Druckfreigabe/approval for printing

Without corrections/ ohne Korrekturen ☐

After corrections/ nach Ausführung der Korrekturen ☐

Date/Datum: .....

Signature/Zeichen: .....

7
Planetary Sample Handling and Processing

Kris Zacny, Antonio Diaz-Calderon, Paul G. Backes, Kiel Davis, Chris Leger, Erik Mumm, Edward Tunstel, Jason Herman, Gale Paulsen, and Yoseph Bar-Cohen

7.1
Introduction

This chapter provides a review of the sample handling tools and issues that are useful for those developing instruments for planetary sampling. The chapter begins with a brief introduction to why sampling is important. It then summarizes theories of comminution, and reviews the existing types of rock crushing and grinding machines, with comments relevant to planetary sampling. The chapter continues with a discussion of the requirements for comminution devices for planetary sampling, and a brief evaluation of the applicability of these machines for this purpose. Finally, there is a section on work currently being carried out on comminution technologies for planetary sampling. The chapter concludes with a discussion of various manipulation and handling platforms and tools. A schematic of sample handling tasks from acquisition to analysis is illustrated in a flow-chart in Figure 7.1.

7.1.1
Why Sampling?

Supporting a broad-based scientific approach necessitates maximizing sample diversity. For example, subsurface samples of sedimentary origin are widely believed to be the best candidates to search for past and present biological activity, while samples of wind-blown fine-grained sands may indicate average crustal composition and the nature of weathering and atmospheric conditions on Mars. "Unweathered" (fresh) core samples of Martian rocks may yield insight into the geological formation and evolution of Mars, while core samples of deep regolith will be necessary for examining solar wind flux and changes in atmospheric density over time. Table 7.1 defines the types of samples required to achieve a broad-based investigation (Neal, 2000). In order to obtain such samples, the sampling strategy will likely feature a number of sampling devices such as a rock coring drill, a sample scoop,

Drilling in Extreme Environments. Edited by Yoseph Bar-Cohen and Kris Zacny
Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-40852-8

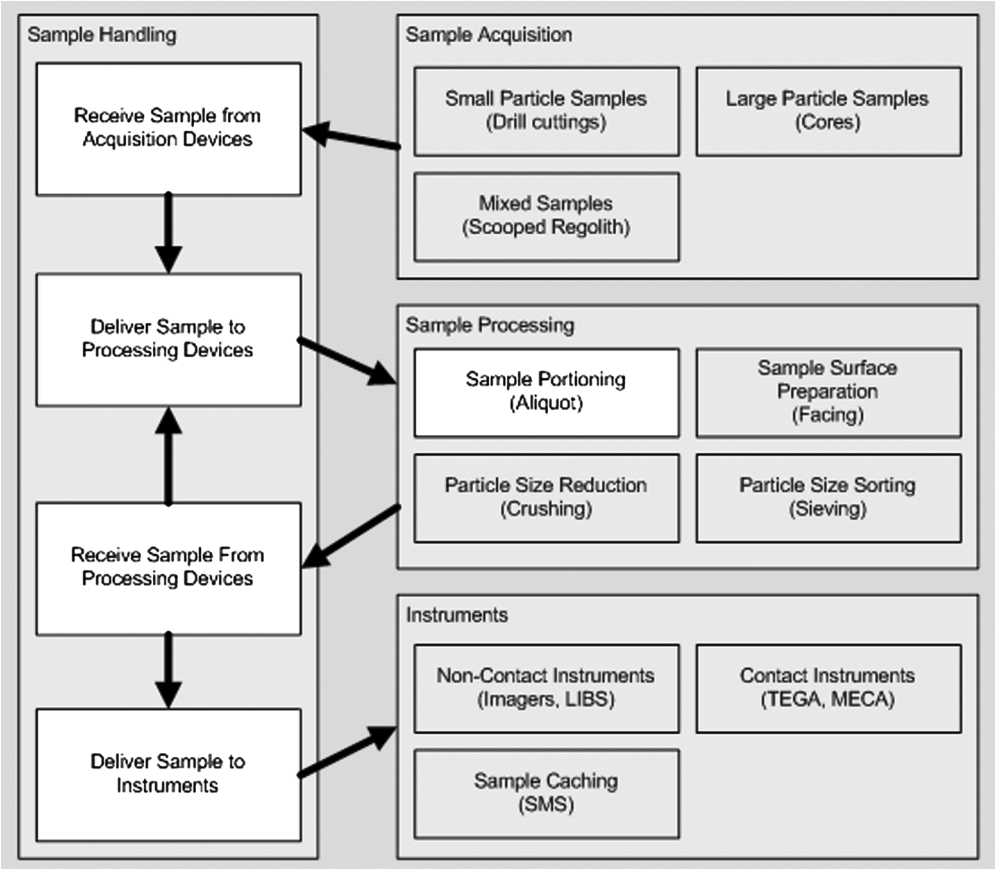


Figure 7.1 Schematic of sample handling tasks, from acquisition to analysis.

Table 7.1 Example of sample types and expected information[a] (Neal, 2000).

	Information			
Sample type	**Biogenic**	**Atmospheric/solar wind**	**Lithospheric/geological**	**Resource**
Atmosphere	2	4	3	1
Fresh igneous rock	1	4	4	2
Weathered rock	3	4	4	1
Sedimentary rock	4	4	3	4
Soil	4	4	4	4
Deep regolith	4	4	2	4
Ice	4	4	1	4

[a]Numbers represent increasing importance from 1 to 4, with 4 being of greatest importance.

Table 7.2 Sample requirements for various scientific instruments.

	Raw sample type					
Instrument	**Weathered surface fines**	**Surface pebbles/ duricrust**	**Fresh rock cores**	**Regolith: cores**	**Regolith: loose material**	**Sample particle size (μm)**
XRD/XRF	3	3	3	3	3	45–100
LD-TOF-MS	1	2	3	3	3	100–850
GC/MS	2	2	3	3	3	100–850
Raman	1	2	3	3	3	unaltered rock (clean)
MI	2	3	3	3	3	>100

"Raw sample type" numbers represent a sample-type's importance or usefulness to the instrument from 1 to 3, with 3 being of highest importance.

a rock abrasion tool, a deep regolith core drill, and/or a trenching device. Whatever the case may be, scientific instruments will most likely need access to a variety of sample types, including:

- subsurface samples of consolidated and unconsolidated regolith
- surface samples of fine grained Martian loess, pebbles, and duricrust
- core samples of fresh rock
- tailings from any of the selected sampling instruments.

The *in situ* instrument candidates have varying sample particle size and volume requirements (Table 7.2). Some instruments are designed to examine powder samples with particle sizes less than 100 μm, whereas others are designed to raster across smooth rock surfaces. Some instruments require samples on the order of 1 mg, whereas others may require 1 g of sample (Figure 7.2). For example, the

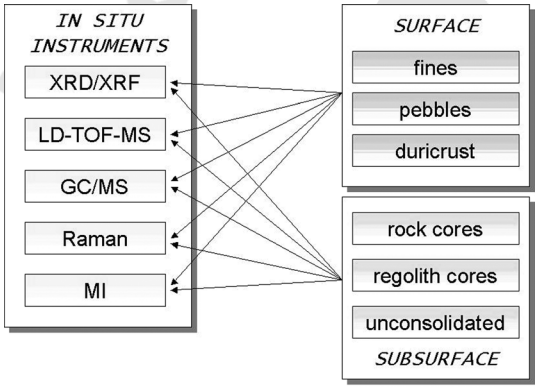


Figure 7.2 Instruments require wide access to a diverse sample assortment.

Page Proof WILEY-VCH

analysis of powder X-ray diffraction (XRD) data is greatly improved when "the beam encounters a statistically significant number of crystallites in close to random orientation; this situation is more closely realized with finer particle sizes" (Vaniman *et al.*, 1999). According to Vaniman *et al.*, crystallite sizes from 1 to 10 μm are ideal, but particles smaller than 100 μm will suffice in most cases. While XRD/X-ray fluorescence (XRF) spectrometry requires ultra-fine particle sizes, mapping instruments such as a Raman spectrometer, a microscopic imager (MI), or a laser desorption time-of-flight mass spectrometer (LD-TOF-MS) require larger grain structures to be preserved in order to determine a rock's (or coarse-grained soil's) mineral assemblage, grain size distribution, and spatial relationship among minerals. Thus, the Raman spectrometer requires no special sample preparation other than a dust-free rock surface or clean rock-core sample (Haskins *et al.*, 2000). The Mars Exploration Rover (MER) MI has a resolution of 30 μm per pixel, so samples should not be reduced to particle sizes less than 100 μm in order to study individual mineral grains, clasts, and particles in rocks (Bell *et al.*, 2000). The LD-TOF-MS laser spot diameter is adjustable between 10 and 500 μm for nested microprobing (Brinkerhoff, 2001). If a spot diameter of roughly 50 μm was chosen, then samples should not be reduced to particle sizes less than 100 μm in order for compositional variations from grain to grain to be studied.

With such an assorted range of instruments and sample types (i.e., different shapes, sizes, and origins), it is inevitable that a certain degree of sample manipulation and processing will be required to ensure that instruments are able to access different sample types. Table 7.2 illustrates the convergence of instrument purpose, sample type, and sample size constraints. For example, the gas chromatograph–mass spectrometer (GC/MS) experiment is designed to measure a broad spectrum of organic molecules. We see that a core sample of unweathered sedimentary rock or sample of deep regolith would offer the highest probability of finding organic molecules. In this case, processing might involve pulverizing and sifting the sample until the desired amount of product was obtained. Suppose this same sample was then to be analyzed by XRD/XRF for cross-correlation purposes. In this case, further pulverization and sifting would be required. However, if the same sample were to be analyzed by a Raman spectrometer, then virtually no processing would be required, except perhaps for brushing dust from the core and then simply placing the intact core sample within the Raman spectrometer's range.

7.1.2 Comminution Requirements for Planetary Applications

When investigating comminution processes for planetary application, we need to look at various parameters, including (1) the required particle sizes of the product, which is determined by the requirements of a scientific instrument, and (2) the crushing and grinding equipment itself.

From the particle size requirement standpoint, instruments such as an XRD (for mineralogical analysis) normally require the smallest particles sizes, in the range 5 μm or less (Bish and Reynolds, 1989). However, recent advances that introduce

sonic or ultrasonic vibration to a sample holder, and thereby fluidize the powder, eased the upper limit on the particle size to 150 μm (with an X-ray beam less than 100 μm in diameter) (Sarrazin *et al.*, 2004). Other instruments such as a GC/MS can accept particles larger than 100 μm, whereas a Raman spectrometer and ordinary imaging require intact rock faces. Note that many drilling techniques provide drilled cuttings which are smaller than 100 μm.

Below is a list of criteria by which crushing and grinding equipment can be evaluated for planetary sampling. This is an "open" list and can be expanded or modified in the future.

Criteria related to the material being processed:

1. *Amount of fines produced:* For industrial applications, incidental production of powdered rock can be undesirable, but for planetary sampling it is highly desirable.
2. *Size reduction ratio:* Amount of size reduction performed by the crusher (e.g., 5 : 1 means that the crusher reduces a 50 mm diameter rock to 10 mm particles).
3. *Sample versatility:* Which types of materials can the crusher process (soft, hard, ice-bearing, sticky, etc.).
4. *Final product:* Properties of the final product, such as particle size distribution, particle shape, and phase distribution (if material consists of different minerals).
5. *Thermal effects:* How much the crushing process tends to raise the temperature of the sample.

Criteria related to the crusher itself:

6. *Mechanical simplicity.*
7. *Robustness of the mechanism.*
8. *Efficiency:* How much electrical power/energy the crusher uses to crush a rock of a given size.
9. *Scalability:* How well a particular design of crusher can be scaled down in size and still perform adequate crushing of the desired feed size.
10. *Wear and contamination of the sample:* How quickly the crushing surfaces wear and how much of the material removed from the crushing surfaces contaminates the sample.
11. *Cross-contamination of the sample gape (clearing out of sample):* How well the remaining material from one rock sample can be cleared out of the crusher such that cross-contamination with a future sample is minimized.
12. *Ease of cleaning.*
13. *Ease of product access and hand-over:* Facility with which final product is transferred to analytical instruments.
14. *Ease of feed introduction:* Facility with which a rock sample is fed into the crusher.
15. *Gape and gap adjustability (feed and product size):* Ability to alter the maximum size of rock introduced into the crusher and the ability to alter the maximum size of the final product.
16. *Processing speed:* Amount of time necessary to process a given rock with a given amount of power.
17. *Required actuator force:* Amount of actuator force required to crush a given rock.

page proof WILEY-VCH

18. *Ease of aborting and ejecting sample:* Facility with which a sample can be ejected after a failed crushing process.
19. *Sensitivity to orientation with respect to gravity:* How well the crusher works at an inclined angle.
20. *Impact danger:* What is the possibility that pieces of crushed rock could be flung from the device and damage other parts of the lander?
21. *Smallest available Commercial, off-the-shelf COTS size:* Bench-top crushers, grinders, and pulverizers for the purposes of testing or modification for planetary sampling.

7.2 Comminution

The collection of samples for analysis (or return to Earth) from the surface and subsurface at Mars and other locations will require the development of sample handling and processing systems that may derive from already existing technologies used on Earth, or possibly from completely innovative ideas. One of the chief processes used in geological research, and one that will be necessary for planetary sampling, is the comminution of rock for chemical (XRF) and mineralogical analysis (XRD).

Comminution has been an extremely important human activity since prehistoric times, and today it is widely used by many different industries. Comminution of geological materials is primarily performed by the mining and aggregates industries and also for geological research, which is of most relevance to this application. Comminution machines come in a wide array of types and permutations. Those used in the mining and aggregates industries are very large, capable of processing many tons of material per hour. Those used in geological research are often scaled down versions of the larger machines, but there are also many types that are only applied for small-scale use.

Geologists on Earth will generally remove a rock sample from the field with a rock hammer. They will then bring the sample into the laboratory and use a variety of laboratory machines to comminute the rock into smaller chunks, grain sized pieces, or powder. The material is manually fed into these devices and the devices are operated with supervision or on a timer. For a robotic mission, however, the crushing must be mechanized and autonomous, and the machine must also fulfill all of the requirements of an instrument suitable for space flight, such as small mass and low power consumption.

7.2.1 Background to Comminution

Comminution refers to various methods of particle size reduction. The equipment used for comminution can be divided based on the size of the fragments they produce. Crushers produce relatively coarse chunks, whereas grinders, also known as mills, produce finer particles. Pulverizers produce micron and sub-micron size particles. Crushing is often performed in several stages to reduce the particle size to

page proof ©WILEY-VCH

such a level that grinding can be carried out. This is because most of the crushers have a reduction ratio (size ratio of initial rock to final product) of around 10 : 1. In industry and research, there are usually at least three steps in a comminution circuit, as a single device does not create the final product that is desired; however, there exist overlapping size classes where it is possible to crush and grind the rock with a single device.

7.2.2 Theory of Rock Breaking

Different types of rocks break differently. Some of the considerations include types of constituent minerals, their distribution and physical properties, and the size and shape of particles (Hayes, 1993). For example, granites tend to fracture into sand-sized particles, as these types of rocks are made of relatively large (visible with the naked eye) minerals (T. Teague, UC Berkeley, Department of Earth and Planetary Sciences, personal communication, 2006, tteague@berkeley.edu). In addition, how the rock will break also depends on the external factors such as the form of applied stress (compression, tension, and shear), the strain rate, and whether rock is constrained or unconstrained.

Various techniques of rock comminution are used (Hayes, 1993). These include:

1. slow compression
2. fast compression (impact)
3. abrasion
4. combinations of the above.

In slow compression, the stress level is increased gradually until the resolved shear and tensile stresses are sufficient to propagate pre-existing cracks, that is, the weakest points. Since large cracks propagate first, the particle sizes tend to be relatively large.

During fast compression, or impact (e.g., impact of a hammer on a particle), compressive stress waves are propagated throughout the material. In severe impact the stress levels induced are high but, since they are compressive, fracture does not occur immediately. When the stress waves meet the free surfaces on the other side of the particle and are internally reflected, they form a tensile wave. As this high-stress tensile wave moves through the material, existing cracks in the structure are extended, new cracks are formed, and fracture of the sample occurs. Thus fracture occurs when the tensile stresses are sufficient to propagate pre existing cracks. The particle sizes produced from such events are smaller than from slow compression.

In abrasion, where rubbing of particles against each other or with hard surfaces occurs, high shear stresses are generated in the region of the particle surface. As a result, fracture is localized to the surface. Particle sizes fall generally into two categories: large (close to the original particle size) and very small (i.e., abraded). Figure 7.3 shows particle sizes reduced by various comminution processes.

Figure 7.4 shows the size distribution for three different methods of rock comminution. As stated previously, abrasion gives the smallest particles, and compression the largest. Also note the difference in size ranges. Abrasion tends to give a narrow size distribution, fast compression or impact a broad distribution,

page proof WILEY-VCH

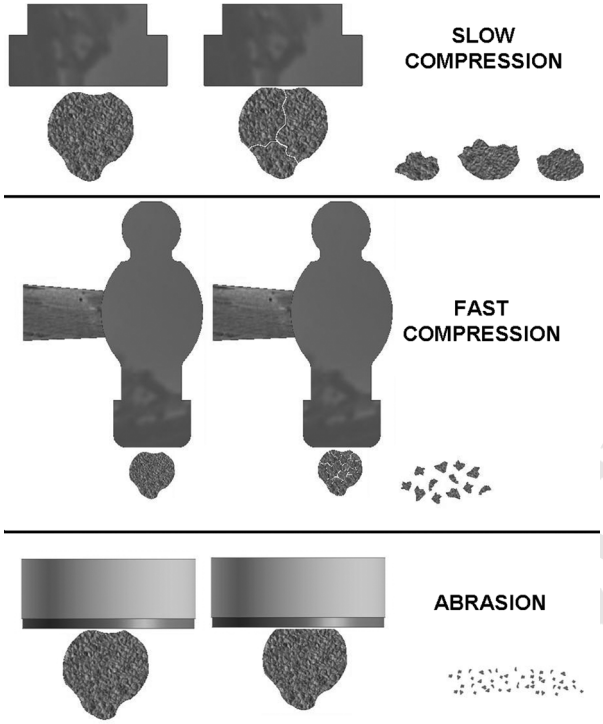


Figure 7.3 Particle sizes produced by three comminution processes (Hayes, 1993).

and slow compression an intermediate distribution. Note that the type of crushed material also influences the situation. This includes the proportion of each mineral present, the distribution of mineral grains within the particle, the physical properties of individual minerals, and pre-existing defects, for example, cracks in the particles.

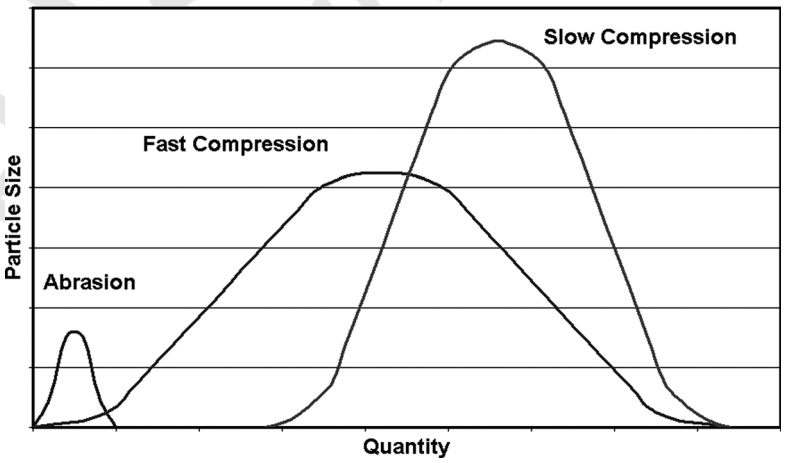


Figure 7.4 Characteristic size distribution from different comminuting action (Lowrison, 1974).

7.2.3
Energy Requirements in Breaking Rock

It is virtually impossible to predict the energy requirements to crush rock based solely on the fundamental principles of rock fragmentation; however, empirical observations can be used for predicting energy requirements. In general, much of the crushing energy (over 90% and sometimes as much as 98%) is dissipated as thermal energy, that is, heat (Cheatham, 1968). This is because most of the energy is used in applying stresses to the entire volume of rock, but only a small portion of that energy leads to breakage (Gaete-Garreton, Vargas-Hernandez and Velasquez-Lambert, 2000).

Because theory cannot be used to predict the energy requirements of comminution, researchers have to rely on empirical methods. There are three empirical relations that govern the energy requirements for particle size reduction, which were developed by Rittinger, Bond and Kick (Cheatham, 1968). Figure 7.5 shows the energy required (y-axis) to reduce initially large rock to a particular size (x-axis). Rittinger, Bond and Kick developed relationships to fit this empirically obtained curve. As shown in Figure 7.5, the Rittinger and to a lesser extent Bond equations are used to estimate energy requirements in grinding processes, that is, where finer particles sizes are produced. The Kick equation is more applicable to crushing processes, where larger particles are produced.

Table 7.3 shows the approximate energy (including mechanical efficiency) required for various stages of particle comminution. Note that in most cases, the reduction ratio (size ratio of initial rock to final product) is 10. It is clear that fine grinding requires 10 times greater energy than coarse grinding or crushing. The table also suggests that the Bond equation gives the most accurate estimation of energy requirements for a large range of particle sizes.

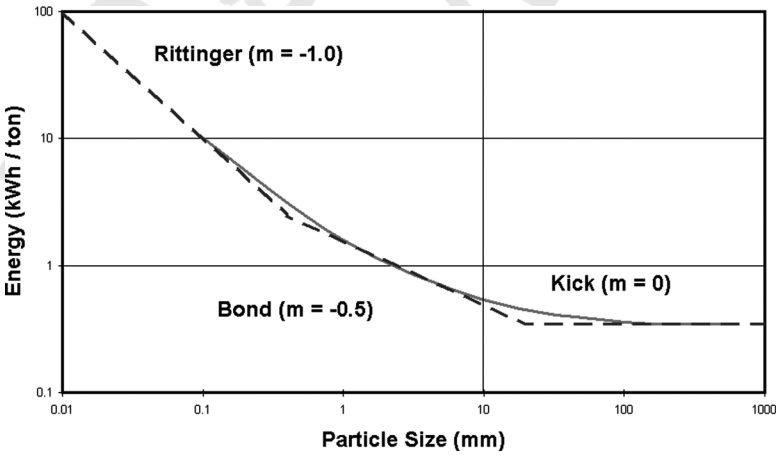


Figure 7.5 Typical energy characteristic for size reduction by crushing and grinding (Hukki, 1961). Note: $1\,\mathrm{kW\,h\,t^{-1}} = 3.6\,\mathrm{J\,g^{-1}}$.

Table 7.3 Energy for size reduction by crushing and grinding (Hukki, 1961).

Method of comminution	Size reduction	Net energy consumption (kW h t^{-1} (×3.6 J/g)) Actual	Predicted by Rittinger	Predicted by Bond
Explosive shattering	From infinity to 1 m	Unknown	0.0009	0.07
Primary crushing	1 m–100 mm	0.35	0.009	0.22
Secondary crushing	100–10 mm	0.6	0.09	0.69
Coarse grinding	10–1 mm	1.6	0.9	2.18
Fine grinding	1–0.1 mm	10	9.0	6.91

Since Bond's theory is the most accurate (for that reason, it is generally the most frequently used in industry), we will describe it in more detail. Bond stated that the total work required to crush or grind the material is inversely proportional to the square root of the diameter of the product particles. The general equation is

$$W = 10W_{\mathrm{i}}\left(\frac{1}{\sqrt{d_{\mathrm{final}}}} - \frac{1}{\sqrt{d_{\mathrm{initial}}}}\right)\left[\frac{\mathrm{kW\ h}}{\mathrm{ton}}\ \mathrm{or}\ \frac{3.6\mathrm{J}}{\mathrm{g}}\right] \tag{7.1}$$

where d (μm) is the particle diameter. W_{i} is the so-called the work index; it is the energy required to break the rock (including the mechanical efficiency) determined by standard laboratory tests. Preferably, the work index of a rock should be determined on the same type of equipment that is to be used in the actual grinding or crushing operation. Table 7.4 gives some values of W_{i}.

Example

Calculate the motor power required to reduce the size of a limestone rock from 10 mm (10 000 μm) to 100 μm at the rate of 10 g min^{-1} (0.17 g s^{-1}). Using the above equation and data from Table 7.4, the required power of the motor is

$$W = 10 \times 47 \times \left(\frac{1}{\sqrt{100}} - \frac{1}{\sqrt{10000}}\right) \times 0.17 \approx 7\ \mathrm{W} \tag{7.2}$$

To check whether the above value makes sense, we can use values of energy from Table 7.4. Note, however, that values in Table 7.4 are not rock specific. The energy required to reduce the particle sizes from 10 mm to 100 μm is 11.6 (1.6 + 10) J g^{-1}. For a 10 g sample that will be 116 J. If the 10 g sample is required to be ground within 60 s, the motor power required would be approximately 2 W, which is within the same order of magnitude as previous value of 7 W.

7.2.4 Analysis of Broken Material

The desired result of a comminution process can vary. Some applications require particle sizes to fall within a certain size range, whereas others require particles to be

Table 7.4 Typical values of Bond work index, W_i, for some common materials (Bond, 1961).

Material	W_i (kW h t^{-1})	W_i (J g^{-1})
Rock		
Andesite	22	79
Basalt	19	68
Dolomite	13	47
Gneiss	20	71
Granite	16	58
Limestone	13	47
Phosphate rock	11	40
Quartzite	11	40
Sandstone	11	40
Mineral		
Feldspar	12	43
Hematite	14	50
Magnetite	11	40
Mica	148	533
Quartz	15	54

of a certain shape. Whatever the requirement, the sections below describe some of the techniques that can be used in the analysis of broken material.

7.2.4.1 Particle Size Distribution

A size distribution of particles sizes can be estimated using a microscope/camera and software (see, e.g., http://www.mountech.co.jp/en/products/macview.html). A more precise assessment can be performed using two laboratory methods: sieve analysis and the hydrometer analysis.

Particle size distribution is normally obtained by following the Standard Test Method for Particle-Size Analysis of Soils as described in ASTM Standard D422-63. The distribution of particle sizes larger than 75 μm (retained on a No. 200 sieve) is determined by sieving, whereas the distribution of particle sizes smaller than 75 μm is determined by a sedimentation process, using a hydrometer. Note also that sieving can be performed dry or wet. Figure 7.6 shows a stack of sieves with the top ones having large openings and the bottom ones the smallest. Smallest particles pass through the top sieves and are retained on the lower sieves or a bottom pan. Sieves can also be used sometimes for analyzing particle sizes smaller than 75 μm; however, because the particles are so small, surface effects (surface charge, etc.) can skew the data. Hydrometer analysis relies on placing the material in suspension (water) and determining their rate of settlement. Large particles will settle faster than smaller particles. The mass of solids in the suspension can be obtained by measuring its specific gravity using a hydrometer (hence the name of the test). Particles larger than 150 μm are not suitable for this analysis as they settle more quickly than we can measure.

page proof WILEY-VCH

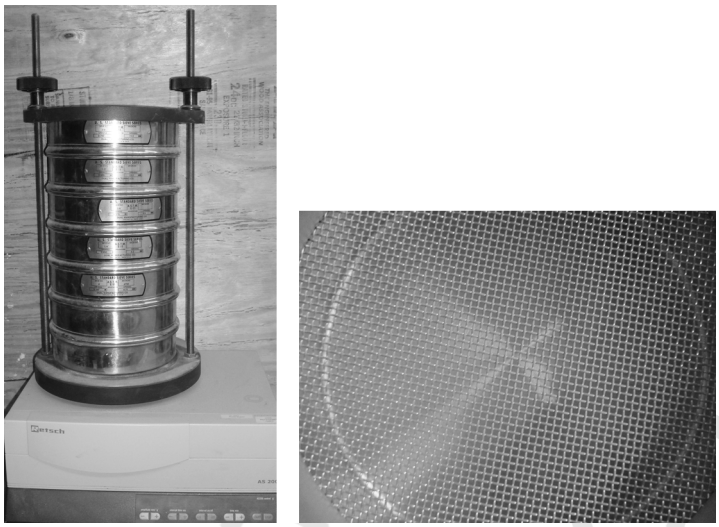


Figure 7.6 Mechanized shaker with a series of sieves (a) and an example of a sieve (b).

Particle size distributions are plots of the percentage of the solids by weight smaller than diameter versus the grain diameter (on a logarithmic scale), as shown in Figure 7.7. For example, 80% of the material indicated by curve A is smaller than 0.04 mm.

Figure 7.7 shows five different curves for various particulate materials. Curve A indicates fine-grained material and curve B shows coarse-grained material. Curves C, D and E indicate various particle distributions. Steep curves, such as curve C,

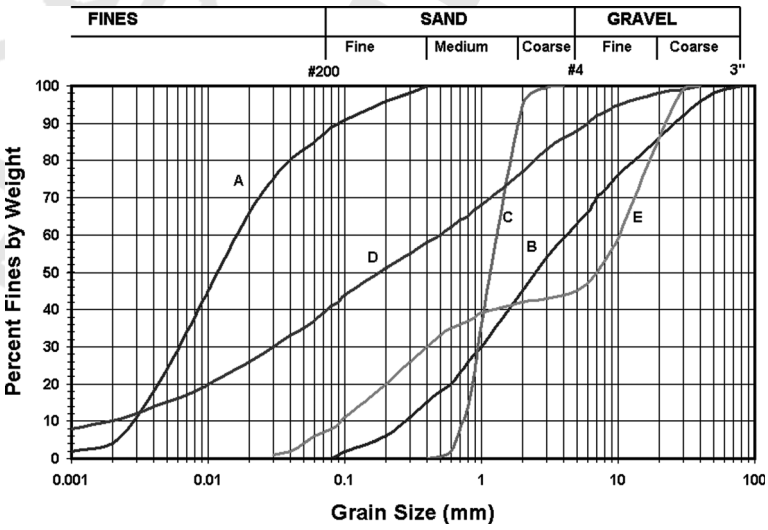


Figure 7.7 Grain size distribution curves for five different particulate materials (Coduto, 1998).

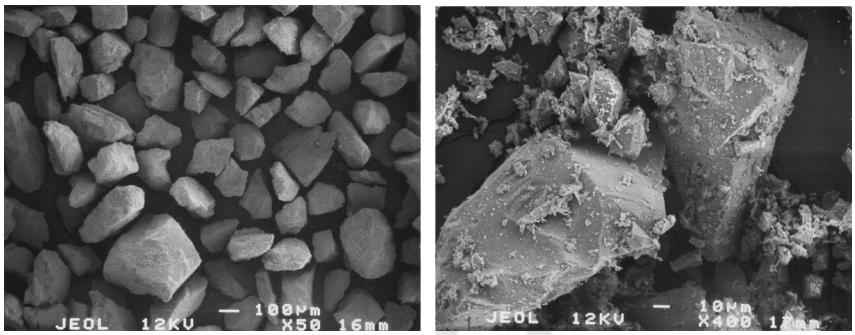


Figure 7.8 Scanning electron micrograph of crushed particles using the Honeybee Robotics attrition grinder.

show that particles fall within a narrow size range. Such a distribution is called well-sorted (or poorly graded). Curve D, on the other hand, shows that material contains particles with a very wide range of sizes. Such a curve is referred to as a poorly-sorted (or well graded). Curve E indicates gap-graded material, as it is lacking particles in a certain size range.

7.2.4.2 **Shape of Particles**

The shape of particles can be easily assessed using an optical microscope. The shape of particles can give an indication of the type of minerals being crushed. For example, amorphous materials tend to break locally, whereas crystalline materials break more uniformly. In addition, materials consisting of grains having pores, or consisting of particles that are agglomerates or particles of one material embedded in the matrix of another, break into units of certain sizes. In general, crushing or grinding produces angular to very angular shapes as shown in Figure 7.8.

7.2.4.3 **Degree of Fineness**

All crushing processes produce a certain percentage of fines, that is, the percentage of product that is below certain size. It is possible that a crusher will deliver enough fines that no grinding will be necessary. For example, approximately 20% of the product from the Jet Propulsion Laboratory (JPL) jaw crusher (jaw crushers normally produce coarse particles) is below 150 µm in size (Figure 7.9). Thus, if the instrument requires 1 g of particles below 150 µm, then the initial feed into the JPL crusher has to weigh 5 g. Table 7.5 shows a relative comparison of the material produced by various types of comminution equipment. For example, an attrition mill produces five times as much fines as a ball mill does.

7.2.5 **Sample Caking During Grinding**

One of the undesirable conditions during grinding is so-called "caking" or particle agglomeration, which prevents further particle size reduction. In most cases, caking

Figure 7.9 Particle size distributions obtained from the JPL jaw crusher (Chipera *et al.*, 2004).

is caused by moisture; however, it can also be caused by heat, static charge accumulation, the fusing of particles under pressure, and other causes. Tests conducted under Mars conditions will certainly provide clues to other possible causes of caking.

7.2.6 Cryo Grinding

The structures of clays (which were identified on Mars), can be difficult to distinguish by XRD because they are subject to matting and preferred orientation when pulverized by normal means. In some soft minerals there can also be distortion of the crystal lattice due to impact. When chilled during grinding, these minerals can often be broken up more completely, exhibiting a more nearly random orientation

Table 7.5 Comparison of various types of comminution equipment as a function of the degree of fineness achieved (Lowrison, 1974).

Type of mill	Relative fineness (compared with unit test impact crusher)
Unit test impact crusher	1
Ball mill	1.2
Swing hammer mill, coarse clearance	1.6
Swing hammer mill, fine clearance	3.6
Attrition mill (rotor, grid discharge)	5.9

Table 7.6 Mohs' hardness values for a variety of materials.

Mohs' hardness	Material
10	Diamond
8	Topaz
7	Quartz
6.5	Knife blade
4	Copper coin
2.5	Finger nail
2	Gypsum
1	Talc

of grains and maintaining greater structural integrity. Note also that, in general, the colder the sample, the more finely it can be ground. Some of the National Aeronautics and Space Administration (NASA) Moon rocks were pulverized in this way (Spexcsp).

7.2.7
Hardness of Material vs Hardness of Crushing/Grinding Surfaces

Hardness seems to be the most important property when considering comminution. Hardness is defined as the resistance to being scratched and it can be applied to both the comminuted material and to the surfaces of the comminution equipment. Mohs developed a hardness scale based on the scratch test; material that can scratch another material is considered to be harder and is placed further up the table. Table 7.6 shows the Mohs' hardness for a number of materials. For example, quartz (7) can scratch gypsum (2), but it can be scratched by diamond (10). For this scale to be more practical, the hardness of a knife blade, a copper coin, and a finger nail is also given in the table.

Over the years, other methods of measuring hardness have been developed, including Vickers, Brinell, and Rockwell. These tests rely on pushing an indenter with a set force into the test material and measuring either the depth of penetration (Vickers and Rockwell) or the diameter of the crater the spherical indenter made (Rockwell). These numbers are then converted into units of hardness There exist a number of tables that relate these hardness scales and Mohs' scale. When considering what material to use as a crushing surface, consideration needs to be given to the type of material to be crushed. The grinding surface should be harder than the material to be ground and should be of a substance whose presence in the sample will not interfere with analysis.

7.3
Classification of Comminution Equipment

There are two main methods of classifying comminution equipment: (1) according to the size of final product, and (2) according to the comminution process.

PAGE PROOF © WILEY-VCH

Table 7.7 Classification of equipment by size of product (Lowrison, 1974).

Type of equipment		Size range
Explosive shattering		Infinity to 1 m
Primary crusher		1 m–10 cm
Secondary crusher		10 cm–1 cm
Grinding mills	Coarse	1 cm–1 mm
	Fine	1 mm–100 μm
	Very fine	100 μm–10 μm
	Superfine	10 μm–1 μm
Pulverizes		Sub-μm

7.3.1
Classification According to Size of the Product

Table 7.7 presents a classification of equipment by the maximum size of the product. Note that the same equipment may be designed to give product in two or more size categories. Thus, a better classification may be based on the communizing action of the equipment.

7.3.2
Classification According to Comminution Process

Figure 7.10 shows a classification of equipment based on the method of comminution. The sections below describe these types of equipment in more detail. An asterisk by the name indicates that these devices are available in laboratory-sized COTS units. (Note that even these "small" devices may weight several hundred pounds.) This is not an exhaustive list of comminution devices; there are many other types not mentioned here. Nevertheless, this is a good summary of existing comminution technologies that might prove useful for planetary sampling.

7.4
Nipping (Compression) Machines

This type of crusher grabs the rock material between two hard surfaces that are oriented at an angle to one other (the nip angle). As the surfaces are pressed together, the high forces generate shear in the rock that breaks the rock into smaller pieces. Nipping machines are intended to crush rocks into a coarse product that will in turn be fed into another device for pulverization; however, they do incidentally produce a certain amount of fines.

page proof WILEY-VCH

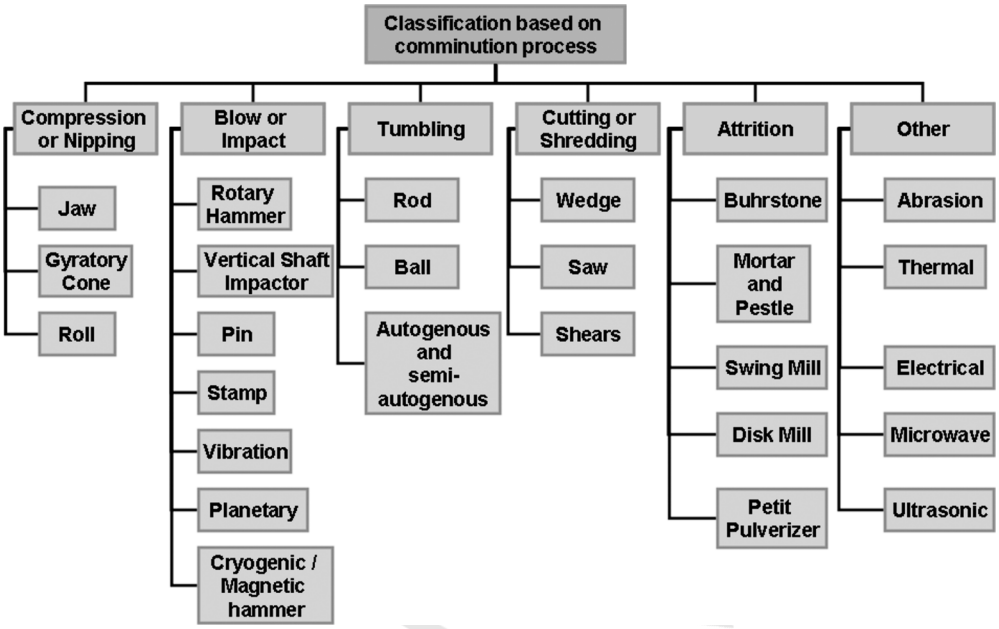


Figure 7.10 Classification of equipment based on comminution process (Lowrison, 1974).

7.4.1
Jaw Crushers

Jaw crushers are distinguished by two plates that open and shut like animal jaws. The jaws are set at an acute angle to each other, and one jaw is pivoted so that it swings relative to the other fixed jaw. Material fed into the jaws is alternately gripped or nipped and released to fall further into the crushing chamber. Comminution is by grain-to-grain transfer of compressive stress from the jaws leading to tensile fracture of fragments at point contacts. Jaw crushers are classified by the method of pivoting the swing jaw. Figure 7.11 shows its functional diagram. In this example, an eccentric Pitman imposes a cyclic open–close action on the swing jaw. In these designs, the crushing force increases as particles move downwards into the narrowest part of the jaws.

Jaw crushers are very heavily built machines designed for the rapid throughput of large volumes of hard rock. Application to the sample processing unit (SPU) might be possible as a primary crusher, but poor handling of soft agglomerating samples rich in clay and of low energy efficiency and high mass probably make it a poor choice. Cleaning of the jaws may also be problematic.

The jaw crusher crushes rock between two flat surfaces, one stationary, and the other moveable. The two surfaces are oriented in the shape of a “V” and rock is fed into the wide “gape” at the top of the V. The moving surface is actuated with high force by an eccentric that causes the surface to move in an elliptical path that includes

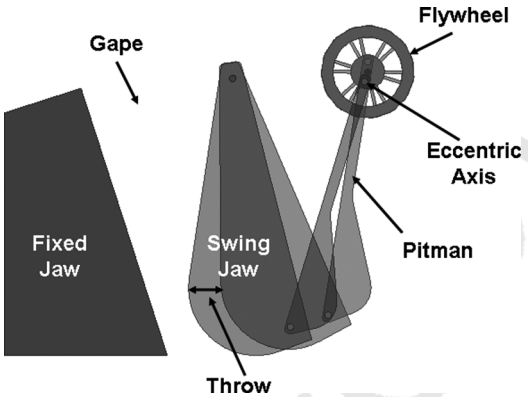


Figure 7.11 Schematics of a jaw crusher (Lowrison, 1974).

both horizontal and vertical motions. As the rock is crushed into smaller pieces, these pieces are able to fall into the narrower portions of the jaws and become crushed into smaller and smaller pieces. The maximum feed size should be around 85% of the gape at the top. The gap between the surfaces at the bottom determines the largest size piece that is produced by the crusher and can be adjusted.

The power requirements for a jaw crusher are very dynamic, having very high peaks when crushing is occurring, and being very low when the jaws are opening. To smooth out the power load on the driving motor, a flywheel is often used to drive the jaws. Note that the jaw crusher is carrying useful work for only half of the operating time because of its cyclic action. In industrial applications, this is considered a disadvantage that reduces the throughput of the machine compared with other types. For a planetary sampling application, this is less of an issue. Jaw crushers are known to be good for crushing materials high in clay (Lowrison, 1974).

Jaw crushers are classified by the method of pivoting the mobile jaw. If the jaw is pivoted at the top, it has a fixed receiving area and is known as a Blake crusher. If the jaw is pivoted at the bottom, it has a fixed delivery area and is known as a Dodge crusher. A universal crusher has a jaw pivoted in an intermediate position and in turn has a variable receiving and delivery area. One innovation is the use of a double toggle jaw that reduces sliding motion between the rock and the walls, which is not productive in terms of crushing and can lead to excessive wear (de la Vergne, 2003). A movie describing how the jaw crusher works can be found at the Retsch website (http://www.retsch.com). A PhD thesis on jaw crushers by Donovan 2003 is a good source of information showing the power consumption, product size, and capacity of this type of crusher.

7.4.2
Gyratory and Cone Crushers

These devices crush rocks between the slanted walls of an enclosed cylindrical chamber and a central spindle that moves around eccentrically. The particles are

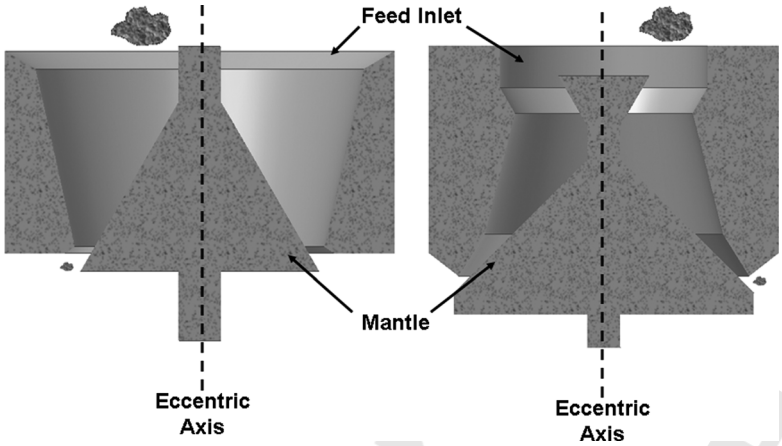


Figure 7.12 Schematic of a gyratory (a) and cone crusher (b) (Hardgrove, 2001).

fractured under slow compressive stresses with some shear stresses. Feed moves into the crusher under the influence of gravity. In the gyratory crusher, the chamber walls open upwards and the spindle is attached at the top. In a cone crusher, the chamber walls angle inwards towards the top, and the spindle is attached at the bottom. As the spindle moves, one side pushes closer to the chamber wall, providing the crushing action, while the other side moves further from the wall, allowing recently crushed particles to move down to a narrower crushing space. In effect, each cross-section of this type of crusher is like two jaw crushers (Figure 7.12). Since there is always a pair of surfaces performing the crushing action, the throughput of gyratory or cone crushers is much higher than that of jaw crushers; however, a jaw crusher can accommodate a larger feed size than a comparably sized gyratory or cone crusher. The largest size of the final product is determined by the gap at the bottom. By moving the spindle vertically, the size of the bottom gap can be adjusted.

7.4.3 Roll Crusher

The roll crusher crushes material between a cylinder and a flat surface, or between two or more cylinders. The mode of operation of roll crushers is very simple, consisting of two horizontal cylinders which revolve towards each other.

One of the rolls is usually fitted with a spring release, to avoid damage to the rolls in the case of uncrushable material finding its way into the feed. Roll crushers are known to have high efficiency and to produce a product within a narrow size range. A disadvantage is that they tend to have a low size reduction ratio, although there are innovative designs that claim to have solved this problem (Figure 7.13).

Unlike jaw and gyratory crushers, where reduction is progressive by repeated pressure as the material passes down to the discharge point, the crushing process in rolls is a single pressure as the material passes through the gap. Hence rolls are often

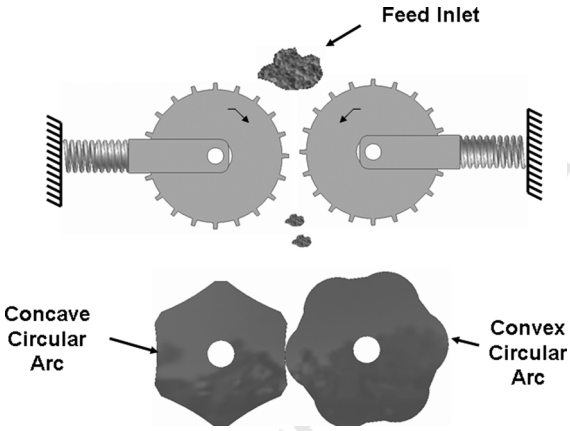


Figure 7.13 (a) Roll crusher with knobs (Lowrison, 1974); (b) innovative non-circular design that has lower wear and a higher reduction ratio (Velletri and Weedon, 2001).

used in series with each subsequent set having a smaller gap and the product of the previous set providing the feed for the succeeding set (Figure 7.13). Smooth-surfaced rolls are usually used for fine crushing whereas toothed or corrugated roll surfaces are used for coarse or primary crushing (Figure 7.13). In the latter, intermeshing teeth dig into and grip rock fragments so that the action is a combination of compression and ripping. Large pieces in relation to the roll diameter can be handled with toothed roll crushers. In addition, the teeth impart a "cracking" action to individual particles, enhancing comminution.

Roll crushers are touted for their ability to handle friable, sticky, frozen, and less abrasive feeds – an attractive feature for planetary application (Lowrison, 1974). One advantage for planetary exploration is that they do not rely on gravity feeding as much as jaw and gyratory crushers (Velletri and Weedon, 2001). The diameter of the rolls must be significantly larger than the rocks they crush (i.e., to crush a rock 1 cm in diameter, the rolls would be more than 10 cm in diameter).

In addition, it is easy to see how rolls can be cleaned by application of a wire brush roll to each set between batch feeds of samples. Finally, roll crushers are cited as being one of the most energy efficient of crusher designs. This combination of desirable features makes the roll crusher one of the top choices for planetary application.

7.5 Impact Machines

Impacting machines make use of the transfer of high kinetic energy to the rocks, being essentially automated hammers. This form of rock breaking is considered to be more efficient than slow compression (Lowrison, 1974).

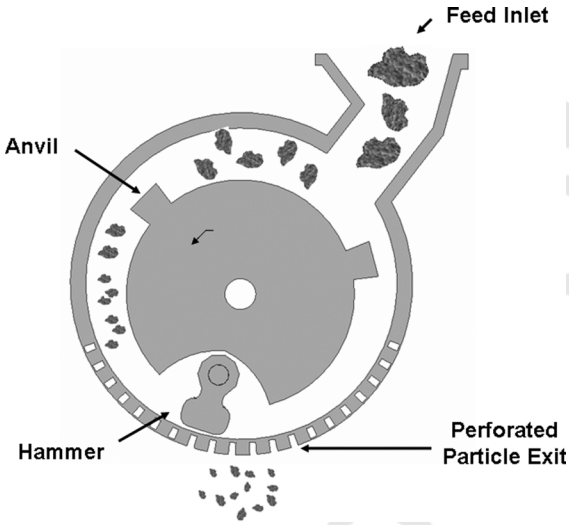


Figure 7.14 Schematic of a Spex micro hammer-cutter mill. Courtesy Spex Certiprep Group.

In impact crushers, comminution is by impact by sharp blows applied at high speed to free-falling rock. The moving parts are hammers, which transfer some of their kinetic energy to the rock particles on contacting them. The internal stresses created in the particles as a result of these impacts are large enough to cause them to shatter. These forces are supplemented by causing the accelerated particles to impact upon an anvil or breaker plate.

Figure 7.14 shows a cross-section of a typical hammer mill. The hammers and breaker plates are made of hard, abrasion-resistant material – typically alloy steel or carbide. The hammers are usually pivoted so they can move out of the path of oversized material entering the crusher chamber. The exit from the mill is perforated, so that material that is not broken to the required size is retained and swept up again by the rotor for further impacting.

This type of crusher is designed to give the particles velocities of the order of that of the hammers. Fracture is due either to the severity of impact with the hammers or to the subsequent impact with the anvil. Since the particles are given very high velocities, much of the size reduction is by attrition, that is, breaking of particle on particle, and this leads to little control on product size and a much higher proportion of fines than with compressive crushers. On the other hand, they are capable of producing large reduction ratios, up to about 40 : 1.

Due to the high rate of wear on these machines, they are normally limited to use with relatively non-abrasive materials, but for the small volumes needed for an SPU this should not be a serious issue. Cleaning could be a difficult issue with these machines if the internal parts were to become coated with refrozen mud or other sticky material. This is a problem common to most of the designs described above, but the high impact forces in this case suggest that impact crushers would be less susceptible than most and would tend to be self-cleaning.

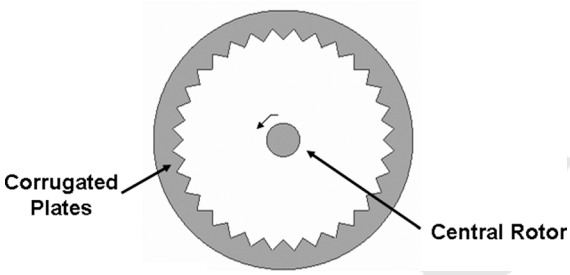


Figure 7.15 Schematic of a vertical shaft impactor. Courtesy Abon Engineering.

7.5.1
Rotary Hammer

Rotary hammers have multiple flat surfaces arrayed around a cylinder that rotates at high speed inside a chamber. Rocks fed into the chamber are subjected to high-speed hammer blows. In some designs, the hammers are articulated, so that excessively forceful impacts do not overtax the rotation mechanism. Impact hammers are not considered to be suitable for hard rocks because of the excessive wear produced (de la Vergne, 2003).

7.5.2
Vertical Shaft Impactor

In a vertical shaft impactor (Figure 7.15), material is accelerated by the centrifugal action of the rotating central rotor, and thrown outwards and against the corrugated plates. Material explodes on impact against these plates (Abon Engineering). Vertical shaft impactors are only made in industrial sizes and it is unlikely that a laboratory-sized version would develop the necessary kinetic energy to comminute rocks as effectively as a large one.

7.5.3
Pin Mill

A pin mill (Figure 7.16) has two discs that rotate relative to one another (one may be stationary). Protruding from the discs are many small pins, arranged so that those from one disk do not touch those from the other disk as the mechanism rotates. Pin mills are very effective at comminuting relatively small feed particles into powder (in the 50 μm range) in a narrow size range.

7.5.4
Stamp Mill

The stamp mill (Figure 7.17) is one of the oldest crushing technologies. It consists of a very heavy weight, the pestle, made from a hard material that is raised and dropped

Page proof WILEY-VCH

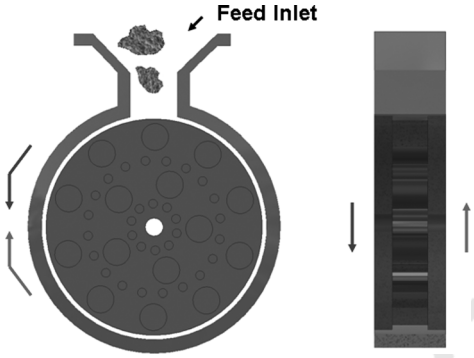


Figure 7.16 Schematic of a pin mill. Courtesy Ling Kwang Industrial Co.

on rocks that sit on an anvil. Industrial stamp mills often have pestles weighing 1 ton or more. The use of gravity for comminution is probably not useful for planetary sampling, because of the high mass required (especially on bodies with lower gravity than Earth). A possible exception to this is if some types of mechanisms were used to accelerate the pestle.

7.5.5 Vibration Mill

Like a ball mill (see Section 7.6.2), the grinding in a vibration mill (Figure 7.18) takes place inside a chamber, with the material to be comminuted interacting with small spheres or cylinders of a very hard material. Instead of tumbling, however, the vibration mill vibrates by the action of a rapidly rotating eccentric. Vibrating mills are very energy efficient compared with tumbling mills, are smaller and of lower mass, and tend to produce jagged particles. They are not suitable for grinding ductile materials, and they have an upper limit on feed size that is determined by the size of the spheres or cylinders (Lowrison, 1974).

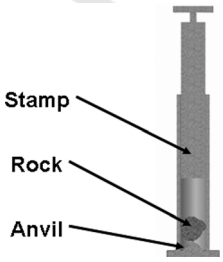


Figure 7.17 Schematic of a manual stamp mill. Courtesy Sierra Manufacturing.

page proof WILEY-VCH

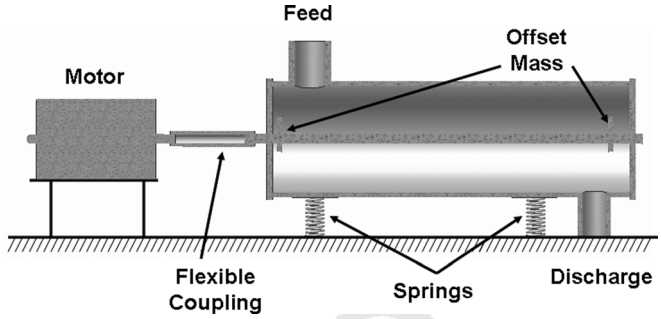


Figure 7.18 Schematic of a vibration mill (Lowrison, 1974).

7.5.6
Planetary Mill

Material to be ground is placed, along with grinding spheres, inside a cylinder, which is placed on a circular platform. The cylinder is rotated along its axis, concurrent with the rotation of the platform, creating a "planetary motion" (Figure 7.19) that creates very high impact speeds between the spheres and the material. Grinding is more efficient and faster than with a conventional ball mill.

7.5.7
Cryogenic/Magnetic Hammer Mill

This mill uses a magnetic coil to oscillate a hammer that is held inside a container along with the material to be ground (Figure 7.20). It is intended to be used in a liquid nitrogen bath, for samples that must be chilled before being ground (Spex Certiprep Group).

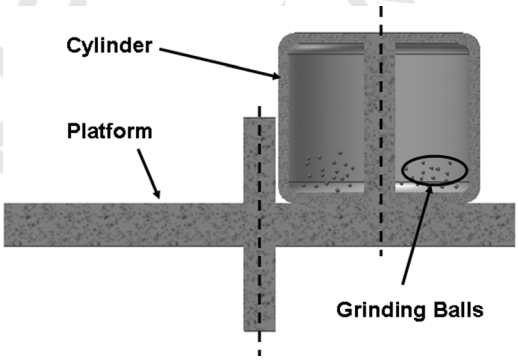


Figure 7.19 Schematic of a planetary mill. Note the sample container (arrow) with its own axis, located on a circular platform with a separate axis.

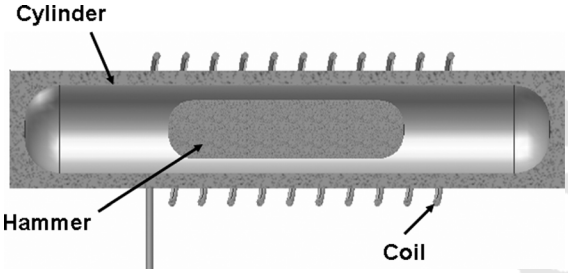


Figure 7.20 Magnetically driven mill. Courtesy Spex Certiprep Group.

7.6 Tumbling Mills

Tumbling machines use a combination of gravity and rotation to comminute. Basically, think of a clothes dryer, except that instead of clothes, rocks are placed inside, sometimes along with a material much harder than the rocks. As the chamber tumbles, a combination of impacts, from falling pieces, and abrasion wear down the rocks into smaller pieces, which eventually fall out through a mesh screen or other opening.

Ball, rod, pebble or tube tumbling mills have a cylindrical or conical shell, rotating on a horizontal axis, and are charged with a grinding medium such as balls of steel, flint or ceramic or with steel rods. Due to the rotation and friction of the mill shell, the grinding medium is lifted along the rising side of the mill until a position of dynamic equilibrium is reached. The grinding bodies cascade and cataract down the free surface of the other bodies, about a dead zone where little movement occurs, down to the toe of the mill charge where impact crushing occurs.

7.6.1 Rod Mills

In a rod mill, the rocks are tumbled along with long, horizontal cylinders made of a very hard material. In industry, they are used to create a product size of 0.5–5 mm (Lowrison, 1974).

7.6.2 Ball Mills

A ball mill is the same as a rod mill (Figure 7.21), except the rocks are tumbled with spheres, or other shapes with a similar aspect ratio, made of steel or another type of hard material. If the balls are made of a material other than steel, these are sometimes referred to as pebble mills. Ball mills are known to be very effective at creating a very fine product, with a size range of 10–500 μm, with longer run times creating smaller particles (Lowrison, 1974). Ball mills are known for being fairly inefficient, as much

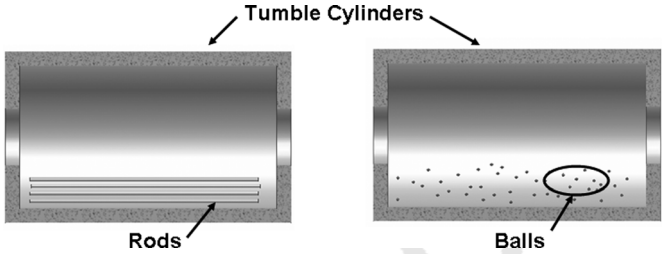


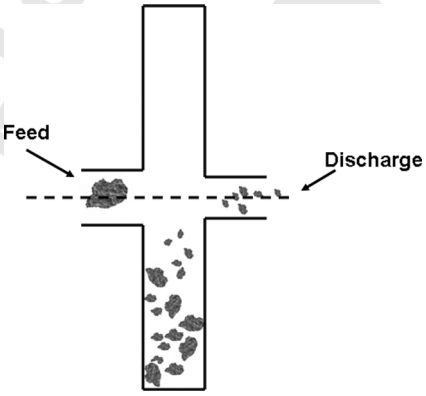
Figure 7.21 Schematic diagrams of a rod mill (a) and a ball mill (b) (Hayes, 1993).

energy is expended in tumbling the structure and its contents, and the grinding action tends to proceed rather slowly.

The speed of rotation of the mill shell is important in controlling the principal comminution mechanism and the characteristics of the resulting product. At relatively low speeds, the medium tends to roll down to the toe of the mill and abrasive comminution dominates. At higher speeds, the medium is projected clear of the charge, describing a series of parabolas before landing on the toe of the charge. This cataracting leads to comminution by impact and a coarser end product. Figure 7.21 shows an example of a rod tumbling mill with bottom discharge. Axial overflow discharge is also a common design approach.

7.6.3
Autogenous and Semi-Autogenous Mills

These devices could also be classified as attrition machines. The rocks are comminuted by interaction with other rocks of the same material and the walls of the tumbler. This causes impact breakage of larger rocks and compressive grinding of finer particles. Breaking is achieved by using mills of high diameter-to-length ratio (Figure 7.22), so that the particles fall through larger distances than in conventional



Q4 **Figure 7.22** Schematic diagram of an autogenous grinding mill (Hayes).

rod or ball mills. A semi-autogenous grinding mill (SAG) combines the principles of autogenous and ball mills by using grinding media (e.g., steel balls) and the material itself.

Cleaning of tumbling mills appears problematic, with autogenous types presenting the fewest problems. One can envision inserting brushes to clean the surfaces of the tumbling shell, but cleaning of any grinding medium would be difficult.

7.7 Cutting Machines

Cutting is defined as the breaking of a material into smaller pieces by the action of a force applied over a narrow surface area.

7.7.1 Knives, Shears, and Wedges

This cutting method makes use primarily of plastic deformation, or brittle fracture at the point where force is applied. Knives and shears are useful for plastic, deformable materials, and wedges have the ability to fracture hard materials into smaller chunks. As a comminution device for planetary sampling, the wedge has two possible methods of application. If applied with a slow, compressive force, it could break rocks into smaller chunks fairly efficiently, but with little production of powder. If attached to a percussive hammer, it could potentially comminute rock very quickly into a large variety of particle sizes, which could be separated by sieving. The production of powder by such a device could be facilitated by having the wedge hammer the rock particles into a rounded groove (essentially a long, thin mortar that could also be swept clean fairly easily between samples).

7.7.2 Saws

Saws are useful for cutting hard and brittle materials and work primarily through the action of abrasion (Lowrison, 1974). For planetary sampling, a small band, wire, or circular saw could be used to cut off small pieces of a rock, exposing a pristine inner surface and creating pulverized rock in the form of saw dust. There would need to be a mechanism for collecting this powder, and clearing out the powder from previous samples would also be an issue.

7.8 Attrition Machines

These machines make use of contact between particles (in addition to force provided by crushing surfaces) of the material being crushed to comminute.

page proof © WILEY-VCH

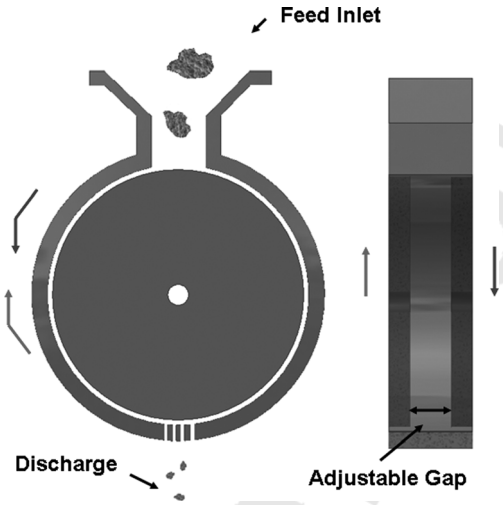


Figure 7.23 Schematic of a small disk grinding mill.

7.8.1
Disk Attrition Mills

Disk or attrition mills are the modern counterparts of buhrstone grinders, consisting of two counter-rotating circular plates faced with hard materials (Figure 7.23). Particles passing between the adjustable gap between the hard points are sheared and abraded against one another. Modern disk mills operate at high rotary speeds, so there is an additional impact action on rock particles. Figure 7.23 shows an example of a relatively small disk mill. Disk mills are used to grind a wide variety of materials, their main drawback being the heat generated by the large frictional forces associated with their operation. Also, it is difficult to see how cleaning could be implemented in a simple manner.

7.8.2
Buhrstone

One of the oldest forms of grinding machines, it consists of a large, often concave, millstone, on which the material to be ground is placed, and a second, smaller, convex stone, which is pushed back and forth over the material (Lowrison, 1974). In another form, the moving stone is rotated about an axis instead of being pushed back and forth (Figure 7.24). A rotary buhrstone mill can have either horizontally or vertically positioned stones. Grooves in the stones facilitate the movement of the material (material moves towards the outer edge of the stones). The fineness of the product is controlled by the pressure between the stones and by the grinding speed. For example, a finely ground product is achieved by slowly rotating the stone with high pressure on the material being ground. The output of a Buhrstone mill is low and its power requirements are high. The stones require frequent maintenance, even when

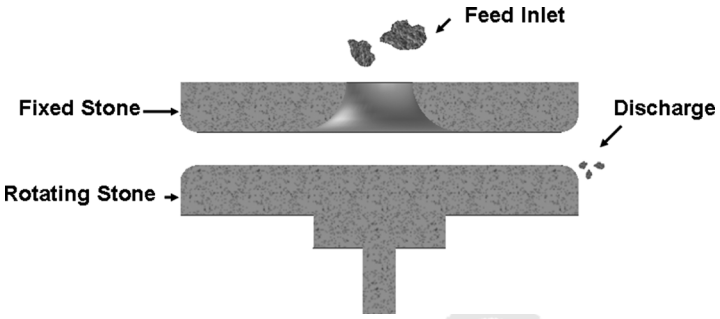


Figure 7.24 Schematic of a buhrstone mill (Kessler, 2001).

grinding only slightly abrasive materials (Kessler, 2001). From the perspective of planetary sampling, the buhrstone mill has many advantages, including simplicity, the ability to create plenty of pulverized sample, and the relatively open working area, which can be swept clean between samples. The mechanized sample handler (MeSH) crusher/grinder is essentially a form of this instrument, made of tungsten carbide instead of stone, and has flat surfaces (as opposed to convex/concave).

7.8.3
Mortar and Pestle Mill

Also dating to antiquity, this device consists of a rounded bowl (the mortar) and a stick with a rounded end. The pestle is most commonly used to compress the material to be ground into the mortar, but can also be used to break material with impacts. Motorized mortar and pestles, made of agate, are used in geology laboratories to create powders with extremely small particle sizes. With dry comminution, caking is prevalent (T. Teague, UC Berkeley, Department of Earth and Planetary Sciences, personal communication, 2006, tteague@berkeley.edu). The most effective grinding takes place with the aid of a liquid, such as water or alcohol.

Chief drawbacks to the mortar and pestle approach, as with so many of the others, is the difficulty in cleaning between samples. One can anticipate caking of compacted fines, especially if there is melting of any water-ice from the samples. In this eventuality, transfer of sample to instruments and subsequent cleaning of the grinding parts could prove difficult. Powered wire brushes would be one way to attempt cleaning and perhaps a workable design could be achieved. However, there seems to be no particular advantage of this design over a small cone crusher, as described above.

7.8.4
Swing Mill

This is a laboratory device used to grind small samples to a fine powder (but not quite as fine as a mortar and pestle). The material to be ground is placed in a sealed cylindrical bowl, along with a circular puck (and sometimes an additional ring). All of

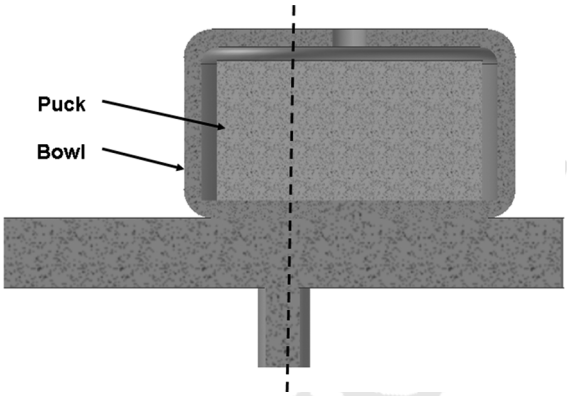


Figure 7.25 Schematic of a swing mill. Courtesy Spex Certiprep Group.

the grinding surfaces are made of a hard material, such as tungsten carbide. The bowl is swung around in a small circle at high speeds. The material is ground between the surfaces of the puck and the walls of the bowl, and also by interaction between the particles (Figure 7.25).

7.8.5
Disk Mill (or Colloid Mill)

These use two rotating, vertical, parallel disks that are spaced very close (0.02–1 mm) to each other (Figure 7.26). Material is fed either from the top or through the axis of one of the disks. The higher the speed of rotation, the smaller is the final product, which can be on the order of microns. For very small products, the particles are fed while suspended in slurry (Lowrison, 1974).

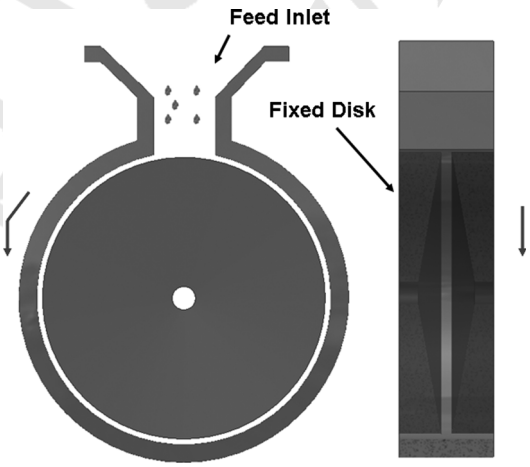


Figure 7.26 Schematic of a disk mill. Courtesy Retsch.

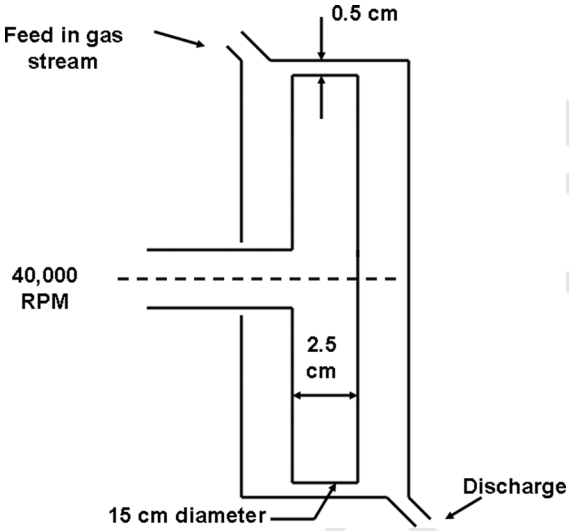


Figure 7.27 Schematic of a petit pulverizer (Lowrison, 1974).

7.8.6 Petit Pulverizer

A single disk is rotated at very high speeds (40 000 rpm) inside a chamber, with only 0.5 mm clearance (Figure 7.27). The feed particles are introduced to one side of the disk by means of a gas flow, and the product exits from a tube on the opposite side of the disk. The reference for this information (Lowrison, 1974) is apparently a patent from 1951 and it is not clear that this device was ever used; however, the claim was made that the particles are "made to spin at 10–100 million rpm and that disintegration occurs by the internal stress induced by the centrifugal forces ... in theory, such tensile breaking should require the least energy" (Lowrison, 1974).

7.9 Other Methods of Comminution

7.9.1 Abrasion

Instead of crushing a rock in grinders/mills or crushers, it is possible to use an abrasive tool, such as a grinding wheel, to grind away the rock slowly. Particles produced from this type of grinding are inherently small. For exposing pristine rock faces, this device already has heritage in the form of the rock abrasion tool (RAT) (Gorevan *et al.*, 2003). The abrasive medium could be similar to the grinding pads on

Page Proof © WILEY-VCH

the RAT or the diamond-impregnated segments as used in coring/drilling. The key to enabling this as a comminution device would be to design a robust method of collecting the powder it produces. Also, it might be desirable to make the device more powerful, to create powder samples more quickly.

7.9.2 Thermal Comminution

Rocks are heated and, either through differential thermal expansion of their parts or vaporization of trapped water, the rocks split into pieces. This process occurs in Nature, and causes so-called "onion" weathering or exfoliation of rocks.

7.9.3 Electrical Comminution

In electrical comminution, rock fails via tensile failure after applying high-voltage pulses. Rock is placed in the path of a high electrical current that creates an electrical field which exceeds the dielectric strength of the rock. The result is plasma explosion that effectively fragments the rock.

7.9.4 Microwave Comminution

Certain minerals respond to microwaves by heating up; these include most sulfides, metal oxides, sulfo salts and arsenides. This has been proposed as a way of assisting comminution, by using the microwaves to induce micro-cracking, thereby reducing the power necessary for mechanical comminution. Thus far, attempts at making this viable have been unsuccessful due to inefficiency, but there are promising new technologies that may be capable of applying the microwaves in a more focused fashion (Whittles, Kingman and Reddish, 2003).

7.9.5 Ultrasonic Comminution

The theory behind ultrasonic comminution is that application of high-frequency vibrations can deliver energy into tiny cracks in the rock, facilitating their propagation and the eventual breakage of the rock. While showing this theoretical promise, there do not appear to be many successful applications yet (Gaete-Garreton, Vargas-Hernandez and Velasquez-Lambert, 2000), except for those in which the ultrasonic energy is transmitted through a fluid medium (Lowrison, 1974). Gaete-Garreton *et al.* (2000) created a roll crusher in which one of the rollers was designed to be a tuned ultrasonic source. They reported successfully decreasing the amount of energy required to comminute granite, increasing the proportion of fine particles, and also decreasing the wear on the rollers. An ultrasonic drill developed by NASA/JPL (Bar-Cohen *et al.*, 2005) could also pulverize small areas of a rock *in situ* without the need for bringing a rock to a larger crusher.

page proof ©WILEY-VCH

7.9.6
Explosion

Explosion is the method of choice for removing large quantities of hard rock from the ground, and also comminuting very large pieces of hard rock.

7.10
Selection of Comminution Equipment for Planetary Sampling

In industry and research, it is almost always preferable to use more than one comminution device to arrive at the desired product. For reasons of simplicity, cost, and mass, a planetary sampling application would most likely try to rely on a single device. The question then is, if one were to perform comminution in a single stage, which type of machine would best serve the purpose? On the other hand, it is known that no single machine can reduce rock material to a very high grade of powder, and there may eventually be a need for this capability in planetary sampling.

Figure 7.28 shows general guidelines for the selection of communion equipment. In particular, various types of comminution equipment are plotted against the Mohs' hardness of material to be comminuted (x-axis) and the sizes of final product (y-axis). Table 7.8 lists the equipment type, its principle comminution mechanism and the type of materials that are suited and unsuited for comminution (Tarjan, 1981).

7.10.1
Single-Stage Comminution

A device that will serve to complete comminution in a single stage would have to accept a rock or core sample of some minimum size (perhaps 1 cm for a core sample or larger for a rock removed from the ground). Table 7.9 shows that among these are the jaw crusher, the gyratory crushers, roll crushers, rotary hammer mill, autogenous mill, and the stamp mill. To this list can also be added the buhrstone, the saw, the wedge, and the grinding wheel. From this list, several can be ruled out, the reasons for which are shown in Table 7.9, leaving the jaw crusher, buhrstone, wedge, saw, and grinding wheel. Other important criteria are the ability to produce fine powder but also retain some material as pristine rock faces, the energy efficiency, the ease of sample collection, the ability to minimize cross-contamination between samples, the mechanical simplicity and robustness, and the ability to abort and eject failed samples. Another factor is the ability of the machine to function while tilted (i.e., if a rover were on a steep slope).

Table 7.10 shows a selection matrix of viable comminution methods for planetary sampling applications. This is a somewhat subjective ranking, but indicative of a process that could be used to select a design. The reasoning is as follows:

- *Powder product*. The buhrstone, grinding wheel, and saw are known to produce highly pulverized material. The jaw crusher also produce fines, but they are not expected to be of very high quality. A slowly compressed wedge would probably produce very little pulverized material.

Page Proof WILEY-VCH

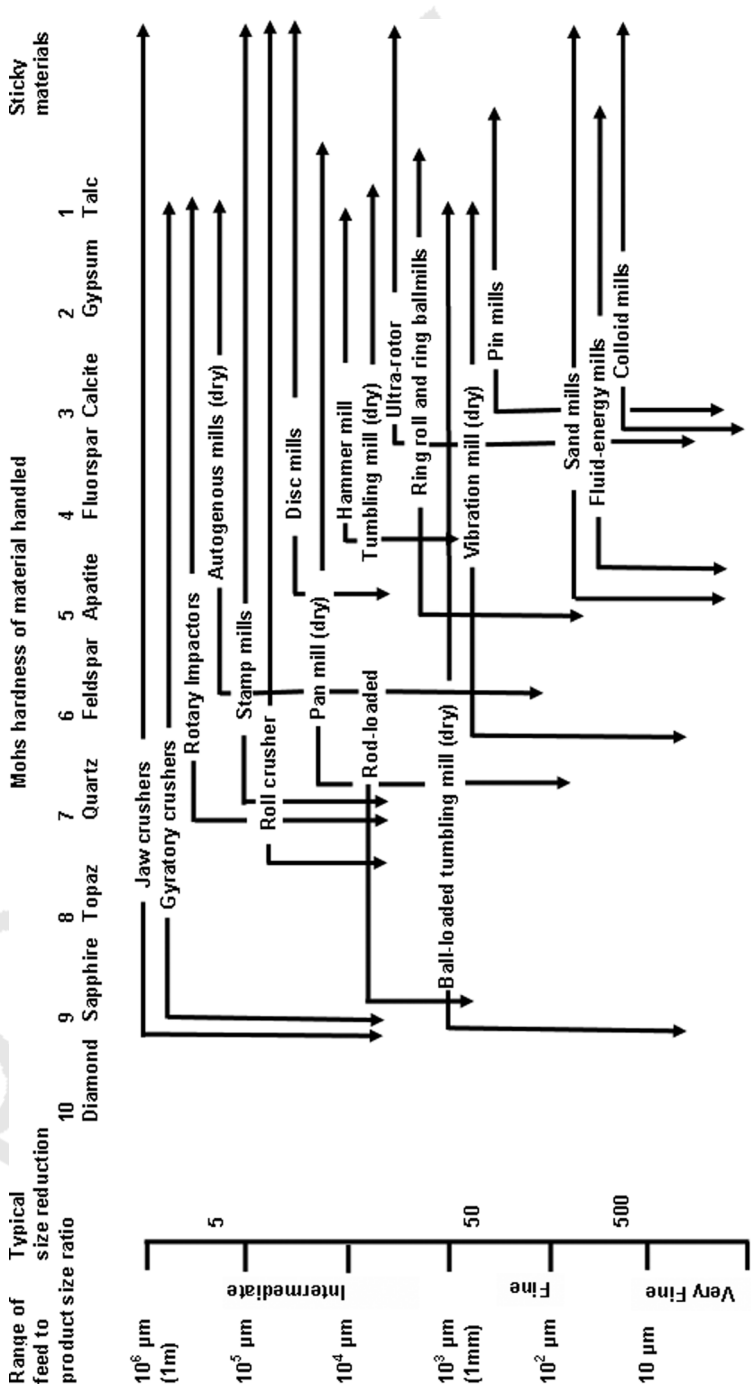


Figure 7.28 Guidelines for the selection of comminution equipment (Lowrison, 1974).

Table 7.8 Selection of equipment based on type of material.

Equipment	Comminution mechanism	Material suited for comminution	Materials unsuited for comminution
Jaw crusher	Pressure	Hard, medium hard	Soft, sticky
Gyratory/cone crusher	Pressure/impact	Hard, medium hard	Soft, sticky
Impact mill	Impact	Medium hard	
Hammer mill	Impact, shear	Non-abrasive	Abrasive

- *Rock face*. All of these methods should do fairly well at producing pristine rock faces that could be imaged or exposed to a Raman spectrometer.
- *Cross-contamination*. It is assumed that all of these methods, except the jaw crusher, would comminute a rock sample on some sort of flat, enclosed stage. After comminution, the area could be wiped clean with a fine brush, leaving only a small amount of residue, which would be only a tiny fraction of the material being processed in the next sample. The jaw crusher, with its enclosed crushing surfaces, would be more difficult to sweep out, but the amount of cross-contamination would likely not be too high.
- *Simplicity/robustness*. The grinding wheel and the saw have the fewest moving parts, but the other types, although not as simple, should be fairly robust.
- *Ejecting aborted sample*. The jaw crusher would require a special mechanism to remove a rock from the jaws. With the other devices, again using the assumption that comminution would take place on a flat stage, it would be relatively easy to push material off the stage.
- *Ease of sample collection*. The jaw crusher requires no special mechanism for delivering its product, as the comminuted material just falls out from between the gap at the bottom. For the buhrstone, and the wedges, the product would have to be swept off of the stage and, for the saw and grinder, a special mechanism would be required to capture the powder that flies off the grinding area.

Table 7.9 Crushing devices that are not recommended for the planetary applications.

	Reason for discarding
Gyratory/cone crusher	Slightly larger than equivalent jaw crusher and with higher throughput (not necessary for planetary application)
Roll crusher	Large size and mass needed to nip a rock of the minimum size
Rotary hammer mill	Large size and mass needed to nip a rock of the minimum size (Kubach, 2006)
Autogenous mill	Size and a requirement for multiple rock samples
Stamp mill	High mass or very high energy impact mechanism required

Page Proof WILEY-VCH

Table 7.10 Selection matrix for viable methods of comminution for planetary sampling: 1, most preferable; 2, acceptable; 3, least preferable.

Comminution machine	Powder product	Rock face	Cross-contamination	Simplicity, robustness	Ejecting aborted sample	Ease of sample collection
Buhrstone	1	1	1	2	1	2
Grinding wheel	1	1	1	1	1	3
Jaw crusher	2	1	2	2	2	1
Saw	1	1	1	1	1	3
Wedge (fast)	3	1	1	2	1	2
Wedge (slow)	3	1	1	2	1	2

7.10.2 Double-Stage Comminution

In the case of devices that are capable of producing very high-quality powders, there are also some types of machines that could be appropriate and others that should be removed from consideration. Note that the grinding wheel and the saw, which have already been considered, could also be included in this category. Tumbling machines are probably not suitable for comminution in planetary exploration because of mass and power considerations, and possibly because of cross-contamination issues. A small rotary hammer mill could produce large quantities of fines (probably not of the highest quality). To reduce contamination with worn material, the impact surfaces should be made of tungsten carbide. The size of the fines produced by a rotary hammer mill can be regulated by the airflow created from the rotation (different sized particles have different capture velocities). Some type of housing would have to be used to catch the fines and this could introduce cross-contamination issues (C. Kubach, Sepor Inc., personal communication, 30 January 2006, http://www.sepor.com).

Planetary mills and vibration mills, both of which make use of grinding media in the form of small balls or other shapes, could potentially be made of small size and low power consumption. Coarse feed passed from the first comminution stage could be fed into small containers that already contained the grinding media and, after processing, the powder produced could be separated from the grinding media with a sieve. The pin mill also seems to be a relatively simple and robust device; here the main issue would be cross-contamination, because the pins have a lot of surface area. Tests would have to be performed to see if a previous sample could be flushed out of a pin mill with a dry run of the subsequent sample. A motorized mortar and pestle could also be a good choice, except that the issue of caking would have to be mitigated somehow.

page proof © WILEY-VCH

7.10.3
New Technologies and Innovations

In addition to already existing technologies, there is also the possibility that new methods for comminution could be developed. The standard tools used in terrestrial mining today are very power hungry and, for mining in space, perhaps older mining tools could be revived with the addition of new technologies. Some of the ideas summarized below are referenced by Quinn (2001).

7.10.3.1 Solar-Powered Rock Crusher

Quinn (2001) suggests the use of the shape memory alloy Nitinol for a solar-powered attrition crusher (it could also be considered a sort of mortar and pestle) for mining asteroids. It is indicated that Nitinol can generate forces of up to 40 t in^{-1}. In this case, alternate cooling and heating of opposed Nitinol rods would be used to grind a pivoting pestle against an anvil (Figure 7.29). Solar power is suggested as the heat source, but heating with electrical resistance could also be used.

7.10.3.2 Thermal Spring Pickaxe

A pickaxe (wedge) would be powered by bimetallic springs that contract and expand with changes in temperature (Figure 7.29). When cooled, the spring would retract and be locked in position. With the addition of heat, the spring applies force against the locking mechanism and, when unlocked, recoils forward with high force. Again, solar power is suggested, but ohmic heating could also be used.

7.10.3.3 Adaptive Wedge

This would use piezoelectricity, magnetorestriction, or thermal expansion to work its way into fractures and break off rocks.

7.11
Review of Recent and Current Work on Comminution for Planetary Sampling

This section presents three independent efforts by NASA JPL (the JPL jaw crusher), the Northern Centre for Advanced Technology (NORCAT) [the sample processing unit (SPU)] and Honeybee Robotics [the mechanized sample handler (MeSH)] in developing different types of crushers.

7.11.1
Jaw Crusher

The JPL crusher is based on the jaw crusher system as shown in Figure 7.30. During a crushing sequence, approximately 20% of the grind material falls below the 150 μm range, which is required for XRD analysis Large particle sizes tend to give poor analysis results using XRD. For example, using particles crushed by the jaw crusher,

Page Proof © WILEY-VCH

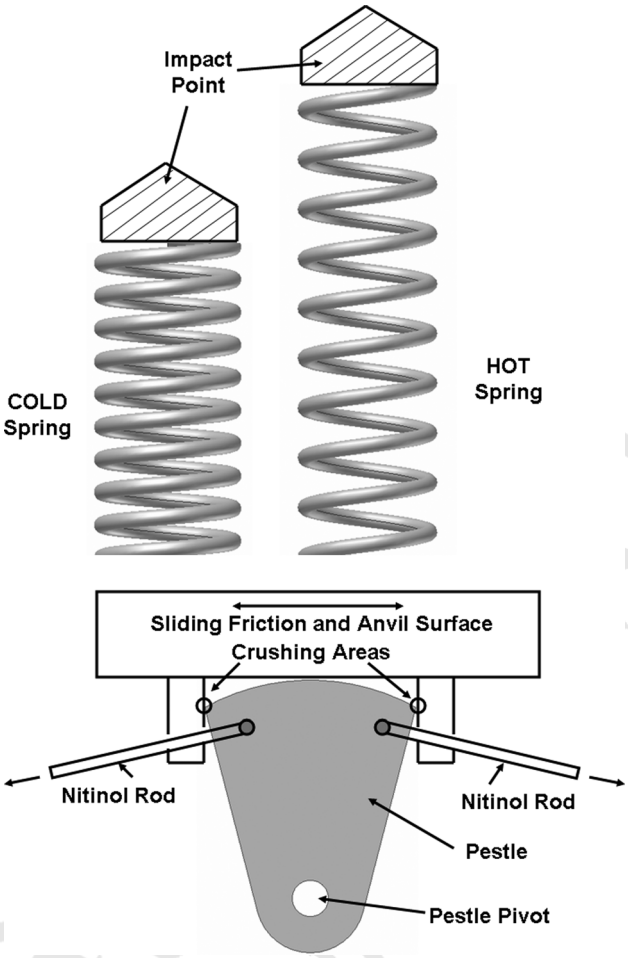


Figure 7.29 Concepts for a solar powered rock crusher and a thermally activated pickaxe (Quinn, 2001).

the XRD showed 40% of the mineral type to be quartz (as opposed to the actual 70%) (Chipera *et al.*, 2004). However, continuously vibrating powder using, for example, piezos improves the efficacy of XRD measurement, since the powder tends to be fluidized and in turn more crystallite orientations are exposed (Sarrazin *et al.*, 2004).

7.11.2
Sample Processing Unit (SPU)

The NORCAT SPU is designed to reduce particle size of near-surface rock and soil samples and drill cores, and subsequently distribute the fine-grained product to scientific instruments. In surveying the possible designs for an SPU, we have eliminated exotic, largely untested approaches and instead have concentrated on

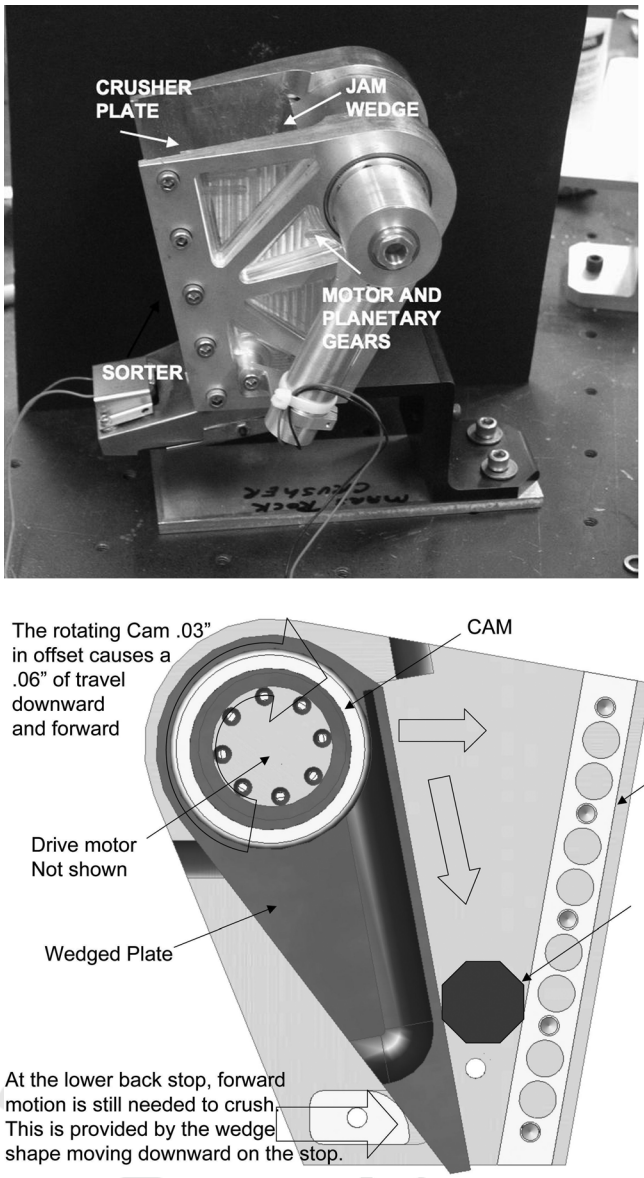


Figure 7.30 Photograph of a JPL jaw crusher (Chipera *et al.*, 2004).

proven commercial designs, mostly from the ore milling industry. The latter are divided into the following broad categories: jaw crushers, gyratory crushers, roll crushers, impact crushers, attrition mills, and tumbling mills. Given the lack of data at the relevant scale and simulated planetary (Moon and Mars) conditions, we find little basis upon which to select among designs using mass, power or volume criteria. Instead, we focus on the probable ease of inter-sample cleaning as the basis

of down-selection, with the result that roll crushers appear to be the most promising approach.

The primary purpose of the SPU is to reduce the particle size of samples to an unsorted aggregate with maximum particle size of 1 mm. The SPU must accept a sample from the sample transfer unit (STU) consisting of solid and unconsolidated rock and soil samples and solid core samples. A wide variety of rock types must be processed, including high compressive strength, cohesive igneous rocks such as basalt. Some of the samples may contain a substantial fraction of water-ice and/or CO_2-ice.

It is assumed that some samples will contain up to approximately 50% by volume of water-ice in between-grain pore spaces. It is possible, perhaps probable, that this ice will melt and refreeze during processing in the SPU as a result of regelation (pressure melting of ice) and heat from mechanical strain (crushing, grinding of rock particles). As a result, it is expected that the surfaces of the SPU will become coated with a thin layer of refrozen, fine-grained mud that will present difficulties for any cleaning mechanism. This assumed melting–refreezing process may also result in particle agglomeration requiring multiple stages of regrinding.

In the terrestrial ore milling industry, primary crushers are massive, heavy-duty machines of low energy efficiency, often 1% or less. They are designed for large-volume throughput of an ore feed with relatively uniform physical properties. For a Mars SPU, the raw feed is likely to be highly variable in physical properties and high-volume throughput is not an issue. Furthermore, cleaning of ore processing mills, for example when changing the raw feedstock, is rarely, if ever, a requirement. For the SPU, cleaning between individual samples is a primary requirement. Despite these differences, some of the proven designs from the ore milling industry deserve examination for possible adaptation to the SPU.

All of the machines described above have more or less extensive commercial histories of application, and so could, in principle, successfully process Martian rock or core samples. Distinguishing among them on the basis of power and/or mass is difficult to do at present because most instances are much larger than what would be needed for the SPU, and empirical scaling data are of questionable applicability over the range needed. Scaling is problematic also because there are no data at any scale under Martian conditions and the Martian samples will be variable with currently unknown physical characteristics. Qualitatively, those designs that utilize compressive forces are likely to have the best efficiencies, but there is little basis to eliminate any approach on the issues of mass or power alone at this time.

However, a more selective criterion appears to be the ease of cleaning the devices between sample batches in order to meet the inter-sample contamination requirement. Most of the candidate machines are designed for large-volume processing of relatively constant feeds, and cleaning is not an issue. Dismantling for wear and breakage maintenance is common enough for commercial machines, but automated dismantling for cleaning of SPU parts between every sample does not seem practical or desirable.

One method by which all of the devices could be cleaned is to pass an abrasive cleaning charge such as crushed quartz aggregate through them, possibly multiple

times, if needed, to carry away all residual sample fragments. Although this approach would likely be successful for any of the processor designs, the mass requirement for expendable cleaning material would most likely prove unacceptable.

Therefore, in the absence of complete autogenous self-cleaning, some sort of brush to remove clinging sample particles mechanically would seem to be the best approach. Among the designs, roll crushers stand out as one for which brush cleaning could be most easily implemented. One or more wire brush rollers could be applied to the crushing rolls automatically between samples. In our estimation, this feature alone moves roll crushers to the top of the candidate list for an SPU. Autogenous tumbling mills are another design for which brush cleaning could be implemented, albeit with more difficulty.

7.11.2.1 **Crusher System**

Task constraints were imposed upon the design as follows:

- *Constraint 1:* The processor would accept samples of 10–15 mm diameter up to 25 cm in length.
- *Constraint 2:* The unit would discharge particulate of 1 mm nominal diameter or less.
- *Constraint 3:* The feedstock would likely contain ice.
- *Constraint 4:* Mass and power must be optimized.

7.11.2.2 **Roll Crusher Design**

A roll crusher-type system was selected and an initial design created that would use a three-stage crushing technique (Figure 7.31). This unit used three separate nip sizes of 8, 2 and 1. The three-stage approach was found to be too large and required three individual motor drive lines, thereby increasing the complexity of the system.

The design team then decided to utilize a set of crusher rolls constructed for Mars-based work under some earlier contracts and crush appropriately sized samples of various rock types. The results showed that virtually all rock types put

Figure 7.31 Photograph of a RESOLVE crusher internals. Courtesy: NORCAT.

Page proof © WILEY-VCH

through the crusher could be crushed in a single pass with a nip set at 1 mm. Rock types included basalt, anorthosite, dolomite, and sandstone. The differences in torques between nip settings of 8, 2, and 1 mm were not dramatic and averaged to about 70 N m at 1 mm nip. It was decided to construct a single-pass crusher mechanism.

The mechanical motion of this unit has two segmented rolls that oppose each other and having a nip of 1 mm. The rolls are put into motion by two sets of drive motors to oscillate the rolls against one other. The unit is entirely enclosed, thus any volatiles released during the crushing phase would be captured and sent for analysis while the crushed material is passed on to the next stage.

7.11.3 Mechanized Sample Handler (MeSH): an Integrated Sample Crushing, Sieving, and Distribution System

The objective of this effort was to develop an automated system for *in situ* processing and distribution of consolidated and unconsolidated Martian rock and regolith samples (Herman *et al.*, 2006). The MeSH system was intended to address directly the science objectives of future Mars missions, by providing the capability to:

- accept a range of sample types from different sample acquisition devices
- validate samples prior to processing and distribution
- prepare samples for specific science instruments
- cache samples for later analysis (and eventually sample return)
- distribute samples to science instruments.

A shared sample handling system (i.e., a system that can accept raw samples from a variety of sample acquisition devices and then distribute a processed sample to each *in situ* scientific instrument in the required form) will add great value to any mission (Figure 7.32).

7.11.3.1 MeSH Concept

Although MeSH is a comprehensive system, it is useful to break it down into distinct subsystems. These subsystems are considered: sample hand-off (MeSH-SHO), sample separation and preparation (MeSH-SSP), and sample distribution (MeSH-SD). For the purposes of this discussion, the term "sample handling" is meant as an umbrella term that includes some or all of these lower-level functions. In the following, a brief description of each subsystem is given.

7.11.3.1.1 MeSH-SHO The purpose of MeSH-SHO is to provide an interface for sample acquisition devices such as a coring drill or sample scoop. After samples are deposited, instruments and sensors are used to:

- Confirm the sample is of sufficient volume.
- Map core samples before they are crushed using instruments such as a Raman spectrometer.
- Take high-resolution images of the samples in their natural state.

page proof © WILEY-VCH

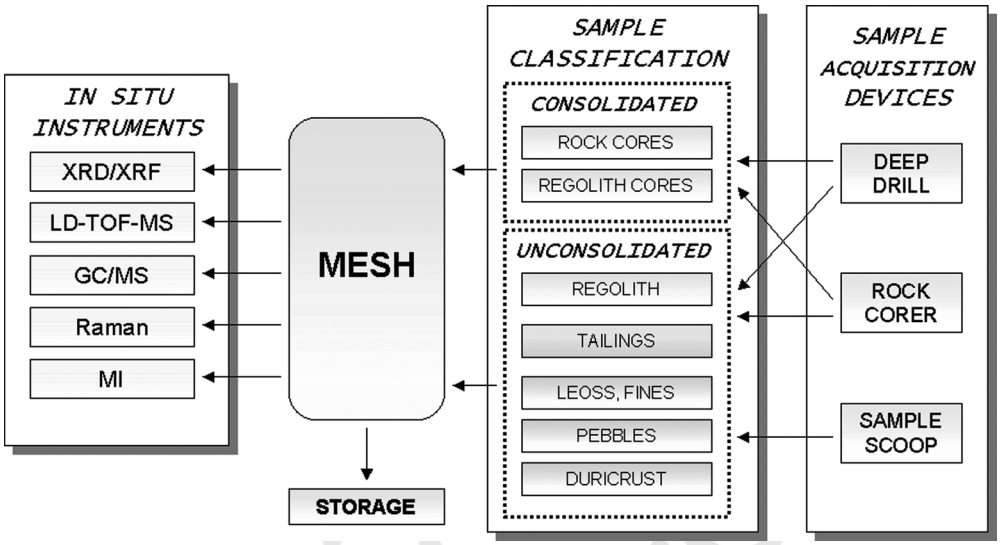


Figure 7.32 Block diagram of the MeSH: an integrated sample crushing, sieving, and distribution system.

Once the initial analysis is completed, the sample is passed on to the next subsystem, MeSH-SSP, and a cleaning operation is performed with a series of wipers to clean the input port(s).

7.11.3.1.2 **MeSH-SSP** The purpose of MeSH-SSP is to separate and prepare validated samples for distribution to the instrument suite. A raw sample would be passed from MeSH-SHO into a chamber where it is first crushed under high force. The comminution sequence is shown in Figure 7.33.

The pulverized material is moved to the desired sieve location by rotating the entire equipment deck. It is important to note that the sieves were to be used in any order. For example, it was not necessary to use the 850 μm before using the 100 μm, or vice versa. Once the sample has arrived at the sieve, the vibratory actuator is engaged in order to start the sieving process. Sieving is also stopped temporarily at programmed points in order to evaluate the volume of product that has been sifted. To check whether sufficient product has been generated, a plunger pushes the product into a sample cup. The plunger mechanism features a spring-loaded tip and integrated limit switch that acts as a discrete force sensor. Volume estimates are derived from the dimensions of the sample cup and the position at which the plunger limit switch is tripped.

MeSH-SSP offers a highly flexible and intelligent configuration. If productivity has slowed during sieving, MeSH-SSP is capable of bringing the sample back to the "anvil" location where it can be further pulverized. If this does not work, then the system can clear the sample chamber by taking the left-over material to an ejection port. The system, now empty, can return to the sieving site and proceed to clean the sieve by energizing the vibratory actuator. Integrating simple sensors (e.g., limit

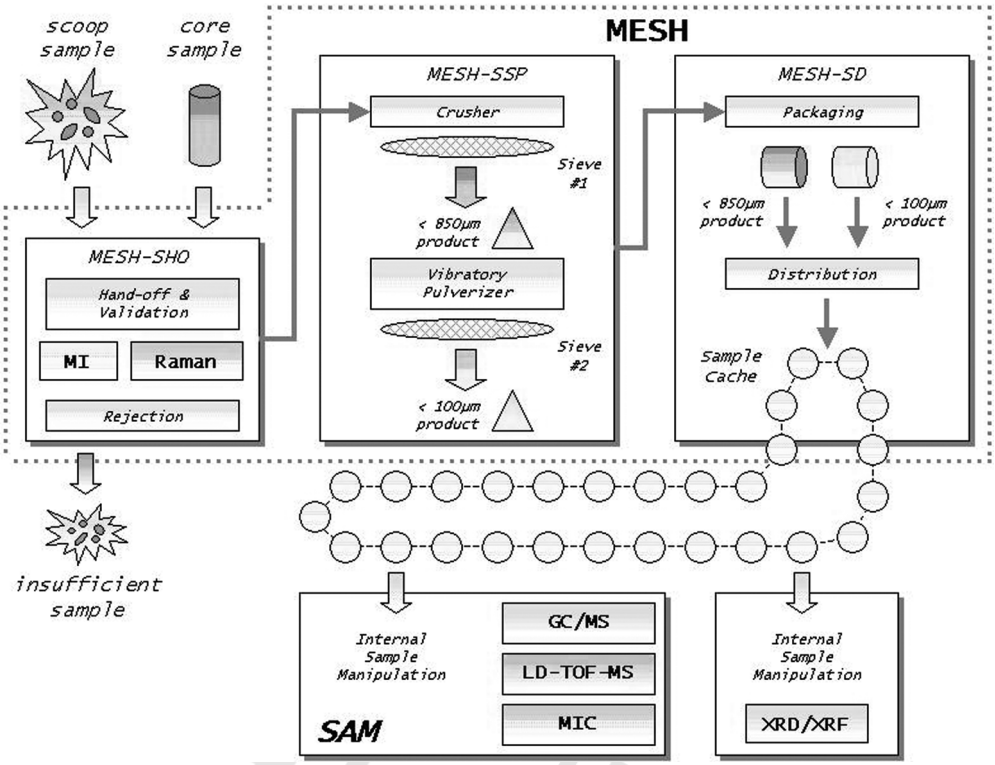


Figure 7.33 MeSH conceptual block diagram.

switches, strain gages) in key locations enables a high degree of autonomy. In addition, a by-product of load sensing in the crushing chamber increases science return by providing rock compressive strength information.

7.11.3.1.3 **MeSH-SD** The purpose of MeSH-SD is to package and distribute the product to the suite of *in situ* scientific instruments. The term "package" should only be interpreted as meaning that the sample (powder) would be placed in small vessel such as a cup or capsule, so that is protected as it waits in the distribution queue.

7.11.3.2 Comminution Test Beds

The original MeSH concept included a compression actuator to crush the sample – in other words, compressive action was the sole means for comminuting a sample. Several quick experiments demonstrated that pure compression would not be sufficient. Experiments using the setup described below demonstrated the efficacy of a second milling action. The solid core sample was first compressed to the extent possible by the machine and subsequently a rotational milling action was engaged under a moderate load. This milling action caused a spreading and self-attrition of the sample.

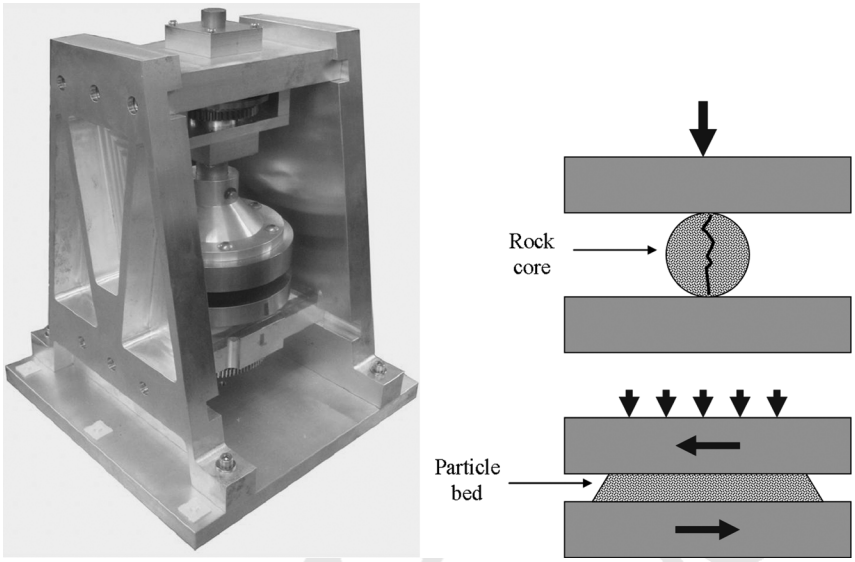


Figure 7.34 Miniature rock press and attrition mill breadboard.

7.11.3.2.1 **First-Generation Miniature Rock Press and Attrition Mill** To study this combined crushing and grinding effect scientifically, a simple breadboard was designed and built (Figure 7.34). The breadboard contained two actuators – one linear actuator to crush the core and one rotational actuator to spread and mill the particle bed. The breadboard also included sensors for measuring the compressive force and milling torque.

7.11.3.2.2 **Comminution Breadboard Experiments** Tests were conducted to determine the comminution efficiency in a variety of materials, including hematite, two varieties of basalt, sandstone, limestone, and chalk. These rocks represent a wide range of hardness (basalts being hardest and chalk the softest) and abrasivity (sandstone being most abrasive). Experiments were performed to assess process repeatability and to measure fine fraction yield across multiple crushing and milling cycles.

The results of the breadboard tests were extremely positive, confirming that the selected crushing/milling approach was very effective at rapidly reducing solid rock cores to $<150\,\mu m$ fines for a variety of rocks (Figure 7.35). The crushing–milling method was also fairly repeatable – the 3σ variation was less than 10%. Within four crushing–milling cycles, over 90% of a Palisades basalt core's mass was reduced to $<150\,\mu m$ fines. The tests also yielded force and power levels required to crush/mill a variety of rocks.

7.11.3.2.3 **Sample Representativeness – Differential Comminution** As with all sampling and sample processing devices, there is a concern regarding the level of bias introduced by the process – in particular, there is always a question of how representative the powder being produced by the crushing device is to the original

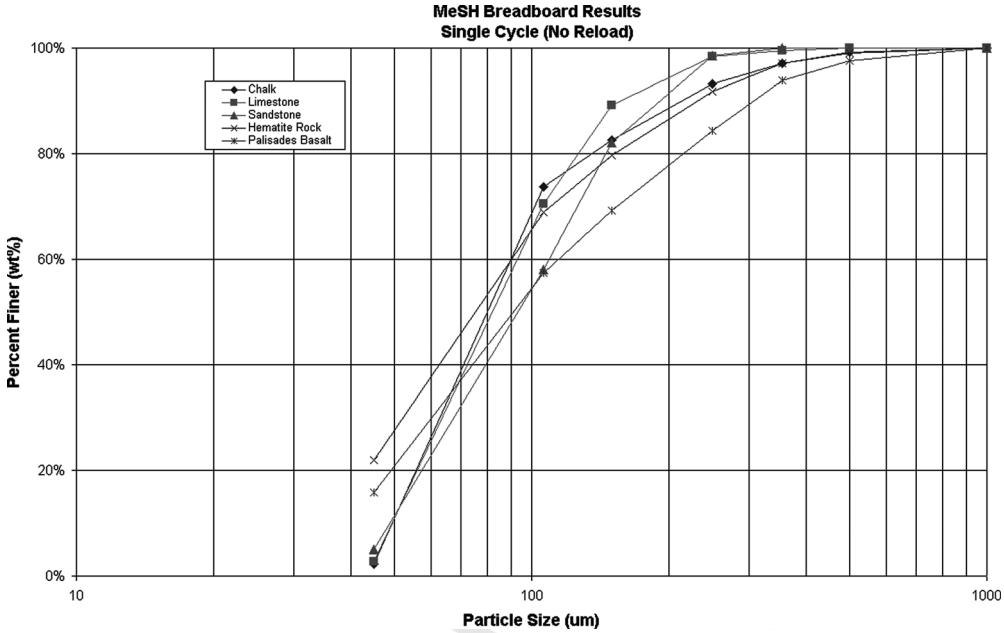


Figure 7.35 Results of crushing tests for various types of rocks.

rock core. Some of the rocks being tested (e.g., basalts) were comprised of multiple mineral phases with some phases being harder or softer than others. In an ideal case (Figures 7.36 and 7.37), one wants the comminution process to break down the entire core sample into a fine (<150 μm), well-mixed (homogeneous) powder. In this way, the crusher's product is representative – as all mineral phases have an equally random chance of passing through any sorting stages (e.g., sieve and portioner) on their way to the scientific instruments. However, a crushing device will tend to break up softer minerals first and may not sufficiently reduce the particle size of harder mineral phases. This is called differential comminution. The result is that information about the rock is potentially lost as the coarse materials are sorted out of the fine fraction that moves on to the instruments.

To determine if the powder produced by the MeSH comminution process was representative of the base rock, XRD and visible–near infrared (VNIR) spectral analyses on a set basalt samples were performed (Figure 7.38). For each basalt type, both the coarse and fine fractions produced by the MeSH system were submitted for comparative analysis (Herman *et al.*, 2006).

Based on the XRD results (Figure 7.39), both size fractions (coarse and fine) had the same mineral composition for all intents and purposes. However, there was some evidence of differential comminution, especially for the coarser grained Palisades basalt (e.g., more chlorite in the <150 μm fraction). The VNIR spectral analysis (Figure 7.39) supported the XRD results. Similar patterns imply no detectable differences in mineralogical composition between size fractions. There were multiple possible explanations for lower albedo of <150 μm size fraction of the

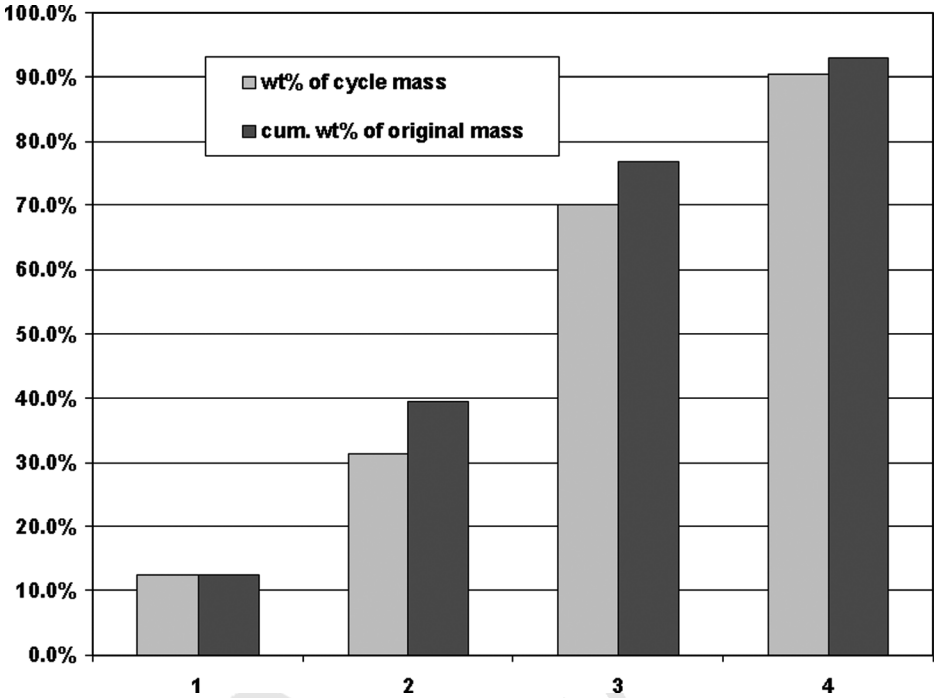


Figure 7.36 Test results showing yield per cycle for a comminution process.

Palisades basalt (e.g., higher levels of contamination by grinder steel and differential comminution).

7.11.3.2.4 **Sieving** The second stage of the sample process chain in the MeSH concept is sieving. The goal was to separate all particles smaller than 150 μm from the bulk crushed particulate. Design variables affecting sieving efficiency include sieve screen type and the induced vibration method, and also the amplitude and frequency of the induced vibration. Conceptual methods to induce vibration included both a

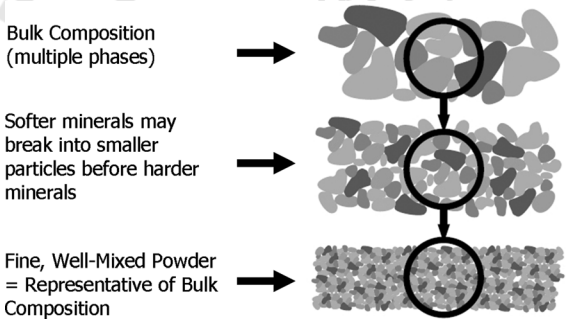


Figure 7.37 Example of a differential comminution.

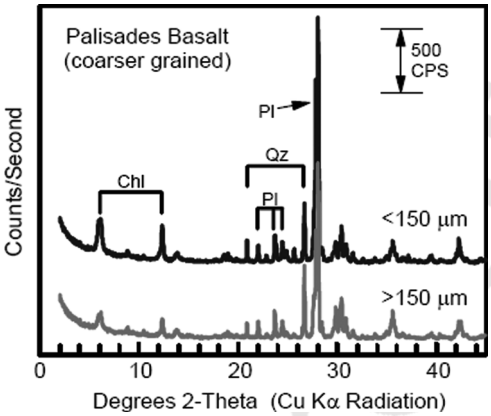


Figure 7.38 XRD results for <150 and >150 µm size fractions of Palisades basalt. Data obtained on fine powders of each size fraction provided a common basis for comparison. Courtesy D. Morris, NASA/JSC.

spinning inertial mass and utilizing an ultrasonic transducer. Each of these design variables was investigated using the sieve breadboard.

Sieve Screen Type Sieve screens from Stork-Veco and Precision Eforming were investigated. Both manufacturers supplied two 150 µm screens; one with square holes and the other with round holes. The Stork-Veco screen had a venturi hole profile whereas the Precision Eforming screen had a straight profile. Test results showed that the type and brand of sieve had an effect on the quality of the sieving process (Figure 7.40).

Figure 7.41 shows how each of the sieve types performed during testing. Of the two hole geometries, circular and square, the square profile has higher sieving percentages than the circular profile. Figure 7.41 also compares the two different

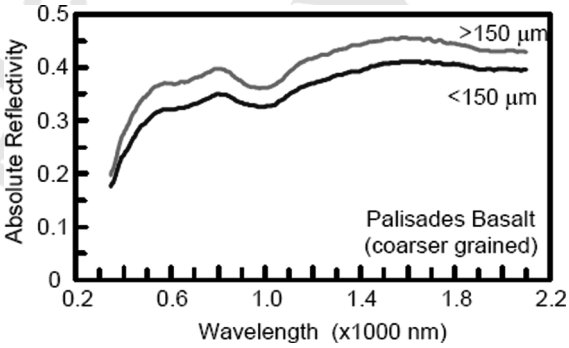


Figure 7.39 Visible and near-IR Spectra for <150 and >150 µm size fractions of Palisades basalt. Data obtained on fine powders of each size fraction to provide a common basis for comparison. Courtesy D. Morris, NASA/JSC.

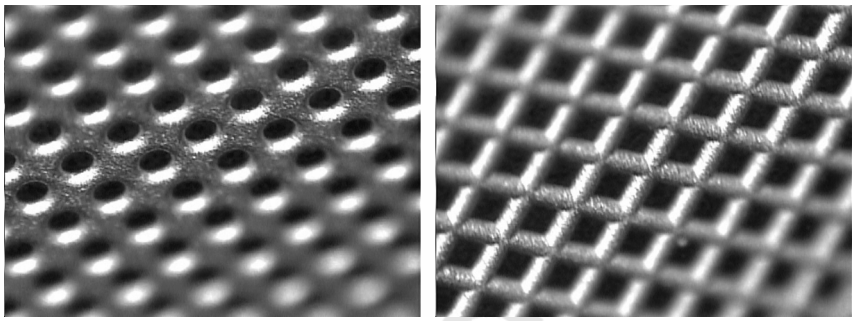


Figure 7.40 Examples of 150 μm sieve screens: round profile (a) and square profile (b). More fines would pass through the sieve with square profiles.

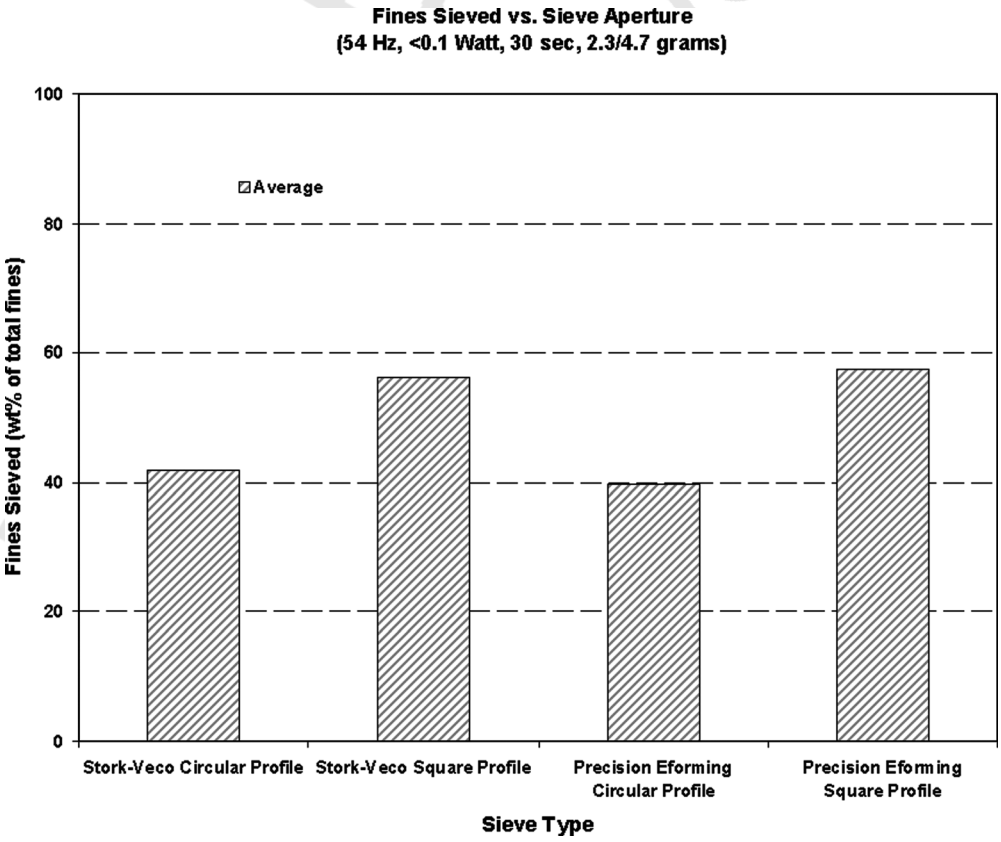


Figure 7.41 Graph showing the effectiveness of different types of sieves.

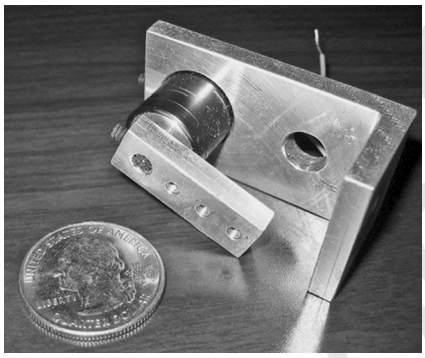


Figure 7.42 Photograph of a sieve vibration mechanism using the spinning offset mass.

sieve brands. On average, the Stork-Veco brand has a higher sieving percentage than the Precision Eforming brand.

Vibration Using Offset Mass The spinning offset mass apparatus used during breadboard testing is shown in Figure 7.42.

Varying the voltage input for the system had a significant effect on both the frequency and the energy input of the system. Figures 7.43 and 7.44 illustrate how power and time affect the effectiveness of the sieve and the amount of the sample collected. As the power input to the system increases, the percentage of total fines sieved also increases; however, at a power input of ~0.05 W (67 Hz frequency), the relative gain in fines sieved per input power decreases significantly. Holding power

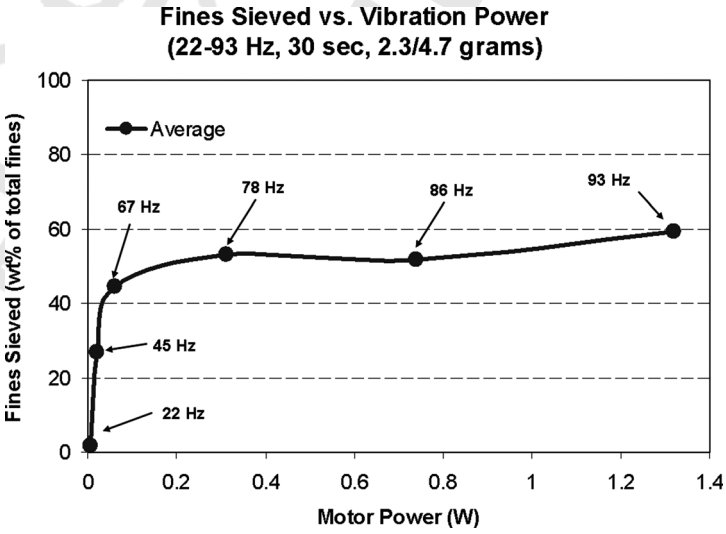


Figure 7.43 Sieving results: fines sieved vs vibration power.

page proof
CLEANCH

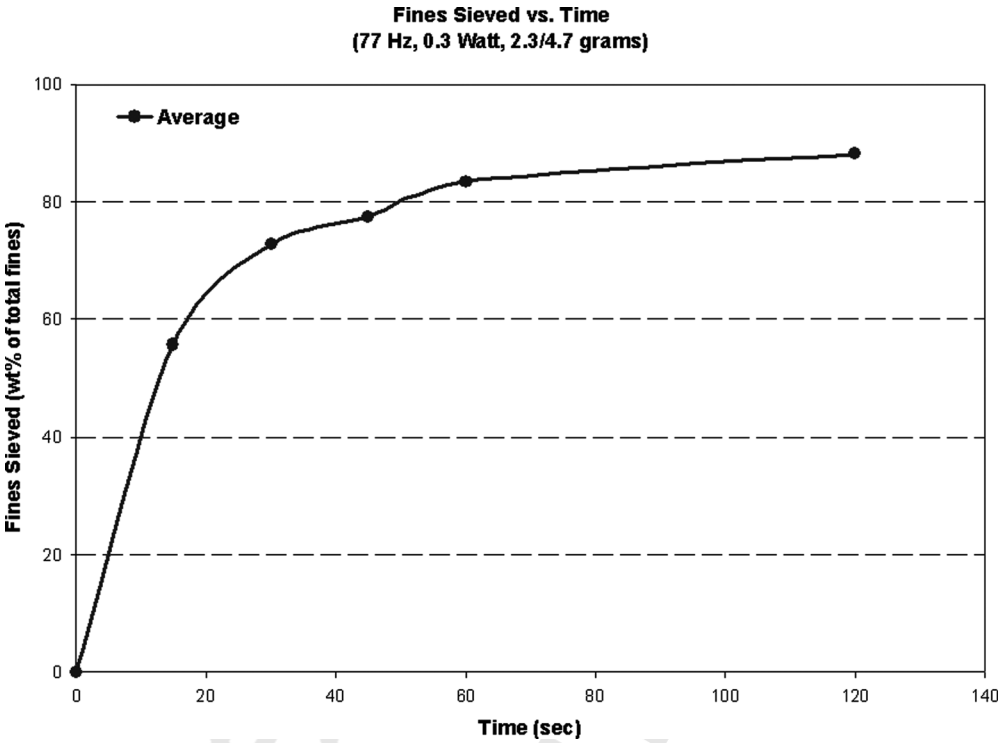


Figure 7.44 Sieving results: fines sieved vs time.

input constant, the percentage of total fines sieved increases as the duration of vibration increases. Again there is a noticeable knee in the curve at ~30 s where the relative amount of fines sieved per unit time decreases significantly. These data can allow fine tuning of the system input to allow for optimal power and energy efficiency. It should be noted that based on the data below, a long time would be required to allow all fines to be sieved. At the end of the 120 s test, only 90% of fines had been sieved.

Ultrasonic Vibration A COTS ultrasonic transducer was used (Figure 7.45) to investigate the relative effectiveness of utilizing an ultrasonic forcing function to excite the sieve screen. It was postulated that the ultrasonic transducer would excite higher modes of vibration in the sieve screen which would further excite the particulate being processed.

The results were varied and it was determined that a significant amount of error existed in the data. After 30 s of vibration, the percentage of fines sieved ranged from 45 to 70%. As this percentage was significantly less than that for the spinning inertial mass method, and the increased requirements that an ultrasonic transducer would levy on a flight system's electronics, the inertial mass method was selected for integration into the MeSH system.

Figure 7.45 Example of a Dr Hielscher UIS250L ultrasonic transducer used to excite the sieve screen.

7.11.3.3 **MeSH Design**

Overall specifications for the complete system design include the following:

- mass: 23 kg
- volume: 38 cm (H) × 30 cm (W) × 30 cm (D)
- testing base plate includes five sample drop-off locations
- three locations for aliquot samples
- one location for fine material dump
- one location for coarse material dump
- processed core sample visible via an inspection camera throughout various stages.

As shown in Figure 7.46, the brassboard includes a preload subsystem, crushing subsystem, sieving subsystem, and metering subsystem. The crushing and sieving subsystems were designed to allow for replacement of the sample cup and crush platen. This modularity allows for the testing of multiple materials for those components.

Figure 7.47 shows various stages throughout the MeSH sample chain. The sample processing routine begins by placing a rock core in the sample cup. The sample cup is positioned beneath the crush plate and the sample cup is preloaded to the crush base plate. Following the automated crush routine, the sample cup is released and moved away from the crush subsystem. The sieve container closes on the sample cup and the wrist axis spins the closed assembly 180°, dropping the processed sample on to the sieve. The spinning offset mass is turned on for a specified amount of time; allowing particulate less than 150 μm in size to drop through the sieve screen into the fines container. The fines container is oscillated via the wrist axis, causing the fine particulate to flow over and fill a 0.05 cm^3 aliquot chamber. The fines container is rotated to a slight angular position so any remaining fines will flow away from the aliquot chamber. The fines container is brought back to a level position and then moved over the desired sample drop-off location (Figure 7.48). The aliquot door is opened, allowing the sample to flow from the aliquot chamber into the desired sample cup.

page proof WILEY-VCH

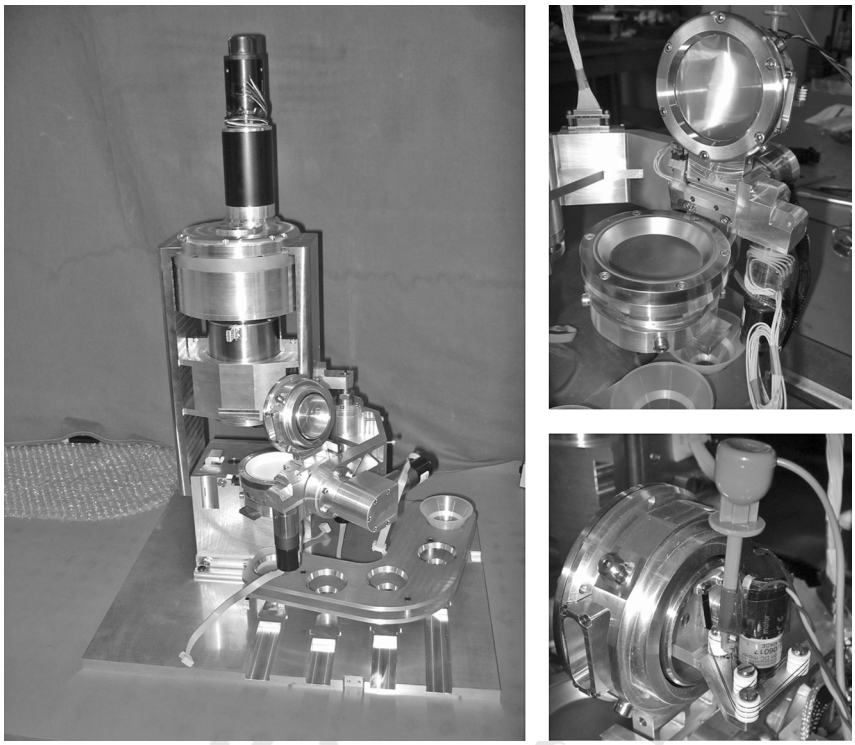


Figure 7.46 Photograph of a MeSH system prototype.

7.11.3.3.1 **Crusher Subsystem Design** The crusher subsystem uses a combination of piston-die press (PDP) mode and attrition mill (AM) mode to process a sample core (Figure 7.49). The crusher subsystem utilizes two parallel axes to perform these tasks: crush and churn. As shown in Figure 7.49, the crusher subassembly utilizes a steel Acme lead screw and bronze nut to create the vertical crush axis motion. A spine (shown in red) allows for the transmission of torque between the churn axis motor and the crush element throughout the full crush axis range of motion. The crush axis was designed to supply 6000 lbf peak force and 4200 lbf continuous force. The churn axis was designed to supply 425 in-lb peak torque and 319 in-lb continuous torque. The load path between the moving crush element and the primary structure included heavy-duty cylindrical rolling-element thrust bearings to react the high loads generated during the crush routine.

In PDP mode, the crush axis applies a compressive load to fracture a fresh core sample. In AM mode, the crush axis applies a compressive load while the churn axis simultaneously rotates the crush element causing a self-grinding "attrition" action to occur between coarse particles.

The upper and lower platen materials and finish were chosen to minimize wear and contamination. Those components were procured out of CPM-10V steel, 99.8% alumina ceramic, and zirconia-toughened alumina to allow for material testing.

Figure 7.47 MeSH sample chain: from a core to a final product.

7.11.3.3.2 **Sieve Subsystem Design** As shown in Figure 7.50, the sieve subsystem consists of three serial axes: elbow, wrist, and hinge. The elbow axis is used to position the subassembly in the proper locations for crushing, sieving, and metering operations. The wrist axis is used to rotate the crush cup/sample cup subassembly to transfer the crushed sample from the crush cup on to the sieve screen. The hinge axis is used to close the sample cup on to the crushing cup after a crushing operation and prior to a sieving operation.

The preload subsystem is located beneath the sieve subsystem and is used to preload the crushing cup to the crush base plate to create a closed load path during crushing operations. It consists of a ball screw that simultaneously drives preload fingers and preload pins. The preload fingers pull the crushing cup to the crush base

Figure 7.48 Photograph of a fines container (sieve screen removed).

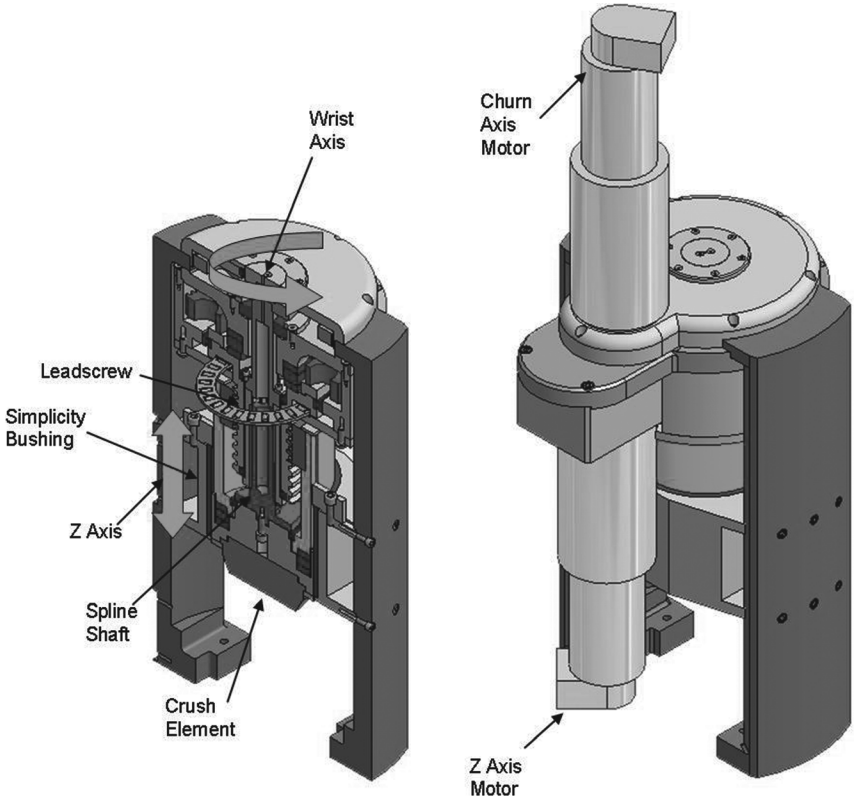


Figure 7.49 Schematics of the MeSH crusher subsystems.
(Please find a color version of this figure on the color plates).

plate via spring-loaded tabs. The preload pins extend up into the bottom of the crushing cup to react torque loads applied during the AM crush mode.

The sieve subsystem uses a 150 μm Stork-Veco square-profile sieve screen to separate fine particulate from the bulk-processed core. An inertial mass on the brushed motor shaft is used to vibrate the sieve screen. The sample cup and crushing cup are suspended on wavy springs. This lowers the natural frequency of the sieve subsystem while dynamically isolating it from base structure.

7.11.3.3.3 **Control Software** Mid- and high-level routines were written to allow for automated sequencing and end-to-end process runs. At a high level, the core processing routine is as follows:

1. Fracture solid core into coarse fraction via die-press action.
2. Back off and turn vibrate motor on to "clean" particulate from platen edges.
3. Spread coarse particles on crush platen via light churning action.
4. Comminute coarse particles into fines via heavy churning action.
5. Close and rotate sieve subassembly.

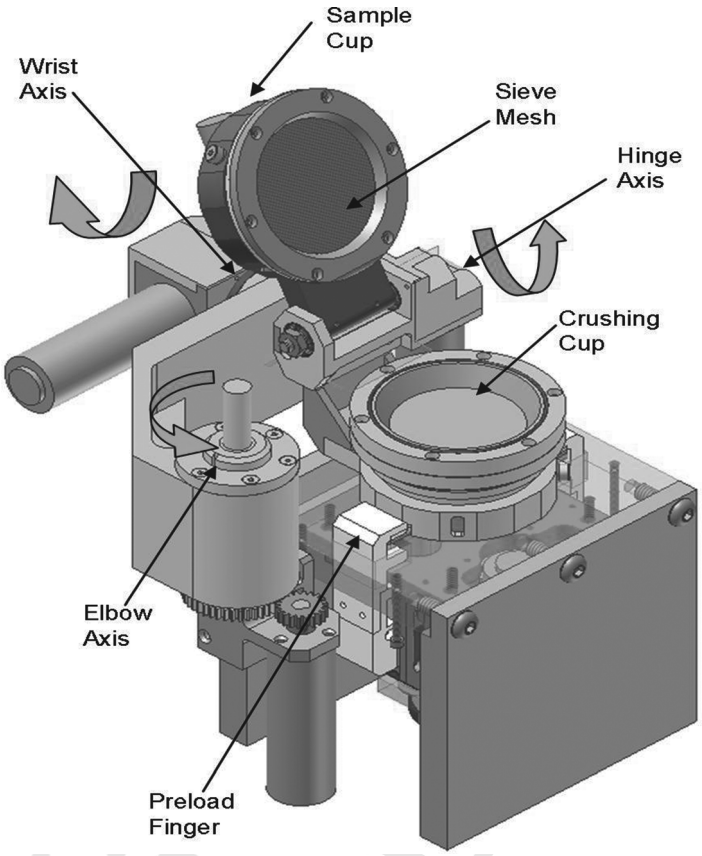


Figure 7.50 Components of the MeSH sieving subsystem.
(Please find a color version of this figure on the color plates).

6. Oscillate and vibrate sieve subassembly to separate fines into the fines chamber.
7. Oscillate and vibrate sieve subassembly to fill aliquot chamber and move remaining fines away from aliquot chamber.
8. Open aliquot chamber cap and turn on vibrate motor to drop sample at selected location.

A graphical user interface (GUI) was developed to allow for low-level manual control, and also high-level system commands (see Figure 7.51). The GUI displays engineering telemetry and the current system status to allow a test engineer to monitor MeSH system processes in real time (see Figure 7.52). The control application logs the complete system state for the lifetime of all commands to allow for post-test data display and analysis.

7.11.3.4 **Laboratory Tests**

The brassboard test program originally intended to characterize the system's performance in terms of:

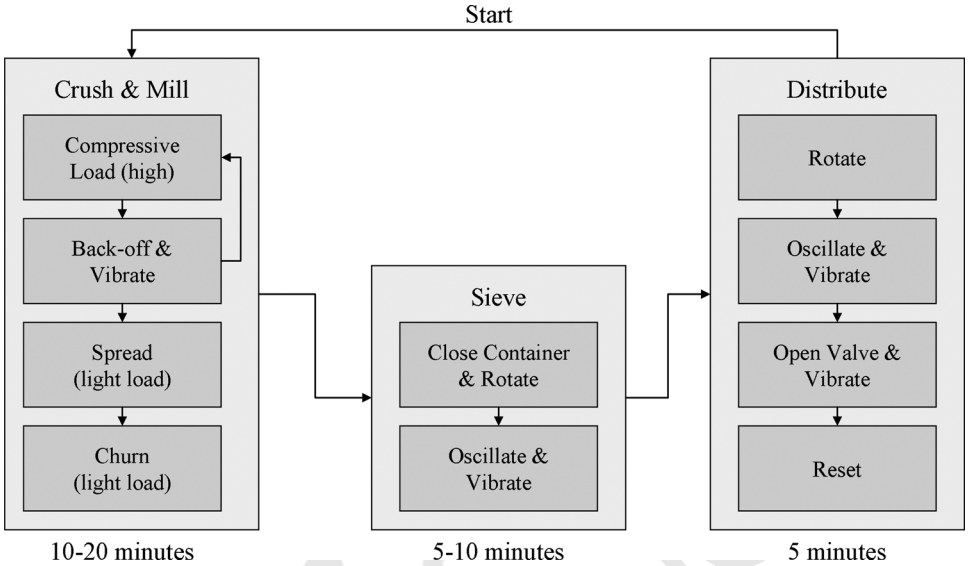


Figure 7.51 Schematic of a high-level core processing algorithm.

- *Yield* The wt% of original sample that was reduced to <150 μm, passed through a sieve and therefore was able to be portioned and delivered to instrument.
- *Sample contamination* The wt% of delivered sample that was foreign material (either from previous samples or wear products coming from system hardware elements).

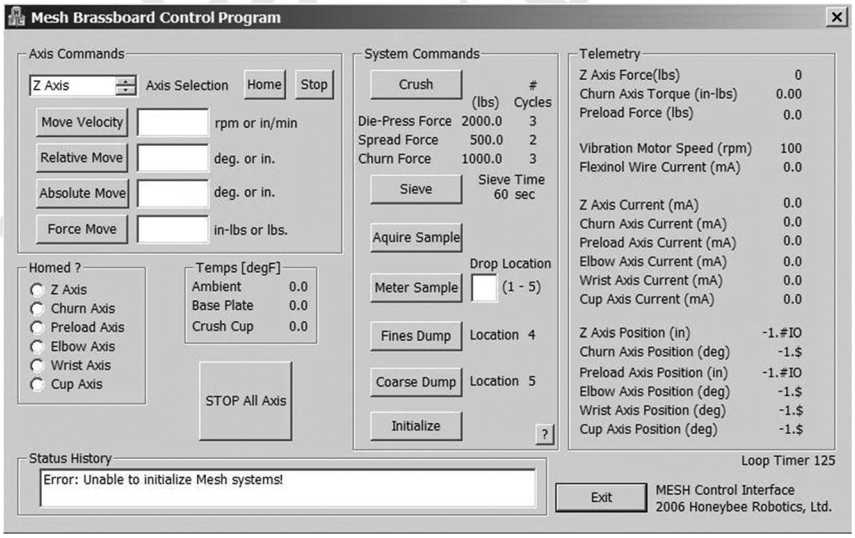


Figure 7.52 Graphical user interface o MeSH control software.

Table 7.11 Summary of rocks physical properties.

Rock	Type	UCS (MPa)	BTS (MPa)	CAI (MPa)	HR (MPa)
Saddleback Basalt	lgneous	89–119	6.9–7.9	4.9–5.1	37.8–42.9
Belleville-1 Basalt	lgneous	217–269	11.2–16.8	5.2–5.7	51.2–58.3
Belleville-2 Basalt	lgneous	116–128	10.8–13.3	5.0–5.2	44.1–49.2
Kaolinite	Sedimentary	2.0	0.1–0.2	1.1–1.3	44.1–49.2

Courtesy NASA/JPL and Colorado School of Mines.

- *Sampling bias* How representative the "prepared" sample of the base rock or material from which it came is from a chemistry/mineralogy perspective.

7.11.3.4.1 **Rock Samples** All tests were performed using either Saddleback basalt (JPL provided, ~90–120 MPa) or Bellville-1 basalt (JPL provided, ~220–270 MPa. Table 7.11 shows rock physical property data for these basalts.

7.11.3.4.2 **Test Setup** Most of the testing was performed on the bench. The MeSH system prototype was placed in a "dry-box" for the purpose of controlling humidity (Figure 7.53). The "dry-box" had trays of desiccant that maintained a humidity level of 20% or less. Several tests were performed in a thermal vacuum chamber where the atmosphere was maintained at ~6 Torr and >90% CO_2.

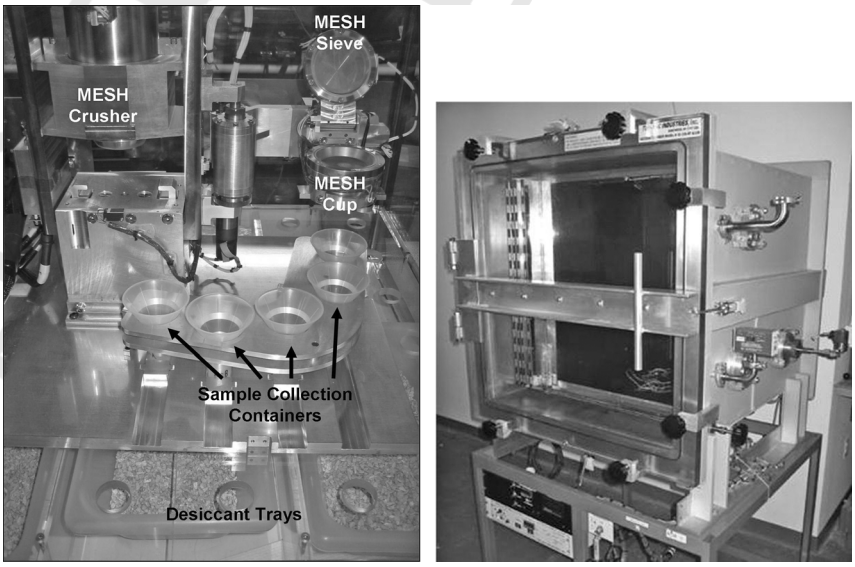


Figure 7.53 Prototype of the MeSH system inside a dry-box (a) and thermal vacuum chamber used for testing under Mars-like conditions (b).

page proof
EYE ICH

7.11.3.4.3 **Basic Crushing Performance Test** Tests were performed to verify the force required initially to crush Saddleback basalt cores and to characterize the yield of a single crushing cycle. It was confirmed that 3–4 kN (670–900 lb) is required to fracture initially an 8 mm diameter core with a mass of 3–5 g. Full compaction, defined as when the 8 kN down-force limit was exceeded, was achieved at roughly one-quarter to half of the core diameter under constant force. A single crushing cycle took 15 min, consumed 0.45 W h (average 2.1 W, peak 8.8 W) and typically yielded 25 wt% fines less than 150 μm.

7.11.3.4.4 **Basic Sieving Performance Test** It was important to understand the sieving efficiency as a function of mass and sieving energy, since it drastically affected the yield and subsequent crushing cycles. Tests were performed using various core sizes and periodically measuring the sieve throughput in the context of a single crush–sieve cycle (Figure 7.54). In other words, the material on the sieve was created by the crusher over the course of a single crushing cycle and therefore had a relevant particle size distribution to start with.

After the single crushing cycle and 4 min sieving operation, the following results were obtained:

- 2.3 g core yielded 1.22 g <150 μm fines (0.85 g through the sieve)
- 4.7 g core yielded 1.22 g <150 μm fines (1.08 g through the sieve).

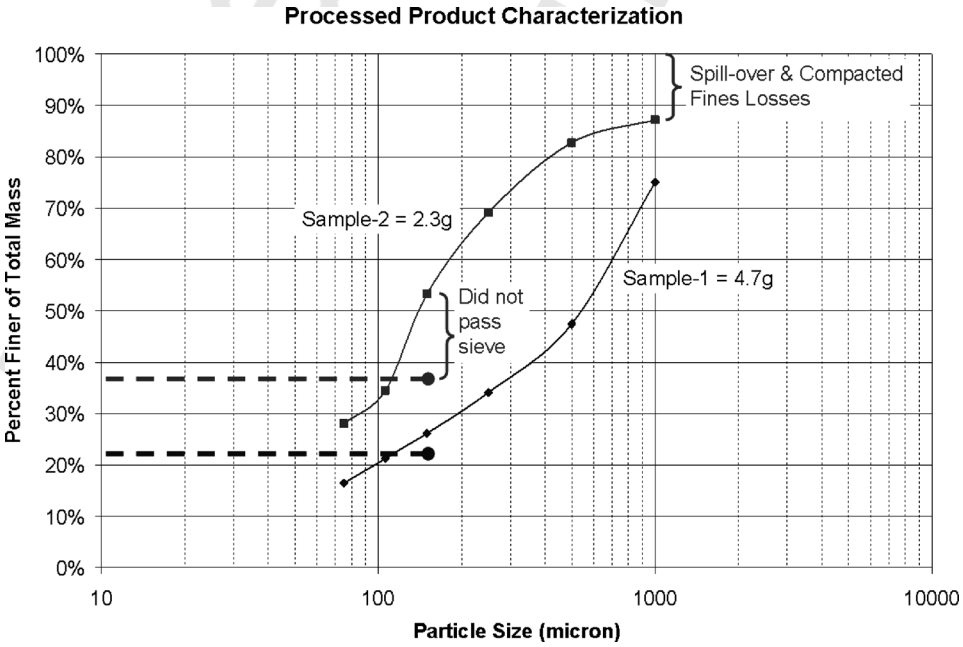


Figure 7.54 Crushed product created by single crushing cycle. The rock used was Saddleback basalt.

Recall that the density of basalt fines is approximately 1 g cm^{-3} and that the sample analysis at Mars (SAM) instrument (which will analyze organics and gases) on board the 2009 Mars Science Laboratory (MSL) Rover requires ~0.15 cm^3 and the Chemistry and Mineralogy (CheMin) XRD/XRF instrument (which will quantify minerals and mineral structures) requires ~0.05 cm^3.

For both cases (2.3 and 4.7 g core), a substantial amount of the <150 μm fines passed through the sieve within the first minute of sieving operation – 41% (0.51 g) and 73% (0.89 g), respectively. Continuing the sieving operation for an additional 3 min (for a total of 4 min) resulted in an average sieve throughput rate of 107 mg min^{-1} in the case of the 2.3 g core and 78 mg min^{-1} in the case of the 4.7 g core.

Based on these results, it was decided that duration of 10 min would be used for sieving operations for all subsequent tests.

7.11.3.4.5 **Environmental Test** Tests were performed to understand variations in baseline performance due to effects of the Mars environment. Three tests were performed in a thermal vacuum chamber (6 Torr, >90% CO_2, −40 °C) using Saddleback basalt cores 8 mm in diameter and 2 cm long. Multi-cycle tests (five cycles) were run.

Crushing and churning (milling) remained effective in reducing particle size at low pressure and temperature. Sieving at reduced temperature/pressure proved problematic; significant clumping and sticking of particles to sieving screen are the suspected culprit (see Figure 7.55).

7.11.3.4.6 **Significant Findings** The test program yielded many interesting and significant results. Perhaps the most interesting results were related to system yield, which is a product of comminution and sieving performance. Given the design of this system, the efficiencies of the comminution and sieving steps were interrelated as described below.

Comminution Capacity The amount of force to fracture a rock core of "fixed" length lying on its side scales linearly with compressive strength and mass:

- For a 3–5 g, 8 mm Saddleback basalt core (90–120 MPa), a compression force of 3–4 kN was required to cause initial fracture prior to milling.

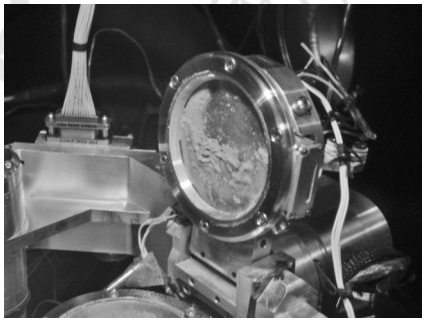


Figure 7.55 Example of a sieve clogging in Mars chamber. The rock used was Saddleback basalt.

page proof WILEY-VCH

- For a 6–7 g, 12 mm Saddleback basalt core (90–120 MPa), a compression force of 6–7 kN was required to cause initial fracture prior to milling.
- For a 2–3 g, 8 mm Belleville-1 basalt core (220–270 MPa), a compression force of 5–9 + kN was required to cause initial fracture prior to milling.

It is easy to imagine a scenario where the crushing capacity of is quickly exceeded if too much material is fed into the crushing stage. Given that the system was sized to supply peak compressive loads of 26.7 kN, feeding more than 7–10 g of Belleville-1 basalt into this system is not recommended – this corresponds to 2.5–3.6 cm^3 of core assuming an average density of 2.75 g cm^{-3} –or, in other words, 3.2–4.6 cm of 1 cm diameter core.

An interesting observation was noted during the tests involving the stronger Belleville-1 basalt. The force limit of 8.9 kN was not sufficient to fracture the core initially in two of the three cases; however, because the compression stage was not back-drivable, very high stresses in the core were produced during the churning cycle, which ultimately fractured the core and allowed the overall comminution sequence to execute successfully.

Comminution Power and Specific Energy For a 3–5 g, 8 mm Saddleback basalt core (90–120 MPa), a single crushing cycle took 15 min and consumed 0.45 W h at an average power of 2.1 W and a peak power of 8.8 W. Typically, five crushing cycles were required to reduce more than 60–70 wt% of the solid rock to <150 μm fines (this represents performance without any manual intervention between crushing cycles, and the comminution efficiency would improve as more fines were removed from the particle bed, as discussed below). However, one way of looking at this is that it takes 2.25 W h to reduce ~2.6 g of Saddleback basalt to <150 μm fines or 0.87 W h g^{-1} <150 μm.

Comminution and Sieving Efficiency and Interdependence Recall that the system is designed to work the material in the following fashion: crush and mill → sieve → crush and mill some more → sieve some more → etc.

For a 3–5 g, 8 mm basalt core, approximately 15–20 wt% will be reduced to <150 μm fines during each crush–mill–sieve cycle, assuming that the sieving process is some what effective at removing fines from particle bed. If fines are not removed, they insulate or isolate the larger particles from the stresses required to reduce their size further. Therefore, comminution rates drop as the sieving efficacy drops (i.e., the particle bed contains too many fines).

On the other hand, for a given sieve vibration power level, the sieving efficacy is affected by the mass of material sitting on the sieve. More mass on the sieve reduces the particle motion and slows the sorting process. This in turn slows comminution as described above.

The overall lesson is that the comminution and sieving rate is a function of the input mass. As the mass decreases, the comminution and sieving rate will accelerate. Therefore, the minimum comminution and sieving rate should be verified at the largest input mass.

Page proof WILEY VCH

Sample Contamination Recall that aside from vibration, there are no other cleaning methods (e.g., brushes) currently employed by the brassboard. For a 3–5 g, 8 mm Saddleback basalt core, as much as 4–7% (∼200 mg) of the mass remains in the form of residue in the crushing container and the fines container. The residual mass tends to hold steady (does not accumulate) across sample runs, implying that residue is probably replaced at some rate with new matter. This replacement rate is not known.

Very little wear of the steel platens (CPM 10V, HRC 63) has been observed after crushing over 100 g of basalt cores. This implies very little contamination by wear products. Again, we cannot say whether the minute amounts of steel transferred to the fine sample would be observable by relevant instruments analyzing the sample.

7.12 Operational Platforms

Space agencies have employed numerous interplanetary robotic spacecraft, planetary probes, surface landers, and rovers to collect the substantial amount of data contributing to our current understanding of the solar system. Destinations visited include nearly all of the planets in the solar system, and also asteroids and comets. The use of robotic technology in space has reached a maturity such that multiple robotic spacecraft are operating at any given time throughout the solar system. At Mars alone, multiple robotic spacecraft – including satellites, landers, and rovers – are in operation today performing scientific missions aimed at understanding the past or present habitability of that planet. The most recent orbiting spacecraft that are still in operation at Mars were delivered by NASA and the European Space Agency (ESA) and include Mars Odyssey, Mars Reconnaissance Orbiter, and Mars Express. The most recent rovers that are still in operation are NASA's twin Mars Exploration Rovers (MERs), Spirit and Opportunity, which have been operating at different locations on the Martian surface since 2004. They have both collected data that lead scientists to conclude that liquid water once flowed on the surface of Mars in the regions where they were landed. The NASA Phoenix Mars Lander destined for the Martian arctic arrived in mid-2008.

Many of the platforms employed for robotic space exploration today and into the future are designed for *in situ* operations. They build on the successes of earlier reconnaissance spacecraft that performed fly-by and orbiting missions throughout the solar system. Subsequent missions of today aim to acquire successively more scientific knowledge by delivering instrumented platforms into planetary atmospheres and/or on to the surfaces of planets, moons, and small bodies. A small set of recent and planned missions seek to go a step further to acquire and analyze physical samples of material *in situ* and some seek to return collected samples to Earth for analysis in comprehensive laboratories. Here we focus on systems for contact sampling of terrestrial material from stationary and mobile platforms on or near solar system body surfaces.

page proof WILEY-VCH

7.12.1 Stationary Platforms

7.12.1.1 Landers

Spacecraft landers deliver operational platforms to the surface of solar system bodies. The landers perform atmospheric entry and descent toward the surface, followed by safe touchdown at the intended landing site. Typically, lander deceleration is passively facilitated by atmospheric drag (on planets such as Mars or Venus that have atmosphere) and/or actively achieved using parachutes and rocket motors. So-called "soft" landers utilize deceleration by structural legs on lander platforms. The legs also serve to establish an upright posture on the surface. This approach was successfully used by the Viking Landers sent to Mars in the 1970s and by the Phoenix Mars Lander that arrived at Mars in 2008. Also in the 1970s, the NASA Apollo astronauts landed the Lunar Module in a similar fashion. Alternative landing approaches are also possible. One such approach that has proven successful several times at Mars employed airbags to cushion the impact with the surface after lander deceleration through the atmosphere. Inflated airbags cushioned the lander and its payload as it bounced on the surface. After coming to rest, the airbags deflated and retracted to expose the lander. Each successful attempt to date of using airbags has delivered a rover payload to the Martian surface. These missions include the Mars Pathfinder (MPF) rover Sojourner in 1997 and the twin MER rovers Spirit and Opportunity.

Robotic landers that do not carry mobile surface systems as payloads are intended to conduct missions while their platforms remain stationary at their final touchdown location. Their payloads typically include a suite of *in situ* and remote sensing science instruments and they are often equipped with robotic mechanisms or appendages for placing instruments on a surface or sample acquisition from a surface in the reachable vicinity of the lander. This was the case for the Viking and Phoenix landers, all of which were equipped with multi-linked robotic arms (RAs)and scoop end-effectors for surface sampling. Robotic landers that do carry mobile surface systems as payloads remain stationary on the surface while the rover egresses to explore the surface environment within its traverse range. Depending on the mission architecture and design, the lander may remain an integral part of the surface mission via lander-mounted instruments and equipment.

7.12.2 Mobile Platforms

Mobile operational platforms take on a variety of configurations and purposes typically governed by their specific missions and target environments. They enable mobility and instrument transport to environments where science data may be acquired – be it on, above, or below the surface of solar system bodies. Several prevalent types of mobile operational platforms are discussed below.

page proof

7.12.2.1 Rovers

Generally, a rover refers to a mobile robot that is capable of moving about on natural terrain surfaces. Thus far, rovers have been the most popular solution for planetary surface mobility. Although all rovers that have been operated on space flight missions to date have employed wheels for locomotion, tracked and legged locomotion systems are viable alternatives for some applications and can offer certain advantages in very rough or steep terrain. Unlike lander legs, which remain stationary once deployed, rover legs provide a walking capability as an alternative surface mobility mode for transporting science payloads and sampling systems. To date, rovers have proven most useful for accessing science targets on surfaces of moderate slope and roughness and within local surface regions of tens of square kilometers.

7.12.2.2 Airships

Robotic realizations of aerial vehicles such as controllable airships (balloons, blimps, or dirigibles), would be capable of accessing science targets from above at different altitudes, in varied terrain types, distributed across many square kilometers and potentially on a global scale. Such "aerobots" would operate within atmospheres of planets and moons facilitated by buoyancy, winds, and active control of flight altitude and lateral drift. Aerobots could serve as surface sample acquisition platforms when equipped with appropriate sampling mechanism delivery systems and altitude control of surface approach and near-surface hover. Science destinations of current primary interest include planets Mars and Venus, and also Titan, Saturn's planet-like moon.

7.12.2.3 Small-Body Spacecraft

Deep-space probes can also serve as operations platforms for sample acquisition systems that are meant to acquire samples from small, airless bodies in space. They can serve as a means to access samples from the asteroid belt, some planetary moons, and Kuiper Belt Objects in our solar system. A challenging aspect of their application on such missions is safe operations in proximity to a small body and in its typically very low gravitational field. Particularly challenging is the task of imparting forces on the small body for the purpose of collecting a sample. Feasible solutions have been proposed and developed that span a range of complexity. Some include sampling mechanisms deployed by booms so that the sampling activity could be attempted with the spacecraft at a safe stand-off distance (conceptually similar to sampling from airships). Other approaches call for spacecraft contact with the body at much closer proximity and with greater forces, the use of projectiles, harpoons, and/or tethers, and also landing on and even traversing a small body surface. For example, hopping robots have been proposed for surface mobility in low-gravity environments where hopping forces can be achieved by exerting low reaction forces against the surface. A major challenge in the context of using hopping robots for sampling operations is achieving the positioning control needed to hop to specific designated locations from which samples are desired. Although this remains a research problem, hopping robots have been designed for flight missions to the Mars moon Phobos by Russia in the late 1980s and to asteroid Itokawa by JAXA in the early 2000s. They were intended

page proof WILEY-VCH

to perform scientific measurements rather than acquire samples. In the case of the Phobos mission, the spacecraft carrying the hopper robot failed due to computer malfunction before the phase of the mission in which the hopper was to be deployed. In the case of Itokawa, deployment of the robot to the asteroid surface was unsuccessful.

7.12.2.4 Other Concepts

The solar system exploration agenda for the world's space agencies also includes plans to access and sample the subsurface environments of terrestrial planets, moons, and small bodies. Near-term focus is on the Moon, Mars, and the ice-covered surface of Jupiter's moon Europa, below which is presumed to be an ocean of water. The subsurface of Mars is of interest because it is believed to be the only place on the planet in which liquid water potentially exists and because its sedimentary rock layers are believed to contain information about the geological, hydrological, and climatic evolution of the planet and also any signs of extinct life. Purported subsurface water-ice on the moon and Mars is also considered a critical resource for sustaining robotic outposts and future human explorers. A variety of techniques will be required for subsurface sample acquisition in these varied environments.

Hence there is significant focus on ways and means to drill and bore into the surfaces of these bodies to depths beyond what may be capable from rover platforms. A number of robotic prototypes for planetary subsurface drills and moles are under development within the space robotics community. Some are being tested in deep drilling field experiments at Mars analogue sites on Earth. Other subsurface mole-type prototypes for lunar and Mars applications are being proposed and improved by active research and technology development programs. Of note is the fact that some designs are only intended to access the subsurface for *in situ* scientific measurements (as necessitated by certain scientific objectives) whereas others are intended for subsurface sample acquisition and retrieval and/or processing for analysis. There are many challenges to overcome for automation and robotics. Most challenges being addressed currently relate to understanding the physics and mechanical system requirements for drilling into consolidated and unconsolidated materials comprised of soil, rock, and/or ice to both shallow and great depths. A recent literature review covering key issues, technologies, and methods for lunar and Mars mining elaborated on the key challenges of subsurface drilling (Satish, Radziszewski and Ouellet, 2005).

Mobility systems for *in situ* scientific data acquisition and sampling are equipped with robotic mechanisms that carry instruments or interact physically with the target environment through force-controlled contact and/or manipulation. The mobile platforms serve the purpose of moving the reachable workspace of such mechanisms within reach of science targets and samples. Typical mechanisms range from one degree of freedom (DOF) boom-like appendages to multi-degrees of freedom open-chain linkages, or arms, for reaching positions of interest. When mounted at the end of such mechanisms, tools and instruments can be placed against or in proximity to samples of interest. Other types of mechanisms, or end-effectors, for applying mechanical action at positions of interest can range from simple open–close grippers

to dexterous anthropomorphic hands. Robot manipulator arms and mechanisms affixed to mobile platforms typically utilize computer vision-based perception, proximity sensors, and force/torque sensors to achieve gross and fine manipulation. Dexterity for the latter is often enabled by additional mechanical degrees of freedom and/or advanced automatic control techniques.

7.13 Appendages

7.13.1 Manipulators

The manipulator provides essential support to other platform-mounted scientific instruments and also conducting arm-specific soil mechanics experiments. The kinematic configuration of manipulators for planetary sample acquisition is driven by characteristics of the tools to be attached, mounting location, cost, and weight of the manipulator.

The type of task a manipulator is to perform largely defines its kinematic configuration. The robotics literature classifies manipulators into several criteria (SPONG), including geometry (or kinematic configuration), type of application for which they were designed, and manner in which they are controlled. Here we will adopt the geometric classification criteria to be consistent with the robotics literature (SPONG). The type of joints used in the first three joints usually determines the geometric classification of a manipulator. The wrist is usually described separately. The most commonly used joints in a general-purpose manipulator include *revolute* (R) and *prismatic* (P). With these criteria, most of the existing manipulators can be classified into four different types (SPONG): *articulated* (RRR), *spherical* (RRP), *cylindrical* (RPP), or *Cartesian* (PPP).

The kinematic configuration used for planetary manipulators typically belongs to the articulated class. This configuration provides for relatively large freedom of movement in a compact space (a much needed characteristic to be able to stow the manipulator in the tight space of its launch restraints). The articulated manipulator design for this class of special-purpose manipulators belongs to the *elbow* type. In this configuration, joint axis z_2 is parallel to joint axis z_1. Both joints are perpendicular to joint axis z_0. An example of an elbow manipulator is shown in Figure 7.56 and its workspace is shown in Figure 7.57.

The wrist in most planetary manipulators is mounted at the end of the forearm with a revolute joint. The axis z_3 of this joint is parallel to axis z_2. The instruments are mounted on the end-effector, which is mounted on the wrist. The design of the end-effector is task dependent. For example, the end-effector of a manipulator designed to dig trenches will be a scoop attached at the wrist to create the backhoe configuration. This is the design used in past robotic designs including the Mars Polar Lander, Moonrise and most recently Phoenix. Mounting a number of instruments is accomplished by designing the end-effector as an articulated turret.

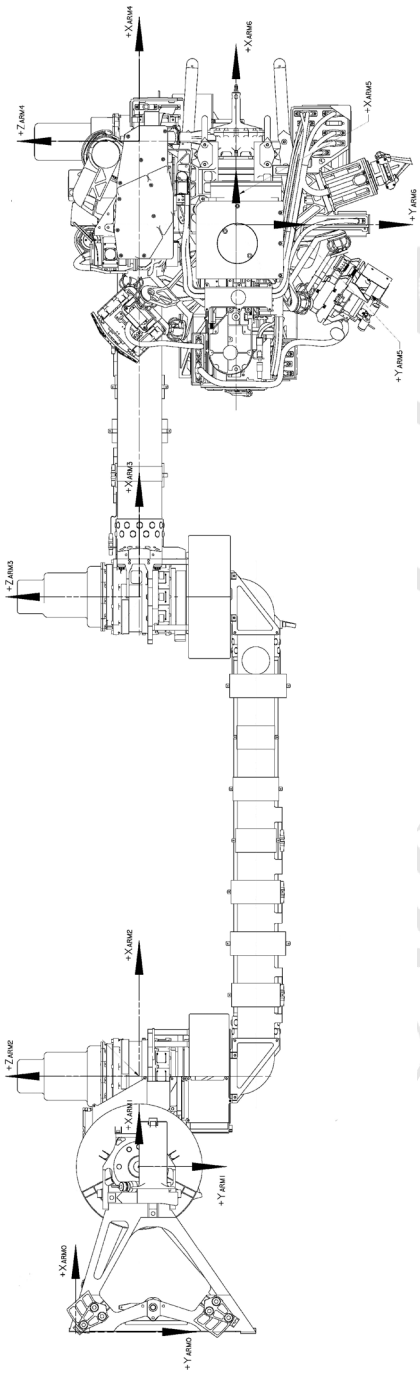


Figure 7.56 Example of the elbow manipulator. Courtesy JPL/Caltech/NASA.

WILEY-VCH Proof

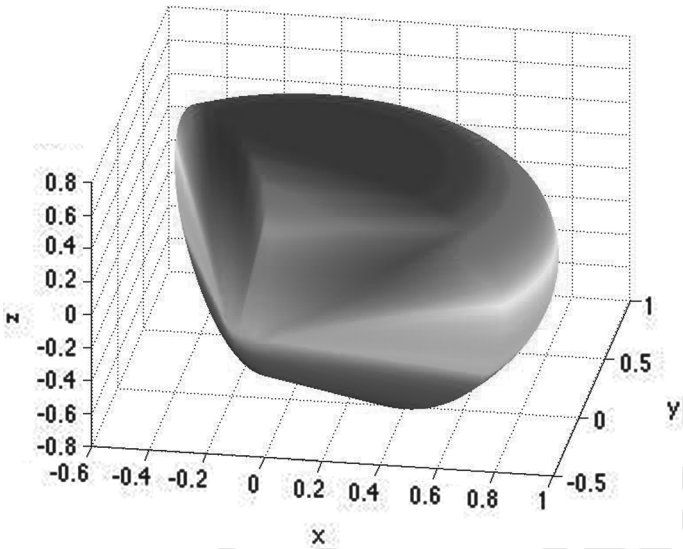


Figure 7.57 Workspace of the elbow manipulator. Courtesy JPL/Caltech/NASA. (Please find a color version of this figure on the color plates).

The joint axis of the turret (z_4) is perpendicular to axis z_3 therefore parallel to axis z_1. This provides azimuthal motion for the turret and the ability to interchange tools if multiple tools are mounted in the turret. An example of this design is used in the manipulator for Spirit and Opportunity rovers and also the manipulator for the MSL.

Recent planetary missions have flown robotic manipulators to allow collection of samples. Figure 7.58 shows the historical context of recent planetary manipulators. Some of their properties are shown in Table 7.12.

The Phoenix RA is a four degrees of freedom manipulator with a backhoe design providing motion about shoulder yaw (azimuth) and shoulder, elbow, and wrist pitch (Bonitz, 1997). The arm links are made of a low-mass graphite–epoxy composite. The end-effector consists of the following tools: a scoop for digging and soil sample acquisition, ripper tines for preparing hard soils, secondary blades for scraping, and the soil temperature probe. In addition, there are two tools that are not part of the end-effector: the RA camera, mounted near the end of the forearm, and the ***RA*** air temperature sensor, mounted above the elbow.

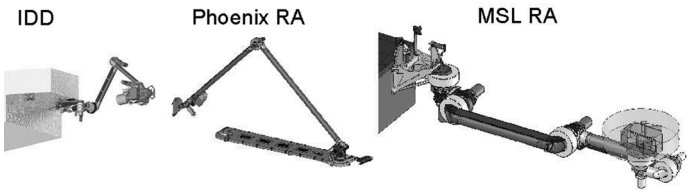


Figure 7.58 Planetary robotic arm historical context. Courtesy JPL/Caltech/NASA.

Table 7.12 Planetary robotic arm historical context.

	MER IDD	Phoenix RA	MSL RA
Length (m)	0.75	2.4	1.75
DOF	5	4	5
Turret mass (kg)	2	1	15
Actuator mass (kg)	2.25	3.5	21
Total mass (kg)	4.25	8.9	>50
Required tip force (N)	10	40	300
Life (sols)	90	90	669

The MER instrument deployment device (IDD) is a 5-DOF manipulator depicted in Figure 7.59. The IDD is mounted on the underside of the rover's warm electronics box. The IDD carries a suite of *in situ* instruments on its end-effector. The instruments are the Mössbauer spectrometer (MB), the alpha particle X-ray spectrometer (APXS), the MI, and the rock abrasion tool (RAT). The primary function of the IDD is to place the instruments on targets (rocks, soil, magnets, and the CCT) for collection of scientific data. A 5-DOF manipulator has the disadvantage that the final orientation of the instrument (instrument twist) to be placed on a target is not controlled. Figure 7.60 shows the MER IDD and Phoenix RA side-by-side for reference.

The MSL RA is a 5-DOF manipulator depicted in Figure 7.61. Its kinematic configuration is similar to that of the MER IDD; however, the MSL RA has an

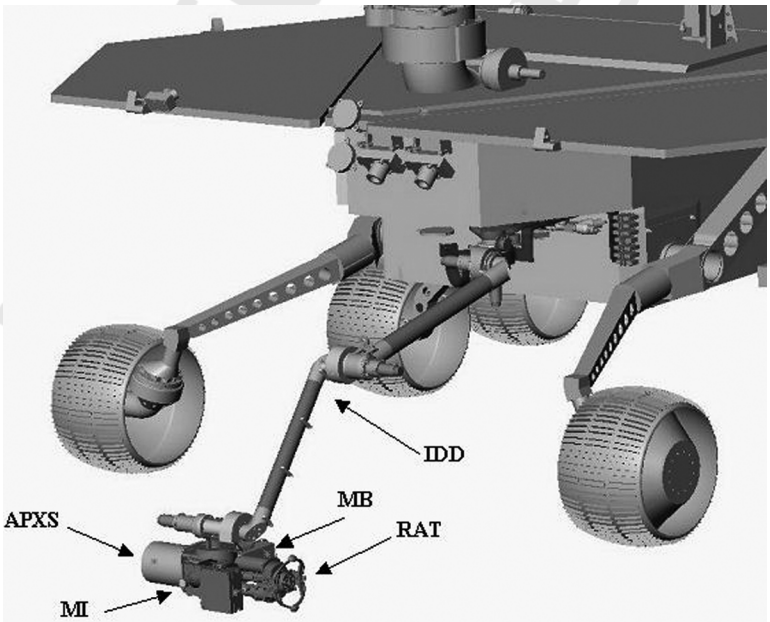


Figure 7.59 MER IDD. Courtesy JPL/Caltech/NASA.

Figure 7.60 MER IDD and Phoenix robotic arm. Courtesy JPL/Caltech/NASA.

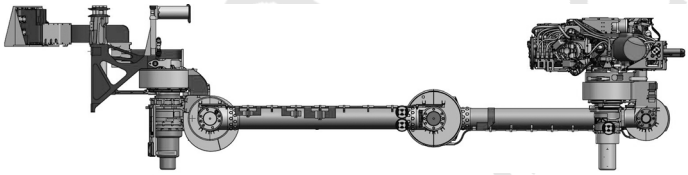


Figure 7.61 MSL manipulator arm. Courtesy JPL/Caltech/NASA.

order-of-magnitude higher payload and an order-of-magnitude higher tip force than any of the preceding manipulators. The MSL RA carries a suite of *in situ* instruments on its end-effector. The instruments are the powder acquisition drill system (PADS), the surface removal tool (SRT), the APXS, the Mars hand lens imager (MAHLI) and the Collection and Handling for *In Situ* Martian Rock Analysis (CHIMRA).

7.14 Sample Acquisition from Surface Platforms

7.14.1 Terrain Sensing Techniques

7.14.1.1 Tactile

Terrain sensing via tactile feedback (Diaz-Calderon, Backes and Bonitz, 2007) permits sample acquisition when (1) communication to Earth is not possible, (2) it would increase the mission costs, or (3) it would incur unacceptable operations timeline delays. Tactile feedback can be achieved via contact sensors and/or force–torque sensors located in the manipulator. Using motor current readings can reduce or eliminate the need for dedicated force-feedback sensors.

When the end-effector of the manipulator is in contact with the environment, it is applying a force, F, on the environment. This force can be mapped to motor torques, τ, via the manipulator Jacobian:

$$\tau = J^T F \tag{7.3}$$

Applied motor torque can be mapped into motor current by means of the *motor torque constant*, κ_m, which relates motor current, i, to the output torque:

$$\tau_m = \kappa_m \, i \tag{7.4}$$

A contact detection algorithm that utilizes joint current inputs needs to be able to robustly identify changes in motor currents that are the result of increased applied force at the end-effector. This can be achieved by using a cascaded filter system utilizing two linear-phase low-pass finite impulse response filters (Equation 7.5). This provides a smooth motor current signal. The combination of the filters provided a reference signal (σ_1) and a delayed signal (σ_2). Contact can be detected by comparing the magnitude of the difference between the two signals, $\delta\sigma$, against a threshold:

$$y(n) = \sum_{m=0}^{N-1} h(m)\, x(n-m) \tag{7.5}$$

7.14.1.2 Vision-Based Terrain Sensing

Although some sample acquisition may not require visual sensing of terrain, which can be expensive in terms of computation, communication bandwidth, or both, there are many factors that can make the use of machine vision appropriate for sample acquisition. Here we take the MER (Squyres *et al.*, 2003; Baumgartner *et al.*, 2005) as a starting point for the process of instrument and tool placement, as it illustrates many of the essential points. From a scientific perspective, the choice of sample may be important, particularly when the body being sampled is heterogeneous or has seen enough prior investigation that untargeted samplings are of limited benefit relative to the cost of the mission. Multispectral imaging can permit some discrimination of different target materials, although it can be hampered when surfaces are not free from dust. The PanCam and Mini-TES instruments on the MER were the primary means of choosing targets for *in situ* investigation, which often required several days to complete. Autonomous target selection may be the only option if the time available for the entire sampling/instrument placement phase of a mission is shorter than the round-trip communication latency or approaches the expected lifetime of the mission (as was the case for the Soviet Venera landers). Autonomy may be acceptable when the cost of an autonomous sampling or *in situ* investigation is relatively low and opportunistic targets are feasible, but if significant time and energy, or a limited resource such as drill bit life, must be expended, then a human-in-the-loop model is appropriate.

Apart from informed target selection, visual sensing is also useful for ensuring safe instrument placement. Sampling mechanisms for landed planetary missions, where there is high design pressure to reduce mass, may not be able to afford the

Page proof WILEY-VCH

same structural factors of safety as microgravity or terrestrial mechanisms and therefore may be more easily damaged due to inadvertent contact with terrain or other parts of the spacecraft, or overload conditions during intended contact. The 5-DOF instrument deployment device on the MER rovers had a mass of 4 kg (with nearly 1 kg being cabling), while carrying scientific instruments weighing 2 kg. This led to an arm that was easily capable of damaging itself in certain configurations, unlike terrestrial manipulators that can be designed with withstand any force condition that its actuators can create. In this case, visual sensing was required not just for accurate placement of instruments, but also for assessing target suitability from a spacecraft safety perspective.

Unlike target selection, which can be done largely with monoscopic, although multispectral, images, vision sensing for instrument placement can require three-dimensional reconstruction of the terrain in order to determine surface location, orientation, and roughness (Leger, Deen and Bonitz, 2005), and also to detect potential collisions. MER's 12-bit, 1024×1024 grayscale engineering cameras (Maki *et al.*, 2003) are well suited for this, with lens selection appropriate to give enough visual surface texture for stereo correlation, although other scanned or flash lidar may also be feasible – the two key requirements are accuracy and density of measurements for surface reconstruction.

Determination of surface position is the first and most direct step in analyzing surface geometry for instrument placement. As instrument placement involves not just position but orientation, which must also be determined: *in situ* and sampling instruments may have a preference for being placed with their tool axes perpendicular to the surface to ensure good contact for high-force operations such as drilling or grinding or, for *in situ* instruments, to minimize the distance between the sensor and the surface, to maximize resolution of images, or improve the signal-to-noise ratio for spectrometers. Surface orientation may be less important for scooping mechanisms dealing with regolith. Another driver for determining surface orientation is that contact-sensing mechanisms may only work reliably over a limited range of contact angles ($\pm 15^\circ$ in the case of the MER contact sensors). Local plane fitting is a standard and obvious choice for determining surface orientation. For sampling applications, the spherical volume in which data are considered for the plane fit at each point on the surface should have a radius equal to that of the contact face of the tool or instrument being placed.

Surface roughness may also be relevant on multiple length scales. At a fine scale, a surface may have protrusions that would contact delicate parts of an instrument or tool before the contact sensors reach the surface. This is exacerbated by contact sensor designs that have widely spaced contacting features (which thus allow more room for protrusions between them), and minimized by contact sensors that cover most of the area of the tool face. At a slightly larger scale, surface roughness must be considered as it relates to placement accuracy. Since there is some amount of positional uncertainty in a tool placement, the surface normal over the range of possible contact points must be considered for any individual placement. If the surface normal varies more over this region than the allowable tool-to-surface angular misalignment, then positional error may lead to an unsafe placement.

Finally, surface roughness on a larger scale must be considered from a collision perspective. Concave regions, such as those between rocks or near the base of a rock as it rests on the terrain below it, or in trenches or holes created by the sampling system itself, increase the risk of collisions between the sampling mechanism and the terrain. With multiple space-rated tools and instruments on an end-effector, it is difficult to provide enough structural protection to prevent damage from all forces that can be generated from unintended contact. Three-dimensional machine vision is essential for safeguarding the sampling mechanism against collisions, whether the system is autonomous or is being operated with a human in the loop. MER's Rover Sequencing and Visualization Program (RSVP) software was used by operators to visualize instrument placements on a terrain model reconstructed by stereo vision (Wright *et al.*, 2005). This method was used for most of the MER instrument placements. The rover's flight software was later enhanced to permit autonomous instrument placement (Hayati *et al.*, 2007), which included all of the steps mentioned above (surface reconstruction, surface normal and roughness estimation) and also on-board reachability analysis and manipulator collision detection using an octree-based terrain model, and an articulated model of the manipulator (Figure 7.62). A key part of building the terrain model was explicit modeling of 3D regions in which there were no data which confirmed that the space was free or occupied: rather than regarding volumes as safe until seen to be dangerous, the algorithm regarded volumes as dangerous until confirmed to be safe. This algorithm was based on the premise that lines from both stereo cameras to each sensed point on the surface were known to be free of obstructions; thus, any voxel in the octree that was not intersected by a ray from the camera to a triangulated surface point must be treated as an obstacle, since it is not safe to move a mechanism through a region that has not been seen. For example, only the surface of a rock facing the camera is visible, but it is not safe to move a mechanism behind that surface (yet without touching the surface itself) – the unseen volume behind the surface must be treated as an obstacle. As another example, stereo reconstruction may fail over a portion of the image because a rock is so close to one or both cameras that it cannot be correlated. It would obviously be

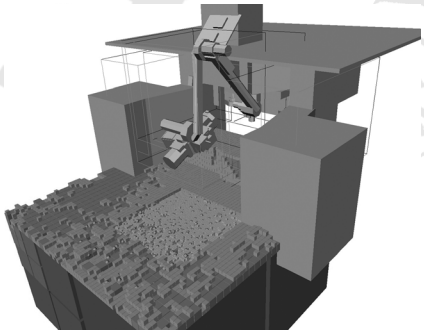


Figure 7.62 On-board collision models of MER arm, rover, and terrain from autonomous instrument placement on Opportunity rover, sol 1069. Courtesy JPL/Caltech/NASA.

hazardous to regard a lack of sensed obstacles as evidence that the workspace is safe. Human operators can sometimes compensate for some lack of correlation or other dropouts in range data by using the appearance of the surface in an image – for example, if stereo correlation is unreliable on a sand dune, or if lack of shadows and lighting variation make it obvious that a surface is flat. However, this is more difficult to do in an autonomous system, which must therefore be made more conservative.

One additional use for visual sensing in sampling operations is to document the sampling activities. Imaging the tool in contact with the surface, and imaging the surface after sample acquisition, inform subsequent scientific analysis of the samples (particularly when dealing with heterogeneous targets). Documentation imagery is also vital for understanding mechanism history and state to aid in fault recovery.

7.15
Sample Acquisition from Aerial Platforms

In addition to solutions and systems for acquiring samples from platforms that are resident on planetary surfaces, engineers and scientists are actively conceiving systems that permit sample acquisition from spacecraft and planetary aerial platforms. Missions to explore and return samples from the surfaces of small bodies in the solar system such as asteroids and comets have driven the approaches and designs proposed to date. Key characteristics of these bodies are that they do not have atmospheres and have very low and variable gravitational fields due to their typically small sizes and irregular shapes relative to planets and moons of planets. Studied to a lesser extent – but of increased recent interest – is the development of approaches and designs for systems that enable airborne platforms to acquire samples from surfaces of planets and moons that have atmospheres. In these cases, most attention has been paid to planets and moons at which surface mobility is difficult to achieve with today's technology but which are of high scientific interest.

Here we discuss a representative set of sampling approaches and systems proposed for non-landed sample acquisition. The emphasis is on systems that would perform surface contact sampling as the primary means to acquire surface samples. It should be noted that the scientific community also has strong interest in non-surface samples of substances throughout the solar system from planetary atmospheric constituents to solar wind and interstellar dust. Solar wind samples and cometary and interstellar dust particle samples have already been acquired (through in-flight, non-contact means) and returned to Earth by the NASA Genesis mission in 2004 and the NASA Stardust mission in 2006, respectively.

Future missions of current scientific priority call for *in situ* sampling at, and/or sample returns from, comet and asteroid surfaces. Viable approaches to acquiring various samples are discussed below with mention of representative prototypes or flight hardware that have been proposed or flown on missions to date. In the case of small bodies and airless moons, concepts of operation typically include extensive prior mapping and remote sensing for surface, shape, and gravity characterization.

page proof © WILEY-VCH

These activities permit sample site selection, which is followed by higher resolution mapping of the sampling site before attempts to descend for surface sampling operations. Safe and controlled descent is typically aided by some combination or subset of imagers, laser rangers, radars, and contact sensors. These prior mission operations activities are not discussed in our focus on the approaches and tools for sampling.

7.15.1 Small-Body Sampling from Spacecraft

Small-body sampling mechanisms are typically required to operate over a broad range of design constraints, since the relevant properties of target small bodies are rarely known a priori. Their surface properties can range from talcum power consistencies to ice or hard rock. To ensure sample integrity, sample mechanisms also must be designed to minimize contamination or alteration of the collected sample. These design challenges are compounded by the difficulty of acquiring samples in microgravity domains by means of mechanical force against the small body. A variety of mechanisms and approaches have been proposed to address some of these challenges for asteroid and comet sampling. We describe some of them below in rough order of required proximity to the small-body surface.

Comet nucleus sample return missions may involve an impactor that penetrates the comet surface, captures and encapsulates a core sample, and spring-ejects a sample capsule for retrieval by its host spacecraft (Lorenz, Boynton and Turner, 2006). This approach avoids the close approach, hover, or momentary landing required by other spacecraft impact sampling approaches. This is not without that trade for additional functionality for rendezvous and capture needed to retrieve the sample canister for return to Earth. The actual sampling mechanism proposed for this solution is a coring penetrator. It operates by cutting a cylindrical core in the comet surface material assisted by kinetic energy delivered during the impact. An advantage of its design is that it would preserve vertical stratigraphy of the encapsulated sample, a desirable capability that can enable more scientific information to be gleaned from comet samples that are particulate mixtures containing volatiles. Details of the coring penetrator design can be found in a paper by Lorenz, Boynton and Turner (2006).

The next stage in complexity for contact sampling of small bodies is represented here by harpoon sampling devices. This class of samplers includes mechanisms that are essentially impactors tethered to spacecraft which can therefore be retrieved by reeling in the tether following sample acquisition. A number of harpoon samplers have been proposed. A representative concept features a set of sampling tips that can be used to sample different consolidated surface material types (Bartlett *et al.*, 2006).

Similar approaches employ flexible booms to deliver more sophisticated sampling mechanisms to the target surface allowing the spacecraft to maintain a safe stand-off distance during sampling operations. One approach that has been proposed is the use of a high-speed sampling head with counter-rotating cutters that serve to scrape surface material up and into the sampler (Bartlett *et al.*, 2006). The sampling operation can be completed in a matter of a few seconds or less, with reliable sample

collection ensured by compliance that the flexible boom offers towards forcing the active cutters to conform to the small-body surface. The boom is also used to retract the collected sample to the spacecraft. This approach is also applicable to surface sampling on bodies with atmospheres where the sampler is a payload on an aerial platform such as a balloon. Similar spacecraft touch-and-go sampling approaches have been proposed with the aim of acquiring 10 kg of sample in 1 s from the surface of the Mars moon Deimos (Behar, Rivellini and Nicaise, 2003). Yet another similar system for touch-and-go sampling varies in boom and sample mechanism design opting for a relatively stiff, self-straightening tubular structure in place of a flexible boom (Nygren, 2000). This tubular mechanism is suspended from a hovering spacecraft that delivers a sampler to and retracts it from an asteroid surface. It buckles as necessary to provide lateral compliance to accommodate spacecraft drift. In this case, the sampler consists of an auger rotated by a flywheel and a toroidal sample collection chamber that is wrapped around and rotates with the auger. The flywheel stores energy required to drill approximately 10 cm into the surface and transfers energy to the auger as it decelerates during interaction with the asteroid surface.

There are other systems that call for closer proximity to the target body. The least complex systems in this class employ the simplest sampling devices characterized by minimal complexity in mechanical design and passive operation. Examples include contact sampling devices that rely on momentary contact with sampling mechanism surfaces that are coated with adhesive substances. A representative prototype for such samplers was designed to collect at least 10 g of regolith from a small-body surface when using spacecraft motion to place a surface sampler coated with wax or grease against the small body in a touch-and-go operation (Lees *et al.*, 2006). This is a simple and robust way to collect loosely consolidated surface material known to comprise regolith of some small bodies. In addition to surface regolith sample collection during spacecraft to small-body impact, techniques and prototypes have been developed for collecting bulk material samples and core samples that maintain stratigraphy (Lees *et al.*, 2006).

JAXA is using its Hayabusa spacecraft to conduct the MUSES-C asteroid sample return mission from asteroid Itokawa (Yano *et al.*, 2006a). Hayabusa is equipped with an impact sampler mechanism designed to operate in close proximity to and in contact with a variety of asteroid surface types. The mechanism consists of a 1 m long cone-shaped sampler horn on the underside of the spacecraft out of which small projectiles are fired at the asteroid surface while the horn is in contact with the surface. The projectiles serve to fracture the surface, causing material to be ejected up through the horn and into a sample canister inside the spacecraft. The Hayabusa spacecraft attempted two touchdowns on the surface of Itokawa in November 2005. The first touchdown was aborted due to a sensor-based safety reaction to a detected obstacle. However, the sampler horn did contact the asteroid surface, and it is believed that some material could have been collected on the aborted attempt (Yano *et al.*, 2006b). The second touchdown sequence executed as planned with a confirmed contact by the sampler horn and commanding of projectile firing. There is some question about whether a safeguard command recorded in the onboard

telemetry may have overridden the projectile fire command, and therefore some uncertainty as to whether samples were collected. In any case, the canister was closed to enable sample insertion into the return capsule and we anxiously await the result from JAXA after a successful return of the capsule to Earth expected in 2010. Chapter 6 contains a number of images and descriptions of the spacecraft and its sample acquisition system.

Other more complicated but potentially more capable designs are under consideration for operations in close proximity to and in contact with small-body surfaces for touch-and-go sampling. One such system proposes a two-link robotic arm with a sampler at its end-effector and capable of contact force control that is probably robust to a range of small-body surface compliance properties (Acikmese, Quadrelli and Phan, 2007; Song and Vidyasagar, 1989).

In 2014, the ESA Rosetta spacecraft is planned to rendezvous with a comet, deploy a lander to its surface, and study the comet from orbit. Its lander, Philae, will be attached to the Rosetta spacecraft and released after orbit about the comet is achieved. The lander uses shock absorbers on its three landing legs to inhibit bouncing in the low gravity and push-down/hold-down thrusters to accelerate descent and impede rebound after touchdown; it will be anchored to the comet using a tethered harpoon fired into the comet surface (Ulamec *et al.*, 2006). In addition to an onboard scientific instrument payload, Philae will carry a sample drill and distribution system (SD2) capable of estimating collected sample volume (Finzi *et al.*, 2007). Chapter 6 also contains detailed descriptions of the drill and associated technology. A similar concept was proposed for the NASA/JPL Space Technology 4 mission, which was cancelled in 1999 due to budgetary constraints. Its spacecraft was also designed to rendezvous with and orbit about a comet, deploy a lander (Champollion) that would anchor itself to the comet using a harpoon, and perform *in situ* analysis of the comet nucleus using a drill for sample acquisition (Weissman, 1997). The Champollion lander was in fact initially intended as a surface science package for the Rosetta mission, but was withdrawn as a mission element and later revived for Space Technology 4.

7.15.2 Sampling from Aerobots

Methodologies and concepts for sample acquisition from aerobot platforms are areas of active research in preparation for use at future mission destinations on Venus, Mars, and Titan. The approaches that are receiving most attention involve landing for significant periods to sample the surface by drilling (for example), performing more momentary touch-and-go sampling operations (similar to those mentioned above for small-body sampling), or deploying the sampling mechanism(s) from a stand-off hover position with the aid of a tether.

Mission concepts for Venus sample return have baselined the use of a balloon to deliver a lander to the surface of Venus, drill for rock core samples for a period lasting more than 1 h, stow a core sample in an ascent vehicle, and inflate a secondary balloon for ascent to a sufficiently high altitude to launch the sample canister into Venus orbit

(Cutts *et al.*, 1999). Some Titan mission concepts that baseline autonomous surface sample acquisition from aerobots would require that samples be acquired without landing (Hall *et al.*, 2006). This would be enabled by a capability to hover or maintain low speed relative to the ground. Montgolfiere balloons, also known as "hot air balloons," have been proposed for exploration at Mars and Titan using this approach. Tests on Earth of unmanned Montgolfiere balloon altitude control have demonstrated controllability sufficient to allow acquisition of multiple surface samples (Jones and Wu, 2006). An approach proposed for surface sampling of Titan would employ a sampling device deployed via a tether from a Montgolfiere balloon at an altitude of 100 m above the surface. Notional concepts for associated sampling devices would permit sample acquisition of surface ice and/or methane lakes. Acquired samples would be retracted by tether to the balloon's gondola for analysis (Jones and Wu, 2006).

More complex system architectures have also been conceived for acquiring samples at Titan using aerobots (Honeybee Robotics, 2008). One study considered an aerobot blimp that would use tethers to deploy and retract a collection of harpoon-like devices and/or instrumented sondes on Titan's surface (Quadrelli *et al.*, 2004). The harpoon-like devices would be lowered from the blimp to acquire samples to retract to the blimp for analysis using onboard instruments. During the course of the study, the sonde concept evolved from the tethered harpoon concept to a mobile sonde concept suitable for potentially different surface types on Titan. Sonde design options included touch-and-go mechanisms or "sticky-tape" adhesive materials that could be suspended from the blimp on a tether and dragged across the surface to acquire samples (Quadrelli *et al.*, 2004). Similar system architecture was proposed that included a group of small robotic vehicles deployed from, and aerially transported by, a gondola base station attached to a Montgolfiere balloon or a dirigible (Jamshidi, Tunstel and Zand, 2000). Rather than make use of tethers to deploy and retract samplers, the system concept called for periodic landing for robotic vehicle surface deployment, sample collection, and return. Chapter 6 has a more thorough description of these sampling methods.

7.16 Conclusion

Planetary exploration missions present unique challenges for sample acquisition, handling and processing. Systems need to be developed that meet stringent mass, power and reliability requirements. A range of sampling tools can generate different types of samples which may need comminution to break down the samples to smaller dimensions before being transferred for storage or instruments for analysis. The variety of planetary body types results in different architectures for access to sampling sites, tool deployment approaches, and sampling techniques. Missions such as the Mars Phoenix lander have demonstrated operational approaches for planetary sample acquisition, handling and processing and new approaches are under development to provide samples from additional solar system science destinations.

page proof WILEY

Appendix A: COTS Small-Scale Laboratory Comminution Equipment Companies

The following are some of the companies that manufacture laboratory (bench-top and free standing) comminution equipment:

Abon Engineering: http://www.abon.com.au/products/vsi.htm.

Bico: http://www.bicoinc.com/index.html.

Bratt Technologies: http://www.brattech.com/.

Fritsch: http://www.fritsch.de/index.php.

Ling Kwang Industrial Co.: http://www.mill.com.tw/.

Retsch: http://www.retsch.de/english/db/listing.php?PG=1.

SCP Science: http://www.scpscience.com/.

Sepor: http://www.sepor.com/.

Spex: http://www.spexcsp.com/sampleprep/index.aspx.

Appendix B: Glossary

Abrasion	Removal of material through rubbing against hard surfaces
Feed	The particles/rocks that are fed into a comminution device
Fines	Pulverized material that is produced incidentally by a crusher
Grinder	A machine for producing fine particle size reduction through attrition and compressive forces at the grain size level
Grinding	Comminution that produces finer particles
Comminution	A group of mineral processing techniques used to turn rocks into powder
Comminution circuit	The sequence of devices/processes used to comminute material
Crusher	A machine designed to reduce large, solid chunks of raw material to smaller chunks
Crushing	Comminution that produces relatively coarse chunks
Mill	A machine designed to reduce small chunks of raw material to powder
Nip angle	The angle between two surfaces that are gripping a piece of rock in the crushing process
Product	The particles/rocks that are created and released by a comminution device
Reduction ratio	Size ratio of the initial material to the final product

page proof WILEY-VCH

Appendix C: List of Abbreviations

COTS	Commercial, off-the-shelf
SPU	Sample processing unit
STU	Sample transfer unit
MeSH	Mechanized sample handler
MeSH-SHO	MeSH sample hand-off
MeSH-SSP	MeSH sample separation and preparation
MeSH-SD	MeSH sample distribution

Acknowledgments

Research reported in this chapter was conducted at the JPL, California Institute of Technology, and Honeybee Robotics under various contracts with NASA.

The authors would like to thank the following reviewers of this chapter: Jeff Leeds, Space Department, JHU Applied Physics Laboratory, Laurel, MD; Samad Hayati, Chief Technologist for Mars Exploration, JPL; Joe Parrish, Vice President of Research and Development, Manassas, VA; and Ted Iskenderian, Supervisor, Robotics and Mechanisms Group, JPL. Also, the authors would like to thank David Glaser of the University of California Berkeley, James Blacic of Los Alamos National Laboratory, and Dale Boucher of Northern Centre for Advanced Technology Inc. (NORCAT) for their contributions to the chapter.

References

Acikmese, B., Quadrelli, M.B. and Phan, L. (2007) A force control algorithm for small celestial body surface sampling. AIAA Guidance, Navigation and Control Conference and Exhibition, Hilton Head, SC, August 2007, Paper AIAA 2007, 6322.

Bar-Cohen, Y., Chang, Z., Sherrit, S., Badescu, M. and Bao, X.(March 7–10, 2005) The ultrasonic/sonic driller/corer (USDC) as a subsurface drill, sampler and lab-on-a-drill for planetary exploration applications. Proceedings of the SPIE Smart Structures Conference, SPIE Vol. 5762-22. Available online at http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/papers/SPIE-05-review-USDC.pdf.

Bartlett, P.W., Basso, B., Paulsen, G., Gorevan, S. and Yachbes, I. (2006) Asteroid and comet surface sampling methods from non-landed spacecraft. Lunar and Planetary Science Institute Workshop on Spacecraft Reconnaissance of Asteroid and Comet Interiors, Santa Cruz, CA, 5–6 October 2006, Paper 3031.

Baumgartner, E., Bonitz, R., Melko, J., Shiraishi, L. and Leger, C. (2005) The Mars Exploration Rover Instrument Positioning System. Proceedings of the 2005 IEEE Aerospace Conference, Big Sky, MT, March 2005.

Behar, A., Rivellini, T. and Nicaise, F. (May, 2003) Brush-wheel Sampler Concept for Gulliver Deimos Sample Return Discovery Proposal, JPL Technical Reports Server, http://hdl.handle.net/2014/7305.

Bell, J.F., Herkenhoff, K.E., Schwochert, M., Morris, R.V. and Sullivan, R. (2000) The Athena Pancam and Color Microscopic

page proof © WILEY-VCH

Imager (CMI). Concepts and Approaches for Mars Exploration, Lunar and Planetary Institute, Houston, TX, 18–20 July 2000, Abstract 6104.

Bish, D.L. and Reynolds, R.C. Jr (1989) Modern powder diffraction, *MSA Reviews in Mineralogy*, **20**, 73–99.

Bond, F.D. (1961) Crushing and grinding calculations. Parts I and II, *British Journal of Chemical Engineering*, **6**, 373–378 and 543–548.

Bonitz, R. (1997) Mars Surveyor'98 Lander MVACS robotic arm control system design concepts. Proceedings of the 1997 IEEE International Conference on Robotics and Automation Albuquerque, NM, April 1997.

Brinkerhoff, W.B. (2001) In-situ laser time-of-flight mass spectrometry on planets and small bodies. Presented at the 2nd Workshop on Harsh-Environment Mass Spectrometry, Center for Ocean Technology, St. Petersburg, FL, 18–21 March 2001.

Cheatham, J. (1968) Rock breakage by crushing, blasting, and drilling. *Engineering Geology*, **2** (5), 293–314.

Chipera, J., Vaniman, D.T., Bish, D.L., Sarrazin, P., Feldman, S., Blake, D.F., Bearman, G. and Bar-Cohen, Y. (2004) Evaluation of rock powdering methods to obtain fine grained samples for CHEMIN, a combined XRD/XRF instrument. Lunar and Planetary Science Conference, LPSC XXXV, Abstract No. 1400.

Coduto, D. (1998) *Geotechnical Engineering: Principles and Practices*, Prentice Hall, Englewood Cliffs, NJ.

Cutts, J.A., Rodgers, D.H., Cameron, J.M., Hall, J.L., Kerzhanovich, V.V., Nilsen, E.N., Rand, J. and Yavrouian, A. (1999) Venus surface sample return: role of balloon technology. AIAA Balloon Technology Conference, Norfolk, VA.

de la Vergne, J. (2003) *Hard Rock Miner's Handbood*, 3rd edn, McIntosh Engineering, http://www.mcintoshengineering.com/.

Diaz-Calderon, A., Backes, P. and Bonitz, R. (2007) An autonomous robotic scooping approach for planetary sample acquisition. 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 2007.

Donovan, J. (2003) Fracture Toughness Based Models for the Prediction of Power Consumption, Product Size, and Capacity o Jaw Crushers, PhD thesis, Virginia Polytechnic Institute.

Finzi, A., Bernelli Zazzera, F., Dainese, C., Malnati, F., Magnani, P.G., Re, E., Bologna, P., Espinasse, S. and Olivieri, A. (2007) SD2 – how to sample a comet. *Space Science Reviews*, **128** (1–4), 281–299.

Gaete-Garreton, L.F., Vargas-Hernandez, Y.P. and Velasquez-Lambert, C. (2000) Application of ultrasound in comminution. *Ultrasonics*, **38**, 345–352.

Gorevan, S.P., Myrick, T., Davis, K., Chau, J.J., Bartlett, P., Mukherjee, S., Anderson, R., Squyres, S.W., Arvidson, R.E., Madsen, M.B., Bertelsen, P., Goetz, W., Binau, C.S., Richter, L. and Hoehe, L. (2003) Rock abrasion tool: Mars exploration rover mission. *Journal of Geophysical Research*, **108** (E12), 8068, DOI: 10.1029/2003JE002061.

Hall, J.L., Kerzhanovich, V.V., Yavrouian, A.H., Jones, J.A., White, C.V., Dudik, B.A., Plett, G.A., Mennella, J. and Elfes, A. (2006) An aerobot for global *in situ* exploration of Titan. *Advances in Space Research*, **37** (11), 2108–2119.

Hardgrove, R.M. (2001) Crushing and pulverizing, AccessScience Encyclopedia of Science and Technology Online, McGraw-Hill, http://www.accessscience.com, DOI:10.1036/1097-8542.169400 (last modified 23 February 2001).

Haskins, L., Wang, A., Joliff, B. and Kuebler, K. (2000) Why send the Athena Raman spectrometer to Mars? Concepts and Approaches for Mars Exploration, Lunar and Planetary Institute, Houston, TX, 18–20 July 2000, Abstract 6028.

Hayati, S. *et al.* (2007) Advanced robotics technology infusion to the NASA Mars Exploration Rover (MER) project. Proceedings of the 2007 IFAC Symposium on Intelligent Vehicles (IAV2007).

Hayes, P. (1993) *Process Principles in Minerals and Materials Production*, 3rd edn, Hayes

Publishing, Brisbane, available online: http://www. fep.uq.edu.au/Books/Hayes93/toc.asp.

Herman, J., Zacny, K., Morris, R. and Davis, K. (2006) Development of crushing and sieving technologies for use in sample preparation in Mars exploration. Lunar and Planetary Science Conference, LPSC XXXVII, Abstract 2332.

Honeybee Robotics (2008), Touch and Go Sampler: Touch & Go Sampling System Fact Sheet, http://www.honeybeerobotics.com/pdf/tgss_fact_sheet.pdf.

Hukki, R.T. (1961) Proposal for a Solomonic settlement between the theories of Von Rittinger, Kick and Bond. *Transactions of AIME*, **220**, 403–408.

Jamshidi, M., Tunstel, E. and Zand, M. (2000) Autonomous large area planetary surface exploration with aerially migrating robots using stochastic learning collaboration. Proposal to NASA. Research Announcement NRA-99-OSS-5, Surface Systems Thrust Area, February 2000.

Jones, J. and Wu, J.J. (2006) Montgolfiere aerobots for Titan. 4th International Planetary Probe Workshop, Pasadena, CA, June 2006.

Kessler, G.W. (2001) Buhrstone mill, AccessScience Encyclopedia of Science and Technology Online, McGraw-Hill, http://www.accessscience.com, DOI:10.1036/1097-8542.098900 (last modified 6 April 2001).

Lees, J., Chabot, N., Persons, D. and Hartka, T. (2006) Small body sampling techniques being developed at Johns Hopkins University Applied Physics Laboratory. International Astronautical Conference (IAC), Valencia, Spain, October 2006, Paper IAC-06-A3.5.04.

Leger, C., Deen, R. and Bonitz, R. (2005) Remote image analysis for Mars exploration rover surface operations. Proceedings of 2005 IEEE Conference on Systems, Man, and Cybernetics.

Lorenz, R.D., Boynton, W.V. and Turner, C. (2006) Demonstration of comet sample collection by penetrator. *Acta Astronautica*, **59**, 1000–1007.

Lowrison, G.C. (1974) *Crushing and Grinding, the Size Reduction of Solid Minerals*, Butterworth, London.

Maki, J.N., Bell, J.F. III, Herkenhoff, K.E., Squyres, S.W., Kiely, A., Klimesh, M., Schwochert, M., Litwin, T., Willson, R., Johnson, A., Maimone, M., Baumgartner, E., Collins, A., Wadsworth, M., Elliot, S.T., Dingizian, A., Brown, D., Hagerott, E.C., Scherr, L., Deen, R., Alexander, D. and Lorre, J. (2003) Mars Exploration rover engineering cameras. *Journal of Geophysical Research*, **108** (E12), 12-1–12-24.

Neal, C.R. (2000) Issues involved in a Martian sample return: Integrity preservation and the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) position. *Journal of Geophysical Research*, **105**, 22487–22506.

Nygren, W.D. (2000) Rapid remote sample collection mechanism for near-Earth asteroid sample return. Lunar and Planetary Science Institute Near-Earth Asteroid Sample Return Workshop, Paper 8031.

Quadrelli, M.B., Chang, J., Mettler, E., Zimmermann, W., Chau, S. and Sengupta, A. (2004) System architecture for guided herd of robots exploring Titan. IEEE Aerospace Conference, Big Sky, MT, March 2004, pp. 379–387.

Quinn, L.P. (2001) Mining with limited force tools and microscale mining machines. The Ants of Toutatis, Colorado School of Mines, Space Resources Roundtable, available online at http://www.mines.edu/research/srr/2001%20papers/Toutatis%20SSR3.pdf.

Sarrazin, P., Chipera, S., Bish, D., Blake, D. and Bryson, C. (2004) A novel saple-handling approach for XRD analysis with minimal sample preparation. Lunar and Planetary Science Conference, LPSC XXXV, 2004, abstract available online at http://www.icdd.com/profile/march04abs/Sarrazin_march-04.pdf.

Satish, H., Radziszewski, P. and Ouellet, J. (2005) Design issues and challenges in lunar/Martian mining applications. *Mining*

page proof © WILEY-VCH

Technology: IMM Transactions Section A, **114** (2), 107–117.

Song, W.M. and Vidyasagar, M. (1989) *Robot Dynamics and Control*, John Wiley & Sons, Inc., New York.

Squyres, S.W., Arvidson, R.E., Baumgartner, E.T., Bell, J.F., Christensen, P.R., Gorevan, S., Herkenhoff, K.E., Klingelhofer, G., Madsen, M.B., Morris, R.V., Rieder, R. and Romero, R.A. (2003) Athena Mars Rover Science Investigation. *Journal of Geophysical Research*, **108** (E12), 8083.

Tarjan, G. (1981) *Mineral Processing*, vol. **1**, Akadémiai Kiadó, Budapest.

Ulamec, S., Espinasse, S., Feuerbacher, B. *et al.* (2006) Rosetta Lander – Philae: implications of an alternative mission. *Acta Astronautica*, **58** (8), 435–441.

Vaniman, D., Bish, D., Chipera, S., Sarrazin, P., Blake, D. and Collins, S.A. (1999) Sample preparation and mounting strategies for robotic XRD/XRF analysis. Lunar and Planetary Science Conference, LPSC XXX, Abstract 1431.

Velletri, P. and Weedon, D.M. (2001) Comminution in a non-cylindrical roll crusher. *Mineral Engineering*, **14** (11), 1459–1468.

Weissman, P.R. (1997) Champollion: a comet lander and sample return demonstration mission. Lunar and Planetary Science Conference, LPSC XXVIII, Paper 1785.

Whittles, D.N., Kingman, S.W. and Reddish, D.J. (2003) Application of numerical modeling for prediction of the influence of power density on microwave-assisted breakage. *International Journal of Mineral Processing*, **68**, 71–91.

Wright, J. *et al.* (2005) Terrain modelling for in-situ activity planning and rehearsal for the Mars exploration rovers. Proceedings of the 2005 IEEE International Conference on Systems, Man, and Cybernetics. Q3

Yano, H. *et al.* (2006a) Touchdown of the Hayabusa spacecraft at the Muses Sea on Itokawa. *Science*, **312**, 1350–1353.

Yano, H., Kubota, T., Miyamoto, H. *et al.* (2006b) Hayabusa's touch down sites at the smooth terrain on asteroid 25143 Itokawa: initial investigation. Lunar and Planetary Science Conference, LPSC XXXVII, Paper 2463.

page proof WILEY-VCH

Keywords/Abstract

Dear Author,

Please check and/or supply keywords and an abstract. These will not be included in the print version of your chapter but in the online version.

If you do not supply an abstract, the section heading will be used instead.

Keywords: sampling; planetary sampling; comminution; milling; mills; crushers; attrition.

page proof
WILEY-VCH

Author Query

1. Section 7.13.1, 2nd paragraph: you have "(SPONG)" three times. What does it mean?
2. Section 7.13.1, 7th paragraph: please give CCT in full.
3. For the Wright reference and the two Yano et al. references, please give all authors.
4. You cite Hayes: is this the reference Hayes, 1993?

page proof
WILEY-VCH