

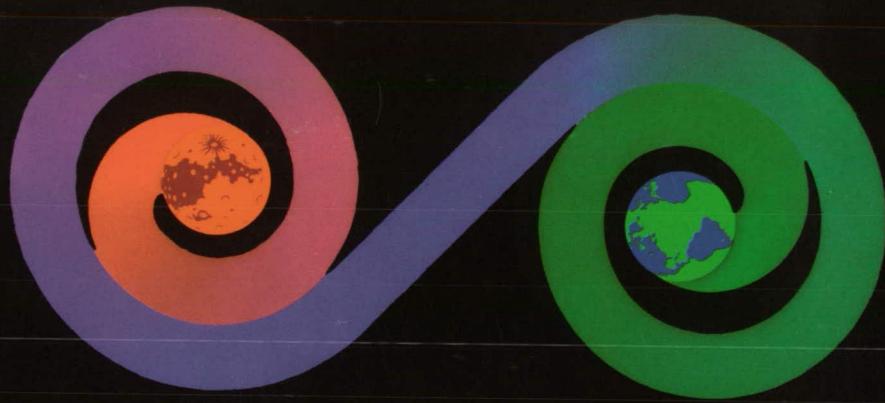
NASA-CR-191992

ANNUAL EXECUTIVE REPORT

UNIVERSITY OF ARIZONA/NASA
SPACE ENGINEERING RESEARCH CENTER
for the Utilization of Local Planetary Resources

a national center for space engineering, research, and education

1989-1990



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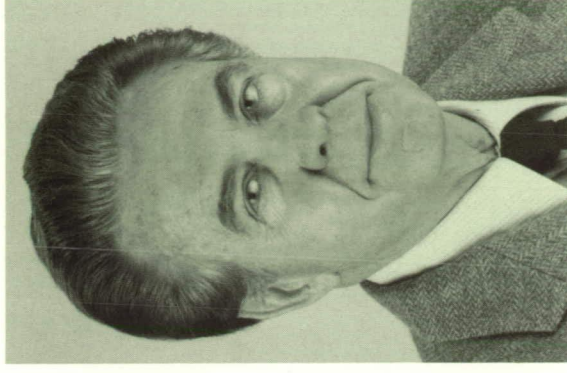
A SPACE TECHNOLOGY ROLE IN SOLVING ENVIRONMENTAL PROBLEMS ON EARTH

While environmentalists are working diligently to protect Earth's features, including its atmosphere, soil, forests, animal life, oceans and so forth, space enthusiasts, including scientists, engineers, and lay people, see space development as another way of protecting and renewing the Earth.

Benefits from scientific research and emerging technologies related to space have already enhanced human life. These enhancements include: discoveries relating to processes on other planets that, when applied to Earth, have made us more aware of the greenhouse effect; discoveries related to planetary atmospheres that have alerted us to the destructive potential of the Super Sonic Transport and chlorofluorocarbon propellants in aerosol cans; the development of technologies for the manned space program, especially materials and electronic components that have direct application on Earth; high speed telecommunications; and others too numerous to mention.

Additionally, practical environmental benefits are becoming apparent to us as space-related research continues and applications are improved and commercialization progresses.

As habitats are developed that allow man a permanent presence in space — the ultimate dream of space advocates — the direct effect will be to increase the habitability of the Earth. The same technologies that can protect life on Mars, where the amount of water in most places is less than in the driest desert on Earth, can help to transform uninhabitable places on Earth. The necessity to rely on indigenous building materials, locally grown foods, locally generated energy, carefully recycled life-support materials,



DR. TERRY TRIFFET,
DIRECTOR

Dr. Triffet is the founding Director of SERC. He is former Associate Dean for Research of the College of Engineering and Mines at the University of Arizona, as well as a Professor of Materials Science and Engineering. His research interests are broad, encompassing such diverse topics as the modeling of neural networks with applications to automation and

robotics for use in space manufacturing and computational fluid dynamics applied to the evaluation of planetary systems. His primary interest is in extraterrestrial-resources utilization. He has extensive experience managing interdisciplinary engineering/science programs.

and the vast treasury of experience in dealing with inhospitable environments, will directly benefit inhabitants of marginal environments on Earth. The result will be to reclaim large land areas for human use and ease pressure resulting from expanding populations.

Among the most pressing of Earth's environmental issues is energy. At the moment we are locked into two unpleasant alternatives: live with an increasingly polluted atmosphere, or return to the Stone Age in terms of our energy requirements. Neither is tolerable. But this issue can be addressed successfully by the space community: the building of solar power satellites to beam a cheap and endless supply of electricity in the form of microwave energy can be realized now, thanks to the concept of utilizing indigenous near-Earth materials. Whereas previous calculations deemed such a project prohibitively expensive if all materials are lifted from Earth, current assessments based on using local materials have reduced costs sharply and will make the building of solar satellites feasible.

Likewise, other projects limited by the high cost per pound of transportation to low Earth orbit (LEO) can be reinstated, enhanced or purchased for a reduced price. From the space station Freedom to habitable biospheres on Mars, the goal of a permanent manned presence in space is manageable. Other energy sources, such as Helium-3 from the lunar regolith, may also emerge as our experience in space matures.

It is not too difficult to project a refreshed image of Mother Earth among those who have been "off-world" for four or five years, long enough to travel to the Mars system, function there awhile, and return. I am not referring to a new philosophical insight about Earth, but rather the forced enhancement of a spacefarer's ability to see the potential of areas of Earth presently considered only marginally inhabitable. The next step is to apply the

technologies newly developed for space colonization to replenishing Earth—"terraforming" it, if you will. It is entirely possible that what we learn and the methods we develop to explore and inhabit the solar system will enable us to make these areas "bloom as the rose".

Environmentalists may well wish to join their space-activist brothers in helping to bring about the space age. They will find it will serve their own goals as well.

--T. Triffet

HISTORY AND PURPOSE

In 1987, responding to widespread concerns about both the health of American space technology development and the academic preparation of 21st-century space professionals, NASA announced a nationwide competition to establish a number of Space Engineering Research Centers. These centers were to be founded on the campuses of nine Universities with strong Doctoral programs in Engineering. Over 115 proposals were received by NASA in November 1987. These proposals were submitted from every major engineering program in the nation. The proposals were sent out for external technical review in December and January, and on the basis of technical excellence alone a group of 25 finalists were named in March 1988. The finalists were subjected to site visits by NASA representatives, and judged on the basis of their ability to make major contributions to near-term NASA flight programs. The University of Arizona's proposal was selected in May as one of the winners, with a budget of approximately \$7 million guaranteed by NASA for a minimum funding period of five years.

ADVISORY COMMITTEE

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Alvin L. Tanner, Fluor Daniel, Inc.
Robert D. Waldron, Rockwell In-
ternational

James R. Arnold, California Space
Institute

The selection criteria for these centers included the originality and innovation of the proposed research, the prospects for near-term utilization of the technologies developed, and the magnitude of the contribution that these technologies could make to American capabilities in space. Of equal importance, these Centers were charged with a major role in the education of a new generation of space professionals who would be not only solidly grounded in space technologies, but also familiar with current scientific understanding of Solar System environments. These new professionals would be able to step beyond the traditional space technologies developed in the 1960s and 1970s, building upon the latest scientific and technological understanding to open the Solar System to mankind in the 21st Century.

The role of the UA Center is to develop the technologies necessary to produce a wide variety of useful products using the materials and sources of energy that occur naturally in near-Earth space. An additional purpose is to lower the cost and extend the scope of large-scale space activities. Over the next 25 years, NASA sees its major activities as being drawn from a list which includes: a permanently-occupied space station, a lunar base, unmanned scientific exploration of the Solar System, the monitoring of environmental processes on Earth and a manned expedition to Mars and its satellites.

This wide scope implies that resources native to the portion of the Solar System outside the orbit of Venus and inside the inner edge of the asteroid belt are of immediate interest. Besides Earth, the bodies found within this volume of space are Earth's Moon, Mars, the Martian moons Phobos and Deimos, and approximately 600 asteroids larger than a kilometer in diameter, some of which may be the nuclei of extinct comets. In other words, the scope is narrowly focused on Earth's nearest neighbors. On a smaller scale, but closer to home, orbital debris such as dead satellites, spent rocket motors, and expended fuel tanks (especially the Space Shuttle External Tank) are available for use

in low-Earth orbit (LEO).

The University of Arizona benefits from a number of factors that singularly qualify it to lead in the study and use of extraterrestrial resources. The science departments provide a solid base of expertise in the physical and chemical characterization of extraterrestrial materials, and the engineering departments contribute expertise in aerospace, mechanical, electrical, computer, chemical, mining, processing, and other engineering disciplines.

The Lunar and Planetary Laboratory (LPL) is one of the world's leading centers for research into the composition, structure, origin, and evolution of the Solar System. The analytical expertise available on campus is exceptional in its breadth and depth, including an Inductively Coupled Plasma Mass Spectrometer (Geosciences Department) and a world-renowned Strategic Metals Recovery Research Facility (Chemistry Department).

The University of Arizona is home of the Center for Separation Science, which has flown a number of biological separation and purification experiments on the Space Shuttle. The Department of Aerospace and Mechanical Engineering (AME) houses a major program in In-Situ Propellant Production (ISPP) as well as contributing a wide diversity of experience in aerospace engineering theory and practice. The University's Optical Sciences Center is a world leader in laser and telescopic optics research. The Chemical Engineering Department has an existing laboratory for kinetic study of process reactions.

Many other examples could be cited: the UA research effort is ranked among the top 20 university programs in the nation, and there is a great diversity of relevant expertise and

NASATECHNICAL REPRESENTATIVE COMMITTEE

Murray Hirschbein, Code RM,
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Bland Stein, NASA Langley Re-
search Center
Steven C. Hartman, Code RS, NASA
HQ
Gordon Johnston, Acting Program
Director, Code RS, NASA
HQ

useful equipment already in place. Interdisciplinary research efforts, such as the Theoretical Astrophysics Program and the Crystal Genesis Project, are already established. A joint AME-LPL degree program in space engineering, combining science and engineering, predates the establishment of the center by several years.

As evidence of its commitment to the center proposal, the UA administration contributed \$250,000 in equipment money, established two new faculty positions (in LPL and AME), and salary for a minimum of 10% of the time of each faculty member involved in the center's research program. The University has also provided space for the center in an attractive, new research-park facility several miles from the main campus.

Aerospace companies in Tucson include Hughes, AiResearch (Allied-Signal) and Lockheed. Tucson is the astronomical capitol of the world, with more observatories within a 50-mile radius than any other point on Earth. It is the home of Kitt Peak National Observatory, the Smithsonian Institution's Multiple-Mirror Telescope, and the UA Mirror Laboratory that is spin casting very large (over 6 meters) light-weight telescope mirrors with unusually small focal ratios, suitable both for Earth-based and space-based observatories. Tucson is the home of the Space Biospheres Ventures' Biosphere II Project, a closed-ecosystem experiment, for which the UA's Environmental Research Laboratory is the environmental design contractor.

The Planetary Science Institute (a subsidiary of Science Applications International Corporation) is located adjacent to the campus. It is a research institute with extraordinary expertise in the study of asteroids and comets and of the effects of impact processes on the surfaces of the Moon and smaller bodies.

Tucson has one of the highest levels of space awareness of any community in the nation.

It has served as a breeding ground for space advocacy groups, and presently has several space-oriented interest groups. Several prominent space artists and writers of popular books on astronomy live in Tucson. The State of Arizona maintains the Flandrau Planetarium on the UA campus, featuring frequent planetarium shows and special space-related lectures.

From basic research through applied science and process development to spacecraft construction, zero-gravity flight-testing, and commercialization, Tucson and the University of Arizona present an excellent environment for achievement and innovation.

THE SPACE MINING & MANUFACTURING CONFERENCE 1989

The Annual Invitational Symposium was held in Tucson, Arizona, on 24-26 October 1989. Space mining and manufacturing were featured and invited presentations were delivered by prominent scientists and engineers representing the Center, other academic institutions and various industries. Their papers covered topics ranging from basic science to the design and automation of processors for dealing with the special materials and conditions encountered in space.

The three days were divided into sessions devoted to six major topics:

1. resources of the inner solar system,
2. properties of extraterrestrial materials,
3. processing of propellants,
4. automation of materials processing,

5. systems optimization, and
6. database development.

John S. Lewis, Principal Investigator for Science at SERC, opened the science plenary session with a lecture on the resources available on the Moon, Mars and its satellites, and local asteroids. He discussed the need for locally-derived propellants, life support fluids, radiation shielding, refractories, metals and structural construction materials to support large-scale space activities.

The economics of off-Earth manufacture of these basic commodities suggests that the benefits are in the billion-dollars-per-year range. Other speakers in this session presented papers on the specific resources found on the Moon and on Mars, including Mars's atmosphere.

Jeffrey Taylor, of the University of New Mexico, presented a lecture on the properties of the Moon, Mars, Martian satellites and near-Earth asteroids. Talks on specific materials, including the lunar regolith, lunar ilmenite, carbonaceous materials and planetary atmospheres were presented later in the session.

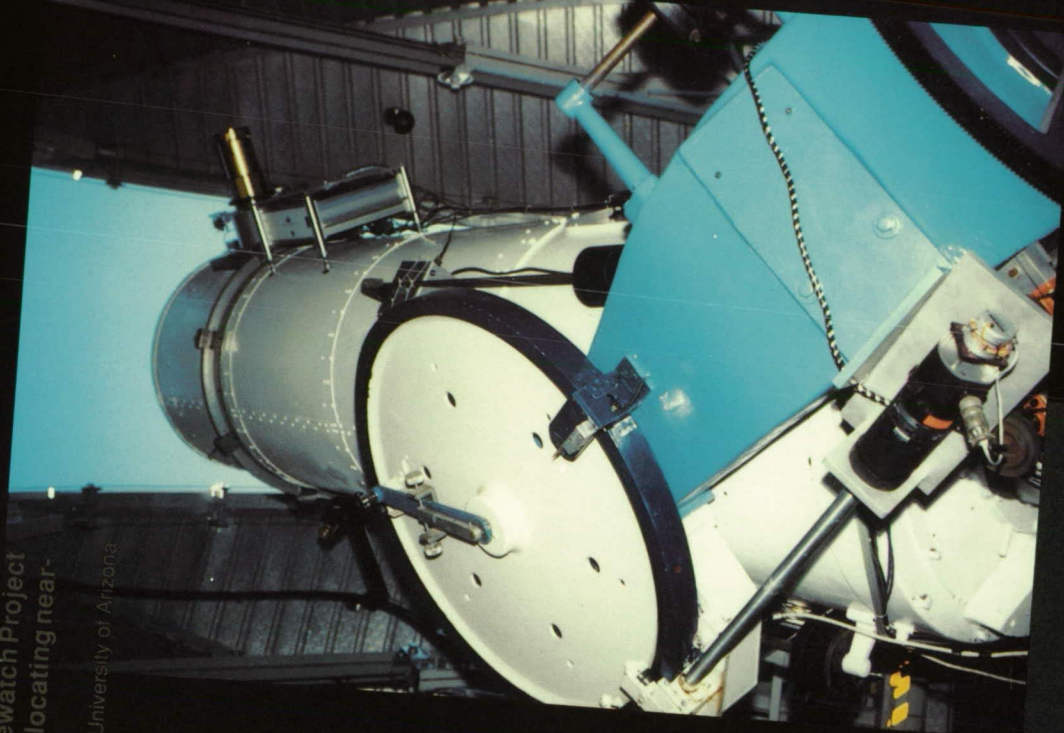
Robert D. Waldron, a senior scientist at Rockwell International Corporation, introduced the session on processing propellants with a talk on processes applicable to the Moon for extracting propellant constituents and their byproducts. He also proposed an evaluation scheme for propellant processing methods. Other speakers discussed mining methods and the processing of metallic and non-metallic byproducts, including both volatiles and glass-ceramics.

Jerry Suintor of the Jet Propulsion Laboratory, Pasadena, discussed the use of automa-

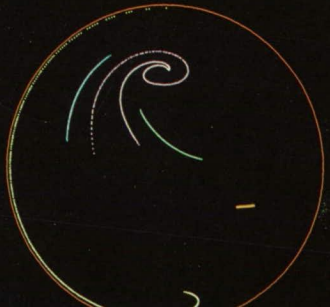


The Lunar and Planetary Lab's Spacewatch Project telescope on Kitt Peak, dedicated to locating near-Earth asteroids.

© Teri Schemenauer, Lunar and Planetary Lab, University of Arizona



The SERC ilmenite reduction team studies mineral reactions through SEM and Auger techniques.



Computer simulation of successive iterations in the mixing process.



Computer-enhanced radar images of near-Earth asteroid 1989 PB, obtained using the 1,000-watt radar/radio telescope in Puerto Rico. Near-Earth asteroids are prime targets for mineral extraction operations.





Mission San Xavier del Bac



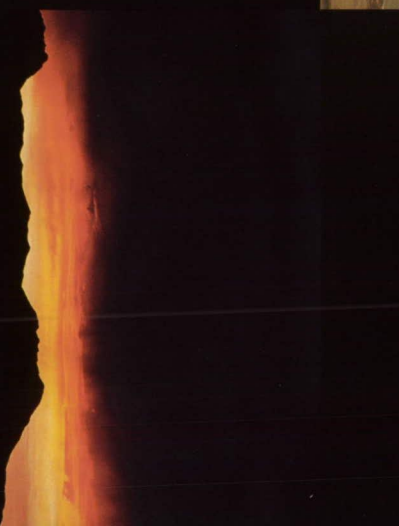
Old Main at the University of Arizona



Downtown Tucson



Sonoran Desert Near Tucson

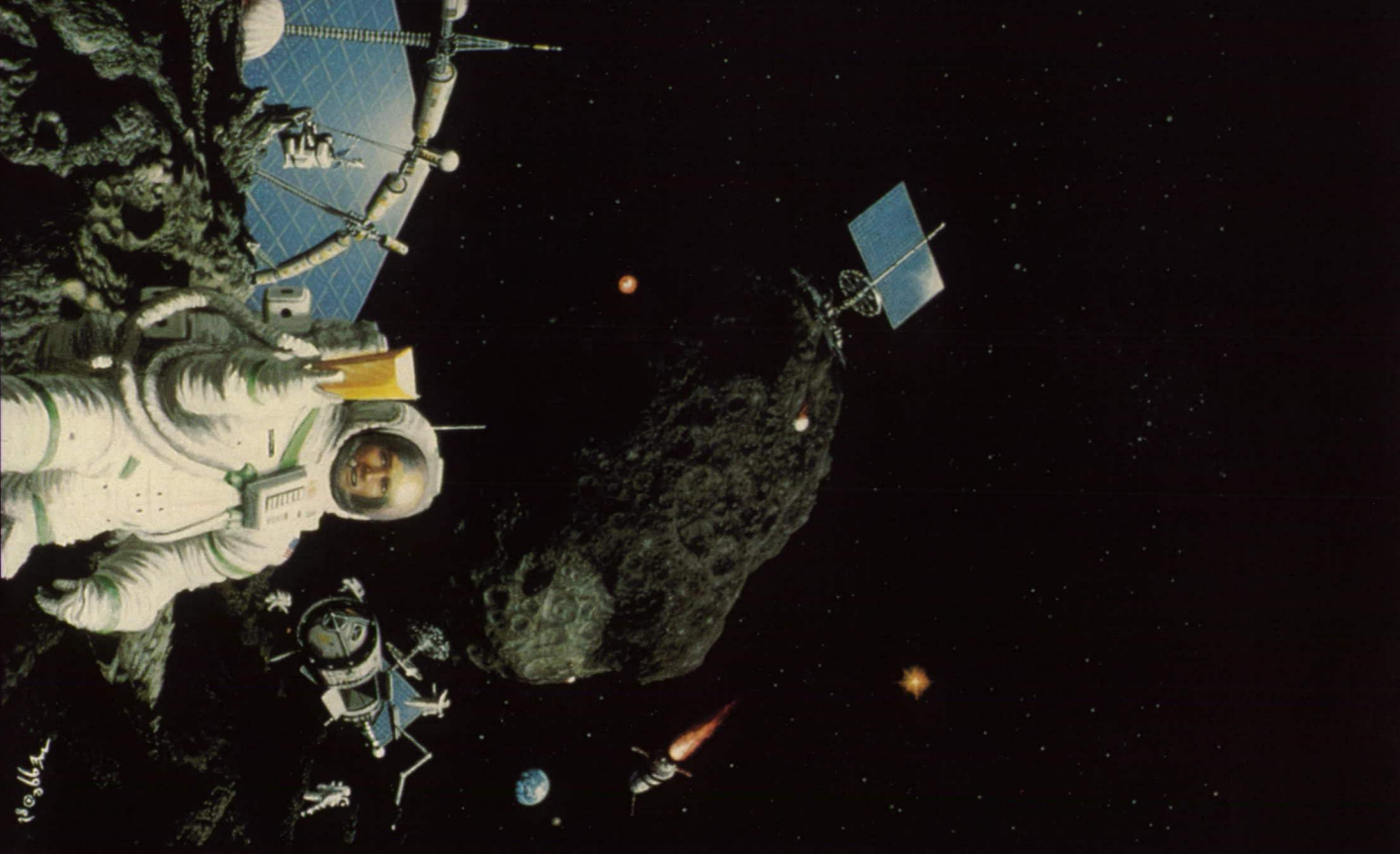


Tucson Sunset



SERC is investigating various means of obtaining oxygen for space vehicles with both propulsion and life support. The Moon makes it a better launch site than the Earth.

© Dennis Da...



David Egge, Research Painting International, 734 E. Lake Street, Suite 222, Minneapolis, MN 55407, (612)825-2214



AML/SEERC Building



Dennis Davidson's conceptual depiction of a lunar base as it might appear as a launch site. SEERC is developing the technology that will allow such lunar bases to serve also as oxygen extraction plants.

© NASA

tion in processing these materials. Considerations affecting automation, such as monitoring and control systems communications, robotics, mining, and beneficiation, were presented by other speakers in this session.

Kumar Ramohalli, Principal Investigator for Engineering at SERC, discussed a Figure-of-Merit approach to extraterrestrial resource utilization, offering a framework for process evaluation within the context of total mission optimization. Other speakers discussed system optimization for a lunar base, modeling an oxygen production facility for lunar ilmenite, and energy management considerations affecting processes on bodies other than Earth.

David R. Criswell, from the University of California at San Diego and California Space Institute, presented a plenary lecture on the development of a database on the use of lunar materials. The database, designed to be used on personal computers, consists of pre-1989 references related to lunar resources.

A final session was devoted to contributed papers on a variety of topics that in some cases did, and in other cases did not, fit the primary session themes. For example, papers were presented on extracting hydrogen from the lunar soil, utilizing lunar oxygen to reduce transportation costs, predicting helium distribution on the surface of the Moon, and on the legal aspects of mining extraterrestrial resources. It was intended that this session provide a platform for both conventional and unconventional treatments of space processing issues, and this practice will be continued in future symposiums.

Additionally, several special presentations were made by researchers working in the space-resources field. Dr. Steven Howe of Los Alamos National Laboratory presented a luncheon talk on the CETEC facility, a proposed center for testing extraterrestrial

engineering and construction procedures, processes, and equipment. Dr. Eugene Levy, Director of the Lunar and Planetary Laboratory at the University of Arizona, spoke at the banquet on the evolution of the Solar System, giving broad perspective to the role of space resources and their origin.

Mark Nelson of Space Biospheres Ventures presented a talk on the Biosphere II program, a project for studying biospheres both on Earth and in space. Closely related to this was the presentation of Carl Hodges, Director of the University of Arizona Environmental Research Laboratory, who delivered a paper during the regular session on extracting life-support substances during the processing of materials in space.

The wide range of topics covered in this conference is indicative of the importance of space resources utilization, and it is of special interest that many leading engineers and scientists who began their careers in more traditional subject areas have now begun to apply their expertise to the exciting new field of space mining and manufacturing. This promises that the present decade will see dramatic developments in our ability to live and work in off-Earth environments. Extraterrestrial resources truly are our "stepping stones to the stars".

SERC RESEARCH PROJECTS

SPACE ENGINEERING PROJECTS

- Development of techniques for automated production of propellants utilizing extra-

terrestrial materials.

- Calculating “Figure of Merit” for a wide range of missions.
- Investigation of methods to ensure system optimization for off-planet processing facilities.
- Investigation of robotic extraction and processing technologies.
- Investigation of recycling technologies for space debris.
- Investigation of methods which use carbon and carbonaceous wastes to reduce lunar ilmenite and produce oxygen.
- Research into the the handling and storage of large quantities of hydrogen.
- Investigation of the heating and cooling loads that are necessary for large scale condensation of water.
- Development of temperature control circuitry for use in mixing propellants in lunar and Martian environments.
- Development of computer simulations that demonstrate mixing of propellant constituents.
- Development of an on-board subsurface data recognition apparatus for use on a lunar of Martian rover vehicle.

SPACE ENGINEERING
RESEARCH GROUP

Dr. Kumar Ramohalli,
Principal Investigator

Dr. Farhang Shadman
Dr. Thomas L. Vincent
Dr. Parviz Nikravesh
Dr. Charles Glass
Dr. Rocco Fazzolare
Dr. Chandrakant S. Desai
Dr. David Lynch
Dr. David Criswell
Dr. Brian Fabes
Dr. Andrew Cutler

- Development of computer simulations which allow systematic study of power system requirements that will be necessary for the production of oxygen from lunar ilmenite.
- Development of “cold” plasma chlorination techniques for use on lunar materials to produce oxygen and chlorinated metals.

- Research into the production of construction materials from lunar soils in the absence of water.

SPACE SCIENCE PROJECTS

- Research in the utilization of the carbonyl process for separating metals.
- Research and design of schemes for processing carbonaceous chondrite material.
- Investigations of the ilmenite oxygen process to test the feasibility of recovering oxygen, iron and rutile from lunar surface materials.
- Development of lunar soil simulants for use in research.
- Development of computerized, observational data analysis for use in the detection of near-Earth asteroids and comet cores (a dedicated telescope with a 2048 x 2048 element, CCD detector array).
- Research and analysis of 3 to 4 micron spectra of asteroids in order to determine their water content.

- Investigation into the mineralogical properties of near-Earth asteroids.

- Fundamental research into the thermodynamics of volatile species in carbonaceous chondrites as a function of pressure and temperature.

- Research into the feasibility of electrochemical separation of lunar soil into oxygen gas, metals, shielding material and construction materials through electrolysis of a silicate melt.

- Investigations into the recovery of precious and strategic materials from extraterrestrial native metals and from metal byproducts of the ilmenite and magma electrolysis processes.

- Research into the conditions necessary to optimize production of oxygen while minimizing energy consumption.

- Mapping of lunar ilmenite concentrations using remote sensing data from Earth-based and Apollo orbital sources.

- Research into the beneficiation of lunar ilmenite feedstocks to enhance oxygen production.

- Initial development of high precision methods for the analysis of rare and economically attractive elements in various space materials.

- Investigation of the physical characteristics and constituents of the lunar regolith.

SPACE SCIENCE RESEARCH GROUP

Dr. John S. Lewis,
Principal Investigator

Dr. Thomas T. Meek

Dr. Tom Gehrels

Dr. Don Davis

Dr. Larry Lebofsky

Dr. Jibamitra Ganguly

Dr. Henry Freiser

Dr. Larry Haskin

Dr. Robert Singer

Dr. Joaquin Ruiz

Dr. Timothy Swindle

- Study of processes for the extraction of ^3He from the lunar regolith for potential use in generating fusion power.

SERC RELATIONS WITH INDUSTRY

The center has pursued a variety of industrial outreach activities during the last year. The major emphasis of these activities is on laying the groundwork for collaborative industrial projects which utilize space resources. SERC is interested in establishing cooperative research projects and possible donations of advanced equipment to the center. The focus of the initial outreach efforts has been primarily on domestic aerospace, construction engineering and metal-processing industries.

The uniqueness of the center as the only academic research facility in the world working on technologies for using space resources makes the center an essential ingredient in the development of space ventures. SERC is ideally positioned to provide the integrated research know-how for successful public-private partnerships in space resource utilization. Several contacts have been made by firms specializing in space transportation, the design and construction of chemical processing plants and industrial research consortia. It seems clear that industry appreciates the critical importance of the SERC research team to future commercial ventures in space.

On the international front, SERC has cultivated a working relationship with IFTECH, the Institute for Future Technologies, a Japanese research consortium. SERC and IFTECH planned a research project concerning the extraction of ^3He from lunar mate-

rials. This isotope has particular merit as a possible fuel for fusion reactors that generate electrical power. SERC has prepared a report on the results of this research. Other international firms interested in the extraction and handling of iron, nickel and cobalt have also contacted the center to explore joint projects.

The NASA's Johnson Space Center anticipates the release of a request for proposal (RFP) for the design of a pilot plant to produce oxygen on the Moon. This is one example of a project that could profitably combine the efforts of aerospace manufacturers, construction firms and SERC. Many other examples come to mind, from the development of solar power satellites, to the construction of lunar bases, to mining native metals on near-Earth asteroids. SERC's knowledge of processing schemes for manufacturing in space provides the center with a vital element in the creation of joint ventures. Imagine the potential of a collaboration between an aerospace firm with considerable experience in space and rocketry, a major engineering construction firm specializing in chemical processing plants that emphasize robotics, and SERC with our sophisticated understanding of the nature of the interplanetary environment. The potential for the success of such an arrangement is tremendous.

THE AUTOMATION OF EXTRATERRESTRIAL SYSTEMS FOR OXYGEN PRODUCTION (AESOP) WORKSHOP

SERC's primary mission is one of research focused on technologies that result in lowering the costs and increasing the feasibility of permanent space utilization and settlement. As such, the Center is dedicated to sponsoring information-sharing and

working conferences designed to further this broad mandate.

One such conference was the AESOP Workshop, sponsored by SERC and the California Space Institute. Held in La Jolla, California, during July 1989, the purpose was to highlight the problems and issues that may be expected to arise in designing and building automated space mining and manufacturing facilities.

Although specific mission planning has not yet been completed in response to Presidential initiatives and NASA directives, a number of space exploration and development scenarios have been outlined. Common to nearly all of these, and fundamental to their success, is the assumption that space resources — especially materials from which propellants may be derived — will be utilized on an ever-expanding scale.

A number of recommendations were formulated by the AESOP Workshop participants. These were focused on the research stages and program requirements that will be necessary for space automation to be undertaken successfully. The following list of general requirements resulting from the discussions at the workshop are presented to illustrate the level of thought and long-term planning that drives the research effort at SERC.

1. Tradeoff studies to determine choices between redundant and replaceable components and subsystems.
2. Analysis of modularity to determine best module boundaries for optimum productivity when failure occurs.
3. Analysis of the effects of operation in an enclosed or pressurized environment.
4. Studies of the high temperature, long-term corrosion resistance of some of the high-tech ceramics and other materials proposed for use in space.

5. Determination of mining and beneficiation requirements and procedures.
6. Tribology studies under simulated lunar conditions.
7. Investigation of electrostatic methods of lunar dust control.
8. Better characterization of all aspects of asteroidal resources.
9. Determination of the sensitivity of specific systems to leakage and control malfunctions.
10. Determination of the costs and benefits of providing artificial gravity.

SERC'S LEADERSHIP ROLE

The center's leadership role in the advancement of human knowledge of the potential of space resource utilization will be pivotal in planning, implementing and executing future endeavors. The research themes that the SERC team is pursuing have resulted in the center's achieving a prominent position in the study of space resources and the technologies necessary for their eventual use by humanity. The history of the University of Arizona's commitment to the space sciences, materials research, astronomy, mining and engineering is entering a new chapter, one that features the center's work. The institutional, research and business sector linkages that have been formed in the last year will result in dynamic partnerships that will unite the traditional sciences and the emerging commercial space industry.

The comprehensive research team that has been assembled, the conferences and symposia that have been organized, and the pioneering work that SERC has accomplished to date are indicative of the limitless potential for our future among the stars.

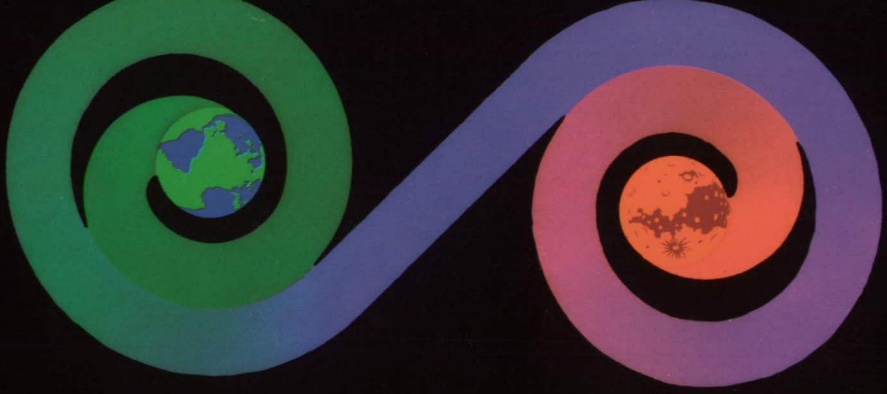
PUBLICATIONS

Publications that share the results of the center's investigations are a critical component of the research effort at SERC. Since the center has only been in business for a year and a half, major emphasis in our publication program has been devoted to disseminating information about the center itself. The following is the list of SERC publications and informational materials produced to date:

SERC Brochure
WR-89/1 AESOP Report
AIS-89 First Annual Invitational Symposium Proceedings
AIS-89/A First Annual Invitational Symposium Abstract
APR-89 Annual Progress Report 1989
APR-90 Annual Progress Report 1990

In addition, individual SERC researchers have published a number of professional papers. References to these may be found in the standard indexes, or by writing to them in care of SERC.

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