Final Report

NSF-NASA Workshop on

AUTONOMOUS CONSTRUCTION AND MANUFACTURING FOR SPACE ELECTRICAL POWER SYSTEMS

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EXECUTIVE SUMMARY

A 3-day Workshop was held in Arlington, Virginia from April 4 to 7, 2000 with the support of the National Science Foundation and NASA. The purpose of the workshop was to identify fundamental and applied research issues associated with manufacturing and construction of very large systems in space and/or on the moon. A number of such macro-space systems have been identified and studied, but the most attention has been given to systems designed to convert and deliver massive amounts of solar energy to the Earth's power grids from either Earth orbit or the Moon. The manufacture and assembly of such systems, as well as the production of photovoltaic cells, major structures, transmission subsystems, and robotic facilities from lunar materials will probably require the use of large numbers of semi-autonomous yet cooperating robots. Thus, whether in space or on the moon, these solar power systems are representative of the problems and issues that will have to be addressed in the manufacturing, construction, and assembly of many types of macrosystems in space or on planetary surfaces.

The workshop therefore concentrated on identifying the research issues in manufacture and assembly of both Satellite-based Power Systems (SPS) and Lunar-based Power Systems (LPS). This workshop took no position on the relative merits of space SPS vs Lunar LPS systems for energy delivery to Earth, as either serves as an adequate example for identification of the research issues in space macrosystems and production on the moon using indigenous materials. The workshop participants happened to bring much more detail with them on the LPS than on SPS options, and thus the workshop appeared to concentrate more on the LPS. While this report reflects that disparity, it should not be taken as an endorsement of the LPS approach over the SPS, as credible trade studies between the two approaches apparently do not yet exist. It is important, therefore, to keep in mind that it was not the purpose of this workshop to delve into the desirability or programmatic issues with either system, but rather to use both of them as a means of identifying desirable research directions for semi-autonomous construction and assembly applicable to a broad class of large space systems. The conclusions and recommendations of the workshop should be taken in that context.

The cost of establishing a significant SSP capability for all of humanity within a reasonable time frame is perhaps the most significant issue facing the basic concept. Merely extrapolating existing technology and operational modes is clearly insufficient. Human activities in space today cost on the order of millions of dollars per hour; lifting mass into earth orbit costs on the order of tens of thousands of dollars per pound; and our present pace of space operations would require centuries instead of decades to attain the goal of providing terawatts of power for Earth. In principle, by advancing robotics technology the construction and operation costs of such macro-space structures could be reduced by large factors. Additional large factors could be gained by utilizing space material resources from the lunar surface, enabled by advanced robotics, in the effective processing of raw material and manufacturing much of the required materials in space. If, in addition, means were found to make the manufacturing robots partially or mostly self-replicating, the amount of material brought from Earth for such manufacturing could be greatly reduced. Together these capabilities have the potential to enable such large cost reductions, in a reasonable time, so as to bring Space Solar Power systems into the realm of the practical and viable.

Therefore this workshop was organized into four subgroups, concentrating respectively on system challenges of space solar power, robotics and technology issues, manufacture on the Moon and lunar power systems, and self replicating automata. The major findings and recommendations from these groups appear below, and are based on the formal presentations and extensive discussions held by the four subgroups.

FOREWORD BY THE SPONSORS

Mr. John Mankins, National Aeronautics and Space Administration

The prospects for exploration and commercial development of space during the coming several decades presents a compelling challenge for many individuals, organizations and countries. Certainly reliable and affordable transportation to space is the first and foremost hurdle that must be surmounted. Achieving affordable and abundant power in space is almost as important. Becoming "energy rich" is a critical goal for technology researchers pursuing the capabilities that will be needed for sustained campaigns of human exploration beyond low Earth orbit. Moreover, as space visionary Dr. Gerald O'Neil recognized twenty years ago, without energy there can be no industrialization.

The large space systems that will be enabled by – as well as enabling – an energy-rich future in space will only be affordable if they can be manufactured, constructed and operated in ways that are dramatically different than those possible today. Highly intelligent and adaptive machine systems will be critical to the technical and economic viability of such large systems. Innovative uses of space resources must be considered and pursued where appropriate. "Brilliant" communities of machines that adapt and reconfigure autonomously must emerge just as networks of desktop computers have largely supplanted the business mainframes of a generation ago.

The workshop co-sponsored by the National Science Foundation and NASA addressed some of the critical technology research challenges that must be addressed. The workshop and this report represent a good foundation upon which to build future meetings and future cooperative research and technology undertakings.

John C. Mankins
Manager, Advanced Concepts Studies
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NASA Headquarters

Dr. Paul Werbos, National Science Foundation

This report by Bekey et al marks a major advance in our understanding of the policy issues associated with low-cost solar power -- in my opinion. Officially, this report represents the views of the seven authors, not the views of the sponsoring agencies or even the views of the funding officers like myself who supported the workshop. Here I will give my personal views. These views are heavily shaped by the ten years I spent at the Energy Information Administration of the Department of Energy, where I was responsible for evaluating and then generating long-term energy forecasts, just as much as they are shaped by my twelve years at NSF.

It was a great pleasure at this workshop to talk again with Fred Koomanoff, whom I worked with years ago when he ran the tough and critical DOE evaluation of solar power satellites. Many advocates of SSPS were disappointed by DOE's evaluation of some of the early SSPS proposals -- but it played a critical role in laying out the problems, and stimulating the new, more creative proposals discussed at this workshop. I hope that there will be a more official follow-up from NSF as such, coordinated with NASA and DOE but at the time I write this, I am the only person at NSF who has seen this report. This workshop had its genesis years ago, when Dan Greenwood came into my office, showed me some of Criswell's latest papers, and asked bluntly: "Do you believe him? Or do you not? Do you think we should be solving our energy problems this way? Or not?" My response was and remains: "It would be grossly irresponsible and dishonest for someone in my position to answer *either* yes *or* no at this time." After the workshop, I feel much more optimistic than before about the lunar-solar option; the answers really were there for a number of questions which worried me a great deal before the workshop. I would strongly urge the skeptical reader to examine the full CD version of this report, to get at least some flavor of the deep and serious technical discussions which took place at the workshop.

Nevertheless, there are still many open questions which need to be proved out, both for the lunar version and the earth-launched version. *Uncertainty* is the central fact of life in any rational approach to energy policy. Under existing technology -- given what we now know about the problems of greenhouse gasses, of nuclear terrorism, and of many other issues -- we simply cannot be certain the human species will be able to survive at all, in my opinion. Many of the conference participants wanted to discuss such issues at great length but I pleaded with the Bekeys to avoid getting deep into those issues, because other groups have already addressed them at very great length elsewhere. (e.g., See Lindsey Grant, ELEPHANTS IN THE VOLKSWAGEN, W.H. Freeman.) Suffice it to say that a truly low-cost renewable option for baseline electric power on a global basis could possibly make or break the future of the human species. If there is any hope at all -- even a 5 percent probability -- of creating such an option within this century, it would be grossly irrational for us to neglect the full exploration and evaluation of that option.

The rational strategy is to identify the key uncertainties in *all* of the promising options, and focus research as effectively as possible on reducing these uncertainties and exploring new technologies which show promise in overcoming the potential showstoppers -- above all, the showstopper of cost. Some people would call this strategy a "wait and see" approach; however, I would think of it as a strategy of "go out and *find out*, and do your best to make it possible." Many people believe that the best way to make a new technology work is to adopt a "can do," optimistic approach. Certainly determination is an important ingredient in making these kinds of things work. But I have seen many huge government projects fall apart when they were captured by a certain kind of optimist, unable to face up to major problems in a forthright and open way. I have seen programs produce nothing because of problems which were actually *solvable* -- because of optimists who were unable to face up to the problems enough to put real resources into the portfolio of novel and risky technologies required to solve these problems.

Among the questions I asked before this workshop were: "If we can do this so cheaply on the moon, why can't we do it on earth, as proposed by Mesarovic and Pestel in the Second Report to the Club of Rome? Where is the detailed, up-to-date audit trail, comparable to what we had when we evaluated synfuels technology? Are any of these people aware of what's been happening in computational intelligence in the last ten years, or is everyone geared up to put money into more classical AI pipedreams like the intelligent Martian robot that a certain famous researcher promised NASA in twenty years -- in the 1960s? Is anyone even willing to take a break from the old debate between advocates and opponents, and start formulating the key questions we need to actually get started on something real? Do we even know where to begin?". I hope that the organizers will forgive me for the obnoxious way in which I kept pushing those questions in the months leading up to this workshop. Most of those questions were answered satisfactorily, in my view, enough for a first cut at it.

This workshop was a Herculean feat, which probably would have been impossible without the unique skills and energy of the Bekey brothers. I was especially impressed by Ignatiev's presentation on how to exploit the vacuum and materials on the moon in order to reduce the inherent cost of making solar cell assemblies. I was impressed by the quiet remarks of other NSF grantees in the chip-making area, who pointed out that many other chip-making technologies could exploit this unique environment as well. I was impressed by the agreement between Whittaker and Criswell that a lunar power system might require only about 5,000 robots -- not so many that self-replication is really necessary, but certainly a large enough number to require new research on what they called "teleautonomy." In effect, they asked: "How do we organize a system of 1,000 robots and 100 humans supervising them so as to build a large integrated system?" Whittaker has done similar things on a smaller scale, now being applied in the mining industry on earth, but more research is needed in order to scale up.

The research issues here are fundamental and generic in nature; they are not the ad hoc and extremely domain-specific kinds of issues which have dominated much of classical AI. Which is the better option -- the lunar option or the earth-launched option? I do not believe that any tradeoff studies done today could answer that question. The earth-launched option has some obvious advantages, but is much more dependent on the cost of transportation to earth orbit. NSF is now funding some very advanced work at Princeton University, at ANSER, at the Stevens Institute of Technology and at Accurate Automation which has the potential to reduce the transportation costs by orders of magnitude -- but it may take decades of struggle to get this all the way from basic research to working SSTOs, especially given the complexity of the problem and the politics, and the power of assorted vested interests. The lunar option has a real potential to become cost-competitive long before the earth-launched version, if it is given a real chance. But again -- we don't yet know. We need to explore all of these options, as effectively as we can, if our goal is to maximize our probability of survival as a species.

Many people worry about the risks involved in putting millions of dollars into unproven, high-risk advanced technologies -- especially when they see these risks in a real and concrete way in the budgets they are responsible for. But I worry much more about the risks to humanity if we do not -- the risk of losing trillions of dollars of potential benefits, and even a risk to our very survival. Even when unsuccessful, truly advanced cutting-edge research usually delivers new knowledge and educational benefits which conservative and predictable corporate welfare does not. Many futurists would argue that a solution to the world's energy problems would not be enough, by itself, to ensure our survival. I agree -- it is not sufficient, but it *is* necessary. It should be one part of a larger portfolio.

There are other issues -- such as world population growth -- which may be even more important. Yet I was impressed by John Mankins' suggestion that a 10 megawatt demonstrator power satellite might be used to accelerate global wireless Intrenet communications. I wonder: could such a "demonstrator," combined with new educational software and new low-cost interface technology, allow us to have a real, accelerated impact on improving education in the Third World, both to males and to females? (These education variables, in turn, are critical drivers of population growth and productivity growth.) Preliminary inquiries to Hughes satellite services and to education researchers at Carnegie-Mellon suggest that this possibility would be worth evaluating further. Perhaps there may even be a basis for further workshops between NASA and NSF and other agencies, to explore other aspects of this fascinating web of new options and new technologies in service to humanity.

Dr. Paul Werbos
Control, Networks, and Computational Intelligence
The National Science Foundation

Summary Of Findings And Recommendations

Challenges of Space Solar Power—Summarized by Dan Greenwood

The issues associated with such macro projects, which are larger than anything yet attempted in space, must be looked at from the systems engineering perspective. There are a number of major issues that are included but not limited to the following: orbital location, antennas, environmental effects, deployment of large systems, social/cultural implications, needs for power, competition from terrestrial approaches, state of the art of robotic manufacture and assembly, sizing, costs and benefits of the completed systems, mass production of new technologies, and others.

What are the needs for and drivers in robot intelligence for assembly operations in orbit or on the lunar surface? Do we really need self replicating robots or does replacement of production facilities from Earth suffice? We must learn more about control of large groups of interacting robots and we must generate plans to incorporate increasingly sophisticated levels of robot capability. We need to research ways of verifying the performance of very complicated robots that may have to function as manufacturing, installing, monitoring and repairing robots. A robot may have to be able to repair another robot or self-repair. We must demonstrate the production of glass and amorphous silicon from material which simulates that lunar regolith at the earliest possible time so that the basic feasibility of the initial steps in the LPS manufacturing can be established. Whether robots should be passive or active and the associated failsafe issues needs to be addressed. What is the degree of autonomy that is required or can be entrusted to "smart" robots in building orbiting structures? Research must determine how relatively autonomous robots can interact with humans when both are subject to erroneous behavior--for example, whose judgement is best in cost or life-critical situations.

There are a number of questions relating to the competitiveness of such systems and what it takes to understand and minimize the environmental impact issues of power from space. The incremental development and testing of the new technologies, and their credible demonstration will be a key step in building confidence that these macro systems can be built and operated. The potential for carbon nanotubes (Buckytubes) appears to be significant and assessing their role in SPS development is a worthwhile research activity which was not done in the NASA Fresh Look study. We should find ways of automating design tools and making the human machine interface more natural and intuitive. There are a large number of system competitiveness issues that were identified which, though they probably fall outside the scope of the thrust of this workshop, nonetheless, will be as crucial to the viability of these systems as are the robotics and mass manufacture questions addressed. Some of these issues were therefore included in the group findings in Chapter 2.

Technology Issues in Robotics for the Construction of Space Solar Power Systems

Summarized by David Miller

The group determined that there are at least three enabling robotic technology areas that cut across all of the different scenarios for space solar power generators, and all of the major robotic approaches for each of those scenarios. These areas are:

In-situ production of robot parts: This area involves the automated manufacture, assembly and repair of robot parts and subassemblies. This is a first step towards making a self-replicating robot. It is also tightly related to any type of in-situ manufacturing – a capability that is needed in most of the construction scenarios.

Large numbers of cooperating robots: This area involves the capability of having multiple robots cooperate in completing a task that cannot readily be done by a single robot. Research is needed in both groups of heterogeneous and homogenous robots. The SSP will involve large numbers of robots (thousands) all of which need to act in a semi-coordinated fashion.

Automated task scheduling and planning tools (including simulation): This area covers AI planning, automated scheduling, shop scheduling and particularly simulation. Planning and scheduling have been research topics for decades. It will be difficult to understand which techniques are most applicable to the SSP without an improved simulation capability. Simulation techniques also need to be improved in order to allow better understanding of sensing, communication and other issues that crop up in these scenarios and are impractical to test and evaluate in the laboratory.

Innovative new thin film technologies were described in one of the presentations that aim to replace conventional structures with gossamer structures and control them adaptively with information, which could result in major weight and cost savings. But the robotic assembly of such structures is radically different than that of more conventional structures and probably will require different robotic techniques.

This group also recommends using the construction of a rectenna as a common domain for the terrestrial testing of the research systems created in each of these areas.

Lunar Solar Power and Lunar Manufacturing – Summarized by David Criswell

There is an overwhelming need on Earth for clean, low cost, and abundant energy that is renewable. A Lunar Solar Power System could supply this needed power to Earth well within the 21st century. The key to the Lunar Solar Power System is the construction of most of the operating components on the Moon from lunar materials. The construction of adequate lunar derived photovoltaic cells from lunar simulates has been convincingly demonstrated by Dr. Alex Ignatiev in the laboratory. The essential production procedures have been demonstrated in orbit about Earth onboard the Wake Shield facility.

Terrestrial cells, and other solar conversion systems, must be made to resist long-term degradation by air, water, dust, and other chemical and biological agents. Terrestrial solar conversion systems must be mechanically rugged. These degrading factors are not present on the Moon and thus the arrays need not be massive and rugged. The manufacturing of solar cells and other solar conversion devices should be inherently significantly less costly on the Moon than on the Earth. On Earth the deposition and implantation processes must be operated within vacuum systems that are expensive to build, operate, and maintain. In comparison, the cost of lunar solar arrays are reduced by manufacturing the solar converters in the lunar vacuum. Sunlight can be used directly for evaporation of constituents. The solar converters and structural components are very much reduced in mass through such options as depositing solar cells directly on the lunar surface.

The Lunar Solar Power System can be fully understood and planned through a reasonable set of technical developments, demonstrations, and life-cycle analyses. An extensive base of technology, production expertise, and operational experience exists in the fields of radar, radio astronomy, wireless telecommunications, terrestrial photovoltaics, the Apollo and other lunar programs, launch systems, and the terrestrial industries of materials handling, glass products, and microelectronics. Detailed design and engineering for the creation, operation, and maintenance of the Lunar Solar Power System can be established through a sequence of progressively higher fidelity demonstrations on Earth, in low

Earth orbit, and on the Moon. Several reasonable methods exist to significantly reduce present estimates of the up-front cost of the Lunar Solar Power System. Lunar materials can be used to make significant mass-fractions of the production machinery transported from the Earth to the Moon. Lunar materials and beamed power can support transportation between Earth orbit and the Moon and reduce the cost of logistics. Advances in robotics and teleoperation /virtual presence allow Earth-based personnel to control the production, assembly, and maintenance of the Lunar Solar Power System and to expand the lunar industrial capabilities beyond power production. Recommendations are provided for analyses, component and systems development, and for ground, orbital, and lunar demonstrations.

Self-replication – Summarized by George Friedman

Potential self-replication designs can support the Space Solar Power (SSP) objectives in at least three ways: lowered construction costs, lowered transportation costs by using extraterrestrial material and, most significantly, acceleration of the pace of space development so that humanity can benefit from space power over a time frame of decades rather than centuries. John von Neumann conceived of at least two models of self-replicating automata: the kinematic model which works in the real physical world, and the cellular automata model which works in the virtual world of computer memories. Although it is only the former which is useful to the SSP mission, it is the latter which has received orders of magnitude more attention from researchers.

The most significant SSP-relevant work on self-replication for space power was an in-depth 1980 NASA study, but it failed to receive funding. One reason for the lack of kinematic model success is certainly the greater difficulty of designing complex systems in the real world rather than an abstract, virtual world, but there may be other reasons, associated with setting unnecessarily idealistic goals. These "greedy illusions" include: complete closure, complete autotrophy, completely universal constructors, completely internal "autonomous" robotic genomes, central rather than distributed robotic assemblies and the required depth of artificial intelligence. A fundamental finding is that: *we should focus on the rich domain of the possible rather than yearn for presently impossible fantasies. Humanity really needs space power soon, and it is attainable.*

There exists a paced series of economical research directions which include: development of an operational effectiveness model, a more detailed simulation of alternative production network system concepts for self replication, the examination of teleoperated and autonomous "robotic genome control," the use of molecular nanotechnology for the universal constructor, as well as more studies in von Neumann's early work in automata theory, complexity, evolution and biologically inspired design of large systems.

CHAPTER 1

BACKGROUND OF THE WORKSHOP

1.1. Introduction

A 3-day Workshop was held in Arlington, Virginia from April 4 to 7, 2000 with the support of the National Science Foundation and NASA. The purpose of the workshop was to identify fundamental and applied research issues associated with construction and manufacturing of very large systems in space and/or on the moon. Such issues will arise in connection with the construction and/or assembly of systems designed to convert and deliver massive amounts of solar energy to the earth's power grids, as well as with the automated production of photovoltaic conversion systems from lunar materials.. The manufacture and assembly of such systems will probably require the use of large numbers of semi-autonomous yet cooperating robots. Thus whether in space or on the moon, these solar power systems are representative of the problems and issues that will have to be addressed in the construction and manufacturing of many types of macrosystems in space or on planetary surfaces.

The workshop therefore concentrated on identifying the research issues in manufacture and assembly of both Satellite-based Power Systems (SPS) and Lunar-based Power Systems (LPS). This workshop took no position on the relative merits of space SPS vs Lunar LPS systems for energy delivery to Earth, as either serves as an adequate example for identification of the research issues in space macrosystems and production on the moon using indigenous materials. While it appeared that credible trade studies between the two approaches will be eventually required, it was not the purpose of this workshop to delve into the desirability or programmatic issues with either system, but rather to use them as a means of identifying desirable research directions applicable to a broad class of large space systems. Thus the conclusions and recommendations of the workshop should be taken in that context.

The Workshop was attended by 55 people representing a variety of interested communities, from government to space science, from robotics to self-replication. The complete list of attendees is given in Appendix 1, and the complete program is reproduced in Appendix 2.

The Workshop was organized into four subgroups, concentrating respectively on system challenges of space solar power, robotics and technology issues, lunar power systems, and self replication. The major findings and recommendations from these groups appear in the following chapters, and are based on the formal presentations and extensive discussions held by the four subgroups.

1.2 Motivation

As we move into the 21st century, it is increasingly important to the survival of our species that we identify renewable sources of electrical energy, since even the most optimistic estimates indicate that economically useful supplies of fossil fuel supplies will be largely exhausted within the next century. Generation of large amounts of electrical energy in earth orbit or on the moon and its transmission to earth are among the possible solutions to the problem. Very large macrosystems in space and/or on the moon will be required to attain such objectives, and the design, construction and operation of such large systems will pose problems of enormous magnitude.

1.3 History

The idea of generating large amounts of electrical power in space using large satellites equipped with photovoltaic cells, and transmission of the power to earth using microwaves was proposed by Peter Glaser in 1968. In the 1970s a number of careful and well funded studies by DOE and NASA proposed several feasible configurations, and a "reference" system with satellite collectors several km in length and width. Evaluation of this reference system concept by the National Academy of Sciences resulted in a pessimistic assessment due to uncertainties in the environmental effects in the vicinity of the receiving rectifying antennas ("rectennas"), possible effects on the ionosphere, the extremely high cost of development and deployment, and the resultant high cost of the generated electricity. This assessment unfortunately did not include even the call for the definition of a research program to resolve these issues, and thus the report essentially killed the SPS.

In the 1995-97 period NASA conducted a "Fresh Look" study of Space Solar Power system (SSP), commissioned by Ivan Bekey and directed by John Mankins. The study concluded that in order to overcome the technical and economic show-stoppers of the 1970's SPS reference concept, new technologies and system architectures could radically reduce the difficulty and cost of SSP development, deployment, and operations costs and therefore result in a number of viable SSP system concepts. The economic viability of all these new system options were dependent on major advances in the technologies of power generation and beaming, structural design, mass production, and launch vehicles.

During the past several years a number of studies resulting from the NASA Fresh Look Program have demonstrated novel approaches to these earlier technical problems. Rather than using large flat panels covered with solar cells, the current configurations frequently are based on modular replicated structures, modular phased array antennas for conversion and transmission of the power, and modular means for collection and conversion of sunlight. The modular constructs allows mass production of large number of modules and subunits, resulting in major reduction in cost from the earlier unitary constructs. In addition semi-autonomous robotic assembly takes the place of hundreds of astronauts, which also is crucial in reducing cost and establishing feasibility. Thus, given these approaches and technological advances the generation, collection, transmission and reception of vast quantities of power economically enough to be competitive with terrestrial power should be attainable.

These space solar power systems, and the parallel concept of siting similar systems on the surface of the moon, are critically dependent on two general areas:

- Cooperative multirobot semi-autonomous assembly of the needed collectors and transmission systems to reduce assembly difficulty, time, and cost, and

- Semi-autonomous manufacturing of photovoltaic cells and other major components from lunar materials in the lunar environment, which would reduce both their manufacture and transportation costs.

Both of these areas pose system issues of enormous magnitude. Clearly, some work in cooperative robotics (using a few or even a dozen robots) has been demonstrated. However, there are fundamental scientific and technical issues associated with the autonomous or semi-autonomous operation of hundreds of free-flying, robotic vehicles in space, assembling solar collectors, transmitters, and antennas. How are such robots controlled? How can they coordinate their work? Are hierarchical organizations of robots necessary, or can they work in a "democracy"? Can we learn lessons from the cooperative behavior of social insects, e.g., the construction feats of African termites? And lastly but certainly not least: is a small degree of human supervision or control desirable to greatly simplify the robot's tasks? Because of the uncertainty of these issues we have taken to describing the robots as "semi-autonomous" rather than "autonomous".

An option exists for manufacturing the needed solar cells and some structural components of the SSP from lunar material on the surface of the Moon, rather than transporting them from Earth. Furthermore the major system option of actually siting the entire system on the Moon (the LPS) requires that virtually all the components be manufactured and assembled in the lunar gravity, using semi-autonomous manufacturing facilities of unprecedented scope. This adds the major issues of how to perform the assembly and operation of mostly-autonomous manufacturing and assembly facilities on the lunar surface. Ideally such facilities should be self-assembling, make use of local raw materials, be robust and self-repairing, and require mainly robots rather than human astronauts. Under the ideal scenario a group of robots performs cooperative assembly of a manufacturing facility on the moon, including appropriate diggers and conveyors to obtain local material and use of solar cells for generation of needed electrical power. The NASA Administrator (or the President of the United States) presses a button; lunar "sand" is processed, components are molded, cut and assembled, and fully operational photovoltaic units come out the facility, ready to be assembled into a lunar power generating station or shipped to Satellite Solar Power Satellite sites in orbit.

Clearly, the problems here are even more complex than those faced by the solar satellite-building robots, since they involve both manufacturing and assembly. What knowledge is required to make such manufacturing possible? Do we have the knowledge to create components and systems using only materials available on the lunar surface? How are the designs and assembly instructions for the factory stored, accessed, and implemented? Do different robots have different capabilities? What happens if one or a group of robot becomes incapacitated by meteorites? Can the lifetime and reliability of such factories be modeled? How much autonomy in the robots is possible or desirable? Would a small degree of human supervision have disproportionately large effects on the feasibility and cost of such operations? And, the deep underlying question: Can such a factory build a clone of itself?

1.4 The Workshop

The workshop attempted to identify the research issues associated with these two scenarios by both formal presentations and a number of breakout discussion groups. The following section presents detailed reports from the four discussion groups. The slides used in the formal presentations listed in the program (Appendix 2) are included in the accompanying CD, as is material that was going to be presented by Neville Marzwell before he became ill. The output from this workshop is a research agenda to address these issues, which we believe are fundamental to the goal of achieving practical SSP technologies within the next 20 years, and the successful fielding and operation of SSP systems in the following decades.

As evidence of growing current interest in this topic, an excerpt from a recent article in the *Journal of EPRI*, the Electrical Power Research Institute, entitled "Solar Power from Space: Beaming Electricity from Space-Based Power Systems Could Brighten the Environmental Outlook" is presented in Appendix 3.

It must be remembered that these issues will also be of crucial importance to other space macrosystems in the future, making the recommended research broadly useful.

CHAPTER 2

CHALLENGES IN SPACE SOLAR POWER SYSTEMS

(Summary by Dan Greenwood)

2.1 The Challenges

The world currently uses power at the level of trillions of watts (TW)and, within the next several decades a requirement of average power demand in the neighborhood of twenty TW's is a conservative estimate. To conserve resources and to minimize pollution a renewable, predictable, economic and reliable source of energy is necessary. Solar energy collected on earth is a candidate for providing energy at the TW level. However, it is currently not economically competitive with nonrenewable energy sources, and is not predictable without very expensive energy conversion, storage, and redistribution systems. Both the SPS and LPS are systems that are capable of providing power at the TW level renewably and predictably. The economic viability of both systems depends on improvements in earth or moon based manufacturing and reduced costs of launching materials, people and equipment into orbit.

To produce a space macrosystem capable of generating enough to meet global demands it will be necessary to transport millions of tons of material into orbit for developing an SPS system and several hundred of thousands of tons of machinery and supplies for manufacturing an LPS system. To begin deploying such systems in 20-30 years, and to minimize the health risk of exposure of humans to space radiation, it will be mandatory to use robotics and telerobotics in their construction and deployment. Regardless of the time that such systems are deployed, robotics and advanced automation will always be critical to assuring minimal cost development and safe and reliable operation. It was the goal of the workshop to identify the nature of the research and development required in the next decade to facilitate the deployment and operation of space macrosystems such as the SPS and LPS in any of the many possible eventual embodiments of such systems.

Many of the workshop participants were not knowledgeable of the substantial amount of analysis previously performed and of the proof of concept experiments conducted on space power generation and power beaming. Furthermore, since a specific and universally accepted problem definition does not exist, many of the issues identified and concepts debated were largely of a general or intuitive nature. In addition, since some of the participants were very familiar with the subject material and had large of amounts of data on hand to support their views, there was often information overload on the part of those participants who newly were initiated into the subject matter by the space power experts in attendance. Despite this mismatch of abilities of assimilate the often unfamiliar concepts and terminology of the information providers, it appears the a basic ability to communicate and understand the issues posed, meaningful questions and issues evolved by the final day of the three day workshop. The workshop attendees were truly a multidisciplinary group, consisting of experts in robotics, self-replicating systems, material processing, space macrosystems, neural networks, energy systems, systems engineering, radiology and many other professions. Such a group is representative of the large number of diverse skills that will be necessary to design and implement the space macrosystems presented and deliberated during the workshop. Some of the concepts and technical challenges that this group considered to be worthy of future R&D support from NSF and NASA are the following:

2.2 Problem Definition

For both SPS and LPS it is necessary to make explicit the baseline system concept from which the specific problems applicable to a robotic approach can be defined. The mix of human and robotic tasks needs to be determined. In the case of SPS plans for new technologies in material developments could have a major impact in the robotics applicable to building the structures in orbit. Handling flexible versus rigid components imposes vastly different constraints on robotic aids(the CMU simulation of a robotic assembler which moves along the girders of a rigid structure would not be applicable to a flexible film structure, for example). We must explore ways to reduce system costs by utilizing smart materials, collaborating robots and self deployable structures.

There are many possible ways to design the LPS and to terrace the development of a basic capability. We need to define first steps and realistic goals that build confidence in subsequent steps. Can we define a minimal system which is completely robotic which operates on the lunar surface and which can scale to a larger system which has humans in the loop? We must research the following basic processes for bootstrapping a minimal LPS robotic capability:

1. Excavation: lunar power sources, equipment capabilities, control, re-cycling, repair, life-cycle,
2. transportation, maintenance, sensors
3. Beneficiation: same as 1)
4. Chemical Refining: processing, materials, same as 1)
5. Hot forming: heat transfer, same as 1)
6. Cold assembly: same as 1)
7. Macromanufacturing: miniaturization to reduce mass, same as 1)

2.3 Research issues

The issues associated with such macro projects must be looked at from the systems engineering perspective (the Apollo Project or ISS are relatively small projects compared to what both SPS and LPS would entail).

Orbital issues: Control, launch logistics, debris, interference with other space and science missions, coordination of large groups of people throughout the world.

The receiving antennas (rectennas) could account for 80% or more of the cost of the LPS so specific cost components must be identified and methods to reduce cost must be researched. The aluminum required to build a rectenna contributes to the cost and producing aluminum uses relatively large amounts of electricity. Since both SPS and LPS need rectennas and both systems produce electricity ways of self generation should be determined. Thus, the first rectennas could be deployed near aluminum processing facilities that already exist.

The environmental impact of rectennas and associated power lines to link these new sources to the power grid will be very critical to public acceptance and we need much research to optimize this process. Microwaves when used as specified for SPS and LPS have not been shown to have any short term negative impact, however, no long term testing has been done. The placement of rectennas will be critical and will take significant interaction with land planners and political and public leaders. Social and cultural issues must be circumscribed: who owns what and how are developing countries to folded into the enterprise. Lunar manufacturing is estimated to require the most mass from earth so correspondingly more research should go into ways of reducing the equipment needed to perform this aspect of developing the LPS.

The potential for advanced materials such as carbon nanotubes (Buckytubes) appears to be significant and assessing their role in SPS development is a worthwhile research activity. It appears from the overview of the SPS Fresh Look study given by John Mankins that none of the design options presented considered future development in flexible materials or nanotubes and SPS planning should consider fairly near term developments in these areas. This area is so promising that it is worthwhile to seek funding to expedite the research and development of the technology.

Whether robots should be passive or active and the associated failsafe issues need to be addressed. What is the degree of autonomy that is required or can be entrusted in "smart" robots in building orbiting structures?

There will be new demands placed on existing power, material and personnel resources. Methods of resource utilization and systems trade-offs will have to be made. For example, radio frequency allocation is a critical issue for power beaming and the desirable operating frequency (2.4 GHz) is near a communications band and interference will be difficult to avoid. What is the impact on other users and how will priorities be set when the are conflicting benefits for contending systems.

Terrestrial based solar power generation has a growing constituency and power beaming is often considered a competing endeavor. Ways must be found to utilizing terrestrial and space power synergistically. For example, ideal terrestrial solar collection sites are often far removed from users of the power and power beams with orbiting reflectors could be used to circumvent the need for building new power lines. Thus, we must research spin-off potential. We must develop plans for making sure that the right mix of educational skills will be in place to produce and maintain such macrosystems of several decades. The proper incentives for youth of today must be generated to make careers in the required fields worthy of the struggle to achieve the necessary educational levels. We should find ways of automating design tools and making the human machine interface more natural and intuitive. Humans and robots will have to interact in novel ways to develop the LPS and the level of "intelligence" required from robots must be ascertained through simulations and actual testing. Research must determine how relatively autonomous robots can interact with humans when both are subject to erroneous behavior...for example, whose judgement is best is cost or life critical situations?

How much capability is enough? What are the drivers in robot intelligence for in orbit or lunar surface assembly? Do we really need self replicating robots or does replacement from Earth suffice? Much of what the public or investors will accept concerns the pros and cons of the various alternatives. Cost of equipment and personnel is very dynamic and economy of scale has brought the developed countries truly incredible levels of prosperity in a relatively short time. Previous power beaming cost-benefit analysis was done by a small number of people with little awareness of new problem constraints such as the reality of global warming and the rapid industrialization of China and India and the extra burden on the environment and fossil fuels that such development entails. We must enable collaboration between knowledgeable space and energy technologists and economists through government sponsored R&D.

The LPS entails tiling large areas on the lunar surface with solar cells, small transmitters, and antenna elements the size of billboards. While the process of installing one "tile element" or "collection/transmission plot" may be straightforward, the number of elements is in the millions and, clearly, their installation must be automated to guarantee a return on investment in the five to ten year time frame or a little longer with a good portion of government sponsorship. Consequently, immediate research attention should be given to the utilization of cooperative robots or telerobots to perform the basic tiling process along with manufacturing the components of the basic LPS tiling element. The deployment of the requisite rectennas in the developed countries is something that could be highly roboticised, but developing countries may chose to have a more labor intensive deployment. Research into ways of reducing the cost of rectenna manufacture and deployment is very critical to both the LPS and the SPS and breakthroughs here could have a very significant impact on ultimate cost of such systems.

We must learn more about control of large groups of interacting robots and we must generate plans to incorporate increasingly sophisticated levels of robot capability. The system design should start out with manual intensive operations and gradually replace manual labor intensive tasks with robotic intensive tasks. We need to learn more about chaotic systems and emergent processes via simulations of lunar manufacturing and rectenna deployment since large numbers of robots would have to be controlled with faults and disruptions occurring as processing is taking place.

We need to research ways of verifying the performance of very complicated robots that may have to function as manufacturing, installing, monitoring and repairing robots. A robot may have to be able to repair another robot or self-repair. We must demonstrate the production of glass and amorphous silicon from material which simulates the lunar regolith at the earliest possible time so that the basic feasibility of the initial steps in the LPS can be established.

CHAPTER 3

ROBOTICS

(Summary by Peter Will)

3.1 Systems issues

The issue of robotic construction is closely intertwined with the question of whether the construction will be in free space or on the lunar surface. The same techniques and solutions are not likely to be applicable to both. Robots in general deal in the realm of applying forces to objects (maybe itself included) for some purpose. Although the lunar gravity is less than earth's, it provides a more stable environment for construction than being in orbit in that there is a gravity and objects therefore have a preferred direction of motion –downwards- and preferred stable rest positions- on the surface . As on the earth's surface forces on the Moon have to be large enough to overcome friction in order to be able to move objects of any size. Operation is space on the other hand allows very small forces operating over long times to achieve high speed and momentum operation. These energy density considerations absolutely constrain any design. It is important to decide on these environmental conditions as early as possible. The choice of place and environment is critical, one has gravity albeit lower than earth, the other has none. In one things fall to earth and have considerable weight, in the other you could park a subassembly in space for a second or two and regrasp if required.

Traditional manufacturing can work on the Moon, new methods are needed in space. Logistics and material supply are vastly different in the two domains. This affects cost and manufacturing strategies. This issue of place dominates the choice of technologies applicable to the Solar Power problem.

Robots need materials for constructing artifacts. The lunar surface offers a more favorable opportunity to obtain extraterrestrial material than near-earth orbiting asteroids and certainly more favorable than lifting material from earth at tens of thousands of dollars per pound. If solar power satellites built on the lunar surface are transported to earth orbit, the cost would be reduced by about a factor of 20 compared to lifting them from earth. One of our greatest challenges will be to manage the bootstrapping of the evolution from human-dominated systems controlling the construction of satellites built form earth resources to teleoperated and eventually fully autonomous systems constructing power systems from extraterrestrial resources. The spectrum of potential robotic applications is formidable: from the mining of ore to refining, to production of feedstock, to fabrication of subassemblies, to construction of major structures, to operation, maintenance and repair, and, eventually, even to the self-replication of additional robots.

Since information and its communication costs but a trivial percentage of the cost of space structures, every opportunity should be taken to trade information for energy. This applies to the design of machines and structures even down to the tagging of assets with data telling what materials it is made of and the processes that were used to make it. An earth example is the Automatic Braking System used in automobiles, the information content is what makes the ABS system work. Similar arguments of this spirit but carried to the limit will be necessary especially when we must meet the challenges of designing massive vehicles and structures as well as building maintaining and diagnosing faults in systems that support the activities of human beings in non terrestrial environments.

3.2 Robotics and systems issues

In broad terms, robotics has both vastly succeeded and vastly failed. The successes include the design of hardware and software for working in factories, walking, crawling, swarming, communication and control. The failures have been in applying robotics to loosely structured applications. The big issue in robotics applications is not the robot itself- although that gets all the glamour- but the presentation and structuring of the material that the robot will use. Different applications require different structuring methods; different gravity environments will require different approaches.

Power, and essential requisite for robotic activity, will be free whether the activity is in orbit or on the moon. We will first build the power syutems required for robotics and bootstrap from there.

Robotic systems should be modularized for repair, maintenance and parts replacement, including the scavenging of parts from one robot to another. A robot system in space or on the moon is expected to do about two operations per second , 24 hours an earth day for twenty earth years…the mission time of a Voyager satellite. This is about 3 million operations per year for twentyu years. This requirement poses huge challenges to the predictive as well as failure diagnosability of electromechanical products beyond anything in tererestrial environments.

Configuration management should be used at all systems and component levels, enabling the robotic community to utilize al available components for replacement, repair, and redundancy.

Unit Processes

Many kinds of unit processes are needed to realize the SPS vision, they range from providing material for construction, building living quarters for people, building factories to make and assemble artifacts, through producing food for the necessary people involved in the operation. They also include, making ingots, beams, bars, wire-pulling the use of tools, building manufacturing cells etc. They also include clearance of rocks and mining activities, open cast and deep rock mining. Many of these activities involve the application of large forces. This is a problem in robotics whether on the earth , on the moon or in orbit. The consequences of an error are severe in orbit.

The wide variety of possible robotic system architectures, including construction robots, control networks, degrees of autonomy, hyper-redundancy, hierarchical cooperation, modularity, and degrees of mobility should be studied. Self and mutual repar issues need investigation as well as the design of systems for scavengabilkity. BMW under strict German law already designs for recycalbility by melting plastic and metalk for reuse. Efficiency reasons on the Moon or in orbit might necessitate reuse of field replacable units. Here we will require design for cannibalization in addition to design for the usual “ilities”.

System designers should employ detailed simulations of robots and their interactions prior to the actual building of hardware. Then they should validate the simulations via hardware testing in realistic environments. They should attempt to simulate the lunar environment with terrestrial tests – perhaps in the desert.

The systems issues of task organization, design for assembly, design for maintainability, design for repair, status monitoring and the transition from terrestrial to space power systems should be examined carefully.

Studies Needed.

We need the study of robots for making and repairing other robots or itself.

We need to trade off between robots that are fixed in position or attaché to the factory floor or orbiting structure vs free flying robots—issues needing study include relative positioning accuracy requires, the forces to be exerted and the dexterity required (Earth robotics is best applied wher the assembly direction is lined up in the direction of gravity)

We need to study the use of Hyper-redundant robots and manipulators to climb in between amongst structures. Versus statically attached robots.

Large structure will require cooperative robots. The present state of the art is that there are cases of only a few robots that have ever demponstrated cooperation. The problem was poised tqenty tears ago and is still the subject of research papers involving two robots cooperating. What are the scaling implications of getting groups of robots to construct large structures in space or on the moon?

Simulation Facilities are needed. These could be used to design robots and artifacts but should also used in Virtual Operation using the same software.

No comprehensive simulators exist where comprehensive means, kinematic, dynamic, FEM for strength of materials, electromagnetic unified into one framework.

Sensory simulation systems are VERY primitive and need development. Lunar or orbital operation will critically depend on sensor architectures.

A major research question deals with progressive assembly in space…is the base always stable? Is it desirable to be a structure or is it still kinematic chain, The system may have structural integrity when it is all built..think of the keystone in the arch of a bridge…. how does it get built? Will we build scaffolding in space or is there a better way to ensure integrity?

3.3 <u>Top five research tasks</u>

The following five research tasks are recommended and should be conducted first in a terrestrial environment:

(a) Develop a structured, evolutionary, always kinematically stable construction methodology.
(b) Design multi-degree-of –freedom, modular, hyper-redundant robots able to build and climb in, over, and around such structures.
(c) Develop configuration management systems down to the modular unit with full provenance for re-use and cannibalization.
(d) Develop software for all of the above.
(e) Construct integrated simulation systems for kinematic, dynamic, and electro-magneto-static systems design using finite element models and virtual reality operation and training.

CHAPTER 4.

ROBOTIC CONSTRUCTION OF SATELLITE SOLAR POWER SYSTEMS

(Summary by David Miller)

4.1 Issues in Robotics and Space Solar Power

This group was charged with reviewing the panels and determining the tall-poles in robotics that stood in the way of implementing a space solar power solution.

Early on, the group came to consensus that some other issues were inhibiting their ability to carry out the charge. In particular, several different space power solutions were proposed that made differing demands on the robotic systems needed to deploy them; secondly, there were many radically different robot approaches to each of the proposed power generator solutions. The differing robotic approaches each had their own technology challenges. Thus, it was felt that an approach to the power system as well as an approach towards its power solution needed to be identified prior to identifying the top technology issues in the area of robotics. By the end of the workshop it was still believed by the group that a selected scenario would help to focus the technology needs in the area of robotics. However, it was also decided that there were some broad areas of robotics research that cut across all of the scenarios.

The remainder of this portion of the report will itemize these different scenarios and their implications on robotics. We will then identify the cross cutting technology areas. Finally we suggest a common domain that would make a good testbed for exploring these technology areas.

4.2 SSP approaches and robot issues

All three SSP approaches: in orbit assembly from terrestrial materials, in-orbit assembly from lunar materials, and lunar assembly from lunar materials share several characteristics; most notably that there are huge structures that need to be assembled primarily by robots. Additionally, all the scenarios require a large degree of accuracy and the structures will need some level of maintenance and have to be serviced over a long lifetime. However, each of the scenarios also has its own unique issues.

Most of the scenarios for in-orbit assembly using terrestrial materials have thousands of shipments into LEO for each of the power generators. Each of these 10-20 ton shipments needs to be manipulated into position, unpacked, stored, retrieved, moved into final positions and then fixed into place. Realistically, each of those shipments will probably be one or a few subassemblies, each massing several tons. Robots either have to be free-flyers (and therefore will need to be able to self refuel) or will have to crawl across the existing structure as they manipulate each piece. Since the pieces will be so massive, several robots will have to be used in order to assure that the piece remains under control.

In-orbit assembly from Lunar materials has other problems. In this scenario, each of the subassemblies is made from hundreds or thousands of small packets of raw material, shipped up to orbit from a lunar mass-driver. But the material arriving from the Moon would be raw, and would have to be processed in space into buildable components, a difficulty that was not examined in this workshop. Even then the assembly robots in this scenario would need to be able to manipulate masses of a few kilograms to a few tons. Assembly will also be required at a larger variety of scales and smaller size of detail. In-orbit assembly from Lunar materials also implies that there is a robotically constructed facility on the Moon. Robots on the surface will have to build the mass driver and maintain a flow of raw materials leading to the driver so that those materials can be launched to the in-orbit site, a major degree of additional complexity.

The third scenario, power stations on the Moon, would involve much more extensive surface robotics than those contemplated above. In this scenario the robots need to assemble manufacturing facilities. From these they need to feed in raw materials and churn out power elements. Finally the robots would need to distribute and maintain those elements. Other approaches to surface power were suggested at the workshop, including a means of producing solar panels in place. This scenario solves some problems while introducing others. The overall complexity of the problem appears to remain approximately the same. One of the trickiest robotics problems for the Lunar surface option is mobility. While surface mobility is well studied, and can be more readily tested than that of free-flyers, the Lunar environment is very difficult with regards to lubrication and bearings; getting a robot system capable of travel over thousands of kilometers without human maintenance is a big challenge.

Innovative new thin film technologies were described in one of the presentations that aim to replace conventional structures with gossamer structures and control them adaptively with information, which could result in major weight and cost savings. But the robotic assembly of such structures is radically different than that of more conventional structures and probably will require different robotic techniques.

4.3 Issues with large structures and robots

There were four general robot strategies that were brought up during the workshop. These four strategies are independent of the location of the power station or the origin of the materials (though these issues have major impact on the details of the system.) These strategies are:

Capable Robots: In this strategy, bigger, better and more intelligent versions of today’s manufacturing robots are used to assemble the station. These robots might look like improved versions of the Space Station robot system. The robots will contain general and special purpose manipulators, and will move about the structure retrieving and attaching modules to the structure according to an overall, carefully coordinated plan.

Intelligent self-assembling structures: In this strategy, each piece of the structure is its own robot. The pieces have some mobility on their own, some sensing and a limited amount of manipulation. When the pieces are dropped off in the general area of the assembly, they move into place and attach themselves to their neighbors. They then make any necessary additional electrical or mechanical connections. The advantages of this approach are that the robotic elements do not have to have long lifetimes, or be capable of being refueled or refurbished. The obvious disadvantage is that many more manipulators and sensors are needed than to have a few capable systems assemble many static pieces.

Termites - Collections of Homogenous Robots: In this approach, hundreds to hundreds of thousands of relatively small and less capable robots assemble the structure. The structure may still consist of large subassemblies that need to be moved into place and then attached. However in this strategy the movement is not planned explicitly, but rather the group behavior of the robots leads the pieces to be moved into place through emergent swarm behaviors. Robots communicate with their neighbors in trying to achieve a group goal.

Coral – Swarms of Homogenous Single Use Robots: In this strategy each robot accretes the proper pieces and then joins in a formation with the other robots – and stays there. The result is the structure that is formed by the material brought in by each element. Ideally, these robots would have been created through automated self-replication of the original robot (as in a true coral system). This approach would require very inexpensive robots indeed.

Swarms: This assembly strategy never actually gets assembled. The large structure is actually created by having a swarm of coordinated independent semi-intelligent objects acting in concert. A solar reflector might be created in this way by having thousands of small free-flyers, each with a piece of mirror attached to themselves, fly into and then maintain a parabolic formation. One advantage of this strategy is that if the system is ever damaged, the swarm could reconfigure to eliminate the damaged elements but still maintain whatever level of uniformity might be required. Another advantage is that in structures such as phased arrays, performance depends on accurate knowledge of each elements positions relative to others. Normally this knowledge is achieved through a precise, rigid structure. In the swarm it could be achieved by actual knowledge of position combined with the appropriate signal corrections.

4.4 Technological “tall poles”

This group settled on three critical technological tall poles in the area of robotics for space assembly. Many other challenges have been mentioned throughout the report, but these seem to be critical to most or all of the scenarios that have been discussed. They are:

8. In-situ production of robot parts
9. Large numbers of cooperating robots
10. Automated task scheduling and planning tools (including simulation)
11. In-situ production of robot parts

In-situ production of robot parts

The first tall pole spans a spectrum from the ability of robot systems to be able to repair other robots all the way to self-replicating machines. The rationale for this being a critical area is simply that the huge number and long lifetime of these robot systems demands the ability for robots to be repaired in the field. If a new robot replaced every robot that suffered a failure, not only would the expense be tremendous, but dead robots would become a significant and dangerous source of space debris. For most of the scenarios that have been discussed, it is not necessary that all parts of the robots be able to be produced from in-situ materials that are manufactured in the field. The automated exchange of sub assemblies would go a long way towards making the large structure assembly process doable.

Significant gains are made when the sub assemblies can be produced locally either from raw materials or by scavenging parts from broken assemblies and inserting new parts only when necessary. For SSP scenarios that involve the use of in-situ materials, being able to manufacture at least the structural elements of the resources, on-site, would be highly desirable.

The criticality of this area can be reduced slightly if the reliability of the robot systems can be vastly improved. To do this will require advances in related areas that may prove just as difficult to solve. There is almost no history of mechanical systems with a reasonable lifetime (millions of cycles, hundreds of months) operating in the space environment. In order to successfully and economically deploy these large space structures, robots will have to achieve reliabilities comparable to or exceeding a modern automobile. Current semi-autonomous robot systems have reliability spanning tens of cycles and dozens of minutes before human intervention is required. Tribology issues and improvements in the performance of brushless motors in the low-density plasma environment of LEO or the Lunar surface need to be addressed.

Even if these tribology and related reliability issues can be solved, they do not obviate the desirability for in-situ production of parts. At some point it will become highly desirable to have the machines be able to reproduce themselves. Self replicating robots will greatly lower the required launch mass to produce an SSP generator. The same technology that is needed to manufacture in-situ parts for the generator should eventually lead to the in-situ production robot parts and robots.

Of course the ability to produce parts and the ability to repair and assemble new robots are not necessarily the same thing. We must learn to be able to design robots for ease of self-repair and self-replication. This runs counter to current practices in both robotics and spacecraft design. Currently these devices are highly specialized and usually hand-assembled. Design practices must be changed to allow for higher degrees of automation in the production process.

Large cooperating groups of robots

This second area is relevant to every scenario for SSP generator production. On the Moon or in orbit, these structures are huge and will involve thousands upon thousands of robots in the structure's fabrication. In some instances, the sub assemblies are so large that numerous robots will be involved in maneuvering them into place. The coordination among multiple robots that are mechanically linked through the object that they are moving has proven to be challenging even when performed on simple terrestrial problems. Performing such manipulations in micro-gravity, or over rough terrain, or with large flexible structures has yet to be attempted let alone mastered.

There has been some work on cooperation between moderate sized sets of homogenous robots. However, the SSP projects are so large and have so many aspects that it is almost certain that very large numbers of robots will be needed, and that while there may be lots of duplication, there will be several types of robots in that group. Cooperation among large numbers of heterogeneous robots has yet to be demonstrated.

Even if a scenario is used where each sub-assembly is its own mobility system, cooperation among large numbers of robots will still be necessary. In addition to coordinating actions between all of the sub-assembly's neighbors, any movement through the construction site will require moving past numerous other robots without adversely effecting any of their own plans or operations.

Each robot will have to operate largely autonomously. Teleoperation of all the robots is not practical due to the large number of robots (tens of thousands) and the high bandwidth needed for teleoperation in dynamic domains (streaming real-time video). In Lunar or even geo-synchronous operations, the time-delay is an additional hazard when using tele-operation. However it is likely that teleoperation could play a major role in the initial stages of development and deployment, transitioning to more semi-autonomous robot operation as time and experience are accumulated. In any event, some overall control (the assembly equivalent of the air traffic controller) will probably always be needed to oversee the operations. Any of these levels of semi-autonomous scheduling, planning and execution monitoring are currently far beyond the demonstrated state of the art.

Scheduling and Planning Tools

The third tall pole for robotics research is tools to assist in the planning and scheduling of large multi-robot tasks such as the assembly of a SSP generator. For most of these structures it is expected that construction will be done in accordance with a plan. This means that the various robots must be assigned tasks and that the execution of those tasks adhere to a schedule, otherwise resources will end up sitting idle while the plan is repaired. Shop scheduling on this scale has not really been done. Previous large structure construction (e.g., dams, the Pentagon, etc) have had some shop scheduling, but also have relied on local foremen on the scene to perform local optimizations in order to keep the entire project moving. As of this time, the abilities of virtually any construction foreman far outshine the capabilities of the most advanced robot system. Not only is the human able to more accurately gauge the rate of progress and the capabilities of their staff, but the human is better able to shift perspective and merge their local objectives back into the whole.

On a project the size being contemplated for SSP, the project is simply to big to be grasped. Additionally, the work conditions are foreign to any human construction experience. Much of the human advantage is eliminated – however, eliminating the human capabilities in no way makes the robot system more able to perform. In order to do these tasks, new tools, usable by either humans or machines, are needed.

Scalable simulations are critical. The movements of parts and robots around the construction site will make the air traffic control problems of large airports seem trivial in comparison. Also critical are simulations at a much finer grain. What can a robot perceive in this environment and how will it know when the part is actually in the proper place? These are new tasks and people have poor intuition of what needs to be sensed and what the proper reactions should be. Short of flying numerous test missions, simulation offers the best tool for building intuition and experience that can be used for designing the systems and the appropriate control.

Robot simulations are notoriously bad -- especially when one looks at simulating large systems. A simulation can only project the interactions that are programmed into it. Better models of sensor noise and interaction, robot communication, chaos, and the physical environment in which the robots will be working, are needed. Physical testing in a 1g environment is largely inadequate, and neutral buoyancy simulations offer their own difficulties. Reliable and useful computer simulations of all aspects of robot operations in the space environment need to be created in order to adequately develop and test the robot technology needed to do the SSP assembly and maintenance.

4.5 Recommendations

The group felt very strongly that some sort of demonstration should be performed as soon as practical to help get political and popular support behind the SSP concept and behind the robotics technology program. One near-term demo, which would also serve as a technology driver in the robotics area, would be the creation of a rectenna.

The rectenna is composed of largely identical parts wired in a repeated pattern. It is therefore highly scalable. This repetitive feature also makes the system very amenable to assembly by multi-robot systems. The rectenna is a good testbed for trying out different architectures for multi-robot cooperative systems. The rectenna is by no means the most difficult problem in this area, but it is a reasonable milestone.

Additionally, rectennas can be very large. The project can easily become a realistic test of the reliability and lifetime of the various elements in the robot system. Ample opportunity for robot repair and part replacement will be offered during the construction of a moderate size rectenna. While this domain will not test the issues of reliability in the space environment, it is again an important milestone and perhaps one that has more immediate spin-off technology possibilities than the full up space-construction.

Similarly, the rectenna testbed is a good environment for testing out a number of tools to assist in automated scheduling and planning. The rectenna has the scale, and much of the complexity of interaction, that would be found during the construction of a SSP generator. But unlike the space structure, the rectenna can much more easily be compared to a simulation in order to provide some ground truth in order help tune these systems and validate the simulation models.

The robotic construction of a rectenna will require fundamental advances in a number of areas. The rectenna can be a good domain to allow different research groups to work together. It can also provide a well defined metric to aid in the evaluation of the different technologies that are produced. Finally, it is not only a driver to create these technologies, but it itself is a necessary piece that needs to be developed in order to enable the construction and deployment of space solar power stations.

CHAPTER 5.

LUNAR SOLAR POWER SYSTEMS, AND SOLAR CELL MANUFACTURING ON THE SURFACE OF THE MOON

(Summary by David Criswell and Alex Ignatiev)

5.1 Overview of the Lunar Solar Power System

It is technically and economically feasible to provide to Earth at least 100 TWe of commercial solar electric energy from facilities on the Moon (T = tera = 10^{12}; W = Watts)[1, 2]. Commercial power systems now supply Earth with approximately 13 TWt of thermal power or the economic equivalent of 4.5 TWe of electric power. The Lunar Solar Power (LSP) System can supply to Earth power that is independent of the biosphere and does not introduce CO_2, ash, or other material wastes into the biosphere. It is estimated that the Lunar Solar Power System can deliver electric energy at significantly less cost than conventional systems. The Lunar Solar Power System provides inexhaustible new net electrical energy that is decoupled from the biosphere. The net new LSP System power enables the creation of new net material wealth on Earth. Given 2 to 3 kWe/person of clean electric power, humanity's material needs can be acquired from common resources and recycled without the use of depletable fuels [2, 3]. LSP power increases the ability of tomorrow's generations to meet tomorrow's needs. LSP power enables humanity to move beyond simply attempting to sustain itself within the biosphere to nurturing the biosphere.

The essential features of the LSP System are the Sun, Moon, microwave power beams from a power base on the Moon, and microwave receiver rectennas on Earth. (Refer to the figures in the Criswell presentation on the accompanying CD). The LSP System uses bases on opposing limbs of the Moon. Each base transmits multiple microwave power beams directly to Earth rectennas when the rectennas can view the Moon. Each base is augmented by fields of photoconverters just across the limb of the Moon. Thus, one of the two bases in the pair can beam power toward Earth over the entire cycle of the lunar day and night. This version of LSP supplies extra energy to a rectenna on Earth while the rectenna can view the Moon. The extra energy is stored and then released when the Moon is not in view. Alternatively, satellites in orbit about Earth can redirect beams to rectennas that are not viewing the Moon.

Power beams are considered esoteric and a technology of the distant future, yet Earth-to-Moon power beams of near-commercial intensity are an operational reality. A picture of the South Pole of the Moon was taken by the Arecibo radar in Puerto Rico. The Arecibo beam passes through the *atmosphere* with an intensity the order of 20 - 25 W/m ^{2}. The LSP System is designed to provide power beams at Earth with intensities of less than 20% of noon-time sunlight (230 W/m ^{2}). Lower intensity beams are economically reasonable. The intensity of microwaves scattered from the beam will be orders of magnitude less than allowed for continuous exposure of the general population.

5.2 Demonstration Base for the Lunar Solar Power System

The lunar portion of an LSP System prototype Power Base is described. The Earth is fixed in the sky above the Power Base. A Power Base is a fully segmented, multi-beam, phased array radar powered by solar energy. This Power Base consists of tens to hundreds of thousands of independent power plots. Each power plot emits multiple sub-beams. Sets of correlated sub-beams from all the plots are phased electronically to produce one power beam. A given base can project tens to hundreds of independent power beams.

A power plot consists of four elements. There are arrays of solar converters, shown here as north-south aligned rows of photovoltaics. Solar electric power is collected by a buried network of wires and delivered to the microwave transmitters. Power plots can utilize many different types of solar converters and many different types of electric-to-microwave converters. In this example the microwave transmitters are buried under the mound of lunar soil at the Earthward end of the power plot. Each transmitter illuminates the microwave reflector located at the anti-Earthward end of its power plot. The reflectors overlap, when viewed from Earth, to form a filled lens that can direct very narrow and well defined power beams toward Earth.

To achieve low unit cost of energy, the lunar portions of the LSP System are made primarily of lunar-derived components. Factories, fixed and mobile, are transported from the Earth to the Moon. High output greatly reduces the impact of high transportation costs from the Earth to the Moon. On the Moon the factories produce 100s to 1,000s of times their own mass in LSP components. Construction and operation of the rectennas on Earth constitute greater than 90% of the engineering cost [2]. Up front cost can be significantly reduced by making the massive portions of machines of production and support facilities from lunar materials [4]. People in "virtual work places" on Earth can control most aspects of manufacturing and operations on the Moon.

LSP is practical with 1980s technology and a low overall efficiency of conversion of sunlight to Earth power of ~0.15 %. Higher system efficiencies over 35%, are possible by 2020. Greater production efficiencies sharply reduce the scale of production processes and up-front costs. An LSP System with 35% overall efficiency will occupy only 0.15% of the lunar surface and supply 20 TWe to Earth. Twenty terawatts of electric power is economically equivalent to 60 TWt or 5 times the capacity of all existing commercial power systems. There are no "magic" resources or technologies in Fig. 3. Any handful of lunar dust and rocks contains at least 20% silicon, 40% oxygen, and 10% metals (iron, aluminum, etc.). Lunar dust can be used directly as thermal, electrical, and radiation shields, converted into glass, fiberglass, and ceramics, and processed chemically into its elements. Solar cells, electric wiring, some micro-circuitry components, and the reflector screens can be made out of lunar materials. Soil handling and glass production are the primary industrial operations. Selected microcircuitry can be supplied from Earth. Unlike Earth, the Moon is the ideal environment for large-area solar converters. The solar flux to the lunar surface is predicable and dependable. There is no air or water to degrade large-area thin film devices.

An LSP demonstration Power Base, scaled to deliver the order of 0.01 to 0.1 TWe, can cost as little as 20 billion dollars over 10 years [2]. This assumes the establishment of a permanent base on the Moon, by one or more national governments, that is devoted to the industrial utilization of lunar resources for manufacturing and logistics. Such a base is the next logical step for the world space programs after the International Space Station. Planning should begin immediately.

The technical and economic viability of the Lunar Solar Power System can be demonstrated in a well defined sequence of terrestrial, cis-lunar, and lunar demonstrations that grow in fidelity and scale in response to clear measures of success at each stage of development. Development of the Lunar Solar Power System leverages the skills and capabilities of aerospace organizations, U.S. and international. It's development will also attract major terrestrial industries to the development of lunar resources. For example, machine tooling, glass, and chemical corporations can develop precursor lunar industries that will manufacture from lunar materials major portions of the machinery that builds and puts in place the Lunar Solar Power components on the Moon. In this manner terrestrial firms can decrease the cost of transport of machinery to the Moon and accelerate the growth of the Lunar Solar Power System [2, 4]. In addition, terrestrial companies will build and operate the rectennas on Earth that receiver the power from the Moon.

The Power Bases direct microwave power beams to rectennas on Earth. The intensity of each beam can be controlled to provide load following power. The beams pass through clouds, rain, and dust. There is no need for long-distance power transmission lines or indeterminately large systems to store power. Power beams are assumed to have an intensity of ~ 20% that of sunlight just above the rectenna (~ 230 W/m ^{2}). A few hundred meters from the edge of the rectenna the intensity will be 1% or less of the central intensity. Farther from the rectenna the stray power of a 20 TWe system will drop in intensity to that of the light from a full moon. LSP can be competitive with the conventional systems even if the beam is operated at intensities below those allowed for continuous exposure of the general population (10 W/m ^{2} at 1.5 GHz to 100 W/m ^{2} at 15 GHz). The energy received by the rectenna can be fully offset by reflecting back to space, from the area of the rectenna or elsewhere, an equal amount of low-quality solar energy. LSP energy can be environmentally neutral.

Rectennas are the major cost element of the LSP System. Rectennas will occupy as little as 5% of the land-area per unit of received energy as now devoted to the production and distribution of electricity. A rectenna can begin to output commercial power after it reaches ~0.5 km in diameter. Additional construction is paid for out of current revenue. A rectenna one-square-kilometer in area with an average output of 180 MWe produces every year the electric energy equivalent to burning 3.3 million barrels of oil or 650,000 tons of coal in a fossil-fueled electric plant.

Rectennas can be placed virtually anywhere on Earth. It is reasonable to situate them over open land that is not used. It also appears reasonable to place them over agricultural land and industrially zoned property and facilities. They would provide additional revenue the order of 40 \$/m ^{2}-Y for power sold at 0.03 \$/kWe-h. Rectennas can be placed in countries or regions that do not have indigenous energy resources. Rectennas enable non-polluting solar electric power to efficiently support recycling, use of common mineral resources, and petrochemical processing of hydrocarbons into more valuable process chemicals and products. Rectennas provide both developed and developing countries equal access to electric power for economic growth and the enhancement and preservation of the local environment.

5.3 Lunar Solar Power System and sustainable economic growth

The 70 year life-cycle cost of energy for a power-prosperous world is so enormous that it is difficult to understand its scale and significance. The power system of a prosperous 21st century must provide ~1,000 TWe-Y of energy by 2070. Assume that Gross World Product (GWP) per person is 4,000 \$/person-Y over that period. This sums to 2,400 trillion dollars if there are 10 billion people by 2050. Conventional coal, fission, and terrestrial photovoltaic systems scaled to deliver 1,000 TWe-Y of energy will cost 50% to ~200% of this total GWP over the 70 years. Our present "poor" world simply cannot afford to build and operate the needed coal, fission, and complete terrestrial renewable power systems. The renewable systems must include expensive energy storage, global power re-distribution, and the conventional power systems for back up. Today ~ 10% of GWP is expended on the production and consumption of commercial energy and the remediation of its effects. This corresponds to a total expenditure of ~240 trillion dollars between 2000 and 2070 to maintain the inadequate power systems of our energy-improvised world. The less costly Lunar Solar Power System will provide lower cost electricity. Abundant, clean, and lower cost electricity will accelerate the creation of new wealth.

It is widely recognized that the lack of affordable and environmentally benign commercial energy limits the wealth available to the majority of the human population [1, 5, 6, 7]. Between 1960 and 1986, the total electric energy Ee (Y) used every year, measured in T kWe-h, was an excellent index of the annual GWP in trillions of dollars (T$e(Y)) in a given year "Y." Equation 1 includes the annual increase in productivity of energy Eff(Y) of approximately 1%/Y. The cost of 1,000 TWe-Y of energy delivered between 2000 and 2070 is taken to be 200 T$.

$$T\$e(Y) = 4.3\ T\$ + [1.2\ T\$/TkWe\text{-}h] \times Ee(Y) \times Eff(Y) - 200T\$/(70\ Y) \qquad \text{Equation (1)}$$

Applying Equation (1) to the production of 1,000 TWe-Y of energy by 2070 predicts an integral net GWP ~ 14,700 T$ by 2070 or 12,300 T$ more than the 2,400 T$ predicted for a "poor" world. Equation 1 also implies an average annual income in 2070 of 36,000 $ per person. This is approximately 10 times present per capita world income. The dashed curve of Fig. 5.4 in the CD depicts the cumulative depletion of terrestrial fossil thermal energy by a prosperous human population in TWt-Y of thermal energy. There is ~ 4,000 to 6,000 TWt-Y of economically accessible fossil fuels. Thus, the "Fossil" energy use stops changing between 2050 and 2100 when the prosperous world consumes these fossil fuels. Conversely, the Lunar Solar Power System introduces "net new energy" to the world and enables net new economic growth with no depletion of terrestrial resources. Note that 1 TWe-Y ~ 3 TWt-Y in economic output. The Lunar Solar Power System enables this net new growth both on and off Earth.

5.4 Manufacture of solar photovoltaics directly on the lunar surface

Energy is fundamental to nearly everything that humans would like to do in space, whether it is science, commercial development or human exploration. If indigenous energy sources can be developed, a wide range of possibilities emerges for subsequent development. Some of these will lower the cost of future exploration; others will expand the range of activities that can be carried out; and some will reduce the risks of further exploration and development. This picture is particularly true for the Moon where significant electric power will be required for a number of lunar development scenarios including science stations; lunar resource processing; tourism; and Lunar Solar Power systems. Of direct interest is the Lunar Solar Power system scenario where there will be a requirement for the generation of TW of electric power beamed to the Earth. The development of a Lunar Solar Power system will rely critically on the availability of vast numbers of solar cells. The total area of solar cells required on the Moon to produce 1 TWe of average power output on Earth depends on the overall efficiency of the system. An early demonstration LSP System with a low over all efficiency of 1.3% and 5% efficient solar cells would require ~$1\text{x}10^{11}$ m^2 of cells per 1 TW. The specific area could be as low as ~ $3\text{x}10^{9}$ m^2 per TWe for an advanced LSP with 35% overall efficiency. The transport and installation of such immense numbers of cells will be a challenge that can be significantly mitigated by manufacturing the required solar cells on the surface of the Moon. What is required for a lunar electric power system is a fabrication facility which can be installed on the Moon and which will utilize the resources of the Moon to fabricate solar cells on location.

The Moon has the natural resources from which to fabricate the solar cells, and has an addition major benefit in the presence of ultra-high vacuum at its surface. The natural resources (lunar regolith) allow for the extraction of the basic materials needed for fabrication of solar cells: silicon, iron, magnesium, calcium, rutile, aluminum, etc. The vacuum environment allows for the vacuum deposition of thin film silicon solar cells directly on the surface of the Moon. It is therefore proposed that thin film silicon solar cells be directly manufactured on the surface of the Moon. This is done by the integration of both a regolith processing step that is robotically undertaken to extract the needed raw materials for solar cell growth and by a solar cell vacuum deposition process undertaken by an autonomous robotic rover that lays down continuous ribbons of silicon solar cells on the lunar regolith surface.

Regolith processing on the Moon to extract both oxygen and silicon can incorporate carbothermal reduction of an ore such as anorthite ($CaAl_2Si_2O_8$). Several processes have been proposed previously, however, for anorthite as an example, a closed cycle process is required on the Moon to reduce resupply of reagents from Earth. Methane can be used as the reducing agent in a modified process instituted to eliminate methane cracking. This results in a closed cyclic process yielding both oxygen and silicon:

$CaAl_2Si_2O_8$ ------> $CaO + Al_2O_3 + 2\ Si + 2\ O_2$

Iron and TiO2 can be obtained by hydrogen or carbothermal reduction of the mineral ilmenite (FeTiO3), which is abundant in the lunar maria, by one of the following reactions:

$FeTiO_3 + H_2$ ----------> $Fe + TiO_2 + H_2O$ or:
$FeTiO_3 + C$ ----------> $Fe + TiO_2 + CO$ or:
$3FeTiO_3 + CH_4$ ----------> $3Fe + 3TiO_2 + 2H_2O + CO$

With these limited number of regolith processing steps the basic elements required for solar cell fabrication can be generated on the Moon. Refer to Table 5.1 in the CD.

Thin film solar cell fabrication can be conducted on the lunar surface through the direct vacuum deposition of the necessary material layers. This vacuum fabrication is proposed as a sequential thin film process executed on the lunar surface. The first step melts lunar regolith to create a glass substrate. An electrical conducting layer for the bottom electrode is evaporated on the glass substrate. The subsequent elemental silicon evaporation is such that the silicon is deposited in both p-doped and n-doped layers. A top conducting grid is then applied to the silicon layers, followed by an antireflective top coating.

Preliminary studies in the development of silicon solar cells from silicon extracted from lunar regolith (simulated) have been undertaken, and show that such silicon can be used to fabricate thin film silicon solar cells through vacuum deposition. It is well to note that although the regolith-processed silicon was of moderate quality, i.e., not semiconductor grade, the vacuum processing for the thin film growth also pre-purified the silicon to yield moderate quality solar cells.

A movable "crawler," of ~200kg mass, would traverse the lunar surface depositing solar cells. As part of the traverse the crawler would clear larger rocks and boulders from the terrain directly in front of it, thus preparing a bed for the fabrication of the lunar glass substrate for the solar cells. The thermal energy required for each set of the evaporations in the above process would be obtained from direct solar energy collected by one set of up to six ~1 m2 line-focus solar collectors each outputting ~ 1,000 W. The first of the solar collectors on the crawler would locally melt the top ~0.4 cm of the regolith to form a lunar glass substrate directly on the lunar surface and develop a bottom contact layer. The second set of solar collectors would evaporate the silicon and the required dopants onto the lunar glass substrate. The next collector would deposit the metallic top electrodes and the cell interconnects through a contact mask, the final collector would apply the anti-reflection coating. Individual cells would be connected in alternating series/parallel fashion to form arrays. In this manner, the crawler could migrate over the lunar surface (maneuvering around large obstacles) and continuously lay down solar cells on an undulating landscape. The cells would be integrated into a power system with periodic array-grouping junctions.

Regolith processing to extract the needed elemental materials would be undertaken on a second robotic vehicle. The initial set of lunar solar cells could be fabricated from raw materials brought from the Earth. Approximately 40 kg of raw materials would be required for the fabrication of ~ 100kW of thin film solar cell electric power capacity. The robotic processing vehicle would be ~ 200kg mass, and would be added to the production site only after the first set solar arrays had been fabricated. The robotic materials processor would use power from the solar arrays to process up to 200 kg of materials, which would then be supplied to the solar cell crawler to fabricate more solar cells. These two vehicles would comprise the initial facility for the development of a demonstration Lunar Solar Power system.

The above concept for robotic lunar solar cell fabrication is preliminary and will be amplified and refined by additional data generated in the materials extraction experiments using lunar regolith simulant, and by additional silicon solar cell growth experiments under simulated lunar conditions. The collaboration with experts in the robotics field is also critical to success of such a program. The merging of robotics with materials chemical processing and vacuum thin film growth will assure a strong flight program and successful development of a lunar electric power system.

5.5 Lunar solar power system and manufacturing findings

1. Solar-electric commercial power provided to Earth from space or lunar-based facilities can benefit the economy of Earth. (Recommendations 1, 5)

2. Lunar manufacturing is possible. In some cases lunar manufacturing may be superior to manufacturing on Earth because the primary products are better suited to the lunar environment and resources. Essentially all materials and energy needed to produce solar power systems on the Moon and systems to beam the power to Earth are available on the Moon. (Recommendations 2, 3, 4, 5, 9)

3. Machines and components deployed from Earth can be used to make power components from lunar resources, producing much greater installed power than can be obtained from an equal mass of power equipment deployed from Earth. (Recommendations 2, 3, 4, 6, 7)

4. If lunar materials can also be used to fabricate part of the production equipment, even greater leverage can be obtained. The complete fabrication of production equipment from lunar materials can lead to a state of near self-replication, or bootstrapping, and very rapid growth of installed power transmission capacity on the Moon. (Recommendations 4, 5, 9)

5. The Lunar Solar Power System concepts presented by Dr. David R. Criswell and Dr. Robert D. Waldron are compelling but require independent validation. (Recommendations 1, 5, 8)

6. Building solar cells on the Moon, as described by Dr. A. Ignative, should be inherently less costly than on the Earth. On Earth the deposition/implantation processes must be operated within vacuum systems that are expensive to build, operate, and maintain. The terrestrial cells must be made to resist degradation by air, water, and other chemical and biological agents. Terrestrial cells must be mechanically rugged. In comparison, the cost of lunar solar arrays are reduced by producing the solar converters in the lunar vacuum. Sunlight can be used directly for evaporation of constituents. The solar converters and structural components are very much reduced in mass through such options as

depositing solar cells directly on the lunar surface. (Recommendations 2, 6, 7, 8)

7. Lunar production systems can be teleoperated/supervised from Earth. As materials extraction, fabrication, and assembly processes become more complex, the autonomous robotic systems should provide greater efficiencies. Both teleoperated and robotic systems require development for all phases of the lunar and space operations. (Recommendations 3, 7, 9)

8. A certain level of robotic cooperation is needed in production and operation of the Lunar Solar Power System. The required level of robotic intelligence that is needed has not been determined but developmental pathways can be seen. (Recommendations 3, 7, 9)

9. The expansion of productive capacity on the Moon, denoted as self-replication or bootstrapping, derives from human expertise and information supplied from Earth to the productive machines on the Moon. In this manner the lunar manufacturing can leverage the skills and resources of terrestrial industry and attract terrestrial manufacturing companies to the development of space/lunar power and other systems. (Recommendations 4, 5, 9)

5.6 Lunar solar power system and manufacturing research recommendations

The following recommendations include very rough estimates of the investments and time required for the research, development, demonstrations, and evaluations. Many of the tasks can be done in parallel. This minimizes the time required to establish a growing Lunar Solar Power System.

1. Independently verify the Lunar Solar Power System designs as proposed by Dr. David R. Criswell and Dr. Robert D. Waldron. (Findings 1, 5)

Evaluation	5 M$	1 year

2. Demonstrate on Earth the viability of making useful solar conversion systems from simulated lunar materials and test the systems. Demonstrate at least two different solar conversion systems that offer lower cost than terrestrial systems. Demonstrate key "unit processes" such as excavation and hauling, extraction of raw materials (Si, Fe, TiO_2, etc.), materials and logistics, solar array production, test and verification, and repair and removal. (Findings 2, 6)

Laboratory Demonstrations	10 M$,	2 years
Prototypes production	50 M$,	4 years

3. Demonstrate on Earth the production, primarily from simulated lunar materials, of the following functional elements of a power plots of the Lunar Solar Power System: systems to collect solar electric power; conversion of the solar electric power to microwaves (at least two approaches); phasing of the microwave sub-beams to form multiple independently controlled beams; and, forming large synthetic apertures by passive and/or active reflectors. Unit processes to be demonstrated include: production of glass and ceramic components; production of solar-to-electric components; fabrication of structures; production of microwave sources; production of microwave-reflective meshes; and, teleoperated and robotic production, assembly, and emplacement. Demonstrate the emplacement and operation of the forgoing components and system. (Findings 2, 3, 7, 8)

Laboratory Demonstrations	20 M$,	3 years
Prototypes production	100 M$,	5 years

4. Identify key unit processes, if any, that must be demonstrated under conditions of lunar-gravity and/or lunar-vacuum. Demonstrate these particular unit processes early on in orbit about Earth using unmanned satellites, the Shuttle, and/or International Space Station. Identify unit processes, if any, that must be demonstrated on lunar materials available from the Apollo collection or that must be done on the Moon. (Findings 2, 3, 4, 9)

On-orbit demonstrations	TBD	3 years
Apollo lunar samples	TBD	2 years
On the Moon	TBD	see recommendations #8 and #9.

5. Develop life-cycle models for the development and operation of the Lunar Solar Power System. Make the models available and refine the models. Consider all aspects of the life-cycle (ex. design, demonstrations, prototype implementation, economic and environmental effects and benefits, organizing, financing, governing, full-scale construction, maintenance, and removal). Examine worldwide science and technology activities for practices, devices, and systems applicable to Lunar Solar Power System demonstrations, operations, and implementation. (Findings 1, 4, 5, 9)

On-going program	3 M$/y	8 years

6. Test representative products, assemblies, components, and systems at the prototype and pre-production levels. There will be considerable phasing and overlap of research, development, and demonstration projects and programs. (Findings 2, 3, 6)

Prototype	100 M$	6 years
Pre-production	500 M$	6 years

7. Conduct three to four competitive demonstrations of full scale production units within sealed environments on Earth (vacuum and inert atmospheres). For example, deploy complete sets of mobile production/assembly units via a C-130 size cargo aircraft to remote desert sites. From a remote control site direct the production/assembly units to enter large pressure-supported plastic domes. Each dome is transparent, filled with an inert atmosphere, and the floor is covered with simulated lunar soils and rocks. Use solar power that enters the dome during the day to power the production/assembly units. These units manufacture the major components and assemble and maintain representative "power plots" of Lunar Solar Power System. The power plots constructed in the domes are phased together to direct beams to local receivers, receivers in space, and receivers (signal-level) on the Moon. (Findings 2, 3, 6, 7, 8)

Demonstration	2 B$	4 years

8. Land three to five "Surveyor-class" unmanned spacecraft on the Moon. The landers carry microwave transmitters that are operated together to direct signal-level beams to research receivers on Earth. The landers demonstrate the Moon as a stable platform for the transmission of narrow beams to Earth and to receivers in orbit about Earth. The landers also support a wide range of tests of solar cells and other components for the Lunar Solar Power System. (2, 5, 6)

Landers	1 B$	5 years

9. Seek innovative methods of reducing the mass of production equipment and supplies/consumables

that must be transported from the Earth to the Moon to build the Lunar Solar Power System and support logistics between the Moon and Earth. Evaluate production systems (e.g. power, chemical reactors, mobility systems including excavation and hauling) designed for being constructed on the Moon primarily from lunar materials. Aggressively explore and demonstrate the feasibility of "starting kits" and boot-strapping of production equipment from lunar materials. (Findings 4, 8, 9)

Design and demo explorations	50 M$/y	5 years
Demonstration (Earth and Moon)	500 M$/y	7 years

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CHAPTER 6.

SELF-REPLICATING AUTOMATA FOR SPACE SOLAR POWER

(Summary by George Friedman)

6.1 Self-Replication in the context of the SSP mission

In order to evaluate the contribution of any new technology, it is imperative to define the mission it is intended to serve and the potential advantages it provides toward that mission. As is thoroughly described earlier, the mission is to supply a significant portion of humanity's power needs from space to the earth's surface in a time frame of decades, not centuries.

The cost of building such a macrostructure as the SSP is a crucial issue in the fundamental viability of the concept. The two most challenging cost drivers are the transportation costs of lifting mass from the earth to orbit -- presently thousands of dollars per pound -- and the costs of constructing macrosystems in space by thousands of astronauts -- presently at millions of dollars per man hour. The primary thrust of the workshop was to investigate the potential of advanced robotics to reduce substantially the *construction* costs. An important ancillary thrust was to investigate the feasibility of employing extra terrestrial materials to reduce the *transportation* costs. Self-replicating automata, the subject of this chapter, was investigated, not only to further reduce construction and transportation costs, but to multiply the rate of all space development so that the goal of schedules in terms of decades rather than centuries could be attained effectively.

6.2 Historical overview of mission-oriented self-replicating automata research

The intellectual origins of self-replicating automata are generally agreed to lie with John von Neumann[1], one of the twentieth century's most creative and prolific geniuses. His works on theoretical physics, the atomic bomb, theory of games, decision theory, digital computer architecture and the general theory of automata are legendary. During the last years before his tragic death in 1957, his time was largely occupied by self-replication -- his "unfinished symphony," so to speak.

von Neumann's architecture for the general purpose digital computer is perhaps his most pervasive contribution to humanity. He was impatient with the very labor intensive development of programs external to the early digital computers and suggested that the program be stored internal to the computer memory and -- most significantly -- permit the computer's control and arithmetic unit to perform operations on the program as they would on ordinary data. According to my first professor of computer science[2], this self-referential stratagem horrified the early computer scientists who feared chaos by permitting the sacrosanct programs to be autonomously manipulated. Yet despite these fears, hundreds of millions of internally stored program digital computers have been built, literally transforming science, engineering, communication, business and commerce worldwide.

von Neumann's concept for a self-replicating automaton was also somewhat self-referential and remarkably similar to his computer architecture concepts. The "parent" automaton contains a tape with all the information necessary to replicate itself. This "genotype" tape controls a "universal constructor" (UC) -- also within the parent -- which not only *translates* the tape in order to build an identical offspring -- the "phenotype,"-- but also *copies* the tape so that the offspring can itself replicate additional generations. Remarkably, this work was accomplished prior to the Watson and Crick DNA research in which the same transcription/replication dual use of DNA was shown to be the universal biological reproduction architecture as well.

Thus, von Neumann's work destroyed at least two "false dichotomies": (a) Data and programs, previously kept carefully apart, were now seen to be different forms of information and amenable to formal mathematical manipulation, and (b) Constructors and products of these constructors, previously thought fundamentally different in function and forming only transitive relations, were both now seen to be interacting elements -- both transitive and intransitive -- in a complex network of constructors and products which in turn can produce parts or all of their constructor parents.

von Neumann called the real-world physical embodiment of his self-replication machine the "kinematic model." The level of detail required to perform a rigorous analysis proved to be difficult for his early work, so he developed instead an abstract mathematical universe for his hypothetical machines and their environments. These constructions were called "cellular automata (CA)" and generally consisted of a two dimensional array of discrete state machines which interacted with their neighbors following simple, rigorous rules. Time and space in the CA models are discrete and the CA lives entirely within the virtual universe of computer memories. Although the CA work aided the understanding of the logic of self-replication, it is clear that it is von Neumann's kinematic model, not the CA models which are required to support the SSP mission.

Moshe Sipper[3] summarized the 50-year history of self-replication from von Neumann's original concepts to the present. It is clear from this summary, as well as from extensive contacts with researchers in the field of self-replication, that the CA approach has received orders of magnitude more attention than the kinematic model. In the CA world, full self-replication has indeed been achieved, with Chris Langton's "Q-loops" being a notable early example[4]. On the other hand, there has been neither success nor research approaching success regarding the kinematic model necessary for the real-world application to space.

It is truly a scientific and engineering mystery why, for two concepts so conceptually similar as von Neumann's computer and self-replicating architectures, the former has been implemented hundreds of millions of times and the latter has had absolutely zero implementations! To state that the computers work in an abstract "toy" world and kinematic models must work in the real physical world is only scratching the surface.

In Sipper's overview, he categorizes the kinematic model research under "other" and notes papers in Scientific American in the 1950's by Kemeny[5], Moore[6], and Penrose[7]. Although treating the physical world and quite intellectually stimulating, these works did not advance von Neumann's concepts. Two more references are worthy of note here:

Ralph Merkle[8], made two valuable suggestions in support of realizable kinematic models. First, he suggested that the instruction tape -- or genotype -- be externalized from the body -- or phenotype -- of the replicating machine. This concept is closely analogous to relieving an autonomous robot of its self autonomy and permitting the far greater cognitive capability of a human to take control via teleoperation. Secondly, he suggested that the function of the universal constructor -- undoubtedly the most difficult subsystem of the kinematic model -- be accomplished by an assembler based on molecular nanotechnology (MNT). This approach, at least theoretically, promises construction of any design to atomic precision wherein the cost, size and complexity of the constructor is more practical than with macroconstructors for certain difficult components such as microelectronics, ball bearings or micromechanical assemblies. The crucial issue here is: “can the MNT technology be matured rapidly enough to support the required SSP schedules?” MNT is still quite young but growing rapidly, with increasing research budgets. Self-replication is only one -- and not the highest -- priority within the MNT world.

By far the most significant and relevant work in applying self-replication to the SSP mission is the NASA/ASEE 1980 Summer Study[9]. Chapter Five of this extremely thorough report (CP2255) was devoted to self-replicating concepts and was written by the team of Richard Laing (leader), Rodger Cliff, Robert Freitas, Jr, and Georg von Tiesenhausen. The scenario for this in-depth study is precisely relevant to the main thrust of this workshop. The team conceived of a 100-ton “seed” which is transported to the lunar surface and not only erected a factory which manufactured solar cells and other SSP-relevant structures, but also replicated itself so that the output of the family of factories would -- in the limit -- be exponentially expanding. Thus, if this complete self-replication is achievable -- implying a “material closure” of 100% -- then the team argued in an enthusiastic display of imagination, the original seed could expand to cover the entire surface of the moon, and eventually this technology could provide the basis for human interplanetary and interstellar colonization. Even with incomplete self-replication, the authors discussed closures of less than 100% and showed how these concepts could provide leverage to all space operations by reducing the need to lift mass from earth into orbit by orders of magnitude -- and on a time scale which would not require centuries.

The report, published over a year later, was thoroughly written, fully referenced and documented, with a detailed list of research recommendations and program plans. Unfortunately -- perhaps due to a change of administration according to the then NASA administrator Robert Frosch[10] -- the funding for the research plan was zero. The same can be said of the research recommendations by the Chapter Four team, led by David Criswell, that examined more traditional technologies for space manufacturing.

Despite this very disappointing history of self-replicating research, there have been several expressions of concern that once machines have the capability to self-replicate, they will evolve into a super race that will doom mankind’s future[11]. Only a few weeks before this workshop, the New York Times[12] published a prominent article quoting the chief scientist at Sun Microsystems who warned that the human species may be on the verge of collective suicide, due in part to the emergence of machine self-replication.

This presentation of self-replicating system history -- delivered by George Friedman -- was augmented by excellent brief talks by Barry McMullin on von Neumann’s theories of self-replication, complexity and evolution, by Chris Langton on CA self-replication and evolution of virtual robots, and Pierre Marchal on bio-inspiration and evolving programmable gate arrays.

6.3 Litany of greedy illusions which hampered progress

The deep mystery persists: what can explain the gigantic gulf which exists between the implementation of von Neumann’s computer and self-replication architectures? One reason, already mentioned, is that the UC must perform in the more unforgiving real world compared to the abstract world of the computer’s arithmetic unit. However, there may be many other reasons, having to do more with goal setting and perceptions of the research community, rather than with “reality.” Most of these perceptions strive for “perfect” self-replication, despite the fact that our mission does not require perfection. Thus, they are called, “greedy illusions,” and include:

The illusion of exponential growth. As in the famous Harris cartoon, if the "miracle" of perfect self-replication occurs, humanity can colonize the galaxy at a trivial cost. However, exponential growth is attainable only with 100% closure (C). Otherwise, we can achieve a production amplification (A), where A = 1/(1-C), which is quite valuable for reasonably attainable closures of 90% or more. This would reduce transportation cost by a very attractive order of magnitude or more. If we stubbornly insist on 100% closure, then we face great divergent challenges and enormous "investment costs" in replicating, for example, microelectronic assemblies with ratios of producer/product mass of 10^5 or more.

The illusion of complete autotrophy. Drawing optimistic analogies from the biological world, many researchers strive to plant a "tiny seed" and have it devour a billion-ton asteroid in less than a year. Most organisms we deem interesting are not autotrophic (they can't "eat dirt") and depend on an enormously complex chain of simpler organisms for processing their food. (If an approximate measure of the difficulty of an organism's function is the length of its genome, then it surprises many that the difficulty of a plant's function of manufacturing food from less organized matter is more difficult than the function of a animal's catching prey or of a human doing higher math!) Even von Neumann's kinematic model replicated by picking out subsystems from a "sea of parts" rather than from unprocessed raw materials. We must first concentrate on what the self-replicating machine *does* -- its "metabolism" -- then we can examine self-replication. Otherwise, we will be just replicating a machine whose only function is replication; like a virus. Certainly, this would not be useful for the SSP mission.

The illusion of the truly universal constructor (UC). von Neumann examined the UC in the context of Turing's universal computer and was interested in a constructor with the capability of building *any* design that the instruction tape (genotype) could specify. This is absolutely *not* required for the SSP mission! We need construct only that which we need, which is only an infinitesimal fraction of all possible designs. Even the biological world, with all its diversity, employs just an infinitesimal fraction of the designs available in "'protein space." Eventually, MNT may show us avenues to build more flexible UCs, but our priority should be only on that which is well understood, buildable and useful for SSP.

The illusion of full, internal, "autonomous" self-replication. A slavish following of "bio-inspiration" would dictate incorporating the genotype within the body of the phenotype -- the way we observe it in nature. But why not employ the same conceptual stratagem we do with robots which cannot yet exhibit human levels of cognition: merely broadcast (usually remotely) instructions from teams of humans with their full cognitive abilities? Thus, rather than settling for "democratic" self-replication of any species which just happens to survive and reproduce its own kind, we can give the operating team of humans the "godlike" power to order up *any* new species at the time and place it is needed for the job at hand. Moreover, analogous to recycling biomass, the remote human operators can even reconfigure operationally existing species to new, unprecedented species as the need may arise. Not only will this separation provide more flexibility that the biological scheme, but it avoids the troublesome (to many) issues of self- referential logic and it substantially postpones the dreaded perception about runaway machines taking over the human race.

The illusion of contiguity. There is an implicit assumption in much of the literature that the self-replicating machines must consist of a single complex assembly (that's almost what we see in nature if we ignore the complementary activity of the sexes.) In the engineering world, it appears abundantly more practical to envision a large, distributed set of cooperating elements, such as a modern industrial factory. Then it becomes interesting and practical to ask questions such as: "what is the simplest factory that can manufacture a useful product and also manufacture a complete replication of itself (with and without human intervention)?" Or: "What is the simplest factory which can self-replicate *autotrophically* (with and without human intervention)?" For the cases permitting human intervention at least we have an existence proof:

The set of all factories in the United States can produce useful products *and* they -- as a system -- clearly have the ability to produce more of their own kind (or where else did they come from?).
So far, there is no existence proof of the case without human intervention -- except biological analogy. And when we want to rely on bio-analogy, we had better know far more than we presently do about the detailed mechanisms of even how a single cell replicates.

The illusion that artificial intelligence is sufficiently deep for autonomous self-replication. This issue overlaps the decades-old, overly optimistic illusion that AI can really represent non-trivial human cognitive capability. We should not forget the early predictions of how simple it would be for the computer to be world chess champion or perform automatic language translation -- both were predicted for the 1960's and were just barely accomplished in a most fragile manner in the 1990's, requiring over a million-fold more computational power than first thought necessary. There still persist major gaps in our understanding how much of human activity can be delegated to robots and, similarly, to what extent can the robotic building of the next generation of robots be automated. Thus, the issue of "sliding autonomy" is as relevant to self-replication research as it is to ongoing research in advanced robotics.

The illusion that self-replication research is an intellectual island. There are conjectures that self-replication theory is fundamentally different and separate from the more mainstream robotics research, and that is a reason for its lack of support and disappointing progress. However, as was frequently mentioned in the paragraphs above, self-replication has many issues and themes in common with advanced robotic concepts and it would be constructive for future research to consider self-replication -- as well as evolution -- as a natural intellectual extension of the robotics field. For example, the research agenda at the Space Studies Institute at Princeton considers a continuous spectrum of activities from direct man-in-the-loop, fully teleoperated robotics, increasingly autonomous robotics with AI, fully autonomous robots, cooperating hierarchies of robots, diagnosing and repairing robots, replacement and reconfiguring robots, and finally, self-replicating and evolving robots.

Bottom line conclusion from this litany of greedy illusions which hampered progress:
We should focus on the rich domain of the possible, rather than yearn for presently impossible fantasies. Humanity really needs SSP soon and it is attainable. Colonization of the galaxy can come later.

6.4 Findings (of the discussion group)

In contrast to the lack of real progress in lowering transportation costs to orbit, microelectronic technology has advanced by over a factor of 10^{10} since von Neumann's day.
This in turn has enabled enormously increased opportunities in computer science, detailed simulation, communications, robotics -- and extending into self-replication. These extended applications are realizable in the near future in support of the SSP mission.

Self-replication research has been hampered by several illusions which strived for idealistic rather than practical goals. Directing self-replication research on practical goals in support of the SSP mission should achieve at least partial success and very substantial effectiveness leverage.

Realistic and detailed simulation tools could provide a practical aid to the design and analysis of innovative self-replication concepts.

Evolutionary behavior and design tools such as genetic algorithms could provide valuable insight into future designs and their optimization.

Bio-inspiration provides valuable insight to many innovative concepts, but we should not limit ourselves only to examples found in the biological world. For example, we can base designs on "Lamarkian evolution" and reconfigurability, neither of which is available in biology.

The lunar surface could provide a practical operations base for SSP, whether solar power satellites are used or not. In order to take advantage of extra-terrestrial resources, we can use the lunar surface, near earth-orbit asteroids (NEAs) or space debris.

The truly universal constructor, with a closure of 100%, would be nice, but not necessary for the first several generations of SSP.

Humanity can control the "Frankenstein threat" of evolving robots taking over humanity.

A reason that the kinematic model has shown such little success compared with von Neumann's computer architecture and cellular automata is that is must work in the unforgiving reality of the physical world, rather than in the mathematical abstraction of the virtual (toy) world. However, it is not so hard that real progress cannot be made.

There exist significant research areas to pursue in support of self-replication applied to the SSP mission at an economical pace.

6.5 Research recommendations with funding estimates (by the discussion group)

1. Define system-level measures of effectiveness and models which couple the effect of alternative technologies and designs to investment costs and total system effectiveness; ~$0.2M
(see page 27 of the view graphs for a simple example of possible trade studies on this model.)

2. Develop a simulation capability with sufficient detail to determine manufacturing flow networks which are both transitive and intransitive and permit the determination of such parameters as closure, investment costs, production amplification and the degree of autonomy from human involvement. ~$0.5M. (these simulations do not require the level of detail that is normally needed for the evaluation of robotic designs in a dynamic environment.)

3. Employing the simulation capability in item 2, examine a robotic hierarchical society which involves the natural extrapolations of : self and mutual diagnostics, self and mutual repair, parts replacement from spares provisioning, parts replacement from scavenged parts of failed robots, and the construction of entirely new robots -- including the reconfiguration of healthy robots -- to serve emerging needs. The sea of parts available in the construction vicinity -- although a long "bill of materials"-- should enable a far longer list of possible robot species. Since this concept is not autotrophic it will not be completely self- replicating, but it should substantially increase the total system reliability and flexibility. ~$1M.

4. Employing the simulation capability in item 2, define the entire process from the mining of available raw material to the finished useful product, including the robotic society. Assuming that the "genome" of the robots will be under full human control, examine alternative approaches to accomplish replication closure: how are the robotic subsystems manufactured and how are *their* parent machines manufactured,..etc. Determine producer/product cost and mass ratios and alternative investment costs for each level of closure. Estimate the optimum level of self-replication investment to maximize mission levels of effectiveness. ~$2M

5. Repeat item 4, except that varying degrees of autonomy -- or internalization -- of the robotic genomes shall be considered. ~$3M.

6. Migrate the understanding of self-replication attained by the past few decades of research on cellular automata to the understanding of the kinematic model. ~$0.2M

7. Continue to mine von Neumann's intellectual heritage through scholarly reviews of his work on the general theory of automata, complexity, reliability of large systems with unreliable components, and evolution. ~$0.1M

8. Examine additional biological and "super-biological" analogies which may benefit the SSP mission, including: epigenesis (growth and development), immune systems, learning, Lamarkian evolution (passing on acquired characteristics to progeny), language acquisition and reconfigurability. ~$0.2M

9. Encourage the molecular nanotechnology community to accelerate their research into universal constructors useful to the SSP mission. ~$1M

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APPENDIX 1
List of Participants

Research Issues in Space Macrosystems: Autonomous Construction and Manufacturing for Space Electrical Power Systems

Courtyard Marriott Crystal City, Arlington, VA 22202, April 5-7, 2000

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APPENDIX 2
Workshop program

Research Issues in Space Macrosystems: Autonomous Construction and Manufacturing for Space Electrical Power Systems

Courtyard Marriott Crystal City
Arlington, VA

5.

April 5-7, 2000

3.

FINAL WORKSHOP AGENDA

Tuesday, April 4, 2000

8:00- 9:30 PM	No host wine and cheese get-acquainted reception

Wednesday, April 5, 2000

7:45- 8:00 AM	Registration
8:00- 8:15 AM	Welcome, introductions, program goals and objectives George Bekey and Ivan Bekey
8:15- 8:45 AM	Charge to the Workshop Paul Werbos, National Science Foundation
8:45- 9:30 AM	Space Solar Power- History, promise and status John Mankins, NASA Headquarters
9:30-10:15 AM	Vision for the future of smart autonomous systems in space "Red" Whittaker, Robotics Eng. Center, Carnegie Mellon University
10:15-11:00 AM	Solar Power Satellites: Technology Challenges Ivan Bekey, Bekey Designs
11:00-12:30 PM	Group Meeting 1: Groups will concentrate on priorities and basic issues in the "Challenges"
12:30- 1:45 PM	Lunch
1:45- 2:15 PM	Plenary session: reports from the breakout groups
2:15- 3:00 PM	Cooperative work by multiple autonomous systems: the state of the art George Bekey, University of Southern California
3:00- 3:45 PM	Distributed intelligent learning systems: Learning, design and control Pradeep Khosla, Carnegie Mellon University
3:45- 5:15 PM	Group meeting 2: Identify research issues in the use of multiple intelligent systems for space assembly tasks

6:30 PM	Dinner presentation: “Thinking About Big Space”, T. F. Rogers, Chief Scientist Space Transportation Association, Chairman, Sophron Foundation

Thursday, April 6

8:00- 9:00 AM	Plenary session: Reports from the breakout groups
9:00- 9:45 AM	Autonomous assembly of space structures: Issues and problems Neville Marzwell, Jet Propulsion Laboratory (Not presented due to illness)
9:45-11:30 AM	Group meetings 3: Research issues in space structure assembly
11:30-12:30 PM	Reports from the breakout groups
12:30- 1:45 PM	Lunch
1:45- 2:30 PM	Lunar processing and manufacturing - General issues David Criswell, Unversity of Houston
2:30- 3:15 PM	Solar cell development on the surface of the moon Alex Ignatiev, University of Houston
3:15- 5:00 PM	Group meetings 4: Research issues in lunar manufacturing
6:30 PM	Dinner presentation: “The Planet Moon Project”, David Schrunk Co-author, “THE MOON: Resources, Future Development and Colonization”

Friday, April 7

8:00- 9:00 AM	Plenary session: Reports from the breakout groups
9:00- 9:45 AM	Toward self-replicating machines; bionic systems (self healing, evolution) George Friedman, Space Studies Institute and University of Southern California
9:45-11:15 PM	Group meetings 5: Research issues in self replication
11:15-12:15 PM	Final plenary session: reports from breakout groups
12:15-12:30 PM	Closing remarks George Bekey and Ivan Bekey
12:30- 1:30 PM	Lunch
1:30- 5:30 PM	Organizers and group leaders meet to prepare report

APPENDIX 3

“Solar Power from Space: Beaming Electricity from Space-Based Power Systems Could Brighten the Environmental Outlook”

(Highlights from an article in the Spring 2000 Issue of EPRI Journal, p. 6 – 17)

Palo Alto, Calif., -- April 20, 2000 New, breakthrough energy concepts must be implemented in order to provide sustainable energy for the 10 billion global population expected by the year 2050, according to the Electric Power Research Institute's "Roadmap," a pathway to the future for electric power. Collecting solar energy in space may be one way to fit the bill.

According to an article in the Spring 2000 issue of the EPRI Journal, sun-facing photovoltaic arrays in stationary Earth orbit at an altitude of 22,300 miles would receive eight times as much sunlight as they would at the earth's surface, on average. Space arrays would also be unaffected by the Earth's day-night cycle, cloud cover and atmospheric dust. Transmitters connected to large space-based solar photovoltaic arrays could then beam as much as several billion watts of power to Earth at microwave radio frequencies for collection by a wide area rectifying ground antenna and conversion to electricity.

The idea of beaming solar power from space was first proposed more than 30 years ago, but now the perceived need for such a source is greater and the outlook for eventual economic feasibility within the next several decades is more favorable. Additional government funding for a space solar power (SSP) exploratory research and technology program was authorized for fiscal year 1999 and is continuing in the current fiscal year.

John Mankins, NASA's manager for advanced concept studies notes that key developments in recent years in such areas as information technologies, robotics, power generation, and electronics all promise to reduce the costs of SPS. The physics and fundamental technology for such a scheme are well known and largely in hand, although substantial development would be necessary to actually build a space power system.

Says Kurt Yeager, EPRI's president and CEO, "Solving the 'trilemma' of population growth, resource consumption, and environmental cost, and providing a sustainable global supply of electricity will require some 'outside the box' thinking. To look beyond the planet for a solution is indeed thinking outside the box."

Other scientists have envisioned that building solar collectors on the moon will ultimately provide an elegant solution to launching the heavy mass of satellite components into orbit. It would also solve the problem of debris from satellites that could threaten both commercial satellites and space flights from earth. The lunar soil could supply silicon to build solar arrays and metals such as iron and aluminum for support structures and electric wiring. The components and production processes could be fully developed and tested on earth before a return to the moon.

David Criswell, director of the Institute for Space Systems Operations at the University of Houston, says, "The moon's environment is extremely dry and there is absolutely no weather. All the things that make solar energy difficult on earth are absent on the moon."

According to Criswell, lunar solar power could supply a 2050 world population of 10 billion people with enough energy to meet all basic human needs at low cost, and with few, if any, environmental downsides of the other energy alternatives.

Most ardent believers in the potential for space-based solar power stop short of suggesting that an urgent, capital-intensive development effort should be an objective for the near term. Many technical, economic, environmental, legal, and regulatory issues will need to be resolved internationally before a consensus to pursue such development could be achieved. Supporters of space solar power say that the significant progress achieved thus far in demonstrating the technology and feasibility of wireless power transmission from space makes the case for pursuing the program.

EPRI's Kurt Yeager says, "While much research and technical effort is centered on the shorter term, the lower risk, and the incremental advance, it is heartening to realize that the energy, enthusiasm, and intellect of some dedicated technologists are directed toward the pursuit of a revolutionary, as opposed to an evolutionary solution. Whether solar power satellites and lunar solar power bases will eventually come to pass remains to be seen. But much can be learned in an attempt to answer the important questions that accompany such a vast undertaking."

The Electrical Power Research Institute, EPRI, headquartered in Palo Alto, California, was established in 1973 as a center for public interest energy and environmental research. EPRI's collaborative science and technology development program now spans nearly every area of power generation, delivery and use. More than 1000 energy organizations and public institutions in 40 countries draw on EPRI's global network of technical and business expertise.

Note: This article was excerpted from a feature article and published in the Spring2000 issue of the EPRI Journal. For a reprint of the article or for photos, please contact Jackie Turner at 650-855-2272 or jturner@epri.com.

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800.313.3774 or 650.855.2000

APPENDIX 4

PRESENTATIONS AT THE WORKSHOP

(The full presentation materials are included in the CD ROM)

4-0: Paul Werbos, The National Science Foundation
“The Charge to the Workshop”

4-1: John Mankins, NASA Headquarters
“Space Solar Power: History, Promise and Status”

4-2: William “Red” Whittaker, Carnegie-Mellon University
“Robotics for Space Macrofacilities”

4-3: Ivan Bekey, Bekey Designs, Inc.
“Technology Challenges for Space Solar Power Delivery Systems”

4-4: Pradeep Khosla, Carnegie-Mellon University
“Distributed Intelligent Learning Systems”

4-5: George Bekey, University of Southern California
“Cooperative Work by Multiple Robots”

4-6: Neville Marzwell, NASA/ Jet Propulsion Laboratories
“Technology Challenges for Space Solar Power”

4-7: David Criswell, University of Houston,
“Lunar Solar Power Systems”

4-8: Alex Ingatiev et al:
“Production of Solar Cells on the Surface of the Moon from Lunar Regolith”

4-9: George Friedman, Univ. of Southern California & Space Studies Institute
“Self-Replication Technology for the Space Solar Power Mission”

END