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Bureau of Mines Research on Lunar Resource Utilization

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The Bureau of Mines is cooperating with NASA to provide through a program of multidisciplinary research the basic scientific and engineering knowledge that will be needed to utilize extraterrestrial mineral resources for support of future space missions. The concept, scope, and present status of the Bureau's program are described in this paper.

INTRODUCTION

A scientific challenge unparalleled in history faces man in his exploration of space. In an amazingly short time he has demonstrated his ability to probe the far reaches of the solar system by sending unmanned space vehicles to the Moon, Mars, and Venus, and into orbit around the Sun. In the next few years he expects to land on the Moon. This achievement will mark the beginning of the exploration of the Moon and the planets by man himself.

The problems posed by manned lunar exploration have been receiving serious study for several years. In some cases, such as the problem of transporting man on the Moon, full-scale vehicles have already been constructed. Much thought has also gone into the design of lunar bases which will be essential for any sustained exploration effort. Because supplying these bases will be a major logistical problem, success in using the Moon's raw materials to reduce the dependence of lunar bases on supplies shipped from Earth may be a critical element in advancing lunar and planetary exploration (refs. 1 to 8).

Although the actual use of raw materials that may be available on the Moon for the support of manned bases is probably at least a decade away, the problems of lunar mining and processing have been under active consideration for some time (refs. 9 to 19). When requirements for a new technology are foreseen, it is important to allow adequate lead-time for obtaining the basic knowledge needed for the efficient solution of engineering and hardware development problems. The need for a farsighted approach is especially acute in the area of extraterrestrial resource utilization, where learning by experience is not tolerable and crash programs to develop urgently needed information are very costly. This is exactly what NASA's Office of Advanced Research and Technology had in mind when, in mid-1965, it began providing funds to the Bureau of Mines for research on the basic scientific and engineering knowledge needed for developing an extraterrestrial mining and processing technology.

The purpose of the present paper is to describe the nature and extent of the Bureau's research and to outline briefly the progress thus far achieved. References 20 to 22 report in some detail on specific parts of the research program.

METHOD OF ATTACK

Although the use of mineral resources on any body in space falls within the scope of the Bureau's program, emphasis has been placed on mining and processing problems on the Moon as a matter of first priority. The idea of mining and processing mineral resources is intended to apply here in its broadest sense.

Thus we are concerned with problems involved in using lunar-surface materials in virgin form for such purposes as shielding or insulation, in modifying surface materials for use in construction or other applications, and in extracting from lunar-surface or near-surface materials such products as water, oxygen, or other useful constituents.

Our method of attack on these problems is based on the premise that mining and processing of mineral resources involve the application of energy to a material to accomplish the removal or separation of all or part of the material under the conditions imposed by the environment in which the material exists or is placed. Mining and processing technology will evolve from research in an orderly and progressive manner as knowledge of the following is developed:

(1) Properties of the material

(2) Effect of environmental factors on these properties

(3) Parameters of the various energy mechanisms that can accomplish removal of the material

(4) Laws or relationships that govern the interaction of a specific energy mechanism and material under the existing or an imposed environment

Because the Bureau is using the same approach to develop new and improved methods for mining and processing on Earth, we are meeting the needs of the NASA program largely by extending the scope of research already in progress at the Twin Cities Mining Research Center and a number of other Bureau centers. The resulting expanded research benefits the Bureau by providing new information and fresh perspectives that may apply to its own program. At the same time it meets the needs of NASA in an efficient manner, since it makes use of a broad base of capability in Bureau manpower and facilities and limits NASA funding to that required to extend the current research to the extraterrestrial situation.

Actually the basic knowledge needed to develop a technology for mining and processing on the Moon is the same as that needed for advancing mining and processing technology on Earth, except for the modifying effects of two important factors: (1) space logistics and economics, and (2) the lunar environment. Operations under conditions where air and water are precious materials, where initial plant investment is of minor concern, and where ordinary manual labor is difficult or impossible are bound to be different from operations that we are familiar with on Earth. A gravity force one-sixth that of Earth, surface temperatures ranging from −250° to 250° F, the absence of an atmosphere (resulting in a pressure 10^{-13} that of Earth), and no protection from radiation or micrometeorites will certainly affect the properties of materials and the nature of physical processes in ways not always easily predicted from our earthbound experience.

The first factor—space logistics and economics—imposes limits on the size, weight, and power requirements for mining and processing equipment and emphasizes the need for simplicity, reliability, and automation for mining and processing systems. These restrictions must be considered when one is contemplating the scientific knowledge needed for developing a lunar technology because they will be critical at the later stage of actual engineering development. The second factor—the lunar environment—is critical to all aspects of mining and processing on the Moon. It undoubtedly has had a major influence on the present character of the lunar surface. The effects of the lunar environment, particularly the hard vacuum, on the properties of the materials being mined and processed and on the physical mechanisms involved in the mining and processing pose some of the most difficult problems in obtaining the basic knowledge needed. The lunar environment will continue to be a determining factor when the time comes to design specific equipment and methods for use on the Moon.

THE RESEARCH PROGRAM

The present program consists of 16 closely related research tasks at 7 Bureau centers, with planning and coordinating activities carried out by a small interdisciplinary core group at the Twin Cities Mining Research Center. The individual tasks were initiated at different times between September 1965 and January

1967 after an initial period of background study and task definition by the core group. Most of the tasks are planned for a 3-year duration, although a few are 1- or 2-year survey or feasibility studies.

Figure 1 shows the locations of the centers involved in the program. The number of tasks at each center is indicated. Each task involves a multidisciplinary team of from two to eight researchers working under the investigator in charge. Each task is a part of regular Bureau research at the particular center concerned, and most members of a research team work only part time on the NASA task. The total effort involved in the program represents about 15 man-years per year.

The research tasks are concerned with the major problem areas of mining and processing which we categorize as follows: resource identification, rock fragmentation, materials handling, ground control and support, mineral beneficiation, thermal decomposition, electrolytic reduction, chemical reduction, and secondary processing.

Two of the seven tasks at the Twin Cities Mining Research Center are providing general support for lunar resource utilization studies. The first of these, under the direction of David Fogelson, comprises the selection and collection of materials that simulate those likely to be found on the Moon. The second, which involves all of the research laboratories at the Center, incorporates these simulated lunar materials into the basic fragmentation research currently in progress in order to determine a broad range of physical properties of the materials in Earth environment. Mr. Fogelson will describe the progress of these two tasks in another paper in this volume (ref. 20).

One of the other tasks at the Twin Cities Mining Research Center is providing additional insight into the possibilities of finding mineral resources on the Moon. Dr. Rolland Blake has completed a study of volcanism and

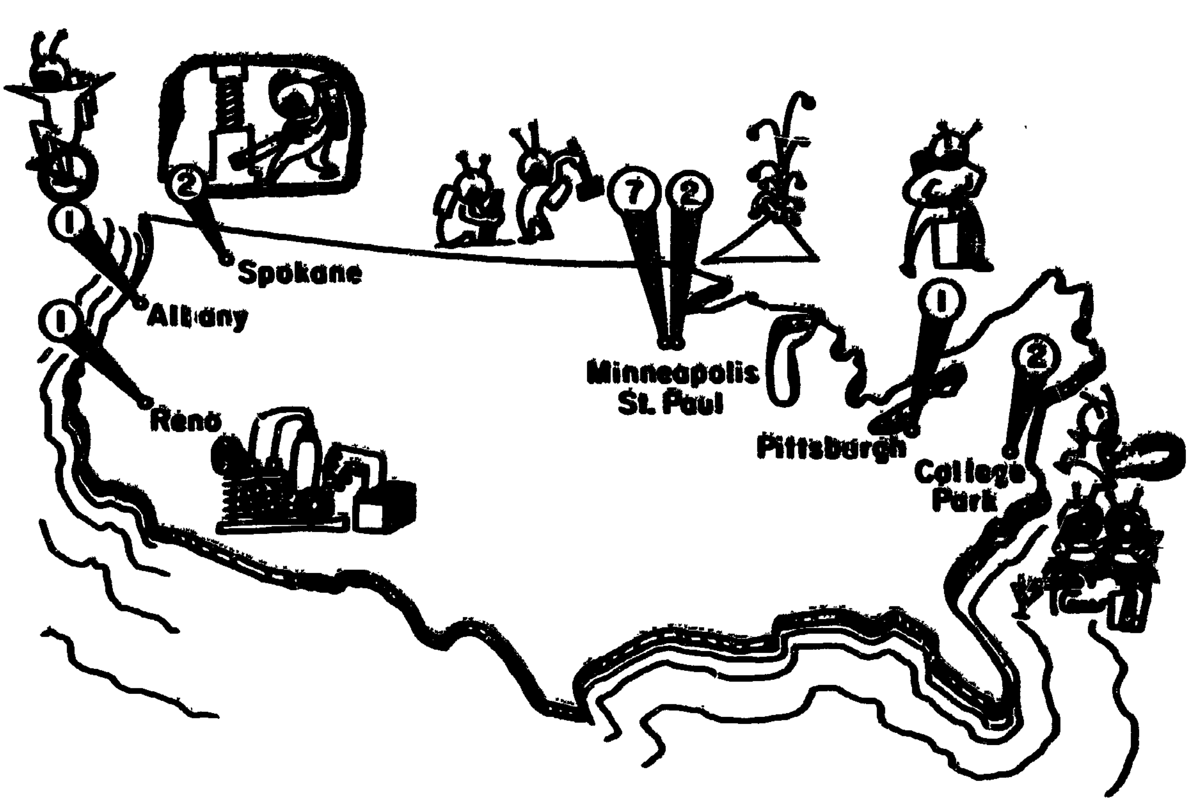

FIGURE 1.—Task location for Bureau of Mines program of multidisciplinary research leading to utilization of extraterrestrial resources. The number of tasks at each center is indicated.

ore genesis as related to lunar mining and will report the results in another paper in this volume (ref. 21).

Rock Fragmentation and Basic Property Studies

The other tasks at the Twin Cities Mining Research Center are aimed primarily at rock fragmentation, but some of them are providing basic information pertinent to other problem areas of mining and to some areas of processing, too. They are all concerned with the effects of lunar environment on the properties and behavior of rock.

One of them is a study of chemical reactivity and cold welding of freshly formed surfaces. This task is under the direction of Clifford Schultz and its objective is to measure equilibrium constants for the adsorption of gases on the surfaces of silicate minerals and to relate them to the fractional coverage necessary to inhibit cold welding of vacuum-formed surfaces. Measurement equipment has been devised, constructed, and calibrated, and experimental work is in progress. These studies will complement the excellent work by Ryan on adhesion of mineral surfaces in ultrahigh vacuum (ref. 23).

In a closely related task, also under the direction of Schultz, the effect of lunar vacuum on surface properties of rock is being determined. Here the objective is to develop information on the fundamental frictional behavior of mineral surfaces as related to their environment; to measure friction, surface energy, and hardness in ultrahigh vacuum; and to establish relations among these surface properties and between surface and bulk properties. An ultrahigh vacuum system capable of simulating lunar vacuum has been placed in operation together with auxiliary equipment capable of accurately determining conditions in the system while experiments are underway. A device for use in the vacuum system to measure friction between different mineral and mineral-metal combinations was designed and constructed.

Outgassing studies were conducted with the simulated lunar rocks that are being used in this and other research tasks. Results of these studies were reported in October 1967 (ref. 24). Table 1 shows representative data. Reliable information on the state of the test specimen, not available in many vacuum tests conducted previously, is essential for planning or interpreting results of property measurements or behavioral studies in ultrahigh vacuum.

TABLE 1.—*Outgassing of Simulated Lunar Rocks in Ultrahigh Vacuum (Low Bakeout Temperature)*

Sample	Ultimate pressure, 10^{-10} torr	Outgassing rate at ultimate, 10^{-12} torr liter sec
Empty chamber	1.5	
Dacite	2.0	Nil
Pumice	2.5	2.0
Tuff	4.5	8.0
Serpentinite	7.0	8.0
Basalt	23	100
Granodiorite	30	230

The fifth research task at the Twin Cities Mining Research Center is under the direction of Egons Podnieks. Its objective is to determine the effect of lunar vacuum on the strength and elastic properties of rock and on rock-failure processes. The task is an extension of fundamental rock physics studies in progress at the Center to develop an understanding of rock bonding and failure mechanisms and the factors which affect these mechanisms. In essence, the experimental method used in these studies consists of analysis of the microstructure of rock specimens before and after loading with an elaborately controlled and instrumented compression machine. Auxiliary equipment used with the uniaxial loading machine includes a pressure cell for controlling the environment and confining pressure around the test specimen and an ultrasonic pulsing system for measuring pulse velocity and attenuation in the specimen during loading.

An ultrahigh vacuum system for use with the loading machine has been purchased. Its performance characteristics are identical with those of the system being used in the surface property studies, but the chamber configuration is designed to fit the loading ram. A bellows system and specially designed platens were constructed and are being installed in the chamber. Specimen preparation and preconditioning methods and experimental techniques for use in the chamber were worked out making use of the experience and data developed in the surface properties studies. While the ultrahigh vacuum system was being readied for use, preliminary studies of environmental effects on two simulated lunar rocks were carried out using the pressure cell. Variation of specimen environment from water-vapor-saturated, atmospheric pressure to ultradry, moderate vacuum (10^{-3} torr) produced significant changes in strength and elastic properties. Of particular interest to the study of failure mechanisms were indications in the moderate vacuum tests of degassing bursts, which occurred simultaneously with microseismic noise indications picked up by the pulsing system, as the load-versus-deformation curve became nonlinear just prior to failure of the specimen. Quantitative measurement of the extent and nature of such outgassing will be possible in the ultrahigh vacuum chamber.

The sixth research task at the Twin Cities Mining Research Center is a 2-year study, scheduled to be completed in 1968, of the feasibility of extending to lunar vacuum environment current thermal fragmentation studies and property measurements at elevated temperatures. The task, which is under the direction of Robert Marovelli, also includes measurements at atmospheric pressure of thermophysical, strength, and elastic properties of rock over the lunar-temperature range. In this latter phase of the task, measurements of thermal expansion, tensile strength, and bending strength have been completed on 10 simulated lunar rocks. For most of the rocks the expansion coefficient increases with increasing temperature in a uniform manner through the lunar-temperature range. Rock strengths are significantly greater at the low end and significantly smaller at the high end of the lunar range than are room-temperature values. The strength of basalt was found to increase 50 percent in going from room to liquid nitrogen temperature (ref. 25). Measurements of thermal conductivity are in progress and attempts to reduce the size of specimens needed for these measurements so they may eventually be conducted in the Center's vacuum chambers have been successful.

High-energy electrothermal techniques of rock fragmentation are of major interest for lunar application. Direct use of electrical energy on the Moon has advantages over mechanical or explosive energy, and high voltages and high frequencies may be more manageable in the lunar environment than they are on Earth. In order to help determine the feasibility of studying thermal fragmentation in simulated lunar vacuum, modest vacuum capability (10^{-5} torr at 2000° C) was added to a recently purchased thermal shock research furnace. Thermal fragmentation studies over the pressure and temperature range of this equipment are in progress.

Use of a high-temperature furnace similar to the thermal shock furnace is not practical in a small ultrahigh vacuum system because the heating elements sublime. Other heat sources in use at the Center, such as the oxygen lance and plasma torch, are even less practical. A more promising heat source is the high-frequency dielectric heating apparatus. However, fragmentation techniques involve multielectrode arrays and meaningful results require test specimens a cubic foot or larger in size. Probably the most realistic approach for initial studies of thermal fragmentation in lunar vacuum is a combination of a small vacuum chamber and an external heat source, such as a laser, or the focused energy from one of the more conventional light sources. Final recommendations will be made after the studies in the thermal shock furnace are completed.

The seventh research task at the Twin Cities Mining Research Center is a study of the basic problems involved in drilling on the Moon. The effects of lunar vacuum and temperatures on cuttings removal and on cooling and lubricating bits are being investigated under the direction of James Paone, who will report the progress of this work as part of a paper on lunar drilling in this volume (ref. 22).

The last of the current research tasks in the problem area of rock fragmentation is located at the Bureau's Pittsburgh Explosives Research Center where information relevant to the use of explosives on the Moon is being developed under the direction of Frank Gibson. Problems of safety and contamination weigh against the use of explosives, but their efficiency and versatility make them very attractive as a primary tool for lunar excavating. The work at Pittsburgh is aimed at minimizing possible hazards associated with the storage, handling, and use of explosives in an environment characterized by high vacuum, extreme temperatures, and a flux of small hypervelocity particles.

Short-term effects of low pressure (10^{-6} torr) and lunar temperature extremes on explosive sensitivity and detonation velocity were investigated using several explosives with stability characteristics that make them candidates for lunar application. The only significant effect detected was a decrease in sensitivity at low temperatures. X-ray crystallography and thin-film chromatography are being investigated as methods for detection of possible long-term effects.

The sensitivity of explosives to initiation by impact of small particles, such as might occur from micrometeoroid bombardment, is being determined by adapting techniques developed for other types of hypervelocity studies at the Pittsburgh Center. Preliminary experiments using 1/8- to 1/4-inch-diameter spherical projectiles launched from a 50-caliber antitank gun showed that explosive detonation occurred at velocities of the order of 1 km/sec for projectile mass of the order of 1 gram. The relation between projectile mass and velocity for detonation determined from these experiments was extrapolated to smaller masses and higher velocities to assist in the design of hypervelocity impact experiments now in progress.

A third phase of this task consists of the study of explosive blast-wave propagation in low-pressure environment. Particularly critical for lunar use of explosives is the problem of acceleration of solid explosion products or pieces of encapsulating material by the explosive gases when no atmosphere opposes the expanding gases. A 12-foot spherical firing chamber is being equipped to study detonation of 100- to 1000-gram charges at pressures of the order of 10^{-6} torr.

Material-Handling and Ground-Support Studies

Two research tasks are being carried out at the Bureau's Spokane Mining Research Laboratory, one concerned with material-handling problems and one with ground-support problems. The first is a study under the direction of David Nicholson of the effect of lunar environment on the behavior of fine particles. Bureau studies of the behavior of fine-particle slurries used in mine backfill applications have been extended to include dry fine particles and lunar vacuum, temperature, and gravity influences.

Static and dynamic frictional properties important in handling, transporting, and stowing fine particles are being measured, first in controlled Earth atmosphere and then in lunar vacuum. Property measurement techniques are designed so that vacuum tests can be performed in the Bureau's ultrahigh vacuum chambers at the Twin Cities Center. Parameters included in the property studies, in addition to environment, are composition, density of packing, size distribution, and shape. Property measurements in Earth atmosphere are being made on both basalt prepared in an impact mill and basalt prepared in a ball mill. Basalt prepared in the impact mill, and having a particle-size distribution close to that determined for the lunar surface from the Surveyor III pictures, demonstrated a substantial degree of cohesion after moderate compression. Trenching of the perfectly dry material in normal Earth atmosphere produced results qualitatively identical with those of the Surveyor III trenching experiment.

In the second task at the Spokane Laboratory, protection and support problems for underground lunar shelters are being studied under Robert Bates. Research is being conducted on the properties of synthetic materials, such as foamed plastics, and natural materials, such as sulfur. The load-behavior relations for underground linings in the lunar environment are being studied.

The most important factors controlling lunar shelter design have been delineated. They include radiation, meteorite, and thermal protection, sealing for internal pressurization, and stability and support of ground. At depths less than 25 feet, the primary concern is adequate radiation and meteorite protection. Below 150 feet, support for overburden loads becomes important. Between 25 and 150 feet, the only significant problem is sealing to retain internal pressure. Because the most pressing problems are those involved in constructing near-surface shelters using indigenous materials, emphasis is being placed on using possible lunar-surface materials for protection and sealing purposes.

Mineral-Processing Studies

The five remaining research tasks in the Bureau's program are concerned with the different problem areas of processing technology. Four of these are devoted to fundamental problems of extracting water or oxygen from lunar rocks. The importance of studying these problems was pointed out at the first meeting of the Working Group on Extraterrestrial Resources in 1962 (refs. 26 to 28), and the recommendations of the Working Group (ref. 2), stimulated research on some of the problems. The Bureau's tasks are intended to supplement the excellent work that has been done by others over the past several years.

One of the tasks falls in the problem area of mineral beneficiation. Foster Fraas at the College Park Metallurgy Research Center is investigating adsorption and contact electrification in a vacuum to determine their effects on the separability of nonconducting minerals. The possibility of working with mineral concentrates rather than rocks to extract water or oxygen is an appealing one because of the lower energy requirements and higher productivity. If intrusive igneous rocks are found on the Moon, concentration of minerals which are easily reduced or contain significant amounts of water may be a good possibility, for the grain size of intrusive rocks is normally larger than that of extrusive rocks.

Equipment which has been designed and constructed for the College Park task includes a stainless-steel vacuum chamber with a turbomolecular pump and bakeout system capable of 10^{-9} torr, a vibrating electrifier with bellows feedthrough, a feed hopper, and a particle recirculating system. Initial tests using a mixture of quartz and microcline particles about one-half millimeter in size are in progress.

The research task at the Albany Metallurgy Research Center is related to the problems of thermal decomposition. Hal Kelly is directing a 2-year study of the stability of hydrous silicates and oxides in high-temperature and high-vacuum environment. The presence on the Moon of hydrothermally altered rocks, because of their high water content and the relative ease with which water can be extracted, would be of major importance for lunar resource utilization. This class of rocks has been the subject of intensive investigation (refs. 29 to 35). The work at Albany is providing data previously lacking on the probable stability of various minerals on the lunar surface and the energy required to remove water or oxygen from these minerals by thermal decomposition in a high-vacuum environment.

Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) equipment at Albany were modified to provide testing capability in air and in vacuum down to 10^{-6} torr at temperatures up to 1200° C. Specially designed tantalum calorimeter parts permit DTA measurements up to 1500° C in vacuum. Data have been obtained on one or more minerals in the olivine, mica, zeolite, epidote, bauxite, and amphibole groups. Other minerals are presently being tested.

Information needed to determine the feasibility of electrowinning oxygen from silicate rocks is being obtained in the research task under Donald Kesterke at the Bureau's Reno Metallurgy Research Center. The most readily available raw material on the Moon is likely to be extrusive igneous rocks. Oxygen is present in these rocks in the form of silicates and oxides. Production of oxygen by electrolysis of molten rock is theoretically possible, through modification of techniques developed for preparing various reactive metals by fused-fluoride electrolysis of their oxides. Previous investigations of this method of oxygen production (refs. 33 and 36) have shown a need for more information to determine whether it may be practical. The work at Reno is aimed at determining the fundamental physical and electrical properties of various silicate melts and finding suitable nonreactive electrode and crucible materials for use with the melts.

Various silicate rocks were tested to determine their melting characteristics, relative viscosities, and relative electrical conductivities. Fluxing agents in amounts of 10 weight-percent were required to promote fluidity and conductivity in the 1200° to 1500° C temperature range. Fluoride, oxide, borate, and phosphate agents were evaluated. Silicate melts containing lithium fluoride were the most conductive. Increasing the temperatures of the melts to the 1400° to 1500° C range improved conductivities by factors of two or three compared with conductivities at 1300° C. Currents of more than 100 amperes at 40 volts can be attained at 1500° C.

Consumable graphite electrodes are being used in the experimental work. Investigation of possible nonreactive electrode materials, which would be desirable for successful lunar application, has been disappointing. Experiments with platinum and iridium exposed to 1200° to 1500° C melts resulted in complete dissolution or severe corrosion of the metals within a short time after immersion. Attempts to saturate hot-pressed boron nitride with a silicate-flux mixture for possible use as an electrode material were unsuccessful. Search for suitable materials will continue.

The fourth task related to the extraction of water or oxygen from rock is in the problem area of chemical reduction. Dr. Sanaa Khalafalla at the Twin Cities Metallurgy Research Center is supervising a study of the basic mechanism and reaction kinetics involved in the reduction of silicates with carbon. The reduction of silicates with carbon is neither new nor exotic. It is the basis for a substantial ferrosilicon industry in this country and Canada. Rosenberg and others, studying the manufacture of oxygen from lunar materials, demonstrated that a closed-cycle silicate reduction by methane can be carried out with virtually no loss of methane (ref. 37). However, very little fundamental kinetic data are available on direct reduction by carbon.

Dr. Khalafalla's group is obtaining such data for reactions between carbon and various oxides and silicates in a vacuum furnace. A simple mineral system (silica) is being studied first. More complex mineral systems (silicates) will be investigated later.

The degree of reduction of silica-graphite mixtures in both loose powder and briquet form was studied at pressures below 10^{-4} torr and temperatures up to 1450° C. Graphite particle size was varied from 0.01 to 25 millimeters and silica size from 0.06 to 1.4 millimeters. Maximum reaction occurred with a reactant particle size of about 0.10 millimeter. With this size, the bed porosity was sufficient to permit the escape of carbon monoxide while securing maximum interparticle contacts. Molar ratios of silica to graphite were varied from 0.05 to 6.5, with maximum reaction at a ratio of about 2. The reaction appeared to be a solid-solid one not involving gaseous intermediates, as a better correlation of the extent of reaction was found with number of interparticle contacts than with surface area of the reactants. In a 5-hour period at 1400° C, over half of the oxygen present was extracted from an equimolar mixture of 0.15 millimeter silica and graphite powder.

Dr. Khalafalla's group also completed a 1-year study of the feasibility of reducing silicates with activated hydrogen in a plasma torch. They concluded that the process was not feasible, although the phenomena involved in mineral dissociation in the high-temperature plasma are might be worth further investigation.

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