temperature
Crosshead Speed: 0.1 in/min
Dates: 10/1/85 & 1/13/86
Ref. Nos: 10/1/85 & 1/1/86
Tested by: Renee Coonen
Chart Speed: 0.5 in/min

No.	Name	Fracture Stress			Load Lb.	Fracture Stress, PSI	Fracture ^a Toughness		Remarks
		Diameter In.	Width In.	Thickness In.			KPa	n	
1.	Rhyolite	0.2345			197	38,913	0.628		Crosshead speed 0.5 in/min
2.	Mod 2	-			218	43,061	0.595		
3.	-	-			223	44,049			
4.	-	-			204	40,296			
5.	-	-			220	43,456			
6.	-	-			207	40,888			
7.	-	-			231	45,629			
8.	-	-			229	45,234			
9.	-	-			221	43,654			
10.	-	-			203	40,098			
11.	-	-			248	48,987			
1.	Rhyolite	0.2400			423	77,972	0.770		Bad fracture
2.	Mod 3	-			423	77,792	0.772		
3.	-	-			356	65,622	0.750		
4.	-	-			400	73,732			
5.	-	-			270	49,769			
6.	-	-			446	82,211			
7.	-	-			406	74,838			
8.	-	-			255	47,004			
9.	-	-			395	72,811			
10.	-	-			270	49,769			
11.	-	-			375	69,124			
12.	-	-			421	77,603			
1.	Coso-	0.2515			105	8,416	0.621		**
2.	obsidian	-			89	7,134	0.700		
3.	-	-			117	9,378	0.750		
4.	-	-			102	8,176	0.725		
5.	-	-			86	6,894	0.750		
6.	-	-			85	6,813			
1.	Obsidian	0.5020	0.2507		124	2,943	1.086		Marginal
2.	D.C. Core	-	-		108	2,579	1.034		
3.	-	-	-		157	3,744	1.219		
4.	-	-	-		137	3,257	1.290		
5.	-	-	-		142	3,375	1.227		
6.	-	-	-		166	3,946	1.322		
7.	-	-	-		156	3,708	1.228		
8.	-	-	-		133	3,173	1.140		
9.	-	-	-		179	4,255	1.109		
10.	-	-	-		191	4,540	1.369		
11.	-	-	-				1.143		
12.	-	-	-				1.241		
1.	Fused						0.738		
2.	Silica						0.713		
3.	-						0.743		
4.	-						0.716		
5.	-						0.762		
6.	-						0.721		

^aThe fracture toughness (K_{IC}) values do not correspond with the values for fracture stress (MOR).

**Bad fracture on the fractometer. Refer to Figures 1 and 9

Figure 1. An acceptable K_{1C} test sample. The crack propagated in the same plane and fractured the sample in half.

Figure 2. An unacceptable K_{1C} test sample. The crack continued out of the plane of fracture at a point of crystalline formation.

date: November 5, 1985

to: Bob Wemple - 6242

from: E. P. Roth and A. J. Anaya - 1824

subject: Specific Heat Measurement of Rhyolitic Obsidian Glasses

The specific heat of three Rhyolite glasses have been measured. These glasses consisted of one sample of natural rhyolitic obsidian magma obtained from Coso, CA and two Sandia prepared rhyolitic glasses (MOD2 and MOD3) which were prepared to match the properties of the natural material. The specific heat measurements will be used with the measured thermal diffusivity and density to calculate the thermal conductivity.

The specific heat was measured from 67-707 C using a Perkin Elmer Differential Scanning Calorimeter (DSC2). The measurements were made over two overlapping temperature ranges: 67-522 C and 517-707 C. The specific heat data was obtained using NBS sapphire references and was accurate to within $\pm 4\%$.

Figure 1 shows the data for the COSO rhyolitic obsidian. Three measurements were made of this material: two scans were made over the low temperature range to check for any irreproducible changes in the material after the initial temperature scan and to check for measurement reproducibility, while a third scan was run over the high temperature range. The maximum difference between the two low temperature scans was 2.5% and the high temperature scan agreed quite well with the low temperature data. This material did not show any apparent glass transition over the measured temperature range and the material did not show any visible signs of change after the high temperature cycling.

Figure 2 shows the data for the MOD2 glass. This material showed a slight endotherm near 100 C, indicating a slight release of water. At the higher temperatures, the material showed a sharp glass transition near 480 C. After the low temperature scan, the material had darkened somewhat but retained its initial shape. After the high temperature cycle, the material had obviously softened, becoming rounded at the edges and also becoming much clearer.

Figure 3 shows the data for the MOD3 glass. This material showed a strong endotherm at 100 C probably due to water release. During this run, the material lost $\sim 0.5\%$ in weight. After this run, the material had visibly changed. The upper and lower surfaces had coarsened and turned white while the edges had turned black. After high temperature

cycling, the material degraded even further, turning black on all surfaces and undergoing some rounding at the edges. The specific heat data show that the material had a glass transition near 430 C but smaller than for the MOD2 material.

Figure 4 shows a comparison of all three materials. Table I lists the specific heat data for all three materials.

Currently, work is continuing on trying to perform the thermal diffusivity measurements using the laser flash diffusivity apparatus. Some equipment modifications have already been performed in order to measure these semi-transparent materials. Standard Pyrex material is being measured initially in order to verify the new measurement procedures required for these types of materials. We will be comparing our measurements with the thermal conductivity data that was obtained by M. Moss, 1824 on the thermal comparator. We will keep you informed on our progress.

EPR/AJA:1824:jh

Copies to:
1820 R. E. Whan
1824 J. N. Sweet
6242 T. Y. Chu

TABLE 1. Natural Rhyolite: Low Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
67.	.196
77.	.199
87.	.202
97.	.205
107.	.208
117.	.210
127.	.213
137.	.215
147.	.217
157.	.219
167.	.221
177.	.223
187.	.225
197.	.227
207.	.229
217.	.230
227.	.232
237.	.233
247.	.235
257.	.236
267.	.238
277.	.239
287.	.240
297.	.241
307.	.242
317.	.243
327.	.245
337.	.246
347.	.247
357.	.248
367.	.249
377.	.249
387.	.250
397.	.251
407.	.252
417.	.253
427.	.254
437.	.255
447.	.255
457.	.256
467.	.257
477.	.257
487.	.258
497.	.259
507.	.260
517.	.260

Natural Rhyolite: High Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
497.	.264
507.	.262
517.	.262
527.	.262
537.	.261
547.	.261
557.	.261
567.	.261
577.	.262
587.	.261
597.	.261
607.	.264
617.	.265
627.	.264
637.	.262
647.	.261
657.	.261
667.	.262
677.	.263
687.	.265
697.	.269

Rhyolite: MOD 2, Low Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
67.	.206
77.	.211
87.	.215
97.	.220
107.	.226
117.	.224
127.	.225
137.	.227
147.	.228
157.	.230
167.	.232
177.	.234
187.	.236
197.	.237
207.	.239
217.	.241
227.	.242
237.	.244
247.	.245
257.	.247
267.	.249
277.	.250
287.	.252

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
297.	.253
307.	.255
317.	.256
327.	.258
337.	.259
347.	.261
357.	.262
367.	.264
377.	.265
387.	.266
397.	.268
407.	.270
417.	.272
427.	.274
437.	.277
447.	.281
457.	.287
467.	.298
477.	.318
487.	.357
497.	.416
507.	.413
517.	.348

Rhyolite: MOD2, High Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
504.	.339
514.	.340
524.	.339
534.	.339
544.	.339
554.	.339
564.	.340
574.	.339
584.	.339
594.	.339
604.	.340
614.	.340
624.	.341
634.	.342
644.	.342
654.	.342
664.	.342
674.	.344
684.	.347
694.	.357
704.	.343

Rhyolite: MOD3, Low Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
67.	.213
77.	.221
87.	.231
97.	.247
107.	.262
117.	.247
127.	.236
137.	.233
147.	.232
157.	.233
167.	.234
177.	.234
187.	.236
197.	.237
207.	.238
217.	.239
227.	.241
237.	.242
247.	.244
257.	.245
267.	.247
277.	.248
287.	.250
297.	.250
307.	.251
317.	.255
327.	.257
337.	.257
347.	.259
357.	.264
367.	.265
377.	.267
387.	.269
397.	.276
407.	.283
417.	.288
427.	.302
437.	.321
447.	.340
457.	.355
467.	.351
477.	.342
487.	.338
497.	.338
507.	.337
517.	.339

Rhyolite: MOD3, High Temperature Scan

<u>T(C)</u>	<u>Cp(cal/g-C)</u>
504.	.324
514.	.326
524.	.326
534.	.325
544.	.326
554.	.325
564.	.325
574.	.324
584.	.324
594.	.323
604.	.323
614.	.321
624.	.319
634.	.317
644.	.316
654.	.315
664.	.314
674.	.313
684.	.312
694.	.313
704.	.315

•COS2P
302/1005

Figure 2

•MOD2AP
7/23/1985

Figure 3

•MOD3AP
202/1985

Figure 4

•COSIP
302/1985

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: October 14, 1985

to: T. Y. Chu - 6242

M. Moss *J. N. Sweetman*

from: M. Moss and Greg Haseman - 1824

subject: Thermal Conductivity of Rhyolitic Obsidian (Case 1360.010)

One of the two samples of rhyolitic obsidian (both No. 3) was measured in the Dynatech compsrator. The other sample was not suitable for measurement. Since rhyolitic obsidian softens at approximately 650°C, mean sample temperatures no higher than 600°C were used.

The thermal conductivity data are shown in Fig. 1. The hand-drawn curve is accurate to approximately $\pm 7\%$. The data lie between those for Pyrex and fused silica (Ref. SAND82-0109). The temperature dependence of the conductivity is characteristic of a glass.

MM/GM:1824:jh

Copy to:

1820 R. E. Whan

1824 J. N. Sweet

6242 J. C. Dunn

Figure 1. Thermal conductivity of rhyolitic obsidian No.3.

Sample Length = 9956
Motor Fuel #2
K°C V.N.

$$\Delta U_{kn} = \Delta m - \Delta s + \bar{z}_{ref}$$

At: 25°C
 $\Delta m =$ _____
 $\Delta_{ref} = 0.000015$
 0.000015

At: 700°C
 $\Delta m = 0.00317$
 $\Delta_{ref} = 0.00361$
 0.00361

$$\alpha = \frac{\Delta L}{L} \times \frac{1}{\Delta T} = \frac{0.035295}{.9456} \times \frac{1}{617}$$

$$\alpha = 52.365 \times 10^{-7} \text{ from } 23^\circ \text{ to } 700^\circ$$

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: January 29, 1986

to: Bob Wemple - 6242

E. P. Roth A. J. Anaya

from: E.P. Roth, A.J. Anaya - 1824

subject: Determination of Thermal Conductivity of Obsidian Dome Granite

The thermal conductivity of an obsidian dome granite (1760 ft. depth) was determined from the measurement of specific heat and thermal diffusivity. The specific heat was measured using differential scanning calorimetry, while the diffusivity was measured using the laser flash diffusivity apparatus. The samples were measured from R.T. to 500 C and the data compared to thermal conductivity data obtained for the same material on the thermal comparator by M. Moss, 1824.

Figure 1 shows the specific heat data obtained for two scans on the same sample. The first scan showed a slight water release at 100 C followed by a broad endotherm centered at 260 C. A second scan showed no water release but a sharper endotherm starting at 250 C. Repeat measurements were made on a second sample which had almost identical behavior as the first sample. It is not clear what gives rise to the endothermic transition.

Figure 2 shows the thermal diffusivity data. Three temperature scans were made as indicated in the figure. Scans 2 and 3 showed reduced diffusivity compared to scan 1. Measurement of the sample density showed that the density dropped from 2.343 g/cm³ to 2.198 g/cm³ after the first temperature scan. Cracking and void formation would account for the decrease in density and would also result in increased thermal resistance, causing the reduction in diffusivity.

Figure 3 shows the thermal conductivity values calculated from the diffusivity, specific heat, and density. The drop in thermal conductivity follows the measured reduction in diffusivity. Figure 4 shows a comparison of our thermal conductivity values and the thermal conductivity data obtained directly with the thermal comparator. The initial values of thermal

conductivity agree within a few percent. However, our repeat measurements gave lower values of thermal conductivity than did the comparator. These variations may arise from differences in the size of the samples used in the two measurements: the diffusivity samples were thin 0.5 inch discs while the comparator samples were thick circular slabs almost 2 inches in diameter. Differences in internal stresses could account for different cracking patterns.

Tabulated values of specific heat, diffusivity, and thermal conductivity are given in Table I.

Copies:

R.E. Whan	- 1820
J.N. Sweet	- 1824
T.Y. Chu	- 6242

Table I.

Specific Heat:

	T(C)	Cp(cal/g-C)
1	.4685E+02	.1797E+00
2	.4885E+02	.1808E+00
4	.5285E+02	.1825E+00
5	.5485E+02	.1837E+00
6	.5685E+02	.1849E+00
7	.5885E+02	.1855E+00
8	.6085E+02	.1859E+00
9	.6285E+02	.1858E+00
10	.6485E+02	.1866E+00
11	.6685E+02	.1876E+00
12	.6885E+02	.1884E+00
13	.7085E+02	.1889E+00
14	.7285E+02	.1895E+00
15	.7485E+02	.1906E+00
16	.7685E+02	.1912E+00
17	.7885E+02	.1916E+00
18	.8085E+02	.1915E+00
19	.8285E+02	.1925E+00
20	.8485E+02	.1932E+00
21	.8685E+02	.1931E+00
22	.8885E+02	.1935E+00
23	.9085E+02	.1944E+00
24	.9285E+02	.1955E+00
25	.9485E+02	.1957E+00
26	.9685E+02	.1960E+00
27	.9885E+02	.1966E+00
29	.1028E+03	.1984E+00
30	.1048E+03	.1991E+00
31	.1068E+03	.1992E+00
32	.1088E+03	.1995E+00
33	.1108E+03	.2001E+00
34	.1128E+03	.2010E+00
35	.1148E+03	.2013E+00
36	.1168E+03	.2020E+00
37	.1188E+03	.2032E+00
38	.1208E+03	.2031E+00
39	.1228E+03	.2032E+00
40	.1248E+03	.2042E+00
41	.1268E+03	.2043E+00
42	.1288E+03	.2048E+00
43	.1308E+03	.2056E+00
44	.1328E+03	.2059E+00
45	.1348E+03	.2063E+00
46	.1368E+03	.2065E+00
47	.1388E+03	.2072E+00
48	.1408E+03	.2074E+00
49	.1428E+03	.2074E+00
50	.1448E+03	.2081E+00
51	.1468E+03	.2085E+00
52	.1488E+03	.2092E+00
54	.1528E+03	.2101E+00
55	.1548E+03	.2105E+00
56	.1568E+03	.2112E+00
57	.1588E+03	.2119E+00

58	.1608E+03	.2118E+00
59	.1628E+03	.2123E+00
60	.1648E+03	.2126E+00
61	.1668E+03	.2133E+00
62	.1688E+03	.2133E+00
63	.1708E+03	.2141E+00
64	.1728E+03	.2144E+00
65	.1748E+03	.2146E+00
66	.1768E+03	.2155E+00
67	.1788E+03	.2159E+00
68	.1808E+03	.2167E+00
69	.1828E+03	.2170E+00
70	.1848E+03	.2175E+00
71	.1868E+03	.2181E+00
72	.1888E+03	.2185E+00
73	.1908E+03	.2188E+00
74	.1928E+03	.2202E+00
75	.1948E+03	.2206E+00
76	.1968E+03	.2209E+00
77	.1988E+03	.2216E+00
79	.2028E+03	.2220E+00
80	.2048E+03	.2223E+00
81	.2068E+03	.2222E+00
82	.2088E+03	.2224E+00
83	.2108E+03	.2222E+00
84	.2128E+03	.2230E+00
85	.2148E+03	.2239E+00
86	.2168E+03	.2234E+00
87	.2188E+03	.2232E+00
88	.2208E+03	.2237E+00
89	.2228E+03	.2241E+00
90	.2248E+03	.2241E+00
91	.2268E+03	.2242E+00
92	.2288E+03	.2251E+00
93	.2308E+03	.2255E+00
94	.2328E+03	.2253E+00
95	.2348E+03	.2257E+00
96	.2368E+03	.2266E+00
97	.2388E+03	.2273E+00
98	.2408E+03	.2276E+00
99	.2428E+03	.2281E+00
100	.2448E+03	.2292E+00
101	.2468E+03	.2301E+00
102	.2488E+03	.2311E+00
104	.2528E+03	.2338E+00
105	.2548E+03	.2368E+00
106	.2568E+03	.2416E+00
107	.2588E+03	.2479E+00
108	.2608E+03	.2521E+00
109	.2628E+03	.2518E+00
110	.2648E+03	.2493E+00
111	.2668E+03	.2461E+00
112	.2688E+03	.2440E+00
113	.2708E+03	.2431E+00
114	.2728E+03	.2414E+00
115	.2748E+03	.2400E+00
116	.2768E+03	.2390E+00
117	.2788E+03	.2386E+00
118	.2808E+03	.2384E+00
119	.2828E+03	.2378E+00

120	.2848E+03	.2366E+00
121	.2868E+03	.2362E+00
122	.2888E+03	.2363E+00
123	.2908E+03	.2363E+00
124	.2928E+03	.2364E+00
125	.2948E+03	.2362E+00
126	.2968E+03	.2360E+00
127	.2988E+03	.2361E+00
129	.3028E+03	.2354E+00
130	.3048E+03	.2354E+00
131	.3068E+03	.2352E+00
132	.3088E+03	.2350E+00
133	.3108E+03	.2352E+00
134	.3128E+03	.2352E+00
135	.3148E+03	.2352E+00
136	.3168E+03	.2350E+00
137	.3188E+03	.2350E+00
138	.3208E+03	.2350E+00
139	.3228E+03	.2355E+00
140	.3248E+03	.2355E+00
141	.3268E+03	.2356E+00
142	.3288E+03	.2363E+00
143	.3308E+03	.2363E+00
144	.3328E+03	.2363E+00
145	.3348E+03	.2365E+00
146	.3368E+03	.2363E+00
147	.3388E+03	.2367E+00
148	.3408E+03	.2368E+00
149	.3428E+03	.2368E+00
150	.3448E+03	.2365E+00
151	.3468E+03	.2370E+00
152	.3488E+03	.2373E+00
154	.3528E+03	.2377E+00
155	.3548E+03	.2377E+00
156	.3568E+03	.2377E+00
157	.3588E+03	.2377E+00
158	.3608E+03	.2379E+00
159	.3628E+03	.2385E+00
160	.3648E+03	.2387E+00
161	.3668E+03	.2391E+00
162	.3688E+03	.2389E+00
163	.3708E+03	.2386E+00
164	.3728E+03	.2392E+00
165	.3748E+03	.2393E+00
166	.3768E+03	.2391E+00
167	.3788E+03	.2397E+00
168	.3808E+03	.2404E+00
169	.3828E+03	.2406E+00
170	.3848E+03	.2408E+00
171	.3868E+03	.2408E+00
172	.3888E+03	.2408E+00
173	.3908E+03	.2409E+00
174	.3928E+03	.2414E+00
175	.3948E+03	.2419E+00
176	.3968E+03	.2426E+00
177	.3988E+03	.2431E+00
179	.4028E+03	.2429E+00
180	.4048E+03	.2432E+00
181	.4068E+03	.2436E+00
182	.4088E+03	.2441E+00

183	.4108E+03	.2448E+00
184	.4128E+03	.2452E+00
185	.4148E+03	.2453E+00
186	.4168E+03	.2458E+00
187	.4188E+03	.2465E+00
188	.4208E+03	.2462E+00
189	.4228E+03	.2459E+00
190	.4248E+03	.2461E+00
191	.4268E+03	.2467E+00
192	.4288E+03	.2470E+00
193	.4308E+03	.2470E+00
194	.4328E+03	.2476E+00
195	.4348E+03	.2477E+00
196	.4368E+03	.2479E+00
197	.4388E+03	.2482E+00
198	.4408E+03	.2488E+00
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200	.4448E+03	.2494E+00
201	.4468E+03	.2502E+00
202	.4488E+03	.2505E+00
204	.4528E+03	.2510E+00
205	.4548E+03	.2506E+00
206	.4568E+03	.2508E+00
207	.4588E+03	.2514E+00
208	.4608E+03	.2522E+00
209	.4628E+03	.2524E+00
210	.4648E+03	.2523E+00
211	.4668E+03	.2524E+00
212	.4688E+03	.2528E+00
213	.4708E+03	.2529E+00
214	.4728E+03	.2531E+00
215	.4748E+03	.2538E+00

Thermal Diffusivity:

Scan 1

T(C) diffusivity(cm²/sec)

49	.008945
55	.00906
120	.008128
132	.00831
204	.007842
279	.00679
358	.00584
416	.005
489	.00536

Scan 2

T(C) diffusivity(cm²/sec)

166	.006855
266	.00565
347	.005606
358	.0056451
421	.00574
490	.00561

Scan 3

T(C) diffusivity(cm²/sec)

58	.007547
134	.006834
208	.006504
317	.005767

Thermal Conductivity:

Scan 1

T(C)	K(Watt/cm-C)
4.90000E+01	1.63015E-02
5.50000E+01	1.67420E-02
1.20000E+02	1.63492E-02
1.32000E+02	1.69861E-02
2.04000E+02	1.72355E-02
2.79000E+02	1.60349E-02
3.58000E+02	1.37925E-02
4.16000E+02	1.42298E-02
4.89000E+02	1.39000E-02

Scan 2

T(C)	K(Watt/cm-C)
1.66000E+02	1.35750E-02
2.66000E+02	1.29823E-02
3.47000E+02	1.23748E-02
3.58000E+02	1.25082E-02
4.21000E+02	1.31679E-02
4.90000E+02	1.37000E-02

Scan 3

T(C)	K(Watt/cm-C)
5.80000E+01	1.31633E-02
1.34000E+02	1.31360E-02
2.08000E+02	1.34339E-02
3.17000E+02	1.26024E-02

Figure 1

W00030

WGR2AP

NGRA1

WGRA1

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: December 5, 1985

to: R. P. Wemple - 6242

Ok. Wm. J. M. Haseman

from: M. Moss and G. M. Haseman - 1824

subject: Thermal Conductivity of Granite Core from Obsidian Dome
(Case 1540.030)

The thermal conductivity of your sample of the granite core from Obsidian Dome (1760 ft.) was measured with the Dynatech comparator (ref. SAND82-0109).

As shown in Fig. 1, upon first heating the conductivity fell with increasing temperature, and stabilized at around 650K. Upon cooling from 773K, a lower path was traced which was then retraced in a second heating/cooling cycle. It seems likely that the higher initial conductivity was due to the presence of fluid (water?) in the pores. Once the fluid was driven off, the conductivity dropped to levels characteristic of the dry, porous material. However, the variation of conductivity with temperature of the dry rock is not typical of most geologic materials, viz., the rapid fall in the region of 473 to 573K. This is not understood.

The sample lost 0.25g during measurement, presumably pore fluid. Its final density was 2.23g/cc. If the grain density is assumed to be that measured in our lab for granite-like quartzo-feldspathic tuff (2.6g/cc), then the calculated porosity is 14%. This void volume is an order of magnitude larger than that represented by the water (?) loss - the rock was not nearly saturated. Based upon a model previously developed for saturated tuff, this rock could be expected to have a room-temperature conductivity of approximately $2 \text{ Wm}^{-1}\text{K}^{-1}$ if it were fully water-saturated.

MM/GMH:1824:jh

Copy to:

1820 R. E. Whan
1824 J. N. Sweet
6242 J. C. Dunn

Figure 1 Thermal conductivity of granite core from Obsidian Dome (1760 ft). Solid curve represents heating (H) and cooling (C), first cycle. Dashed curve represents heating and cooling, second cycle.

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