NASA
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The University of Arizona

(NASA-CR-188219) RESOURCES OF NEAR-EARTH SPACE: ABSTRACTS Only (Arizona Univ.) 52 p CSCL 03B

N91-26019
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N91-26097
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The Second Annual Symposium of the University of Arizona/NASA Space Engineering Research Center for Utilization of Local Planetary Resources

A Conference in the Space Science Series

RESOURCES OF NEAR-EARTH SPACE

Abstracts

JANUARY 7-10, 1991
7600 East Broadway
Tucson Hilton East Hotel
Tucson, Arizona

FOREWORD

The present conference represents the second in the series of annual symposia sponsored by the University of Arizona's NASA Space Engineering Research Center. It is jointly sponsored by the University's Space Science Series, edited by Dr. Tom Gehrels. Since the utilization of space resources is the primary mission of the Center, and a volume devoted to this important subject is not presently included, Dr. Gehrels suggested that the symposium might be organized and conducted in such a way that the Proceedings might become a volume in the Series.

Dr. John Lewis, Science Principal Investigator of the Center, Professor of Space Sciences in the Lunar and Planetary Laboratory, and a noted authority in the field, undertook the project. You are here to witness and participate in the result. For this reason, however, conventional Proceedings will not be published unless the SEI funding requested to subsidize the volume, or funding from some other source, fails to materialize. The Proceedings would then be issued in a format similar to this Abstracts volume by the Center.

In any event, a delay of about a year must be expected in the former case, and not less than six months in the latter. To produce a volume in this well-known Series, widely regarded as one of the most authoritative in the astronomical sciences, is a considerable undertaking. But the result should be well worth waiting for-- as well as moderately priced.

It should also be noted that although the nature of the intended publication enforces emphasis on science aspects, the overall program of the Center is actually much broader, laying equal emphasis on engineering research and development, experimentation, and even bench-level system testing. The following four pages are included for those who may be interested in the scope of the SERC program, while the fifth page lists all of the present volumes in the Space Science Series.

Dr. T. Triffet
SERC Director

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for utilization of local planetary resources

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RESEARCH PROGRAM OBJECTIVES AND PROGRESS

OBJECTIVES

By theory, experiment and bench-level testing of small systems, to develop scientifically-sound engineering processes and facility specifications for producing propellants and fuels, construction and shielding materials, and life support substances from the lithospheres and atmospheres of lunar, planetary and asteroidal bodies.

Current emphasis is on the production of oxygen, other useful gases, metallic, ceramic/composite and related byproducts from lunar regolith, carbonaceous chrondritic asteroids, and the carbon dioxide rich martian atmosphere.

PROGRESS

PROJECTS CONTINUED FROM 1989-90 PROGRAM:

o EXTRACTION OF VOLATILES AND METALS FROM EXTRATERRESTRIAL MATERIALS
Principal Investigator: John S. Lewis UA/LPL

Subcontracts:

- OXYGEN AND IRON PRODUCTION BY ELECTROLYTIC SMELTING OF LUNAR SOIL
  Investigator: Larry A. Haskin, WU/MCSS

- INFORMATION FOR THE DEVELOPMENT OF A PROCESS TO PRODUCE OXYGEN BY ELECTROLYSIS OF LUNAR MOLTEN SILICATES
  Investigator: Rudolph Keller, EMEC

- AN INVESTIGATION OF SOME MECHANICAL AND THERMAL PROPERTIES OF LUNAR SIMULANT MATERIALS HEATED AT 2.45 GHz
  Investigator: Thomas T. Meek, UTEN/MSE

- ASTRONOMICAL DATABANK ON LOCAL SPACE RESOURCES
  Investigator: Don R. Davis, SAIC/PSI

o BENEFICIATION OF ILMENITE FROM PLANETARY MATERIAL
  Investigator: Joaquin Ruiz, UA/GEOSC

o VOLATILE BEARING PHASES AND VOLATILE RESOURCES IN CARBONACEOUS CHONDRITES: COMPOSITIONS, MODAL ABUNDANCES AND REACTION KINETICS
  Investigator: Jibamitra Ganguly, UA/GEOSC

o THE RECOVERY OF PRECIOUS METALS IN SPACE
  Investigator: Henry Freiser, UA/CHEM

o COMPOSITION OF NEAR-EARTH ASTEROIDS
  Investigator: Larry A. Lebofsky, UA/LPL

o NEAR-EARTH ASTEROIDS AND COMETARY CORES
  Investigator: Tom Gehrels, UA/LPL

o DETERMINATION OF LUNAR ILMENITE ABUNDANCES FROM REMOTELY-SENSED DATA
  Investigator: Robert B. Singer, UA/LPL

o FEASIBILITY OF PRODUCTION OF SOLAR COLLECTORS FROM LUNAR MATERIALS FOR SOLAR POWER IN SPACE
  Investigators: Kumar Ramohalli, UA/AME/SERC
  Roger Davenport, SAIC/SD

o PRODUCTION OF OXYGEN FROM LUNAR ILMENITE
  Investigator: Farhang Shadman, UA/CHE

o COLD PLASMA PROCESSING OF LOCAL PLANETARY ORES FOR OXYGEN AND METALLURGICALLY IMPORTANT METALS
  Investigator: David Lynch, UA/MSE

o CONTINUOUS MONITORING OF THE LUNAR OR MARTIAN SUBSURFACE USING ON-BOARD PATTERN RECOGNITION AND NEURAL PROCESSING OF ROVER GEOPHYSICAL DATA
  Investigator: Charles E. Glass, UA/MGE

o QUANTITATIVE COMPUTER SIMULATION OF EXTRATERRESTRIAL ENGINEERING DEVICES
  Investigators: P. Nikravesh, Tom Vincent, and A. Arabyan
  UA/AME

- DEVELOPMENT AND MECHANICAL PROPERTIES OF CONSTRUCTION MATERIALS FROM LUNAR SIMULANTS
  Investigator: Chandra Desai, UA/CEEM

- DEVELOPMENT OF A LUNAR UTILIZATION DATABASE
  Investigator: Andrew H. Cutler, UA/SERC

PROJECTS INITIATED IN 1990-91 PROGRAM

- CO_2 REDUCTION BREADBOARD DESIGN AND CONSTRUCTION
  Principal Investigator: Kumar Ramohalli, UA/SERC/AME

- SOLID ELECTROLYTE CELL DESIGN FOR AN OXYGEN PRODUCTION PLANT ON MARS
  Investigator: K.R. Sridhar, UA/AME

- INNOVATIVE TECHNIQUES FOR THE PRODUCTION OF ENERGETIC RADICALS FOR LUNAR MATERIALS PROCESSING VIA CONCENTRATED SOLAR ENERGY
  Investigators: David C. Lynch, UA/MSE
  Rocco Fazzolari, UA/NEE

- CHEMICAL COMPRESSORS FOR EXTRATERRESTRIAL LANDER
  Investigator: David C. Lynch, UA/MSE

- PROCESSING OF GLASS-CERAMICS FROM LUNAR RESOURCES
  Investigator: Brian D. Fabes, UA/MSE

- MODELING, SIMULATION AND CONTROL OF AN OXYGEN EXTRACTION PLANT
  Investigators: Larry C. Schooley, Francois E. Cellier, and Bernard Ziegler, UA/ECE

- UTILIZATION AND FURTHER DEVELOPMENT OF THE STEWARD OBSERVATORY ASTEROID RELATIONAL DATABASE
  Investigator: Mark V. Sykes, UA/SO

SERC/culpr PUBLICATIONS

- Annual Progress Report 1988-89; APR-89
- Annual Progress Report 1989-90; APR-90
- Annual Progress Report 1990-91; APR-91
- AESOP Workshop Report; WR-89/1
- First Annual Symposium on Space Mining and Manufacturing
  Proceedings; AIS-89
  Abstracts; AIS/A-89
- Second Annual Symposium on Resources of Near-Earth Space
  Abstracts; AIS/A-90
- Annual Executive Report 1989-90; AER-90
- Technical Memorandum: Mining Lunar Soils for He-3; TM 90/1

THE SPACE SCIENCE SERIES

During the past twenty years, the University of Arizona's Lunar and Planetary Laboratory and Department of Planetary Sciences have conducted the Space Science Series Conferences, in connection with publication of the Space Science Series Books (University of Arizona Press). The General Editor of the Space Science Series is Tom Gehrels, University of Arizona. RESOURCES OF NEAR-EARTH SPACE is the 23rd conference and book in the Space Science Series.

Planets, Stars and Nebulae, Studied with Photopolarimetry, T. Gehrels, ed., 1974, 1133 pages.
Jupiter, T. Gehrels, ed., 1976, 1254 pages.
Planetary Satellites, J.A. Burns, ed., 1977, 598 pages.
Protostars and Planets, T. Gehrels, ed., 1978, 756 pages.
Asteroids, T. Gehrels, ed., 1979, 1181 pages.
Comets, L.L. Wilkening, ed., 1982, 766 pages.
Satellites of Jupiter, D. Morrison, ed., 1982, 972 pages.
Venus, D.M. Hunten, L. Colin, T.M. Donahue, and V.I. Moroz, eds., 1983, 1143 pages.
Saturn, T. Gehrels and M.S. Matthews, eds., 1984, 968 pages.
Planetary Rings, R. Greenberg and A. Brahic, eds., 1984, 784 pages.
Protostars & Planets II, D.C. Black and M.S. Matthews, eds., 1985, 1293 pages.
Satellites, J.A. Burns and M.S. Matthews, eds., 1986, 1021 pages.
The Galaxy and the Solar System, R. Smoluchowski, J.N. Bahcall, and M.S. Matthews, eds., 1986, 485 pages.
Meteorites and the Early Solar System, J.F. Kerridge and M.S. Matthews, eds., 1988, 1269 pages.
Mercury, F. Vilas, C.R. Chapman, and M.S. Matthews, eds., 1988, 794 pages.
Origin and Evolution of Planetary and Satellite Atmospheres, S.K. Atreya, J.B. Pollack and M.S. Matthews, eds., 1989, 881 pages.
Asteroids II, R.P. Binzel, T. Gehrels, and M.S. Matthews, eds., 1989, 1258 pages.
Uranus, J.T. Bergstralh, E. Miner and M.S. Matthews, eds., 1991, in press.
Mars, H.H. Kieffer, B.M. Jakosky, C.W. Snyder and M.S. Matthews, eds., in press.
Solar Interior and Atmosphere, A.N. Cox, W.C. Livingston and M.S. Matthews, eds., 1991, in press.
The Sun in Time, C.P. Sonett, M.S. Giampapa and M.S. Matthews, eds., 1991, in press.
Protostars and Planets III, E.H. Levy, J.I. Lunine and M.S. Matthews, eds., in press

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J. Lewis

Utilization of space resources: A historical view
L. David

Legal status of use of non-terrestrial resources
A. Dula

10:00 -10:20am Break

Session M2, The Moon

Prediction and discovery of lunar ores
L.A. Haskin, R.O. Colson & D. Vaniman

A geochemical assessment of possible lunar ore formation
L.A. Haskin, R.O. Colson & D. Vaniman

Possible lunar ores
S.L. Gillett

Chemical and physical state of the lunar surface
T.J. Ahrens & D. McKay

Remote compositional mapping of lunar titanium and surface maturity
J.R. Johnson, S.M. Larson & R.B. Singer

Beneficiation of lunar ilmenite
J. Ruiz, M. Hutson and D. Steinke

12:05–1:15Lunch

Afternoon Session: 1:15 pm to 5:20 pm

Session M3, The Moon

Utilization of lunar ilmenite: Basalt or regolith?
S.K. Kawatra & K.A. DeLa'O

Mining and beneficiation: A review of possible lunar applications
P. Chamberlain et al.

Extraterrestrial resources: Implications from terrestrial mining experience
D.L. Kuck & S.L. Gillett

Propellant production on the Moon
S.D. Rosenberg

Oxygen production processes on the Moon: An overview
L.A. Taylor & W.D. Carrier, III

Oxygen extraction from lunar soil by fluorination
W. Seboldt, S. Lingner, S. Hoernes & W. Grimmeisen

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Oxygen production by pyrolysis of lunar regolith
C.L. Senior

Mechanisms of ilmenite reduction and their impact on the design of effective reactor systems
R.A. Briggs & A. Sacco

Reaction engineering for materials processing in space: Reduction of ilmenite by H_2 and CO
Y. Zhao & F. Shadman

Electrolysis of lunar soils to produce oxygen and metals
R.O. Colson, L.A. Haskin, R. Keller & A. Taberaux

Magma eclectrolysis: An update
R.O. Colson & L.A. Haskin

Refractory materials from lunar resources
B.D Fabes & W.H. Poisl

6:30 to 8:30pm RECEPTION

Hors d'oeuvres and no-host cocktails

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Dynamical relationships of NEAs to belt asteroids
R. Greenberg & M. Nolan

Asteroid/meteorite streams
J. Drummond

The spectral relationships between NEA and meteorites
D.T. Britt, D.J. Tholen, J.F. Bell & C.M. Pieters

10:00-10:20am Break

Session T2, Near-Earth Asteroids

Spectral relationship of NEAs to other asteroids
F. Vilas, et al.

Physical properties of NEAs
G. Veeder, J.R. Spencer, M. Nelson & D. Cruikshank

The surface of near-Earth asteroids
M. Hoffmann

Characterization of low-albedo asteroids
L.A. Lebofsky & M. Nelson

Kinetics of volatile release during heating of carbonaceous asteroidal material
K. Bose & J. Ganguly

Near-infrared observations of primitive asteroids and a possible extinct comet
E.S. Howell & L.A. Lebofsky

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Session T3, The Moon

^{3}He and other lunar volatiles
B. Fegley, Jr. & T. Swindle

Helium resources of Mare Tranquillitatis
E.N. Cameron

Lunar sulfur
D.L. Kuck

A production of solar photovoltaic cells on the Moon
D.R. Criswell & A. Ignatiev

Solar cells for lunar applications by vacuum evaporation of lunar regolith materials
A. Ignatiev

3:00-3:20 Break

Session T4, The Moon

Consolidation of lunar regolith: Microwave vs. direct solar heating
J. Kunitzer, J.G. Strenski, S.J. Yankee & B.J. Pletka

Costs and benefits of lunar oxygen: Engineering, operations and economics
B. Sherwood & G.R. Woodcock

Mechanical properties of structural materials from lunar simulants
C.S. Desai, K. Girdner, H. Saadamatmanesh & T. Allen

Lunar base siting
R.L. Staehle & R. Dowling

Industrial modification of the lunar atmosphere
H.J. Smith

Finding and utilizing lunar lava tubes
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Asteroid mining
G.E. Canough & R. Gertsch

An ISU study of near-Earth asteroid mining
J.D. Burke, et al.

Short-period comets
P. Weissman & H. Campins

Enstatite chondrites and achondrites as asteroidal resources
M. Hutson & J.S. Lewis

Near-Earth asteroids: Metals occurrence, extraction and fabrication
R.M. Westfall

10:00-10:20am Break

Session W2, Near-Earth Asteroids

Metallic asteroidal materials
J.C. Gradie & J.S. Lewis

A.J. Willoughby

Stacking the odds in favor of a space propulsion jackpot
A.J. Willoughby

Development of an electrostatic propulsion engine with sub-micron powders as reaction mass
F. Herbert & K.R. Kendall

The role of near-Earth asteroids in the SEI
D.R. Davis, W.K. Hartmann, A. Friedlander, J. Collins, J. Niehoff & T.D. Jones

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Afternoon Session: 1:00-5:20pm

Session W3: Phobos and Deimos

Chemical and physical properties of the martian satellites
J.F. Bell, D. CruikshanK & F.P. Fanale

The composition of Phobos: Meteorite analogs based on KRFM and VSK spectral data
D.T. Britt & S.L. Murchie

Mass budget for mining the moons of Mars
A. Zuppero & G.A. Landis

Optimum rocket propulsion for energy-limited transfer
A. Zuppero & G.A. Landis

Survey of resource opportunities and critical evaluation of economic requirements
B.C. Clark (Martin Marietta)

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Session W4: Mars

Water on Mars: Volatile history and resource availability
B.M. Jakosky

The global distribution of martian permafrost
D.A. Paige

Water resources and hydrology of Mars
V.R. Baker, V.C. Gulick, J.S. Kargel & R.G. Strom

Physical and chemical properties of the martian soil: Review of resources
C. Stoker & J.L. Gooding

Getting water from the water of hydration of Mars
O. Gwynne, J.P. Cozzatti, A. Zent & C.P. McKay

Atmospheric water on Mars: Energy estimates for extraction
T. Meyer

Dust and solar power on Mars
R.M. Haberle, et al.

THURSDAY, JANUARY 19
MORNING SESSION, 8:15am to 12:05pm

Session Th1: Mars

Distillation of H_2O from hard-frozen martian permafrost
P. Zent & O. Gwynne

Martian impact crater ejecta morphologies as indicators of subsurface volatile distribution
N.G. Barlow

Potential for the identification of localized water-bearing regions on Mars
T. Roush & J. Pollack

G.J. Flynn

Planetary surface structure and evolution of Mars
S. Franck

Primary igneous rocks on Mars: Composition and distribution
R.B. Singer & Harry Y. McSween, Jr.

10:00-10:20am Break

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Evolution of ore deposits on terrestrial planets
R.G. Burns

The potential for crustal resources on Mars
B.M. Cordell & S.L. Gillett

Options for martian propellant production
W. Dowler, J. French & K. Ramohalli

Experimental data from an oxygen plant for Mars
P.A. Schallhorn, J. Colvin, K.R. Sridhar & K. Ramohalli

Production of life-support materials from martian resources
C.P. McKay & P.J. Boston

12:05-1:15pmLunch

Afternoon Session: 1:15-5:05

Session Th3: Mars

Oxygen production on Mars: A figure-of-merit approach
B. Preiss, T. Pan & K. Ramohalli

Chemical approaches to carbon dioxide utilization for manned Mars missions
A.F. Hepp, G.A. Landis & C.P. Kubiak

Production and uses of liquefied atmosphere (CO_2) on Mars
R.D. Waldron

The formation of peroxynitrates and oxygen on Mars
R.C. Plumb & J.O. Edwards

Mars Observer: A global mapping mission
F. Palluconi

Mission and transportation systems uses of in-situ derived propellants
E. Repic

3:00 to 3:20 Break

Session Th4: Beyond Near-Earth Space/Overviews

Outer planets and icy satellites
E.M. Drobyshevskii

Comparative economics of space resource utilization
A.H. Cutler

Some thoughts on mercurian resources
S.L. Gillett

Planetary Engineering
J.B. Pollack & C. Sagan

The optimum shape for a rigid rotating shell enclosing an isotropic spherical planet
T. Covington

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S1-91
ABS. ONLY
14557

SESSION M1, INTRODUCTION

N91-26020

Utilization of Space Resources: A Historical View

Leonard W. David
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202-546-0363

While widely accepted today, the use of non-Earth resources in official space planning circles has been long in coming. This paper will attempt to highlight popular and governmental acceptance of using extraterrestrial resources, be they asteroids, comets, or other celestial bodies. Particular emphasis will be placed on those individuals, such as the late Dandridge Cole, who pioneered early discussion and thought on the topic over a period of several decades.

The evolution of using extraterrestrial resources in governmental space policy, such as NASA's *Outlook for Space* (1976) and *Pioneering the Space Frontier* (1986), authored by the National Commission on Space, will be reviewed.

Put forward in this paper is the view that a redefinition of "resources of near-Earth space" may be warranted, particularly in consideration of using high vacuum, solar radiation, and magnetospheric phenomenon for experimentation and application purposes. Lastly, a prospective look at public reaction to utilizing space resources is presented.

SESSIONS M2-M4, THE MOON

S1-91
ABS. ONLY
14558

N91-26021

P. 1

Mechanisms of Ilmenite Reduction and Their Impact on the Design of Effective Reactor Systems

R.A. Briggs and A. Sacco
Dept. of Chemical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609

One of the first activities at a lunar base could be oxygen recovery from ilmenite ($FeTiO_3$). Oxygen produced from lunar soils could be used to fuel transportation vehicles operating in near-Earth space. The first step in developing a suitable reactor system for lunar operation is to determine the mechanisms and rates of oxygen removal from ilmenite.

In-situ gravimetric measurements and microscopic examinations were used to determine the hydrogen reduction mechanisms of synthetic ilmenite discs between 823-1353K. A shrinking-core reaction model, modified to account for the growth of an iron film on the surface of discs, was capable of predicting experimentally observed conversion-time relationships. An activation energy of 43.2 ± 2.6 kcal/gmole was determined to be representative of reaction control. The observed reduction mechanism, kinetic rates, and associated activation energy established a base line from which comparisons could be made to improve oxygen yield and removal rates. One proposed technique to improve the rate and extent of oxygen removal was to preoxidize ilmenite.

Preoxidation is commonly used during the reduction of ilmenite ores in the iron industry and has been employed for many years to lower operating temperatures and increase reduction rates. This technology could prove beneficial for oxygen production facilities on the Moon as less massive reactor vessels and/or less energy could be associated with a process including preoxidation.

X-ray diffraction and energy dispersive spectroscopy were utilized to follow the progression of ilmenite oxidation at 1123K and 1140K and the reduction of pseudobrookite (Fe_2TiO_5) at 873K and 973K. Structures formed during the progress of oxidation were related to the system's phase diagrams. Results indicated that after initially producing ilmenite-hematite solutions and rutile (TiO_2), pseudobrookite was the end product of oxidation at all temperatures examined (1048-1273K). Initial results from the reduction of pseudobrookite indicate a series of phases are produced including ferropseudobrookite ($FeTi_2O_5$), ulvospinel (Fe_2TiO_4), and ilmenite. Rates of pseudobrookite reduction were typically 50-200 times that of ilmenite.

Considerations toward the processing of ilmenite suggested by laboratory results will be discussed. Further laboratory work needed to be undertaken prior to choosing the optimal reactor type and its dimensions will be presented.

S3-91

Mining and Beneficiation: A Review of Possible Lunar Applications

N91-26022

Peter G. Chamberlain, et al.

Successful exploration of Mars and outer space may require base stations strategically located on the Moon. Such bases must develop a certain self-sufficiency, particularly in the critical life support materials, fuel components, and construction materials. This paper reviews technology for the first steps in lunar resource recovery-mining and beneficiation. The topic is covered in three main categories: site selection; mining; and beneficiation. It will also include (in less detail) in situ processes. The text describes mining technology ranging from simple digging and hauling vehicles (the "strawman") to more specialized technology including underground excavation methods. The section of beneficiation emphasizes dry separation techniques and methods of sorting the ore by particle size. In situ processes, chemical and thermal, are identified to stimulate further thinking by future researchers.

P-1

S4-91

Electrolysis of Lunar Soil to Produce Oxygen and Metals

N91-26023

P-1

Russell O. Colson, Larry A. Haskin and R. Keller

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Our discussion of melt electrolysis will consist of three sections. We will first discuss the implications of the chemistry and physics of fluxed and raw melts on melt electrolysis. This will include discussion of the factors that influence melt resistivity, melt viscosity, oxygen production efficiency, and the theoretical energy required to produce oxygen. Second, we will discuss the implications of phase equilibria and solubilities in silicate melts on the selection of materials for container and electrodes. We will discuss the implications of proposed container and electrode materials on melt composition and how this effects expected resistivities, viscosities, etc., as outlined in the first section. Finally, we will give a general discussion of the basic features of both the fluxed and unfluxed melt electrolysis including their advantages and disadvantages and how they compare with alternative processes.

1. 2

S5-91

Magma Electrolysis - An Update

N91-26024

P-1

Russell O. Colson and Larry A. Haskin

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Electrolytic extraction of O_2 from molten lunar soil is conceptually simple and thus a candidate process for producing O_2 on the Moon. We are testing possible container and electrode materials for durability in corrosive high-temperature silicate melts and looking for complications that might increase energy requirements.

We have now produced O_2 by electrolysis of 1-2 gram quantities of silicate melts in spinel ($MgAl_2O_4$) crucibles; in these melts, spinel is a stable phase. The concentration of FeO was kept low (%) because FeO decreases O_2 production efficiency. Platinum electrodes were placed about 0.5 cm apart in the melt. The spinel crucible was still intact after 40 minutes of electrolysis, when the experiment was halted for examination. The Pt anode was also intact; its Pt was maintained in a dynamic state in which the anode was continuously oxidized but quickly reduced again by the silicate melt, inhibiting migration of Pt away from the anode.

In melts with low concentrations of $Al_2O_3 + SiO_2$ (2wt%), the energy of resistance heating was only ≈10 - 20% of the theoretical amount required to produce O_2. In melts substantially more concentrated in $Al_2O_3 + SiO_2$, higher melt viscosity resulted in frothing that, in the worst case, caused high enough melt resistivities to raise the energy requirements to nearly 10 times theoretical.

Both Fe and Si are produced at the cathode; in iron-rich melts, we observe a- and c-iron and molten ferrosilicon. We also observed production at the cathode of a previously unrecognized gas; we have not yet identified it.

We have measured the solubility of metallic species in silicate melts. They are too low to reduce significantly the efficiency of O_2 production.

3.

8'.

S6-91
ABS. ONLY

N91-26025

Refractory Materials from Lunar Resources

B.D. Fabes and W.H. Poisl
Department of Materials Science and Engineering, University of Arizona, Tucson AZ 85721

p. 1

Refractories - materials which are able to withstand extremely high temperatures - are sure to be an important part of any processing facility or human outpost which is built on the Moon. Containers for processing lunar oxygen (whether produced by magma electrolysis, reduction of ilmenite, or any of the other proposed schemes) will need high temperature components. And fabrication of structural materials from lunar resources (whether metal, ceramic, or composite-based) will need both containment vessels to hold high temperature melts and molds in which to form the final shapes. Certainly, it would be desirable to fabricate such vessels and molds on the Moon, rather than having to carry them up from the Earth. At fist glance, this might appear to be a trivial task, since the Moon's surface consists of a variety of refractory compositions. To turn the regolith into a useful fire brick or mold, however, will require water or other binders and additives which are likely to be in extremely short supply on the Moon.

In this paper we will examine the steps needed to make fire bricks and molds for lunar-derived structural materials, pointing out the critical steps and resources which will be needed. While these processes and applications may seem somewhat mundane, we emphasize that it is precisely these rudimentary processes which must be mastered before we can talk reasonably about making aerobrakes, and other "fancier" refractories from lunar resources.

S7-91
ABS. ONLY

N91-26026

Possible Lunar Ores

Stephen L. Gillett
Department of Geology, Mackay School of Mines, University of Nevada, Reno, NV 89557

p. 1

Despite the conventional wisdom that there are no lunar ores, geochemical considerations suggest that local concentrations of useful rare elements exist on the Moon in spite of its extreme dryness. The Moon underwent protracted igneous activity early in its history, and certain magmatic processes can concentrate incompatible elements even if anhydrous.

Such processes include: (1) Separation of a magma into immiscible liquid phases. Depending on composition, these could be silicate-silicate, silicate-oxide, silicate-sulfide, or silicate-salt. In terrestrial anorthosites, for example, ilmenite is commonly concentrated in nodules formed by immiscibility. Immiscible sulfides may be particularly important because many important metals (e.g., Mo, Cu, Zn, Pb) are chalcophile. Phosphate immiscibility has recently been documented in lunar rocks and has great potential for concentrating rare elements, especially halogens. Phosphorus itself may also be a useful reagent. Most speculatively, other salts, e.g., halides, may have been concentrated by immiscibility. (2) Cumulate deposits in layered igneous intrusions. In particular, much Cr is present as Cr^{++}, and such larger ions become concentrated in late-stage melts. Cumulate crystal settling can also lead to immiscibility of an Fe-rich phase in late-stage fractions. (3) Concentrations of rare, refractory, lithophile elements (e.g., Be, Li, Zr) in highly differentiated, silica-rich magmas, as in the lunar "granites."

Terrestrial mining experience indicates that the single most important characteristic of a potential ore is its concentration of the desired element. The utility of a planet as a resource base is that the welter of interacting processes over geologic time can concentrate rare elements automatically. This advantage is squandered if adequate exploration for ores is not first carried out.

2.

91.

S8-91
ABS. ONLY

N91-26027

A Geochemical Assessment of Possible Lunar Ore Formation

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The Moon apparently formed without appreciable water or other relatively volatile materials. Interior concentrations of water or other volatile substances appear to be extremely low. On Earth, water is important to the genesis of nearly all types of ores. Thus, some have reasoned that only abundant elements would occur in ore concentrations. The definition and recognition of ores on the Moon challenge our imaginations and our terrestrial perceptions of ore bodies. Lunar ores include solar-wind-soaked soils, which contain abundant but dilute H, C, N, and noble gases (including ^3He). We must mine for oxygen; soils contain ≈45%(wt). "Mainstream" processes of rock formation concentrated Si, Mg, Al, Fe, and Ca, and possibly Ti and Cr. The highlands surface contains ≈70%(wt) feldspar (mainly $CaAl_2Si_2O_8$), which can be separated from some highland soils. Small fragments of dunite [mainly olivine, $(Fe,Mg)_2SiO_4$] were collected; dunite may occur in walls and central peaks of some craters. Theoretical extensions of observations of lunar samples suggest that the Moon may have produced ores of trace elements. Some small fragments have trace-element concentrations 10^4 times higher than the lunar average, indicating that effective geochemical separations occurred; processes included fractional crystallization, silicate immiscibility, vaporization and condensation, and sulfide metamorphism. Operation of these processes acting on indigenous materials and on meteoritic material in the regolith could have produced ores. Infalling carbonaceous meteorites and comets have added water and hydrocarbons that may have been cold-trapped. Vesicles in basalts, pyroclastic beads, and reported transient events suggest gas emission from the lunar interior; such gas might concentrate and transport rare elements. Large impacts may disperse ores or produce them through deposition of heat at depth and by vaporization and subsequent condensation. The main problem in assessing lunar resources is our ignorance about the largely unexplored Moon.

S9-91
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N91-26028

On Prediction and Discovery of Lunar Ores

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Sampling of lunar materials and remote geochemical, mineralogical, and photogeologic sensing of the Moon's surface, while meager, provide first-cut information about lunar composition and geochemical separation processes. Knowledge of elemental abundances in known lunar materials indicates which common lunar materials might serve as ores if there is economic demand and if economical extraction processes can be developed. remote sensing can be used to extend our understanding of the Moon's major geochemical separations and to locate potential ore bodies. Observed geochemical processes might lead to ores of less abundant elements under extreme local conditions.

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S10-91

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P-1

Remote Compositional Mapping of Lunar Titanium and Surface Maturity

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Lunar ilmenite ($FeTiO_3$) is a potential resource capable of providing oxygen for life support and spacecraft propellant for future lunar bases. Estimates of TiO_2 content (and hence primarily ilmenite content) in mature mare soils can be made using an empirical relation between the 400/560 nm reflectance ratio and TiO_2 wt% established by Charette et al. (*JGR* 79, 1605, 1974) and refined by Pieters (*PLPSC* 9th, 2825, 1978). We have constructed a TiO_2 abundance map for the entire near-side lunar maria accurate to ±2 wt% TiO_2 using CCD images obtained at the Tumamoc Hill 0.5m telescope in Tucson, employing bandpass filters centered at 400 nm and 560 nm. Highest TiO_2 regions in the maria (8 wt%) are located in western Mare Tranquillitatis. We have also found that greater contrast differences between regions on the lunar surface can be obtained using 400/730 nm ratio images. The Charette et al. (1974) relation might well be refined to accommodate this possibly more sensitive indicator of TiO_2 content.

Another potential lunar resource is solar wind-implanted ^3He which may be used as a fuel for fusion reactors. Relative soil maturity, as determined by agglutinate content, can be estimated from 950/560 nm ratio images (McCord et al., *Icarus*, 29, 1, 1976). Immature soils appear darker in this ratio since such soils contain abundant pyroxene grains which cause strong absorptions centered near 950 nm due to Fe^{2+} crystal field transitions. It has been shown that a positive correlation exists between the amount of ^3He and TiO_2 content in lunar soils (e.g., Wittenburg et al., *Fus. Tech.*, 10, 167, 1986), suggesting that regions high in TiO_2 should also be high in ^3He.

Reflectance spectrophotometry (relative to the MS-2 standard area) in the region 320-870 nm has also been obtained for several regions (Johnson et al. *LPSC* XXI, 567, 1990). Below about 340 nm, these spectra show variations in relative reflectance that are caused by as yet unassigned near-UV absorptions due to compositional differences. This work is supported by NASA grants NAGW-247 and NAGW-1332 #3 (SERC).

S11-91

N91-26030

14567

P-1

Utilization of Lunar Ilmenite: Basalt or Regolith?

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This paper presents a critical discussion of whether lunar basalt or regolith should be used as a resource for mineral processing schemes on the lunar surface, with pros and cons for each argument presented. A literature review has shown that the majority of authors feel that mining the lunar basalt, crushing it, and then processing to remove the desired minerals, would be the route to take. The authors present the argument that this method would not be a sound mineral processing practice. Mining and crushing are difficult propositions even on earth; to attempt such processes in the hostile lunar environment would be a phenomenal task. It would be better to start with a simpler scheme, such as processing the regolith, which can be adapted to the multitude of unknowns facing the first lunar production plant.

If, however, the lunar mining trend is followed, it must be kept in mind that mining and processing technology which is radically different from what is currently available and used here on earth will have to be developed. Podnieks and Roepke (1987) and Lindroth and Podnieks (1987) have summarized the "new" technology that may be applicable, but this technology is very similar to the current, 99% inefficient technology used on Earth. Extremely different mineral processing methods must be developed, methods which may have no relevance on Earth. One such possible technique is sodium vapor fragmentation of basalt. Initial testwork has been conducted at Michigan Technological University on terrestrial basalt with extremely promising results, though much time and effort will be needed to fully develop this process.

Electrolysis of Lunar Resources in Molten Salt

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Oxygen and metals can be produced by electrolysis of lunar oxides dissolved in a molten salt electrolyte. With NASA support through its SBIR program, EMEC Consultants has developed a process concept to produce silicon, aluminum and oxygen from anorthositic soil. This concept is being modified to focus on a most simple approach to lunar oxygen production. The envisioned process accommodates a broad variety of ore feed, with no or minimal benefication, and produces no process wastes.

Oxygen-evolving anodes are a prerequisite for electrolytic oxygen production. Such stable electrodes are being developed for terrestrial industrial aluminum production. It is planned to examine their feasibility for lunar electrolysis.

5/2-91
NBS ONLY

N91-26031

Extraterrestrial Resources: Implications from Terrestrial Experience

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p-1

Terrestrial mining experience indicates that the overwhelming criterion of a potentially economic deposit is its recoverable concentration of the desired mineral or element. Recovery can be based on contrast in physical and/or chemical properties, but processes based on physical properties are typically less expensive. As several processes generally are used in sequence, they have a profound effect on extraction costs.

These criteria will also apply to extraterrestrial resources. Although the extreme cost of access to space makes even ordinary materials extremely valuable, this inaccessibility also makes capital and maintenance costs extremely high.

The following four development stages will apply, especially with the additional unknowns of an extraterrestrial environment:

(1) Exploration for the highest grade of the mineral or element desired. Because the extraction plant must be simple, cheap, and rugged to minimize capital and maintenance costs, high grade is extremely important.

(2) Laboratory testing of various physical and/or chemical separation techniques on the possible ore to determine if the material can indeed be recovered economically.

(3) A pilot plant test, in which a large sample is dug from the deposit to determine excavation rates, power requirements, and equipment wear. This sample is then run through a pilot mill designed on the basis of the laboratory testing. Pilot plant testing must be carried out at increasing scales, but several trials are generally necessary at each scale before the size of operations can be increased. Moreover, pilot testing is necessary for each new mineral deposit.

(4) Last is the full-scale mine and plant start-up. New problems invariably occur at this point, but they can be kept to a minimum if the pilot plant tests were realistic.

If such a development plan is followed rigorously, major cost overruns, with their potentially disastrous effects on resource development, can be avoided.

5/2-91
NBS ONLY

N91-26032/4569

Oxygen Extraction from Lunar Soil by Fluorination

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p-1

Mining and processing of lunar material could possibly lead to more cost-efficient scenarios for permanent presence of man in space and on the moon. Production of oxygen for use as propellant seems especially important. Different candidate processes for oxygen-extraction from lunar soil have been proposed, of which the reduction of ilmenite by hydrogen has been studied most. This process, however, needs the concentration of ilmenite from lunar regolith to a large extent and releases oxygen only with low efficiency. We therefore discuss another possibility - the fluorination method - which works with lunar bulk material as feedstock. Liberation of oxygen from silicate or oxide materials by fluorination methods has been applied in geoscience since the early sixties. The fact that even at moderate temperatures 98 to 100% - yields can be attained, suggests that fluorination of lunar regolith could be an effective way of propellant production. Lunar soil contains about 50% oxygen by weight which is gained nearly completely through this process as O_2-gas. The second-most element Si is liberated as gaseous SiF_4. It could be used for production of Si-metal and fluorine-recycling. All other main elements of lunar soil (Ca, Al, Mg, Fe) will be converted into solid fluorides which also can be used for metal-production and fluorine-recycling. Preliminary results of small scale experiments with different materials (lunar soil simulants) are discussed, giving information on specific oxygen-yields and amounts of by-products as function of temperature. These experiments were performed with an already existing fluorine extraction and collection device at the University of Bonn, normally used for determination of oxygen-isotopic abundances. Optimum conditions, especially concerning energy consumption, are investigated. Extrapolation of the experimental results to large industrial-type plants on the moon is tried and seems to be promising at first sight. The recycling of the fluorine is, however, crucial for the process. It might be achieved by means of electrolysis. This needs further investigation. The technical problem of transport and handling of the toxic and corrosive fluorine seems to be solvable and could be done by inert storage vessels (nickel, steel).

514-91
ABS. ONLY

N91-26033

Oxygen Production by Pyrolysis of Lunar Regolith

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Oxygen has been identified as the most important product of initial lunar materials processing efforts. A source of oxygen on the moon provides an alternative to the costly transportation of propellant to the moon or to Low Earth Orbit. Pyrolysis, or vapor-phase reduction, involves heating a feedstock to temperatures sufficient to decompose the constituent metal oxides and release oxygen. The process relies on the vaporization of metal oxides in the form of reduced suboxides (e.g., SiO, AlO) or atomic species (e.g., Fe, Ca). The reduced species must then be condensed without re-oxidizing, yielding oxygen in the gas phase.

The feasibility of obtaining oxygen from common lunar minerals was demonstrated using solar furnace experiments. These results will be discussed together with chemical equilibrium models which were extended to include the multicomponent oxides used in experiments. For the first time, both experiments and theoretical models dealt with the complex oxides that make up potential lunar feedstocks. Two major conclusions are drawn from this preliminary work. First, unbeneficiated regolith is a suitable feedstock for pyrolysis. Second, the process can operate at moderate temperatures, circa 2000 K, which could be supplied by direct solar or electrical energy. In addition to these advantages in choice of feedstock and energy source, the pyrolysis process requires no chemicals or reagents, making it an attractive process for lunar oxygen production.

515-91
ABS. ONLY

N91-26034

Oxygen Production Processes on the Moon: An Overview

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The production of oxygen on the Moon utilizing indigenous materials is paramount to a successful lunar colonization. And several processes have been put forth to accomplish this. The lunar liquid oxygen (LLOX) generation schemes which have received the most study to date are those involving: 1) **the reduction of ilmenite** ($FeTiO_3$) by H_2, C, CO, CH_4, CO-Cl_2 plasma, 2) **magma electrolysis**, both unadulterated and fluoride-fluxed, and 3) **several others**, including carbo-chlorination, HF acid leaching, fluorine extraction, magma oxidation, and vapor pyrolysis. The H_2 reduction of ilmenite and magma electrolysis processes have received the most study to date. At this stage of development, they both appear feasible schemes with various pros and cons. However, all processes should be addressed at least at the onset of our considerations. It is ultimately the energy requirements of the entire process, including acquisition of feedstock, which will determine the mode of oxygen productions. There is an obvious need for considerably more experimentation and study. Some of these requisite studies are in progress, and this paper reviews several of the most studied and feasible processes for winning oxygen from lunar materials.

516-91
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14572

N91-26035

Reaction Engineering for Materials Processing in Space: Reduction of Ilmenite by Hydrogen and Carbon Monoxide

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Oxygen is a consumable material which needs to be produced continuously in most space missions. Its use for propulsion as well as life support makes oxygen one of the largest volume chemicals to be produced in space. Production of oxygen from lunar materials is of particular interest and is a very attractive possibility.

The kinetics and mechanism of reduction of ilmenite by carbon monoxide and hydrogen at 800 to 1100°C were investigated. The temporal profiles of conversion for carbon monoxide have a sigmoidal shape and indicate the presence of three different stages (induction, acceleration and deceleration) during the reduction reaction. The apparent activation energy decreases from 18 kcal/mole at 10% conversion to 10 kcal/mole at 50% conversion. The reaction is first order with respect to carbon monoxide under the experimental conditions studied. Both SEM and EDX analysis show that the diffusion of Fe product away from the reaction front and through the TiO_2 phase, followed by the nucleation and growth of a separate Fe phase are important steps affecting the process kinetics. The results from hydrogen reduction show that the mechanism of ilmenite reduction by hydrogen is similar to that by carbon monoxide. However, the titanium dioxide can be further reduced by hydrogen at 800°C to 1000°C. The detailed comparison and theoretical modelling of both reduction processes will be also presented.

13 1.

S17-91
ABS. ONLY

N91-26036 14673

Kinetics of Volatile Extraction from Carbonaceous Chondrites: Dehydration of Talc

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Carbonaceous chondrites are believed to be the primary constituents of near-Earth asteroids and Phobos and Deimos, and are potential resources of fuels that may be exploited for future planetary missions. Calculations of equilibrium phase relations suggest that talc (Ta) and antigorite (Ant) are likely to be the major hydrous phases in the C1 and C2 meteorites (Ganguly and Saxena, 1989), which constitute the most volatile rich classes of carbonaceous chondrites. We are, thus investigating the dehydration kinetics of talc as a function of temperature, grain size, composition and fluid fugacity, as part of a systematic study of the reaction kinetics of the volatile bearing phases that are either known or likely to be present in carbonaceous chondrites. The dehydration kinetics have been investigated at 1 bar, 775-875°C by monitoring the in-situ weight loss as a function of time of a natural talc of composition $(Mg_{.99},Fe_{.01})_3Si_4O_{10}(OH)_2$. The talc platelets had a dimension of 0.8-1 micron. The run durations varied from 233.3 hours at 775°C (48% dehydration) to 20.8 hours at 875°C (80% dehydration). The results can be adequately represented by a rate equation of the form $X = \exp(-Kt^n)$, with $n = 0.5$-0.6, where X is the fractional weight of talc remaining at time t. The rate constant K follows an Arrhenian relation $K = K_o\exp(-Q/RT)$ with $K_o = 3.906e21\ min^{-1}$, and activation energy $Q = 124.7$ kcal/mol. Theoretical analysis suggests that the reduction in the concentration of H_2O in the environment of dehydrating talc, as would be encountered in processing chondritic materials, will have negligible effect on the rate of dehydration, unless there is a change of reaction mechanism owing to the presence of other volatile species. Works on the effect of grain size and dehydration mechanism are in progress.

S18-91
ABS. ONLY
14574

The Spectral Relationships Between NEA and the Meteorites: An Overview Using Principal Components Analysis

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N91-26037

One of the primary reservoirs for meteorites is probably the planet-crossing Aten, Apollo, and Amor asteroids. Comparing the spectral characteristics of these two populations with each other and with the spectra of the main belt asteroids would provide insight into the dynamical processes that deliver meteorites to Earth. One method for obtaining an overview of general relationships in a large spectral data set is the statistical technique of principal components analysis. This technique quantifies general spectral similarities and reprojects the data in a plot of major axes of variation where distance is a measure of relative similarity. A major caveat should be kept in mind however, spectra are sensitive to particle size and viewing geometry effects, and NEA's are probably significantly different from main belt asteroids in both these factors. The analysis was restricted to the spectral range of ECAS filters and included 116 meteorite spectra from the Gaffey (1976) survey and 417 asteroids from the Zellner et al. (1985) survey of which 13 are planet-crossers. Although thirteen asteroids are not much of a sample on which to base conclusions on, a few inferences can be drawn from this exercise. First, the NEA spectral characteristics are, on average, more consistent with the spectra of meteorites than are the main belt asteroids. Second, the S-type NEA's tend to be spectrally more similar to the ordinary chondrite meteorites than the main belt S-types. This suggests that the planet-crossing S-types do not represent the spectral range of the main belt S-type population and that the planet-crossing S-types are on average, more like the ordinary chondrites than the main belt S-types. Third, the only direct asteroidal ordinary chondrite analog, the Q-type asteroid, 1862 Apollo, plots well within the field of the ordinary chondrite meteorites and represents the most common meteorite fall type. Finally, it is interesting that the planet-crossing asteroids occupy similar PCA space with the general trend of the meteorites while most of the main belt objects are offset from the meteorites in statistical space.

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S19-91
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N91-26038

Asteroid/Meteorite Streams

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The independent discovery of the same three streams (named alpha, beta, and gamma) among 139 Earth-approaching asteroids and among 89 meteorite producing fireballs presents the possibility of matching specific meteorites to specific asteroids, or at least to asteroids in the same stream and, therefore, presumably of the same composition. Although perhaps of limited practical value, the three meteorites with known orbits are all ordinary chondrites. To identify, in general, the taxonomic type of the parent asteroid, however, would be of great scientific interest since these most abundant meteorite types cannot be unambiguously spectrally matched to an asteroid type. The H5 Pribram meteorite and asteroid 4486 (unclassified) are not part of a stream, but travel in fairly similar orbits. The LL5 Innisfree meteorite is orbitally similar to asteroid 1989DA (unclassified), and both are members of a fourth stream (delta) defined by five meteorite-dropping fireballs and this one asteroid. The H5 Lost City meteorite is orbitally similar to 1980AA (S type), which is a member of stream gamma defined by four asteroids and four fireballs. Another asteroid in this stream is classified as an S type, another is QU, and the fourth is unclassified. This stream suggests that ordinary chondrites should be associated with S (and/or Q) asteroids. Two of the known four V type asteroids belong to another stream, beta, defined by five asteroids and four meteorite-dropping (but unrecovered) fireballs, making it the most probable source of the eucrites. The final stream, alpha, defined by five asteroids and three fireballs is of unknown composition since no meteorites have been recovered and only one asteroid has an ambiguous classification of QRS. If this stream, or any other as yet undiscovered ones, were found to be composed of a more practical material (e.g., water or metal-rich), then recovery of the associated meteorites would provide an opportunity for in-hand analysis of a potential near-Earth resource.

S20-91
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14576

N91-26039

Discovery and Orbital Characterization of Near-Earth Asteroids

T. Gehrels, J. Drummond, E. Helin, M. Hoffmann, D. Rabinowitz and E. Shoemaker

The fundamentals of photographic discovery ~~will be~~ discussed, and the work at the Palomar Observatory will be described including photographic discovery programs elsewhere. The Spacewatch development of CCD-scanning techniques ~~will be~~ reviewed. Special searches for objects near the Earth ~~will be~~ reported. The existence of four streams among both Earth-approaching asteroids and meteorite-dropping fireballs suggests that at certain times of the year an increase can be expected in both asteroid discoveries and meteoritic events.

S21-91
ABS ONLY
14577

N91-26040

The Surface of Near-Earth Asteroids

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The surfaces of near-Earth asteroids are expected to differ significantly from those of large objects like the moon because of their different origin and evolution. A selection of such objects for an extensive procurement of material will also be made on criteria like the surface roughness and the rotation rate with respect to the surface gravity. From the currently known distribution of near-Earth asteroid rotation rates it is shown that a significant fraction of them is rotating near their escape velocities. The determination of macroscopic surface roughness from rotation light curves under an assumption of a fractal surface geometry ~~will be~~ discussed. Much information is expected from the variation of harmonic expansions of the light curves with the phase angle.

15'

S22-90
ABS. ONLY

N91-26041

Near-Infrared Observations of Primitive Asteroids and a Possible Extinct Comet

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P-1

We have obtained photometry simultaneously in the near-infrared and in the visible, of several D- type asteroids, thought to be composed of the most primordial material in the asteroid belt. These objects have been previously classified as D-type based on their low albedo and broad-band colors in the visible region of the spectrum. One of the objects observed is 944 Hidalgo, which is possibly an extinct comet, based on its orbital elements. Our photometry further constrains the surface mineralogy and is a test of whether differences exist between these objects in different regions of the asteroid belt. Refining our knowledge of the surface composition of these objects will allow a better measure of the amount of thermal processing which has taken place in these so-called primitive asteroids. Spectral slope is assumed to be sensitive to surface composition. There is some variability in spectral slope among those objects classified as D-type, with indications of increasing slope into the near-infrared with heliocentric distance. This is consistent with trends seen in the red region of the visible spectrum of P- and D-type asteroids (Vilas and Smith, 1985, *Icarus*, 64, 503). The spectral features are quite subtle as we expect for these low albedo objects, but there is possible evidence of subtle features in some of the D-type asteroids and possibly some active comets (Cruikshank et al., *BAAS*, 1990). Further analysis of these spectra and the implications for the outer region of the asteroid belt will be presented.

S23-90
ABS. ONLY

N91-26042

Characterization of Low Albedo Asteroids

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P-1

Three asteroid classes were defined from the early spectral surveys of the asteroids: C for carbonaceous, M for metallic, and S for stony. Subsequent spectral studies have defined new asteroid classes and have shown that the original classes can be divided into a number of additional asteroid types. The low albedo asteroids are now classified as types B, C, D, F, G, K and P. These types are concentrated in the middle asteroid belt and beyond. Their visible and near-infrared spectra are generally featureless and dark, with a red slope in the ultraviolet. Some of them show water absorption features in the mid-infrared, indicating the presence of bound water.

The lack of absorption features in the telescopic reflectance spectra has made it difficult to determine the mineralogy of the low albedo asteroids. Some of the asteroid spectra closely resemble laboratory spectra of carbonaceous chondrite meteorites, implying similar mineralogy. These meteorites are chemically primitive, composed of fine-grained matrix material which includes hydrous silicates, complex carbon compounds, olivine and pyroxene, combined with olivine and/or pyroxene chondrules. This disequilibrium mineralogy has lead Jeff Bell to place these asteroids in his sedimentary superclass. The main belt low albedo asteroids are probably very similar to these asteroids, but no meteoritic analogues exist for the most distant asteroid types.

The mineralogic interpretation is complicated by two problems. Phobos and Deimos spectrally resemble the C asteroids, however the theory for the formation of these asteroids does not allow their condensation that close to the Sun. This requires that Phobos and Deimos be captured, but dynamicists have difficulty postulating a plausible mechanism for the capture. The spectral interpretation has also been complicated by the recent work by Dan Britt with shocked ordinary chondrites. These meteorites are also spectrally similar to the C asteroids, but they are mineralogically different. Further work needs to be done to determine whether it is possible for highly shocked material to spectrally dominate the surface of a large asteroid.

Related contributed papers concern processing of carbonaceous material by J. Ganguly, the stability of water and ice on the surfaces of asteroids by Fraser Fanale, and a more detailed discussion of the shocked ordinary chondrite problem by Dan Britt.

S24-91
ABS. ONLY

SESSIONS T3-T4, THE MOON

N91-26044

Helium Resources of Mare Tranquillitatis

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Mare Tranquillitatis, about 300,000 km^2 in area, is currently the most promising lunar source of ^3He for fueling fusion power plants on Earth. About 60% of the mare regolith consists of particles 100 um or less in diameter. Helium and other gases derived from the solar wind are concentrated in the fine size fractions. Studies of very small craters indicate that the average regolith exceeds 3 m in areas away from larger craters and other mare features not amenable to mining. There is no evidence of decrease of helium content of regolith and depth.

Helium is known to be enriched in regoliths that are high in TiO_2 content. Remote sensing indicates that about 90% of Mare Tranquillitatis is covered by regolith ranging from about 6% to +7.5% TiO_2; inferred He contents range from 20 to at least 45 wppm total helium (7-18 wppb ^3He).

Detailed studies of craters and inferred ejecta halos displayed on high-resolution photographs of the Apollo 11 and Ranger VIII areas suggest that as much as 50% of the mare regolith may be physically minable, on average, with appropriate mining equipment. Assuming that the average thickness of regolith is 3 m, and that 50% of the mare area is minable, the ^3He content of minable regolith containing 20 to 45 wppm total He is estimated at about 9,4000 tonnes.

An area of 85,000 km^2 in the northeastern part of the mare appears to be physically more amenable to mining than the western part of the mare. It is largely covered by regolith high in TiO_2 and presumably high in He content.

The helium potential of Mare Tranquillitatis must be verified by systematic surface mapping, drilling, and sampling, as done to determine tonnage and grade of mineral deposits on Earth.

Production of Solar Photovoltaic Cells on the Moon

S25-91

N91-26045

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Solar energy is directly available on the sunward lunar surface. Most, if not all, the materials are available on the Moon to make silicon based solar photovoltaic cells. A few additional types are possible. There is a small but growing literature on production of lunar derived solar cells. This literature will be reviewed. Topics ~~to be~~ explored will include trade-offs of local production versus import of key materials, processing options, the scale and nature of production equipment, implications of storage requirements, and the end-uses of the energy. Directions for future research and demonstrations ~~will be~~ indicated.

Development and Mechanical Properties of Structural Materials from Lunar Simulants

S26-91

N91-26046

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14582

Development of the technologies for manufacture of structural and construction materials on the Moon, utilizing local lunar soil (regolith), without the use of water, is an important element for habitats and explorations in space. Here, it is vital that the mechanical behavior such as strength and flexural properties, fracture toughness, ductility and deformation characteristics must be defined toward establishment of the ranges of engineering applications of the materials developed.

The objective ~~of this paper~~ is to describe the research results in two areas for the above goal: (1) "liquefaction" of lunar simulant (at about 1000°c) with different additives (fibers, powders, etc.), and (2) development and use of a new triaxial test device in which lunar simulants are first compressed under cycles of loading, and then tested with different vacuums and initial confining or in situ stress.

~~In the case of the liquefaction, test specimens are cast~~ + in a furnace for beam bending, triaxial (cylindrical), and ~~cubical~~ (multiaxial) testing. This will lead to parametric evaluation of the stress- strain-strength properties of ~~simulant with~~ different additives.

The vacuum triaxial device has been used to perform preliminary tests involving hydrostatic compression and triaxial compression on samples with different vacuums and confinements. These results are encouraging, and additional research with vacuums greater than about 10^{-3} for (currently available) can provide results of practical usefulness.

S27-91
ABS. ONLY

N91-26046

^{3}He and Other Lunar Volatiles

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P-1

~~We consider~~ constraints and give estimates for the abundances of ^{3}He, other noble gases, and chemically reactive volatiles (e.g., H, C, N, S, F, Cl) on the Moon. For the case of surface inventories, solar wind particles implanted into grains on the surface of the Moon provide an accessible, though not necessarily abundant, source of H, C, N and the noble gases. Solar-wind-implanted species are concentrated in the infest grain sizes, and are only found in the upper few meters of the regolith, where there are grains that have been directly exposed to the Sun. Elemental abundances in surface soils are typically 10s of mg/g, and vary according to the exposure history of the soil. The abundance of the rare, but possibly economically important, isotope ^{3}He is typically a few ng/g. The largest uncertainty in estimates of the total lunar abundance of solar-wind-implanted species comes from the lack of knowledge of their distribution with depth below the upper meter or two. For the case of bulk inventories, constraints resulting from lunar sample analyses and from physical chemical models of volatile behavior during the hypothesized giant impact origin of the Moon ~~will be~~ used to give estimated abundances.

S28-91
ABS. ONLY

N91-26047
74584

Solar Cells for Lunar Applications by Vacuum Evaporation of Lunar Regolith Materials

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P-1

The National Space Exploration Initiative, specifically the near term part of the program, the Lunar component, has major requirements for technology development of critical systems, one of which is electrical power. The availability of significant electrical power on the surface of the Moon will be a principal driver defining the complexity of the lunar base. Proposals to generate power on the Moon include both nuclear and solar (photovoltaic) systems.

The main drawback to ~~all of the approaches~~ to date is that all of the mass for the power systems must be transported from the Earth to the Moon. For the lunar base, this could amount to over 40 metric tons to the Moon for the ~~utilization~~ phase. A more efficient ~~(and possibly synergistic)~~ approach is to attempt utilization of the existing lunar resources to generate the power systems. ~~The~~ synergism may occur from the fact that there have already been lunar materials processing techniques proposed for the extraction of oxygen that would have, as by-products, materials that could be specifically used to generate solar cells.

The lunar environment is a vacuum with pressures generally in the 1×10^{-10} torr range. Such conditions provide an ideal environment for direct vacuum deposition of thin film solar cells using the "waste" silicon, iron, and TiO_2 available from the lunar regolith processing meant to extract oxygen.

It is proposed, therefore, to grow by vacuum deposition, thin film silicon solar cells from the improved regolith processing by-products. The expected efficiencies of the cells would be $\approx$ 3 months.

In the thin film ~~deposition approach~~ for electrical power generation on the Moon, not only will major amounts of mass-to-orbit be reduced, but it will also clearly demonstrate full utilization of lunar resources for power generation.

S29-91
ABS. ONLY
14585

Finding and Utilizing Lunar Lava Tubes

N91-26048

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Horz describes the evidence for lava tubes associated with rills in lunar photoimaging. These tubes have terrestrial counterparts as described by Billings, et al., and Gillett. The widths of these tubes range from tens to hundreds of meters. Their roof thicknesses are at least 0.125 to 0.25 times their widths and stand unsupported on the Moon. To confine one atmosphere of internal pressure, static roof thickness must be at least 16 m.

Favorable locations of lava tubes may be surveyed using roving gravity meters on "Doodle Bugs," which consist of platforms containing equipment for communication with Earth-based control stations. ~~The~~ Doodle Bugs ~~need not be large~~ to support ~~the gravity meter and other equipment. Gravity data are transmitted to Earth along with location and photography of the surrounding terrain. A number of such Doodle Bugs may spiral outward from a landing site, thus building the data base for a map of transected lava tubes. A tube as small as 6 meters in diameter should be easily detected under 16 meters of lunar mare basalt.~~

The stable -20°C temperature of the lava tubes should provide a workable habitat environment. The greater than 16 m of basalt in the roof should give adequate radiation and impact protection.

Typically, after clearing entries and grading ramps, habitats might be placed in tubes and inflated. Later, larger habitats might be built by enclosing tube sections with compacted-regolith dams. The interior can then be sealed to hold an atmosphere. The huge lava tubes inferred ~~rom~~ the photographs are capable of providing habitats hundreds of meters wide, in lengths of kilometers.

S30-91
ABS. ONLY

Lunar Sulfur

N91-26049

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This paper expands ideas introduced by Vaniman, Pettit and Heiken in their 1988 "Uses of Lunar Sulfur." Particular attention is given to uses of SO_2 as a mineral-dressing fluid. Also introduced is the concept of using sulfide-based concrete as an alternative to the sulfur-based concretes proposed by Leonard and Johnson.

Sulfur is abundant in high-Ti mare basalts, which range from 0.16% to 0.27% by weight. Terrestrial basalts with 0.15% S are rare. For oxygen recovery, sulfur must be driven off with other volatiles from ilmenite concentrates, before reduction. Troilite (FeS) may be oxidized to magnetite (Fe_3O_4) and SO_2 gas, by burning concentrates in oxygen within a magnetic field, to further oxidize ilmenite before regrinding and magnetic reconcentration. SO_2 is liquid at -20°C, the mean temperature underground on the Moon, at a minimum of 0.6 atm pressure. By using liquid SO_2 as a mineral- dressing fluid, all the techniques of terrestrial mineral separation become available for lunar ores and concentrates.

Combination of sulfur and iron in an exothermic reaction, to form iron sulfides, may be used to cement grains of other minerals into an anhydrous iron-sulfide concrete. A sulfur-iron-aggregate mixture may be heated to the ignition temperature of iron with sulfur to make a concrete shape. The best iron, sulfur, and aggregate ratios need to be experimentally established. The iron and sulfur will be by-products of oxygen production from lunar minerals.

S31-91
ABS. ONLY

Consolidation of Lunar Regolith: Microwave vs. Direct Solar Heating

N91-26050

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The production of construction materials on the lunar surface will require an appropriate fabrication technique. Two processing methods considered as being suitable for producing dense, consolidated products such as bricks are direct solar heating and microwave heating. An analysis was performed to compare the two processes in terms of the amount of power and time required to fabricate bricks of various size. The regolith was considered to be a mare basalt with an overall density of 60% of theoretical. Densification was assumed to take place by vitrification since this process requires moderate amounts of energy and time while still producing dense products. Microwave heating was shown to be significantly faster compared to solar furnace heating for rapid production of realistic-sized bricks.

(cont., p. 19)

18.4

(Kunitzer, et al.; continued from pg. 18)

Model experiments were also conducted to assess the viability of the processing techniques that were selected. Conventional sintering in a furnace was used since this method duplicates the conditions achieved in a solar furnace. A high titanium mare basalt simulant (Minnesota Lunar Simulant-1) was utilized. Mechanical testing and microstructural analysis indicated that the addition of agglutinates to the simulant is required in order to achieve high densities and mechanical properties commensurate with the original basalt material.

S32-91
ABS. ONLY

Costs and Benefits of Lunar Oxygen: Engineering, Operations and Economics

N91-26051

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Oxygen is the most commonly discussed lunar resource. It will certainly not be the easiest to retrieve, but oxygen's fundamental place in propulsion and life support guarantees it continued attention as a prime candidate for early in situ resource utilization (ISRU). Although science has proposed many ways of extracting oxygen from lunar rocks, only limited engineering design and operations analysis has been done so far to realize these schemes; neither has much economic assessment been performed to determine the circumstances under which lunar oxygen production makes sense.

This paper reviews the findings of recent investigation, sponsored by NASA-Ames Research Center, into the kinds of technologies, equipment, and scenarios - the engineering and operations costs - that will be required even to initiate lunar oxygen production. The infrastructure necessary to surround and support a viable oxygen-processing operation is explained. Selected details are used to illustrate the depth of technology challenges, extent of operations burdens, and complexity of decision linkages. Basic assumptions, and resulting timelines and mass manifests, are listed.

The paper then combines these findings with state-of-the-art knowledge of lunar and Mars propulsion options in simple economic input/output and internal-rate-of-return models, to compare production costs with performance benefits. Implications for three realistic scales of exploration architecture - expeditionary, aggressive science, and industrialization/settlement - are discussed. Conclusions are reached regarding the contextual conditions within which production of lunar oxygen (LLOX) is a reasonable activity. LLOX appears less useful for Mars missions than previously hoped. Its economical use in low Earth orbit hinges on production of lunar hydrogen as well. LLOX shows promise for lunar ascent/descent use, but that depends strongly on the plant mass required. Technological drivers required to realize the benefits of LLOX in various applications (e.g., a sophisticated level of automation) are identified.

S33-91
ABS. ONLY

Industrial Modification of the Lunar Atmosphere

N91-26052

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To rough order of magnitude, the sources and sinks of the present trace lunar atmosphere can be accounted for. In particular, it is clear that the solar wind is the primary agent for rapidly removing gases, other than hydrogen which can escape thermally. But the solar wind has only a finite capability for stripping. If gases are added at rates approaching 100 g/sec, at atmosphere will begin to accumulate. Transition to a state where thermal escape dominates solar-wind loss occurs when the atmosphere has accumulated a total mass of about 108 kg. Assuming that disturbing the lunar regolith liberates about 10-4 by mass of trapped gases, this implies that some kinds of mining operations could handle up to 109 tons of material before creating a long-lived, albeit still exceedingly tenuous, atmosphere which would have no appreciable influence on most lunar activities.

However, one of the compelling reasons for returning to the Moon is to establish it as the principal site for some of the most important astronomical telescopes of the 21st century, able to tackle fundamental problems probably not accessible in any other way. In turn, observations in the far ultraviolet are important especially for astronomical spectroscopy. Should the lunar atmosphere ever exceed an abundance matching that of the Earth at 120 km altitude, ever-larger UV wavelength ranges would be inhibited or lost, as would probably be the ability to use the Moon as a base for very low frequency radio astronomy.

S34-91
ABS. ONLY

14590

N91-26053

P-1

Lunar Base Siting

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As with any planetary body, the lunar surface is quite heterogeneous. There are widely dispersed sites of particular interest for known and potential resource availability, selenology, and lunar observatories. Discriminating characteristics include solar illumination, view of Earth, local topography, engineering properties of the regolith and certain geological features, and local mineralogy and petrology. Space vehicle arrival and departure trajectories constitute a minor consideration. Over time, a variety of base sites will be developed serving different purposes. Resource-driven sites may see the fastest growth during the first decades of lunar development, but selection of the most favorable sites is likely to be driven by suitability for a combination of activities. As on Earth, later development may be driven by geographical advantages of surface transportation routes.

With the availability of near-constant sunlight for power generation, as well as permanently shadowed areas at cryogenic temperatures, polar sites are attractive because they require substantially less Earth-launched mass and lower equipment complexity for an initial permanent base. Discovery of accessible volatiles reservoirs, either in the form of polar permafrost or gas reservoirs at other locations, would dramatically increase the attractiveness of any site from a logistical support and selenological point of view. Amid much speculation, no reliable evidence of such volatiles exists. More reliable evidence exists for areas of certain mineral concentrations, such as ilmenite, which could form a feedstock for some proposed resource extraction schemes. While tentative selections of advantageous base sites are made, new data from lunar polar orbiters and the Galileo polar flybys would be very helpful.

S35-91
ABS. ONLY

14591

N91-26054

P-1

SESSIONS W1-W2, NEAR-EARTH ASTEROIDS

An ISU Study of Asteroid Mining

J.D. Burke, et al.

During the 1990 summer session of the International Space University, 59 graduate students from 16 countries carried out a design project on using the resources of near-Earth asteroids. This paper summarizes the results of the project, whose full report is now available from ISU. The student team included people in all of these fields: architecture, business and management, engineering, life sciences, physical sciences, policy and law, resources and manufacturing, and satellite applications. They designed a project for transporting equipment and personnel to a near-Earth asteroid, setting up a mining base there, and hauling products back for use in cislunar space. In addition they outlined the needed precursor steps, beginning with expansion of present ground-based programs for finding and characterizing near-Earth asteroids and continuing with automated flight missions to candidate bodies. (To limit the summer project's scope the actual design of these flight-mission precursors was excluded.) The main conclusions were that asteroid mining may provide an important complement to the future use of lunar resources, with the potential to provide large amounts of water and carbonaceous materials for use off Earth. However, the recovery of such materials from presently- known asteroids did not show an economic gain under the study assumptions, and therefore asteroid mining cannot yet be considered a prospective business.

S36-20

N91-26055

Development of an Electrostatic Propulsion Engine using Sub-micron Powders as the Reaction Mass

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Asteriod sample return missions would benefit from development of an improved rocket engine. Chemical rockets achieve their large thrust with high mass consumption rate (dm/dt) but low exhaust velocity and therefore a large fraction of their total mass is fuel. Present day ion thrusters are characterized by high exhaust velocity, but low dm/dt and are therefore inherently low thrust devices. However, their high exhaust velocity is poorly matched to typical mission requirements and therefore wastes energy. A better match would be intermediate between the two forms of propulsion. This could be achieved by electrostatically accelerating solid powder grains, raising the possibility that interplanetary material could be processed to use as reaction mass.

An experiment to study the charging properties of sub-micron sized powder grains is described. If a suitable material can be identified, it could be used as the reaction mass in an electrostatic propulsion engine. The experiment employs a time of flight measurement to determine the exhuast velocity (v) of various negatively charged powder grains that have been charged and accelerated in a simple device. The purpose is to determine the charge to mass ratio that can be sustained for various substances. In order to be competitive with present day ion thrusters, a specific impulse (v/g) of 3000 to 5000 seconds is required. Preliminary results will be presented.

More speculatively, there are some mission profiles that would benefit from collection of reaction mass at the remote asteriod site. Experiments that examine the generation of sub-micron clusters by electrostatic self-disruption of geologically derived material are planned.

S37-90

N91-26056

Enstatite Chondrites and Achondrites as Asteroidal Resources

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The highly reduced nature of the enstatite meteorites (chondrites and achondrites) differs from that of all other types of stony meteorites. The silicates in the enstatite meteorites contain almost no FeO. In addition, many normally lithophile elements, such as Na, Ca, Mg, Cr and Ti, display chalcophilic behavior. A study of the chemistry and mineralogy of the enstatite meteorites was undertaken to determine their resource potential.

On average, about 99% of the volume of an enstatite achondrite, or aubrite, consists of only four silicate minerals: enstatite ($MgSiO_3$), Na-rich plagioclase (approximately 90% $NaAlSi_3O_8$), diopside ($CaMgSi_2O_6$) and forsterite (Mg_2SiO_4), with enstatite by far the most abundant mineral (approximately 90 vol% of the meteorite). The remaining 1% of the volume consists of troilite (FeS), kamacite (metallic Fe-Ni) and trace amounts of oldhamite (CaS), daubreelite ($FeCr_2S_4$), ferromagnesian alabandite [(Fe, Mn, Mg)S] and schreibersite [$(Fe, Ni)_3P$]. Thus the aubrites can be considered as a possible source for large quantities of Mg, Si and O, but are of little interest as a source of anything else.

The enstatite chondrites appear to be more promising candidates for resource utilization. These chondrites are generally divided into two groups: EH (for high iron; fine-grained, with abundant chondrules) and EL (low iron, coarse-grained, with little or no evidence of chondrules). Metallic Ni- Fe makes up roughly 20-25 wt% of each type of enstatite chondrite. These meteorites are also a good source of nitrogen. The bulk nitrogen content of the enstatite chondrites ranges from about 200 to 800 ppm, roughly 5-10 times higher than that in ordinary, C3 and C4 chondrites. This is due in part to the presence of two nitride minerals, osbornite (TiN) and sinoite (Si_2N_2O). The latter mineral is restricted to EL chondrites, which typically have a higher bulk nitrogen content than the EH chondrites.

Cr, Mn and Ti, three valuable metals, usually found as minor constituents in a wide number of silicate minerals, are concentrated in a few distinct sulfide phases in the enstatite chondrites. Two sulfides, troilite (FeS) and niningerite (MgS), contain roughly 50% of the total Ti, 50% of the total Cr, and virtually 100% of the total Mn in EH chondrites. In the EL chonrites, about 80% of the bulk Ti, 75% of the bulk Cr and almost all of the Mn can be found in three sulfide minerals: troilite (FeS), daubreelite ($FeCr_2S_4$) and ferroan alabandite (Fe, Mg, Mn)S.

538-90
ABS. ONLY

Short-Period Comets

N91-26057

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P-1

The spacecraft flybys of Comet Halley in 1986 confirmed Whipple's icy conglomerate hypothesis for cometary nuclei and showed that comets are far richer in volatiles than any other class of solar system bodies. Water is the most abundant volatile, comprising roughly 80% of the gas flowing out from the nucleus. CO is next with a content of 15% relative to water, though with approximately half of that coming from an extended source in the cometary coma, i.e., hydrocarbon dust grains. The detection of large numbers of hydrocarbon CHON grains was one of the more significant discoveries of the Halley flybys, as was the ground-based observation that CN occurs in jets, again indicating an extended source. Evidence was also found for more complex hydrocarbons. Estimates of the total dust-to-gas ratio for Halley range as high as 2:1, indicating that a substantial fraction of the volatile material may be tied up in solid hydrocarbons rather than ices. The role of clathrates in trapping more volatile ices is not yet understood. If Halley can be taken to be representative of all short-period comets, which to first-order we think it is, then the short-period comets may provide a significant source of volatiles in near-Earth space. This resource is more difficult to reach dynamically than the near-Earth asteroids, but the high volatile content may justify the additional effort necessary. In addition, there is considerable evidence that at least some fraction of the near-Earth asteroids are extinct cometary nuclei which have evolved into asteroidal orbits, and which may contain significant volatiles buried beneath an insulating lag-deposit crust of nonvolatiles. Our knowledge of comets will be greatly enhanced in the near future by the Comet Rendezvous Asteroid Flyby mission now under development by NASA, and by the proposed Rosetta mission, a joint effort by ESA and NASA to return a cometary sample to Earth for detailed analysis.

539-90
ABS. ONLY

Near-Earth Asteroids: Metals Occurrence, Extraction and Fabrication

N91-26058

Richard Westfall

P-1

Near-Earth asteroids occur in three principle types of orbits: Amor, Apollo and Aten. Amor asteroids make relatively close (within 0.3 AU) approaches to the Earth's orbit, but do not actually overlap it. Apollo asteroids spend most of their time outside of the Earth's orbital path, but at some point of close approach to the Sun, they cross the orbit of the Earth. Aten asteroids are those whose orbits remain inside the Earth's path for the majority of their time, with semi-major axes less than 0.1 AU.

Near-Earth asteroids include: stones, stony-irons, irons, carbonaceous and super-carbonaceous. Metals within these asteroids include: iron, nickel, cobalt, the platinum group, aluminum, titanium, and others. The extraction of ferrous and platinum group metals from the stony-iron asteroids, and the iron asteroids will be focused on in this paper.

Extraction of the metal fraction can be accomplished through the use of tunnel-boring-machines (TBM) in the case of the stony-irons. The metals within the stony-iron asteroids occur as dispersed granules, which can be separated from the stony fraction through magnetic and gaseous digestion separation techniques. The metal asteroids are processes by drilling and gaseous digestion or by gaseous digestion alone.

Manufacturing of structures, housings, framing networks, pressure vessels, mirrors and other products is accomplished through the Chemical Vapor Deposition (CVD) of metal coating on advanced composites and on the inside of Contour-Defining Inflatables (CDI). Metal coatings on advanced composites provide: resistance to degradation in the hostile environments of space, superior optical properties, superior heat dissipation, service as wear coatings and service as evidential coatings. Metal coatings on the inside of Contour-Defining Inflatables produce metal load-bearing products. Fibers such as graphite, kevlar, glass, ceramic, metal, etc., can be incorporated in the metal coatings on the inside of Contour-Defining Inflatables producing metal matrix products which exhibit high strength and resist crack propagation.

S40-90
ABS. ONLY
14596
N91-26059

Momentum Harvesting Techniques For Solar System Travel

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Analex Corporation

Astronomers are lately estimating there are 400,000 Earth visiting asteroids larger than 100 meters in diameter! These asteroids are uniquely accessible sources of building materials, propellants, oxygen, water and minerals. They also constitute a huge momentum reserve, potentially usable for travel throughout the solar system. To use this momentum, we must track these stealthy objects, and learn to extract the momentum we want.

This paper discusses momentum harvesting by momentum transfer from asteroid to spacecraft, and by using the momentum of the extraterrestrial material to help deliver itself to our destination. The purpose is neither to quantify nor justify the momentum exchange processes, but to stimulate our collective imaginations with some intriguing possibilities which emerge when we consider momentum as well as material. A net and tether concept is the suggested means of asteroid capture, the basic momentum exchange process. The energy damping characteristics of the tether will determine the velocity mismatch that can be tolerated, and hence the amount of momentum that can be harvested per capture. As the tether plays out of its reel, drag on the tether steadily accelerates the spacecraft and dilutes, in time, the would-be collision.

This paper introduces a variety of concepts for riding and using asteroids after capture. The hitchhiker uses momentum transfer only. The beachcomber, the caveman, the swinger, the prospector, and the rock wrecker also take advantage of raw asteroidal materials. The chemist and the hijacker go further, they process the asteroid into propellants. Or, an "asteroid railway system" could be constructed with each hijacked asteroid becoming a scheduled train. Travelers could board this space railway system assured that water, oxygen propellants and shielding await them. Austere space travel could give way to comforts, with a speed and economy impossible without nature's gift of earth visiting asteroids.

S41-20
ABS. ONLY
N91-26060
14597

Stacking the Odds in Favor of a Space Propulsion Jackpot

Alan J. Willoughby
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When faced with a variety of technical options to solve a problem, program planners often try to identify one potential winner, then channel their resources into this option. The more scarce their resources are perceived to be, the more likely they are to fall into this trap of illogic. The real ideal solution could well be an optimum combination of options, not just one.

P-1

Many propulsion opportunities now tantalize us as solutions to the potentially high cost of travelling to other planets. Amongst these opportunities, nuclear thermal rockets (NTR), nuclear electric propulsion (NEP) and asteroid derived propellants stand out as high-payoff modest-challenge options, as near term as we resolve to make them. But which to choose? Or should we opt for higher risk higher payoff technology, such as fusion?

The approach advocated here, called "technoflex," is one that addresses NTR, NEP and asteroidal propellants in harmony rather than in isolation. Technoflex is technology rich, and option flexible. Technoflex should cost roughly the same as a classic "phased technology elimination" approach. This paper stresses the synergistic benefits amongst these three options, how they can be efficiently pursued together, and how they can fit with longer range technologies.

Even if no option reaches its highest expectations, the combinations of any two partial winners would still give big dividends. These combinations are cheap propellants in space, dual mode high thrust/low thrust, or versatile propellant NTR. The triple payoff is excellent, even if all three options would pan out below expectations. If only one option reaches its potential, it could make the other two still worth their investment. If all three options meet full expectations, the triple payoff is a space propulsion JACKPOT which will make concern about the initial investment ludicrous as well as open up our solar system to expedient exploration.

542-90
ABS ONLY

SESSION W3, PHOBOS AND DEIMOS

N91-26061

The Composition of Phobos: Meteorite Analogs Based on KRFM and VSK Spectral Data from the Phobos 2 Spacecraft

P-1

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In 1989 the Phobos 2 spacecraft obtained 8-channel 0.3-0.6 mm KRFM spectra and two-channel wide-angle TV VSK images in bandpasses of 0.40-0.56 mm and 0.78-1.10 mm. The TV data were used to map four color ratio units on disk-resolved images of Phobos, and were combined with the KRFM spectra to analyze possible meteorite analogs for the mapped units (Murchie et al., 1990). A total of 58 spectra of 39 meteorites were studied for similarities with Phobos data in spectral shape, absorption features, and visible/near-IR color ratio. Analysis of the spectral data show that, among the meteorites studied, there are no unique spectral analogs for Phobos surface material. Currently, the closest spectral analogs are the optically altered black chondrite meteorites Gorlovka and Pervomaisky. The weak UV absorption bands in some KRFM spectra and the red slope in VSK color-ratio data indicate that carbonaceous chondrite-like material may also be a component of Phobos surface material. However, the lack of close carbonaceous chondrite spectral analogs and the existence of apparent absorption bands in KRFM spectra that are not seen in meteorite spectra suggest that there are processes and/or materials on the surface of Phobos that are not represented in the meteorite collections. The similarities between KRFM spectra of Phobos and the spectra of black chondrites suggest that optically altered mafic silicates may constitute a component of the surface material of Phobos, and that optical alteration and mixing by regolith processes may be an important factor in the evolution of Phobos surface material.

543-12
ABS ONLY

Survey of Resource Opportunities and Critical Evaluation of Economic Requirements

N91-26062

P-1

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A series of mission analyses have been performed to evaluate human missions to Mars and the Moon with and without the aid of planetary resource utilization. The types of trade studies that are considered include the use of resources to manufacture propellant, food, habitat atmospheric gases, and lander habitat structure. Also, the potential for export of resources from the Moon, Mars, Phobos, Deimos, and selected asteroids is also examined. In all cases, mass leveraging is evaluated. For certain cases, economic factors are evaluated as well. It is concluded that some uses are highly leveraging on the mission, whereas others will have lesser impact and therefore should be afforded lesser priority in resource utilization studies. This survey is made with a consistent set of scaling laws for spacecraft propulsion and habitation systems and subsystems, and therefore provides a rational basis for comparing different resource locations and use strategies.

544-91
ABS. ONLY

Mass Budget for Mining the Moons of Mars

N91-26063

P-1

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The mass budget will be detailed for system architectures that use rocket fuels of propellants derived from Deimos and Phobos to transport 10,000 ton payloads of exofuel (exoatmospheric fuels) or exomass (exoatmospheric mass) to Earth orbits. A point design for the system architecture will be used that includes a self-sustaining cycle, which requires no materials from Earth, and an infrastructure, which must be emplaced to start the cycle. Both the use of steam rockets and the use of liquid oxygen and liquid hydrogen will be examined. It will be shown that a system delivering 10,000 tons of payload to a Highly Elliptical Earth Orbit will require approximately 23,000 tons of water for use by nuclear heated steam rockets to effect completely propulsive, round trip maneuvers. It will also be shown that about 8000 tons will be available for sale at Low Earth Orbit, each cycle, and that the number of cycles can number in the tens before critical components be replaced.

S45-20
ABS ONLY

N91-26064

Optimum Rocket Propulsion for Energy-Limited Transfer

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In order to effect large-scale return of extraterrestrial resources to Earth orbit, it is desirable to optimize the propulsion system to maximize the mass of payload returned per unit energy expended. This optimization problem is different from the conventional rocket propulsion optimization.

A rocket propulsion system consists of an energy source plus reaction mass. In a conventional chemical rocket, the energy source and the reaction mass are the same. For the transportation system that will be required for large-scale return of extraterrestrial resources, however, the best system performance is achieved if the reaction mass used is from a locally available source. In general, the energy source and the reaction mass will be separate; the reaction mass is assumed to be abundantly available, while the energy supply will be the limiting resource. One such rocket system is the nuclear thermal rocket, in which the energy source is a reactor and the reaction mass a fluid which is heated by the reactor and exhausted. Another energy-limited rocket system is the hydrogen/oxygen rocket where H_2/O_2 fuel is produced by electrolysis of water using a solar array or a nuclear reactor; the energy content of the fuel is fixed by the energy expended, but the specific impulse I_{sp} may be varied from nearly zero up to the theoretical maximum by injection of inert reaction mass into the exhaust flow.

The problem is to choose the optimum specific impulse (or equivalently exhaust velocity) to minimize the amount of energy required to produce a given mission delta-v in the payload. The somewhat surprising result is that the optimum specific impulse is not the maximum possible value, but is proportional to the mission Δv.

In general terms, at the beginning of the mission it is optimum to use a very low specific impulse and expend a lot of reaction mass, since this is the most energy efficient way to transfer momentum. However, as the mission progresses, it becomes important to minimize the amount of reaction mass expelled, since energy is wasted moving the reaction mass. Thus, the optimum specific impulse will increase with the mission Δv. Optimum I_{sp} will be derived for maximum payload return per energy expended for both the case of fixed and variable I_{sp} engines. Sample missions analyzed include return of water payloads from the moons of Mars and of Saturn.

Water Resources and Hydrology of Mars

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The surface of Mars has been extensively modified by a large variety of water erosional and depositional processes. Although liquid water is presently unstable on the planet's surface, in its cold, hyperarid climate, there is abundant geomorphological evidence of past fluvial valley development, multiple episodes of catastrophic flooding, periglacial landforms, ice-related permafrost, lake deposits, eroded impact craters, and possible glacial landforms throughout much of Mars' geological history. The amount of water required to form such features is estimated to be equivalent to a planet- wide layer approximately 500 meters deep [1].

Some of this water undoubtedly was removed from the planet by atmospheric escape processes, but much probably remains in the subsurface of Mars. Jakosky [2] summarized the present partitioning of water on Mars, expressed as an average global depth, as follows: in the polar caps, 30 meters; in the megaregolith, 500 to 1000 meters; structurally bound in clays, 10 meters; and in high latitude regolith, a few meters. However, most of this water is probably in the form of ice, except in anomalous areas of possible near surface liquid water [3,4], and in regions where hydrothermal systems [5,6] are still active.

The best locations for prospecting are those areas where water or ice is sufficiently concentrated at shallow enough depths to make it feasible to pump out or mine. The most obvious area would be the northern polar cap. In summer, the seasonal CO_2 cap evaporates, exposing a remnant water ice cap, so ice here needs only to be collected and melted. However, landings in polar regions require much larger expenditures of fuel than in equatorial regions. Another potentially large ground-water/ice reserve is the northern plains region, where the enormous outflow channel discharges terminated and probably formed a temporary ocean [7]. Most likely, the northern plains contain multiple ice-rich layers interbedded with sedimentary and volcanic mantling units. Each mantling deposit would have acted as a confining layer, separating subsequent flood flow events by preventing water from infiltrating into deeper aquifer systems. Other likely areas of ground-water/ice reserves would be located in the high latitudes in alluvial fan deposits, channel and valley bottoms, rock glaciers, mass movement deposits, stabilized sand dunes, terrace deposits, lobate ejecta blankets, lobate debris aprons, floors of impact basins especially those in which valleys terminate, deposits located just north of the termini of the Alba fluvial valleys, and permeable glacial sediments, particularly those contained in the postulated kames, eskers and outwash plains in the Southern hemisphere [8]. Finally if any areas of recently active volcanism still exist on Mars, the associated hydrothermal systems would provide an excellent, exploitable source of both energy and near surface liquid water.

REFERENCES

[1] Carr, M.H. 1987. *Nature* 326:30-35.
[2] Jakosky, B.M. 1990. Personal communication. *DPS Meeting.*
[3] Huguenin, R.L., and Clifford, S.M. 1980. *NASA TM 81776*, pp. 153-155.
[4] Zisk, S.H., and Mouginis-Mark, P.J. 1980. *Nature* 288:735-738.
[5] Gulick, V.C., et al. 1988. *XIX LPSC Meeting*, pp. 441-442.
[6] Gulick, V.C., and Baker, V.R. 1989. *Nature* 341:514-516.
[7] Baker, V.R., et al. *Nature*, submitted.
[8] Kargel, J.S., and Strom, R.G. 1990. *XXI LPSC Meeting*, pp. 597-598.

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S47-91
ABS. ONLY
N91-26066 3

Martian Impact Crater Ejecta Morphologies and their Potential as Indicators of Subsurface Volatile Distribution

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P-1

Many martian impact craters display ejecta morphologies suggestive of fluidization during ejecta emplacement. Impact into subsurface volatile reservoirs (i.e., water, ice, CO_2, etc.) is the mechanism favored by many scientists, although acceptance of this mechanism is not unanimous. In recent years, we have undertaken a number of studies to better understand possible relationships between ejecta morphology and latitude, longitude, crater diameter, and terrain. These results suggest that subsurface volatiles do influence the formation of specific ejecta morphologies and may provide clues to the vertical and horizontal distribution of volatiles in more localized regions of Mars. The location of these volatile reservoirs will be important to humans exploring and settling Mars in the future.

Qualitative descriptions of ejecta morphology and quantitative analyses of ejecta sinuosity and ejecta lobe areal extent form the basis of our studies. Ejecta morphology studies indicate that morphology is correlated with crater diameter and latitude, and, using depth-diameter relationships, these correlations strongly suggest that changes in morphology are related to transitions among subsurface layers with varying amounts of volatiles (Barlow and Bradley, 1990). Ejecta sinuosity studies reveal correlations between degree of sinuosity ("lobateness") and crater morphology, diameter, latitude, and terrain (Bridges and Barlow, 1989). Lobateness, together with variations in areal extent of the lobate ejecta blanket with morphology and latitude, probably depends most directly on the ejecta emplacement process (Barlow, 1990). We can compare the physical parameters measured here with those predicted by existing ejecta emplacement models. Some of these parameters are best reproduced by models requiring incorporation of volatiles within the ejecta. However, inconsistencies between other parameters and the models indicate that more detailed modeling is necessary before we can confidently predict the location of volatile reservoirs based on ejecta morphology studies alone.

S48-91
ABS. ONLY

Evolution of Ore Deposits on Terrestrial Planets

N91-26067

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P-1

Ore deposits (i.e., economic local enrichments of individual elements above their crustal abundances) on terrestrial planets materialized after core formation, mantle evolution, crustal development, interactions of surface rocks with the hydrosphere and atmosphere, and, where life exists on a planet, the involvement of biological activity. Core formation removed most of the siderophilic and chalcophilic elements, leaving mantles depleted in many of the strategic and noble metals relative to their chondritic abundances. Basaltic magma derived from partial melting of the mantle transported to the surface several metals contained in immiscible silicate and sulfide melts. Magmatic ore deposits were formed during cooling, fractional crystallization and density stratification from the basaltic melts (e.g., massive and disseminated pyrrhotite-pentlandite ores associated with komatiites; stratiform chromite and Pt veins in layered intrusions). Such ore deposits found in Earth's Archean rocks were probably generated during early histories of all terrestrial planets and may be the only types of igneous ores on Mars. Where plate tectonic activity was prevalent on a terrestrial planet, temporal evolution of ore deposits took place. Repetitive episodes of subduction modified the chemical compositions of the crust and upper mantles, leading to porphyry copper and molybdenum ores in calc-alkaline igneous rocks and granite-hosted tin and tungsten deposits, for example. at oceanic spreading centers, seawater-basalt interactions produced Cyprus-type mineralization observed in seafloor chimney deposits and obducted ophiolite sequences. Such plate tectonic-induced mineralization in relatively young igneous rocks on Earth may also have produced hydrothermal ore deposits on Venus in addition to the massive sulfide and cumulate chromite ores associated with Venusian mafic igneous rock.

Sedimentary ore deposits resulting from mechanical and chemical weathering in educing atmospheres in Archean Earth included placer deposits (e.g., uraninite-gold-pyrite ores) and chromite, ilmenite and other dense unreactive minerals could also be present on channel floors and in valley networks on Mars, while banded iron formations might underlie the Martian northern plains regions. As oxygen evolved in Earth's atmosphere, so too did oxide ores. By analogy, gossans above sulfide ores probably occur on Mars, but not submarine ferromanganese nodules and crusts which have precipitated in oxygenated seawater on Earth.

549-91
ABS. ONLY

N91-26068

The Potential for Crustal Resources on Mars

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Martian resources pose not only an interesting scientific challenge but also have immense astronautical significance because of their ability to enhance mission efficiency, lower launch and program costs, and stimulate the development of large Mars surface facilities.

Although much terrestrial mineralization is associated with plate tectonics and Mars apparently possesses a thick, stationary lithosphere, the presence of crustal swells, rifting, volcanism, and abundant volatiles indicates that a number of sedimentary, hydrothermal, dry-magma mineral concentration processes may have operated on Mars. For example, in Colorado Plateau-style ("roll- front") deposits, uranium precipitation is localized by redox variations in groundwater. Also, evaporites - either in salt pans or even interstitially in pore spaces - might concentrate Cl, Li, and K.

Many Martian impact craters have been modified by volcanism and probably have been affected by rising magma bodies interacting with ground ice or water. Such conditions might produce hydrothermal circulations and element concentrations. If the high sulfur content found by the Viking landers typifies Martian abundances, sulfide ore bodies may have been formed locally.

Mineral-rich Africa seems to share many volcanic and tectonic characteristics with portions of Mars and may suggest Mars' potential mineral wealth. For example, the rifts of Valles Marineris are similar to the rifts in east Africa, and may both result from a large mantle plume rising from the interior and disrupting the surface. The gigantic Bushveld complex of south Africa, an ancient layered igneous intrusion that contains ores of chromium and Pt-group metals, illustrates the sort of dry-magma processes that also could have formed local element concentrations on Mars, especially early in the planet's history when heat flow was higher.

550-91
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N91-26069

Options for Martian Propellant Production

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This paper presents a quantitative evaluation methodology for utilizing in-situ resources on Mars for the production of useful substances. The emphasis is on the chemical processes. Various options considering different feedstock (mostly, carbon dioxide, water and iron oxides) are carefully examined for the product mix and the energy needs. Oxygen, carbon monoxide, alcohols and other chemicals are the end products. The chemical processes involve electrolyses, methanation, and variations.

It is shown that maximizing the product utility is more important than the production of oxygen, methane or the alcohols. An important factor is the STORAGE of the chemicals produced. The product utility is dependent, to some extent, upon the mission. A combination of the stability, the enthalpy of formation, and the mass fraction of the products is seen to yield a fairly good quantitative feel for the overall utility and maximum mission impact.

S51-96

N91-26070

14607

P-1

The Meteoritic Contribution to the Regoliths of Mars, Deimos, and Phobos

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The mass influx of meteoritic material at Earth exhibits two distinct peaks: one centered at 10-5 grams, corresponding to the continuous, planet-wide flux of micrometeorites, and a second corresponding to the rare impacts of objects larger than 1014 grams. Using the measured flux of meteoritic material at Earth and estimates of the Mars/Earth flux ration, Flynn and McKay (1990) have calculated that the micrometeorites add between 2,700 and 59,000 tons of meteoritic material to the surface of Mars annually. This corresponds to the accretion of between 1.8 and 40 cm of meteoritic material per billion years. On the Moon this meteoritic component constitutes 1 to 2% of the mare soils (Anders et al., 1973). Depending on the indigenous regolith production rate on Mars, the meteoritic material on Mars may be present in sufficient concentration to serve as a resource for the volatile and siderophile elements common in chondritic meteorites but rare in basaltic crustal material. In addition, since a significant fraction of the micrometeorites less than 1200 mm in diameter survive atmospheric entry on Mars without melting (Flynn and McKay, 1990), they carry into the regolith the solar wind ions, including H, He, and noble gases, implanted during their space exposure.

Because of their proximity to Mars, the meteoritic fluxes onto Deimos and Phobos should be similar to those calculated for Mars. Unimpeded by an atmosphere, the slowest micrometeorites would arrive at these moons with the Mars/moon escape velocity: 3 km/sec for Phobos or 2 km/sec for Deimos. The orbital velocity of each moon (1 to 2 km/sec) can add or subtract from this velocity, allowing some micrometeorites to impact the Martian moons with velocities insufficient for vaporization (Flynn, 1990). Over time Deimos and Phobos could build up a regolith containing a significant fraction of chondritic meteoritic spectra of Deimos and Phobos with the laboratory reflectance spectra of chondritic meteorites may not be indicative of the bulk composition of the underlying moon but of a regolith containing a significant meteoritic component.

References:

Anders, E., Ganapathy, R., Krahenbuhl, U., and Morgan, J.W. 1973. Meteoritic material on the Moon. *The Moon* 9:3-24.

Flynn, G.J. 1990. Accretion of meteoritic material onto Mars: Implications for the surface, atmosphere, and moons. In *Proc. COSPAR Workshop on the Environmental Model of Mars* (New York: Pergamon), in press.

Flynn, G.J., and McKay, D.S. 1990. An assessment of the meteoritic contribution to the Martian soil. *J. Geophys. Res.* 95:14497-14509.

S52-91

ABS ONLY

N91-26071

14608

P-1

Planetary Surface Structure and Evolution of Mars

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The surface of the planet Mars is characterized by two different hemispheres: old densely cratered structures in the Southern Uplands, and sparsely cratered younger topografically lower regions covering approximatly the northern third of the planet's surface.

Our model for explaining these global surface structures is characterized by the following features:

(1) homogeneous accretion of Mars

(2) formation of a metal melt layer

(3) northward translation of the undifferentiated core due to a Rayleigh-Taylor instability

(4) vigorous convection in southern parts and formation of Southern Uplands' crust

(5) fragmentation of the primordial core, slowly dissolving "rockbergs," beginning of Tharsis uplift and volcanism

(6) formation of the Northern Lowlands' crust from only weakly differentiated silicatic material

(7) reaching of the present state with symmetrically placed core and further thermal evolution.

S53-91
ABS. ONLY

N91-26072

Getting Water from the Water of Hydration on Mars

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P-1

Both Viking landers found evidence of water in small concentration (< 1%) in the soils of Mars. Using the gas chromatograph mass spectrometer the soil samples on Mars were heated to 500°C to release the water. This result lead researchers to believe that the water in the soil of Mars was tightly bound in a hydration state. In the laboratory we have run several Mars analog soils and a few bench mark soils through a microwave to determine the amount of water released using this method. The results suggest that sufficient water can be obtained using this method to augment the activities of a human base on Mars. Using microwaves to obtain the water instead of a convection oven has many advantages. First the microwave energy is tuned to the water molecules, therefore converting more of the energy into releasing the water. Second, microwaves can be used in the near vacuum of Mars without pressurizing a chamber, unlike ovens which need a convection medium to work properly.

S54-91
ABS. ONLY

N91-26073

Chemical Approaches to Carbon Dioxide Utilization for Manned Mars Missions

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P-1

Utilization of resources available *in situ* is a critical enabling technology for permanent human presence in space. A permanent presence on Mars, for example, requires a tremendous infrastructure to sustain life under hostile conditions (low oxygen partial pressure, ultraviolet radiation, low temperature, etc.). There are numerous studies on the most accessible of Martian resources: atmospheric carbon dioxide. As a resource on Mars, atmospheric CO_2 is: (1) abundant, (2) available at all points on the surface, (3) of known presence, requiring no precursor mission to verify, (4) chemically simple, and (5) can be obtained by simple compression, with no requirements of mining or beneficiation equipment operation. Many studies focus on obtaining oxygen and the various uses for oxygen including life support and fuel; discussion of carbon monoxide, the co-product from CO_2 fixation revolves around its use as a fuel, being oxidized back to CO_2. This study examines several novel proposals for CO_2 fixation through chemical, photochemical, and photoelectrochemical means. For example, the reduction of CO_2 to acetylene (C_2H_2) can be accomplished with hydrogen. Acetylene has a theoretical vacuum specific impulse of ≈375 seconds. Acetylene is a gas at room temperature, but has a boiling point of -75°C, making it easier to store than methane. We also examine potential uses of CO, as obtained or further reduced to carbon, as a reducing agent in metal oxide processing to form metals or metal carbides. The metal or semimetals and carbides can then be used as structural or power materials; the CO_2 can be recycled to generate O_2 and CO.

S55-91
ABS. ONLY
N91-26074
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P-1

Water on Mars: Volatile History and Resource Availability

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The existence of water on Mars is undisputed today. Measurements of atmospheric water vapor have shown that the abundance varies with location and season in a systematic way which depends on processes of exchange with the polar caps, regolith, and atmosphere. Channels, which give the appearance of having been carved by water or of having had water involved in their formation, appear in various locations on the surface; some were formed by catastrophic outflow of water from beneath the surface, while others form valley networks which give the appearance of having formed over long periods of time primarily early in the planet's history. The north polar residual cap consists of water ice, possibly containing an amount of water equivalent to a global layer several tens of meters thick. Finally, water is observed within the regolith, as adsorbed water or as water of hydration.

As no direct measurements of water or ice deposits exist, other than for the north polar cap, we must infer the existence of near-surface deposits of water or ice (or lack thereof) based on: (i) the global inventory of water incorporated into the planet and its history over the last 4.5 b.y., as inferred from geochemical evidence; (ii) the geologic evidence for the existence of water at the surface and to where it is likely to have gone; and (iii) the seasonal cycle of water and the implied existence of non-atmospheric reservoirs which can exchange water with the atmosphere on a seasonal basis. The available evidence suggests the following conclusions, in decreasing order of confidence: (i) The north polar residual cap contains water ice at the surface; (ii) the south polar residual cap contains ice near the surface, under a thin (centimeters to meters) layer of residual CO_2 frost; (iii) the top several meters to tens of meters at the north polar cap probably consist primarily of water ice, and the entire several-kilometer thickness may be predominantly water ice as well; (iv) the global near-surface regolith contains adsorbed water, but probably not in amounts sufficient to act as a viable resource; (v) the high-latitude, near-surface regolith (top ten meters) may contain a significant quantity of water ice which is stable against sublimation into the atmosphere; (vi) these deposits might extend to a depth of a kilometer or more, based on its present stability and its putative presence from early in martian history; (vii) the northern lowlands may contain large deposits of water ice near the surface, emplaced by catastrophic flooding in the Chryse region; and (viii) a large fraction of the ice at the surface, and possibly all of the ice except that which is currently in the polar regions, may have been lost to space via photodissociation and thermal and non-thermal escape of its components. The arguments behind each of these conclusions will be discussed in detail.

A major question regarding future exploration of Mars, however, is the availability of such water as a mission resource. Presumably, water as a resource would require the existence of deposits of readily available water within the near-surface regolith at locations which are plausible landing or exploration sites. The only undisputable near-surface water is the north-polar ice deposit, although the thickness of the deposits is uncertain. Of course, missions to the polar regions are difficult, so other locations of water deposits would be extremely valuable.

As no direct measurements of water or ice deposits exist, other than for the north polar cap, we must infer the existence of near-surface deposits of water or ice (or lack thereof) based on: (i) the global inventory of water incorporated into the planet and its history over the last 4.5 b.y., as inferred from geochemical evidence; (ii) the geologic evidence for the existence of water at the surface and to where it is likely to have gone; and (iii) the seasonal cycle of water and the implied existence of non-atmospheric reservoirs which can exchange water with the atmosphere on a seasonal basis. The available evidence suggests the following conclusions, in decreasing order of confidence: (i) The north polar residual cap contains water ice at the surface; (ii) the south polar residual cap contains ice near the surface, under a thin (centimeters to meters) layer of residual CO2 frost; (iii) the top several meters to tens of meters at the north polar cap probably consist primarily of water ice, and the entire several-kilometer thickness may be predominantly water ice as well; (iv) the global near-surface regolith contains adsorbed water, but probably not in amounts sufficient to act as a viable resource; (v) the high-latitude, near-surface regolith (top ten meters) may contain a significant quantity of water ice which is stable against sublimation into the atmosphere; (vi) these deposits might extend to a depth of a kilometer or more, based on its present stability and its putative presence from early in martian history; (vii) the northern lowlands may contain large deposits of water ice near the surface, emplaced by catastrophic flooding in the Chryse region; and (viii) a large fraction of the ice at the surface, and possibly all of the ice except that which is currently in the polar regions, may have been lost to space via photodissociation and thermal and non-thermal escape of its components. The arguments behind each of these conclusions will be discussed in detail.

556-91
ABS. ONLY
14612

Atmospheric Water on Mars, Energy Estimates for Extraction

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N91-26075

In this paper we consider the Mars atmosphere as a resource for water to support a human expedition. Information obtained from the Viking mission is used to estimate the near-surface water vapor level. The variability over the diurnal cycle is examined and periods of greatest water abundance are identified. Various methods for extracting atmospheric water are discussed including energy costs and the means for optimizing water extraction techniques.

557-91
ABS-ONLY

The Global Distribution of Martian Permafrost

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N91-26076

Determining the distribution of subsurface ice on Mars will be one of the major goals of spacecraft exploration in the next decades. Based on the observed water vapor abundance in the Martian atmosphere, the existence of exposed water ice at the martian polar caps, and models for the thermal structure of the martian regolith, one can make a strong circumstantial case for the existence of significant quantities of water ice buried below the surface at high latitudes (Leighton and Murray 1966; Farmer and Doms 1979; Fanale et al. 1986; Zent et al. 1986).

Accurately determining the present global distribution of martian ground ice will be an important step towards understanding the evolution of the martian surface and atmosphere, and could greatly facilitate human and robotic exploration of the planet. The quantitative Mars permafrost studies that have been performed to date have demonstrated the potential importance of a number of factors determining the past and present distribution of subsurface ice on Mars, but have not considered the issue of regional variability. The present distribution of ground ice on Earth is highly inhomogeneous over a wide range of spatial scales. Field studies have shown that variations in the depth of the terrestrial permafrost layer can be caused by a number of factors, with insolation and the thermal properties of the overlying material being among the most important (Leffingwell 1919; Embleton and King 1968). On Mars, we have observations that show that the thermal properties of surface soil materials exhibit wide geographic variability (Palluconi and Kieffer 1981), but the permafrost models that have been employed to date have assumed that these properties are constant with latitude and depth. To consider the distribution of Mars permafrost in greater detail, we have developed a new themal model that can calculate Martian surface and subsurface temperatures as a function of time-of-day and season.

Our intial results indicate that the distribution of Martian permafrost is highly sensitive to the bulk thermal properties of the overlying soil. Viking IRTM observations of diurnal surface temperature variations show that the bulk thermal properties of midlatitude surface materials exhibit a high degree of regional inhomogeneity (Palluconi and Kieffer 1981).

In general, the results show that the global distribution of permafrost is at least as sensitive to the thermal properties of the overlying surface material as it is to variations in surface insolation due to large scale variations in Mars' orbital and axial elements. In particular, they imply that subsurface ice may exist just a few centimeters below the surface in regions of low thermal inertia and high albedo, which are widespread at latitudes ranging from the equator to $+60^{\circ}$ latitude (Palluconi and Kieffer 1981).

In future studies, we will to explore the effects of the Martian atmosphere on the thermal state of the Martian subsurface, and attempt to produce realistic maps of the expected present distribution of subsurface ice.

References

Embleton, C., and King, C. 1968. *Glacial and Periglacial Geomorphology* (New York: St. Martin's Press).

Fanale, F. P. 1986. Global Distribution and Migration of Subsurface Ice on Mars. *Icarus* 67:1.

Farmer, C. B., and Doms, P.E. 1979. Global Seasonal Variation of Water Vapor on Mars and the Implications for Permafrost. *J. Geophys. Res.* 84:2881.

Leffingwell, E. K. 1919. The Canning River Region, Northern Alaska. *U.S. Geol. Surv. Prof. Paper* 109, p. 1.

Leighton, R. B., and Murray, B. C. 1966. The Behavior of Carbon Dioxide and Other Volatles on Mars. *Science* 153:136.

Palluconi, F. D., and Kieffer, H.H.1981. Thermal Inertia Mapping of Mars from 60 deg. S to 60 deg. N, *Icarus* 45:415.

Zent A. P., et al. 1986. Distribution and State of H_2O in the High-Latitude Shallow Subsurface of Mars, *Icarus* 67:19.

S58-91
ABS. ONLY
N91-26077
14614
P-1

Mars Observer: A Global Mapping Mission

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Mars Observer will be launched in September 1991, arrive at Mars in August 1993 and begin mapping in December 1993. Mapping will be conducted from a low-altitude (400 km) polar orbit over a period of one Martian year (687 days). Each of the seven instruments will be able to observe Mars continuously over this period. The scientific mission centers on global Geoscience and Climatology observations of the Mars atmosphere, surface and interior. The seven experiments involve gamma-ray and neutron spectroscopy, magnetometry, surface and atmospheric imaging, atmospheric sounding, laser altimetry, gravity mapping and thermal emission spectroscopy.

S59-91
ABS. ONLY
N91-26078
P-1

The Formation of Peroxonitrites and Oxygen on Mars

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When martian regolith samples are moistened with water a strong oxidant and oxygen gas are released. The many possible oxidants which have been suggested as present, including superoxide (O_2^-) hydrogen peroxide (H_2O_2), and manganese(IV) oxide (MnO_2), as well as peroxonitrite ($ONOO^-$), can be distinguished by their ability to account for the numerous observations of the Viking Labelled Release (LR) and Gas Exchange (GEX) experiments. The magnitudes, kinetics and heat labilities of the LR experiments and the magnitudes and heat labilities of the GEX experiments have been quantitatively replicated with peroxonitrites. Further, it is to be expected from information about the photochemistry of nitrogen in the atmosphere, the calculated fluxes of NO_χ to the surface, the known reactions of NO_χ with carbonates to produce nitrates and photolysis studies of nitrates, that peroxonitrites are present on Mars. However, considerable uncertainty has existed about the form in which oxygen is stored in photolyzed nitrate crystals. Models have ranged from micropores of O_2 to chemically bound oxygen as peroxonitrate (O_2NOO^-), as well as peroxonitrite. We have recently completed studies of the solution chemistry and solid state photochemistry which show that much of the oxygen evolved on wetting comes from thermal breakdown of peroxonitrite after it is dissolved. We report a chemical model for the photochemical processes occurring during UV irradiation of solid nitrates which we believe resolves the several contradictory models discussed in the literature in recent years. There are several as-yet-undetermined chemical parameters in the processes occurring on the martian surface.

S60-91
N91-26079
14616

Oxygen Production on Mars: A Figure-of-Merit Approach

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This paper describes a new approach towards evaluating the overall system performance in space missions; the objective is to demonstrate a new quantitative tool that can effectively synthesize and display the big picture. It considers a large number of individual components and factors that influence the big picture. The approach has been found to be valuable in evaluating various options that must be considered in choosing one or more final ones. The application is especially suited to evaluate missions that consider ISRU.

The Figure-of-Merit can be different for different missions. In fact, it should be different for different priorities. Simple mass at launch, mass at the moment of departure from LEO, the payback time, the mass returned to LEO, the overall life-cycle costs, . . . are possible indicators of the FoM. After mentioning all of these possible definitions, the FoM for various historical missions will be presented. The FoM of a simple Mars Sample Return (MSR) mission is next presented. It is shown that the FoM is not only higher for missions employing ISRU, but that even among ISRU missions, several mundane propellant combinations are more desirable than the highest-performance propellants.

S61-28
ABS. ONLY
N91-26080

Mission and Transportation Systems Uses of In-Situ Derived Propellants

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P-1

This overview paper discusses the uses of in-situ derived propellants for lunar and Mars transportation systems and the impact on mission architectures. Transportation systems include surface rovers, ascent/descent vehicles and space transfer vehicles at both the Moon and Mars. A brief survey of available propellant types, obtained from the previous sessions of the conference, is included to begin the paper, This is followed by a brief description of typical transportation systems proposed for use on the Moon and Mars. Finally, comparisons are made of overall mission parameters such as mass, costs, schedules and performance assuming the use of in-situ derived propellants versus Earth supplied propellants using 4 different mission scenarios to cover the range of missions being studied today.

S62-91
ABS. ONLY
N91-26081

Potential for the Identification of Localized Water-Bearing Regions on Mars

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P-1

Interpretations of airborne telescopic observations of Mars in the thermal infrared have identified absorption features due to several volatile-bearing minerals (Pollack *et al.* 1990). The presence of some of these (e.g., carbonates) support previous suggestions that Mars once had a denser atmosphere early in its history (e.g., Pollack and Black, 1979; Carr, 1986; Pollack *et al.* 1987). While these interpretations provide for ample scientific discussion, from the view of indigenous resource utilization the identification of hydrates is perhaps key to the exploration of Mars.

Water is essential to a prolonged human presence in space and more specifically on Mars. Both life support and any agricultural endeavor require quantities of water which are cost prohibitive to transport over large distances. Additionally, water could provide a source of indigenous chemical fuel which could be used for transportation. Hydrates, from which water can be extracted may prove to be a valuable resource on the Martian surface. It is vital to assess the presence of special environments or localized regions on Mars in which hydrates are concentrated, and map the distribution of this potential resource.

The techniques employed by Pollack *et al.* (1990) are suited for application on orbiting spacecraft, such as the Mars Observer. From such platforms, it would be possible to map the distribution of localized regions which were enhanced in hydrated materials on a global scale. Future missions involving automated rovers or humans could explore these regions in more detail.

S63-91
ABS. ONLY
N91-26082

Experimental Data from an Oxygen Plant for Mars

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P-1

This paper presents experimental data on various aspects of the plant operation intended to produce oxygen from the atmospheric carbon dioxide at any Martian site. It is believed that our design, fabrication and operation of the hardware represent the first of a kind effort in that we have considered the full system rather than individual components.

At the time of this abstract, a solid electrolytic cell is used in the tubular geometry. Anaerobic carbon dioxide is procured from a gas vendor and is used at a pressure of 1 bar (entrance to the plant). The variables include the voltage applied to the cell, the temperature of the cell, the current density, the flow rate and the duty-cycle. The oxygen production rates have been consistent with the specifications of the cell manufacturer. It is projected that a plant weighing between 145 and 197 kg can be built to produce 10 kg of oxygen per day. Various operational characteristics such as cell poisoning, carbon formation, nitrogen embrittlement, local current densities exceeding the breakdown potential for the cell material, reliability, risk, . . . are all being quantitatively assessed.

S64-91
ABS. ONLY
14620

Primary Igneous Rocks on Mars: Composition and Distribution

N91-26083

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Our present knowledge of the crustal composition of Mars will be synthesized and implications discussed for in-situ resource utilization. Sources of information include remote sensing observations, Viking XRF chemical measurements, and characteristics of the SNC meteorites (which most researchers now believe originated on Mars). There are a number of lines of evidence that abundant ferrous-iron rich igneous crustal rocks (and derivative soils) are available at or very near the current martian surface at many locations on the planet. Most of these exposures show spectroscopic evidence for abundant pyroxene, consistent with basaltic compositions. The SNC meteorites, which have basaltic compositions, have also been studied extensively. We will review interpretations of Mars crustal chemistry and mineralogy (petrology) based on these various sources, and discuss their consistencies and differences. We will also review what is known about the regional distribution of these unaltered materials at the surface of Mars.

S65-91
ABS. ONLY
14621

Physical and Chemical Properties of the Martian Soil: Review of Resources

N91-26084

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The chemical and physical properties of martian surface materials are reviewed from the perspective of using these resources to support human settlement. The resource potential of martian sediments and soils can only be inferred from limited analyses performed by the Viking Landers (VL), from information derived from remote sensing, and from analysis of the SNC meteorites thought to be from Mars. Bulk elemental compositions by the VL inorganic chemical (X-ray fluorescence) analysis experiments have been interpreted as evidence for clay minerals (possibly smectites) or mineraloids (palagonite) admixed with sulfate and chloride salts. The materials contained minerals bearing Fe, Ti, Al, Mg and Si. Martian surface materials may be used in many ways. Martian soil, with appropriate preconditioning, can probably be used as a plant growth medium, supplying mechanical support, nutrient elements, and water at optimal conditions to the plants. Loose martian soils could be used to cover structures and provide radiation shielding for surface habitats. Martian soil could be wetted and formed into adobe bricks used for construction. Duricrete bricks, with strength comparable to concrete, can probably be formed using compressed muds made from martian soil. In addition to directly using the surface materials, useful elements and compounds can be extracted from them. Water, arguably the most valuable resource, may exist in hydrated minerals although no specific mineralogical identifications have yet been achieved. Inexact water measurements by the VL molecular analysis (GCMS) experiments indicated that martian surface sediments contained 1-3 wt. % H_2O; although this probably represents a lower limit. Viable mineral candidates containing tightly bound (structural) water include gypsum (21% H_2O), kieserite (13% H_2O), goethite or lepidocrocite (10% H_2O), and nontronite (5-6 % H_2O). Water could be pyrolyzed from all such hydrates but the required energy input would vary with the identity and abundance of the mineral. The high sulfur content and the implication that sulfur may occur as a soluble salt suggests that sulfur can be readily extracted from martian soil. Sulfur and sulfur-bearing compounds are used in the manufacture of a wide variety of useful substances including acids, bases, oxidizing and reducing agents, fertilizers, dyes, catalytic agents, detergents, solvents, explosives, etc.

Machinable metals such as iron, magnesium, and aluminum could also be extracted from martian soils. Based on visible and near-infrared spectroscopic observations it appears that iron occurs in martian soil, probably in the form of poorly crystalline or nanocrystalline iron minerals. In addition, because there is a magnetic or paramagnetic fraction of martian soil, materials for iron extraction could be concentrated by magnetic separation from the bulk soil. Because magnesium is believed to occur as a soluble salt, it represents a possible machinable metal which might be extracted by dissolution/precipitation techniques.

The amount of energy needed to extract aluminum will likely be tied to the specific mineralogical structure it is located within. Mars appears to be abundantly endowed with a variety of resources necessary to sustain a human presence on the surface. However, much remains to be done to identify specific processes for extraction of the resources which are both useful and appropriate to their use on Mars.

S66-91
ABS. ONLY

Production and Uses of Liquefied Atmosphere (CO_2) on Mars

N91-26088

R.D. Waldron

Carbon dioxide is universally accessible on Mars, and can be liquefied and separated from residual atmospheric gases by various compress-refrigeration cycles. Liquid CO_2, stored under elevated pressures, can be used as a source of high pressure gas for nighttime power generation at a Martian base powered by solar energy during the daytime.

Carbon dioxide can also be used for vehicular power. The extractable energy per unit mass of CO_2 can exceed that of commercial lead-acid batteries for operating cycles without heat addition. Improved performance is possible using heat input from the ambient atmosphere or thermochemical agents. A unique vehicular application uses pressurized CO_2 as a non-combustion low performance propellant for intermediate distance surface transportation.

The thermodynamic properties of CO_2 will be presented with typical operating cycles for the application classes described above.

S67-91
ABS. ONLY

Distillation of H_2O from Hard-Frozen Martian Permafrost

N91-26086

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We present a method for distillation of H_2O from hard-frozen Martian permafrost. A cable-tool well is drilled into hard-frozen permafrost to a depth of 10-20 m. We calculate that a 10 m hole could be drilled in the course of a few days. A 10-m shaft with diameter equal to the bore is inserted into the hole, and an air-tight tent-like structure is erected over the bore-hole. Photovoltaic cells mounted on the tent supply electrical energy that is dissipated in the shaft. Drilling power must be supplied by other sources. With 1000 watts, the shaft can be heated to near 350K, producing relatively high temperatures in the vicinity of the bore hole. Surrounding H_2O is vaporized and diffuses up through the regolith. We calculate that a tent, of radius no more than a few meters would be expected to intercept most of the H_2O as it diffused to the surface. Our calculations suggest it would require perhaps 30 days to extract H_2O from most of the volume drained by this technique. Assuming that the hard-frozen regolith is no more than 10% ice, we find that we can extract approximately 2890 kg of H_2O over the course of 30 days. Since the nominal requirement for each crew member is approximately 5 kg/day, one such bore hole might be expected to supply enough H_2) to maintain a crew of 5 for perhaps 100 days. Additional engineering studies will be done to attempt to improve the capacity or efficiency of this method.

S68-91
ABS. ONLY

SESSION Th4, BEYOND NEAR-EARTH SPACE / OVERVIEWS

N91-26087
14624

The Optimum Shape for a Rigid Rotating Shell Enclosing an Isotropic Spherical Planetary Mass

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Analysis of the Dyson Sphere, an extremely advanced civilization's hpothetical contruct entirely surrounding a star, shows that net stress inward to the star increases to maxima at the poles, if the sphere is rotating. This is because the centrifugal "force" in the rotating frame of reference vanishes at zero rotational radius, which occurs at the poles. There is less of the centrifugal "force" at high latitudes than low to offset the star's gravity. I derive a form for a thin, rigid, rotating shell, surrounding a large pointlike mass and/or charge, which will experience the least possible net stress at every point upon it - a shape on which every point not on the shell's equator is as near as possible to being in orbit. In orbit, whose plane passes through the primary body's center of mass or of charge, F(grav), or Fg, is exactly opposite in direction to F(centrif), or Fc, and is equal in amount. At all points not on the equator Fc will not entirely offset Fg, because of Fg's vector decomposition. However, both forces are always constrained to be equal in absolute amount everywhere on the shell, equator included. The shape I derive, given by the figure of revolution around the x-axis of $x = \sqrt{(y-1-72)}$, will prove useful in large-sale space construction. Also, various engineering problems are discussed.

S69-12
ABS ONLY
14625
N91-26088
p-1

Comparative Economics of Space Resource Utilization

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Physical economic factors such as mass payback ratio, total payback ratio and capital payback time will be discussed and used to compare the economics of using resources from the Moon, Mars and its moons, and near Earth asteroids to serve certain near term markets such as propellant in low Earth orbit or launched mass reduction for lunar and Martian exploration. Methods for accounting for the time cost of money in simple figures of merit such as MPRs will be explored and applied to comparisons such as those between lunar, Martian and asteroidal resources. Methods for trading off capital and operating costs to compare schemes with substantially different capital to operating cost ratio will also be presented and discussed. Areas where further research or engineering would be extremely useful in reducing economic uncertainty will be identified, as will areas where economic merit is highly sensitive to engineering performance - as well as areas where such sensitivity is surprisingly low.

S70-90
ABS. ONLY
N91-26089
p-1

OUTER PLANETS AND ICY SATELLITES

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The resources offered by the outer bodies in the Solar System, starting with the main belt asteroids and Jovian System, are not only larger and more diverse but may even be easier to reach than, say, those of Mars. Indeed, the escape velocity for Mars is 5.2 km/s, and for Callisto (including the escape from Jupiter's gravitational sphere) only 4 km/s. The use of their material, including water and organic matter, depends exclusively on the general strategy of exploration of the Solar System.

Of major interest in this respect are the large ice satellites - Titan, Ganymede, and Callisto. Motion through the planetary magnetospheres excites in their ice envelopes megampere currents which, in the presence of rocky, etc., inclusions with electronic conduction should lead to the bulk electrolysis of ice and accumulation in it of $2H_2 + O_2$ in the form of a solid solution. With the concentration of $2H_2 + O_2$ reaching $\approx$15 wt.% the solution becomes capable of detonation by a strong meteoritic impact.

An explosion of Ganymede's ice envelope $\approx$0.5 By ago could account for the formation of the Trojans and irregular satellites, all known differences between Ganymede and Callisto, and many other things. The explosions of a small icy planet with M $\lesssim$ 0.5 Moon created the asteroid belt. Two to three explosions occured on Io, and two, on Europa. The specific features of the longperiod comets close to Saturn's orbit permit dating Titan's envelope explosion as 10.000 yr ago, which produced its thick atmosphere, young Saturn's rings, as well as a reservoir of ice fragments saturated by $2H_2 + O_2$, i.e., cometary nuclei between the orbits of Jupiter and Saturn. Thus these nuclei should contain, besides organic matter, also $2H_2 + O_2$, which could be used for their transportation as well as as fuel for spaceships. Ices of such composition can reside deep inside Deimos, the Trojans, C-asteroids etc.

The danger of a future explosion of Callisto's electrolyzed ices, which would result in a catastrophic bombardment of the Earth by comets, may be high enough to warrant a revision of the priorities and strategy of space exploration. In the first stage one should reveal the presence of electrolysis products in cometary nuclei, and in the second, in Callisto's ices. Should the situation be found critical, organization on Callisto of manned monitoring stations with life support, including the readily available oxidizer and fuel, based totally on local resources will be inevitable. This option has many scientific, technological, economical, and political advantages over the Martian and Lunar projects.

S71-91
ABS. ONLY

N91-26090

Some Thoughts on Mercurian Resources

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P-1

Virtually all scenarios on Solar System development ignore Mercury, but such inattention is probably undeserved. Once viable lunar and (probably) asteroidal facilities are established in the next century, Mercury warrants further investigation, as follows:

(1) Mercury's high solar energy density is a major potential advantage for space-based industries. Indeed, despite its higher gravity, Mercury is roughly twice as easy to leave as the Moon if the additional solar flux is taken into account. Moreover, with solar-driven technologies such as solar sails or electric propulsion, its depth in the Sun's gravity well is less important. In particular, high-performance "ultrasails" (which can suspend themselves at rest with respect to the Sun) have an effective inverse-square repulsion, and thus the depth in the gravity well is much more than compensated for by the additional light flux. Indeed, it is much more efficient ~~to begin ultrasail missions~~ to the outer solar system with a close solar flyby because of the additional acceleration gained.

(2) Because Mercury is airless and almost certainly waterless, it will be an obvious place to export lunar technology, which will have been developed to deal with very similar conditions. Methods for extracting resources from anhydrous silicates will be particularly germane.

(3) Even without solar-powered propulsion, the discovery of low-delta-V access via multiple Venus and Earth encounters makes the planet easier to reach than had been thought. Technology developed for multi-year missions to asteroids and Mars should be readily adaptable to such Mercurian missions.

Mercury will not be our first outpost in the Solar System. Nonetheless, as facilities are established in cis-Earth space it probably merits attention as a "next step" for development.

S72-91

N91-26091

14628

P-1

Planetary Engineering

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Assuming commercial fusion power, heavy lift vehicles and major advances in genetic engineering, we survey possible late-21st century methods of working major transformations in planetary environments. Much more Earthlike climates may be produced on Mars by generating low freezing point greenhouse gases from indigenous materials; on Venus by biological conversion of CO_2 to graphite, by canceling the greenhouse effect with high-altitude absorbing fine particles, or by a sunshield at the first Lagrangian point; and on Titan be greenhouses and/or fusion warming. However, in our present state of ignorance we cannot guarantee a stable endstate or exclude unanticipated climatic feedbacks or other unintended consequences. Moreover, as we illustrate by several examples, many conceivable modes of planetary engineering are so wasteful of scarce solar system resources and so destructive of important scientific information as to raise profound ethical issues, even if they were economically feasible, which they are not. Global warming on Earth may lead to calls for mitigation by planetary engineering - e.g., emplacement and replenishment of anti- greenhouse layers at high altitudes, or sunshields in space. But here especially we must be concerned about precision, stability, and inadvertent side-effects. The safest and most cost-effective means of countering global warming - beyond, e.g., improved energy efficiency, CFC bans and alternative energy sources - is the continuing reforestation of approximately ~~2 x~~ 107 km^2 of the Earth's surface. This can be accomplished with present technology and, probably at the least cost.

CONTRIBUTED ABSTRACTS

S73-90
ABS. ONLY

N91-26092

P-1

Accessibility of Near-Earth Asteroids, 1990

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This paper updates previous research which analyzed the accessibility of all known near-Earth asteroids. Since then, many new near-Earth asteroids have been discovered, and 1982 DB, the most accessible asteroid at that time, has been recovered. Many of these recently discovered near-Earth asteroids have promising orbital characteristics, and it is expected that this paper will identify a new set of the most accessible asteroids. In addition to accessibility (as defined by minimum global delta v), ideal rendezvous opportunities will be identified.

S74-91
ABS. ONLY
N91-26093
74630

Lunar Cement and Lunar Concrete

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P-1

Manned bases on the Moon will require structural materials capable of resisting a differential pressure of one atmosphere, solar wind, micro-meteoroids, and temperature extremes. Small structures for outposts envisioned for the early stage of lunar development may be fabricated on Earth and transported to the Moon. But, large structures suitable to industrial operations must be constructed using in situ lunar materials. A potential material for such construction is concrete, because it is capable of resisting the harsh lunar environment, and made with cement, water, and aggregate that can be produced from lunar materials, except hydrogen for water production.

This paper present results of a ~~SBIR~~ study funded by NASA in 1990 to investigate methods of producing cements from lunar materials. Viable formulations for cement using lunar materials ~~have been~~ developed. A chemical process and a differential volatilization process to enrich lime content in selected lunar materials were identified. One new cement, made from lime and anorthite, analogous to portland cement, developed compressive strengths of 39 Mpa (5500 psi) for 1 in. (25 mm) paste cubes. The second, a hypothetical composition based on differential volatilization of basalt, formed a mineral glass which was activated with an alkaline additive. The 1 in. (25 mm) paste cubes, cured at 100°C (212°F) and 100% humidity, developed compressive strengths in excess of 49 MPa (7100 psi).

This paper also discusses 1) tests performed on specimens made with Apollo 16 lunar soil awarded by NASA in 1986 for determining physical properties of lunar concrete such as compressive strength, tensile strength, modulus of elasticity, and thermal expansion coefficient, and ~~2)~~ an ongoing investigation on a proposed dry-mix/steam-injection procedure for casting concrete on the Moon.

Proven lunar cement and lunar concrete technologies will render concrete construction on the Moon possible. Potential uses of concrete at lunar sites will involve construction of large pressurized structures, launching pads, surface transportation support systems, storage facilities, and facilities for solar energy collectors.

S75-90
ABS. ONLY
N91-26094
74631
P-1

An Observational Investigation of the Comet-Asteroid Connection

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Recent observations indicate that comet nuclei and certain asteroids, particularly the near-Earth asteroids (NEAs) and the distant asteroids, may have much in common. We have investigated the possible connection between comets and asteroids via two methods:

~~(1) We~~ performed a spectroscopic survey of two groups of asteroids that may be related to comets, namely the near-Earth asteroids (NEAs) and Trojan asteroids. This analysis is the first to make use of a homogeneous set of high quality high resolution asteroid spectra. Selection effects that particularly influence NEA observations (such as phase-reddening and albedo bias) are also examined and taken into account. The NEA survey indicates that we cannot dispel the hypothesis of a main belt origin for NEAs, while the Trojan survey shows that the Trojans and the known comet nuclei are spectrally similar over the wavelengths examined.

~~(2) We~~ sought a more quantitative distinction between comes and asteroids; the current distinction, the presence of a coma, is not completely satisfactory since it is a qualitative (as opposed to a quantitative) criterion. To achieve this goal, we attempted to determine the mass loss rates of NEAs. There was no compelling evidence for mass loss in the 11 observed NEAs, but upper limits to NEA mass loss rates were obtained using a simple model. These results do not exclude the possibility that low-activity comets exist in the NEA population and have escaped detection simply because their small sizes result in mass loss rates which are below our detection limit. Thus whether an object is classified as comet or asteroid may ultimately depend on its size, if relying on remote observations alone.

This work suggests that the current criteria for distinguishing between comets and asteroids, and possibly our current understanding of small bodies of the solar system may need to be revised.

S76-90
ABS. ONLY
N91-26095
14632
P-1

Near-Earth and Near-Mars Asteroids: Prognosis of Pyroxene Types

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The diagnostic signs of ferrous absorption band at 505nm and color-index (u-x) found at main-belt light asteroids, and also 6-parametric classification of light stone meteorites have been are the basis of the fulfilled work. The colorimetric data of light near-Earth and near-Mars asteroids from TRIAD and ECAS have been analysed. Composition fields of pyroxenes were obtained for these asteroids by the value of (u-x) and 505-nm ferrous absorption band position within the pyroxenes quadrilateral.

Pyroxenes of the S-asteroids from Apollo-Amor which have spectral parameters similar to achondrites may be presented by diopside-augite series. AA-asteroids (S-type) with spectral parameters are similar to L-chondrites having either chondritic composition or Fe-rich ortho- and clinopyroxense not being met in meteorites mineral. On S-asteroids surface from Mars-crossers (MC) and Mars- approachers (MA) may be pyroxenes with high containing Ca and Fe (as ferrosalite and hedenbergite), and pyroxenes of E-asteroids are typically for stone and iron-stone meteorites (enstatie, hpersthene, pigeonite).

Since meteorites do not represent all variety of the asteroids matter the investigating objects for the visiting may be some S-asteroids from MC and MA zones which resemble mainbelt asteroids by its spectral properties

S77-91
ABS. ONLY
N91-26096
14633
P-1

Helium Abundances on the Moon: Assumptions and Estimates

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Nuclear energy is a high desirable source of energy, and ^{3}He is the most prized of the fusion reactants. As the Wisconsin Group has emphasized, ^{3}He may be the only true economic "ore" on the Moon. The lack of a shielding atmosphere on the Moon permits solar-wind alpha particles to impinge upon the lunar regolith and become implanted into the various solid components. In particular, large quantities of helium (5-50 ppm) are present. The measured parameter of I_s/FeO, a direct indicator of maturity and exposure age, can be used as a first approximation to predict the abundances of many solar-wind components in the soils. However, because ilmenite has a much high retentivity for helium than the other phases, the TiO_2 contents of the soils are better indicators of helium contents [Taylor, *Space 90*]. High-Ti mare basalt regions, such as at the Apollo 17 locale, appear to be the best areas for He mining (15-50 ppm He_T), versus 3-9 ppm in the Highlands. However, the relationships between I_s/FeO, TiO_2, and ^{3}He contents are complicated - e.g., many of the most He-rich soils are immature to submature.

Sampling of the surface soils at a particular locale, such as occurred during the Apollo missions, can give a biased and, perhaps, unrealistic perception about the average maturity of the soils beneath the surface, which indeed can be very immature. In fact, the soil profile as revealed in cores does not represent continuous slow deposition but sporadic events intermixed with periods of quiescent soil development. The upper few centimeters are typically mature since they represent extensive gardening termed *in situ* reworking. Therefore, maturity of a locale is probably not a useful "pathfinder." TiO_2 is the best indicator overall.

Speciation of ^{4}H/^{3}He varies from 1100 to 4000 and depends upon several factors including soil grain size, mineral species, soil maturity, and the age of implantation. Typically about 50% of a soil is < 2 mm and contains 70-80% of the He_T; yet, the speciation if strongly in favor of ^{4}He, whereas the coarser sizes contain less He_T yet higher ^{3}He speciation [Hintenberger & Weber 1973]. Agglutinate formation, involved in soil maturation, involves volatile evolution which may fractionate He species. Becker & Pepin [1989] report that ^{4}He/^{3}He appears to have decreased about 15% in the last 3 Ga; therefore, other factors being equal, surficial soils contain some 15% more ^{3}He than old buried soils.

Assumptions for Calculations: 1) ^{3}He contents are constant with depth in the regolith at least to 3 m, as shown by drill cores; 2) regolith depths are constant over the entire Moon, with 3-5 m in mare regions and 10-20 m in high latitudes; 3) ^{4}He/^{3}He = 2800/1; 4) mare have 5-15 ppb ^{3}He; highlands have 1-4 ppb; average ^{3}He content of regolith Moon-wide = 3-4 ppb; and 5) total at the permanent 70°K near the poles. Based upon these assumptions, **the outer 2 m of the entire Moon contains 400,000 to 500,000 tons of ^{3}He.** For the 17% of the lunar surface which is covered by maria and using an average of 10 ppb ^{3}He, **the outer 2 m of the Maria contains 220,000 tons of ^{3}He.** These are upper limits to ^{3}He contents in the regolith of the Moon.

S78-91

ABS. ONLY

N91-26097

Discovery and Characterization of Lunar Materials: An Incomplete Process

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Our knowledge of lunar materials is based on (1) sample collections (by the Apollo and Lunar missions, supplemented by Antarctic lunar meteorites), and (2) remote sensing (Earth-based or by spacecraft). The characterization of lunar materials is limited by the small number of sampled sites and the incomplete remote-sensing database (geochemical data collected from orbit cover 20% of the lunar surface). There is much about lunar surface materials that remains to be discovered. Listed below are some features suspected from present knowledge; other unsuspected discoveries can be anticipated from future lunar exploration.

a) Polar Materials: There are no samples, no chemical data, and only poor orbital photography from the lunar polar regions. Gases could be cold-trapped in shadowed polar locations where temperatures may be as low as 40 K.

b) Farside Materials: There have been no sample-return missions and few remotely-sensed chemical data for the lunar farside. Some lunar meteorites may come from the farside, but they are rare and their source areas are unknown.

c) Crater-Floor Materials: Many crater floors contain impact-melt deposits. Sampling will be necessary to determine the nature of these materials, and whether they have trapped some of the lunar volatiles released during impact.

d) Crater-Wall and Central-Peak Materials: Earth-based telescopic studies reveal "bedrock" in crater walls and central peaks. These outcrops may include relatively "pure" anorthosites, dunites, or zones of cumulus minerals.

e) Volcanic Shield and Dome Materials: Remote-sensing indicates a variety of volcanic shields and domes, ranging from high-Ti mare basalt to possible KREEP-rich lavas. These elevated features could be mined by simple undercutting.

f) Transient-Event Materials: Orbital instruments can detect radiogenic gases (e.g., Rn) released from the lunar interior, mostly along fractured basin margins. Such gases may reveal structural pathways or reservoirs for volatiles.

g) Meteoritic and Cometary Materials: Meteorites of 10 tonnes are found on Earth; such a find on the Moon could provide Fe/Ni metal, water, or other commodities depending on the object. Geophysical exploration for conductive iron or water-rich meteorites may be simple in the insulating lunar regolith.

This short list of "likely" discoveries isn't exhaustive. We know much about a few spots on the Moon, but little about the full range of lunar materials.