SIMULATED LUNAR IGNEOUS SURFACE ROCK

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

WALTER I. DOBAR

1968

THESIS

SIMULATED LUNAR IGNEOUS SURFACE ROCK

by

Walter I. Dobar

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1968

ABSTRACT

Select geological materials were melted at atmospheric pressure to form a rock melt. The rock melt was then vacuum upwelled in a series of experiments to determine if a simulated igneous rock could be formed with photometric properties which would correlate with those of the lunar surface. The photometric measurements of the basalt and granite melts provided a photometric curve with excellent correlation with the lunar photometric curve. Bearing strength measurements from the vacuum upwelled basalt and granite samples exceeded the 0.5 p.s.i. engineering design requirement used for the lunar surface bearing strength. The porous, low density, material produced during this series of vacuum upwelling experiments has been given the name of "molivac", molten in vacuum, preceeded by the first syllable of the generic name of the rock type used to form the rock melt, i.e., bamolivac is formed from a basalt melt and granmolivac is produced from a granite melt.

ACKNOWLEDGEMENTS

The successful completion of this study program was greatly facilitated by the assistance of many organizations and individuals. The author wishes to express his sincere appreciation to them:

The Bendix Corporation, Aerospace Systems Division for providing the vacuum facilities without which this study program could not have been conducted.

Drs. W.J. Hinze, M.M. Miller and H.B. Stonehouse, Michigan State University, who in conjunction with the writer prepared a proposal for submittal to NASA in 1962 for a $285,000 earth-moon geological correlation study program. The study described herein was conducted when the submitted proposal to NASA was not funded.

Dr. J. Zinn, Michigan State University, for his support of this study by performing the petrographic verification of the geological materials used in this study program.

Mr. John P. Gnaedinger, Soil Testing Service Inc., for his support of this study program by conducting the bearing strength measurements in his laboratory.

Mr. John F. Judge, Editor, Missiles and Rockets Magazine, for his presentation on the vacuum upwelling experiments to the aerospace industry of the United States. This presentation provided an aerospace industry wide review of the facilities, procedures and results of this study program; and Dr. John J. Gilheany, Trident Engineering, for his review and presentation to NASA

Goddard Space Flight Center of the motion picture coverage of the vacuum upwelling experiment resulting in their use in the NASA Lunar Moon Blink Program.

Appreciation is also expressed to Dr. Winifred Cameron, NASA Goddard Space Flight Center, for having the motion picture coverage of the vacuum upwelling experiment reviewed by NASA personnel which resulted in the selection of specific frames of this movie for NASA use as calibration targets for the Lunar Blink Program Instrumentation; Dr. Gerard P. Kuiper, Lunar & Planetary Laboratory, Tucson, Arizona for his personal interest and encouragement of this study program. It was through Dr. Kuiper's interest that an independent series of vacuum upwelling experiments, based on the writer's results, was conducted at the University of Arizona. Dr. Kuiper's use of the results of the vacuum upwelling experiments in his interpretation and final report of the Ranger Lunar Surface Photographs to NASA provided a world wide review of these experiments by the scientific community; Dr. Gilber Fielder, University of London Observatory, London, England for his support by conducting a similar set of experiments based on the writer's work and thereby also independently validating the results published in this study; Drs. C. E. Prouty, and W. J. Hinze, Michigan State University, for their continued encouragement of the author during his pursuit of a graduate degree; and the

graduate committee of Drs. W.J. Hinze, C.E. Prouty, and R. Ehrlich, Michigan State University for their review and constructive criticism of this thesis report submitted to Michigan State University for a graduate degree.

TABLE OF CONTENTS

	Page
Abstract	ii
Acknowledgements	iii
Introduction	1
Geological Materials Investigated	15
Experimental Equipment	18
Vacuum Equipment	18
Furnace Equipment	20
Motion Picture Camera	22
Bearing Strength Equipment	22
Photometric Measuring Equipment	23
Experiment Procedure	24
Wausau Sand & Flint Glass - Single Crucible Samples	24
Wausau Sand - Multiple Crucible Sample	26
Basalt - Single & Multiple Crucible Samples	28
Granite - Single & Multiple Crucible Samples	28
Description of Upwelling Process	29
Wausau Sand & Flint Glass - Single Crucible Samples	29
Wausau Sand - Multiple Crucible Sample	32
Basalt - Single & Multiple Crucible Samples	35
Granite - Single & Multiple Crucible Samples	41

Page

Description of Sample 45

Wausau Sand & Flint Glass - Single Crucible Samples 45

Wausau Sand - Multiple Crucible Sample 48

Basalt - Single & Multiple Crucible 49

Granite - Single & Multiple Crucible 51

Radiation Discoloration 56

Photometric Properties 58

Bearing Strength 64

Discussion of Results 67

Recommendations for Further Investigation 73

References 75

INDEX OF FIGURES

Figure		Page
1	4 x 8 Foot Vacuum Chamber	19
2	Bell Jar Baseplate Assembly	21
3	Bearing Strength Measuring Equipment	22
4	Block Diagram of Photometric Measuring Equipment	23
5	Single Crucible Wausau Sand Sample Upwelling in Vacuum - Initial Upwelling	30
6	Single Crucible Wausau Sand Sample Upwelling in Vacuum - 33 Seconds after Initial Upwelling	30
7	Single Crucible Wausau Sand Sample Upwelling in Vacuum - 57 Seconds after Initial Upwelling	31
8	Wausau Sand Samples Formed from a Rock Melt Upwelled at 1200°, 1500°, 1600°, 1800° Centigrade	32
9	Multiple Crucible Wausau Sand Sample Upwelling in Vacuum - Initial Upwelling	34
10	Multiple Crucible Wausau Sand Sample Upwelling in Vacuum - 2.5 Minutes after Initial Upwelling	34
11	Multiple Crucible Wausau Sand Formed from Melt at 1000° Centigrade with Solidification under Partial Pressure	35
12	Multiple Crucible Basalt Sample Upwelling in Vacuum - Initial Upwelling	36
13	Multiple Crucible Basalt Sample Upwelling in Vacuum - 14 Seconds after Initial Upwelling	36

Figure		Page
14	Multiple Crucible Basalt Sample Upwelling in Vacuum - 17 Seconds after Initial Upwelling	38
15	Multiple Crucible Basalt Sample Upwelling in Vacuum - 1 Minute 45 Seconds after Initial Upwelling	38
16	Multiple Crucible Basalt Sample Upwelling in Vacuum - 3 Minutes 42 Seconds after Initial Upwelling	39
17	Vacuum Upwelled Basalt Sample Formed from Melt at 1000° Centigrade	40
18	Vacuum Upwelled Basalt Sample Formed from Melt at 1200° Centigrade	40
19	Vacuum Upwelled Basalt Sample Formed from Melt at 700° Centigrade	41
20	Vacuum Upwelled Granite Sample Formed from Melt at 1000° Centigrade	42
21	Vacuum Upwelled Wausau Sand Sample Formed from Melt at 1500° Centigrade	46
22	Vacuum Upwelled Wausau Sand Sample Showing Internal Structure Formed from Melt at 1500° Centigrade	46
23	Vacuum Upwelled Wausau Sand Sample Showing Internal Structure Formed from Melt at 1000° Centigrade	47

Figure		Page
24	Vacuum Upwelled Flint Glass Sample which also Shows the Internal Structure Formed from Melt at 1500° Centigrade	48
25	Vacuum Upwelled Wausau Sand Sample Showing Internal Structure Formed from Melt at 1500° Centigrade	49
26	Vacuum Upwelled Basalt Sample - Formed from Melt at 1000° Centigrade	50
27	Vacuum Upwelled Basalt Sample - Formed from Melt at 700° Centigrade	51
28	Vacuum Upwelled Granite Sample - Formed from Melt at 1000° Centigrade	52
29	Vacuum Upwelled Wausau Sand & Flint Glass with a Quartz Crystal Showing Radiation Damage	57
30	Photometric Curve for Vacuum Upwelled Wausau Sand Sample	60
31	Photometric Curve for Vacuum Upwelled Flint Glass Sample	60
32	Photometric Curve for Vacuum Upwelled Wausau Sand Sample Showing Radiation Discoloration	61
33	Photometric Curve for Vacuum Upwelled Flint Glass Sample Showing Radiation Discoloration	61
34	Photometric Curve of Vacuum Upwelled Basalt and Granite Sample	62

Figure		Page
35	Composite Photograph of Lunar Surface as Photographed by the Russian Space Probe Luna 9 with a Vacuum Upwelled Basalt Sample Formed from Melt at 1000° Centigrade Superimposed	68
36	Composite Photograph of Vacuum Upwelled Samples, Quartz Crystals and aa Lava	72

INTRODUCTION

It is frequently said that the more we learn, the more we discover how little we know. Nowhere has that observation been more strongly reinforced than in the geological data sent back from American and Soviet lunar spacecraft during the period from 1965 through 1967.

The writer in this introductary section has reviewed the previous findings obtained by planetary astronomy as reported in the literature prior to 1965. This has been done to provide a background for a comparison with planetary astronomy data, and the results of this study.

A review of the lunar surface probe data Luna 9 and Surveyor 5 obtained during the period of 1965 through 1967 is then summarized by the writer in the concluding section for comparison of the results of this study and the previous planetary astronomy data interpretations.

Previous Studies of Lunar Surface Material

The theory of heat conduction in a homogeneous semi-infinite solid with a known radiation value from the sun being received at its surface and surface heat loss according to the fourth power was used by Epstein, 1929 to develop the thermal inertia expression:

$$(kpc)^{-1/2} =$$

Where:

k = the thermal conductivity of the material, cal/cm/sec/^{o}C

p = the density of the material, gr/cm^{3}

c = the specific heat of the material cal/gr/^{o}C

The scientific community has used this thermal inertia expression in defining a lunar surface material and/or structure from lunar temperature measurements based on the following parameter definitions:

k - does not change with temperature or pressure

p - does not change with temperature or pressure

c - taken as a common value of rocks, 0.2/gr/^{o}C, and this value does not change with temperature or pressure.

The most widely used planetary astronomy infrared temperature measurements of the lunar surface were made during a lunar eclipse by Pettit and Nickelson, 1930 and Pettit, 1940. The heating and cooling curves, temperature change with time, constructed from these infrared temperature data provided the basis for the belief that the lunar surface material has a low thermal conductivity.

A.S. Wesselink, 1948, by solving the nonlinear thermal conduction equations for the infrared temperature measurements of Pettit and Nickelson determined that $(kpc)^{-1/2} = 1,000$ cgs for a homogeneous lunar surface material. His attempts to find a geological material with a similarly high $(kpc)^{-1/2}$ value then led him to the conclusion that there was a dust layer on the moon. This conclusion was based on the thermal conductivity measurement of $k = 3.3 \pm 1.8 \times 10^{-6}$ cal/cm/sec/^{o}C for silica dust at 5×10^{-2} Torr as reported by Smoluchowski, 1910, and recorded in the International Critical Tables.

The two-layer lunar model was advocated on the basis that with $(kpc)^{-1/2}$ = 1,000 cgs for a homogeneous lunar surface material the heating and cooling curves constructed from this model would only approximate the eclipse heating and cooling curve obtained in 1930 and 1940. The two-layer model heating and cooling curves provided a better correlation if the upper surface layer was $(kpc)^{-1/2}$ = 1,000 cgs and underlain with a pumice type material $(kpc)^{-1/2}$ = 100 cgs, Jaeger and Harper, 1950, Jaeger, 1953, Jaeger, 1959; Sinton 1960: Geoffrion, et al., 1960.

Sinton, 1960, obtained infrared temperature measurements for the crater Tycho during the eclipse of September 5, 1960. Cooling curves constructed from these data and interpreted using the two-layer surface model indicated that:

(1) The floor of the crater Tycho is 11 per cent bare rock while the remaining area is covered with dust to a depth of 0.5 mm.

(2) Tycho's environs are composed of thick dust.

Saari and Shorthill, 1962, also obtained infrared temperature measurements during the total eclipse of September 5, 1960 for the craters Aristarchus, Copernicus, and Kepler and their environs. They observed that the cooling curves constructed from their temperature measurements indicated that these craters cooled more slowly than did their environs.

Saari and Shorthill in addition to plotting curves from their temperature measurements also constructed mathematical cooling curves for both a homogeneous lunar surface and a two-layer model. These theoretical cooling curves, however, failed to provide an exact fit with any of their measured cooling curves even though the values they used for $(kpc)^{-1/2}$ in the homogeneous surface model ranged from 20 cgs to 1,736 cgs; and for the two-layer model an upper layer of dust $(kpc)^{-1/2}$ = 1,000 cgs which varied in depth from 0.05 to 0.24 cm. and was underlain with a substratum of $(kpc)^{-1/2}$ ranging from 70 to 140 cgs.

Muncey, 1958, had drawn attention to the possibility that k and c might be proportional to the absolute temperature and if so, $(kpc)^{-1/2}$ could be as small as 200 or 300 cgs at 27°C rather than 1,000 cgs. The possibility of a k and c dependence on temperature may have been considered, but does not appear to have gained acceptance in the thermal inertia impression $(kpc)^{-1/2}$ due to the lack of published temperature dependent curves for $(kpc)^{-1/2}$.

Thus in 1962 the theory of a lunar surface composed of thick dust was well established based primarily on infrared temperature measurement of the lunar surface and the thermal inertia expression of $(kpc)^{-1/2}$ = 1,000 cgs. The implications that this theory had on the engineering requirements of the American Space Program in 1962 were many. Two typical examples are listed below:

(1) The lunar surface material had a bearing strength of 0.5 p.s.i. Aerospace Industries in the United States not only had a problem to design a space-craft that would not exceed a bearing load of 0.5 p.s.i. but they also had a difficult time in obtaining a material with such an extremely low bearing strength for vehicle test beds.

(2) The lunar surface would not support the weight of an astronaut and he would sink into the lunar dust which was reported as deep as 100 meters in 1962.

The theory that volcanic activity had occurred and was still occurring on the lunar surface had been advocated by a small group within the scientific community. Their theory was based on published laboratory and planetary astronomy reports explaining and justifying volcanic type lunar surface materials based on photometric, light polarization and color measurements. These reports however were not successful in explaining a volcanic lunar surface materials such as lava based on lunar heating and cooling curves and the thermal inertia expression $(kpc)^{-1/2} = 1,000$ **cgs or dust.**

The following is a summary of the Planetary Astronomy reports on which the volcanic theory is based.

Kozyrev, 1958, obtained an emission spectrogram of the crater Alphonsus which showed the release of gas from the central peak.

He concluded that this gas was composed of diatomic molecules of carbon (C_2). He obtained another emission spectrograph of Alphonsus on 23 October 1959 which showed a uniform intensity increase from 5300-5400 Å to 6600 Å, Kozyrev, 1962. He concluded from the data that this portion of the spectrogram was representative of the radiation of a black body at 1,200°K (927°C) on the sunlit part of the crater floor. In another portion of this spectrogram Kozyrev found a uniform increase in intensity which began where the Mg band should appear and continued out to H^a band without any indication of element emission bands in this region. Kozyrev stated: "This means that there is emission not only above the bright red detail but also above the whole area of the lunar surface from the detail to the shadow. As a result, we have an artificial increase in the contrast of the red detail, representing an improbably high temperature of 1500°K (1227°C)."

Kozyrev thus concluded that during the exposure the slit of the spectrograph intercepted a lava flow 300 meters in width and calculated that the lava temperature was 1200°K (927°C). He believed that the gases absorbed in the lava would be discharged very violently due to the absence of atmospheric pressure and that a spongy pumice structure would be widespread on the moon.

G. Fielder (1961), reporting on the various published works of hupothesized lunar surface materials that were based on the color

of moonlight, found good agreement with Kozyrev's report of lava as a lunar surface material. The following summary is taken from Fielder:

W. W. Coblentz (1905)	Granite basalt, diorite (mixtures of feldspar, hornblende and mica).
J. Wilsing & J. Scheinder (1909)	Maria believed not unlike lava.
N. Barabasheff (1924)	Basalts, obsidians, lavas, and volcanic ashes.
F. E. Wright (1927, 1930)	Light-colored rocks, such as pumice, quartz porphyries, powders of transparent substances, trachytes, and granites.
J. Dubois (1960)	Darkened gneiss, diorite, trachyte (dark gray areas)

Photometric studies of natural occurring materials such as rocks, sands, lava, volcanic ashes and meteorites were conducted in an attempt to determine if their photometric properties would correlate with the photometric properties of the lunar surface, Hapke, 1963. However none of the materials produced a photometric curve which obeyed the lunar reflection law.

Firsoff, 1959, had suggested that if volcanic activity had produced the lunar surface materials then the texture of this material would be that of a "volcanic foam". Firsoff based his lunar volcanic foam theory on the probability that more outgassing would occur in a lunar volcanic material than would occur in a terrestrial lava because of the

lunar atmosphere being a vacuum in the 10^{-9} to 10^{-14} Torr range. He believed that a high rate of outgassing from a material would result in a very porous surface structure which would obey the lunar reflection law.

Warren, 1962, showed mathematically that such a material as described by Firsoff, "volcanic foam", if its porosity consisted of interconnected voids should obey the lunar reflection law. Warren however was unable to substantiate his "mathematical model" with experimental photometric measurements due to the unavailability of a geological material upwelled in vacuum.

Based on this background, an earth-moon correlation program was prepared and submitted to NASA in 1962. When this study program was not funded by NASA the writer undertook to perform a limited number of earth-moon correlation experiments with the help of Michigan State University, Gulf Research Laboratories, Pittsburgh, Pennsylvania and the Bendix Aerospace Systems Division, Ann Arbor, Michigan.

The first earth-moon correlation experiments performed were in the area of heat transfer within geological materials at vacuum pressures. The author in conjunction with the Gulf Research Laboratories, Messrs. Woodside and Messmer measured the thermal conductivity of solid pumice, obsidian, scoria, sandstone and granite, as a function of pressure, atmospheric to 10^{-2} Torr.

A brief summary of the results of this experiment as reported by Dobar, 1963, follows:

The thermal conductivity of all the samples measured were found to be dependent on pressure. The results of only the pumice and obsidian samples are shown below:

Pumice Solid

K = 1.369 millical/cm/sec/^{o}C at 735.1 Torr
K = 0.692 millical/cm/sec/^{o}C at 3.7 x 10^{-2} Torr

Obsidian Solid

K = 3.260 millical/cm/sec/^{o}C at 741.7 Torr
K = 2.850 millical/cm/sec/^{o}C at 4.4 x 10^{-2} Torr

A crushed pumice sample, particle size 10 microns to 0.5 inch, was then made from the remaining pumice material and its thermal conductivity also measured over the pressure range of atmospheric to 10^{-2} Torr.

Pumice Crushed

K = 0.376 millical/cm/sec/^{o}C at 725.1 Torr
K = 0.010 millical/cm/sec/^{o}C at 2.0 x 10^{-2} Torr

Based on this experiment and the results of Messrs. Woodside and Messmer, 1961, it was proven that the thermal conductivity of a limited number of geological materials was a function of pressure.

This experiment also showed that the thermal conductivity of a solid pumice sample at a vacuum pressure of 10^{-2} Torr is 6820

per cent greater than a granular sample in the same pressure environment thereby showing that a granular material in vacuum transfers less heat than a solid sample.

Using the thermal conductivity (k) results obtained at the Gulf Research Laboratories, the density (p) of the sample material and the specific heat (c) value of 0.2 cal/gr. as is standard practice in solving the thermal inertia equation $(kpc)^{-1/2}$ the following results were obtained.

Pumice Solid

k = 1.369 at 735.1 Torr	$(kpc)^{-1/2}$ = 53 cgs
k = 0.692 at 3.7×10^{-2} Torr	$(kpc)^{-1/2}$ = 76 cgs

Obsidian Solid

k = 3.260 at 74.7 Torr	$(kpc)^{-1/2}$ = 25 cgs
k = 2.850 at 4.4×10^{-2} Torr	$(kpc)^{-1/2}$ = 28 cgs

Pumice Crushed

k = 0.376 at 725.1 Torr	$(kpc)^{-1/2}$ = 109 cgs
k = 0.010 at 2.0×10^{-2} Torr	$(kpc)^{-1/2}$ = 653 cgs

Analysis of the above $(kpc)^{-1/2}$ results showed that solid pumice in vacuum would not equal $(kpc)^{-1/2}$ = 100 cgs as had been used in the two layer lunar model. This analysis also indicated that a granular pumice material would not provide a $(kpc)^{-1/2}$ = 1000 cgs. A review was then made of Woodside and Messmer's previous measurements of granular material to determine if any samples measured by them would provide a $(kpc)^{-1/2}$ = 1000 cgs, none were found.

A review of Smoluchowski's report provided the following:

The thermal conductivity values for powders in a vacuum that have been used for lunar surface materials studies based on $(kpc)^{-1/2}$ are usually taken from the International Critical Tables where a tabulated summary of Smoluchowski's data appears. Due to an unfortunate misinterpretation of Smoluchowski's report, the values reported in the International Critical Tables are erroneous (Liu & Dobar, 1964).

By using figures corrected according to Smoluchowski's instructions, the lowest thermal conductivity measured was 0.5×10^{-5} cal/cm/sec/^{o}C. This corresponds to a maximum value of $(kpc)^{-1/2} = 831$ cgs for quartz sand at a vacuum pressure of 6.4×10^{-2} Torr. This corrected thermal conductivity figure is in good agreement with the thermal conductivity of fine grain granular material measured in vacuum by Woodside and Messmer in 1961. It, however, does not meet the requirement of $(kpc)^{-1/2} = 1000$ cgs which has generally been referenced in hypothesizing a dust material for the lunar surface.

Based on the thermal conductivity measurements made in conjunction with the Gulf Research Laboratories and the following information was made available to him.

The thermal conductivity of a granular olivine basalt at 10^{-3} Torr was not greatly different from that obtained at 10^{-6} Torr. Also the change in the thermal conductivity of granular olivine basalt (100 per cent) from atmospheric to vacuum pressure is in good agreement with Dobar's results for pumice (97 per cent), Bernett et al., 1963.

These thermal conductivity experiments proved that the thermal conductivity of a material is a function of the pressure at the time of measurement. This factor therefore invalidates the solutions to the $(kpc)^{-1/2}$ equation where (k) was not used as a variable with pressure.

The two part report of Lucks et al., 1951-1952, proved that the specific heat and thermal conductivity of a material were also a function of temperature. This factor would also invalidate the solutions to the $(kpc)^{-1/2}$ equation where (c) and (k) were not used as variable with temperature.

At this point a more direct approach was taken to determine the thermal behavior of geological material in vacuum in an attempt to define the lunar surface material. Two samples, obsidian and pumice, were placed in a 28 by 20 foot cryogenically cooled vacuum chamber and a lunar eclipse was simulated while the samples were at a pressure of 10^{-6} Torr, Dobar, 1963. The heating and cooling curves for the pumice and obsidian samples that were obtained from this experiment were found to be in good agreement with the lunar

heating and cooling curves of Pettit, Pettit and Nickelson and also the more recent lunar thermal measurements of Sinton, and Saari and Shorthill. It was concluded that the $(kpc)^{-1/2} = 1000$ cgs equation had not defined the correct material, dust, for the lunar surface in that $(kpc)^{-1/2} = 28$ cgs, obsidian and $(kpc)^{-1/2} = 76$ cgs, pumice provided heating and cooling curves that match those of the lunar surface material when the thermal data was derived in a simulated lunar environment. This experimental data therefore indicated that the lunar surface material was probably rock or a compact unconsolidated material.

Based on the variations found in the physical properties of geological materials with vacuum pressure the next study had as its primary objective to:

> Design, fabricate and/or modify a large vacuum chamber to provide a capability for upwelling a molten material in a vacuum pressure.
>
> Develop a procedure for upwelling a molten material in a vacuum atmosphere.
>
> Upwell a series of rock melts in vacuum to simulate the formation of a lunar extrusive material.
>
> Determine if the photometric properties, light reflection, of the simulated lunar igneous surface rock would

match the photometric curve of the lunar surface material.

Determine the bearing strength, unconfined compression, of the simulated lunar igneous surface rock and compare the results with the 0.5 p.s.i. lunar surface material engineering design requirement.

GEOLOGICAL MATERIAL INVESTIGATED

The geological materials selected for use in the vacuum upwelling experiments were limited to:

Flint Glass

Flint glass was selected for developing the technique for vacuum upwelling a molten material in vacuum because of its low cost, ready availability, and a melting point temperature within the thermal capabilities of the electric furnace. Its composition is within the chemical spectrum of naturally occurring silicate materials and therefore also provided a material representative of a silicate melt.

Wausau Sand

Wausau sand was selected for developing and validating the high temperature portion of the vacuum upwelling technique based on its melting point, high silica content, and ready availability. The melting point temperature of this material provides an upper limit to the rock melt temperature necessary for the vacuum upwell experiments.

Wausau sand also covered the upper limit for the silica content of lavas. The classification of lavas are based largely on the weight percentage of silica which is the dominant oxide in naturally occurring rocks. Lava with a silica content of 66 per cent or above is classified as "acid", those with a silica content of 52 to 66 per cent are known as "intermediate" while those with a content below 52 per cent are termed "basic", Bullard, 1962.

Basalt

Basalt was selected for use in simulating a lunar extrusive based on its wide distribution and abundance as an extrusive on earth.

The basalt used in this study program was obtained from Wards Natural Science Establishment, Inc., and verified by Dr. J. Zinn utilizing petrographic thin sections.

The petrographic thin section analysis was as follows:

Basalt - Bend, Oregon

Composition:	Basic andesine (An 46%)	40%
	Augite	35%
	Serpentine	10%
	Devitrified glass	12%
	Magnetite	2%
	Calcite (secondary)	1%

Granite

Granite was selected for vacuum upwelling at a temperature of 1000°C, 200 to 300°C above its melting point temperature, to determine if vacuum outgassing of a granite melt would alter its chemical composition to that of a tektite. The similarity in the chemical compositions of granite and tektites had led to a hypothesis by Chao, 1962 and Lowman, 1963 that tektites were formed from a lunar surface granitic material which was subsequently modified to a tektite composition. It has been suggested that this chemical modification may have been the result of:

Lunar surface impact melting and associated outgassing due to a vacuum atmosphere and/or aerodynamic heating and associated outgassing of the ejected material when it entered the earth's atmosphere.

The granite samples used in this study program were obtained from Wards Natural Science Establishment, Inc., and verified by Dr. J. Zinn utilizing petrographic thin sections.

Granite - Westerly, Rhode Island

Composition:

Feldspar, perthite and orthoclase plagioclase intergrowths	84%
Augite	5%
Quartz	3%
Biotite	3%
Chlorite (red and green)	3%
Magnetite	1% $\pm$
Carbonate	1% $\pm$

EXPERIMENTAL EQUIPMENT

The following type of vacuum facilities and/or equipment was necessary in performing this series of laboratory experiments:

(1) Vacuum Facilities

A 4 x 8 foot vacuum chamber capable of obtaining a vacuum pressure of 10^{-8} Torr, Figure 1. The vacuum pumping capabilities of this chamber were as follows:

(a) Mechanical roughing pump with a 200 cubic feet/minute pumping capability.

(b) Main oil diffusion vacuum pump with a pumping capability of 30,000 liters/second after the chamber pressure is at 10^{-6} Torr or below.

A bell jar baseplate assembly, Figure 2, was bolted to the side of the vacuum chamber as shown in Figure 1. A quick-opening manually operated valve, bell jar vacuum control valve, was positioned in the baseplate assembly such that it separated the pressure chamber of the vacuum chamber from the bell jar chamber when it was in a closed position. When this valve was placed in the open position it allowed the bell jar chamber to attain an equalization pressure with that of the vacuum chamber.

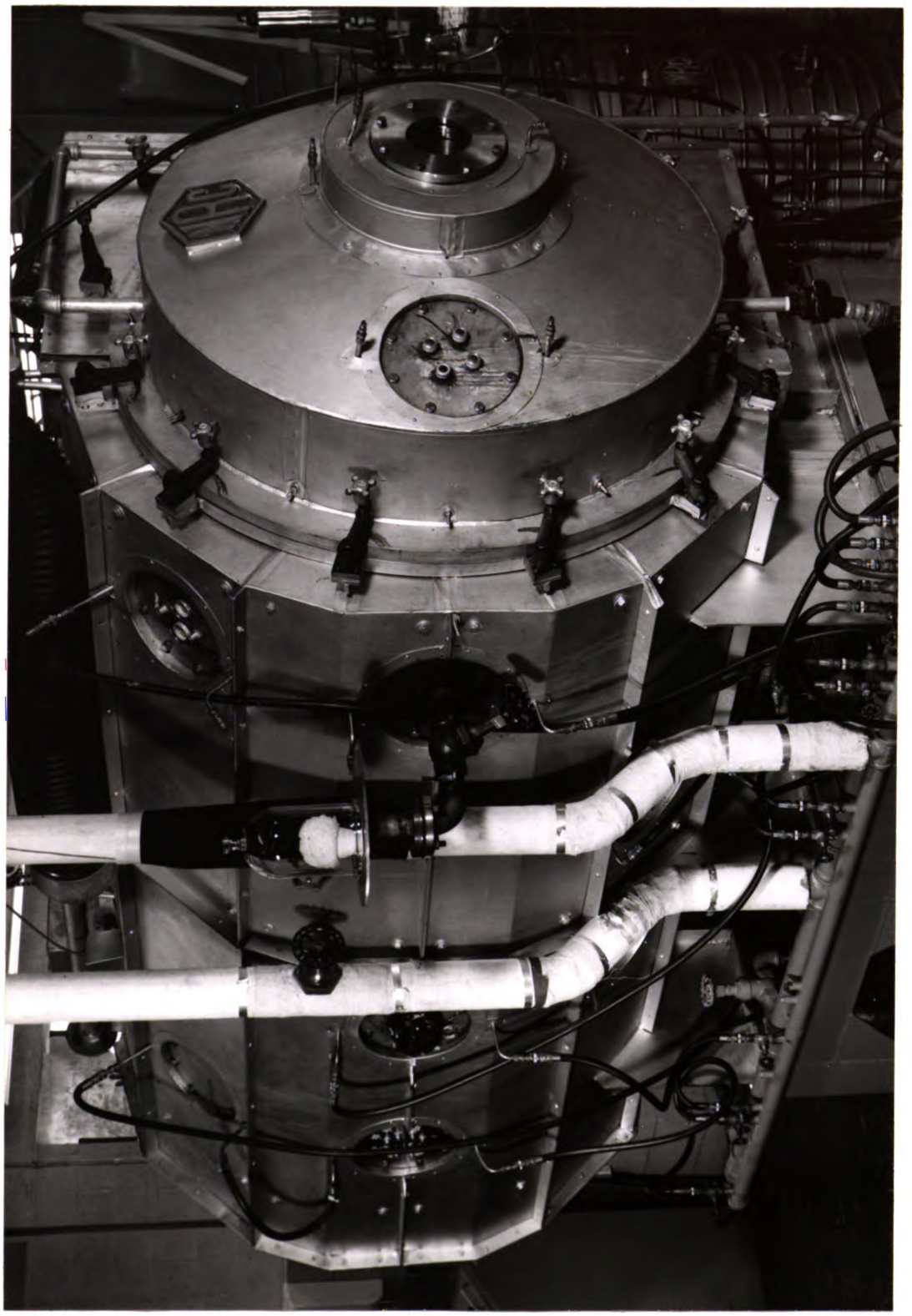

Figure 1. 4 x 8 Foot Vacuum Chamber with Baseplate Attached. A Wausau Sand Sample is Shown Within the Bell Jar. The Large Valve Within the Baseplate Assembly, Nearest Vacuum Chamber is the Bell Jar Chamber Vacuum Control Valve and the Small Valve to the Left is the Bell Jar Vacuum Relief Valve.

Figure 2. Bell Jar Baseplate Assembly Showing Upwelled Wausau Sand Sample Within Bell Jar and the Bell Jar - Rubber Gasket - Baseplate Seal.

The pressure gauges of the chamber were calibrated against National Bureau of Standards reference gauges. This calibration thus provided for an accurate "read out" of the pressure within the vacuum chamber during an upwelling experiment.

A bell jar chamber pressure relief valve was incorporated in the baseplate assembly to facilitate the removal of the bell jar from the baseplate. This valve is shown in the lower right hand corner of the baseplate assembly in Figure 1. The vacuum relief valve was necessary to enable the bell jar to be removed from the baseplate as the pressure within the bell jar chamber could be as low as 10^{-6} Torr after an upwelling experiment.

(2) Furnace

A Temco, Type 1500, electrical furnace capable of providing a 1800°C temperature within the 4 x 6 x 12 inch heating area was used to melt the sample materials used in the vacuum upwelling experiments. To achieve temperatures above 1200°C it was necessary to electrically overdrive the furnace which would result in the furnace heating elements being ruined when the furnace was returned to room temperature. Therefore after a vacuum upwelling experiment with melt temperatures above 1200°C it was necessary to overhaul the furnace.

(3) Motion Picture Camera

A Beaulieu RG-16 electrical drive 16 mm. movie camera with an Angenieu 12 to 120 mm. zoom lens provided the means of obtaining color pictorial coverage of the upwelling process. The use of a 64 frames/second filming rate, approximately 1 frame/16 milliseconds, allowed for "real time" measurements to be made from any sequence of photographs of the upwelling process.

(4) Bearing Strength Equipment

A soil Testing Services unconfined compression test machine model number 26-B was utilized to obtain the bearing strength of the vacuum upwelled samples, Figure 3.

Figure 3, Bearing Strength, Unconfined Compression, Experimental Test Set Up.

(5) Photometric Measuring Equipment

Photometric curves for the vacuum upwelled samples were obtained for comparison with those of the lunar surface using a photomultiplier tube (RCA #5812) and associated electronic equipment. A block diagram of the photometric measurements instrumentation is shown in Figure 4.

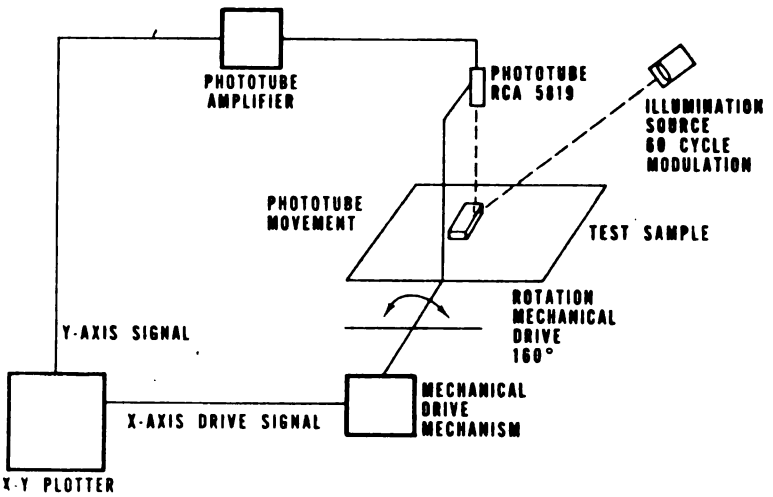

Figure 4. Block Diagram of the Experimental and Instrumentation Setup for Obtaining Photometric Curves of Vacuum Upwelled Samples.

EXPERIMENTAL PROCEDURES

Single Crucible Wausau Sand and Flint Glass Samples

In the initial vacuum upwelling experiments a measured quantity, 50 mm. by volume, of Wausau sand or Flint glass was placed in a crucible. The sample was then melted at 1500°C in atmospheric pressure by means of an electric furnace and held at this temperature to allow a gaseous-liquid equilibrium state to develop. For this study a gaseous-liquid equilibrium state was established as the point where entrapped air bubbles in the melted material disappeared. In this series of experiments this occurred approximately 30 minutes after the sample reached 1500°C. The furnace temperature was then adjusted to either 1800°, 1600°, 1200°, or left at 1500°C for an additional 30 minutes to obtain samples for vacuum upwelling at different melt temperatures. The sample was then removed from the furnace and the crucible was placed directly on the baseplate. The bell jar was then placed over the crucible and attached to the baseplate by means of a vacuum grease-rubber seal. For the sequence of events beginning with the removal of the sample from the furnace through the attachment of the bell jar to the baseplate time was held to approximately 20 seconds, to limit sample cooling to a minimum. The bell jar vacuum control valve separating the vacuum chamber at a pressure of 10^{-8} Torr from the bell jar was then opened. This instantaneously reduced the

atmospheric pressure of the bell jar to that of a vacuum pressure and caused the melt to vacuum upwell from the crucible. The vacuum chamber continued to pump during the decompression-sample upwelling phase to remove any gases that were "outgassed" from the upwelling magma. This vacuum pumping provided a vacuum condition of 10^{-6} Torr during sample solidification. The bell jar vacuum control valve which separated the vacuum chamber from the bell jar was closed when the upwelled melt no longer showed a visible color temperature. The vacuum pressure within the bell jar was then brought to atmospheric pressure by actuating the pressure relief valve. When atmospheric pressure was achieved within the bell jar chamber it was removed from the baseplate. The upwelled sample was then removed from the baseplate and allowed to cool to room temperature.

Motion picture coverage of the vacuum upwelling process at 64 frames/second began when the crucible with the melted sample was placed on the baseplate. It was concluded when the sample reached its final phase of vacuum upwelling-solidification within the bell jar chamber. This motion picture coverage therefore provides a "real time" reference of the upwelling sequences with one frame equaling 16 milliseconds.

Multiple Crucible Wausau Sand Sample

In the second series of vacuum upwelling experiments two crucibles were used and 250 mm. by volume of sample material was

placed in each crucible. The sample was melted and allowed to develop a gaseous-liquid equilibrium at 1500° as described for the single crucible experiments. The two crucibles were then removed from the furnace and placed in a metal holding fixture positioned on the baseplate. This metal holding fixture provided a 0.40 inch surface to surface contact around the circumference of the crucible at a point above the level of the molten material in the crucibles. This procedure change reduced the amount of sample cooling, visible color temperature, that had been observed prior to vacuum upwelling when the crucibles were placed directly on the baseplate. In this second series of experiments the procedure also was modified at the point where vacuum upwelling occurred. The melt upwelled in vacuum but sample solidification was allowed to occur under a partial atmospheric pressure created by the outgassing melt. To achieve this type of sample solidification the following modification to the single crucible procedure was made.

The bell jar vacuum control valve separating the vacuum chamber at 10^{-8} Torr from the bell jar was opened only for a period of 15 seconds and then closed. The vacuum upwelled sample was then allowed to remain under the bell jar outgassing and creating its own partial atmospheric pressure until solidification occurred. Due to instrumentation limitations vacuum pressure gages were not incorporated

in the bell jar assembly therefore the vacuum pressure at which the rock melt solidified is unknown.

The vacuum pressure within the bell jar was then brought to atmospheric pressure by actuating the bell jar chamber pressure relief valve. When atmospheric pressure was achieved within the bell jar the bell jar was removed from the baseplate and then the metal holding fixture and the crucibles containing the sample were allowed to cool to room temperature.

Single or Multiple Crucible Basalt and Granite Samples

The experimental procedure followed in vacuum upwelling of basalt and granite melts was the same as that used for the Wausau sand, Flint glass single crucible experiments except for the following:

The crucibles were placed in a metal holding fixture on the baseplate as described for the multiple crucible Wausau sand experiment to minimize the cooling of the rock melt by heat transfer to the bell jar baseplate assembly.

Melt temperatures for the basalt material were reduced to 700° and 1000° to be more comparable with the temperatures observed for molten basalt lava.

The melt temperature for the granite material was 1000°C or approximately 200° to 300°C above its melting point temperatures. This temperature was selected for the granite

material to allow for maximum outgassing to occur from the granite melt. The chemical composition change due to material outgassing was to be determined from these samples by Dr. Chao of the U.S.G.S. Due to an organizational change within the U.S.G.S. Dr. Chao was unable to perform the required chemical analysis. Therefore the chemical composition change due to outgassing of a granite melt upwelled in vacuum was not determined in this study.

DESCRIPTION OF UPWELLING PROCESS

The rock melt vacuum upwelling processed described in this section were determined by visual observations and from 16 mm., 64 frame per second, color motion picture coverage. Where times are reported for any sequence of events and/or visible color temperatures in the vacuum upwelling process, they were determined by frames per second reference from the movie coverage of that particular vacuum upwelling experiment.

Single Crucible Wausau Sand and Flint Glass Samples

The single crucible samples were vacuum upwelled utilizing a procedure which provided for upwelling and solidification in a simulated infinite vacuum. These samples were observed to upwell initially as a dome shaped mass in 5 to 15 seconds during which they radiated a high intensity light varying in wave length from red to orange depending upon the rock melt temperature at which it was upwelled. The dome shaped mass continued to expand in size while continuing to radiate light at the rock melt's visible color temperature without any violent foaming or frothing surges occurring due to outgassing. Figures 5, 6, and 7 have been arranged in accordance with the upwelling sequence for a magma vacuum upwelled at 1500°C. In this pictorial sequence, Figure 5 shows the upwelling process 7 seconds after initial upwelling, Figure 6 is 33 seconds later, and Figure 7 is 57 seconds after initial upwelling.

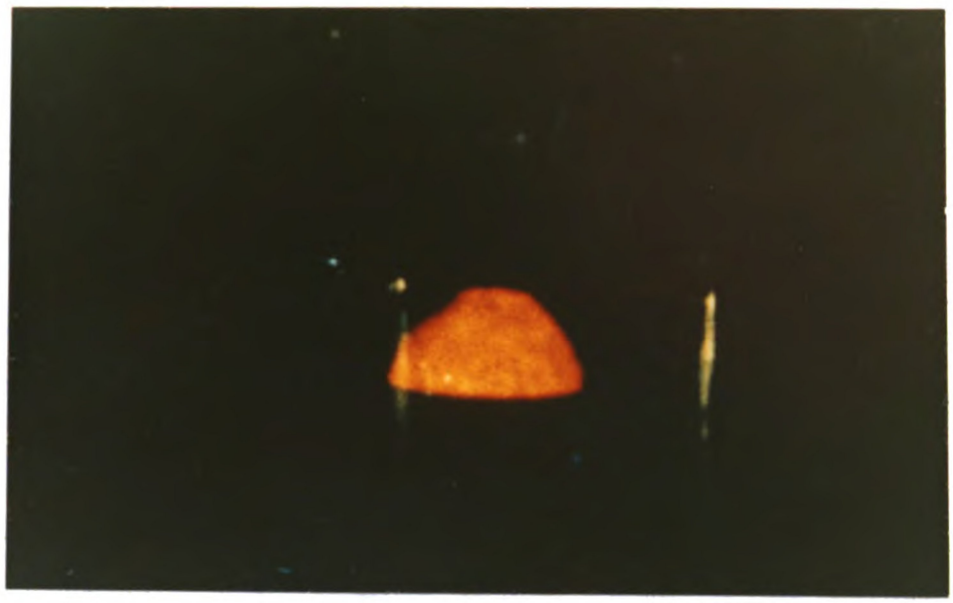

Figure 5. Initial Phase of Wausau Sand, Upwelling in Vacuum. Time 7 seconds.

Figure 6. Second Phase of Wausau Sand Upwelling in Vacuum. Note Visible Color Temperature Increase at Base of Crucible. Time 33 seconds.

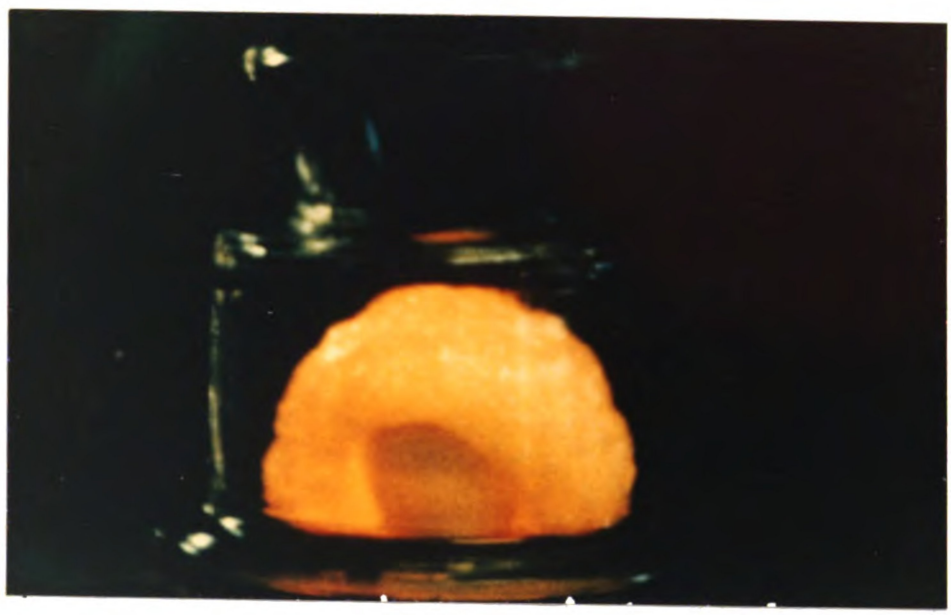

Figure 7. Third Phase of Wausau Sand Upwelling in Vacuum, and just at the Point that Solidification is Beginning to Occur. Time 57 seconds.

The single crucible vacuum upwelling experiments have shown that the initially upwelled domed shaped masses will develop into a variety of shapes depending on the visible color temperature of the rock melt at the time of upwelling. Figure 8 shows a group of samples with a variety of shapes which resulted from the rock melt being vacuum upwelled at different temperatures.

Figure 8. Wausau Sand Samples which were Upwelled in Vacuum at Different Rock Melt Temperatures.

Shown Left to Right are:

Sample Upwelled at a Temperature of 1200°C
Sample Upwelled at a Temperature of 1500°C
Sample Upwelled at a Temperature of 1600°C
Sample Upwelled at a Temperature of 1800°C

Multiple Crucible Wausau Sand Sample

The multiple crucible sample upwelled in vacuum initially as a large dome shaped mass within 6 seconds which almost completely filled the interior of the bell jar, Figure 9. The upwelled rock melt radiated a high intensity light in the red-orange color spectrum while it remained in the position shown in Figure 9 for a period of 2.5 minutes. During this time period there was no visible evidence of violent foaming of the rock melt from rock melt outgassing.

The dome shaped rock melt then suddenly collapsed forming the structure shown in Figure 10. Time separation between Figure 9 and 10 is 32 milliseconds as determined from the motion picture coverage. The rock melt solidified under the partial pressure created by the rock melt outgassing and formed a crater structure, Figure 11.

The formation of a crater structure as opposed to the shapes shown in Figure 8 is attributed to:

> Rock melt retaining its temperature for a longer period of time due to the outgassed materials not being evacuated from the bell jar.
>
> The rock melt by retaining this higher temperature until a partial atmospheric - rock melt absorbed gases equilibrium condition developed collapsed due to the force of gravity.

In Figure 9, the rock melt appears to extend beyond the holding fixture and come in contact with the bell jar. This is an optical phenomenon due to the heavy wall of the bell jar. If the rock melt temperature is above 600°C and contacts the inside of the bell jar the thermal shock will cause an implosion. Due to the danger of a possible implosion in conducting this type of upwelling experiment no further experiments of this type were undertaken.

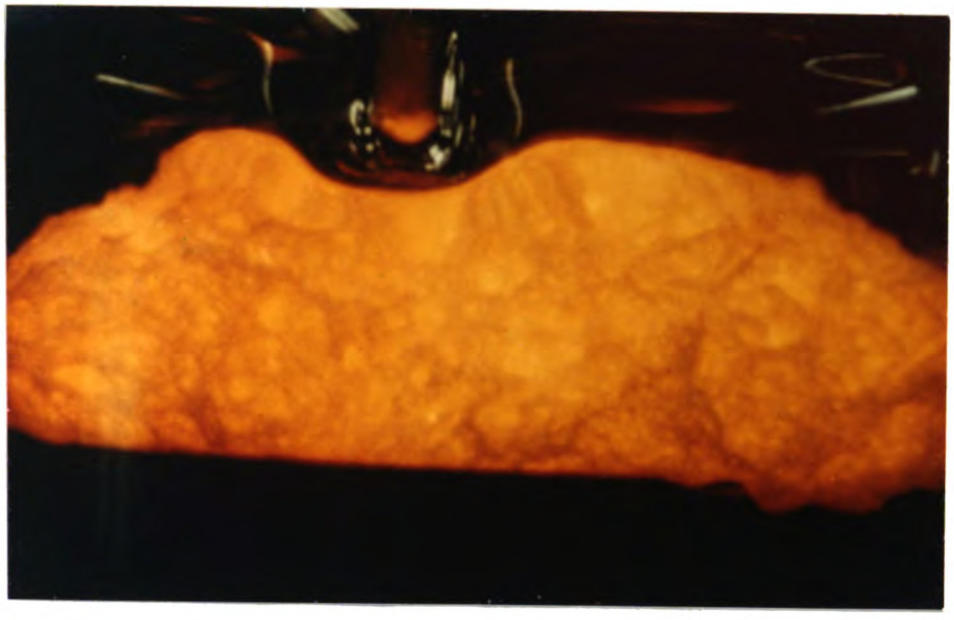

Figure 9. Vacuum Upwelled Multiple Crucible Wausau Sand Sample at a Temperature of 1500° C. Time 4 seconds.

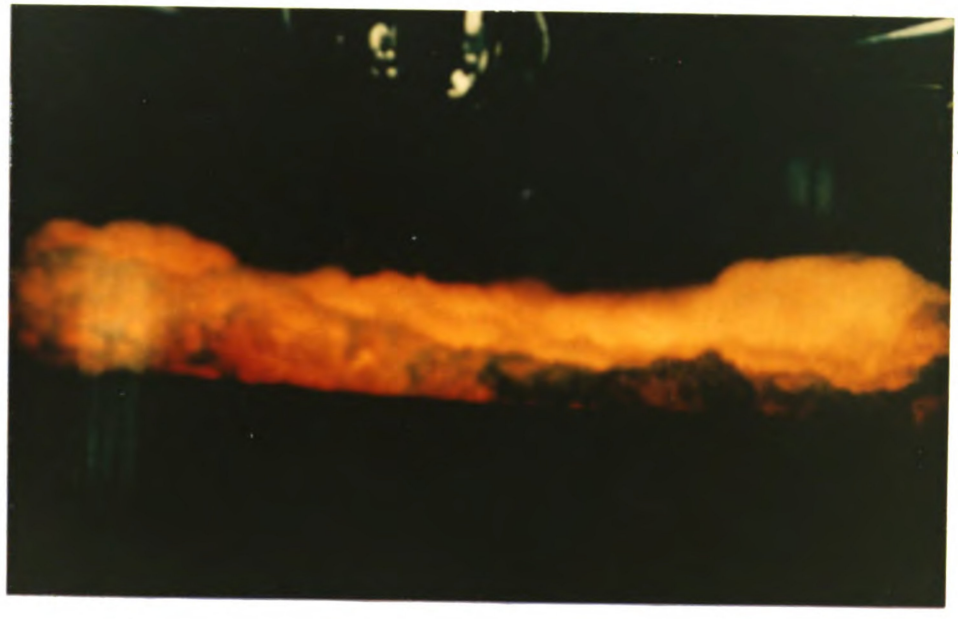

Figure 10. Vacuum Upwelled Multiple Crucible Sample, same as Figure 9, after Collapsing Due to a Partial Atmospheric Pressure Build Up Due to Rock Melt Outgassing.

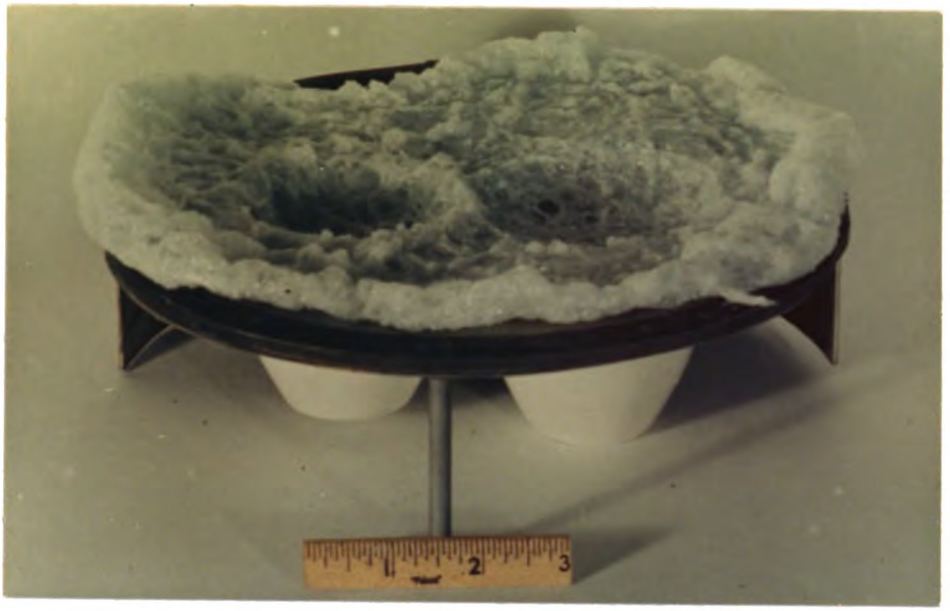

Figure 11. Silica, Wausau Sand, Sample Showing a Crater like Structure after the Silica Magma was Upwelled at 1500°C and a Partial Atmospheric Pressure was Formed within the Bell Jar Chamber due to the Magma Outgassing.

Multiple and Single Crucible Basalt Samples

The basalt melt at 1000°C also upwelled in vacuum as a dome shaped mass in 6 seconds while radiating a high intensity light visible in the red to orange spectrum, Figure 12. This dome shaped mass continued to expand in size until at 14 seconds after initial upwelling the dome's surface suddenly ruptured allowing the high temperature rock melt within the sample, determined by visible color temperature, to begin to flow through the cooler surface material, Figure 13. The higher temperature rock melt continued to flow through the break in the rock melt's outer surface and as its volume increased there was a sharp increase in the radiated light intensity, Figure 14. The rock melt continued to upwell until the outer surface

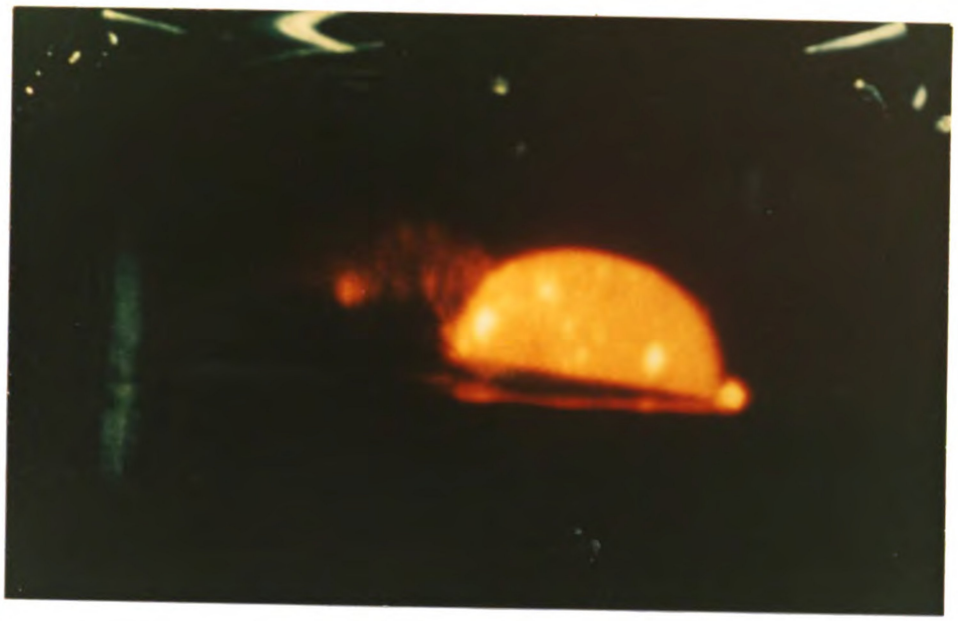

Figure 12. Initial Phase of Basalt Melt Upwelling in Vacuum, Time 6 seconds.

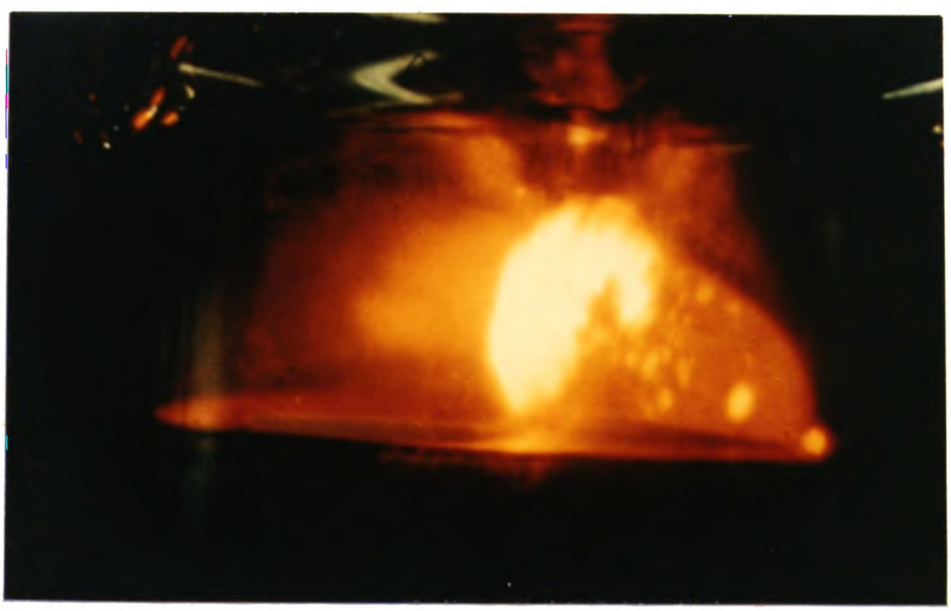

Figure 13. Second Phase of Basalt Melt Upwelling in Vacuum. Note Hotter Melt Breaking Through Cooled Surface Material and the Increase in Light Brilliance. Time 14 seconds.

cooled to a point that solidification began to occur, Figure 15. The sample's color was then a porous red outer surface through which could be seen the internal rock melt at a higher temperature, orange color. As the sample continued to cool the sample's outer surface then appeared as a porous black structure on which there was red and orange polka dots, Figure 16. This color effect was due to the internal rock melt having a higher temperature, orange color, than the surface, black color. The higher temperature rock melt within the sample also caused the thin areas of the porous surface to be heated to a red color temperature which caused the red-orange polka dot appearance on a black background. At this time in the upwelling sequence, 3 minutes and 42 seconds, the red-orange polka dots appeared to move from point to point on the sample in a random manner. This was due to the sample being in an infinite vacuum with high temperature rock melt still within the sample. The high temperature rock melt, orange color, was drawn to the surface by the vacuum atmosphere where it would solidify changing in color from orange to red and finally black. Solidification of the rock melt at the surface would then cause the sample's surface to crack and again expose the internal temperature rock melt. This process continued to repeat itself until the internal rock melt had cooled to a temperature where it was no longer capable of being withdrawn by vacuum pressure.

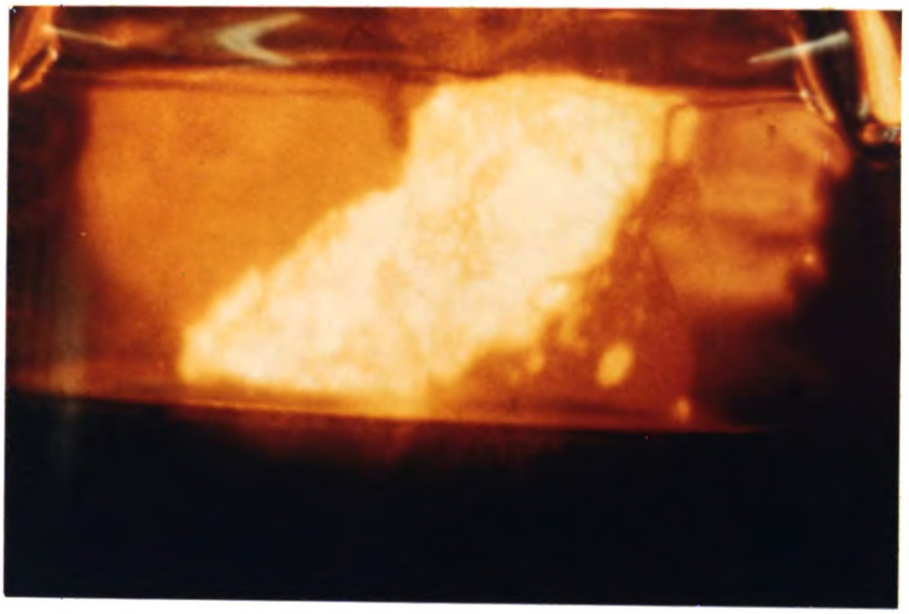

Figure 14. Third Phase of Basalt Melt Upwelling in Vacuum. Note Increased Light Brilliance. Time 17 seconds.

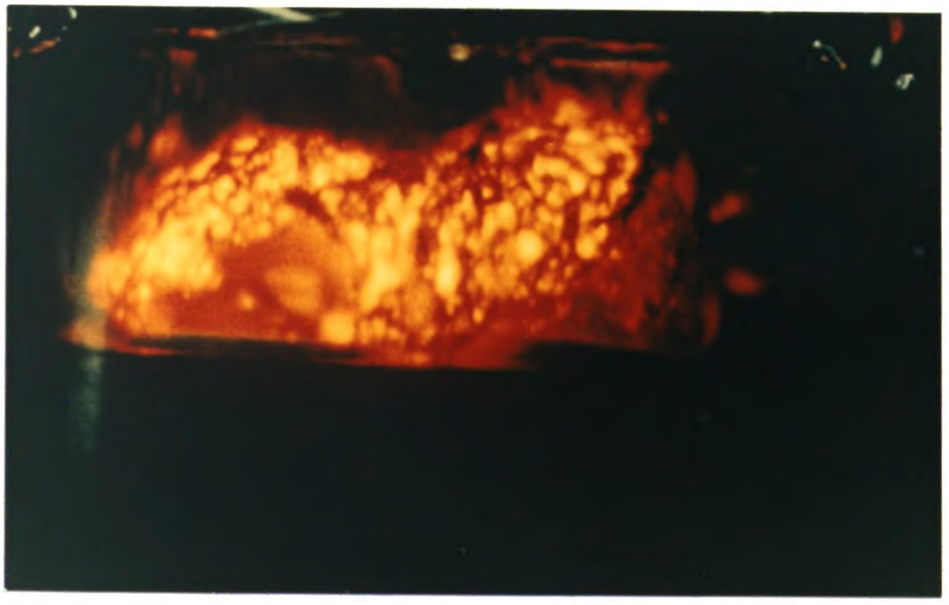

Figure 15. Fourth Phase of Basalt Melt Upwelling in Vacuum Sample Beginning to Cool, Solidify and Lose Part of its Light Brilliance. Note Polka Dot Orange-Red Color. Time 1 minute 45 seconds.

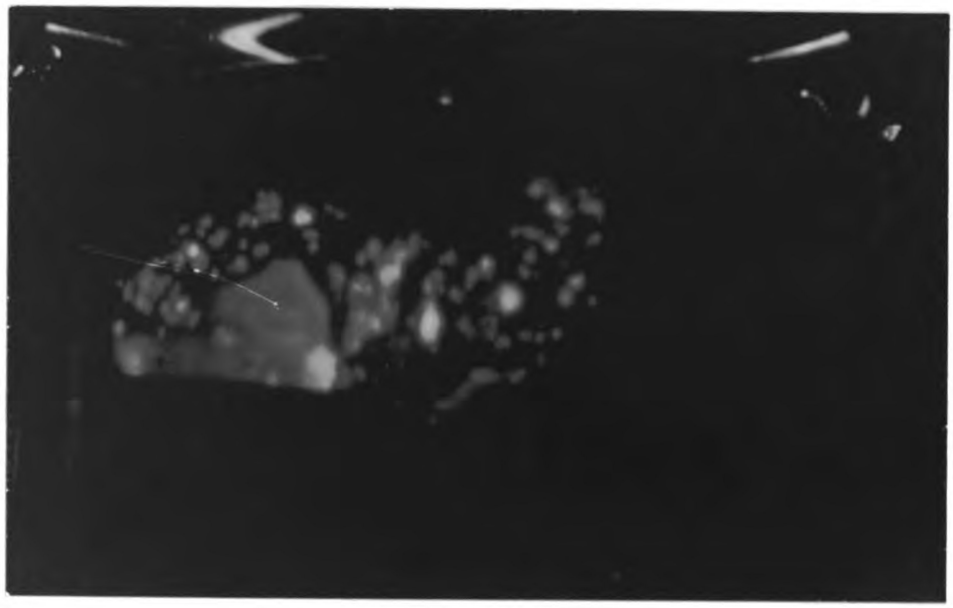

Figure 16. Fifth Phase of Basalt Melt Upwelling in Vacuum, Sample Surface has Cooled but Melt at Higher Visible Color Temperatures, Red and Orange Color, Can Still Be Observed. The "still" Polka Dot Red-Orange Color Shown in this Single Frame from the Motion Picture Coverage Actually Moves About the Sample's Surace when the Film is Projected at its Correct Filming Rate. Time 3 minutes, 42 seconds.

The basalt sample structure after vacuum upwelling of a rock melt at 1000°C is shown in Figure 17.

The basalt upwelling experiments have also shown that the initially vacuum upwelled domed shape masses will develop into a variety of shapes depending on the color temperature of the rock melt at the time of upwelling, Figures 18 and 19.

Figure 17. Basalt Sample after Rock Melt Upwelling in Vacuum at 1000° C.

Figure 18. Basalt Sample after Rock Melt Upwelling in Vacuum at 1200° Centigrade.

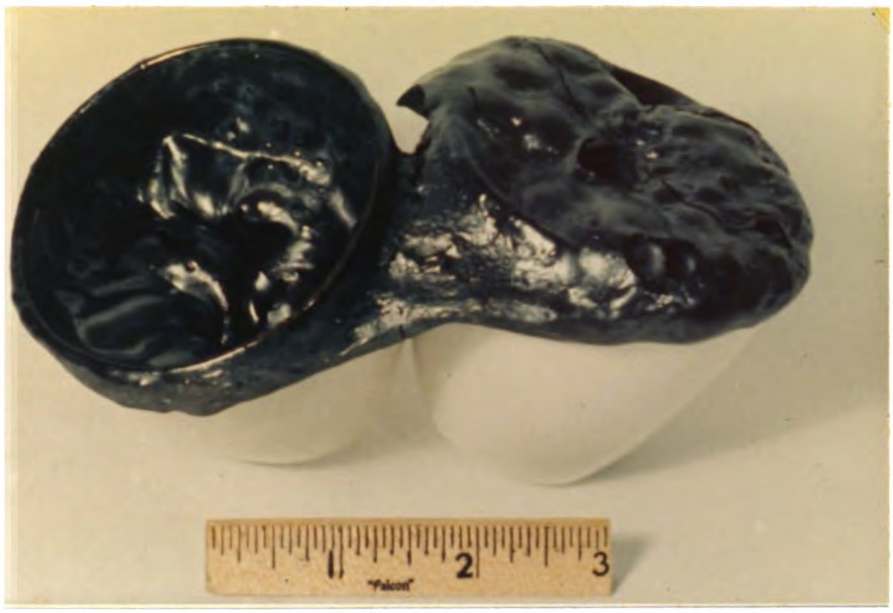

Figure 19. Basalt Sample after Rock Melt Upwelling in Vacuum at 700°C.

Multiple and Single Crucible Granite Samples

The granite melt at 1000°C upwelled in vacuum in the same manner as described for the 1000°C basalt samples. The sample structure formed by the granite melt at a temperature approximately 200 to 350°C above its melting point temperature is shown in Figure 20.

There were no low temperature vacuum upwelling experiments attempted with granite material.

During the upwelling of Wausau sand, Flint glass, basalt, and granite melts in vacuum a visible gaseous discharge similar to that associated with volcanic activity on earth was not observed. To

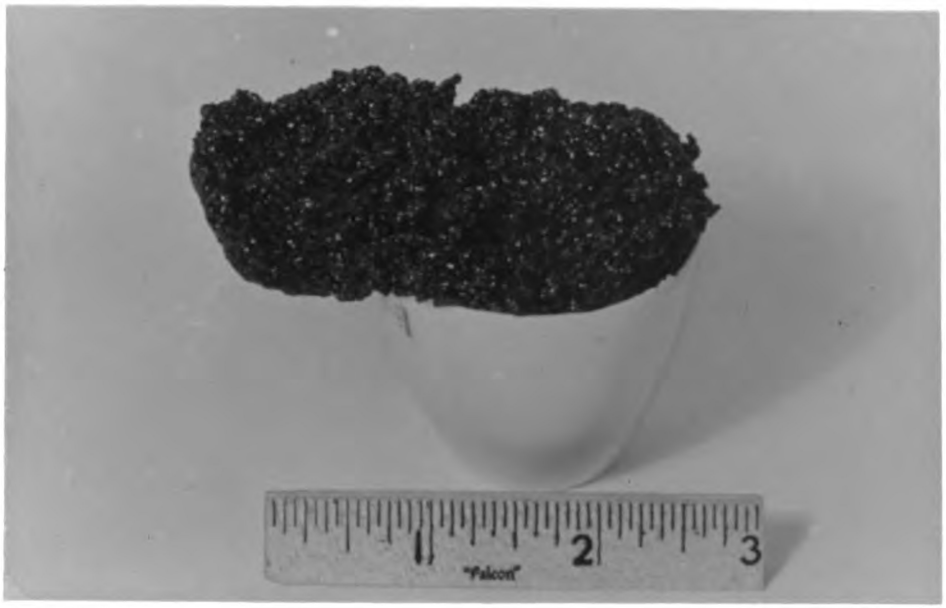

Figure 20. Biotite Granite Sample after Magma Upwelling in Vacuum at 1000°C.

determine if a vacuum atmosphere would support a water vapor discharge, similar to that found above an active volcano, 25 mm. of water was placed in a crucible and subjected to vacuum decompression. A water vapor gaseous discharge was not visually observable; however, the vacuum pressure within the 4 x 8 foot vacuum chamber rose from a 10^{-8} Torr pressure to 2 mm. vacuum pressure in milliseconds. This large pressure rise was observed even though the vacuum pumps for the 4 x 8 foot vacuum chamber were continuing to pump during the vacuum upwelling of the water. Examination of the crucible, bell jar chamber, and vacuum chamber immediately after conducting this experiment disclosed:

The water in the crucible had been completely evaporated.

The crucible was too cold to touch with bare hands.

The sides of the bell jar chamber were not covered with water formed by condensation.

The inside walls of the 4 x 8 foot vacuum chamber was not covered with water formed by condensation.

Thus, this experiment has shown that a small quantity of water, 25 milliliters, released in a vacuum pressure of 10^{-8} Torr/132 cubic foot area will completely evaporate in milliseconds and cause a large increase in the vacuum atmospheric pressure without forming a visible gaseous water vapor discharge.

The rock melt vacuum upwelling processes observed during this series of experiments indicate:

The shape which the rock melt will upwell from a given diameter orifice is a function of the rock melt temperature. It may also be a function of the vacuum pressure and the rate of decompression but during this series of experiments they were constant for all the experiments conducted.

The radiated light intensity and its color are a function of the temperature of the rock melt at the time of initial upwelling.

The amount, by volume, that the rock melt will upwell out of the crucible is a function of the rock melt temperature when decompression rate and vacuum are constants in the process of vacuum upwelling. The amount of gas absorbed by the rock melt was not measured and may also be a function of the amount of material that will upwell from the crucible.

The process of vacuum upwelling of rock melt in a pyrex bell jar to allow motion picture coverage of the upwelling process presents a personnel safety problem due to the possibilities of an implosion.

Water released in vacuum would appear not to form a visible gaseous discharge of water vapor; but will cause a large increase in the vacuum atmosphere pressure.

This process of vacuum upwelling water into a vacuum chamber at 10^{-8} Torr presents an equipment safety problem due to the fact that all the oil within the oil diffusion pump, 50 gallons, will back flow into the vacuum chamber if the pressure rises above 5 millimeters Torr.

DESCRIPTION OF SAMPLES OBTAINED

Single Crucible Wausau Sand

The vacuum upwelled Wausau sand samples are porous masses, 15 to 20 times the original volume of the sample material with an average density of 0.25 gr/cm^3. Their outer surface consists of a rough porous structure similar to lechatelierite, Figure 21, while the internal structure consists of interconnected voids which resembled the structure of a sponge Figure 22 and 23. The webbing forming the interconnecting walls of the sample is opaque and its microstructure is similar to certain varieties of lichen and sponges both of which have reflection curves that correlate with the lunar surface, Hapke and Van Horn, 1963.

Dr. J. Zinn by petrographic analysis of thin sections concluded: The surface structure was formed by solidification of an outer surface layer which was then fractured due to the stresses generated by the rock melt continuing to upwell from below. A new porous surface layer was then formed as the additional rock melt invaded the fractured areas. This process continued to repeat itself until the rock melt within the sample had completely solidified and could no longer supply molten material to the surface.

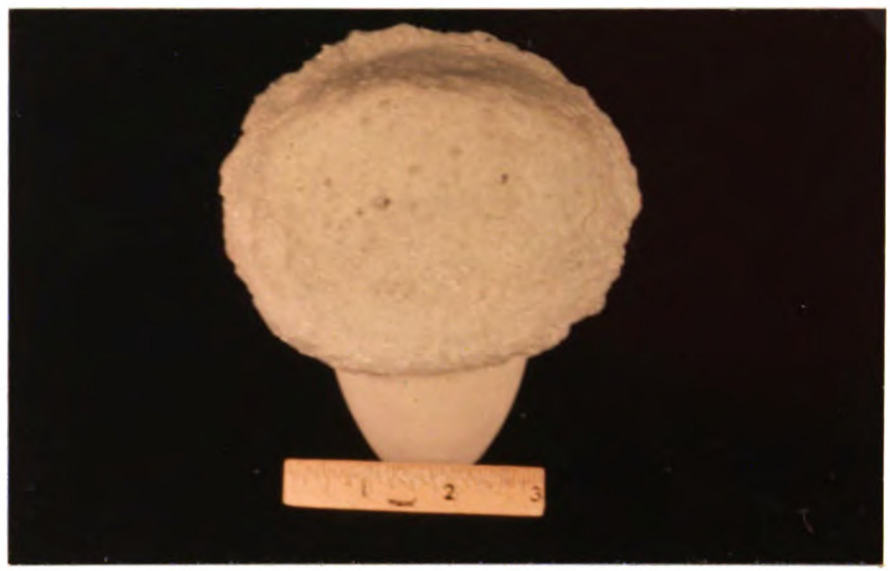

Figure 21. Wausau Sand Sample Formed from Melt at 1500° C Upwelled in Vacuum.

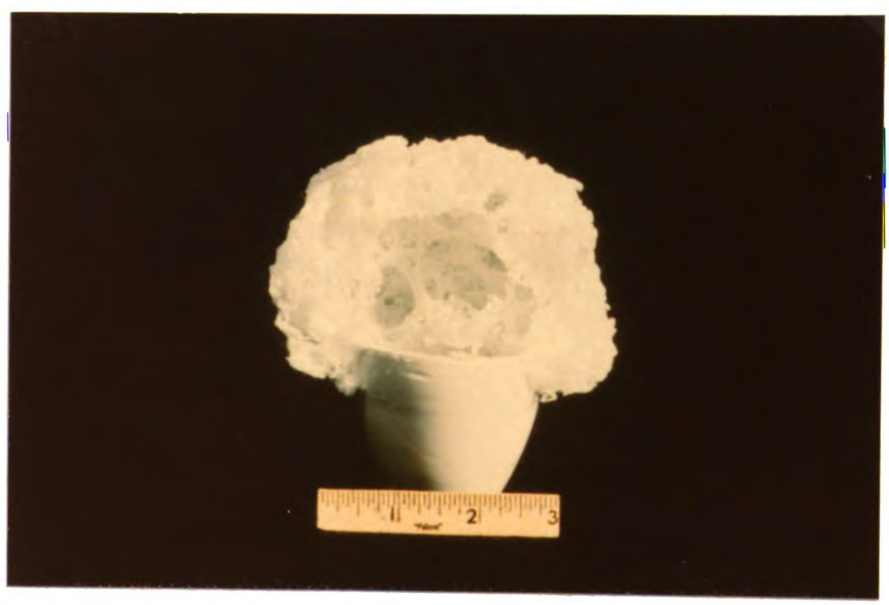

Figure 22. Wausau Sand Sample Showing Internal Structure Formed from Melt at 1500° C Upwelled in Vacuum.

Figure 23. Wausau Sand Sample Showing Sponge Like Structure Formed from Melt at 1500°C Upwelled in Vacuum.

Single Crucible, Flint Glass

The outer surface of the Flint glass samples consists of a porous structure overlaid with material resembling "Pele's Hair" and the internal structure consists of a large void, Figure 24. This internal structure would suggest that a large volume of gas was "outgassed" from the rock melt during vacuum upwelling and formed a "Pele's Hair" structure in a typical volcanic manner. Bullard, 1962 indicates that in lava fountains steam jets blow rock melt into the air a material may be produced which resembles spun glass and is known as "Pele's Hair". "Pele's Hair" is also identified with varieties of "rock wool" which are manufactured by blowing a jet of steam into molten rock.

Figure 24. Flint Glass Sample Formed from Melt at 1500°C Upwelled in Vacuum. Note "Pele's Hair" Structure on Outer Surface and Large Internal Void Area.

Multiple Crucible Sample Wausau Sand

The sample obtained from this experiment was a crater like structure 8 - 12 inches in diameter and approximately 1/2 inch in depth with the interior slope of the crater having the appearance of a slumped surface, Figure 11. The outer surface of this sample exhibited a varying degree of roughness and consists of a porous material with interconnected voids similar to that found in the single crucible silica samples. This porous layer completely covered the upper surface area of the crater and varied in depth from 1/16 inch to 1/2 inch. Below this layer a dense layer of silica is present which contains non-interconnected voids, "air bells", which measure

from 3/16 to 3/8 of an inch in length, and have a diameter of 1/64 to 1/16 of an inch. A cross section showing both the porous and dense layer of silica with "air bells" is shown in Figure 25.

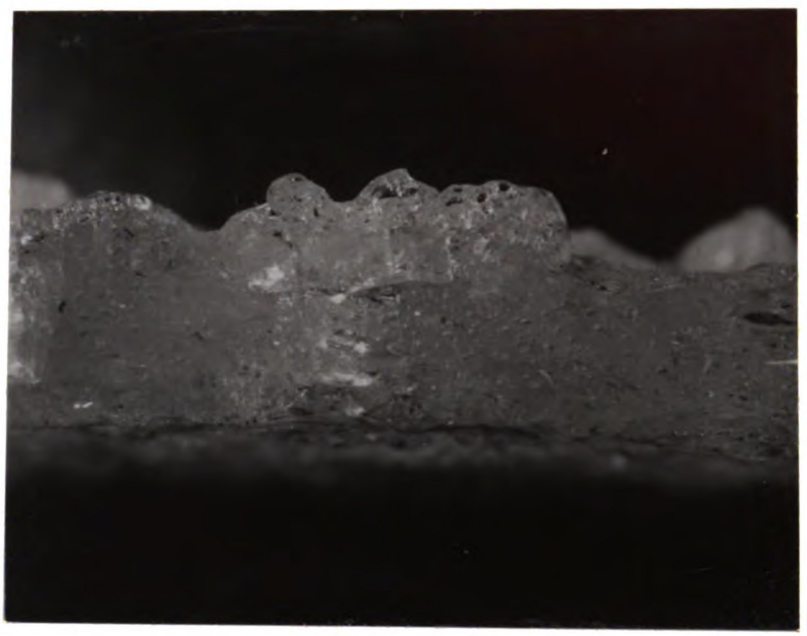

Figure 25. Wausau Sand Sample Showing Internal Structure Formed from Melt at 1500°C Upwelled in Vacuum with Solidification Under a Partial Atmospheric Pressure

Multiple and Single Crucible Sample Basalt

The vacuum upwelled basalt samples were porous masses 5 to 15 times the volume of the original sample material. The average density of the basalt was 0.26 gr/cm^3. The external and internal structure of the basalt samples formed from magma vacuum upwelled at 1000°C are similar to that described for the Wausau sand samples.

The external structure of a basalt sample is shown in Figure 17 and its internal structure is shown in Figure 26.

Figure 26. Basalt Sample Showing Internal Structure Formed from Melt at 1000°C Upwelled in Vacuum.

Basalt Melt upwelled at 700°C formed samples with pitted surfaces similar to that known as karst topography on Earth. These samples also exhibit stress cracks which formed during the vacuum-cooling cycle, Figure 19. The internal structure of these samples consists of a series of large voids, Figure 27. The large internal void structure suggests that or near 700°C the basalt melt has solidified to a

point that it will no longer allow outgassing to occur through its outer surface. The vacuum atmosphere above this semi-solidified rock melt then causes a number of large internal gaseous pockets to occur within the material.

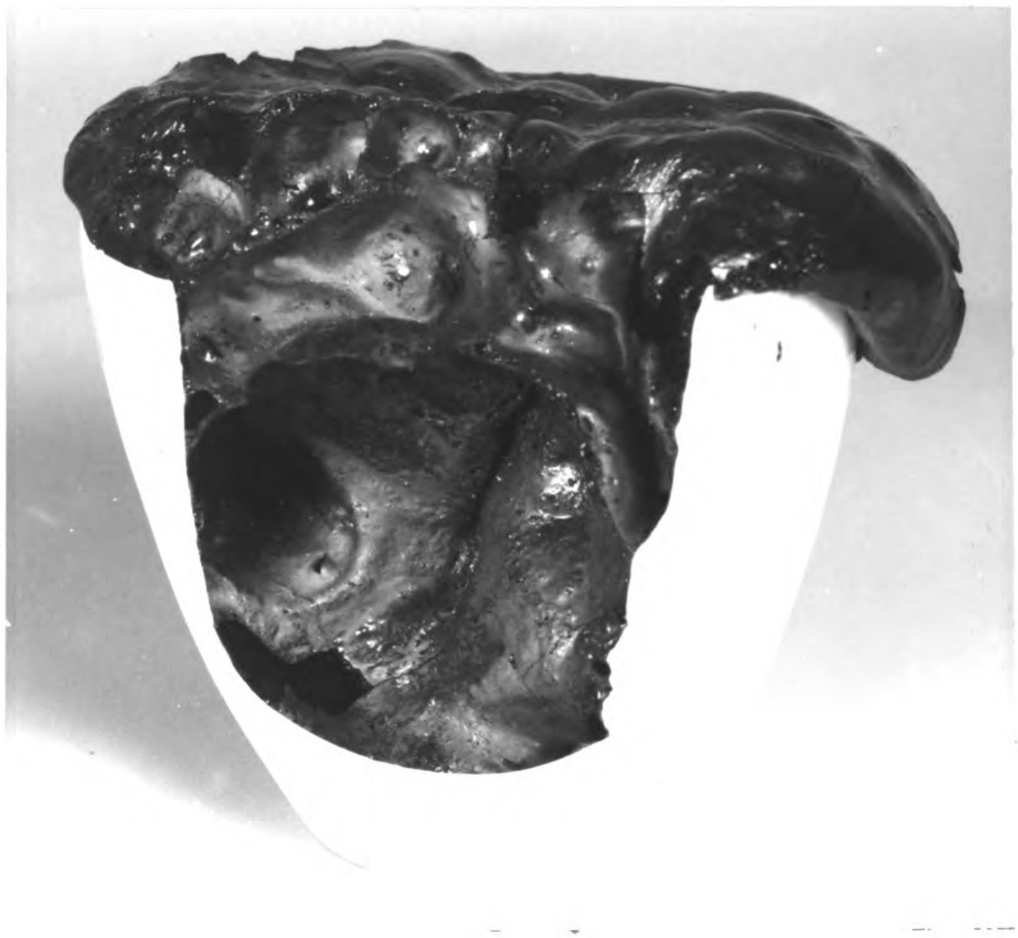

Figure 27. Basalt Sample Showing Internal Structure Formed from Melt at 700°C Upwelled in Vacuum.

Multiple and Single Crucible Sample Granite

The vacuum upwelled granite samples were porous masses 5 to 10 times the volume of the original sample material. The average density of the granite was 0.23 gr/cm^3. The external and internal

structure of the granite samples formed from melts upwelled at 1000°C are similar to that described for both the Wausau sand and basalt samples. The external structure of a granite sample is shown in Figure 20 and its internal structure is shown in Figure 28.

Figure 28. Granite Sample Showing Internal Structure Formed from Melt at 1000°C Upwelled in Vacuum.

The granite was a light colored material prior to vacuum upwelling. After the granite was melted at 1000°C in atmospheric pressure and vacuum upwelled the color of the sample material was black, Figure 20, and similar in structure and color to the vacuum upwelled basalt sample, Figure 17. A detailed investigation was not conducted to determine the reason for the granite material

darkening after it had been melted and vacuum upwelled. Based on the limited data available from this study program the granite darkening could be attributed to:

Color change resulting from remelting of the granite at atmospheric pressure.

Color change resulting from vacuum upwelling.

Combination of atmospheric melting, vacuum upwelling and/or other effects which cannot be defined at this time without further investigation.

The vacuum upwelling and solidification of a rock melt obtained from select geological materials has led to the suggestion that a new rock classification be given to this type of material. The suggested name for the rock classification is molivac (MOlten In VACuum), preceded by the first syllable of the terrestrial rock type used, thus:

Simolivac	silica molten in vacuum
Bamolivac	basalt molten in vacuum
Granmolivac	granite molten in vacuum

It is believed that such designations would be more preferable than the phrase: "under density rock" which is often used in the literature for describing lunar surface materials.

The samples formed during this series of vacuum upwelling experiments indicates that both the internal and external structure of the samples are a function of the temperature and possibly the amount of absorbed gas in the rock melt at the time it is upwelled in

vacuum. When the rock melt is at or above its melting point temperature it produces a sample with a rough porous surface structure with small interconnected internal voids. If the rock melt is below its melting point temperature, it then produces a smooth surface sample with large non-interconnected voids. The exact volume of gas absorbed by the rock melt as a function of time and temperature was not measured during this study program, therefore structure effect due to gas absorption by the rock melt has to be classified as only a possibility.

Where sample densities are reported in this section they were determined by weighing the sample in air on an analytical balance and then determining its volume by water displacement. In determining the samples volume by water displacement it was necessary to wrap the porous samples in light weight 0.0005 inch thick Milar. The Milar covering contributed a maximum increase of 0.25 milliliters to the volume measurements. The sample's volume was then divided into the sample's weight to determine sample density. The sample's mean density as reported in this section was determined from:

Wausau Sand

Sample 1	0.25 gr/cm^3
Sample 2	0.25 gr/cm^3
Sample 3	0.26 gr/cm^3

Sample 4	0.22 gr/cm^3
Sample 5	0.25 gr/cm^3
Basalt	
Sample 1	0.24 gr/cm^3
Sample 2	0.26 gr/cm^3
Sample 3	0.26 gr/cm^3
Sample 4	0.27 gr/cm^3
Granite	
Sample 1	0.23 gr/cm^3
Sample 2	0.24 gr/cm^3

RADIATION DISCOLORATION

Photometric measurements of the lunar surface have shown that only 5 to 15 per cent of the incident light from the sun is reflected by the lunar surface materials. This low albedo indicates that the lunar surface material is probably very dark in color, possibly even approaching the color black in some areas. This dark material, if the original material was not dark in color, could have resulted from the following:

1. Short wavelength solar radiation discoloration
2. Discoloration due to sputtering from solar winds.

To determine the amount of discoloration, darkening, that would result from gamma radiation, two vacuum upwelled silica samples and a clear quartz crystal were subjected to gamma radiation, short wavelength radiation, for a period of 94.1 hours in the University of Michigan's Phoenix Laboratory reactor. The total radiation flux to which these samples were subjected during the 94.1 hour time period amounted to 4.37×10^6 Roentgens which simulated an approximate time period of 27 years of exposure on the lunar surface.

The effect of the gamma radiation was to discolor the silica samples from a pure white to that of a gray-black. This change in coloration is shown in Figure 31 where non-irradiated samples are shown adjacent to the radiated samples.

Figure 29. Radiation Discoloration of Silica

Front Row, Left to Right, Smoky Quartz Crystal, Radiation Discolored Quartz Crystal, Clear Quartz Crystal.

Back Row, Left to Right, Wausau Sand Sample, Discolored Wausau Sand Sample, Discolored Flint Glass Sample, Flint Glass Sample.

The color change in these samples from exposure to gamma radiation is the result of lattice slippage within the crystalization structure of the silica samples. The effect of the discoloration on the photometric properties of the silica samples is shown by comparing Figures 30, 31, 32, and 33.

Therefore, it could be concluded that if the material on the lunar surface contains a high percentage of silica and this material is subjected to high flux levels of gamma radiation it is possible that it will have a low albedo resulting from radiation darkening.

PHOTOMETRIC PROPERTIES

Two photometric properties may be used to characterize the lunar surface material:

1. The low albedo in the visible wavelengths
2. The variation in the brightness of a region with phase angle.

The vacuum upwelling of Wausau sand, Flint glass, basalt, and granite during this study program made a series of samples available for photometric measurements. With these samples it was possible to determine if a simulated magma upwelled in a vacuum pressure of 10^{-8} Torr would have the photometric properties necessary to obey the lunar reflection law.

In determining whether the vacuum upwelled samples would obey the lunar reflection law it was found desirable for correlation purposes to obtain the photometric measurements via a direct curve of phase angle versus percentage of reflected light. This type of photometric curve was obtained by using an x - y plotter with a RCA #5819 photomultiplier tube in a dark room condition. The variation in photomultiplier tube voltages resulting from the amount of light reflected from the sample were fed into the "y" axis of the plotter and the "x" axis was connected to the scanning drive which moved the photomultiplier tube through an arc of 160^{o} across the sample. The electronic equipment

used in obtaining the photometric curves was calibrated against National Bureau of Standards references and the instrumentation system was calibrated for reflection versus phase angle against a magnesium oxide plate which produced a Lambert curve reflection.

The photometric curves of the non-irradiated silica samples show a tendency toward light back-scattering and a variation in the brightness with phase angle which bear a resemblance to the lunar photometric curve, however, these samples do not match this curve, Figures 30 and 31.

The photometric curves of the irradiated silica samples have a sharper point at which the maximum back-scattering of reflected light occurs while at the same time the brightness changes with phase angle. These samples bear a closer resemblance to the lunar photometric curve, Figure 32 and 33. The difference in the photometric curve of the irradiated sample versus the non-irradiated sample is attributed to the darkening of the silica by gamma radiation as the surface texture is the same in both samples.

The photometric curves of the vacuum upwelled basalt and granite samples are shown in Figure 34 and show excellent correlation with the lunar photometric curve.

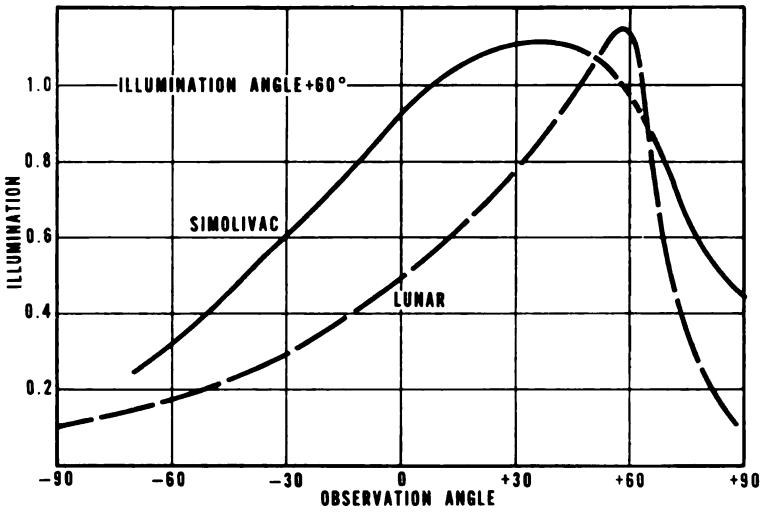

Figure 30. Photometric Curve of Nonirradiated Silica, Wausau Sand Sample Upwelled in Vacuum Compared with the Mean Lunar Photometric Curve.

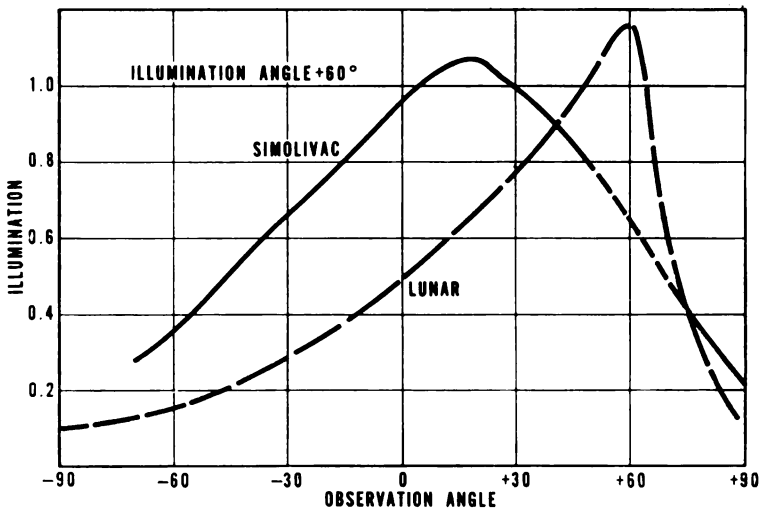

Figure 31. Photometric Curve of Nonirradiated Silica Flint Glass Sample Upwelled in Vacuum Compared with the Mean Lunar Photometric Curve.

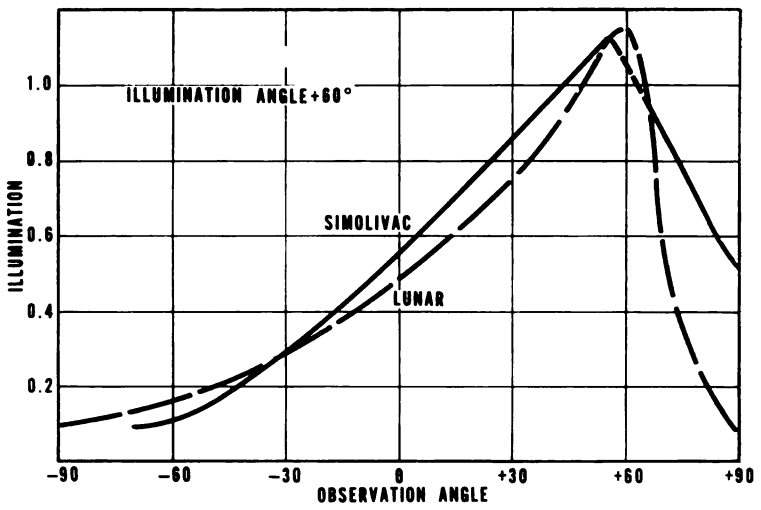

Figure 32. Photometric Curve of Irradiated Silica, Wausau Sand Sample Upwelled in Vacuum Compared with the Mean Lunar Photometric Curve.

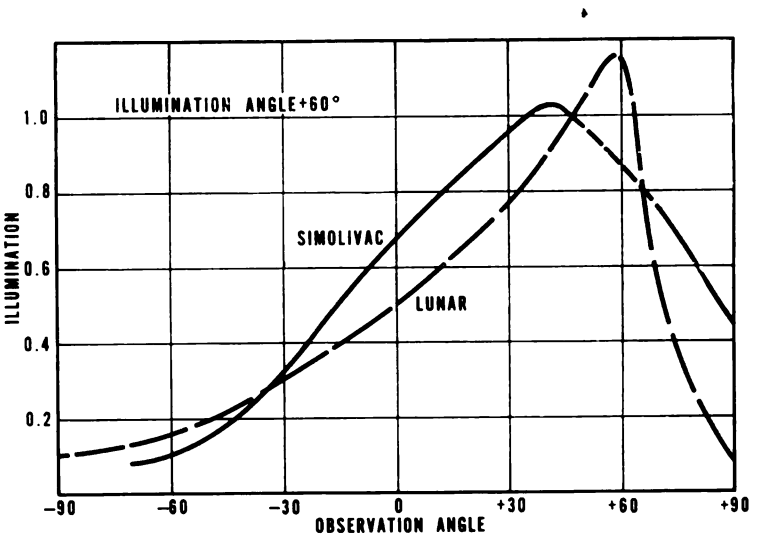

Figure 33. Photometric Curve of Irradiated Silica Flint Sand Sample Upwelled in Vacuum Compared with the Mean Lunar Photometric Curve.

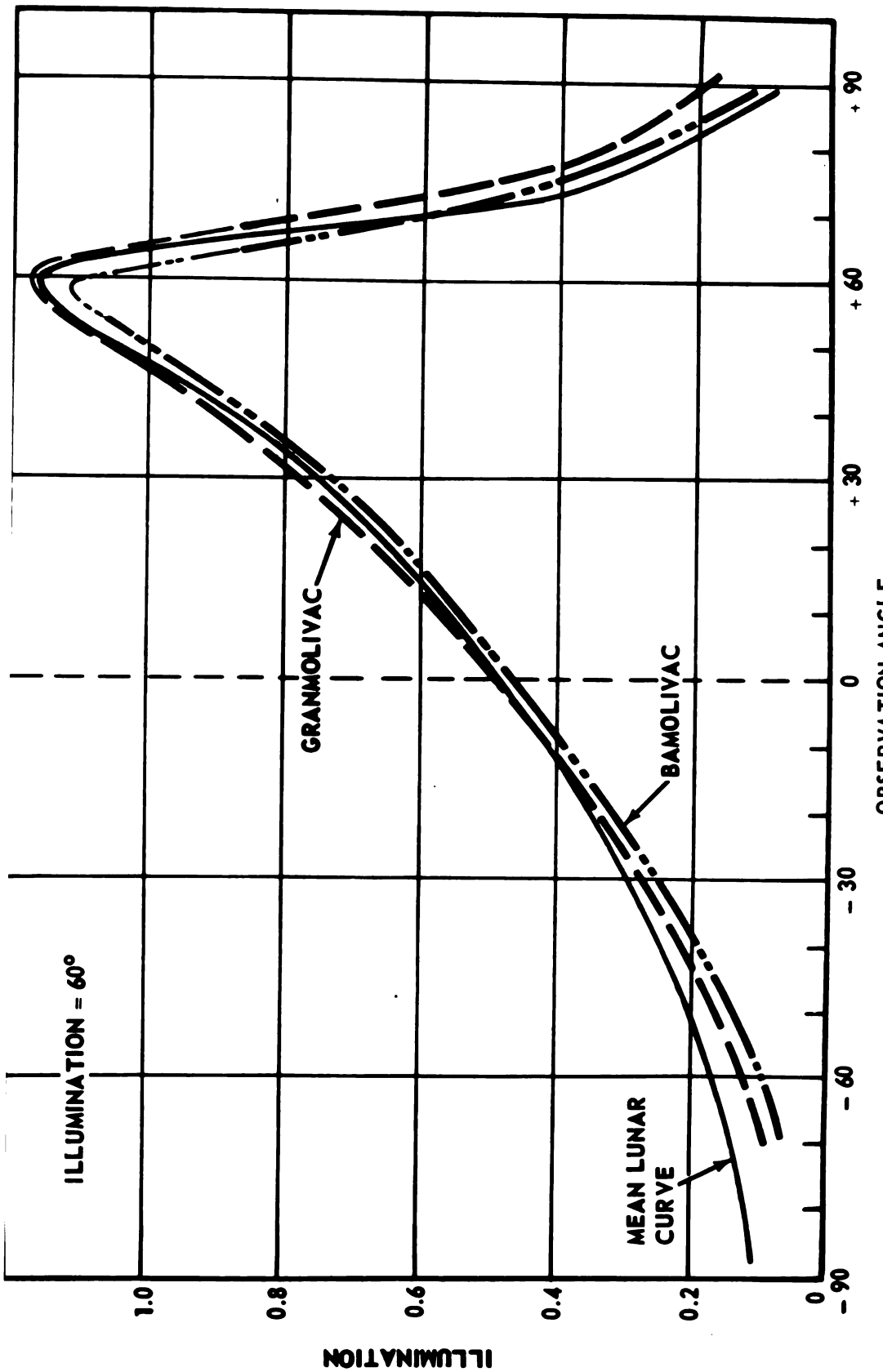

Figure 34. Photometric Curves of Basalt and Granite Samples Upwelled in Vacuum and Compared with Mean Lunar Photometric Curve.

Therefore the photometric results of this study have shown that selective geological materials when they are upwelled in vacuum will match the lunar photometric curve. This series of experiments also confirmed Warren's mathematical model of the behavior of reflected light in a porous structure with interconnecting voids.

BEARING STRENGTH

To obtain the bearing strength of the vacuum upwelled samples it was necessary to first cap the irregularly shaped sample with a small cylinder of plaster of paris as shown in Figure 3 to provide a uniform loading area. The sample bearing strength was then computed on the basis of the surface area beneath the plaster of paris cap, as determined by cap diameter, rather than attempting to approximate the cross section area through the middle of the sample. Analysis of the failed showed that the attached plaster of paris cap did not penetrate into the porous structures of the sample and therefore would not have contributed to the final bearing strength results.

The bearing strength and strain were determined in unconfined compression with Soil Testing Services Model 26 B test machine. The applied stress being measured with a standard double proving ring, while the strain was determined when an Ames dial indicator accurate to $\pm$ 0.0005 inch.

The bearing strength, of the single crucible Wausau sand samples ranged from 33 to 63 pounds per square inch (psi):

Sample # 1	35 psi
Sample # 2	33 psi
Sample # 3	37 psi
Sample # 4	63 psi

Sample # 5	58 psi
Sample # 6	61 psi

The bearing strength of the single crucible Flint glass samples had a bearing strength of approximately 17 pounds per square inch (psi):

Sample # 1	16 psi
Sample # 2	17 psi
Sample # 3	19 psi

The bearing strength of the multiple crucible basalt samples upwelled at 1000°C ranged from 49 to 64 pounds per square inch (psi):

Sample # 1a	53 psi
Sample # 1b	47 psi
Sample # 2a	58 psi
Sample # 2b	61 psi
Sample # 3a	63 psi
Sample # 3b	67 psi

The bearing strength of the multi crucible basalt samples upwelled at 700°C ranged from 17 to 24 pounds per square inch (psi):

Sample # 1a	15 psi
Sample # 1b	19 psi
Sample # 2a	23 psi
Sample # 2b	27 psi

The measured bearing strength of the single crucible granite samples upwelled at 1000° C ranged from 82 to 97 pounds per square inch (psi):

Sample #1	82 psi
Sample #2	97 psi
Sample #3	88 psi

The bearing strength of the material forming the crater structure shown in Figure 11 was not attempted based on the belief that a representative bearing strength measurement could not be obtained for the thin porous layer of material forming the upper surface of the crater structure as shown in Figure 21.

Based on the bearing strength measurements and the sample description the following relationship between bearing strength and sample structure has been confirmed.

1. When upwelling occurs at or the melting point temperature of the sample material, the sample structure consists of many small interconnected voids and the bearing strength is high.
2. When upwelling occurs below the melting point temperature of the sample material the sample structure consists of large void areas and the bearing strength is low.

DISCUSSION OF RESULTS

The color phenomena associated with the vacuum upwelling of "Bamolivac" and "Granmolivac" is in excellent agreement with the observed colors of the Aristarchus, Cobra Head and Schroter's Valley events on the lunar surface as reported by Greenacre, 1963-64.

These magma upwelling experiments also duplicated the color phenomena measured by Kozyrev, 1958, of an earlier lunar surface color event.

"Bamolivac" and "Granmolivac" match the mean photometric curve for the lunar surface materials and are also in good agreement with the Russian space probe Luna 9 lunar surface photograph, Figure 35. The photometric and pictorial data would seem to indicate that the Aristarchus event was probably volcanic and produced magma at the surface which solidified in vacuum similar to "Bamolivac" and "Granmolivac". This conclusion would be in agreement with Greenacre's observation that "everything appears as before immediately after the color phenomena had faded away and was no longer visible".

The American space probes, Surveyor 5, Mare Tranquilitatis and Surveyor 6, Sinus Medii, determined by a gamma ray scattering experiment that the chemical composition of the lunar surface material in the Maria is that of basalt, Aviation Week and Space Technology, January 15, 1968, Geotimes, January, 1968.

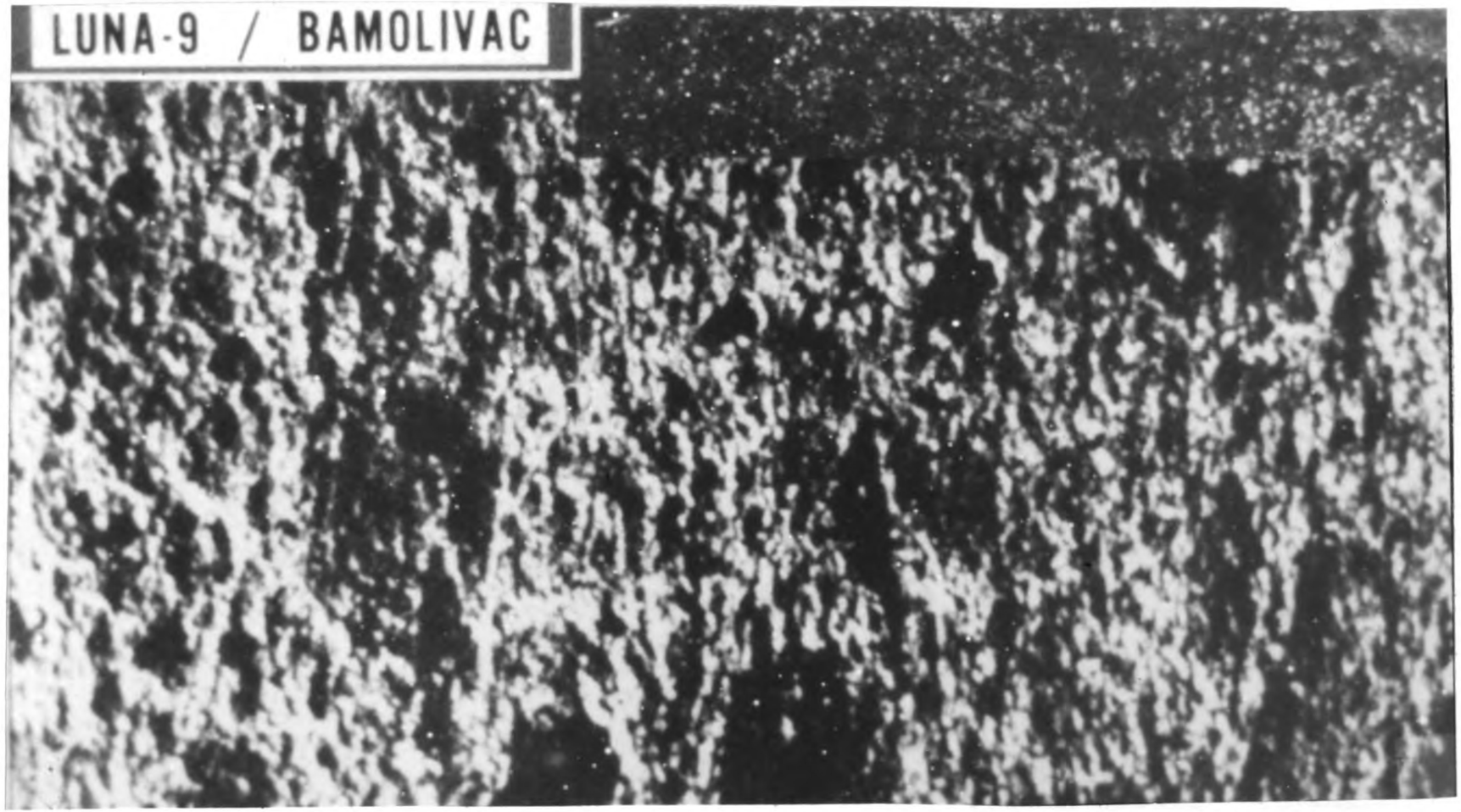

Figure 35. Lunar Surface Material Photograph from Russian Space Probe Compared with "Bamolivac". Lighting Angle and Camera Distance Approximately the same for both Photographs.

Chemical Composition of Lunar Surface at Surveyor 5 Landing Site (in Atomic %)

Element	Abundance on Lunar Surface	Rhyolite	Basalt	Chondritic Meteorite
C	3	0	0	0
O	58 ± 5	62	61	56
Na	2	2	1.5	1
Mg	3 ± 3	0.2	4	15
Al	6.5 ± 2	5	6	1
Si	18.5 ± 3	24	19	16
(S+K+Ca+Ti+Cr+Mn+Fe+Co+Ni)	13 ± 3	3	8	9
(Fe+Co+Ni)	3	0.6	3	8
Heavier than Ni	0.5	0	0	0

The vacuum upwelling of Wausau sand, at a melt temperature of 1200°C and a basalt melt at 1000°C produced dome shaped structures on solidifying. This type of structure is similar to lunar structures found on many of the Maria's and thus would be indicative of possible wide spread volcanic activity on the lunar surface.

The vacuum upwelling of two crucibles of Wausau sand at a melt temperature of 1500°C which was allowed to solidify under a partial pressure from the melt outgassing produced

a circular rim crater with a flat floor which extends for a considerable distance from the point of upwelling. This structure resembles the smaller lunar surface craters and may also be representative of the formation of larger lunar craters because:

1. The rock melt vacuum upwelled in this experiment was not heavily charged with gas or water vapor whereas normally volcanic magmas are charged with a large volume of gas and water vapor.
2. A large volume of magma upwelling on the lunar surface would probably release a large quantity of volcanic gases by means of outgassing. Even though the lunar atmosphere is currently considered infinite the water upwelling experiment would seem to indicate that a partial pressure lunar atmosphere could be formed if the volume of magma upwelled was large.
3. The rock melt vacuum upwelled in this experiment was in a one (1) gravitational field whereas on the lunar surface the gravitational field would be 1/6 g and the volume of material upwelled would probably be much larger.

The Phoenix Laboratory experiment has shown that light colored geological materials will be discolored, darkened, by gamma

radiation. This darkening will lower the material's albedo properties and may be one of the reasons why the lunar surface material has such a low albedo. The darkening of the granite material in this series of vacuum upwelling experiments may also be one of the means by which the lunar surface material obtains its dark color. However, the data obtained in this study were not in enough detail to explain or verify the reason for the granite darkening.

The bearing strength measurements have shown that a rock melt upwelled in vacuum will on solidification produce a structure with a bearing strength of 16 to 97 p.s.i. If this type of igneous rock is present on the lunar surface, the design requirement for a not to exceed 0.5 p.s.i. loading requirement is much too low.

It is therefore concluded that from this series of vacuum upwelling experiments a simulated lunar surface rock was produced by upwelling a basalt melt at 1000° C into a vacuum atmosphere. The proposed name given to this rock is "Bamolivac" and its measured bearing strength is above the United States' Lunar Space Program design requirement of 0.5 p.s.i. for lunar surface materials.

These model studies were carried out in a simulated lunar environment, thermal vacuum and/or vacuum and tend to prove that lava is present on the lunar surface, Figure 35; and that earth-moon correlations, Figure 36, can be made if the physical

properties of the materials being investigated are determined in a similar environment in which they were formed.

Figure 36. Vacuum Upwelled Samples Compared with Lava Sample from Sunset Crater National Monument. The "Granmolivac", Back Row Left, the "Bamolivac", Back Row Center and the Lava Sample, Front Center all have Photometric Curves that will Match the Mean Photometric Curve of the Lunar Surface.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

As a result of this series of vacuum upwelling experiments the following recommendations can be made:

1. A method should be devised whereby the magma within the crucible may be maintained at a predetermined temperature after the crucible has been placed on the baseplate holding fixture.
2. The vacuum facilities should be modified to include a bell jar chamber vacuum pressure measuring capability. This vacuum pressure gage would measure the decompression rate of the bell jar chamber when the magma was vacuum upwelled.
3. A method should be devised which would provide for identifying and measuring the amount of absorbed gases within the magma prior to vacuum upwelling.
4. A Mass Spectrometer should be incorporated in the bell jar baseplate assembly to measure and identify the gases being outgassed from the magma at the time of vacuum upwelling.

5. A procedure should be devised whereby the magma may be charged with water vapor at varying pressures prior to vacuum upwelling.
6. A magma container should be constructed that could provide a variable size orifice through which the magma would be vacuum upwelled.

It is recognized that many more recommendations could be made with regard to the unsolved questions that have arisen from this series of magma vacuum upwelling experiments. Future experiments by scientific investigations will probably be in a particular scientific discipline associated with the individual making this type of study; therefore recommendations for future studies have been limited to the experiment facilities and does not cover Volcanology, Petrology, etc.

REFERENCES

BERNETT, E.C., WOOD, JAFFEE, and MARTENS, 1963, Thermal Properties of a Simulated Lunar Material in Air and in Vacuum, American Institute of Aeronautics Journal, Vol.6.

BULLARD, F.M., 1962, Volcanoes in History, in Theory, in Eruption, University of Texas Press.

CHAO, E.C.T., 1962, Private communication.

DOBAR, W.I., 1963, Temperature, Lunar vs. Terrestrial Rock, Bendix Aerospace Systems Division BSC 39740, Presented AGU meeting, Washington, D.C. 1963.

EPSTEIN, P.S., 1929, What is the Moon Made of? Physics Review, Vol. 33.

FIELDER, G., 1961, Structure of the Moon's Surface, Chap. 5. Pergamon Press, New York, N.Y.
Note: This reference includes
BARABASHEFF, N., 1924
COBLENTZ, W.W., 1905
DUBOIS, J., 1960
WILSING, J. and SCHEINDER, 1909
WRIGHT, F.E., 1927, 1930

GEOFFRION, A.R., KORNER, and SINTON, 1960, Isotherm Contours of the Moon, Lowell Observatory Bulletin No. 106.

GREENACRE, J.A., and BARR, 1964, Another Lunar Color Phenomena, Sky Telescope 27.

HAPKE, B., and VAN HORN, 1963, Photometric Studies of Complex Surfaces, Journal Geophysical Research, Vol. 68.

JAEGER, J.C., and HARPER, 1950, Nature of the Surface of the Moon, Nature 166.

JAEGER, J.C., 1953, Australian Journal of Physics 6:10.

JAEGER, J.C., 1959, Nature 183.

KOZYREV, N.A., 1962, Physics and Astronomy of the Moon, Chap.7, Academic Press, New York, New York.

LIU, N.C., DOBAR, 1964, The Nature of the Lunar Surface; The Thermal Conductivity of Dust and Pumice, Academic Press, New York, N.Y.

LOWMAN, P.D. JR., 1963, The Relation of Tektites to Lunar Igneous Activity, Icarus, Vol. 2.

LUCKS, C.F., THOMPSON, SMITH, CURRAY, DEEM and BING, 1951-52, The Experimental Measurement of Thermal Conductivities, in Specific Heat and Densities of Metallic, Transparent and Protective Materials, Two part report, United States Air Force Technical Report No. 6145.

MUNCEY, R.W., 1958, Calculations of Lunar Temperature, Nature 181:1458-1459.

PETTIT, E. and NICKELSON, 1930, Lunar Radiation and Temperature, Astronomical Journal 71.

PETTIT, E., 1940, Radiation Measurements on the Eclipsed Moon, Astronomical Journal 91.

SAARI, J.M. and SHORTHILL, 1962, Infrared Mapping of Lunar Craters during the Full Moon and Total Eclipse of 5 September 1960, Armed Services Technical Information Agency Document No. 288263.

SINTON, W.M., 1960, Eclipse Temperatures of the Lunar Crater Tycho, Lowell Observatory Bulletin No. 108.

SMOLUCHOWSKI, M., 1910, Bulletin Academy of Science, Cracovie No. 129.

VAN HORN, H. and HAPKE., 1963, Photometric Studies of Complex Surfaces Journal Geophysical Research No. 68.

WARREN, C.R., 1963, Surface Material of the Moon, Science 140.

WESSELINK, A.S., 1948, Heat Conductivity and Nature of the Lunar Surface Material, Bulletin Astronomical Institute of Netherlands, No. 10.

WOODSIDE, W. and MESSMER, 1961, Thermal Conductivity of Unconsolidated Sands, Journal Applied Physics, No. 32.