STUDY OF ABRASIVE TECHNIQUES FOR LUNAR AND PLANETARY SOLID ROCK GEOGOLOGICAL SAMPLING

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

STUDY OF ABRASIVE TECHNIQUES FOR LUNAR AND PLANETARY GEOLOGICAL SAMPLING

by

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SUMMARY

This final technical report discusses research by the Norton Exploratory Research Division of National Research Corporation for the Jet Propulsion Laboratory, under subcontract 951422 of NASA contract NAS 7-100, Task RD-4. Work was conducted during the period November 3, 1965 to May 26, 1967.

Abrasive techniques were experimentally studied at atmospheric pressure for producing rock powders suitable for automated lunar and planetary geological analysis. Diamond grinding wheels and tungsten carbide milling cutters were employed on fine grained basalt, without a coolant, utilizing a surface grinder. Both novel and conventional techniques were tried. A vacuum chamber was designed for conducting intended future grinding experiments at about 10^{-4}Torr.

Grinding by simple vertical penetration was found feasible for producing, without auxiliary sorting, particle sizes suitable for x-ray diffractometry. This method utilized a grinding cam to maintain a fixed grinding contact area. Particle sizes were altered by changing grit size and wheel speed, e.g., powder weight in the generally desirable 0-20μ range was varied from 32% to 65% by changing grit size from 60 to 100, respectively, while maintaining wheel speed at 400 rpm. Wheel wear was small, less than 0.3% of the powder weight. A metallic binder was found to be the optimum wheel bonding agent.

Alteration of conventional grinding parameters was considerably less effective in concentrating powders in the 75-150μ range for petrographic microscopy. Abrasive techniques other than vertical grinding and conventional traverse grinding were therefore investigated. Through a method of grinding parallel ridges and subsequently milling them, considerably greater control was effected; ridge height and width were the primary new controlling parameters. The method produced 17% of the powder weight between 74 and 150μ, 71% between 44 and 420μ. Further development is necessary to produce useable distributions. Automating this method for securing both x-ray and microscopic specimens is discussed.

INTRODUCTION

Martian and lunar surfaces are believed covered by silicate powders underlain by solid rock. To analyze these strata for minerology, automated x-ray diffractometry and petrographic microscope experiments are being planned.[1,2,3] An investigation of the feasibility of using abrasive techniques for the acquisition of suitable specimens is reported here.

Central to the task is the fragmentation of the solid rock into desirable size distributions, approximately within the range 1-20μ for x-ray analysis and within the range 75-150μ for microscopic analysis. About 50% of the specimen is required in the indicated ranges; for microscopy, it is also desired that less than 20% be smaller than 44μ and that less than 5% be larger than 300μ. The distributions preferably should be obtained by abrasion alone to simplify preparation and to preserve the rock's minerological proportions; since minerals fragment into unique size distributions, sieving might alter their representation. Among other requirements and conditions are the following: (1) Size distributions must be largely invariant with rock type, (2) Grinding must proceed without a coolant while leaving specimens unaltered by heating, (3) Specimen contamination, either by grinding wheel wear or by overlying powder must be negligible, (4) Acquisition must occur in vacuum, about 5 Torr and 10^{-10} Torr for martian and lunar environments, respectively, (5) Flight hardware constraints must be met regarding weight, size and power; the respective figures for a Mars probe are 8 lbs, 0.5 ft.^{3} and 50 watts.

Experimentation with several grinding techniques in air is reported here, most novel of which are (a) a grinding cam and (b) ridge and groove surface preparation followed by milling. Their feasibility for producing the required particle size distributions is evaluated. Wheel wear was also investigated and a chamber for vacuum grinding designed. Flight hardware constraints have been given minimal attention. Production of the larger size distribution early proved the more difficult challenge and consumed most of the effort.

APPARATUS

Basic Components and Materials

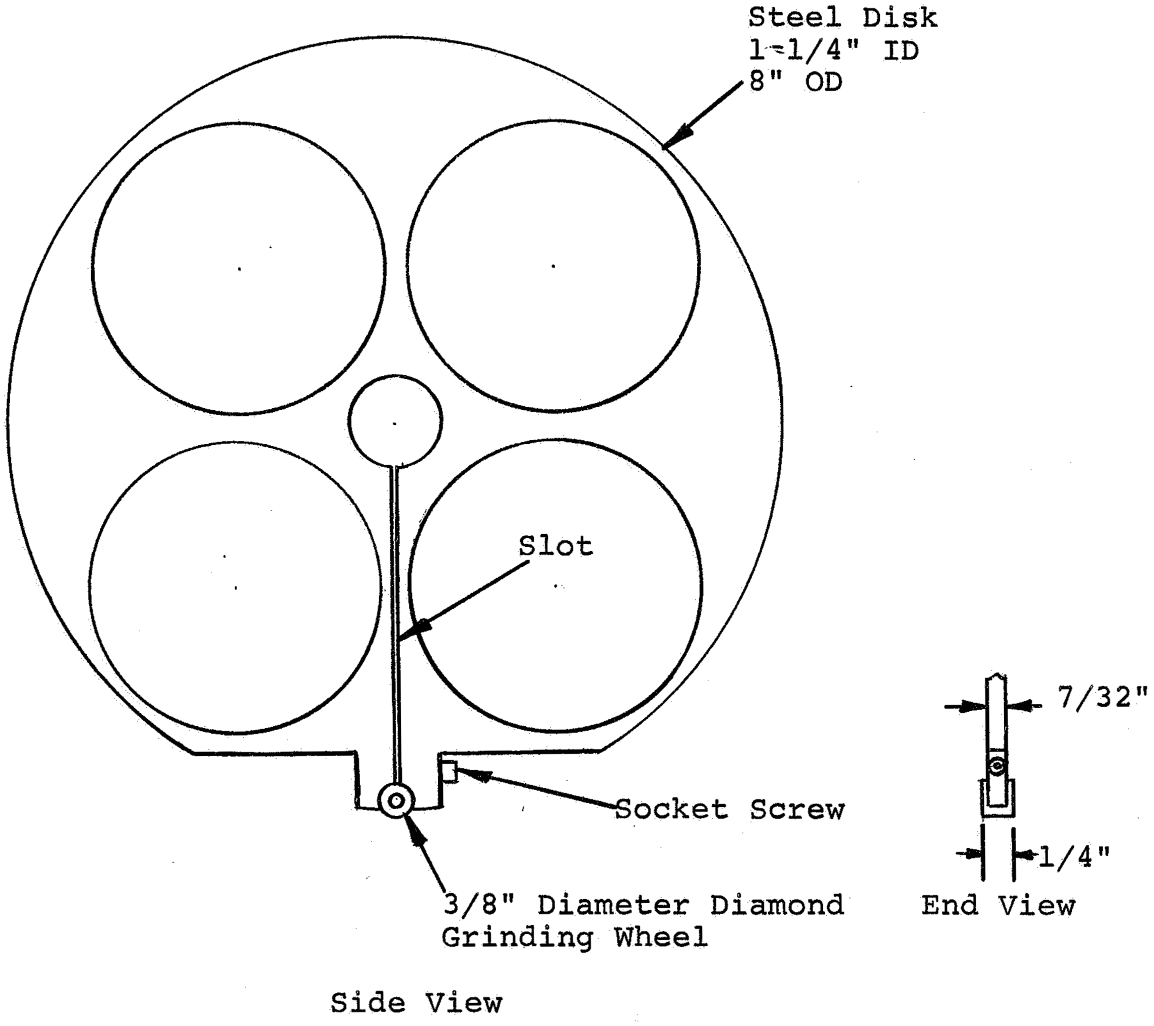
Experiments were conducted on Norton surface grinders with the rock held in a hand vise mounted on a magnetic chuck; an exception was one experiment conducted on a lathe. A surface grinder was used instead of a lighter unit to establish good control of grinding parameters, to permit traverse grinding, and to permit utilization of positive feed, i.e., worm controlled feed rather than spring controlled, in simple vertical grinding. The latter was preferred in the cam design, to be described, because it prevented "bumpy" grinding. Vertical feed, longitudinal feed and cross feed were manually adjustable to within one ten thousanth of an inch. The longitudinal feed was hydraulic in the automatic mode. Vertical feed was automated with a variable speed d.c. motor. Grinding wheel speed was variable and was monitored with a trachometer.

Rock specimens consisted of fine grained, black, unweathered basalt from Lintz, Rhenish Prussia. Basalt was used because, as a widely distributed igneous rock, it is believed representative of the moon's surface; it is commonly used in lunar soil simulation experiments.

Three inch diameter sieves were used for analyzing powder size distributions. Other sorting mechanisms, with the exception of microscopy, were ruled out because they require a constant particle specific gravity, which cannot be expected of a multimineral rock. A photo-etched stainless steel sieve was used for the 20μ size. Brass wire woven sieves were used for larger sizes. A Cenco-Meinzer sieve shaker was used when particles under 44μ were of primary interest, specimens 1 through 7, to be discussed. Its motion, combining tilting with rotation, is considered more reliable in this range. (The accuracy of sieving below 37μ, considered dubious by some, was not investigated in this work.) A Tyler "Ro-Tap" sieve shaker, combining tapping with rotation, was used thereafter when larger sizes were of primary interest.

The Grinding Cam

The initial grinding studies employed a configuration sketched in Fig. 1, a grinding cam. The cam consists of a 7/32 inch thick, 8 inch diameter steel disk to the perimeter of which a 3/8 inch diameter, 1/4 inch thick diamond wheel is attached.



Side View

End View

FIG. 1. GRINDING CAM

The disk is slotted to permit adjusting the grip on the diamond wheel, which is secured with a socket screw. The circular excisions in the disk served to reduce its weight. The cam is secured to the surface grinder shaft through the 1-1/4 inch i.d. center hole.

The cam grinding configuration was designed for the following reasons:

(a) To maintain a grinding area independent of penetration depth when using simple vertical grinding motion. An invariant grinding pressure can then accompany a fixed vertical force or a fixed vertical penetration rate, thus helping to keep particle sizes invariant.

(b) To reduce the production of small particles and narrow the size spread by using a small grinding area.

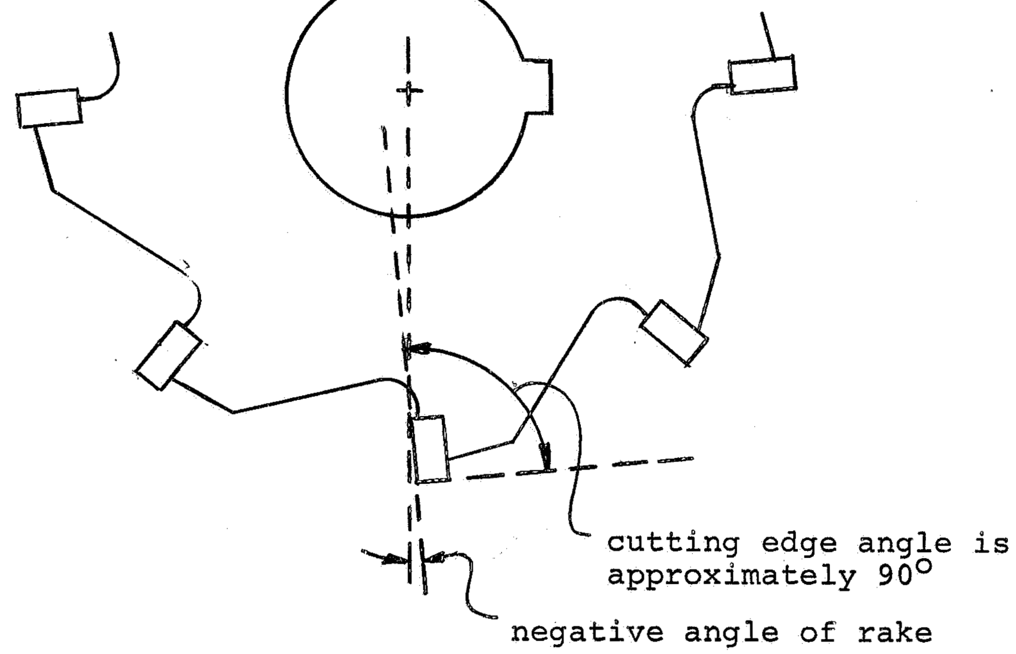
(c) To facilitate the removal of loose material overlying the solid rock through use of one or more protuberances. It also permits, if needed, the use of brushes between protuberances for sweeping away the vestiges of overlying powder, to reduce contamination of the abraded solid rock.

The 3/8 inch diameter grinding wheels varied from 16 grit to 100 grit to permit testing the effect of grit size on powder distribution. Diamond grit was selected for its low rate of wear. Vitreous bonds were initially used to minimize potential x-ray analytical confusion over the origins of trace elements; both resinoid and metallic bonds contain materials sought in rock analysis. After discovering a low wear rate, the bond was changed to a metallic one. Medium hardness bonds (Norton grade "N") were used in all grinding wheels as a compromise between abrasive contamination and rock particle heating. The latter is known to increase with increased bond strength, as well as with increased wheel speed and decreased grit size.

Traverse Grinding Components

Following the cam grinding experiments, only metal bonded diamond wheels were used. Pertinent dimensions are discussed with the associated procedures. In milling experiments, a tungsten carbide, 4 inch diameter, 8 tooth, 3/8 inch thick cutter was used (Super Tool Co. No 4-ST-3). The teeth had a negative rake angle as shown in Fig. 2a; the cutting edge was formed by an angle close to a 90° angle. In addition to these "flat tooth" milling cutters, a "wedge tooth" milling cutter was used, the 90° angle ground to a 20° angle as shown in Fig. 2b.

(a) "Flat Tooth" cutter



(b) "Wedge Tooth" cutter

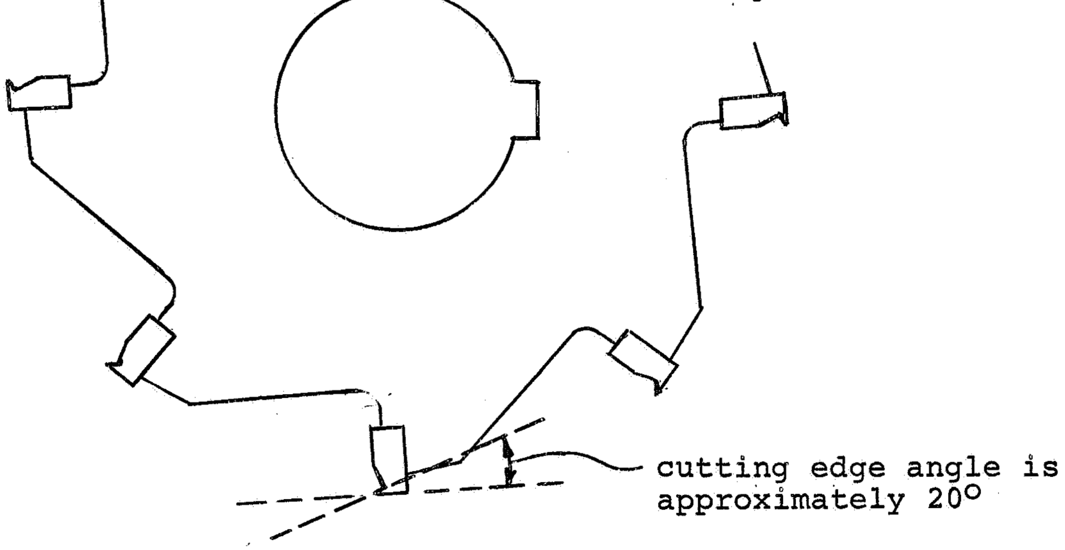


FIG. 2. MILLING CUTTER TEETH

Vacuum Grinding Chamber

A vacuum chamber was designed in which to perform future grinding experiments with the cam configuration. Fig. 3 and Fig. 4 show side and front views respectively. Fig. 5 shows a rotary vacuum seal alternative to that in Fig. 3. The chamber design includes a 18 inch diameter, 12 inch long bell jar coupled by a butyl elastomer gasket to an 18 inch diameter, 9 inch long, steel cylinder. The chamber's back plate is flat. The chamber was designed to be supported by, and thus to move with, the surface grinder shaft housing. All grinding components are contained within the cylinder, with the bell jar permitting an unobstructed view of grinding; its removal permits complete accessibility without disturbing grinding mechanism adjustments.

The rotary seal of Fig. 3, one of two alternative designs, uses conventional components: two elastomer seals are fixed to the shaft housing, which is welded to the vacuum chamber. Oil would be continuously pumped between the seals for cooling and lubrication. Atmospheric pressure pushes the elastomer seal on the right against the rotary shaft and against a shoulder on the shaft housing to assist sealing.

The magnetic rotary seal shown in Fig. 5, manufactured by the Magnetic Seal Corporation, appears far superior to the above, but is less common in high vacuum work and a considerable manufacturer's delay exists in supplying them; the previously described grease seal was therefore designed as a stand-by. Seals are mounted on the chamber using a seal plate, which is adjustable for seal to shaft alignment and made vacuum tight by an O-ring in the back plate. The magnetic seal appears ideal for vacuum grinding. It uses no oil and its small thickness permits its use on a standard grinding collet, although not illustrated that way in Fig. 5. The manufacturer claims the seal to be useable to a speed of 1300 feet per minute. The seal utilizes a magnetized ring fixed to the housing with an o-ring; a second ring is similarly sealed to the rotary component. The rotary sealing surfaces are carbon on metal, held in contact by either magnetic force or atmospheric pressure. Because the rotary part of the seal can maintain contact independent of shaft vibration, great vibrational tolerance should exist.

In the experimental arrangement shown in Fig. 4, the cam is off-center and penetrating two inches of powder covering the rock. A vise holds the rock in a pan with the loose overlying powder. Room remains for placing a collecting cup to the cam's left above the powder surface. The arrangement was designed to permit experimentation with powder collection in vacuum. This includes testing of the cam's effectiveness for clearing away powder adjacent to, as well as above, the rock grinding site. Effective clearance would

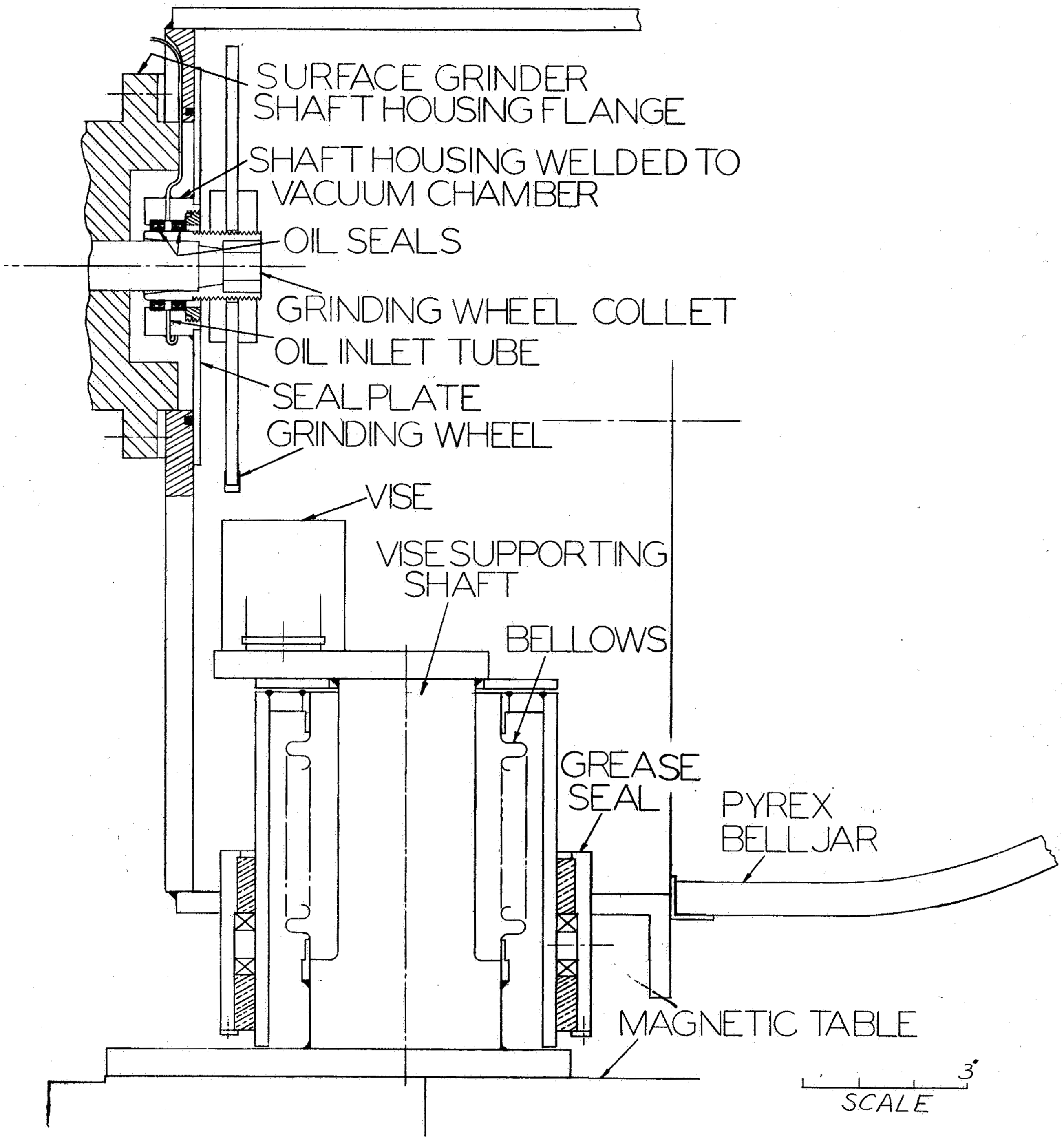


FIG. 3 SIDE VIEW OF VACUUM CHAMBER

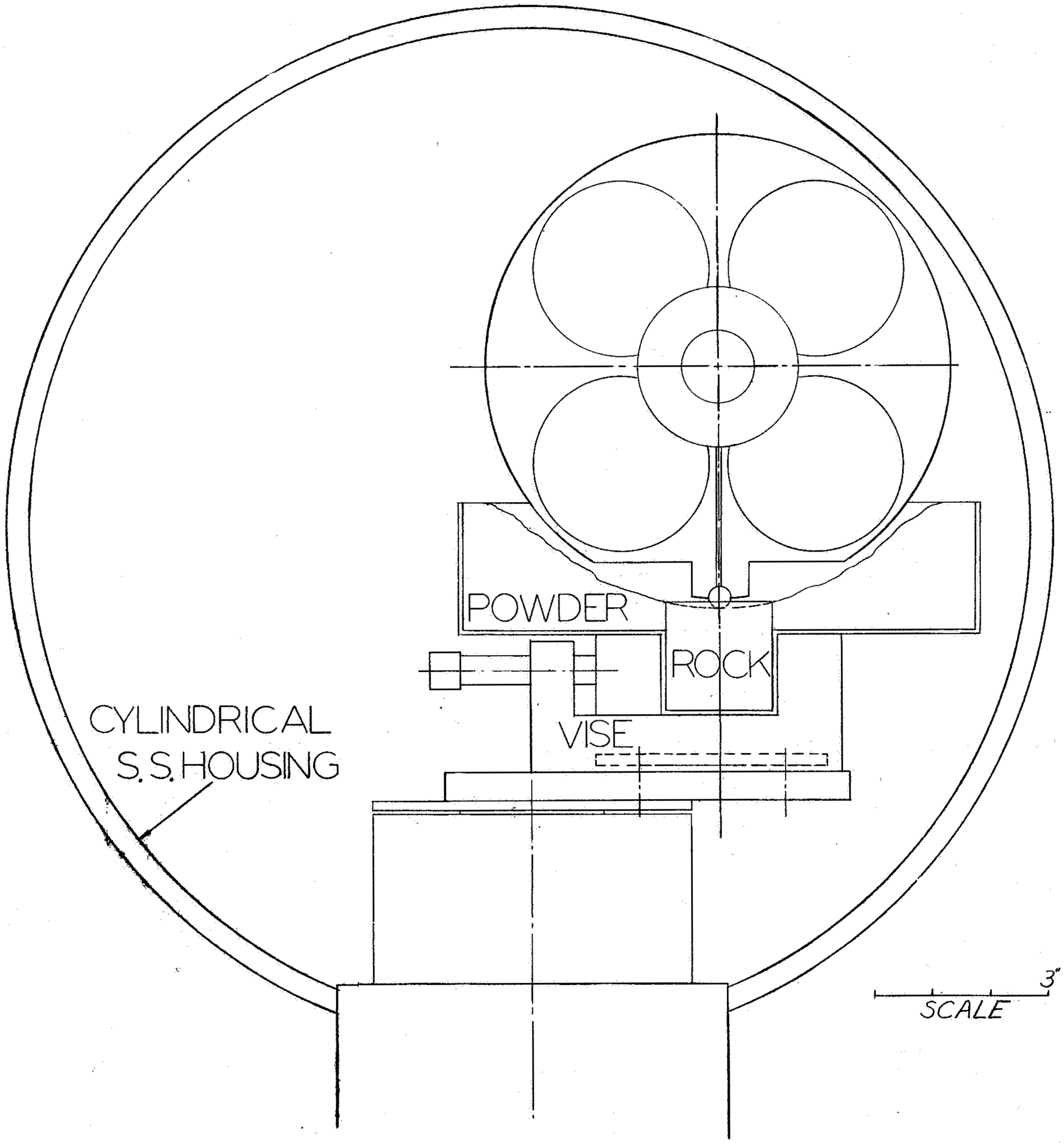


FIG. 4 FRONT VIEW OF VACUUM CHAMBER

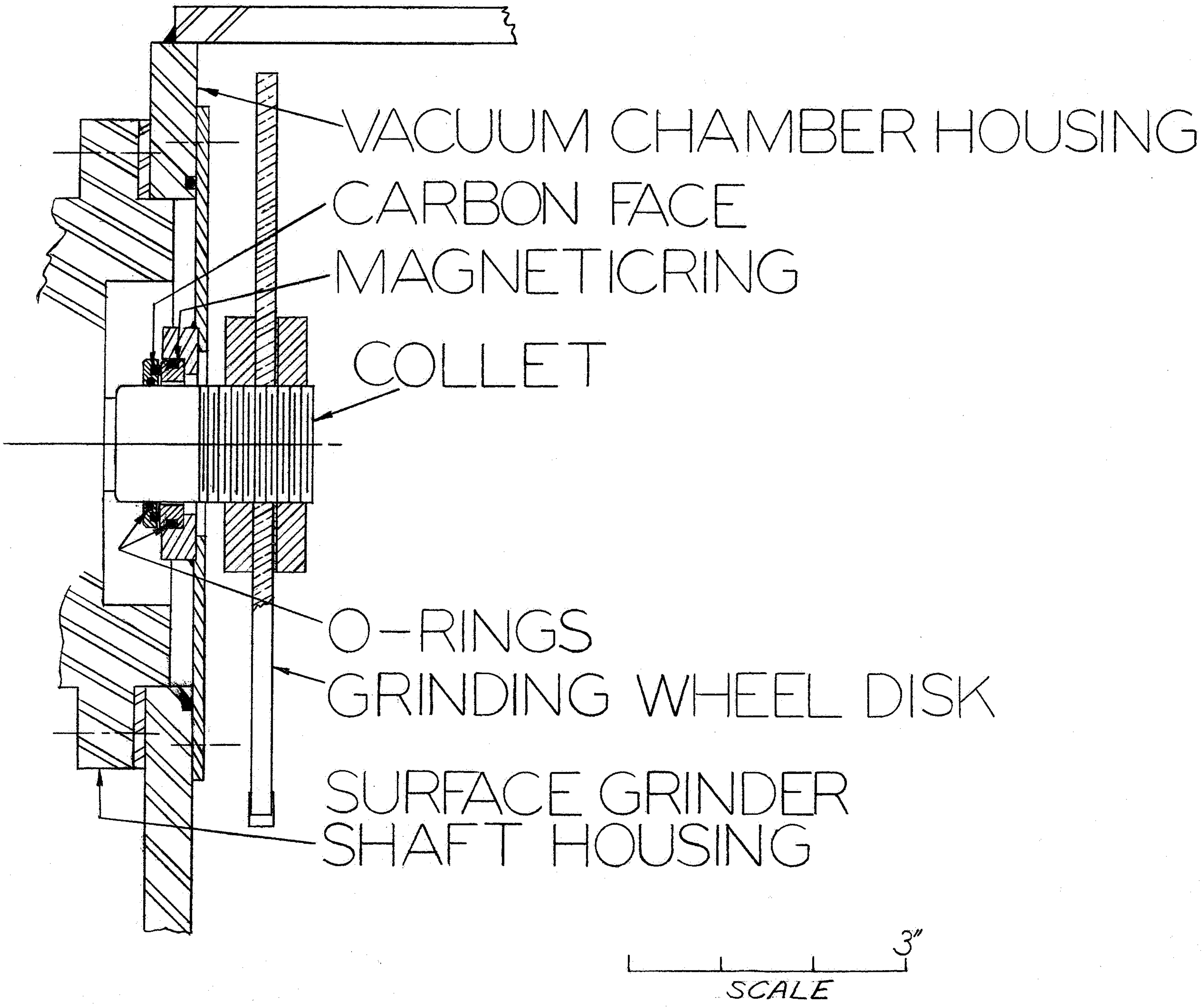


FIG. 5 MAGNETIC ROTARY SEAL

minimize contamination of the solid rock specimen by the overlying powder. It could be effected, if necessary, by grinding a small depth of rock on each side of the site in line with the powder trajectory.

To permit the above experimentation, a compound seal was designed to permit 2-1/2 inches of vertical motion between the grinding wheel and the rock and 1/2 inch of horizontal motion; this was accomplished with a bellows seal combined with a grease seal. The latter permits vertical motion by sliding a greased elastomer, attached to the vacuum chamber housing, against a stationary cylinder. The bellows, sealed to the cylinder at the top and to the vise supporting shaft at the bottom permits, by flexuring, lateral motion between shaft and cylinder.

All seal components were designed with commercially available components. The bell jar, cylindrical steel housing and magnetic seal were purchased.

EXPERIMENTAL PROCEDURES AND RESULTS

Cam Grinding

Experimentation was initiated with the cam method, using simple vertical penetration. Initially a vitreous bonded, 100 grit wheel was used at 400 rpm. Grinding was performed dry as in all subsequent experiments.

Wheel chipping and cracking problems occurred which were ultimately traced to a combination of mechanical and thermal stresses. The problems were overcome through the reduction of wheel speed, frequent wheel dressing, increased grit size and frequent rest periods; however, by far the best solution, was the use of a metal bonding matrix. The latter provides a conducting medium for dissipating the heat and, by virtue of its ductility, also reduces stresses in the wheel where it is clamped.

Prior to specimen acquisition, a flat surface was intentionally worn on new grinding wheels where they contacted the rock, to ensure an essentially constant contact area throughout the grinding of a single specimen; dimensions were typically 3/32 inch in length and 1/4 inch wide, the width of the wheel.

The grinding contact area was also used in computing the percentage of powder contamination by wheel wear, in conjunction with wheel density and the change in wheel radius. Five determinations with vitreous bonded wheels of 60 and 100 grit, gave wheel weight losses consistently less than 0.2 percent of the rock weight loss. This small wear permitted switching to metal bonded wheels. Less than 0.3 percent rock weight loss was measured with a 24 grit metal wheel, this value computed from wheel weighings before and after grinding.

Powder collection was a serious problem. Air currents, generated by grinding, scattered all but a small percentage of the powder. A plastic bag enclosing the rock and grinding wheel with an aperture left for the grinding shaft, ultimately proved the best solution. It usually permitted collecting, after sieving, of 80 to 85 percent of the total weight of the rock ground. This collection efficiency was determined with almost every size distribution determination. Where low efficiencies are indicated, it is probable that higher percentages of fine particles were produced than indicated, since fines appear both more easily blown away and more likely to adhere to container surfaces.

The amount of powder collected was usually between 1-1/2 and 3 grams. Powder typically was accumulated from along a 1-1/2 inch long path in about 5 minutes per gram, using a 50% duty cycle.

Table I shows the powder size distributions obtained. They are listed by the percent weight between sieve sizes, as a function of grit size, wheel speed and vertical penetration rate. The V and M following grit size denotes vitreous and metallic bonding respectively. Specimens 1-7 were sifted on the Cenco-Meinzer sieve shaker for 30 minutes each. Specimens 8 and 9 on the Tyler "Ro-Tap" sieve shaker for 20 minutes each. Vertical penetration was manually operated for specimens 1-3 and was motor driven thereafter. The grinding path length was 0 to 1-1/2 inches for specimens 1 and 2, but maintained at 1-1/2 inches thereafter; however, a comparison of specimens 2 and 3 show the distributions to be little affected by the path length.

Grit size variation was indicated to be the most effective means of altering particle size; the fraction of powder weight which fell below 20μ approximately doubled when the grit size was approximately halved, as seen by comparing specimen 1 with 4 and 2 with 6. Grinding speed is indicated to be next most effective; a comparison of specimen 4 with 5 and specimen 6 with 7 shows that the aforementioned fraction changed from 1/3 to 1/2 when grinding speed was tripled. Surprisingly, vertical penetration rate changes provided no consistent alteration in size distribution over the 3 to 1 speed range examined; this is seen by comparing specimens 1 with 2 or 3, specimen 4 with 6 and specimen 5 with 7.

Since grit size was the most sensitive parameter, a further enlargement was investigated to test control about the 74-149μ range which would be useful for the petrographic microscope. A

TABLE I. - RESULTS OF VERTICAL CAM GRINDING

<table>
<tr><th rowspan="3">Sp. No.</th><th colspan="5">Variables</th><th rowspan="3">Coll. Eff, (%)</th><th colspan="6">Powder Weight Distribution (% per micron category)</th></tr>
<tr><th rowspan="2">Pen. Speed (mils/sec.)</th><th rowspan="2">Wheel Speed (rpm</th><th colspan="2">Grit Size</th><th rowspan="2">Path Length (in.)</th><th rowspan="2">0 to 20</th><th rowspan="2">20 to 44</th><th rowspan="2">44 to 74</th><th rowspan="2">74 to 149</th><th rowspan="2">149 to 250</th><th rowspan="2">250 to ∞</th></tr>
<tr><th>No.</th><th>Diam. (μ)</th></tr>
<tr><td>1</td><td>0.1</td><td>400</td><td>100V</td><td>173</td><td>0-1.5</td><td>51</td><td>65</td><td colspan="5">← 35 →</td></tr>
<tr><td>2</td><td>0.3</td><td>400</td><td>100V</td><td>173</td><td>0-1.5</td><td>70</td><td>59</td><td colspan="5">← 41 →</td></tr>
<tr><td>3</td><td>0.3</td><td>400</td><td>100V</td><td>173</td><td>1.5</td><td>70</td><td>52</td><td>25</td><td colspan="4">← 23 →</td></tr>
<tr><td>4</td><td>0.1</td><td>400</td><td>60V</td><td>406</td><td>1.5</td><td>82</td><td>32</td><td>58</td><td colspan="4">← 10 →</td></tr>
<tr><td>5</td><td>0.1</td><td>1200</td><td>60V</td><td>406</td><td>1.5</td><td>74</td><td>47</td><td>35</td><td colspan="4">← 19 →</td></tr>
<tr><td>6</td><td>0.3</td><td>400</td><td>60V</td><td>406</td><td>1.5</td><td>75</td><td>35</td><td>38</td><td colspan="4">← 27 →</td></tr>
<tr><td>7</td><td>0.3</td><td>1200</td><td>60V</td><td>406</td><td>1.5</td><td>79</td><td>44</td><td>36</td><td colspan="4">← 20 →</td></tr>
<tr><td>8</td><td>0.3</td><td>400</td><td>24M</td><td>1035</td><td>1.5</td><td>91</td><td colspan="2">72</td><td>16</td><td>8</td><td>3</td><td>1</td></tr>
<tr><td>9</td><td>0.3</td><td>400</td><td>16M</td><td>1660</td><td>1.5</td><td>80</td><td colspan="2">61</td><td>15</td><td>13</td><td>7</td><td>4</td></tr>
</table>

comparison of specimens 3,6,8 and 9 shows that a further increase in large particles occurred with further increases in grit size; grit 16, the largest used, gave 13 percent in the most desirable range, as shown in specimen 9. However, the increase in large particles was small, e.g., the fraction of powder weight above 44µ increased by only 50% when grit diameter was increased by a factor of ten, as seen by comparing specimen 3 with 9. Appreciable increases in the fraction of powder in the 74-149µ range therefore appeared unlikely by altering further the three conventional grinding parameters. An investigation of other grinding techniques was begun instead.

Conventional Traverse Grinding

Traverse grinding employed a 4 inch diameter, 1/4 inch thick diamond wheel accompanied by conditions previously found most desireable: metal bonding, 16 grit diamond and 440 rpm wheel speed, near the lowest available. (An error caused a switch from 400 rpm to 440 rpm, which was maintained thereafter for traverse grinding consistency).

Table II shows the size distributions obtained by altering traverse speed and depth of cut per pass. Grinding was performed from right to left with the wheel rotating clockwise. An initial 4 mil* (100µ) depth of cut was used to approximate the desired particle size dimensions: a comparison of specimens 10, 11 and 12 show that an accompanying 36 to 1 variation in traverse speed had but a small effect on particle size; the two highest traverse speeds combined with the larger depths of cut, specimens 11 and 12, gave the most favorable results. Specimens 12 and 13 show that a variation in depth of cut also had little effect on the size distribution.

Conventional Traverse Milling

Qualitative experiments with a milling tool indicated larger particles than previously obtained. This visual examination of particles, acquired without bagging, proved deceptive. Table III shows that traverse milling gave particles smaller than obtained by grinding. In specimens 14 through 17, cut depth was varied, with the wheel speed held at 440 rpm and traverse spped held at 4 inches per minute. The latter speed was admittedly low, however; only 7µ could thereby be traversed between surface contacts by successive teeth.

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*Mil is used throughout the report as an abbreviation for 0.001 inch.

TABLE II. - RESULTS OF CONVENTIONAL TRAVERSE GRINDING

Sp. No.	Variables		Coll. Eff. (%)	Powder Weight Distribution (% per micron category)					
	Trav. Speed $\left(\frac{\text{in.}}{\text{Min.}}\right)$	Depth of Cut (mils)		0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to ∞
10	2	4	90	19	48	14	15	3	1
11	12	5	99	17	44	12	14	11	3
12	73	5	91	16	46	11	12	7	8
13	73	2	99	19	45	14	13	7	3

TABLE III. - RESULTS OF CONVENTIONAL TRAVERSE MILLING

Sp. No.	Variables			Coll. Eff. (%)	Powder Weight Distribution (% per micron category)					
	Trav. Speed $\left(\frac{\text{in.}}{\text{min.}}\right)$	Depth of Cut (mils)	Wheel Speed (rpm)		0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to ∞
14	4	2	440	85	34	55	5	0	0	4
15	4	5	440	88	27	58	10	1	0	4
16	4	10	440	50	15	57	17	6	1	4
17	4	25	440	--	24	45	16	6	1	8
18	1	5	22	--	15	40	20	3	1	22

Specimen 18 would appear to provide more useful information. This experiment was conducted with the milling cutter mounted on a lathe (the only time the surface grinder was not used) to test the effect of a very slow wheel speed, 22 rpm. The accompanying one inch per minute traverse speed allowed approximately a 150μ traverse between teeth. This was combined with a 5 mil (125μ) cut depth. A significant increase in particles above 250μ resulted (22%), but the percentage in the most desired range 74-149μ, remained small and below 44μ it remained too large. A radical change in abrasive techniques appeared necessary.

Side Abrasion

In this method, traverse grinding was conducted down the side of a rock, as shown in Fig. 6, rather than conventionally along a horizontal surface. The intent was to reduce the force holding together the rock particles being abraded, by eliminating support on one side. Specimen 19 in Table IV shows the results obtained with the 16 grit wheel used in previous traverse grinding experiments. Previously, the largest cut depths combined with the larger traverse speeds, specimens 11 and 12, of Table II, gave the best results. Therefore similar conditions were used here: cut depth was increased to 10 mils (250μ) and traverse speed set at 90 inches per minute. A 20 mil cut width, a new variable in side grinding, was tried initially. The wheel speed was kept at 440 rpm. Fifty-four percent below 44μ is a significant reduction compared with previous results, except for specimen 18 of Table II where the rest of the distribution was poor, while the distribution between 44μ and 250μ is comparable to the best previously obtained. The high collection efficiency at 92% adds credence to the increase in large particles.

A milling cutter with teeth ground into wedges, described in the apparatus section, was tried next in this mode, aimed at more chipping, and less crushing (the edges dulled rapidly with use; nonetheless they retained a wedge shape, or positive rake angle, throughout the experiments to be described). Other conditions were kept as above. A further size improvement resulted, shown in specimen 20. To separate the effects of side milling from those of wedge shaped teeth, the latter was used in a conventional traverse mode, as well, other conditions were kept as in specimens 19 and 20; the results are shown in Table IV for specimen 21. A comparison of specimens 21 and 20 shows that side grinding enhances the distribution obtained with wedge shaped teeth, as it did with the grinding wheel. A comparison of the results for specimen 21 with those of Table III, among which 18 is perhaps most comparable, indicates that wedge shape teeth also enhance the distribution.

In specimen 22, side grinding with wedge shaped teeth accompanied by reduced cut depth and cut width, to approximate more closely the ideal particle size, was examined. Fine

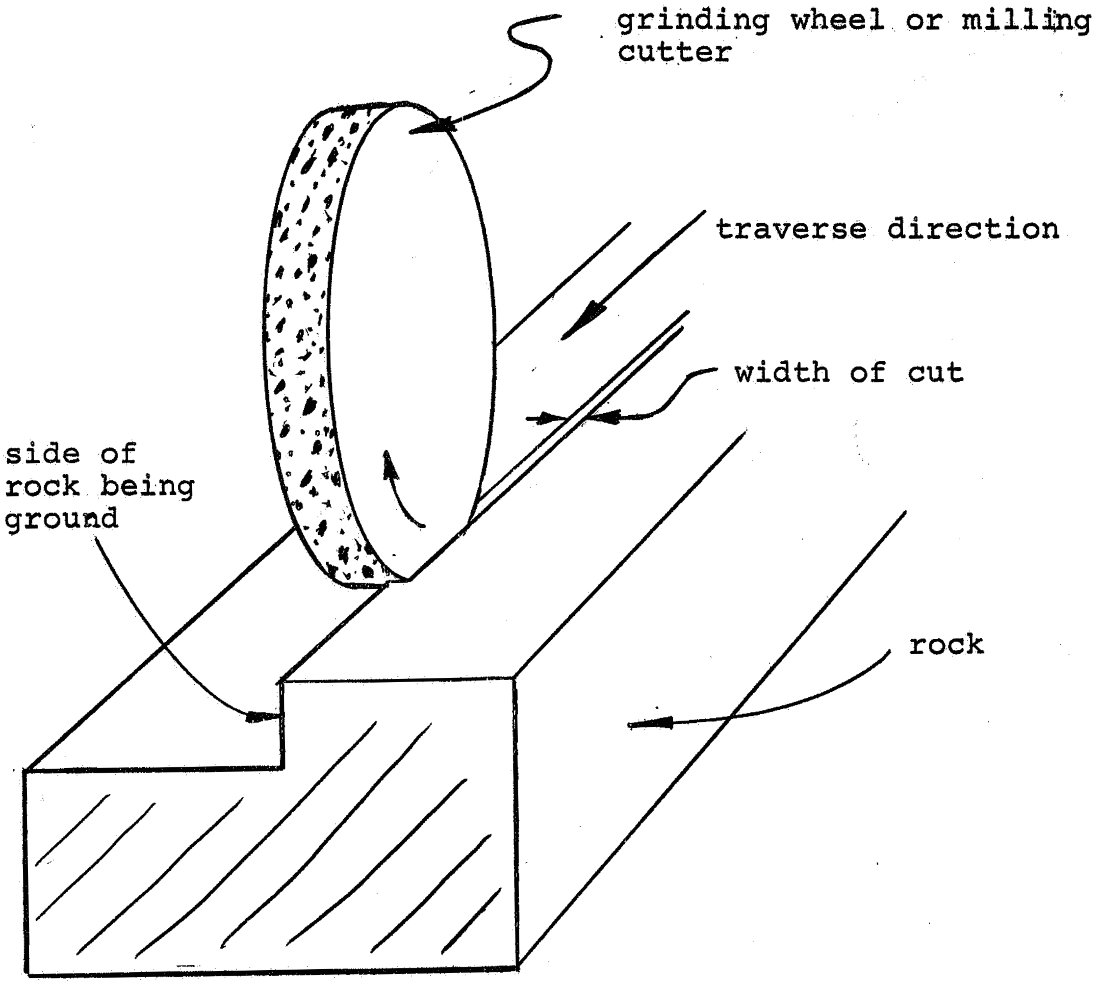


FIG. 6. SIDE ABRASION

TABLE IV. - RESULTS OF SIDE TRAVERSE MILLING AND GRINDING

Sp. No.	Variables				Coll. Eff. (%)	Powder Weight Distribution (% per micron category)					
	Depth of Cut (mils)	Cut Edge	Grind. Mode	Width of cut (mils)		0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to 420
19	10	16 Grit	Side	20	92	13	41	12	13	7	14
20	10	Wedge Teeth	Side	20	84	16	25	13	16	11	20
21	10	Wedge Teeth	Convent.	--	89	19	30	13	15	9	16
22	5	Wedge Teeth	Side	8	81	21	36	15	13	7	9

particles were increased at the expense of the coarse but no peaking in the preferred range occurred.

Both side abrasion and tooth shaping appeared to be definite though limited successes. Tooth shaping experiments appeared the more time consuming, especially because rapid destruction of sharp edges occurred; frequent sharpening would be required. A further application of the principle behind side abrasion was therefore pursued.

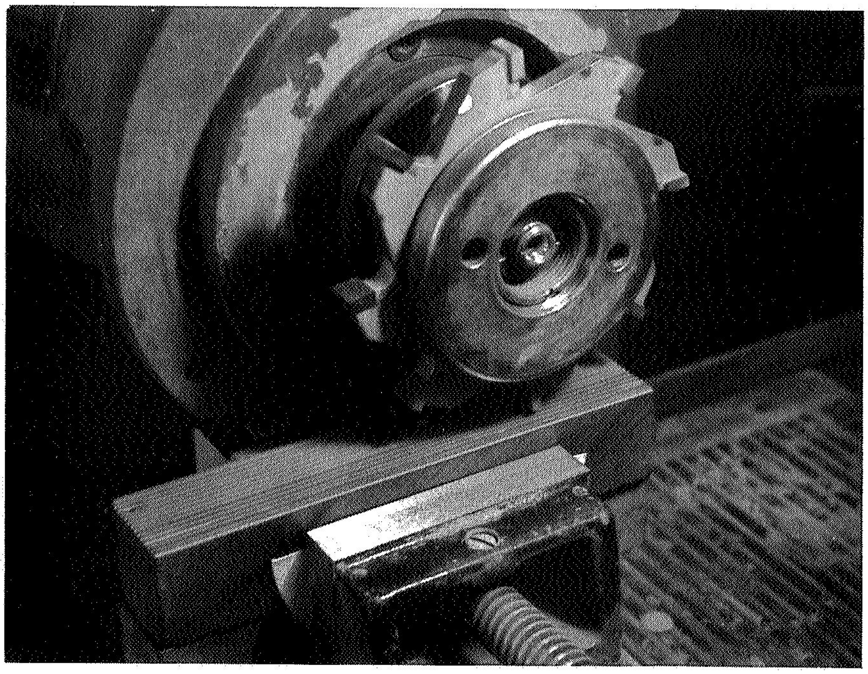
Ridge and Groove Milling

To extend the principle behind side abrasion, a series of parallel grooves were first formed in the rock surface to remove support from the remaining ridge material on two sides. The ridges were than abraded with a flat toothed milling cutter, traversing parallel to the ridges to minimize the number of degress of motion required. The method is illustrated in Fig. 7 with the milling cutter in position to cut the rdiges. A metal bonded 120 grit diamond wheel, dressed automatically after each traverse, was used to produce the grooves. As in previous traverse experiments, milling was from right to left with the cutter rotating clockwise. Powder remaining from the surface preparation was removed before collecting the milled specimens.

Without care, breaking the ridges during their formation sometimes occurred, especially when producing them less than 15 mils thick. Their production was facilitated by (a) frequent wheel dressing, (b) a reduction in wheel vibration, e.g. that caused by uneven or warped collets and flange surfaces, (c) a reduction of traverse speeds, and (d) a reduction in the depths of cut per traverse.

Fig. 8 is a photograph of the milling cutter and rock inside the powder collecting bag. A cardboard frame, taped to the magnetic chuck, moved with the rock and supported the bag. A slot in the bag accommodated the grinding wheel shaft and permitted the relative motion.

The results of initial ridge and groove milling experiments are presented in Table V. Specimens 23 through 27 represent attempts to get quick information on the efficacy of the method. A ridge 40 mils wide and 100 mils high was initially used along with the traverse speed and cut depth employed for specimen 20 of Table IV, the previously most successful experiment. Wheel speeds in all ridge experiments were kept at 440 rpm. The most significant result, shown in specimen 23, was a marked reduction in the percentage of powder produced below 44μ; twenty five percent was substantially



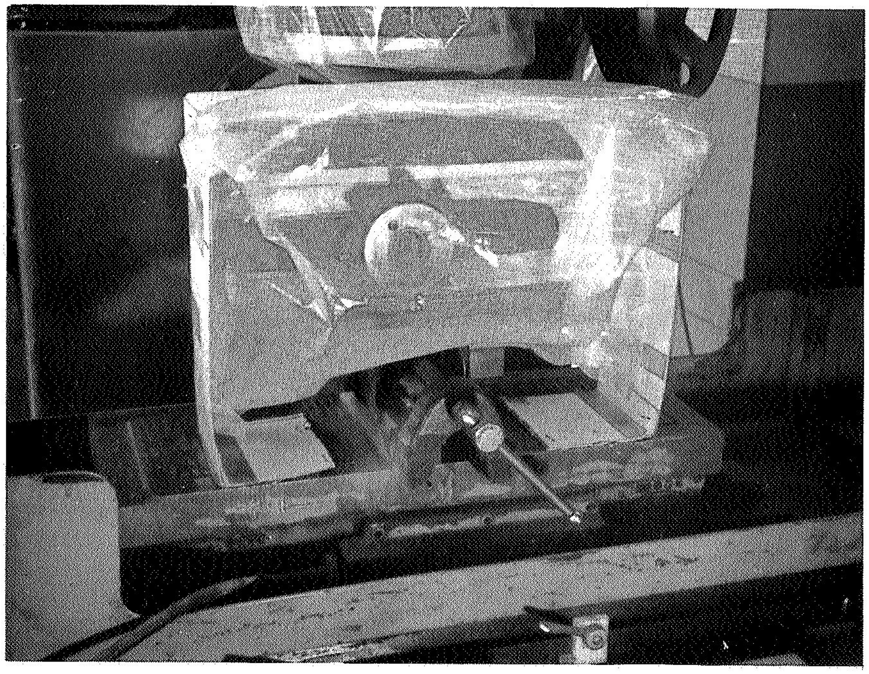


TABLE V. - RESULTS OF RIDGE TRAVERSE MILLING: PART A

Sp. No.	Variable				Coll. Eff. (%)	Powder Weight Distribution (% per micron category)					
	Trav. Speed $\left(\frac{\text{in.}}{\text{min.}}\right)$	Depth of Cut (mils)	Ridge Width (mils)	Ridge Ht. (mils)		0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to ∞
23	84	10	40	100	89	8	17	9	13	11	43
24	14	5	40	100	89	14	23	10	10	9	34
25	30	10	30	50	89	16	25	13	15	10	22
26	30	8	15	35	72	11	20	12	18	17	22
27	30	8	17	40	85	14	22	11	16	16	21

lower than in any previous experiment, although too large a percentage was produced above 250μ.

A reduction of cut depth and traverse speed, shown in specimen 24 failed to improve the distribution further, i.e., in the 74-149 range. However, a reduction in wall width and height to 30 mil and 50 mils, respectively, did improve the distribution, as shown in specimen 25. A further improvement was obtained with a 15 mil and 35 mil width and height, respectively, as seen in specimen 26. These results were the most favorable obtained thus far. However, the many chipped surfaces existent before milling the latter specimen prompted an experiment using slightly thicker walls, 17 mils, to reduce the chipping. The results, in specimen 27, proved consistent with 26; the small increase in the percentage of fines is attributed to the slightly thicker walls and to the somewhat greater collection efficiency.

Specimens in Table VI represent more tightly controlled experiments than those in Table V; only one parameter was varied at a time. The length of rock used in the Table VI experiments, and hence the resulting ridge lengths, were 5-7/8 inches. The rock width was 1-1/16". The milling cutter was left unsharpened through experiment 38 (as it was previously) further to assist control. Ridge heights were kept at 45 mils, with the exception of specimen 40 where they were 35 mils. Sieving was extended to 841μ.

Specimens 28 through 32 demonstrate the effect of altering the depth of cut. In this series, ridge widths were kept at 20 mils and traverse speeds at 15 inches per minute, permitting 115μ to be traversed between surfaces contacts by successive milling teeth. The total depth of cut was kept at 40 mils. The conditions for specimen 28 were repeated for specimen 32; however the milling, performed at a small angle to the ridges in 28, was performed correctly in 32. A 5 mil depth of cut, specimen 30, gave the poorest results, while the remainder were nearly equal. A 10 mil depth of cut, specimen 32, was optimum. It is notable that only one percent of the particle weight of this series was above 841μ.

A louder milling sound was noted accompanying the deeper traverses, indicating greater resistance and possibly smaller resultant particle sizes. Therefore, in test 33, only the top 20 mils of the total 45 mil ridge height was milled, to increase the number of coarse particles; remaining conditions were kept as in test 32. The results were encouraging; only 15 percent of the powder was below 44μ. In test 34 only the top 10 mils of the ridges were removed, further to investigate this phenomenon. Other conditions kept as in test 33. Surprisingly, an increase in fines resulted. A 20 mil total depth of cut, specimen 33, therefore remained optimum.

TABLE VI - RESULTS OF RIDGE TRAVERSE MILLING: PART B

Sp. No.	Variables					Coll. Eff. (%)	Powder Weight Distribution (% per micron category)							
	Trav. Speed $\left(\frac{\text{in.}}{\text{min.}}\right)$	Depth of cut (mils)		Ridge Width (mils)	Edge Cond.		0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to 420	420 to 841	841 to ∞
		Per Pass	Total											
28	15	10	40	20	Dull	78	5	29	13	16	14	15	7	2
29	15	20	40	20	Dull	83	13	24	12	15	15	18	4	0
30	15	5	40	20	Dull	78	16	29	13	14	12	12	3	1
31	15	40	40	20	Dull	81	14	23	12	16	14	15	5	1
32	15	10	40	20	Dull	78	11	20	11	15	15	19	10	1
33	15	10	20	20	Dull	83	4	11	7	13	15	25	23	2
34	15	10	10	20	Dull	85	6	12	8	13	15	23	22	2
35	7.5	10	20	20	Dull	81	10	15	8	13	15	24	15	0
36	30	10	20	20	Dull	88	6	13	8	13	14	21	23	2
37	15	10	20	10	Dull	85	8	18	10	17	22	22	4	0
38	15	10	20	30	Dull	80	9	15	8	11	11	19	23	5
39	15	10	10	10	Sharp	56	17	34	16	20	6	2	4	0
40*	15	10	10	10	Sharp	50	18	31	15	22	7	3	4	0

*Ridge height was 35 mils, 10 mils less than proceeding specimens

In specimens 35 and 36 traverse speeds were halved and doubled respectively relative to specimen 33; other conditions kept as in 33. The 15 inch per second traverse speed, specimen 33, proved optimum.

In specimens 37 and 38, wall thickness was altered relative to specimen 33. A comparison of the three shows the 10 mil wall of specimen 37 preferable to the 20 and 30 mil wall of the other two; only 21 percent of the powder lies above 420μ and a negligible amount lies above 841μ. Specimen 37 also produced the greatest percentage in and about the size range of greatest interest, substantially exceeding that of all previous specimens. It is nonetheless surprising that the 10 mil wall gave a substantially higher powder percentage below 44μ than the 20 mil wall; also surprising is that it gives a slightly higher percentage there than the 30 mil wall.

Specimens 39 and 40, unlike previous specimens, were taken from the same set of ridges, specimen 39 from the first 10 mil depth of cut and specimen 40 from the second. The effects of both a 45 mil and a 35 mil initial wall height could thus be compared from the same initial preparation. For the two specimens combined, the same conditions prevailed as for specimen 37 except that a new milling cutter was used, to test the effect of sharp teeth. Surprisingly this caused a substantial increase in the number of fine particles as shown by comparison of specimen 39 and 40 with specimen 37. The poor collection efficiencies of 39 and 40, caused by the small amount of powder collected, indicates that their true distributions are probably even finer.

A comparison of specimen 39 and 40 also confirms the somewaht surprising results of specimens 33 and 34, i.e., while a total depth of cut of 20 mils gives coarser particles than a total cut of 40 mils, it gives finer particles than a total cut of 10 mils.

DISCUSSION AND CONCLUSIONS

The ability to produce high weight percentages of particles either in the 0-20μ or 20-44μ size category has been demonstrated through the alteration of conventional grinding parameters using the grinding cam. It therefore appears feasible to produce suitable particle sizes for x-ray diffractometry by abrasion alone. An important area still to be investigated, however, is the ability to control the percentage of powder in the undesirable region below one micron. Fig. 9 summarizes graphically the control effected over the weight percentages of particles above and below 20μ by the grinding cam method of simple vertical penetration.

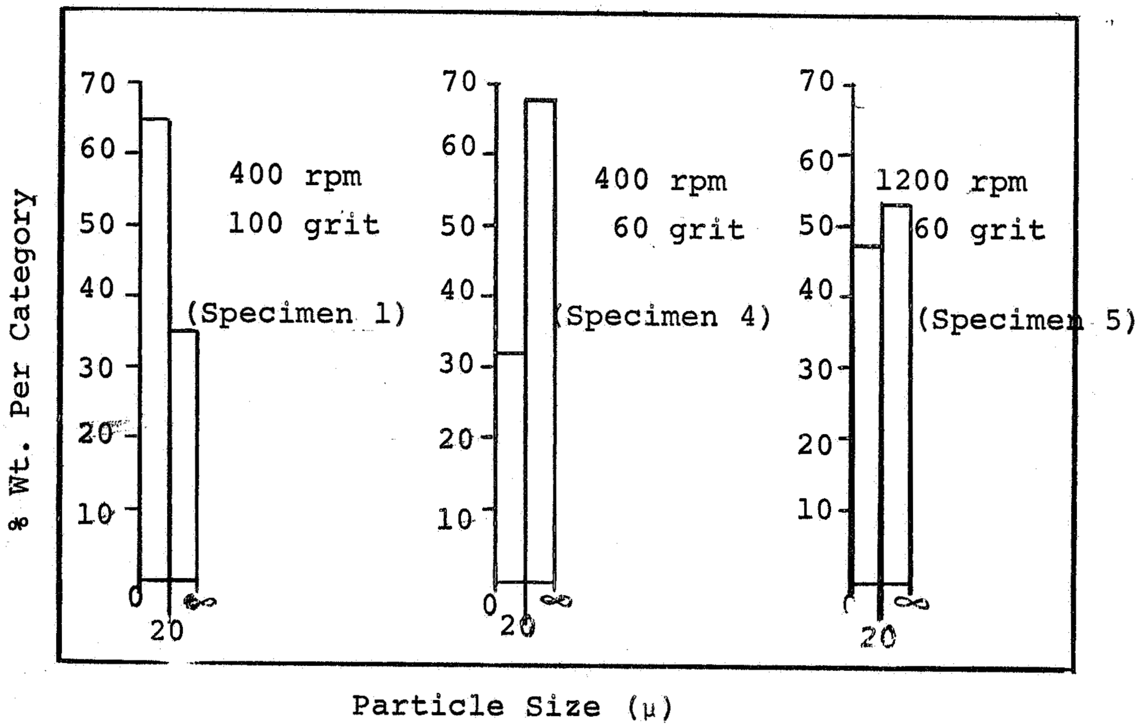


FIG. 9. CONTROL ABOUT 20μ BY VARYING GRIT SIZE AND WHEEL SPEED (CAM METHOD)

The effect of grit size, the most effective parameter, and of wheel speed, the next most effective parameter, is illustrated. A further increase in the percentage of particles under 20μ is expected with additional wheel speed and finer grit. Changes in vertical penetration rate appears to have little affect on the size distribution.

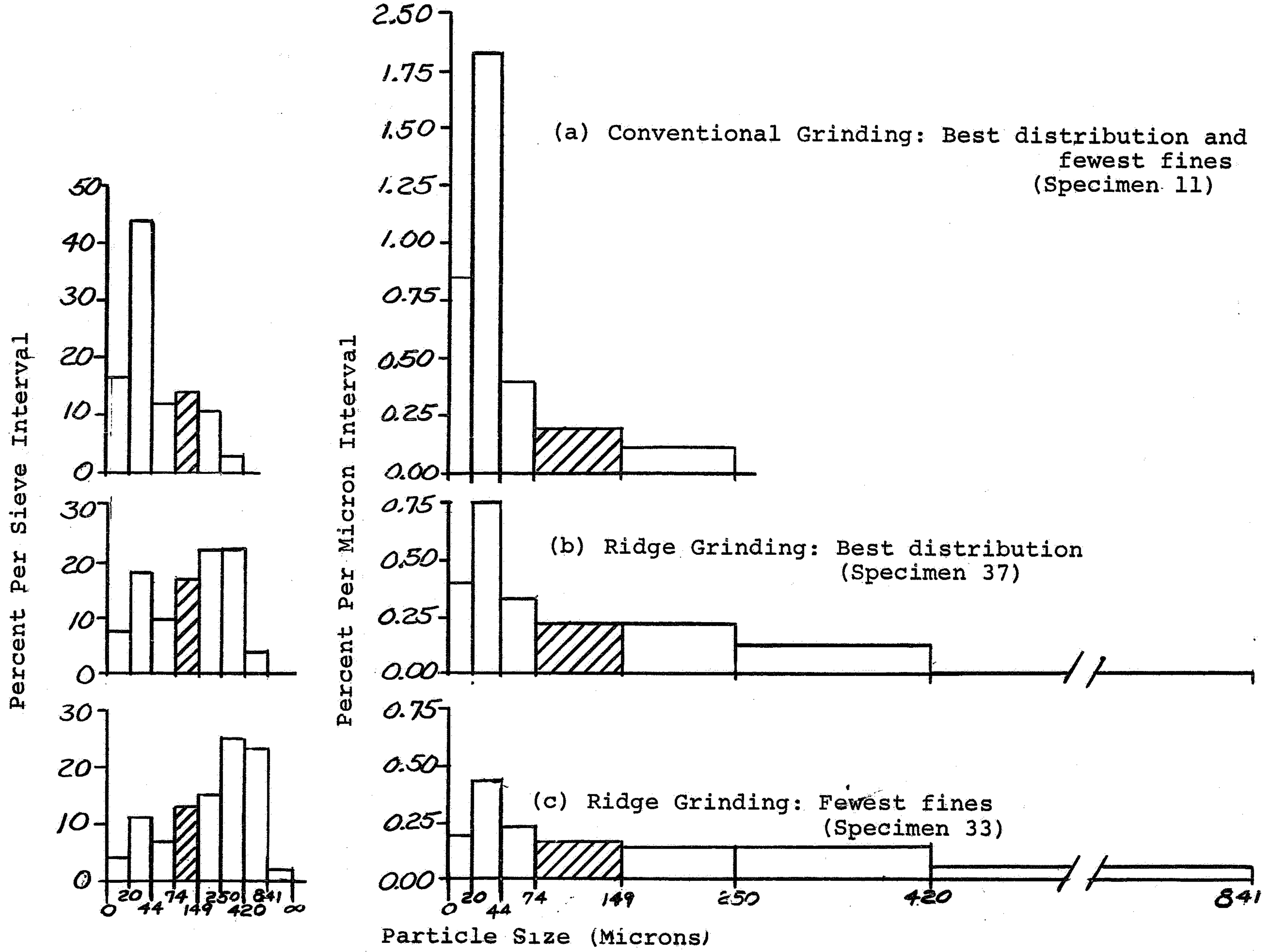
Above 44μ, the weight percentages of particles per micron size interval becomes increasingly insensitive to alteration of conventional grinding parameters, as the mean interval size increases. This is found true in traverse grinding and in milling, relevant to traverse speed and depth of cut variations, as well as in vertical grinding.

The importance of the cam grinding method largely depends on the importance both of restricting acquisition to simple vertical penetration and of maintaining a small fixed grinding contact area. The latter has not been investigated and in traverse grinding it exists even with conventional grinding wheels. At this stage of investigation, it appears that some form of traverse grinding is necessary anyway to obtain suitable specimens for the petrographic microscope.

The use of metal bonded diamond wheels for the dry grinding of rock is indicated. Compared to a vitreous bond, metal is found far less likely to chip and crack from the combination of heat and mechanical stresses encountered. The small percentage of rock powder contamination produced by wheel wear, less than 0.3% by weight, appears to permit the use of a metal bond even if it is one of the materials sought in the specimen analysis. In this regard the wear of milling cutter teeth may be a problem; however, a final milling cutter design could utilize teeth with diamond edges.

The shape of milling teeth, and presumably of grit as well, has an important effect on size distribution. Wedge shaped teeth with the sharp end pointing in the direction of rotation increases the percentage of large particles. This effect is worth further investigation. However, the most successful technique for securing petrographic microscope specimens was the milling of ridges and grooves performed in the rock surface. Particle enlargment by this method is attributed to the reduction of support for the large particles in the remaining surface material. Essentially the same principal appeared operative in more limited form when abrading down the side of a rock.

The optimum distributions obtained for microscopy, through conventional grinding and by the ridge and groove method, are summarized graphically in Fig. 10. Distributions are shown in percentages per micron and per interval between sieve sizes, the latter for observing how microscopy size requirements are met, the former for an undistorted size distribution picture. The indicated distributions are probably slightly coarser than


(a) Conventional Grinding: Best distribution and fewest fines (Specimen 11)

(b) Ridge Grinding: Best distribution (Specimen 37)

(c) Ridge Grinding: Fewest fines (Specimen 33)

FIG. 10. OPTIMUM DISTRIBUTIONS OBTAINED FOR MICROSCOPY

the true ones because of imperfect collection efficiency. Comparison of Fig. 10a and 10b show that the ridge and groove method is appreciably superior to conventional grinding; fines have been considerably reduced while powder near the sizes of interest has been increased. Fig. 10c shows the number of particles below 44μ reduced to an acceptable level for the first time.

Optimum conditions indicated for conventional grinding were a 12 inch per minute traverse speed accompanying the largest grit and lowest speed compatible with other requirements, with little additional improvement indicated for speeds smaller than 440 rpm or for grit larger than number 16. In ridge and groove milling, a decision on optimum conditions requires considerably more investigation. The optimum thus far, shown in Fig. 10b (specimen 37), utilized walls 10 mils wide and 45 mils high, a 10 mil depth of cut per pass, a 20 mil total depth of cut and a dull milling cutter traversing at 15 inches per minute, rotating at 440 rpm.

An important aspect of the ridge and groove method is that more possibilities exist for size control than in conventional grinding. Each new ridge dimension permits new grinding parameter combinations. In some situations, the effectiveness of conventional parameter variation, e.g., wheel speed, may thus be enhanced. Additional techniques associated with the ridge and groove method look promising as well, e.g. altering milling tooth shapes (or using grinding wheels) to change the direction of forces operating on the ridges. Tests 39 and 40 indicate that perhaps a very blunt milling cutter may improve the distribution by reducing the number of fines. Reversing the relative rotary and transverse motions of the milling cutter may also be promising, for diminishing the number of coarse particles.

The ability of ridge and groove grinding to begin concentrating particles about the size range of interest, its improvement over conventional grinding, and the promise for further improvement through the many parameter variations yet to be explored, recommend it as a feasible way of securing particle sizes suitable for petrographic microscopy. The apparent relative ease of securing suitable particle sizes for x-ray diffractometry analysis permits the same technique, or use of the groove cuttings, to be applied to the latter, as well.

Other size distribution studies are indicated additional to the refinements in technique. One is on the effect of the ultimate vacuum environment because of its lack of aerodynamics and because of the increase in particle adhesion observed in powders ground in vacuum.[4] Studies of the effects of rock minerology, surface contour and stability of both substrate and apparatus also are pertinent.

An example of how an automated ridge and groove sampling device might operate is illustrated in Fig. 11. A stack of thin grinding wheels, separated by distances equal to the desired ridge widths, is followed by a milling cutter, which is the width of the rows of ridges. The milling cutter has a radius smaller than the grinding wheels, the difference in radii governing ridge heights before and after milling; total grinding depth and number of traverses are thus not limited by ridge height requirements. The milling cutter's depth of cut is governed by the incremental vertical distance the milling cutter is lowered per traverse. The grinding wheel supplies particles for x-ray analysis and the milling cutter provides particles for the microscope, either simultaneously or subsequently. Separate collecting cups receive the disparate powders.

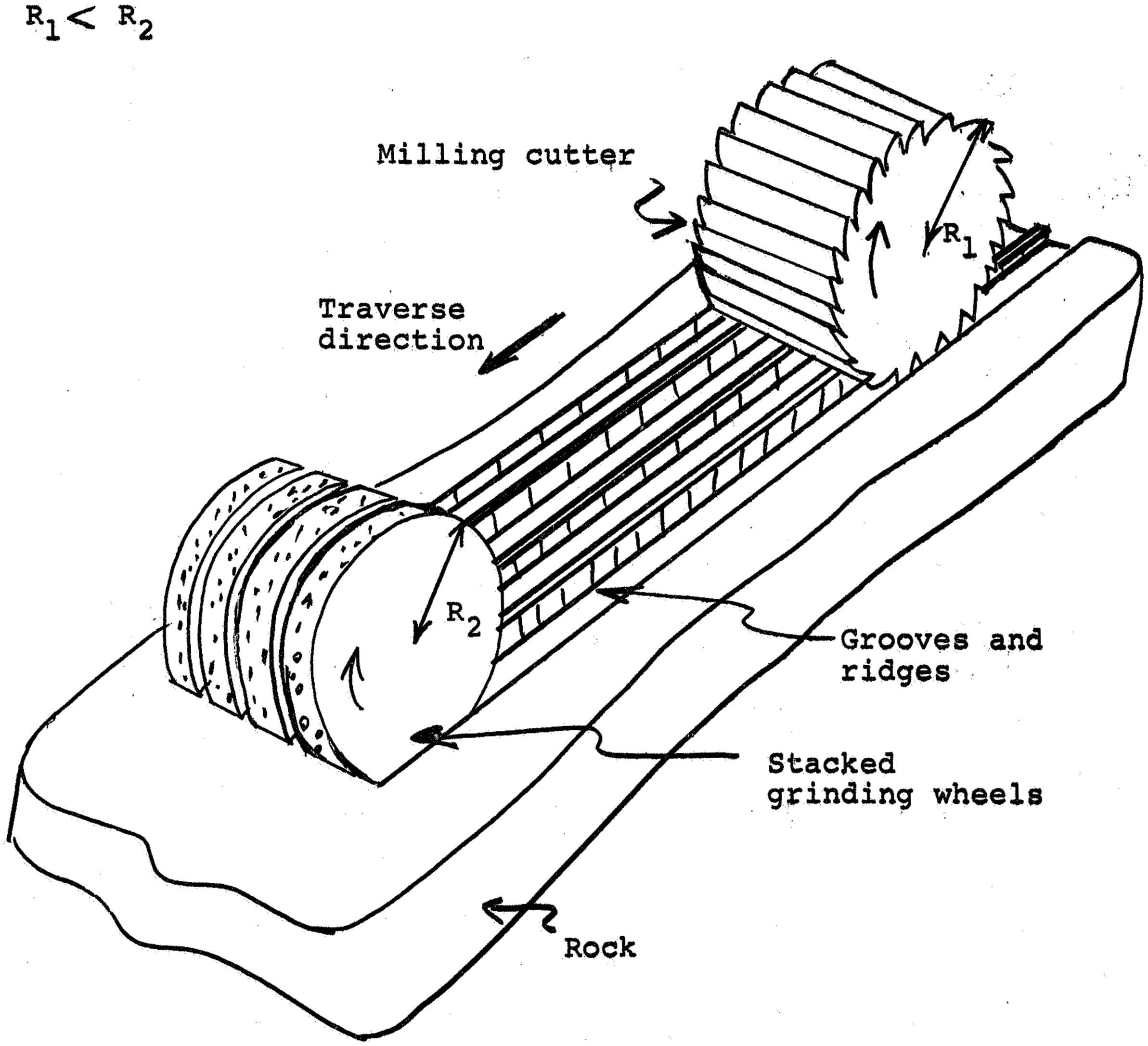


FIG. 11. AUTOMATED RIDGE AND GROOVE METHOD

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