DEVELOPMENT OF ABRASION SAMPLING TECHNIQUES FOR EXTRATERRESTRIAL GEOLOGICAL ANALYSIS

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by
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ABSTRACT

A rock comminution method was developed for acquiring powder specimens compatible with requirements for automated extraterrestrial geological analysis. The production of thin parallel ridges on the rock surface and their subsequent removal by planing produced powder size distributions approaching that desired for petrographic microscopy. Results on both basalt and obsidian were similar, indicating the method suitable for diverse rock types. Prototype concepts are discussed. A vacuum system was also designed and constructed for advanced studies. It incorporates a commercial surface grinder, retaining its directional versatility, precision, and stability. Preliminary vacuum grinding tests showed powder trajectories exhibiting aerodynamic swirling effects at simulated Martian pressures of 4 Torr, but exhibiting ballistic patterns at 0.1 Torr. Powder adherence to grinding wheels was also observed at these pressures.

FOREWORD

This Final Report covers the research effort performed by Norton Research Corporation for the Office of Lunar and Planetary Programs, National Aeronautics and Space Administration under Contract No. NASw-1616 for the period July 6, 1967 to August 5, 1968. This effort continues work initiated at NRC under Subcontract No. 951422, Contract NAS7-100, to develop abrasion sampling techniques for remote biological and geological analysis.

The principal investigator and project manager for the research was Mr. P. Blum, Senior Physicist, with technical consultation provided by Dr. M. J. Hordon, Program Director. The project was under the general supervision of Dr. N. Beecher, Assistant Director of Research for NRC. The technical monitor for NASA was Mr. R. P. Bryson, Code SL, NASA Headquarters Office of Lunar and Planetary Programs.

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SUMMARY

A rock comminution method was developed for acquiring powder specimens compatible with requirements for automated extraterrestrial geological analysis. Ganged diamond grinding wheels were used to produce a group of thin parallel ridges on the rock surface which were then partially removed. Ridge dimensioning provided the requisite constraints, beyond those available in conventional grinding, for producing particle sizes suitable for petrographic microscopy; a prior study found more conventional grinding techniques suitable for x-ray diffractometry. Ridge removal techniques and ridge and cutter parameters were studied to reduce size distribution divergence about the preferred 74-149μ range. A major improvement was found in the use of ridge planing, as compared with ridge milling techniques. The best distribution attained was 37% between 74 and 149μ, 70% between 44 and 250μ; the specified goal was a minimum of about 50% and 75%, respectively. Attainment of the additional concentration desired appears probable with further parameter refinement, without additional innovation. Moreover, a significant amount of the remaining divergence appears to be caused by correctable deficiencies in experimental conditions, which are unnecessary in ultimate operation. Prototype powder acquisition designs using the

ridge method are discussed.

The production and comminution of ridges was studied on two diverse rock types, basalt and obsidian. The conditions required to produce high quality ridges were found to be compatible and the size distribution produced by the same planing comminution conditions were found to be similar, indicating the ridge method suitable to a diversity of rock types.

A vacuum system was designed and constructed in which to conduct advanced abrasive sampling studies. A commercial surface grinding machine was incorporated into the design such that vacuum grinding retains the machine's directional versatility, precision, and stability, as well as viewing facility and accessibility in preparing experiments. Motion in any direction is possible with a range of about 7 inches in the plane of the grinding wheel and over 2.5 inches perpendicular to it.

In preliminary vacuum grinding studies, powder trajectories exhibited aerodynamic swirling effects at 4 Torr similar to those at atmospheric pressure, while at 0.1 Torr they appeared ballistic. Trajectory dependence on pressure in this range makes it advisable for Martian collection methods to be designed for a range of trajectories. Powder adherence to the grinding wheels was also observed, even at these low vacuum levels. Ridge formation was more difficult than at atmospheric pressure and may have been caused by effective wheel dulling by the adherent powder.

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INTRODUCTION

Remote mineralogical analysis of lunar and planetary surfaces by petrographic microscopy and x-ray diffractometry is being planned[1]. As distinguished from Surveyor series element abundance analyses using detector deployment over the surface[2,3], the planned methods have critical specimen requirements[4-7]. Rock samples must be in powdered form, have specified particle size distributions and, for microscopy, be positioned to permit transmission optics. Drilling techniques[8,9] and more recently the feasibility of grinding and other abrasion methods have therefore been studied[10]. A continuation of work begun in the above feasibility study is reported here.

The central task has been to develop an abrading method for producing the desired particle size distribution without auxiliary sorting. Since minerals ordinarily fragment into unique particle size distributions, sieving might yield powder mineralogically unrepresentative of the solid rock. It might also complicate specimen preparation.

In the prior feasibility study, it was found that suitable alteration of conventional grinding parameters, e.g., grit size and wheel speed, could provide the desired powder proportions in the under 20μ size range generally required for x-ray diffractometry. It was also found that wheel wear was negligible and that a metallic binder was the optimum wheel bonding agent. However, parameter alteration alone was insufficiently effective in the petrographic microscopy range, where more than 50 percent of the powder is desired between 75 and 150μ, less than 20 percent below 44μ and less than 5 percent above 300μ. This report discusses the development of a novel abrasion technique which was initiated in the feasibility study to overcome these difficulties. Ridges are first ground in the rock surface and are then comminuted. Their dimensions provide the additional comminution constraints needed to permit desired particle size control. The requisite distributions have thereby been approximated, while continued improvements are anticipated with further development.

An associated vacuum system developed for investigating abrasion methods at low gas pressures is also discussed. Thus far vacuum studies have been limited to observing low pressure effects on ridge formation and on powder trajectories.

APPARATUS FOR STUDIES AT ATMOSPHERIC PRESSURE

Basic Equipment

Experiments were conducted on a Brown and Sharpe model 2B surface grinder, shown prepared for a planing experiment in Fig. 1. The machine was modified to provide variable speed both in grinding and in traverse motion, the latter with optional manual control, using shunt wound motors and speed controllers. A 1/15 hp motor was coupled to the bed traverse handle by a chain drive to provide speeds between 0.2 and 20 in./min. A 3/4 hp shunt wound motor and a reduced diameter driver pulley were installed to provide grinding wheel speeds between 50 and 1750 rpm.

Three inch diameter sieves, wire woven above 44μ and photo-etched at 20μ, were used with a Tyler Ro-Tap sieve shaker. The shaker was chosen for its wide spread use and its accord with shaker movement standards of the American Society for Testing Materials[11-14], thus providing results that are both reliable and comparable with those of other experimenters.

Grinding Wheels for Ridge Production

Five 0.045 in. thick, metal bonded diamond wheels were used ganged together to produce ridges in the rock surface. Fig. 2 shows an end view of the set, illustrating wheel spacing; the wheels are shown on the collet between flanges. A Number 120 diamond grit was used because it appeared from prior experiments

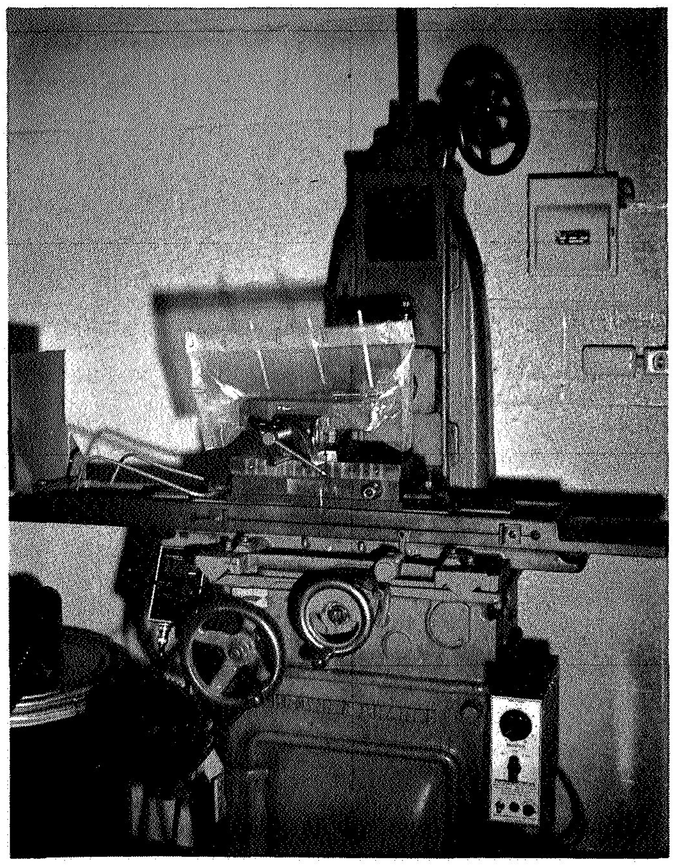


FIG. 1 SURFACE GRINDER PREPARED
FOR A PLANING EXPERIMENT

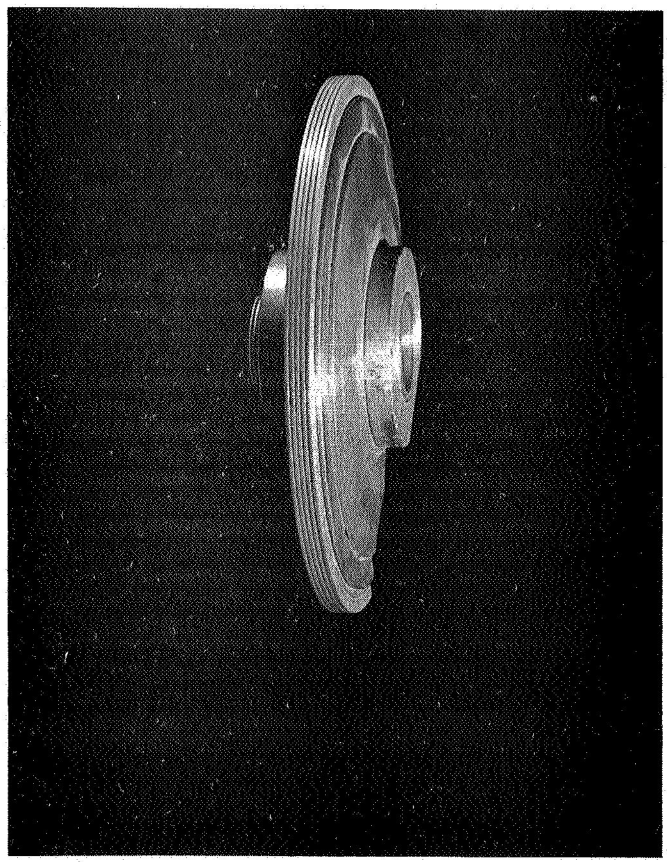


FIG. 2 END VIEW OF GANGED GRINDING WHEELS USED TO PRODUCE RIDGES

to allow the highest dry grinding rate with minimum ridge breakage. Medium strength bonds were used (Norton grade N) as a compromise; if the bond was too strong, rock heating would be great and might melt the particles, if too weak, high wheel wear would occur. Medium diamond concentrations (Norton number 50) also were used as a compromise; too great a diamond concentration would slow the grinding rate, too sparse a concentration would cause high wheel wear. All wheel properties except diameter are the same as those used in the prior feasibility study. Arbor spacers of selected widths were employed between wheels to produce desired ridge thicknesses.

Rocks and Rock Mounting Equipment

Experiments were conducted on unweathered igneous rock, primarily a fine grained black basalt from Lintz, Rhenish Prussia. Basalt was selected because it is widely believed to be the closest in mineralogy to common lunar rocks; it has been frequently used in lunar soil simulation studies. Obsidian from Lake County, Oregon was used in one crucial experiment and pumice from different locations, including the Lipari Islands, Italy, was experimented with qualitatively.

The rocks were used in the form of rectangular parallelepipeds, gripped within plastic bags between the jaws of a vise, the bags used for collecting the rock powder as it was produced. Methods of supporting the bags varied and will be discussed with the associated ridge removing procedures. The vise was held to the surface grinder bed by a magnetic chuck. The first of two arrangements used is shown in Fig. 1. Ultimately the improved arrangement shown in Fig. 3 was used; a vise was sawed in half and remounted to secure the rock at each end, while adjustable screws were attached to the magnetic chuck for precise rock leveling.

Cutters for Removing Ridges

Experimental studies utilized a single tooth tungsten carbide cutter, secured by several methods in a planar mode, and four different tungsten carbide cutters in the rotary mode. Three of the latter were 4 in. diameter, 3/8 in. thick, eight tooth milling cutters. One was a commonly employed milling cutter having a negative radial rake of about 10 degrees and zero axial rake, which is shown in Fig. 4. A second was the same type cutter but ground with a positive radial rake of 10°, shown in Fig. 5.

A third milling cutter was constructed with teeth having a 10° positive radial rake and a 45° axial rake, as well, as shown in Fig. 6. Cutting edges were very slightly curved so that each point on the edge cut the same depth of rock, as did the cutters above having zero axial rake. All milling cutters were mounted at the tip end of a collet, which was constructed with an extra long shaft, 3.625 in., for reasons to be discussed later.

The fourth rotary cutter is a 1/8 inch diameter reamer with four teeth having positive radial rake and zero axial rake, shown in Fig. 7. The reamer was held in the jaws of a chuck modified so that it could be secured to the spindle.

The single toothed cutter is shown in Fig. 8 in the two

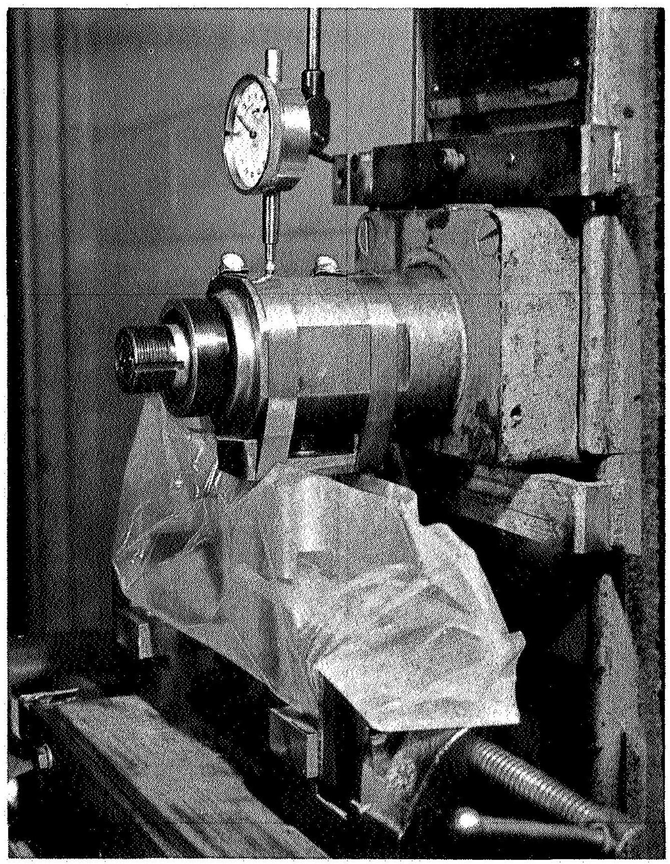


FIG. 3 APPARATUS FOR ROCK MOUNTING, PLANING, COLLECTING POWDER AND MONITORING DEPTH OF CUT

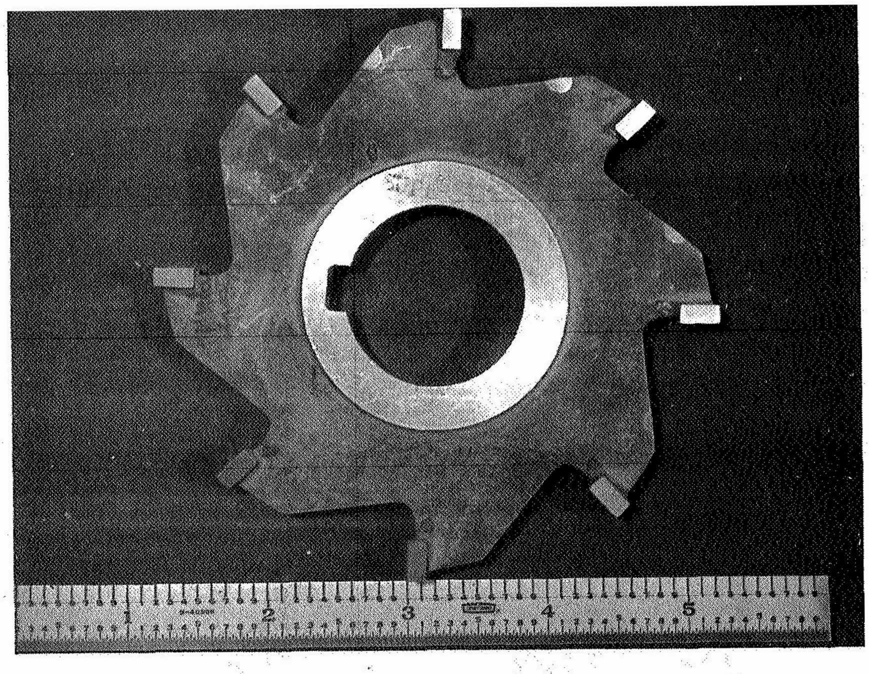


FIG. 4 MILLING CUTTER WITH NEGATIVE RADIAL RAKE

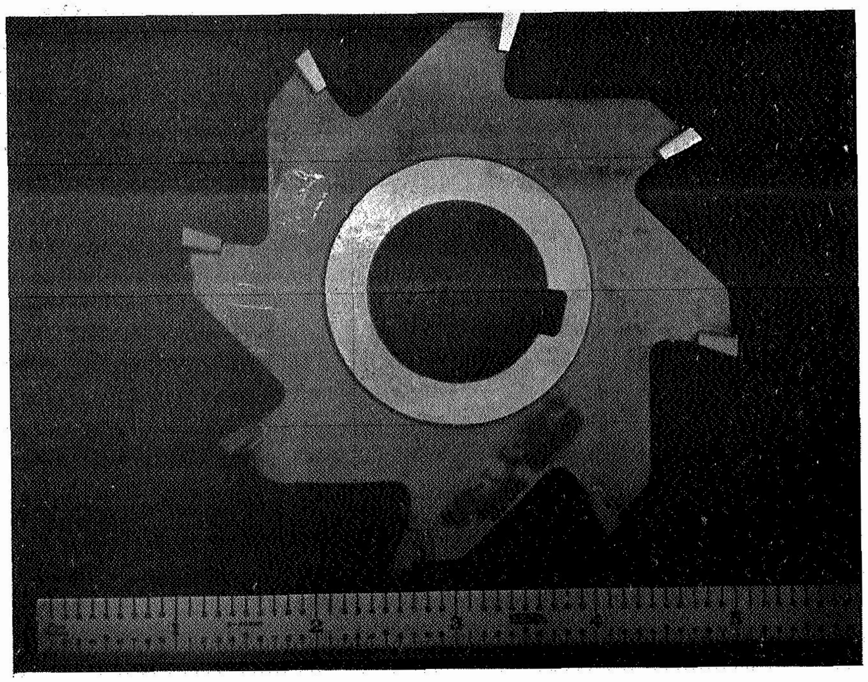


FIG. 5 MILLING CUTTER WITH POSITIVE RADIAL RAKE

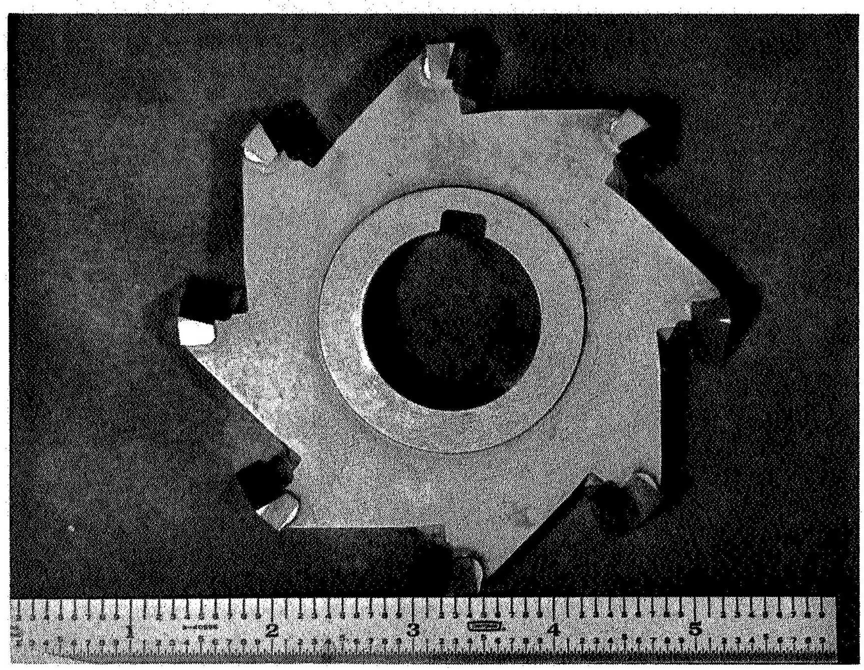


FIG. 6 MILLING CUTTER WITH POSITIVE RADIAL RAKE AND POSITIVE AXIAL RAKE

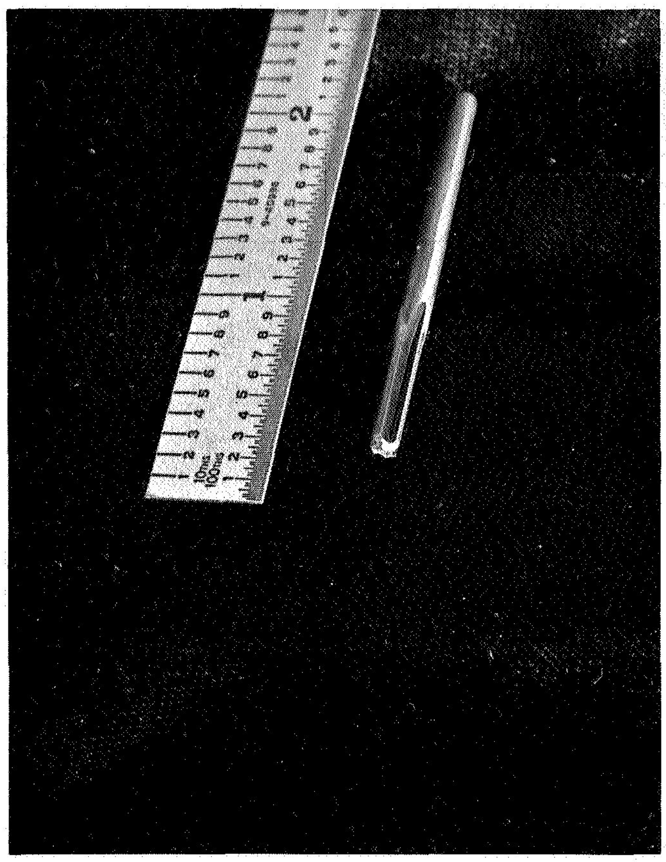


FIG. 7 REAMER WITH POSITIVE RADIAL RAKE

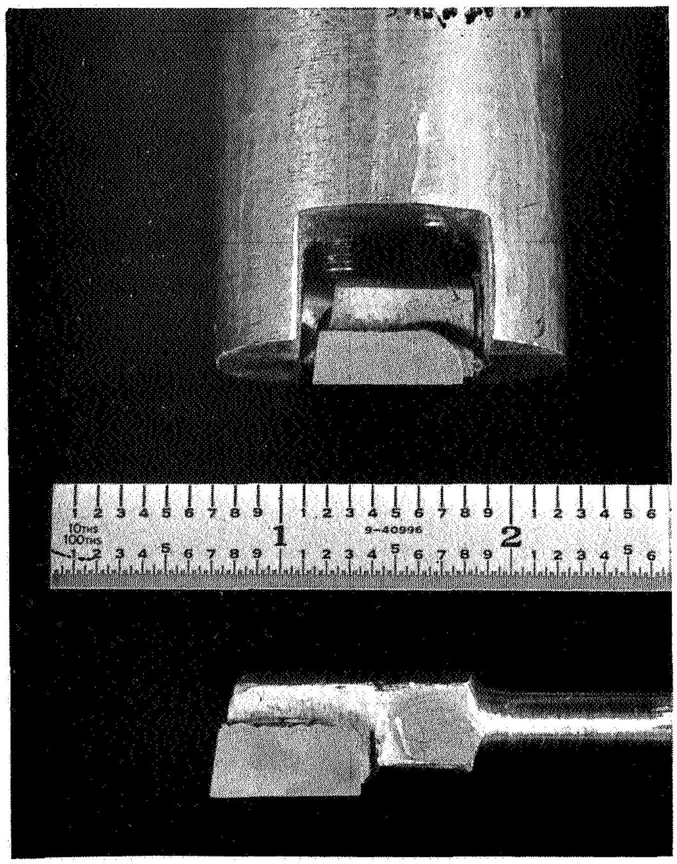


FIG. 8 CUTTERS USED FOR PLANING RIDGES

forms it was used. It was first held by clamping the shank, displayed in the lower picture in a rod at the desired rake angle. The rod in turn was held in the jaws of the above described chuck. It was then drawn across the rock surface while the spindle was prevented from rotating. A more rigid arrangement later used is shown in the upper picture. This holder was secured to the spindle housing as is shown in Fig. 3.

VACUUM GRINDING SYSTEM

Objectives and Basic Design

The vacuum grinding system was designed to permit continued use of the surface grinding machine for vacuum experiments, thus to retain the versatility, stability and precision of the unit. Parallel objectives included viewing facility, accessibility to handling, and large ranges of motion. The system was designed only for vacua producible by conventional mechanical pumps.

Figs. 9 and 10 show front and side views of the surface grinder used in previous experiments with the vacuum apparatus attached. In Fig. 11 a simplified top view of the system is drawn. Grinding is performed in the steel cylinder which is 6 inches long and 17 inches in diameter. A hinged bell jar covers the entire front of the cylinder to permit optimal viewing and accessibility in preparing experiments.

The design centers about the emplacement of the large diameter double elastomer bellows, neoprene on the inside and natural rubber on the outside. This serves as a vacuum enclosure between the spindle and grinding chamber while permitting the requisite omnidirectional translational motion between the two components. The grinding machine's cross-feed, down-feed and longitudinal-feed controls thus remain operable. Despite a small bellows length to diameter ratio, which is imposed by the dimensions of the surface grinder, the 10 in. bellows diameter coupled with its elastomer construction permits ±3.5 in. of translational motion in the plane of the grinding wheel. A 2.75 in. movement is permitted perpendicular to this plane, concomitantly. Circumferential bellows collapse is prevented

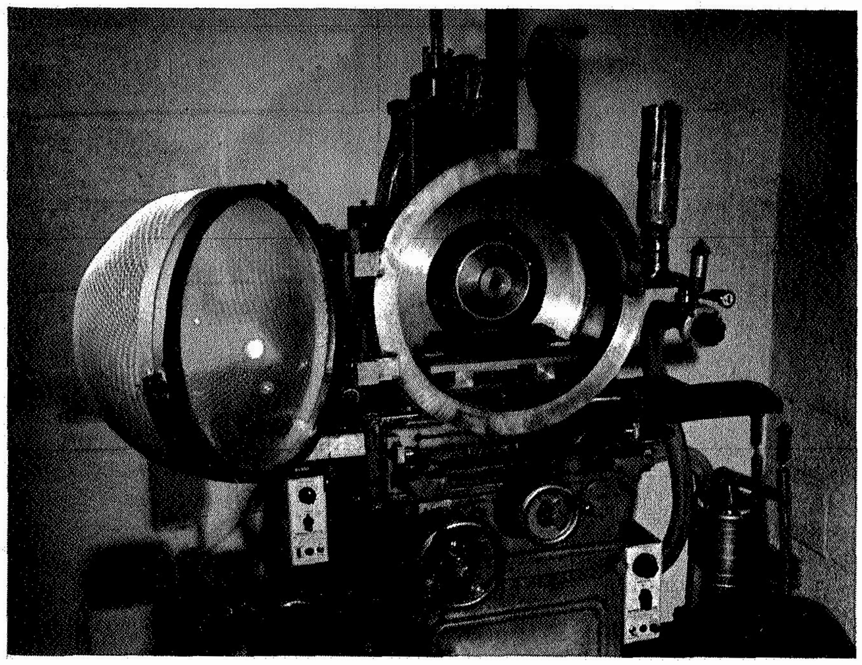


FIG. 9 FRONT VIEW OF VACUUM GRINDING SYSTEM

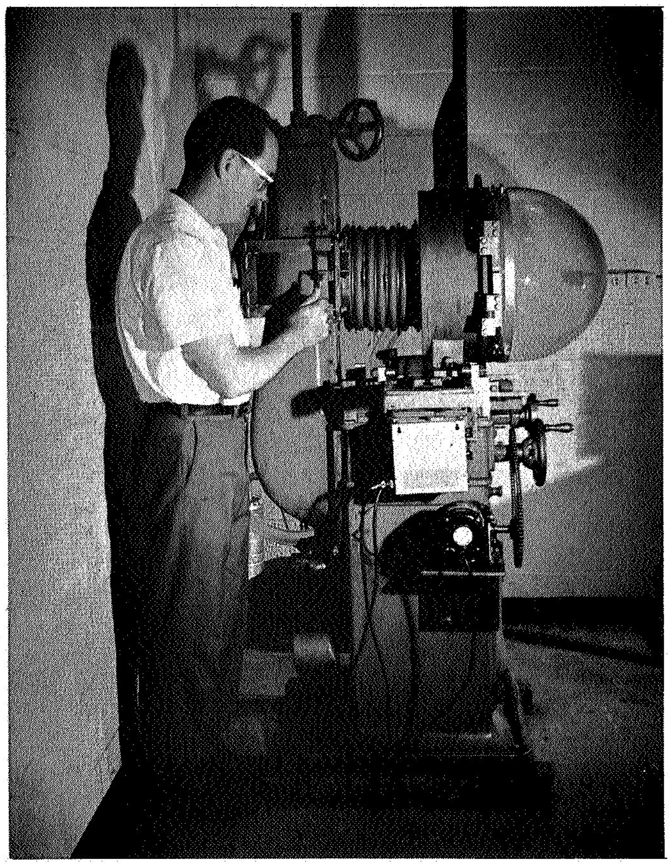
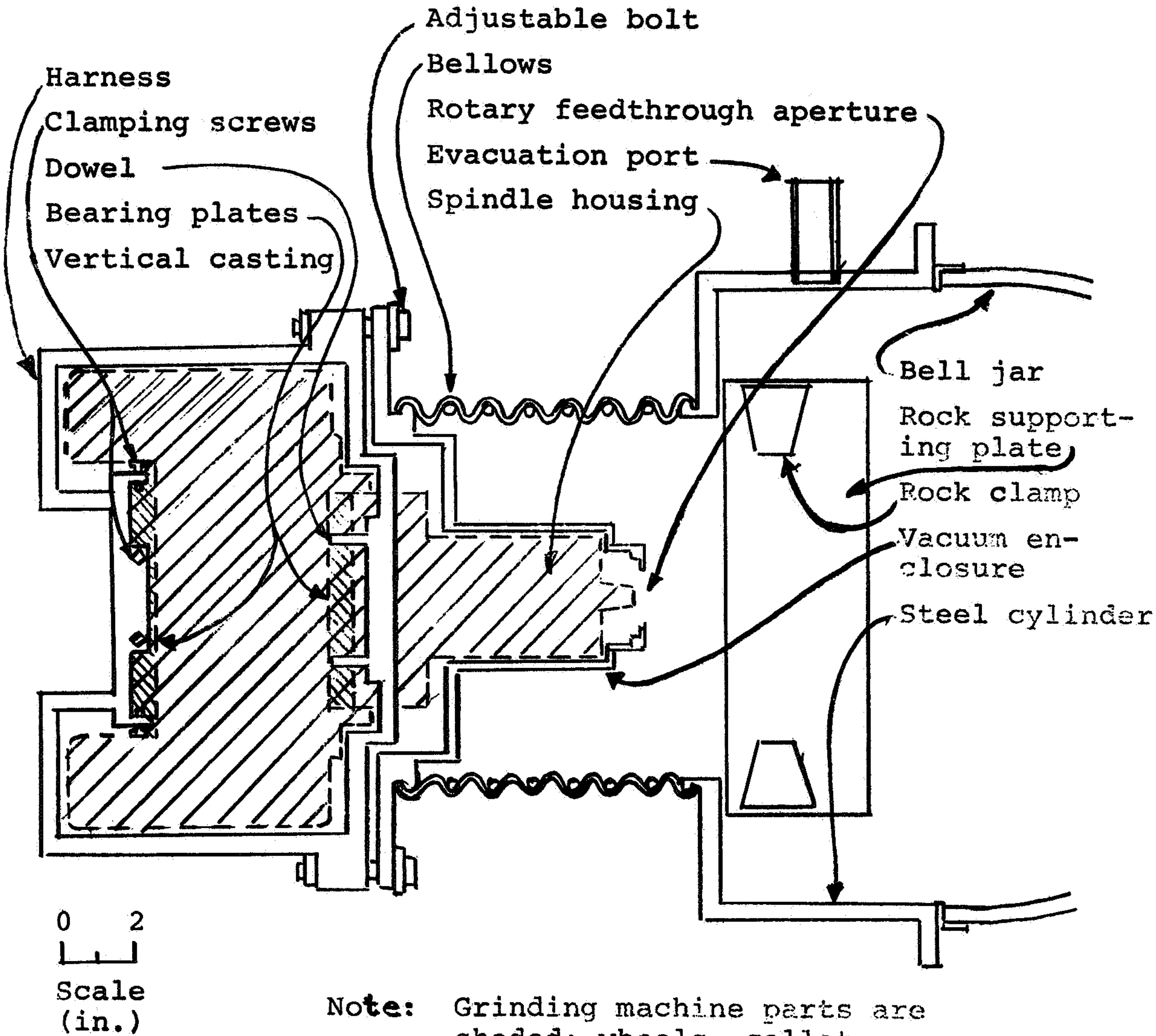


FIG. 10 SIDE VIEW OF VACUUM GRINDING SYSTEM



Note: Grinding machine parts are shaded; wheels, collet, rotary seal and rock are ommitted.

FIG. 11 TOP VIEW OF VACUUM SYSTEM

by steel supporting rings set into the bellows convolutions. The 1/4 in. double bellows thickness prevents collapse between supporting rings. Circular clamps are used between supporting rings about the outside of the bellows to prevent ring dislodgement when the bellows are greatly offset. The bellows combination is mechanically fastened to the grinding chamber cylinder at one end and to a supporting bracket, in turn fastened indirectly to the spindle housing, at the other end.

Distribution of Atmospheric Forces to Facilitate Movements

As a result of the bellows' large cross sectional area, about 1200 lb. of longitudinal atmospheric collapsing force exists. It was therefore necessary to restrain movable machine components connected to either side of the bellows against the large force moments resulting, which change with the direction and amplitude of translational motions. Restraints were designed to prevent or minimize the separation or binding of bearing surfaces to permit continued smooth operation.

For this reason, the bellows supporting bracket was attached to the spindle housing indirectly using a harness about the machine's vertical casting. A perspective view of the two components is shown in Fig. 12. A harness plate rests against the machine's rear bearing plate to distribute the bellows collapsing force uniformly and solely on this component. Lateral and vertical forces are distributed between the machine's front and rear bearing plates using clamping screws and hardened dowels, respectively. However, the dowels attached to the harness plate are free to slide so that the front bearing plate

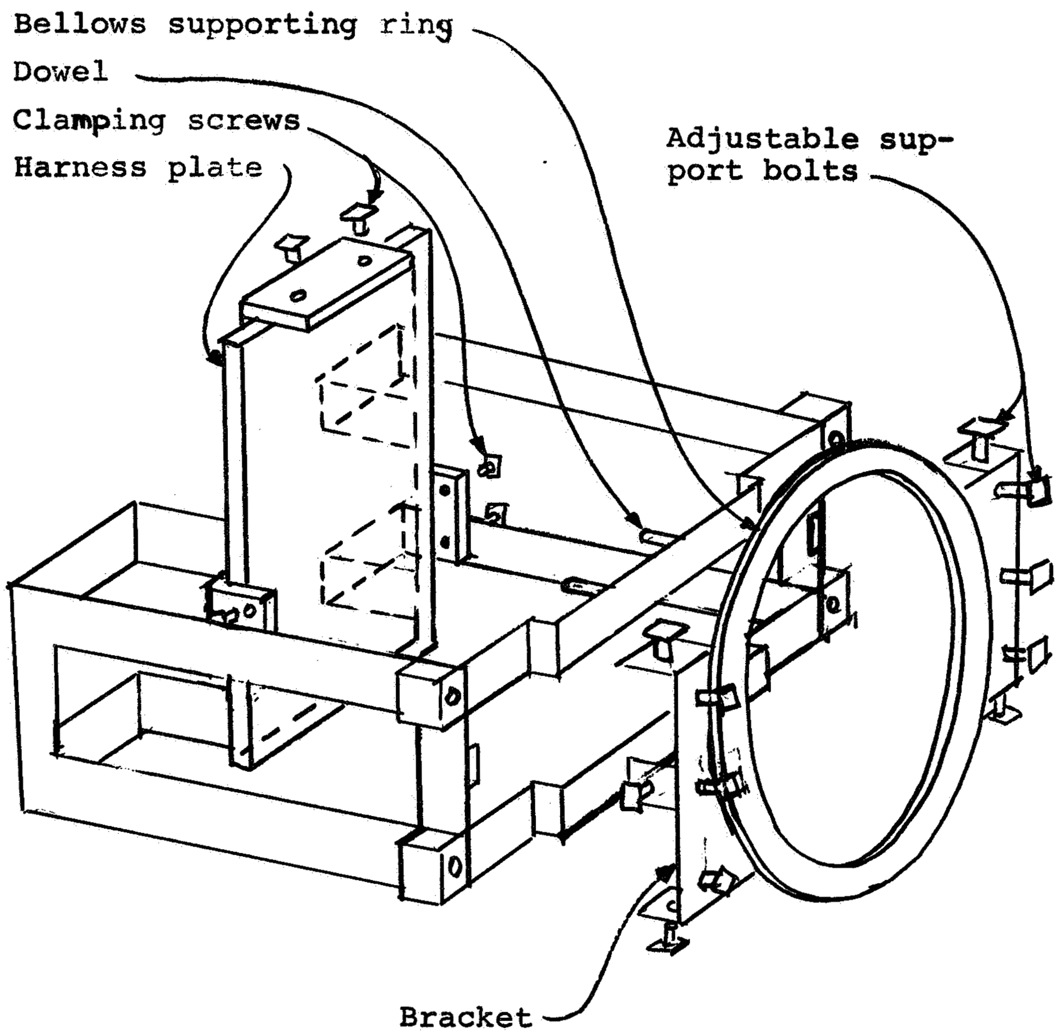


FIG. 12 HARNESS AND BELLOWS SUPPORTING RING BRACKET

will not be pulled by the bellows collapsing forces.

The grinding chamber is bolted to the grinder's longitudinal bed, while both longitudinal and crossfeed beds are restrained vertically as shown in Fig. 13. The longitudinal bed is held down by cam followers secured with brackets to the crossfeed bed and the latter by cam followers bracketed to the surface grinder base. The surface grinder's longitudinal bed surface was precisely leveled for the cam followers by self grinding. The crossfeed bed required installation of adjustable surfaces. Binding between cam followers and the adjustable surfaces and binding between bed bearing surfaces was reduced by an additional arrangement constructed to counteract the bellows collapsing force. The requisite torque was supplied by a weight attached via pulley and horizontal cable to a vertical shaft welded to the top of the chamber. The shaft is partially visible in Figs. 9 and 10. The cable was made 15 feet long to minimize the force component opposing lateral motion.

It was necessary to replace the 1/50 hp motor previously used with a 1/15 hp motor to supply the requisite 75 in-lb torque for vacuum operation. Most of the torque was needed to overcome the bellows restoring force.

Sealing

The double bellows was vacuum sealed and mechanically fastened with V-band couplings. A coupling clamped the bellows to a ring at each end. At one end the ring was welded to the grinding chamber, at the other to the bellows supporting bracket. A tight fit aided by vacuum grease provided a seal between collet

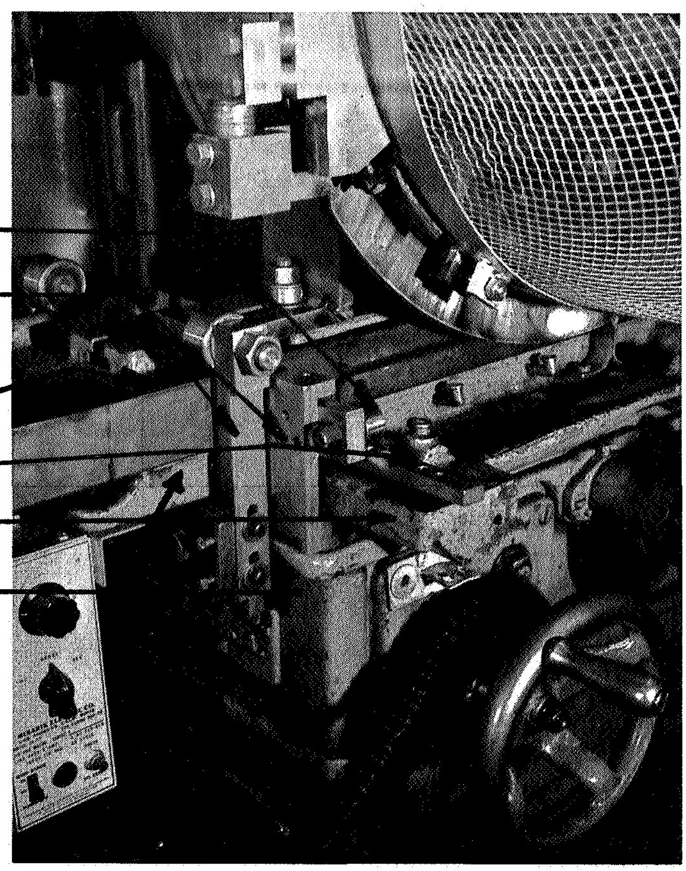


FIG. 13 VIEW OF BED RESTRAINING MECHANISMS

and grinding spindle. A dry carbon-on-metal rotary seal was used to transmit the rotary grinding motion from the spindle to the vacuum grinding chamber.

The two rotary seal components are shown in Fig. 14. The stationary component on the left was attached to the vacuum enclosure surrounding the spindle housing, drawn in Fig. 11. It was sealed in place by an o-ring about its external circumference. The rotary component on the right of Fig. 14 was attached to the collet and sealed in place with an o-ring about its internal circumference. Fig. 15 shows the seal in place relative to the above components. The stationary portion of the seal was positioned relative to the rotary portion by means of the bolts securing the bellows supporting bracket to the harness; the bolting arrangement was designed to permit positioning adjustments in any direction. The carbon ring on the rotary component rubbing on the steel surface of the stationary component is the rotary sealing interface. Atmospheric pressure on the rotary portion of the seal supplied the necessary contact pressure. The seal's small thickness, its ability to seal without the use of fluids, its ability to withstand grinding speeds over prolonged durations with their attendant vibrations, and finally its operability without elaborate alignment or support, contributed significantly to vacuum grinding system effectiveness.

Grinding Components

The grinding wheels used for vacuum operation were supported at the end of the extended length wheel collet previously

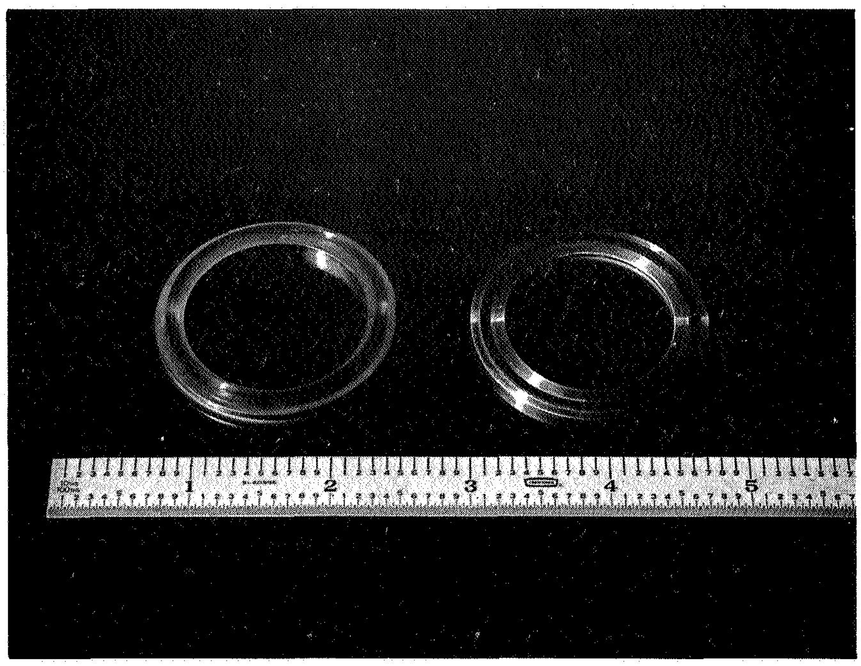


FIG. 14 ROTARY SEAL COMPONENTS

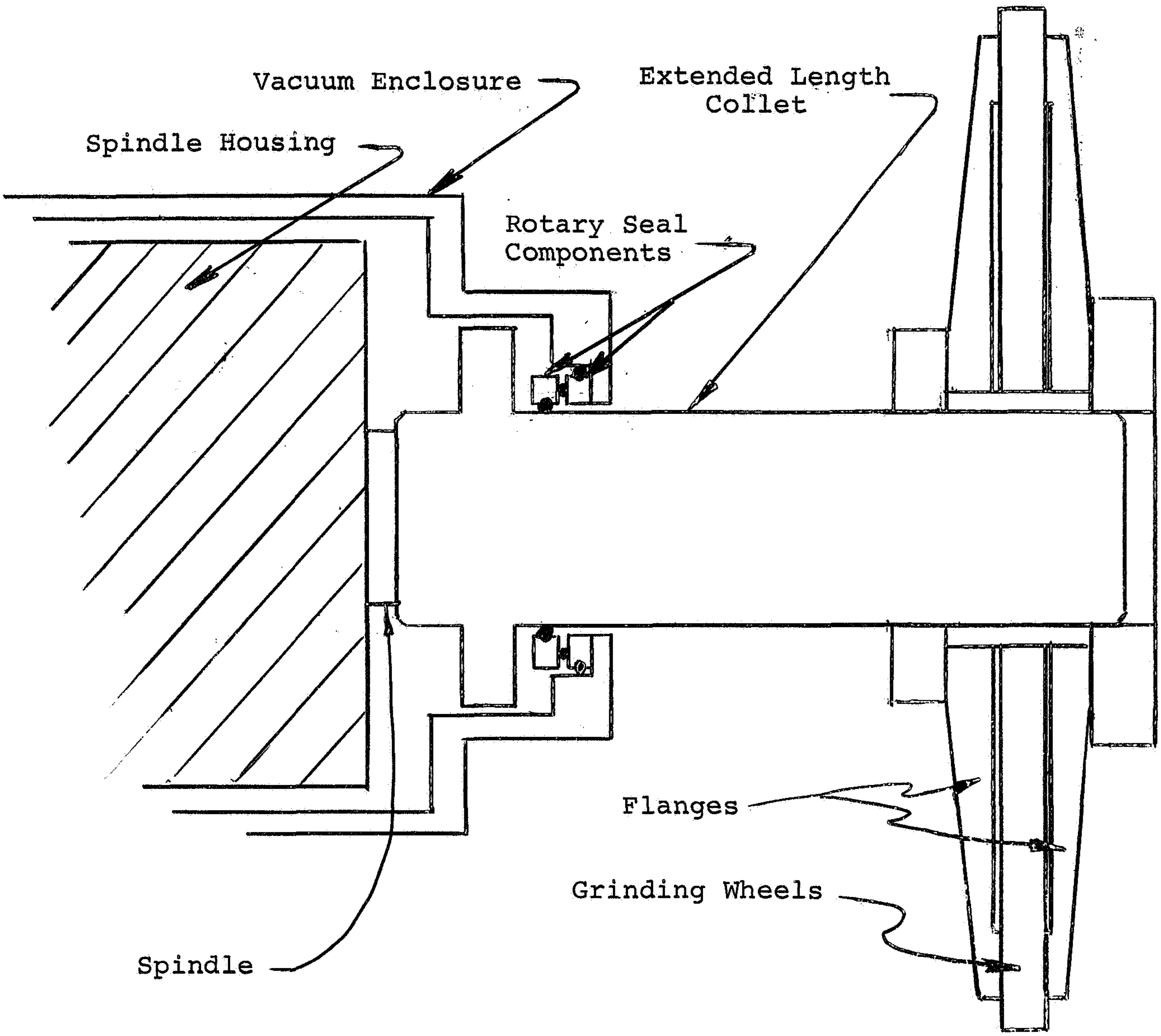


FIG. 15 VACUUM GRINDING WHEEL ASSEMBLY

designed for milling at atmospheric pressure. Because of the limits of bellows compressibility, a shorter shaft would have reduced the crossfeed distance over which grinding could be performed wholly within the steel cylinder and hence the crossfeed distance over which large ranges of lateral motions, previously described, could concomitantly occur. Grinding within the bellows area would severely have limited the lateral motion range.

Fig. 15 shows the grinding wheel arrangement used. Attachment of grinding wheels at the tip end of the collet utilized a sleeve to cover the threads and a second set of grinding wheels and flanges with appropriate inner radii. Close tolerances on the radii of these components, as well as on the collet taper, ensured ridge formation with a minimum of wheel wobble despite the increased eccentricity caused by the collet's extended length.

Since securing the planing tool below the spindle housing as in the work at atmospheric pressure was not practical, an alternate method was devised. A component was constructed for securing the scraper holder, shown at the top of Fig. 8, to the collet. It is used with the spindle locked into position.

Fig. 16 is a close-up of the vacuum chamber interior; the bellows is offset and the grinding wheels and rock are positioned for grinding. A dust shield to the right covers the exhaust port leading to the vacuum manifold. The rock is supported on a platform of adjustable height using steel blocks, of the type shown, in various thicknesses and is secured by laterally adjustable clamps set into slots ground into the rock.

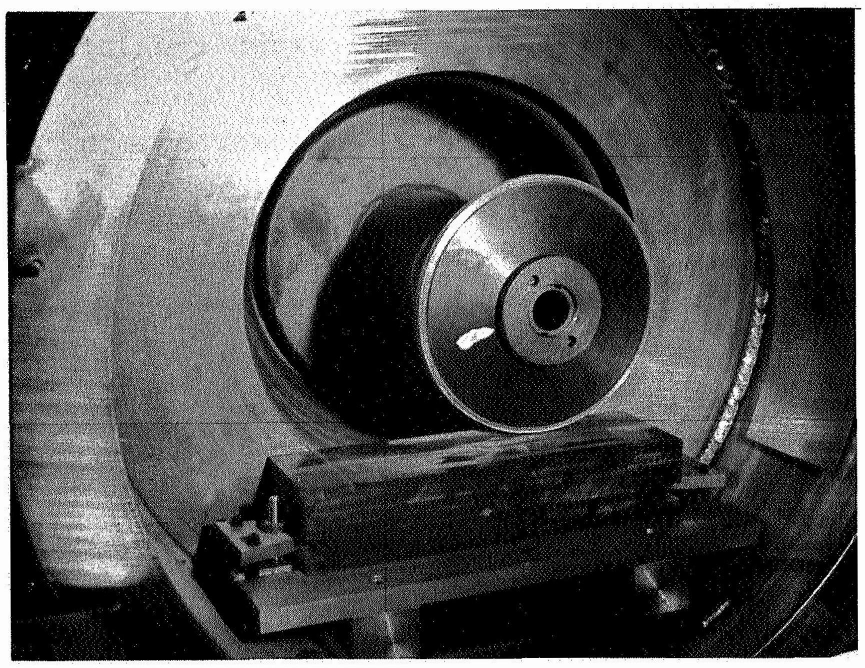


FIG. 16 INSIDE VIEW OF THE VACUUM CHAMBER

Pumping and Pressure Monitoring

The vacuum system is shown schematically in Fig. 17. A copper manifold leads from the port behind the dust shield to a mechanical pump of 140 lit/min pumping capacity. A portion of the manifold is made of flexible Tygon tubing to permit vacuum chamber movement relative to the pump. A copper U-shaped section permits manifold insertion into a liquid nitrogen dewar for cryogenic pumping. Pressure below 1 Torr was monitored by two thermocouple gauges, one at the chamber and one at the pump end of the manifold. An alphatron gauge monitored pressure at the chamber both above and below 1 Torr. The multiplicity of gauges permitted cross monitoring. A gas port permitted venting the chamber to simulated Martian or atmospheric pressure. Valves permitted closing off the chamber from the pumping manifold, the gas port, or both.

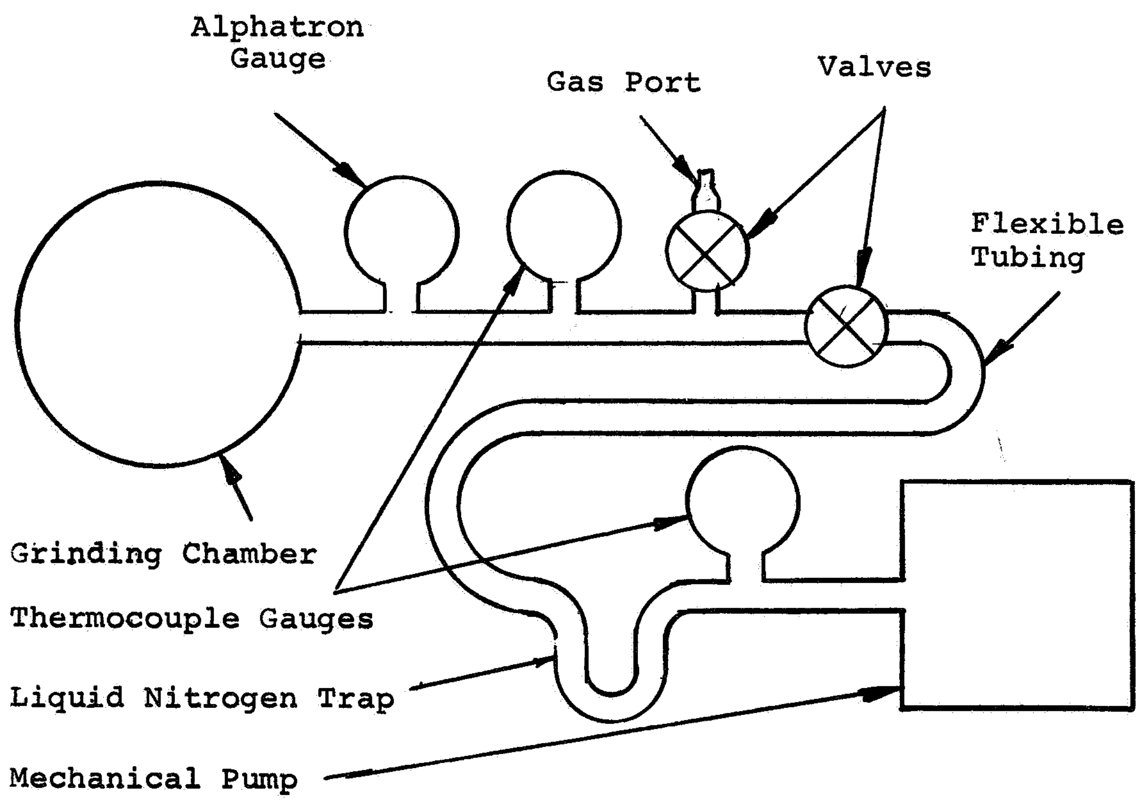


FIG. 17 VACUUM SYSTEM SCHEMATIC

PROCEDURES AND RESULTS OF STUDIES AT ATMOSPHERIC PRESSURE

Basic Procedures

The present study differs from the prior feasibility study in the increased care used in preparing experiments. A prime reason is that procedures have been geared to thinner and shallower ridges, as well as to smaller depths of cut. Machining precision is therefore more critical and powder collection efficiency, because of the small amount of powder produced per unit surface area, more problematical. Most of these problems appear to be experimental in nature since difficulties arise from laboratory conditions and are not necessary adjuncts of ultimate hardware or ultimate environmental conditions.

Because high powder collection efficiency ensures reliable particle size distribution results, the efficiency was determined for each experiment. This was done by dividing the weight of powder retrieved after sieving by the difference in rock weight before and after ridge comminution. Air billowing of powder made it necessary to comminute ridges inside a carefully prepared container. A minimum of a gram of powder was usually required to yield at least 75 percent collection efficiency. Whereas rock surfaces of about 5 sq. in. produced adequate powder quantities in the previous studies, surfaces of 25 to 50 sq. in. were usually required for conditions in the present one. Two inch rock thicknesses were cut as a compromise between adequacy for multiple experiments and minimization of errors in subtracting large weights to determine small differences. The large requisite rock parallelepipeds were prepared by encasing the rocks in a plaster of paris mold to provide an initial flat surface. The encased rocks were then sawed to shape with very large diamond wheels.

The extended length collet, previously cited, was constructed to permit ridge removal over the 3 inch rock width used. It permitted the rock to clear the spindle housing when using the 4 in. diameter milling cutters and permitted the cutters to clear the rock powder container walls.

The collecting bag arrangement varied with the ridge comminution procedure. The most elaborate fixture was the one used with the 4 inch diameter milling cutters and is illustrated in Fig. 18. An aluminum frame 10 in. high, 15 in. wide, and 4.5 in. deep supported a plastic bag of comparable proportions using double backed tape along the inside surfaces. Viewing ports at the ends of the frame permitted rock alignment. The frame was held to the magnetic chuck with steel plates fastened to the bottom of the frame. The milling cutter collet moved along a slot in the bag at the rear of the frame. A steel guard was constructed about the collet and rear of the milling cutter to prevent catching the bag, ruining the experiment and endangering the operator.

When the rotary reamer and planing cutters were used, ridge removal was far less hazardous and permitted smaller bags to be used. As a result, bag supporting frames and cutter protectors were unnecessary and smaller, thick walled (0.006 in.) plastic bags were employed which were self supporting. Fig. 19 shows such an arrangement used during one of the earlier scraping experiments. A similar arrangement was used in the rotary reaming experiments. In the later planing experiments collection was at its simplest since the scraper entered at the top of the

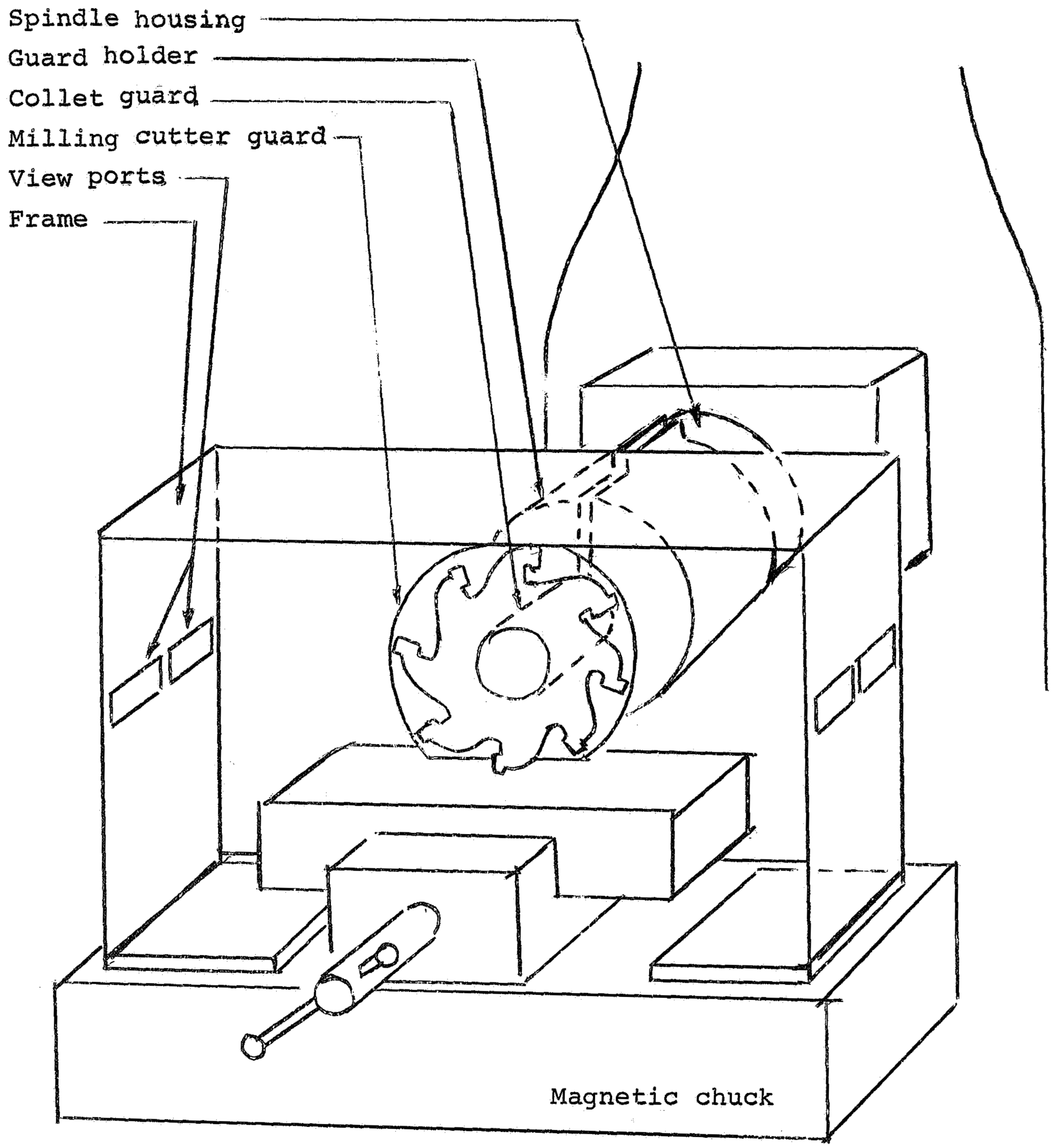


FIG. 18 GUARDS AND COLLECTING BAG SUPPORT FRAME USED IN RIDGE MILLING

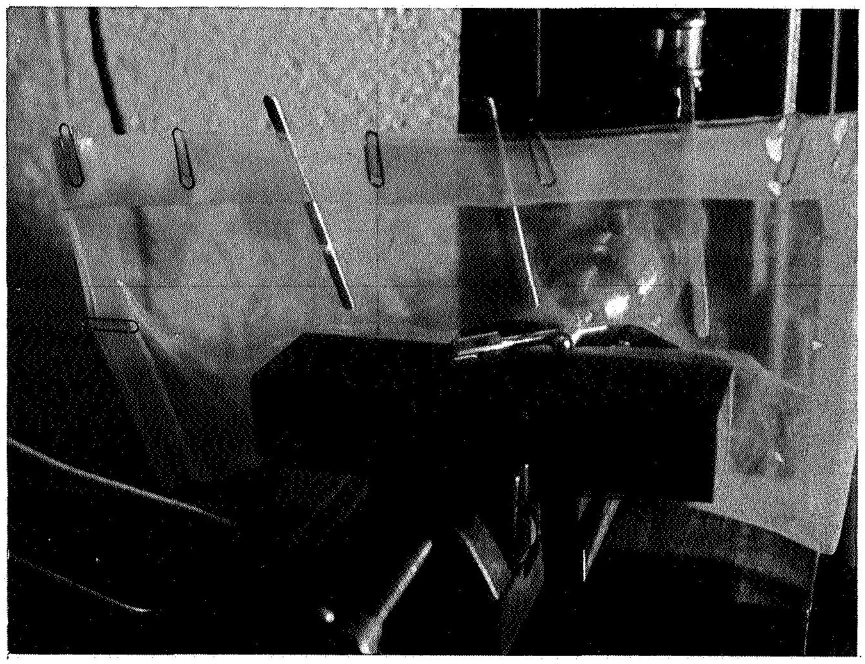


FIG. 19 POWDER COLLECTION METHOD FOR
A RIDGE PLANING EXPERIMENT

bag. The top was simply kept closed by hand during the experiment. Bags were kept at minimum dimensions to minimize powder lost to the walls, since much of this was not collected despite brushing. The bags were emptied directly into sieves which were then shaken for 15 minutes.

Ridge Preparation

In previous studies, ridges were prepared with a single dry grinding wheel. With the intent both of expediting preparation and more closely approximating ultimate apparatus requirements, five wheels ganged together were used in this study, also without grinding fluids. Expeditiousness was limited, however, because of new problems introduced by the ganging procedure and because lower traverse speeds were found necessary than with the single wheel, to minimize ridge breakage.

Ridges were produced by wheels separated with arbor spacers and very firmly clamped between flanges. Spacer and flange diameters were made slightly smaller than the inside diameters of the diamond sections to minimize the effects of wheel and spacer warping. Considerable wheel and spacer positional interchanging and rotation also was required to reduce spacing variations both between successive wheel pairs and around the circumference of each pair. A ridge width constancy of about ±0.0005 in. was thus ultimately achieved. The thickest ridges used were 0.020 in., the narrowest about 0.007 in. Intact ridges as thin as 0.004 in. were prepared in the process of testing wheel spacing to produce a desired width.

Since the ability to produce thin ridges with a minimum of breakage is of fundamental importance, a limited investigation into this problem was conducted. Mineral sections as thin as 0.003 in. are reported for use in petrographic microscopy[15,16], but a kerosene-water grinding fluid was used. Grinding wheels and methods are otherwise markedly similar except for somewhat higher grinding speeds (1600 rpm). Sections thinner than 0.003 in. were achieved by subsequent polishing. Semi-conductor wafering techniques also investigated were found quite dissimilar, however. Much higher speeds, thinner wheels and finer grit are used in this case. The latter would be advantageous to thin ridge cutting if permitted. Without a fluid, however, cuttings are not carried away and therefore would more easily clog the interstices between fine grit, which would necessitate constant dressing. The need for larger grit in turn demands thicker wheels to ensure firm grit bonding. High speeds are a further complication; without a cooling fluid mechanical stresses are induced in both wheel and workpiece producing fractures. In geological sampling, high speeds are unusable even with cooling fluids since the instantaneous high heat produced causes the surface melting of numerous minerals. Since the above techniques were inapplicable to dry grinding of thin ridges, an experimental determination of conditions uniquely suitable was undertaken.

Utilizing the ganged diamond grinding wheels, a limited investigation was made of rotary speeds, rotary-traverse direction combinations, and depths of cut per pass which would permit the fastest grinding of thin ridges combined with the lowest fracture probability. A thickness of 0.008 in. was selected as a result of ridge comminution studies to be discussed. Also investigated was the maximum total height of 0.008 in. thick ridges producible before appreciable fracture probability occurred.

It was found that the percentage of ridges fractured showed no obvious sensitivity to relative rotary and traverse directions. For consistency, however, ridges were thereafter ground clockwise while traversing the wheel from right to left over the rock. Fracturing was found sensitive to rotary speed however; greater fracturing occurred above and below speeds in the 400 rpm range. Hence 440 rpm was used thereafter since it conveniently coincided with the milling speeds used. Most significantly, at a depth of 0.010 in., about half as much fracturing occurred if the ridges were produced in one pass than if produced in multiple ones such as a 5+3+2 thousandths of an inch three-pass sequence. Fracturing percentages also increased markedly at depths greater than 0.008 in. In two passes at this depth a 10 percent loss occurred at 440 rpm, while an additional 0.002 in. cut produced a 60 percent loss; a single 0.010 in. pass produced a 30 percent loss.

Minimal ridge fracture therefore dictated a 0.008 in. maximum ridge height ground at 440 rpm in a single pass equal to the ridge height when 0.008 in. thick walls were being ground. This method was used following the first two planing experiments. (In these two experiments, thicker ridges were first made and then thinned by shifting the wheels laterally, each time grinding from the top down. While 0.030 in. high ridges were thus produced, the method was too complicated for ultimate flight hardware use.) Of course thicker ridges were produced much more expeditiously, with greater heights, and with far less fracture probability.

During the 0.008 in. thick ridge preparations, the grinding wheels were sharpened after each 9 inch pass across the basalt. A Norton number 37C150KV crystolon dressing stick was used for this purpose. The wheels were passed over the 5 inch lengths several times to a depth of a few thousandths of an inch per pass. Too great a depth was avoided to prevent undue rounding of the wheel edges. Sharpening at approximately this frequency was an important procedure in minimizing ridge fracture probability. Wheel edges were also periodically squared by passing the wheels repeatedly over a Norton number 37C320MV dressing stick to a depth of 0.0005 in. per pass, a laborious procedure. Grinding wheels were brushed after sharpening.

Fig. 20 illustrates a typical ridge profile produced. The flaring of ridge sides at the bottom was obviously caused by the worn corners of the grinding wheels and indicates the need for the dressing methods described above. The 0.008 in. thick ridges discussed describe the approximate mean ridge thicknesses over the depth of cut. Ridge thicknesses were measured several times during each surface preparation with a calibrated microscope, viewing both the top of the ridges and their profiles.

Broken ridges wedged between grinding wheels were sometimes observed. The pinching would appear to be at least partially caused by the inability to sharpen adequately the more vertical portions of the grinding wheels due to their inaccessibility. A solution to the ridge pinching problems was attempted by "keystoning" or relieving the grinding wheels as shown in Fig. 21. However, wheel wear quickly reverted the ridge shapes back to the trapezoidal shapes. The 0.003 in. thickness relief over the 1/8 in. thick diamond section was probably insufficient to give an appreciable increase in the speed of preparation.

Prior to preparing ridges for a comminution experiment, the

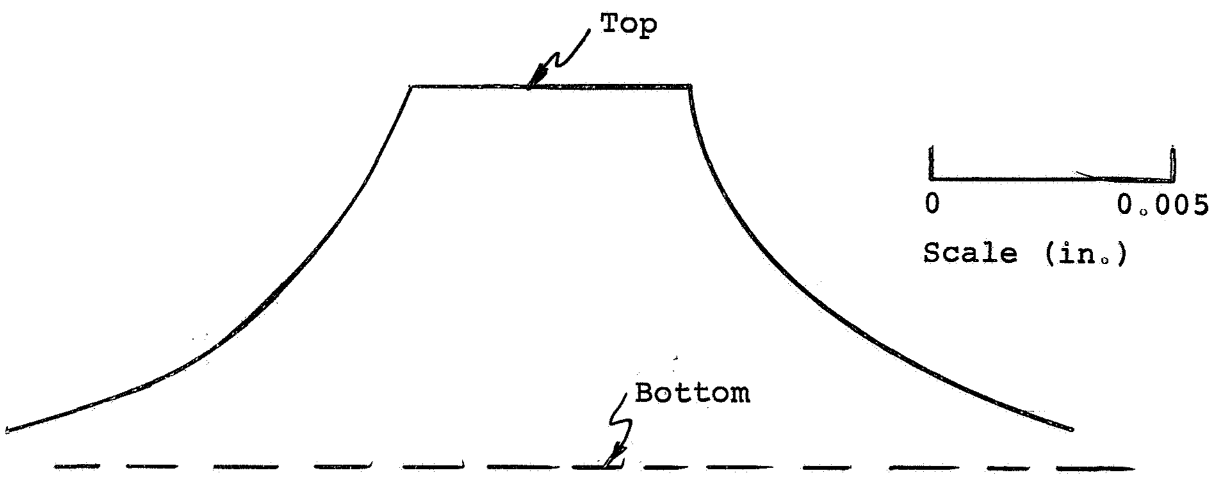


FIG. 20 TYPICAL RIDGE PROFILE

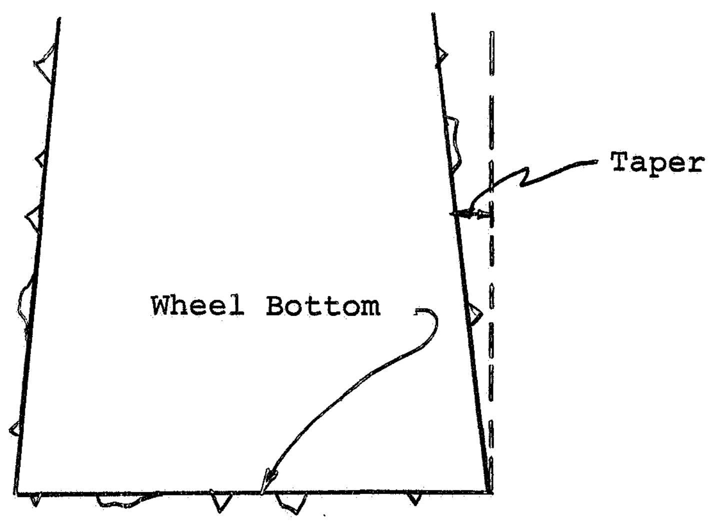


FIG. 21 WHEEL CROSS SECTION AFTER KEYSTONING

surface was ground flat and free of previous ridge material using a dry alundum wheel. The alundum was then replaced by the ganged diamond wheels without altering the position of the rock to assure the maintenance of a level grinding surface.

Ridges 0.008 in. thick were prepared on obsidian with equal ridge quality under the same conditions as those used on basalt. This is important since the applicability of the method to diverse rock types is thus indicated. However, the grinding wheels heated more rapidly on obsidian and were given 5 to 10 minutes of rest to cool after each 4 inches of ridge preparation. The preparation of 0.008 in. thick ridges also was attempted on pumice. Some degree of success was obtained on both a loose and a firm type. However, most ridges left standing were but a few thousandths of an inch high.

Rotary Ridge Cutting

Feasibility study results indicated that ridges 0.010 in. wide or thinner would be optimal for producing the desired petrographic microscopy size distributions. Nonetheless, because of the greater ease in making thicker ridges and the reasonably good results previously obtained with 0.020 in. widths, in particular, promising new parameter variations were first attempted on 0.020 in. wide ridges.

Ridge comminution by milling was the first kind of experimentation undertaken. The prepared rock was placed in the collecting bag arrangement which was shown in Fig. 18 and the ridges aligned parallel with the milling cutter plane of motion. The rock was then leveled using shims between the rock and the vise bottom. The rock surface was determined from the vertical feed setting at which the rotating cutter made initial contact. Rock and cutter were then adjusted to ensure the cutting of integral numbers of ridges.

Table I gives the results of rotary cutting experiments. All but one utilized 0.020 in. wide ridges. Table II gives the results of selected rotary cutting experiments performed in the feasibility study, for comparison. The purpose of the first experiment, test 1 of Table I, was to duplicate on the new apparatus comminution conditions previously producing optimal results with 0.020 in. wide ridges, test 33 of Table II, to see if the same results were obtained. These included a four inch diameter milling cutter with negative rake and dull blades, a 15 in/min traverse speed, 0.045 in. high ridges, a 0.010 in. cut per pass, and a 0.020 in. total cut in basalt. An experimental error caused a 220 rpm rotary speed to be used instead of the previous 440 rpm but this proved to be of small consequence.

A comparison of the size distribution results of the two tests shows them to be quite similar. The small shift toward finer particles in test 1 can be attributed to the greater collection efficiency achieved there. This is because the fines would be more easily blown from the collecting bag, more easily held to surfaces and more readily hidden in small crevices.

The second experiment, test 2 of Table I, was performed to determine the effect of reversing the relative rotary and traverse directions, while keeping other conditions the same as in test 1. Previously the cutter moved clockwise while travelling from right to left across the rock. As a result, while one motion component was parallel to the rock surface, the other was perpendicular and upwards. In test 2, the cutter

TABLE I

RESULTS OF RIDGE MILLING

Test No.	Variables								Coll. Eff. (%)	Powder Weight Distribution (% per micron sieve interval)							
	Milling Cutter				Ridge Size (mils)		Depth of Cut (mils)			0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to 420	420 to 841	841 to ∞
	Diam. (in.)	Mode	Ax. Rake	Rad. Rake	Wd.	Ht.	Per Pass	Total									
1	4	up	0	neg.	20	45	10	20	90	6	15	9	14	15	21	19	1
2	4	down	0	neg.	20	45	10	20	92	6	13	8	15	16	22	19	0
3	4	down	0	pos.	20	45	10	20	68	19	32	12	15	12	7	2	0
4	1/8	up	0	pos.	20	45	10	20	96	10	28	11	13	9	10	18	2
5	4	down	45°	pos.	20	45	10	20	88	7	10	6	10	12	22	33	0
6	4	up	45°	pos	8	8	5	5	42	20	40	24	12	2	1	1	0

TABLE II

SELECTED RIDGE MILLING RESULTS
FROM PRIOR STUDIES (Ref. 10)

Test No.	Variables		Coll. Eff. (%)	Powder Weight Distribution (% per micron sieve interval)							
	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 ∞
33	20	Dull	83	4	11	7	13	15	25	23	2
37	10	Dull	85	8	18	10	17	22	22	4	0
39-40*	10	Sharp	53	18	32	16	21	6	3	4	0

*Conducted and previously tabulated in two parts moved from left to right while retaining the clockwise rotary motion, thus producing a downward perpendicular component; this is tabulated as a down mode, the previous motion as an up mode. Chipping action was thus replaced by a crushing action. As is evident the differences in results were small, although the powder was slightly less dispersed in test 2.

In the third experiment, positive radial rake was tested. The teeth were not dulled in this experiment for fear of minimizing the positive rake effect. The intended 440 rpm was now used. Other conditions were left as in test 2. Results are obviously poorer than in the previous two tests. The smaller attendant collection efficiency indicated the true distribution to be even finer than shown. While additional tests with the positive rake could probably be made to yield larger mean particle sizes, e.g. by using large cut depths, a marked trend toward size concentration was not evident. A comparison of test 3 with 2 in Table I, and of 39-40 with 37 in Table II, indicates that making a negative rake edge positive has an effect similar to sharpening the edge, or little effect at all.

A small diameter cutter was tested next. Ridge chipping with a cutter of radius R approximating the depth of cut appeared interesting, since cut length ℓ and cut depth d would then be equal. Each chip might thereby be cut to approximate the desired dimensions and additonal fragmentation with its attendant randomness might thereby be minimized. Since too small a radius was impractical because of cutter rigidity problems, among others, dimensions larger than previous depths of cut were investigated. The choice is best explained with the aid of Fig. 22. It shows the geometrical relationship existent between R, d and ℓ if traverse motion is zero, or

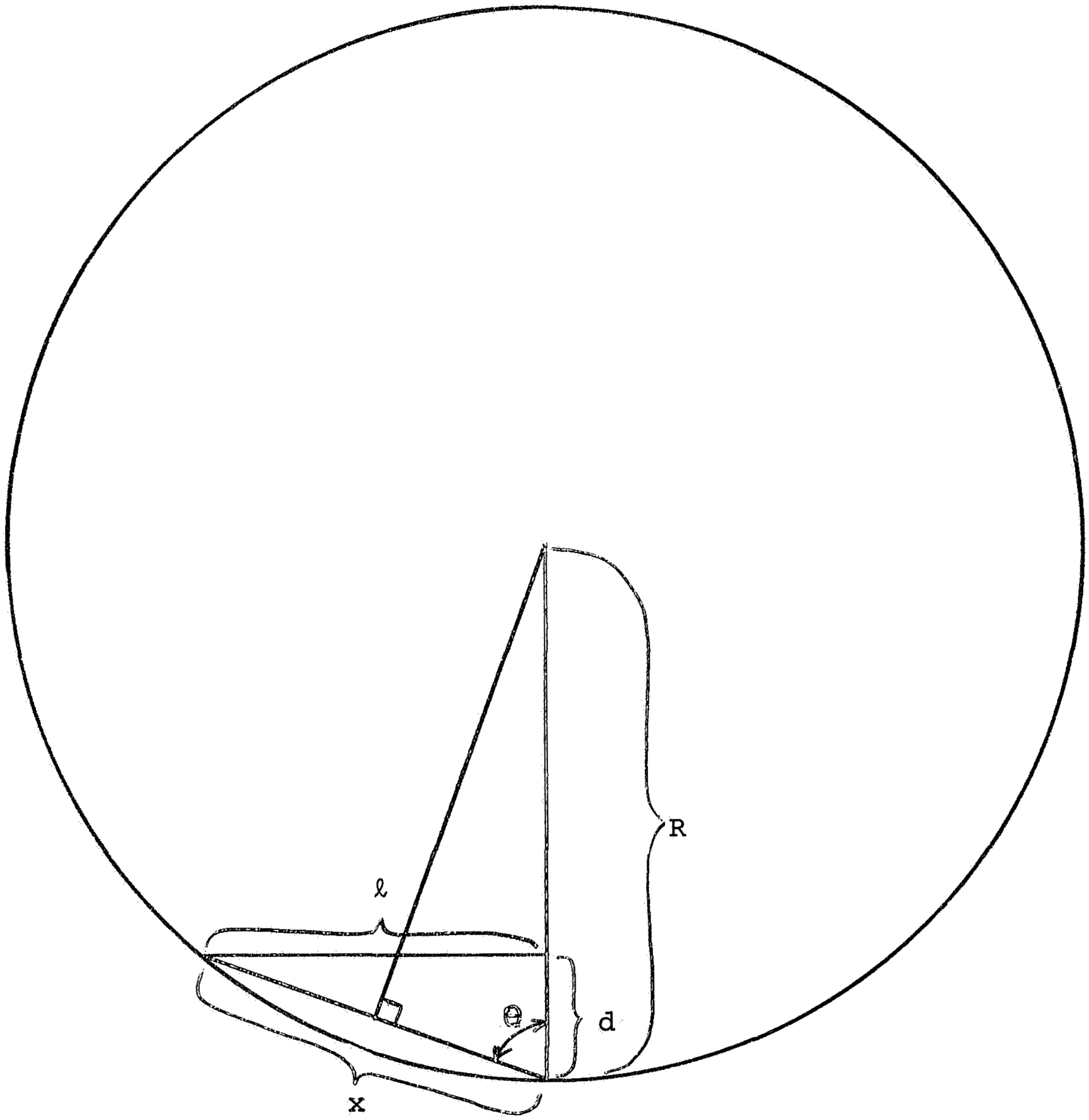


FIG. 22 GEOMETRICAL RELATIONSHIP BETWEEN CUTTER RADIUS (R), CUT LENGTH (ℓ) AND DEPTH OF CUT (d)

if the linear speed of rotation is much greater than the traverse speeds, which is true in all the tests conducted. The following trigonometric relationships can be derived from the geometry:

$$\cos\Theta = \frac{x/2}{R} = \frac{d}{x} \tag{1}$$

$$x^2 = d^2 + \ell^2 \tag{2}$$

Solving Eq. (1) for x gives

$$x^2 = 2dR \tag{3}$$

Equating Eqs. (3) and (2) and solving for ℓ and R gives

$$\ell = \sqrt{d(2R-d)} \tag{4}$$

and

$$R = (d^2 + \ell^2)/2d \tag{5}$$

The choice of a 1/8 in. diameter cutter appeared a reasonable compromise. Substituting a value of R of 0.063 in. and d of 0.010 in. in Eq. (4) results in an ℓ of 0.034 in. or a 3.4 length to depth ratio. This compares with a length to depth ratio of 20 when a 0.010 in. cut is made with a 4 in. cutter. The 1/8 in. diameter cutter was therefore considered an effective test.

The 1/8 in. diameter cutter was purchasable as a reamer, equipped with tungsten carbide blades, as were the milling cutters. However, they were available only with positive radial rakes and with 4 teeth instead of 8. The latter required a reduced traverse speed to maintain rock contact distances between successive cutting teeth equal to those in previous experiments. A 440 rpm rotary speed, 15 in/min traverse speed, and 8 teeth per revolution cutter produces a tooth contact distance, tcd, of

$$\text{tcd} = \frac{1}{440}\,\frac{\text{min}}{\text{rev}} \times \frac{15\ \text{in.}}{\text{min.}} \times \frac{1}{8}\,\frac{\text{rev}}{\text{tooth}} = 0.0043\ \text{in.} \qquad (6)$$

or about 100μ. A traverse speed choice of 7.5 in. per min was therefore necessary to maintain an equal tcd for the 4 tooth cutter at 440 rpm. Ideally the rpm should have been adjusted as well as the tcd, so as to maintain the same linear speed of rotation as in previous tests. However, this would have required a wheel speed of 14,080 rpm, which far exceeded the capabilities of the surface grinder.

The relative rotary and traverse motions were adjusted to provide an upward vertical component, as in test 1, and teeth were dulled to match the edges of test 1. This was accomplished by rubbing a 180 grit diamond wheel several times over the cutting edge. The cutter was held in a chuck fitted to the Browne and Sharpe spindle as described earlier and adjusted by machining and shimming to reduce eccentricity at the tip to within ±0.001 in.

The results, shown in test 4 of Table I show a definite increase in size dispersion. Twenty percent of the particles lie above 420μ and 38 percent below 44μ making both coarse and fine particles too numerous. The decreased cutter diameter may have produced the dispersal either because it increased the vertical force component, i.e. the chipping component, or because it greatly reduced the linear speed of rotary motion.

The results of using a 4 in. diameter milling cutter with both positive rake and 45° axial rake is shown in test 5. The important new parameter was the 45° axial rake. The intent was to use it to produce larger particles, since less resistance exists perpendicular to the ridges than parallel to them. Remaining conditions were the same as in test 2, the cutting edge being dulled in the manner described above. The resultant distribution shows a definite trend toward larger sizes. However, improvement in size concentration is not appreciable, if at all existent.

Test 6 attempted to examine if the large percentage of particles in the large size ranges could be shifted to the desired range without an appreciable increase in fines. The important parameter changes to this end were (a) a reduction in depth of cut per pass to 0.005 in., (b) a reduction of the number of passes to one, which tests in the feasibility study indicated should reduce the percentage of fines, and (c) a reduction of ridge widths to 0.008 in.

Results were again inconclusive. The poor collection efficiency, resulting from the small specimen weight collected, indicated that the concentration in the fines that is evident was likely to be even greater. While a cut between 0.005 and 0.010 in. could increase the mean particle size, the combined results of tests 5 and 6 indicate that the 45° axial rake has not produced a marked increase in size concentration with the rotary cutter.

Planar Ridge Cutting

Improvements in some of the diverse rotary cutting techniques of Table I could doubtless be made through parameter refinement. However, since a marked increase in particle size control failed to emerge, a method with greater potential was sought. It was deduced from the size degradation in test 4 produced by the small diameter cutter that an infinite diameter cutter might have such potential. Planar ridge cutting was therefore attempted, semi-qualitatively at first.

A tungsten carbide glass cutter was scraped across 0.020 in. wide ridges. A negative radial rake and a dulled edge was used, since these were previously evidenced to be optimum conditions. The 15 in/min traverse speed was also maintained. However, a 45° axial rake was employed with the intent of minimizing randomly produced fines. Results were encouraging, showing good particle size concentration but in too large a size range. A quantitative test with thinner ridges was therefore conducted next.

A ridge thickness of 0.008 in. was prepared next as a compromise between closely approximating the desired particle sizes and producing the ridges with minimum difficulty. A smaller 0.030 in. height was prepared as well. This made 0.008 in. ridge formation more practical and was believed more desirable with the thinner ridges to keep particle size down. The two step ridge forming process was used, as described earlier. A 0.005 in. cut per pass was adopted instead of the 0.010 in. previously used in anticipation of coarser mean particle sizes caused by the 45° axial cut, as indicated in test 5. Two cuts, for a total of 0.010 in., were used to acquire sufficient powder for adequate collection efficiency.

The results, shown in test 7 of Table III, were very encouraging, especially considering the relative imprecision of the experiment, which included a good deal of cutter flexure and not too precise a rock leveling procedure; the latter is especially critical when such small depths of cut are made. The percentage of material below 44μ was the smallest ever produced, well below requirements. The percentage of particles above 250μ was very high but nonetheless showed a sharp decline above 420μ, indicating good control.

A second planing test, test 8, was conducted on still shallower ridges to reduce further the percentage of coarse particles. This test also was relatively imprecise. A large ridge height variation, from 0.010 to 0.017 in., existed as well as a remaining cutter flexure problem, i.e., the depth of cut was less than the value set on the vertical feed setting. Nonetheless the size distribution improved in the direction intended and was the best distribution obtained as a comparison with the previous optimum distribution, test 37 of Table II, performed in the prior program, shows. An improvement in ridge

TABLE III

RESULTS OF RIDGE PLANING

Test No.	Variables						Coll. Eff. (%)	Powder weight Distribution (% per micron sieve interval)							
	Rock	Axial Rake	Ridge Size (mils)		Depth of Cut (mils)			0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to 420	420 to 841	841 to ∞
			Wd.	Ht.	Per Pass	Total									
7	Basalt	45°	8	30	<5[a]	<10[a]	75	4	9	7	11	16	43	11	0
8	Basalt	45°	9	10-17	<5[a]	<10[a]	75	6	14	12	19	23	26	1	0
9	Basalt	45°	8	8	<5[a]	<10[a]	33	10	22	21	34	8	3	2	0
10	Basalt	45°	8	8	<3.5[b]	<7[b]	30	9	20	19	37	14	1	1	1
11	Basalt	45°	8	8	4.5	4.5	33	13	22	19	33	9	2	4	0
12	Basalt	45°	8	8	4.5[c]	4.5[c]	89	15	18	10	19	27	6	3	2
13	Obsid.	45°	8	8	4.5	4.5	79	4	17	13	23	27	13	2	1
14	Basalt	0	8	8	4.5	4.5	72	13	20	14	30	20	2	1	1

[a] Cutter flexure

[b] Cutter flexure less than previous

[c] Cutter duller than in test 13

comminution technique was therefore apparent. A need for decreased ridge heights and for more precise experimentation was thus indicated to test the method's full potential.

At this point experiments were conducted on thin ridge preparation methods discussed earlier and ridges 0.008 inches in both height and width were produced by the optimal method resulting. In remaining experiments ridges were usually produced with less than a 10 percent ridge loss.

To permit assigning meaningful values to the small depths of cut to be employed, under 0.005 in., cutter corners were squared off by grinding. The edge was then dulled by hand grinding with a 180 grit diamond wheel and small cutter edge variations removed in the same manner until they were within ±0.0005 in. The cutter that was shown at the bottom of Fig. 8 was used attached to the spindle housing with a chuck as was shown in Fig. 19. After edge preparations, the cutter was aligned with surface grinder motion. The rock was then leveled utilizing the cutting tooth, and vertical feed settings as indicators. The ridge surface was thus leveled to within ±0.0005 in.

The results of the ridge height reduction and of the more tightly controlled conditions are shown in test 9 in Table III. A very marked size improvement is evident. The particle percentage in the desired 74-149μ range is double that obtained in the feasibility study, test 37 of Table II. The percentage above 250μ is below the maximum desired, while the percentage below 44μ is only 12% above the maximum desired. The results were the more impressive because of the remaining cutter flexure problems, not discovered until after this experiment. It indicates the tolerability of the method to depth of cut variations. It may indicate force, rather than depth of cut, to be the more important parameter.

An experimentally detrimental result of the cutter flexibility was the small amount of powder produced from the reduced cut depth, 0.25 grams, of which less than 0.1 grams was collected. The result was very poor collection efficiency, 33%, which diminishes distribution reliability. Subsequent experiments therefore were planned to greatly increase collection efficiency, as well as to reduce appreciably the flexibility of the cutter. These were the most difficult and elusive goals of the project, although ultimately accomplished. Control of associated experimental variables was also improved. The objective was a determination of the full potential of the planar ridge method, temporarily disregarding the practical implications of any ensuing experimental difficulties.

Cutter flexure problems were first traced to flexibility in the cutting tool design, which was gradually modified, and finally to flexure in the surface grinder itself, which required overhauling and replacement of worn components. Ultimately, the effects of residual flexure were eliminated by applying compensatory downfeed on the cutting edge, an important technique for ultimate flight hardware use. The flexure and compensation were monitored with a standard machinist's surface gauge which was independently suspended and applied to the top of the cutting blade holder.

Fig. 23 shows the first rigidification procedure, which prevented both upward flexure in the cutting arm and pivoting in its holder. It reduced flexure before scraping to 0.001 in. Then, since previous planing cuts were estimated to be 0.001 in., a cut setting of 0.0035 in. per pass was used to provide about

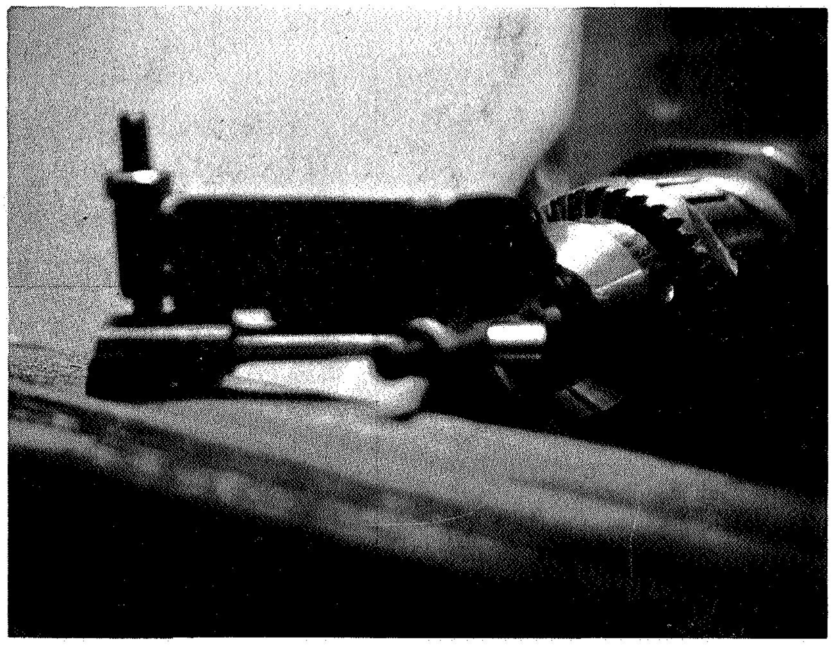


FIG. 23 EARLY METHOD USED TO RIGIDIFY THE SCRAPER

a 0.0025 in. cut to give the needed coarser distribution. Conditions were otherwise maintained as in test 9. The results, shown in test 10, demonstrate a further distribution improvement and were the best achieved in the study: 37 percent in the desired range, only 3 percent above 250μ, 29 percent below 44μ.

Unfortunately, collection efficiency was the poorest achieved and cutter rigidity, although improved, had degraded from the 0.001 in. deflection measured prior to the experiment due to the progression of flexuring to other parts of the apparatus. A small cutter blade tilt relative to the rock surface also was discovered, contributing to a diminution in powder production, as well as cut unevenness. Only 0.5 grams of powder was produced, 30 percent of it collected.

Additional rigidification of the arrangement used in test 10 proved fruitless. Surprisingly little force displaced the cutter over small distances, about 5 lbs per 0.001 in. of deflection. A 20 lb. weight was therefore applied to the cutting arm but proved unsuccessful because the reacting force, or spring, in the cutting arm counterbalanced it. It became obvious that the downward force must be applied freely as it would by the weight of a spacecraft sitting on the ground.

A new cutter holder and mounting method described earlier and shown in Figs. 3 and 8 were found to be the simplest experimental solution. The holder was mounted directly beneath the spindle housing to provide maximum rigidity. At this point, methods of securing and leveling the rock were also improved. Using apparatus described earlier, the rock was gripped at each end in a modified vise and the height at each corner adjusted with leveling screws. The cut depth was determined from the difference in vertical feed setting at the surface before and after planing and from microscopic measurements of the ridge profile before and after planing. In the next test rigidity was indeed maintained to within 0.0005 in. and a single 0.0045 in. cut made. Collection efficiency remained a problem, however, due to the small amount of material removable from the thin ridges with the small depths of cut even over the large 2.75 x 9 in. rock surface.

Test 11 shows the result of the controlled depth of cut experiment. Despite the increased cut depth, the distribution is remarkably close to the previous two tests with similar collection efficiencies.

Intensive efforts were made to increase collection efficiency with the small amount of powder collected. It was found that negligible losses resulted from sieving. When 0.48 g of powder mixed from equal quantities of the seven sieve sizes were sifted, 98 percent was recovered (and the distributions were left virtually intact). Since excellent powder containment was possible with the scraping technique employed, it was deduced that powder was lost in the process of recovering it from the bag. Little more could be done about this aspect except to select bags carefully to ensure the absence of seam crevices. Primarily more powder had to be produced. Good collection efficiency with the 0.008 in. ridges and 0.0045 in. cut depths were finally achieved by planing all four sides of the rock along its length thus producing powder in sufficient quantity to make the losses fractionally small.

A test of cutter rigidity prior to the next experiment showed an increase in flexibility of the surface grinder itself. Restraining of the surface grinder bearing plates was necessary to keep cutter movement below the 0.0005 in. deflection previously attained. Bearing plates were shimmed and clamped, the latter using bolts threaded into the vertical casting to restrict movement during each planing sequence.

The result both of good depth of cut control and high collection efficiency is shown in test 12. The results are not as good as in tests 9, 10 and 11 though still superior to test 37 of Table II. The main disappointment is the 15 percent particle size value produced below 20μ. There are several possible explanations for the discrepancies between tests 11 and 12: (a) Collection efficiency was markedly different between the two tests, (b) A small portion of the scraped surfaces in test 12 contained ridges only 0.006 in. high, apparently a preparation error; because of ridge flaring at the base, thicker ridges, as well as shallower ones, were then being scraped, (c) A variation in edge dullness likely existed; the blade was more extensively used prior to the actual experiment in test 12. Reasons b and c are believed to be the more likely ones.

An obsidian scraping experiment was prepared next to test for distribution consistency between two dissimilar rocks. In the process a further degradation of surface grinder cutting rigidity was observed and efforts were made permanently to solve this problem. Its cause appeared to be the removal of the centrifugal force normally present to enforce high cutting precision. Without rotary cutting the downward dynamic force component which normally affects flexuring forces was absent.

After laborious investigations, unwanted deflections were traced to wear in the surface grinder elevating nut and screw assembly, which were then replaced, and to looseness of fit remaining in the front and rear bearing plates, which were then more tightly shimmed. Remaining flexure, about 0.001 in., was corrected by adjusting the vertical feed during the planing operation. Depth of cut was monitored by a surface gauge suspended independent of the surface grinder. Depths of cut were thus controlled to within a few tenths of a thousandth of an inch. The test used a cutter newly sharpened and subsequently dulled by hand with the 180 grit diamond wheel. These steps were necessary to overcome the overly dulled or rounded edge resulting from repeated use of the cutter in the process of testing and tightening the surface grinder.

Test 12 shows the results of planing obsidian with conditions otherwise the same as those of test 12. The test 12 and 13 results are reasonably close, test 13 giving the better distribution. It is possible that the more rounded cutter used in test 12 accounts for much of the increased percentage of fines produced there, compared with test 13, rather than the difference in rock material. Several additional observations are noteworthy. (a) A greater tendency towards chipping was observed with the obsidian than with the basalt; the outer ridge which would be broken away from the obsidian was not planed for this reason. (b) Residual ridges were observed to vary considerably in thicknesses which may be responsible for some of the remaining size distribution dispersion. Because of ridge flaring at the bottom, these may have been caused by small differences in wheel radii and in cutting depths over the surface of the rock.

Fig. 24 shows obsidian with the residual ridges after planing. Two of the four planed sides are shown. The rock

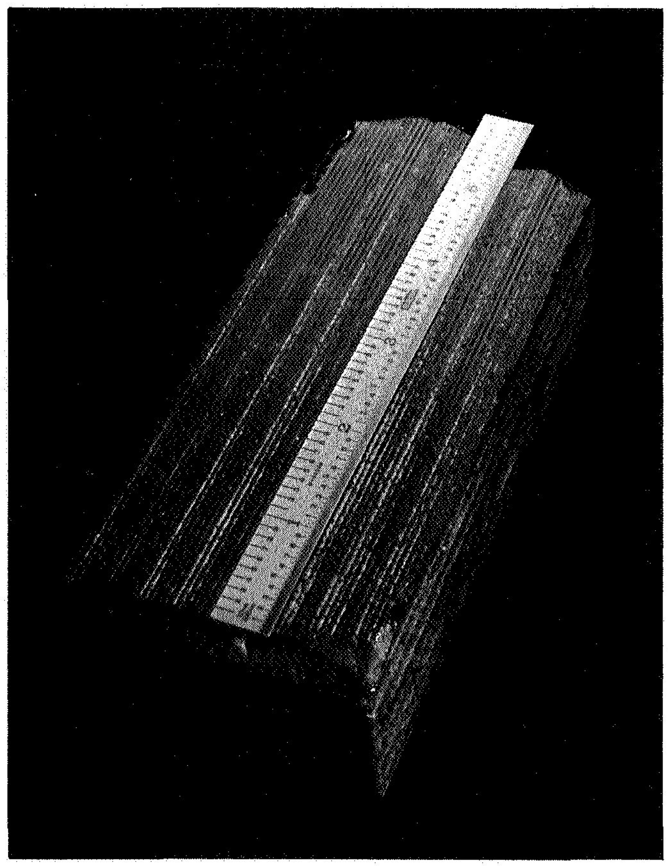


FIG. 24 OBSIDIAN AFTER PLANING

was shorter than the basalt components used.

A final test was conducted on basalt to determine the effect of zero axial rake. Remaining conditions are those tabulated for the prior basalt experiment, test 12, with the exception that the cutter edge was not as dull; the blade was the one used in test 13, without renewing the edge. Another difference was the elimination of the small ridge height variations indicated during test 12. Collection efficiency was reasonable at 72%. The results, shown in test 14, are good. The quality of the distribution is exceeded only by test 10, where poor collection efficiency existed. The indication is that an axial rake between 0 and 45° would be optimum.

Machine rigidity became poor again, flexuring about 0.002 in. Depth of cut was nonetheless maintained to within ±0.0001 in. by adjusting the vertical feed during planing, described for test 13, using a surface gauge as a monitor. The effectiveness of this feedback despite machine flexure indicates the adaptability of the planing technique to devices lacking great rigidity.

PROCEDURES AND RESULTS OF VACUUM STUDIES

Operational Procedures and Results

The lowest pressure thus far attained with the system was 0.09 Torr, about 20 times the terminal pressure obtained with the mechanical pump itself. The pump pressure could probably be approached with a thorough cleaning of the vacuum chamber components, further investigation of leak sources and a prolonged pumping of the system to rid it further of volatiles. The 0.09 Torr pressure level required about half an hour of pumping. It also required pushing the rotary seal components together anew during each evacuation by an estimated few thousandths of an inch. This was accomplished by a fractional turn on bolts securing the bellows supporting bracket to the surface grinder harness. The latter represents a nuisance whose cause, probably improper seal functioning, was not determined. Terminal gas pressure appeared largely insensitive to rotary grinding speed, which was operated between 0 and 1750 rpm. It also appeared insensitive both to the degree of mechanical grinding pressure and to gas released from the rock due to grinding.

Martian surface pressure has been determined from the Mariner 4 mission to be approximately 4 Torr[17,18]. To grind at this pressure, the chamber was first evacuated to terminal pressure, to ensure freedom from leaks, then backfilled with air and valved off from the pump and gas intake nozzle. This procedure was adopted to eliminate all air currents except those generated by grinding.

During chamber evacuation, before grinding was commenced, sufficient weight was supplied at the end of the pulley, described earlier, to counteract the bellows collapsing force. About 300 lbs. was required at the end of the 4 ft. long moment arm. A proper application of weight was signified by the ability to rotate cam followers by hand at both front and rear surfaces, thus eliminating binding. Although movement was reasonably smooth, a small residual jerkiness persisted in the longitudinal bed when operated at very slow traverse speeds. Cross-feed movement, which was manually adjusted, was very easy in the direction of bellows collapse but operable with difficulty in the opposite direction despite the assistance of the weight and pulley arrangement. Vertical movement, which was manually adjusted, was smooth and easy in both directions.

Before chamber evacuation, the rock was leveled for ridge formation by the use of shims between the rock and its supporting plate. The surface was measured by reading the vertical feed settings as previously discussed. Chamber evacuation caused a 0.004 in. change in the mean surface height of the rock but less than a 0.0005 in. height variation over its surface.

Ridge Formation

The vacuum grinding apparatus was tested at atmospheric pressure prior to each vacuum experiment to determine its relative ridge forming effectiveness. Initially, the results were poor because of erratic traverse motions and gross wheel wobble. The former resulted from the strain of the bellows restoring force when the bellows was appreciably off-centered and was corrected by worn component replacement in the grinding machine, lubrication, and suitable cam follower adjustments. Wheel wobble resulted from the somewhat imperfect fit between spindle and collet tapers and exaggeration of the resulting eccentricity at the collet tip by its 3 - 5/8 in. shaft length. Following correction of this problem, as well, the ridges produced at atmospheric pressure were among the best obtained despite the somewhat more stringent ridge dimensions.

Ridges were about 0.007 in. wide, compared with 0.008 previously and did not flare appreciably near the bottom, since the edges of the newer wheels were less worn than those previously used. Remaining experimental conditions were essentially the same as first described for grinding at atmospheric pressure. Ridges were produced in basalt.

A small residual wobble, about ±0.001 in. of grinding motion perpendicular to the grinding wheel plane, may actually have assisted ridge formation. (This amount of wobble, though small, was probably greater than in experiments described earlier.) During trial experiments performed to obtain desired widths, a ridge as thin as 0.004 in. was produced. Wobble very likely eliminated ridge pinching problems by providing an inter-ridge spacing appreciably greater than the width of the diamond wheel.

Two vacuum tests were conducted following resolution of the above problems to test ridge forming effectiveness. Each was conducted at both 0.09 Torr and 4 Torr while repeating remaining experimental conditions. In each test ridge quality was poor. About 70 percent of the ridges produced in vacuum were broken compared with a negligible percentage at atmospheric pressure.

Some of the loss may have been caused by a small residual erratic traverse motion, which was somewhat greater in vacuum. No difference in quality was discernible between the two low pressures tested.

Powder Trajectories

A distinct difference in the powder trajectories was observed at the two low pressures investigated. At 4 Torr, some of the rock powder swirled at right angles to the grinding wheel plane, in the form of a right hand screw. This spiral pattern appeared identical to that produced at atmospheric pressure and was evidently the result of air turbulence produced by the grinding wheel motion even at 4 Torr. At 0.09 Torr, particles were projected more ballistically. However, most of the powder was projected in front of the wheels at all three pressures.

In Fig. 25 the powder patterns formed on the rock by grinding ridges at 760 Torr is shown as viewed from directly above the rock. In Fig. 26 the patterns produced in vacuum are shown. The powder at 4 Torr was projected from the set of ridges near the lower left, at 0.09 Torr from ridges near the upper right. Grinding proceeded from left to right. Other groove sets are extraneous and are from prior experiments. Asymmetry in powder patterns is evident both at 760 Torr and at 4 Torr and is a result of the air currents. At 0.09 Torr no asymmetry is evident however, which is consistent with the lack of aerodynamic effects observed at this pressure, although some asymmetry might conceivably have been indicated if a longer

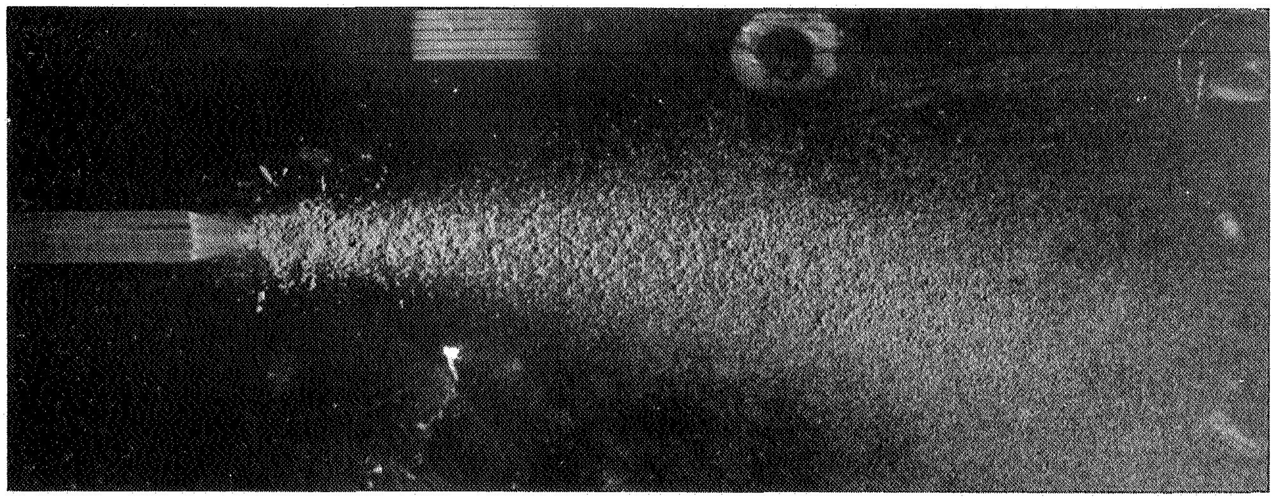


FIG. 25 ROCK POWDER DISTRIBUTION PRODUCED BY GRINDING RIDGES AT 760 TORR

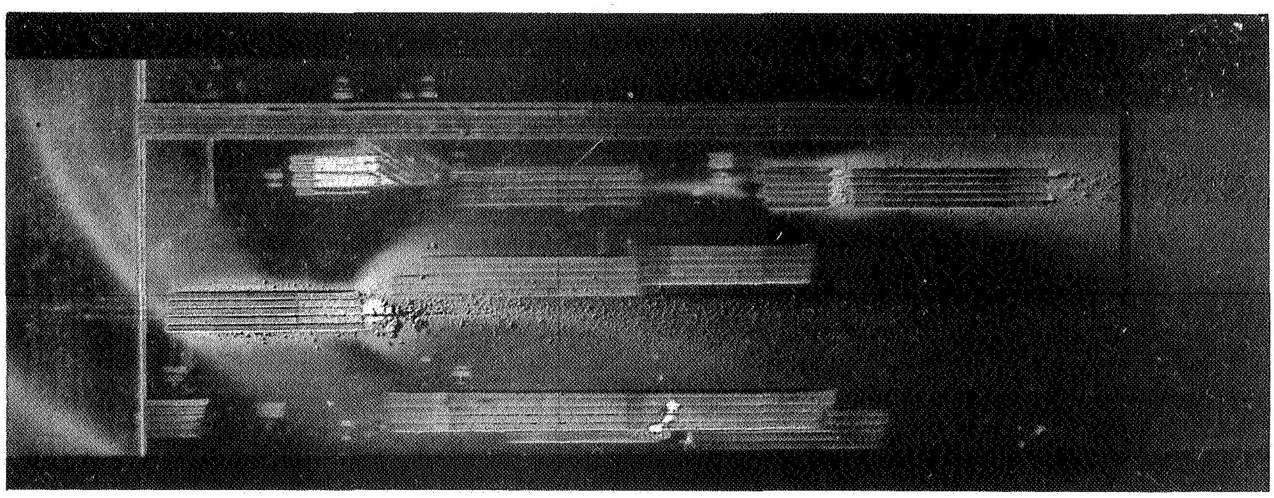


FIG. 26 POWDER DISTRIBUTIONS PRODUCED BY GRINDING RIDGES (a) AT 4 TORR (LOWER LEFT) AND (b) AT 0.09 TORR (UPPER RIGHT)

powder trail had been photographed.

It is interesting to note that powder was piled along the sides of the ridge and grooves at both low pressures but not at atmospheric pressure. A marked increase in flaring or sideward projection of powder is also evident at low pressures, as well as greater proximity of the flaring to the ridge and groove vicinity. Consistent with this increase in lateral powder projection with decreased pressure is the more extensive path length of broadly distributed powder alongside the ridges and grooves at 0.09 Torr than at 4 Torr. The powder diagonally smeared along the lower left portion of the rock, a swath of which was wiped off through the middle, was probably a result of the powder swirling.

More powder appeared to cling to the grinding wheels during vacuum grinding than at atmospheric pressure. This was substantiated by the flinging out of considerably greater amounts of powder when the wheels were run at high speeds after vacuum grinding than after grinding at 760 Torr. This would sometimes occur only after the wheels were brushed on the outside. Powder thus appeared to be caked between the wheels and released only after the outer "crust" was removed. Since grinding at both low pressures was performed without intervening chamber release to the atmosphere, their differential effects on powder adherence are unknown. Increased clinging of powder to the grinding wheels could account for the poorer ridge forming capabilities in vacuum.

DISCUSSION AND CONCLUSIONS

Table IV presents selected results from the present and previous programs. Distribution a represents the minimum desired concentration about 75-150μ (Ref. 1). Distribution g was the best approximation achieved by optimizing conventional grinding parameters. The appreciable improvements made first by the ridge milling innovation, distribution f, and then by ridge planing, distributions b and c are evident. It appears that the remaining requisite improvements can be made, without further innovation, by optimizing the existing parameters. It also appears likely that a significant amount of size dispersion may be the result of reducible experimental deficiencies.

Cut depth and ridge height variations are examples of deficiencies believed to have increased size dispersion, as well as the variations between distributions d and e where rock type was altered, and between distributions d and c, where axial rake was altered. A primary cause was rock leveling imprecision. This is a problem which would be non-existent in ultimate apparatus operation, examples of which will be discussed, because such apparatus would be contour independent. Variations because of this problem were compounded by the tolerance of too great a flaring at the ridge base, due to grinding wheel wear on the corners with successive experiments. This is another deficiency example which need not exist in the ultimate hardware. Evidence for the above was the variations in remaining ridge widths after planing.

Cutter sharpness variations, a third deficiency example,

TABLE IV

COMPARISON OF THE DESIRED DISTRIBUTION
WITH SELECTED TEST RESULTS

Distribution	Variables							Coll. Eff. (%)	Powder Weight Distribution (% per micron sieve interval)							
	Abrasion Method	Rock	Ax. Rake	Ridge Size (mils)		Depth of Cut (mils)			0 to 20	20 to 44	44 to 74	74 to 149	149 to 250	250 to 420	420 to 841	841 to ∞
				Wd.	Ht.	Per Pass	Total									
a	Desired	--	--	--	--	--	--	--	←20→		15	50	10	←	5	→
b	Planing	Basalt	45°	8	8	<3.5*	<7*	30	9	20	19	37	14	1	1	1
c	Planing	Basalt	0	8	8	4.5	4.5	72	13	20	14	30	20	2	1	1
d	Planing	Basalt	45°	8	8	4.5	4.5	89	15	18	10	19	27	6	3	2
e	Planing	Obsid.	45°	8	8	4.5	4.5	79	4	17	13	23	27	13	2	1
f	Milling	Basalt	0	10	45	10	20	85	8	18	10	17	22	22	4	0
g	Convent. Grinding	Basalt	--	--	--	5	5	99	17	44	12	14	11	←	3	→

*Some cutter flexure

may also have contributed significantly to variations between d and c distributions, as well as the intentional rake angle variation. Prior studies demonstrated that a sharp cutter produced excessive fines and, as a result, dull cutters were generally used subsequently. However, excessive cutter bluntness may also have contributed to distribution divergence. The degree of bluntness should therefore be controlled and its effect tested. If found necessary to reduce wear during an experiment, a diamond edge ultimately can be used. The further optimization of grinding parameters should include a methodical alteration of ridge dimensioning, depth of cut, traverse speed and rake anges. A comparison of d and c indicates that an optimum axial rake would be about 25 degrees.

An apparent reason for the smaller particle size divergence produced by ridge planing compared with ridge milling is the maintenance of a constant depth of cut. By comparison, the milling cutter is inherently constrained by its rotary motion to proceed from the bottom of the cut to the top of the ridge; it must thus execute a continuously changing cut depth. This inherent superiority of planing is to be distinguished from the experimental difficulties initially encountered. These existed because planing lacked the downward centrifugal force component of milling due to the absence of circular motion. As a result greater rigidity or other compensatory arrangement was needed to overcome the upward ridge forces.

The method by which this cutter flexibility problem was ultimately solved appears mechanically feasible for ultimate flight hardware application and, combined with simple planing, perhaps less complicated than milling. The electronic height feedback system possible on a spacecraft should easily match the corrections effected manually based on surface gauge readings, which at ±0.0001 in. were already in excess of requirements. Finally, the 25 lbs. of weight estimated necessary from laboratory measurements to overcome upward ridge forces, for the cutter and ridge dimensions utilized, appears to be a reasonable lower weight limit for the spacecraft.

It is interesting that despite high depth of cut precision achieved in planing, for experimental purposes, tests indicate that precise control may be unnecessary, and perhaps undesirable. The three successive tests with unintentionally poor cutter rigidity yielded excellent distributions, including the best of the program, distribution b of Table IV. It may be that constant vertical cutting force gives superior results to constant depth of cut. A problem with the latter distributions was that poor associated collection efficiencies made their validity uncertain. Controlled experimentation with a vertical force parameter would therefore be desirable.

It is evident from distributions d and c in Table IV, where basalt and obsidian have been comminuted using the same conditions, that the ridge planing method produces distributions reasonably invariable with rock type, although additional types should be tested. The small differences may be attributable simply to experimental deficiencies. It is also concluded from the essentially equal ridge quality produced in basalt and obsidian that ridge preparation facility is likely to be largely invariant with rock type as well. Pumice, especially in its less adhesive forms, may be an exception. An area where additional investigation is important is in expediting ridge preparation and in reducing or eliminating the need for wheel dressing. A methodical study of the effect of bond strengths and diamond concentrations would be beneficial to this end. Ridge production with ganged wheels would be facilitated if ridge pinching could be avoided. The use of "keystoned" wheels previously tried but using a greater relief angle may be one solution. The use of a "wobble wheel", a wheel tilted with wobble washers may be another. A third possibility is the use of staggered grinding sections on adjacent wheels.

The system designed and constructed for the vacuum testing of abrasion sampling techniques has accomplished the intended incorporation into a vacuum grinding apparatus of the directional versatility, precision, and stability of the surface grinder along with large ranges of motion, viewing facility and good accessibility. One major improvement is desirable, however. This is to increase the smoothness of some of the movements by removing some residual binding between the grinding bed bearing surfaces. A solution would be the positioning of supports between the vertical casting and the chamber to oppose the bellows collapsing force. By fixing each support to the casting at one end while having it contact the chamber on rollers at the other end, lateral motion would be permitted. Each shaft would consist of two parts separated by a spring such that the sum of spring compressive forces among the shafts would approximate the bellows collapsing force. The spring thus permits cross-feed motion and permits it without opposition. By symmetrically positioning the supports about the vertical center of the bellows, a compact in-line opposition to the collapsing force would be effected. This system would replace the asymmetrical moment arm opposition of the present weight and pulley arrangement used for minimizing bearing surface binding.

The large percentage of ridges observed to have fractured during vacuum grinding confirms the difficulties anticipated. The observed adherence of powder to the grinding wheels may have been the primary cause, by effectively dulling the wheels. Corrective measures, such as continuous wheel brushing, should minimize the problem. However, investigation is required to be certain of the cause. The decided aerodynamic effects observed in the powder trajectories at 4 Torr and the distinct differences from those observed at 0.1 Torr is illuminating. It shows, among other things, that a Martian collection system must be designed to operate over a range of possible trajectories, since Martian pressures are not precisely known.

An illustration of how the ridge planing method might be incorporated into an automated sampling device is illustrated in Fig. 27. Grinding wheels and planer are supported on a shaft which moves in an arc of adjustable radius, thus ensuring tangential rock contact and permitting hunting for solid rock, removal of overlying powder, comminution, particle collection, and powder delivery to the spacecraft. The scraper edge is located on an arc radius smaller than that of the grinding wheel; the radial difference determines the residual ridge height after scraping, which is invariant with the number of passes. The increase in arc radius determines the total ridge height and the depth planed per pass. Acquisition is thus contour independent and repetitive; the previously described experimental rock leveling problems thus become inconsequential. The sequence is as follows: (a) In one direction ridges are prepared and resulting powder projected from the surface by the grinding wheels; the surface is planed concurrently, if the traverse speeds are compatible, and the negative radial

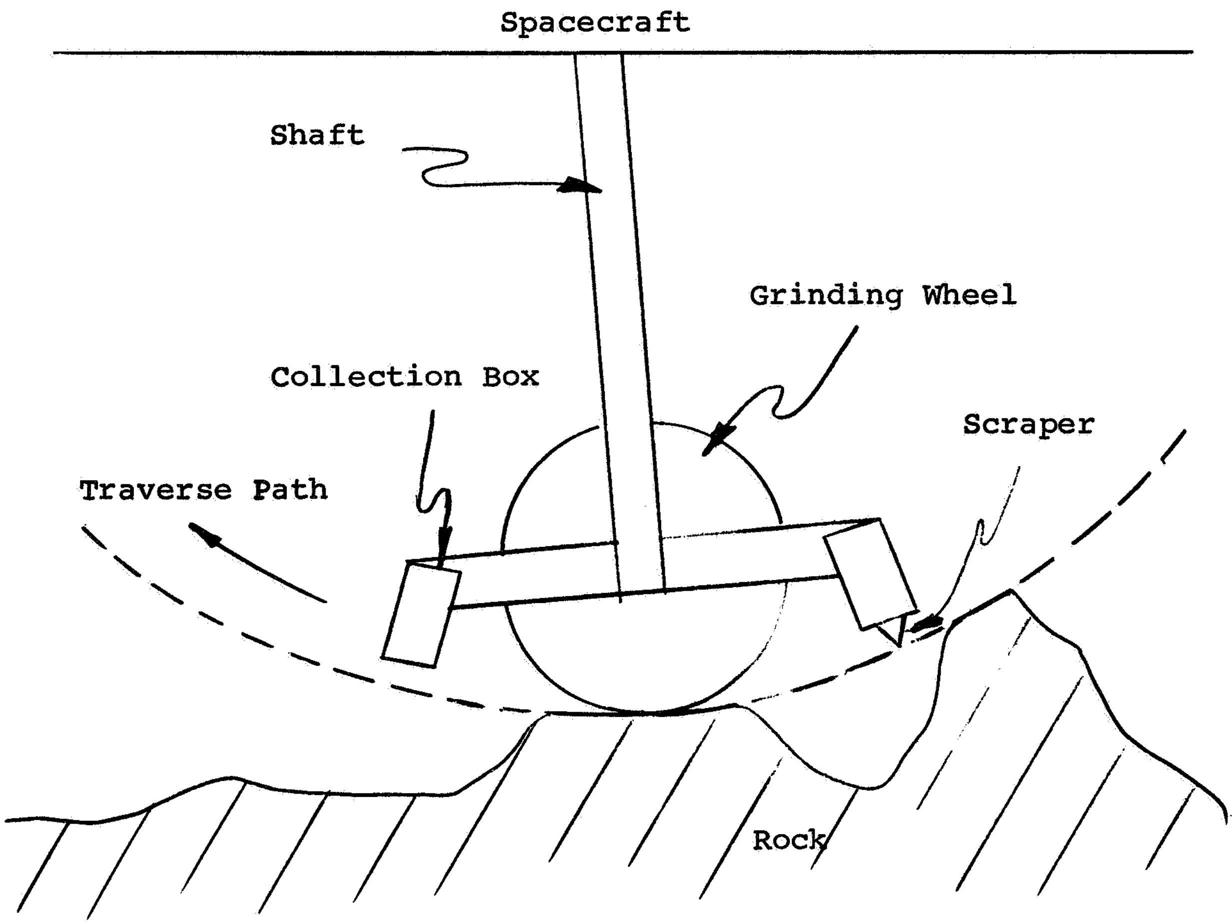


FIG. 27 PROPOSED ACQUISITION DEVICE
USING THE RIDGE METHOD

cutter rake projects the planed particles onto the surface. (b) On the return pass the arc radius is kept fixed, permitting the grinding wheels to project the planed particles into the collection box. (c) The wheels and planer are then lowered and the process is repeated.

The weight and bulk of the device may be minimized by a number of methods. One concept is to extend the radius of one of the ganged grinding wheels. It would then serve as a "key" for locking the traverse motion into a fixed path, thus minimizing vibration and as a result permitting the use of a lighter apparatus. A second concept is the use of alternative end and central vertical shafts for supporting the grinding and planing components. Corresponding central and end path clearing grinding wheels would be used. Providing the trench was extended to the surface with each arc traversed, the path clearing grinding wheels would provide clearance for the supporting shafts, permitting depths independent of wheel radii to be made. Small diameter grinding wheels could then be used.

An alternative method by which the ridge planing method might be incorporated in an automatic sampling device, with possible advantages in terms of simplicity and reduced bulk, is its use in the drill mode, as shown in Fig. 28. A series of concentric diamond core drills would be used with the spacing between drills determining the ridge width. It may be desirable to use some semi-circular core drills, alternately placed, as shown. The voids created by the missing halves would thus eliminate the potentially troublesome ridge pinching problems described previously. After the desired ridge depth is ground, the scraper would be lowered in a slot reserved for it and the ridges planed to provide the desired particle sizes.

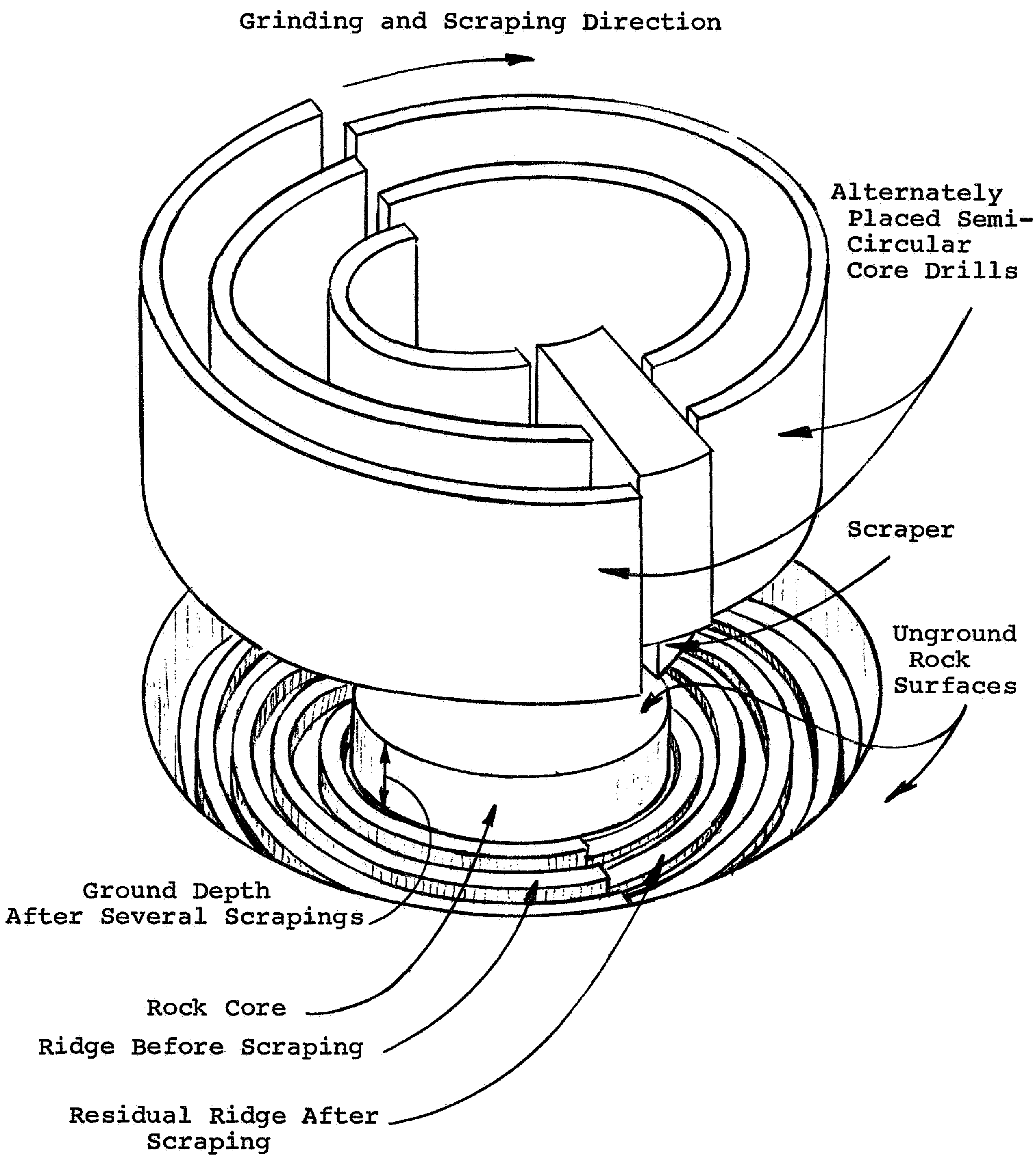


FIG. 28 RIDGE METHOD IN THE DRILL MODE

The scraper would then be raised again and the process repeated. Collection could be effected by gas pressure in the cutting area forcing the undesirable groove cuttings through one port and the desirable ridge cuttings through a separate port.

REFERENCES

1. Personal communications: Bryson, Robert, NASA Headquarters, Office of Lunar and Planetary Programs, Washington, D. C. and Hotz, George M., Calif. Inst. Technol., Jet Prop. Lab., 4800 Oak Grove Drive, Pasadena, Calif.

2. Turkevich, A. L.; Franzgrote, E. J.; and Patterson, J. H.: Chemical Analysis of the Moon at Surveyor V Landing Site, Science, vol. 158, no. 3801, 1967, pp. 635-637.

3. Turkevich, A. L.; Franzgrote, E. J.; and Patterson, J. H.: Chemical Analysis of the Moon at Surveyor V Landing Site: Preliminary Results, in Surveyor V Mission Report Part II: Science Results. Tech. Rep. 32-1246, Calif. Inst. Technol., Jet Prop. Lab., Nov. 1967, pp. 119-149.

4. Nash, D. B. : Sampling of Planetary Surface Solids for Unmanned In-situ Analysis: Strategy, Principles, and Instrument Requirements, Tech. Rep. 32-1225, Calif. Inst. Technol., Jet Prop. Lab., Nov. 1967.

5. Loomis, A. A.: A Lunar and Planetary Petrography Experiment, Tech. Rep. 32-785, Calif. Inst. Technol., Jet Prop. Lab., Sept. 1965.

6. Speed, Robert C.; Nash, Douglas B.; and Nickle, Neil L: A Lunar X-Ray Diffraction Experiment, Advan. X-Ray Anal., vol. 8, 1965, pp. 400-419.

7. Dunne, James A.; and Nicle, J. L.: The Lunar and Planetary X-Ray Diffraction Program: A Summary Tech. Rep. 32-1248, Calif. Inst. Technol., Jet Prop. Lab., Mar. 1968.

8. Hotz, G. M.: Drilling Test Program, in Lunar and Planetary X-Ray Diffraction Program. Tech. Mem. 33-218, Calif. Inst. Technol., Jet Prop. Lab., June 1965.

9. Staff of Hughes Tool Co.: Development and Parametric Study of Small Rotary Percussion Drill for Extraterrestrial Drilling. NASA CR-83849, 1967.

10. Blum, P.; and Hordon, M. J.: Study of Abrasive Techniques for Lunar and Planetary Solid Rock Geological Sampling. NASA CR-90323, 1967.

11. Anon: Standard Method of Test for Sieve Analysis of Granular Metal Powders (B214-64), Part 7 of ASTM Standards, Am. Soc. Testing Mats., 1965, pp. 273-275.

12. Anon: Standard Method of Test for Sieve or Screen Analysis of Fine and Coarse Aggregates(C136-63), Part 10 of ASTM Standards, Am. Soc. Testing Mats., 1966, pp. 88-90.

13. Anon: Standard Method of Test for Sieve Analysis of Granular Mineral Surfacing for Asphalt Roofing and Shingles (D451-63), Part 11 of ASTM Standards, Am. Soc. Testing Mats., 1965, pp. 226-228.

14. Anon: Standard Method of Test for Sieve Analysis of Non-granular Mineral Surfacing for Asphalt Roofing and Shingles (D452-63), Part 11 of ASTM Standards, Am. Soc. Testing Mats., 1965, pp. 229-231.

15. Heinrich, E. W. M.: Microscopic Petrography. McGraw-Hill Book Co., Inc., 1956.

16. Meyer, Charles: Notes on the Cutting and Polishing of Thin Sections. Econ. Geol., vol. 41, 1946, pp. 166-172.

17. Kliare, Arvydas; et al: Occultation Experiment: Results of the First Direct Measurement of Mars' Atmosphere and Ionosphere. Science, vol. 149, Sept. 1965, pp. 1243-1248.

18. Fjeldbo, Gunnar; Fjeldbo, Wencke C.; and Eshleman, Von R.: Models for the Atmosphere of Mars Based on the Mariner 4 Occultation Experiment. J. Geophys. Res., vol. 71, no. 9, May 1966, pp. 2307-2316.

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