SUMMARY OF THE CONFERENCE

I. ASTEROIDS AND NONTERRESTRIAL MATERIALS

Chair: John S. Lewis
Summary: John S. Lewis

The thrust of this first session will be true to its title: "Asteroids and Non-terrestrial Materials," a category that has evolved over a number of years. In part, the reason for calling out asteroids is that logistical studies have suggested that if you want materials at a wide variety of locations in the inner solar system, asteroids are a good place to start. First of all, they're extremely accessible from Earth: many Earth-crossing asteroids are much easier to get to than the Moon. Also, lifting material off of them is very easy because the gravitational pull is so small. Thus exporting material from those asteroids is also very easy.

Nonetheless, there are important and interesting in-situ uses of materials on other bodies of the solar system. The classical examples would be the use of lunar surface material to support operations on the moon — not for export. Another would be the production of rocket propellant out of the atmosphere of Mars — not for export but for local use. That's one of those rare resource use opportunities in which filing an environmental impact statement would be a sheer joy: to extract carbon dioxide from the atmosphere, take it apart into carbon monoxide and oxygen, and bum it as rocket fuel to get out of the atmosphere, producing an exhaust of pure carbon dioxide.

The first talk of the session was given by Robert Waldron, who is a familiar face at these conferences. Bob has been back year after year, presenting us with stories of increasing complexity about the utilization of non-terrestrial materials. His more recent contributions include looking at how to build large arrays of solar cells on the Moon out of local lunar materials.

Bob talked to us on Thursday, on the subject of "A Survey of Resource Utilization Processes for Mars and its Moons."

The circumstances that you find on Mars and on its moons are rather different. Mars, of course, has a permanent atmosphere of carbon dioxide, nitrogen, argon, and trace gases. Also the surface, with the well-documented water content of clay minerals, permanent water ice caps, and seasonal carbon dioxide ice caps, has a number of interesting volatile resources that are quite accessible.

Phobos and Deimos, the moons of Mars, are extremely dark in color. They're similar to carbonaceous meteorites, which are rich in chemically bound water and organic material. Carbonaceous meteorites contain up to 6% by weight of organic polymers. That material is extremely attractive from a resource point of view, however, spectroscopic studies of the satellites of Mars, Phobos and Deimos, shows no sign of water, the water that ought to be there if that meteorite analogy was correct. This seems to be due to collisional erosion of material from the surfaces of Phobos and Deimos. Imagine the gravity well of Mars, with Mars down at the bottom of it and Phobos and Deimos orbiting outside it. Material ejected by impacts from the surfaces of Phobos and Deimos goes into orbit around Mars and is constrained to a very small volume of space from which it is rather easily accreted by Phobos and Deimos onto the surfaces. But the logical expectation is that the material covering the surfaces of Phobos and Deimos has been shock treated so many times that its water content has been lost, but that says nothing at all about what the raw material of the interiors of Phobos and Deimos may be like. The best spectroscopic analog is the carbonaceous meteorites, which contain up to 20% chemically bound water.

This is the context under which Waldron operates. Bob summarized the history of space resource utilization and research for these bodies, even touching on the Moon and other locations. Then he addressed the specific problems that arise trying to process known materials in the Mars system. He reviewed ideas connected with utilizing the atmosphere of Mars to make propellants. The simplest version is simply carbon dioxide cracking to make carbon monoxide and oxygen and burning that as a propellant combination. At a slightly higher level of sophistication, complexity and expense, and probably at a later time, one would also utilize Martian water in order to get hydrogen into the chemistry. Through electrolysis or other chemical rearrangement of water the hydrogen atoms from it can be used to make storable propellants.

The next step in complexity is to add nitrogen to the chemistry. Nitrogen gives some very interesting capabilities that Waldron summarized in his talk. Basically nitrogen can be used to make storable propellants on the surface of Mars. Materials that are liquid under ambient Martian conditions or under conditions not too different than typical conditions on Mars such as, for propellant, hydrazine N2Hu, and for the oxidizer, nitrogen tetroxide or nitric acid. Although nitrogen only makes up about 2 1/2 % of the atmosphere of Mars, these materials are desirable; so easy to handle on Mars, once you make them, that investing some extra effort and some extra energy and complexity in manufacturing them in the first place probably would be justified. Because of the greater complexity of nitrogen use, you wouldn't want to do that first. In order to make hydrazine you need to master not just carbon chemistry, but also hydrogen chemistry and nitrogen chemistry. So you don't start doing all these things, but they do seem to be attainable goals in the not too distant future -- and they confer some obvious advantages.

The purpose of using Martian resources is so the cost of missions to Mars can be brought down dramatically. For example a sample return mission, or a manned mission to Mars, would not have to bring along the propellants necessary for the return trip to Earth. They could land on Mars with a one-ton chemical processing plant and a big empty fuel tank and manufacture the propellant for the return voyage there. The whole idea is to cut our reliance on Earth and to maximize our reliance on non-terrestrial materials - to make us at home elsewhere.

Audience question (Gary Fisher): Do carbonaceous asteroids have any nitrogen in them?

Yes, they do. There's roughly one nitrogen atom for every 7 to 15 carbon atoms, depending on which type of carbonaceous meteorite you're looking at. There are also some classes of meteorites that have nitride minerals in them, such as silicon oxynitride, titanium nitride, and chromium nitride. They simply don't exist on Earth. The most oxidized carbonaceous meteorites have nitrogen, and the most chemically reduced ones have nitrides.

Audience question (Hank Smith): Do we know enough about the asteroids or meteorites to know if there may be any elements that are undiscovered?

No, the way the elements are named are based on the number of protons in them. For example, if there's one proton in the nucleus it's hydrogen, if there's two it's helium and so on. In other words, the only way one could discover a new element would be by going beyond the end of the list of the elements we know already. Otherwise, it would be like discovering a new integer between one and two. The heavy elements are fairly well understood theoretically: they are all highly radioactive and have very short half-lives, so you don't expect to find them in meteorites except perhaps one atom at a time. They just wouldn't last very long. So, no, we don't expect to find new elements. However, what we do find in meteoric material is the material of the entire Earth homogenized. We, on Earth, live on a differentiated planet.

Earth has melted inside, and the materials have separated according to density. The most dense materials, the metals, mostly settle in the core. Many elements that we think of as rare on Earth and we call precious metals, are, in fact, not nearly that rare in the universe, it's just that in Earth they've ended up in the core.

Audience question (Hank Smith): Could you name some of those? Would that be like iron? Would that be like silicon?

Well, it would be iron, yes. Iron is one of them. It happens that iron is also found in ore bodies in the crust, but also a number of the precious and strategic metals are very severely extracted into the core and not well represented in the crust. I would list here the familiar examples like gold and silver, but also platinum, osmium, iridium, rhenium, palladium - a long list of elements, many of which have market values of several hundred dollars an ounce.

Audience question: It's my understanding that the precious metals on Earth came from meteorites anyway.

The Sudbury deposit in Ontario, which is the largest source of nickel in the world, historically, is certainly an asteroid impact — it's an impact scar. But that doesn't mean that the metals we see in it are necessarily from the asteroid. What happens with a large impact is that it fractures the crust and permits mineralization to occur and magmas to rise from great depths in the crust, which confuses the issue gravely. Impacts cause terrestrial processes to change.

Audience question: With the idea of bringing precious metals down to earth from the asteroids — are there ideas of vehicles that could do this with very little energy costs? Does it cost too much to bring them down?

There have actually been a couple of papers written by Dr. Jeffrey S. Kargel on the economics of returning precious and strategic metals from asteroids to Earth. He has also looked at the non-metals. You asked about materials that might be more common in meteorites than on Earth. In addition to the strategic metals, there are the other elements that dissolve in metals, but aren't metals themselves. These include things like sulfur, phosphorous, selenium, arsenic and so on. These are as a rule the exact things you want to use to make modern high-speed solar cells and solid-state electronics, gallium arsenide for example. They represent another economically attractive commodity from asteroids. Kargel has also written a paper on that subject, which was presented at this meeting two years ago.

Audience question (Hank Smith): Is it fair to say that an asteroid is a big meteorite?

Yes, exactly — turn it around. What is a meteorite? A meteorite is a chip off an asteroid. The meteorites that fall to the Earth are not a democratic sample of what's in the asteroid belt. But, of the asteroids that cross Earth's orbit, they're probably a very good indication of what those asteroids are made of There are, by the way, at least 2000 asteroids larger than 1000 meters in diameter that cross Earth's orbit.

Let me finish up with Waldron's paper, so we can get on to the others. If the use of surface minerals is also possible on Mars, then you can extract water from clays or permafrost or from the ice caps. Indeed, extracting the water from the surface rather than from the atmosphere appears to be much easier and much more desirable because the atmosphere is very cold and very dry. There's very little water there.

Bob also proposed reacting carbon monoxide with carbonates such as sodium or potassium carbonate to make maleic acid with calcium cyanide to make a compound CO(CN)2. This compound he suggests, I believe for the first time, as a possible propellant.

Waldron also talked about the sequence of growth from the simplest possible kinds of chemistry on to more complex kinds. Each modest increase in sophistication brings its own rewards and its own new capabilities.

The second paper, "Molecular Nanotechnology and Space resources, II: Implications for Desired Raw Materials" was given by Stephen Gillette from the University of Nevada at Reno.

Steve discussed possible applications of molecular nanotechnology to chemical processing of space resources. He argued quite beautifully, if not absolutely convincingly, that ferrous metals are much less desirable than carbon because of the high ultimate strength of carbon, especially in covalently bonded materials such as buckytubes. His arguments, of course, are valid if indeed a simple and efficient way of making buckytubes from natural sources of carbon were known. His conclusions should be tempered by the fact that there's a lot more iron than there is carbon in most plausible locations. I don't think the metals are going to upstart quite that quickly.

Audience question (Earl Bennett): What you said about the buckytubes, that reminded me that they're found in interstellar space, was that in the asteroids too?

Yes, but you must remember that they're present in such tiny concentrations that if you want to use them you're going to have to make them. You're going to have to take the largest reservoir of carbon there, which is in the form of an intractable, insoluble organic polymer and convert that by means of chemical or quasi-magical processes into buckytubes. I'm a big believer in the progress of chemistry, and I believe it will be possible to do this in the long run, but I don't think we should assume up front that it would be quick and easy.

Then, after convincing us that carbon was the way to the future, Steve then went on to say that silicates are preferable to carbon because you can put together large covalently bonded chains, sheets and perhaps tubes of silicates that are covalently bonded, quite strong in tension. They then might be preferable to carbon. If I have to make a summary of all of this I could not conclude which one was going to win. I would conclude that there are very promising opportunities for research and development in all three of these areas — metals, carbons and silicates, and for this reason I'm going to be spending some time over the next couple of weeks to try to get some research funding for Gillette so he can do some of these things in the laboratory and come back two years from now and tell us what works.

I conclude that experimentation with molecular nanotechnology would be highly desirable. Let's go about the business of finding out whether we can do it.

The third paper, "The Spacewatch Search for Material Resources near Earth" was presented by Bob McMillan from the Lunar and Planetary Laboratory of the University of Arizona. He has been the director of the Spacewatch search for near-Earth asteroids. Bob reported on the progress and near-term plans, the Spacewatch program of looking for asteroids. He reported on the rapidly accelerating rate of discovery of asteroids and he also on the progress of building the Spacewatch 2 telescope. They are using a large mirror that was inherited from a multiple mirror telescope on Mt. Hopkins in Arizona which was recently disassembled and replaced with a large single mirror, the multiple mirror telescope was a technology demonstration program for multiple mirror telescopes which strongly impacted the development of the Keck telescopes in Hawaii. With that mirror, they have been able to build a second-generation Spacewatch telescope that is now very close to operational.

Spacewatch is not at the moment the world's leading discoverer of asteroids, the LINEAR program from Lincoln Laboratories of Massachusetts now holds the record for discoveries. However, Spacewatch plays a unique role, in that Spacewatch is so sensitive that it can extend down to quite small sizes. Spacewatch has actually found several asteroids small enough so they could fit inside this room. This is an unprecedented astronomical accomplishment. I hope at some future meeting to demonstrate this point by actually fitting one inside this room, but I'll need more funding to do that.

One of the reasons that discovering these very small asteroids is important is that they represent local or regional hazards. These objects that are 100 meters in diameter or less are however, the dominant hazard to Earth, on the time scale of a human life, a timescale of 100 years, and on cultural timescales, about 1,000 to 10,000 years. For hazard assessment, these results are extremely important. In fact, it was Spacewatch results that stimulated me to write the book *Rain of Iron and Ice*, which contains detailed computer models of hazards to all the populated Earth, including all of these small NEAs as well as the big ones. Such sensitive search programs also have unforeseen results that you could never guess to advance. One of these is illustrated by McMillan's description of the asteroid 1998 KY 26, which is found to rotate every 10.7 minutes. Now for those of you who have any notion of the rotation rates of bodies in the solar system, this is an eyebrow raiser. Typically anything that rotates more rapidly than about every 100 minutes, suffers a serious loss of crust. That is to say, the gravity of the body is insufficient to hold its surface on, if it's rotating more rapidly than once every 100 minutes. This body, rotating in 10.7 minutes, experiences a centrifugal acceleration which is about ten times gravity. How can this be? This asteroid must be a coherent, strong, solid chunk of rock with tensile strength, which is pretty unusual. Big pieces of rock don't normally have tensile strength. It's a collision fragment, clearly. Collisions tend to accelerate and spin-up fragments. If you set off a stick of dynamite next to a rock, the fragments that come off tend to be spinning rapidly. In 1998 KY26 we have one such coherent, strong rock fragment. If you're looking for something you could hollow out and make a habitat out of, something strong enough so it would stand up to being drilled and blasted, this is a very good candidate. It's also not so big. I don't remember the diameter at this point, but I think it was something like 50 meters. Is Bob here? No? Well, then I'm absolutely certain it's 50 meters. *Audience laughter*.

Audience reply: It was 150 meters.

Is it 150 meters?

Audience reply: That's what I put in my notes.

Yes, that's just as I said. *Audience laughter*.

In many cases the exact diameters are not known because the reflectivities have not been measured yet, so that number could be in error by a factor of two or something.

Audience question (Gary Fisher): How is the rotation rate determined?

By the light curve, that is, the brightness of the object as a function of time. If you look at the intensity vs time for one of these objects, you'll often see something that looks like this, a periodic repeating pattern. Now what you're seeing here is an elongated object, which is rotating end over end. We see a varying cross section area as an object of irregular shape rotating at right angles to the line of site. Simply measuring that period gives you the rotation period of the asteroid.

I should also emphasize that the Spacewatch Program is exceptionally dependent upon private donations for its progress. A fraction of their funding has come from the Air Force; a fraction has come from NASA, but Spacewatch would not exist, and would not have its second-generation telescope if it were not for generous private donations. You've probably read in your newspapers that NASA is spending 3 '/2 million dollars a year on near Earth asteroid searches — this is somewhere between an outright lie and a shell game. For two years NASA represented to Congress that they were on the verge of putting 3 million plus dollars per year in asteroid searches. Those two years they did nothing. The third year, actually last year, I testified before the House subcommittee on space, along with Dave Morrison and Clark Chapman and other members of the asteroid community. We pointed out that NASA has been improvising for the previous two years. This is especially interesting to me because the person who was defending NASA in that period was a former graduate student of mine. I threatened him with retroactive removal of his degree from MIT. *Audience laughter*.

He in turn threatened MIT with loss of funding. *Audience laughter*.

Audience question (Hank Smith): Did you tell him he had rocks in his head?

I don't think I was that gentle.

As a result of Representative Sensenbrenner's outrage last year, NASA's representative promised on the spot that yes, indeed, there would be 3 1/2 million dollars put into asteroid searches this year, and the present NASA budget indeed says exactly that. However, virtually all of that money is from preexisting programs that had the word asteroids in their names that were simply collected together and transferred over under that heading. It appears that there's 1/2 million of new funding in there. All the rest is preexisting programs. I have also heard that that 1/2 million in funding was given to JPL to develop an NEA website. Just what we needed - now I feel safe.

Audience comment (Hank Smith): NASA has actually misrepresented things to Congress. They've done that before.

Well if you're talking about the Space Shuttle, that's a fairly good example. They sold the shuttle to Congress on the basis of launching 60,000 pounds per payloads 60 times per year and worked out the economics on that basis. That was a barefaced lie. That was never achievable.

Audience comment (Hank Smith): And Space Station Freedom also....

Don't get me started on that — Yes. When you're dealing with a mature government bureaucracy, you can expect that sort of behavior. Notice I'm not condoning it, I'm just saying that you can expect it.

Audience comment (Morris Hornik): You should mention, John, since you're a trustee of the institute that some of the first dollars of Spacewatch money came from SSI. SSI has been a continuous supporter of Spacewatch since then.

That's correct. I don't think I need to mention that anymore. I thought everyone knows that. By the way, my first contact with SSI was in 1979, so I'm aware of some of its history, but not all of it.

Because of the public perception that NASA is putting 3 1/2 million dollars of new money into asteroid searches, which is misrepresentation upon a lie, this has been even harder for Spacewatch to raise money from private donations, because people say the government is now funding it generously. Think about it.

The next paper, "Developing a Near-Earth Object Observatory and its Role in Education" was given by Robert Strong from West Liberty State College in West Virginia. Bob represents an organization called "SMART" whose abbreviation is spelled out somewhere. I think it will be sufficient for me to say that this guy is smart. He has done something which I greatly respect and I tremble in awe at some of the daring things he's done for his money. He presented a plan to us for a combination research and educational effort centered in a small astronomical observatory dedicated to the study of near Earth asteroids. By means of a series of maneuvers that can only be described as frighteningly clever, and astonishingly selfless, he has assembled most of a very nice small observatory with a 12-in telescope — quite a competent telescope.

He's also outlined for us his educational outreach uses for such a facility, and I'm telling you, when you have a 12-in telescope that's the only show in town, educational outreach activity is of utmost importance. This should serve, I think, as an inspiration to cash poor educators and educational institutions elsewhere. I should hint strongly to you that the powers that have money are on the verge of smiling more intensely upon that program and seeing that it gets some assistance.

There is actually an obvious front-line use for telescopes in the 10 to 20 inch size range in the asteroid business. That consists of unloading follow-up activities from the major discoveries. In effect these smaller telescopes, once they know where to look, can reacquire an asteroid and track it, and this, of course results in great improvements in the quality of the orbits calculated for those asteroids. A telescope of that size is really not very useful for discovery because it is not nearly as sensitive as the other search telescopes. Follow-up is a very valuable ecological niche to be filled. Let me remind you that astronomy is one of the most astonishing examples in science in which amateurs contribute valuable results every day...or, I should say, every night. Variable star observations, comets searches and so on......

The next paper, "Smelting and Shaping Steel in Zero Gravity Space" was given by Kenneth Stapleford. He proposed producing spherical metallic space structures out of bubbles of liquid metals, which are inflated by their vapor pressure against their surface tension. When we look at the numbers, the metals that can make large bubbles are not themselves useful structural materials — things like lead and sodium. I don't think anyone would want to live inside a sodium bubble. *Audience Laughter.*

However, those shells can serve as a template or a surface upon which you deposit a thick, strong and durable layer of metal. In order to do this, however, you need to have an expanding bubble maintain a constant temperature. You have to surround the bubble with what a German physicist would call a thermal Hohlraum — an outer shell that maintains temperatures. How complex this gets remains to be seen. There are some unresolved questions of whether a gas bubble expanding inside a liquid droplet would center itself automatically and produce a shell with a uniform wall thickness. Those issues need to be addressed. It's not clear whether this approach, when all complexities are taken into account, is actually easier than conventional assembly methods. But it's something that we should be thinking about. If it could be made to work it would be very useful.

The last paper of the session, "Asteroid Resource Development- A Business Case" was given by Thomas Taylor from Global Outpost, Inc. Tom is well known in the space business as a purveyor of startling and financially successful ideas. He's a cofounder of SpaceHab, Kistler Aerospace, and Global Outpost and also has had his hands in several other pies.

He presented to us a fascinating economic case study of a scheme for business development for asteroid resources. I would play around with some of his physics, but when I look at the scope and daring plan, I find myself reaching for my wallet — not because I'm afraid he's going to steal it, but because I think I might like to invest in this as it goes along. He points out that in addition to more obvious short-term business advantages of access to cheap and abundant materials, there's also the motivation of getting all of humanity's eggs out of one basket and helping us to write an insurance policy on our own future.

The idea is to use private money to recover resources for profit. That is in fact the prime short-term motivation. The idea here is not to tap the government, and therefore the taxpayers, for lots of money. Instead it's to generate a revenue stream that the government can then tax. Why should the government object to this? It's a source of revenue not an expense. The answer is that if it's not an expense to the government, then it does not serve as an excuse to maintain a large bureaucracy. That's the weakness in the situation. *Audience laughter*.

Clearly I'm sympathetic with Tom's approach. He's suggested some approaches in developing a system architecture for processing these materials based upon the use of the external tank. In Tom's case I think this is an entirely reasonable and predictable prescription. He closed by proposing a research plan involving a multipronged parallel research effort on closed life support systems on station architecture and on various aspects of commercial involvement in space mining and he concluded with the hortatory remark that space resource recovery will serve as a pull to help bring other kinds of activities into space. I think that anything that reduces costs of operating in space serves as a pull that says: "Look, the barriers in the way of doing the things that you dreamed about 30 years ago are now lower. Now's the time to start dreaming again."

That concludes our session.

II. INTERNATIONAL, LEGAL AND ECONOMIC CONSIDERATIONS

Chairs: Dennis Burnett and Christopher Faranetta
Summary. Christopher J. Faranetta

This session was chaired by Dennis Burnett of Pierson & Burnett in Washington DC I've known Dennis for many years. He provided counsel on the formation of Energia Ltd., which is the US Office of Rocket Space Corporation Energia (RSC Energia). Plus I've had the pleasure of working briefly with Dennis, when he represented the Russian Space Agency in their negotiations with NASA for the finalization of the Phase One Shuttle/Mir program contract.

The first paper, "Business Scenarios for Space Development" was given by Mike Ryan of Bellamine College. Mr. Ryan's paper addressed several potential space business cases. One relatively strong business case was for disposing of nuclear waste in space. His paper also noted that once the launch infrastructure was developed for nuclear waste space disposal it could also be used for other space applications.

Coincidentally, there are actually two papers in this session, which address the idea of nuclear waste disposal in space. The second paper, "Taking Up the Garbage: Disposal of Nuclear Waste in Space" was delivered by Jonathan Coopersmith of Texas A&M University. Jonathan examined more closely in his paper the mechanics of conducting a program to dispose of nuclear waste and material in space.

I support the concept of nuclear waste disposal in space, unfortunately it's a project that would generate a great deal of international public outcry. However, when one looks at the alternatives and potential consequences to very long-term storage or doing nothing, space disposal of nuclear waste and material becomes a prudent final solution.

To undertake such a space disposal project, obviously there needs to be space system testing conducted to understand if the waste can actually have to be carried out to educate the public on the element of risk involved in launching the waste.

Moving on to the third paper, "Privatization, Commercialization, Competition: Is it Time to Recognize a New Space Order?" by Amanda Moore. Amanda talked about the importance of having space interest groups attend and monitor the next United Nations conference on space called Unispace III.

She is absolutely correct about the importance of Unispace III. In fact, Amanda, I charge you to go there and keep an eye on the UN and find out exactly what they think about the space industry and what the UN may legislate against us. "Us" being everyone in this room that believes in space colonization and space solar power. We'll touch on this a little further on, but it's really amazing what can happen when you leave a bunch of politicians or bureaucrats alone. I know I'm stating the obvious but, you let them draw their own conclusions without keeping an eye on them and they can be very disruptive. I think we should, as a group, consider monitoring the UN so that space development will not be legislated out of existence.

Thor Hogan from the ANSER Company delivered a paper, "The Impact of International Treaties on the Space-Based Laser Program" which described the impact of international treaties on the potential deployment of a space-based laser anti-missile system. Thor's presentation discussed the various treaties that now exist between the US and Russia, the history of these treaties and compliance issues.

Obviously, this paper has a very military focus, but if someone is going to be delivering space power to Earth, or if they have space power platform in space, they are, essentially a potential military space power. So there is some potential overlap here on military and civil space law for SSP.

Michel Bourbonniere of the Royal Military College of Canada delivered the next paper. "Law of Armed Conflict in Outer Space." In it, Bourbonniere discusses the security of astronauts, national space assets, as well as the space environment itself. He addresses how dominance in space can be legally achieved by questioning the manner in which laws of war can be applied during an armed conflict, and the need to amend these laws.

The final paper of this session was delivered by Dennis Burnett and was titled "Export Requirements for International Ventures." His paper is a good example of the concerns raised in Amanda Moore's paper. Dennis gave a very good outline of the new technology export and transfer laws that are now in place in the US as of March 15, 1999. These new laws govern the export and control of space technology and technical know-how in and out of the US.

Part of what I do at Energia LTD is exporting high quality electronic components for Russian manned and unmanned spacecraft. In a country the size of Russia it is clearly very important that they have a good civil communication satellite infrastructure. The obvious reasons are that, people will use these satellites to communicate, do commerce, and access the outside world. They will be able to independently access ideas and viewpoints other than what is sanctioned by their own government.

Unfortunately, it's now much more difficult export electronic components, which could be used in satellites. I'm also not being naïve I know that they also could use these satellites for military communications. However you want the Russian military to have good communication because that's how they'll know whether or not they're really being attacked or if it is a false alarm. It is in the United States interest for the Russian military to have good communications if it can be proven that such systems prevent war.

That, essentially was the international legal and economic consideration session.

III. WIRELESS POWER TRANSMISSION

Chair: Peter Glaser
Summary: Morris Hornik

When you're asked to summarize these sessions, you're immediately faced with two challenges: one which is impossible, and one which is irresistible. It is impossible to truly summarize eight papers in roughly two minutes apiece. It is irresistible not to interject one's own thoughts and feelings about some of these papers.

It should be noted that this conference in general, and the session on wireless power in particular, was dedicated to Bill Brown as a tribute to his lifetime of work in making wireless power something we can speak about responsibly. I add my own gratitude to that, having been fortunate enough to do some work with Bill Brown. He was not only a brilliant, tireless and very effective researcher and innovator, he was a complete gentleman at all times, to all of us in this community. He was endlessly enthusiastic and always willing to teach, always willing to learn.

These are rare traits, especially in today's culture, and these are traits he had in common with Gerry O'Neill, who founded this Institute. Nothing anyone ever said about his ideas or his work, or about him personally, ever seemed to bother him. Not because he ignored it, but because he always thought those who said such things didn't really understand and would come to know better. It was not only because he was able to come up with new ways to accomplish very difficult technical tasks, but also because he was able to come up with ways to show people what he had accomplished, that we've developed respectability in the field and attracted some interest and funding, and now can talk about wireless power in a significant way. Bill Brown was one of those people that civilization never fully appreciates, but without them, civilization would not be able to advance. The advancing use of wireless power, I think, will be the long-term tribute to Bill Brown.

To go on with the summary, then. Peter Glaser, who chaired the session, and, after all, does have the 1968 patent on SPS (I wonder what its current status is?) pointed out that the progress of wireless power over the last 30 years shows that the benefits of space solar power can be brought to the world, and, more importantly, will be. A distinction should be drawn: there is space solar power, power generated in space that may be used in space or can be used elsewhere; and there are solar power satellites (SPS), which are generating stations in space producing large amounts of that power. Both of these overlapping concepts become potent through the use of wireless power transmissions, although obviously our focus here is on space solar power, whether it's generated at a lunar station or at a solar power station in orbit.

"The Current NASA Solar Power Satellite Study" by John Mankins

Institutionally, we have NASA Headquarters represented in the person of John Mankins, who led a re-look at the solar power concept in the joint NASA and DOE studies of the very late 1970's. Without going into technical detail (since I have less than two minutes for each of these summaries), the re-look concluded that there are several possible concepts for solar power satellites that would generate power at a final price of 6 to 12 cents per kilowatt -hour (kW-hr). There are some concepts for solar power satellites at geosynchronous orbits that could generate power at 5 to 6 cents per kW-hr, and all global projections show there's a very large world market for power in the 5 1/2 to 7 1/2 cent per kW-hr range. This tells us, without too much arithmetic, that at the very least, a number of geosynchronous satellite concepts for solar power could help satisfy a large world market. He also mentioned that solving these space solar power challenges will solve many of the other challenges associated with any ambitious future in space: the ability to move large amounts of material, major construction, significant control systems in space, and so forth. It should be highlighted that as ambitious as this NASA re-look was, it still was not nearly ambitious enough, and did not consider proper use of non-terrestrial materials. This is something we'll have to keep working on.

"Grand-Bassin: A Step on the Ladder to Energy from Space" by Guy Pignolet

The next speaker was Guy Pignolet of the French national space agency CNES, who is an extremely upbeat and energetic person, but has a message that doesn't sound that way when I read it. That message is: our societies are not yet ready to build solar power satellites. Socially, politically, economically, we're not there yet. The technical challenges are still great and what we must do is build step-by-step. Wireless power transmission for use on Earth gives us just such a series of steps. If we demonstrate that we can do it here, by making industrial use of wireless power transfer on Earth, we will eliminate many of the technical issues associated with doing it in space.

And he's quite correct. The project he describes will use wireless power transmission to provide electricity to a village on the island of La Reunion (which I'm not pronouncing properly). This is a state of the Nation of France, just as New Jersey (more or less) is a state of the US And, just as Hawaii is an American island state in the middle of the Pacific Ocean, Reunion is a French island state in the Indian Ocean. But it has a million French citizens, and also has canyons that rival America's Grand Canyon. Many people vacation on this island for the scenery and for the beaches.

There's considerable concern that if you run a stream of wires and poles and whatnot to power the rural mountain villages, it's going to ruin the look of the place. Not a very good idea! So, what Guy Pignolet is involved in doing is actually providing wireless power to a village in a mountainous region of the island. They're going

to set up their transmission antenna on one ridge and their receiving antenna (rectenna) down in the village proper, and move electricity in sufficient quantities to meet the needs of the village. The project is moving forward rather well. They're doing interesting things, such as designing a rectenna that doesn't look like some huge power utility pole. They're actually taking the trouble, using designers and architects, to make rectennas that look more or less like a farmer's hedge, among other things. Especially when you're dealing with tourists, good technology doesn't necessarily mean ugly design. I'm not sure I'm doing full justice to this concept. I think I can do that by pointing out, however, that the FINDS organization, which funds specific research to advance technology for the development of space, made this project the FINDS major prize winner this year. So there is recognition, and an insertion of cash that will make a difference. I hope to hear a great deal more from Dr. Pignolet as the project continues.

He invited us all to attend a conference at La Reunion Island in the Indian Ocean, and it would be fascinating to take him up on it.

"A Business Analysis for Commercial Space Development and SPS" by Yanai Z. Siegal

The next speaker was Yanai Siegal, long associated with SSI. He gave a very useful presentation which pointed out that business fundamentals must be satisfied if solar power satellites are to be financed and built. They must be competitive with other investment opportunities. If you have money to invest and can put it in whatever you wish, Internet stocks, or an index fund, or "Solar Power Satellites R Us", where do you put your money? The project has to be a good investment. Break-even, the point in time when profits cover startup costs, will be far too many years off for most investors to go into something like SPS, unless there are means found to advance break-even, to make your money back sooner. Yanai suggested, after a quick perusal of that fascinating document, the US Tax Code, that there's a provision in it called the Energy Tax Credit which, if extended to solar power satellite-type projects, multi-year projects, would allow break-even to occur within perhaps four years. The current interpretation of that Code was somewhat in question. You get a 10% credit for the cost of putting a new energy-producing resource into service the year it goes into service, but the issue is, what about the second year, the third year, or the fourth year? If the law does not currently allow us to do that, we have found what may be the most unifying lobbying point in the history of the space movement, because we could not only use it to justify the construction of solar power satellites, and other space solar power, but I think we could find common ground (amazingly enough) between us and others that want terrestrial solar power to be better subsidized. This is obviously something that should be considered by those looking for political avenues to boost space development.

"The Moon as a Solar Power Satellite" by Gerald Falbel

Gerald Falbel gave a presentation which described lunar-based space solar power. Instead of building collectors in orbit around the Earth, we could in fact build a solar collector and power transmission capability on the surface of the Moon, and beam the power back to Earth, possibly through the use of relay reflector satellites in Earth orbit. This would offer substantial construction, operations and maintenance advantages over building free-floating satellites over the Earth, and still provide some of the benefits that are associated with solar power satellites. The coverage of a given area on Earth, and the nature of the relays necessary to guarantee that power gets there, are still substantial and exceedingly complex issues.

Keep in mind that when you're sitting on the surface of the Moon, the Moon is rotating, and that you're looking at the Earth and the Earth is rotating. You're trying to beam power to some particular point on the Earth such that the power simply doesn't go on and off all the time. So you have to build systems to accommodate that requirement. It's a difficult, complex problem.

Although construction, operation, and maintenance of a solar power facility on the moon might be less costly, there are, at this time, no takers for that project either.

"Solar Power Satellite Engine" by Franklin Chen

Moving to a different concept altogether, Franklin Chen proposed (in a paper which I didn't understand until he had presented half of it) that solar power satellites would at the least serve as solar power collectors, whether they converted it to electricity or not.

Such satellites, or even large solar mirrors in orbit, could potentially be used to alter weather conditions on Earth. If you carefully defined atmospheric "cells" in the Earth's climate, and moved sufficient sunlight into them, you'd heat them. With sufficiently good computer models of the Earth's atmosphere, and good sensors to tell you what the actual effects are all of the time, and sensor feedback mechanisms into your computer models, you might find conditions under which changing the ambient sunlight over parts of the atmosphere allow you to do useful things to the weather. This paper was really dealing with SPS as atmospheric engines rather than SPS as generating engines. The use of these large reflectors could change the way our society does many things. It's not just the obvious, lighting cities at night, increasing the growing season for crops, improving climates. Perhaps there's the possibility of increasing or decreasing winds in given areas to make more wind power available, or to arrange other localized effects. There is actually a patent associated with this work!

Emphasized throughout this paper is that the most critical needs are for continuing analysis, proper instrumentation of the Earth and atmosphere, and producing control mechanisms to allow fine adjustment.

Although a novel concept, I note that there was a speculative story in Analog Science Fiction thirty-plus years ago called "The Weather Man" (by Theodore L. Thomas) which was quite touching, and involved issues somewhat along these lines.

"Financing Solar Power Satellites" by Richard Coleman

Richard Coleman spoke on financing the business case associated with solar power satellites. He is a financial professional with considerably varied experience; he has run brokerage efforts and transactions of many different kinds, dealing with venture capital organizations and so forth. He says, quite simply, that technology advances needed for solar power satellites are likely to come from other industries -- from telecommunications and manufacturing industries that need similar types of power systems, control systems, fabrication techniques and materials -and that this will probably be true for the next few decades. In other words, rather than expect to somehow start-up some space enterprise that does everything we're going to need, we'll be able to build from the efforts of other industries, if we're careful and smart.

Mr. Coleman has made considerable effort to survey and plumb the depths of the financial community, to learn what the prospects are for our kinds of efforts. He concludes that, at this time, there are neither visionaries nor pragmatists who will bridge the gap between innovators and the conservative managers of financial institutions. Basically, we need either someone who's got a compelling view of how the future should be and who can talk the language of the parties involved, or else we need someone who has done the analysis and convinced himself that there's a great deal of money (and other good) to be gained. There's no such person at this time.

Audience: In speaking about industry, I would think some of the foreign countries looking for long-range type things to replace oil exporting would get involved.

I understand your point. I think it was suggested in a paper out of the Harvard Business School that if you take a look back at the post-World War II era, you'll find that all the large transportation companies in this country were railroads, and yet not a single railroad ended up operating an airline. They did not see themselves in the transportation business, they saw themselves in the railroad business. Petroleum is in the same situation; they think of themselves as in the petroleum business. Changing this has been tried many times over the last twenty-five years, but we can keep trying.

Mr. Coleman concluded that despite the ultimate practicality of simply going out and building space solar power, we should instead look to a "terracing" approach, as Peter Glaser proposes, doing things a stage at a time, to demonstrate the capability, attractiveness, and practicality of SPS. Mr. Pignolet's project is a great example.

"Concept for Continuous Inter-Planetary Communications" by Stevan M. Davidovich and Joel Whittington

Next, Steve Davidovich and Joel Whittington described a satellite system that allows continuous intra-solar system communications. In other words, no matter where you were within the solar system, whatever planet, whatever part of the asteroid belt, or wherever, you could still be in touch with the rest of the human community within the solar system. The problem is, since almost all of the planets are in the same plane (the ecliptic), occasionally they either occlude the Sun or they are in conjunction with it, or they are aligned so closely with the Sun that radio or optical noise from the Sun makes communications impossible. If you aim a radio antenna towards our Sun you'll pick up all the radio noise coming from it; you may not pick up the very much weaker signal from a spaceship or a space construction facility that appears to be too close to the Sun for your antenna to separate them. How do you solve this problem?

What these gentlemen suggest is that every planet, space station, and manufacturing facility will have its own array of communication satellites. This doesn't help angular separation very much, unless you're quite a distance from where the planet or space station is. But if you were to put three spacecraft into a polar orbit around the Sun so that they're out of the plane of the ecliptic, you've now got the right "targets". Orbiting the Sun at a distance of 1 astronomical unit (the distance between the Earth and the Sun), puts sufficient distance between the Sun and these satellites for your antenna pointing to eliminate interference. Their conclusion was, if you orbited three evenly spaced satellites over the sun's poles, you could have continuous connectivity within the region of the inner planets of the solar system. For the outer planets, you wouldn't quite accomplish that; in the worst cases you'd still have too close a conjunction. Advancing technologies, antenna systems and such, might overcome this in the future.

I must point out that these basic problems were looked at back in the 1940's by the science fiction author and engineer George 0. Smith, who wrote a series of stories about his "Venus Equilateral" solution. He did not have satellites coming out of the ecliptic, he simply had a relay station on one of the Trojan orbit points of Venus (an L4 or L5 point on the orbit of Venus), which, in most circumstances, was good enough.

"Education and Manufacturing in the Next Millennium" by Krishna Shenai

Dr. Shanai of the University of Illinois at Chicago, speaking on behalf of a number of his colleagues as well as himself, pointed out that today there are much more capable and diverse spacecraft functions possible in ever-smaller integrated circuits.

Consider almost everything that a spacecraft needs for electronic infrastructure: internal health-andwelfare monitoring systems, telemetry links back to Earth, command receivers, mission or communications links back to Earth, positioning and navigation systems, attitude controls. All these electronic capabilities can now virtually be put on a single integrated circuit, a "one chip" spacecraft electronic infrastructure! This is extremely impressive if you can actually make it work; we're getting very close, and almost certainly will do it. This effort becomes very technical when you get down to the details of micron-scale geometries and other chip characteristics. Can you do it all on the chip? It appears that we can. Soon, what are currently several boxes on most spacecraft (and are just now becoming a smaller box or two), could be a single integrated circuit, thereby reducing the size, weight, power consumption, complexity and cost of spacecraft. And this, of course, is extremely interesting.

Audience (Earl Bennett): Is this the spacecraft on a chip talk? I wasn't here for it.

Yes.

Obviously, this does not include any motors or gas control jets. They're not electronic devices, so it's hard to generate them out of silicon or gallium arsenide. Nonetheless, it's remarkable that, instead of wiring harnesses and circuit boards throughout the spacecraft, you've got just one board that does all those things, with the appropriate sensors. And sensors can also be put on chips, if mechanically they can see what they need to see; spacecraft today usually orient themselves by "seeing" the limb of the Earth, or by "recognizing" a certain star pattern. They need to have a sensor to do that. It may be that the location of the master chip inside the spacecraft doesn't allow it to look in the correct direction, and separate sensors will be needed.

Audience: Back to something said earlier, about the possibility of establishing solar power stations on the Moon's surface. You said that there would be a problem with the rotation of the Earth and the rotation of the Moon. Since the Moon always shows the same face to us (its rotation equals its revolution), doesn't that solve the problem?

The trouble is that the Earth keeps turning under it. You don't really want power that's only available during the hours the Moon is visible from your location, and so forth.

Audience (John Lewis): I think I can address the rest of the problem. Morris was expressing concern about the rotation of the Moon relative to the Sun because it means that any station on the surface of the Moon is in sunlight only half the time.

That is correct. Unless you're talking about the lunar poles, that's a major difficulty. It is solar flux into the station, before you generate power out from it, only half the time.

Audience: You're talking about electronics on a chip. I have read an article talking about spacecraft micro-thrusters that were based on chip design.

Yes, being done at the JPL Center for Space Microelectronics among other places.

This work was impressive enough that Dr. Shenai's project received a FINDS award for five thousand dollars (although the Reunion Island award received the major prize).

Dr. Shenai concluded with the possibility that continuing advances in computer technology would allow us to do very helpful 3D visualizations and virtual reality for tele-presence, which could lead to improved training, better navigation, and virtual exploration, as well as the now routine virtual prototyping and operational rehearsal, thereby making it possible to not only use fewer people in space for some procedures and assembly, but to make better use of those people as well.

All in all, this whole session was quite interesting and helpful in bridging some of the gaps between what we'd like to do and what we're actually able to do.

I have just a minute or two. So, are there any really interesting questions? I'll take them at this time. If not, thank you for your attention.

Audience: (applause)

IV. STRUCTURES

Chair: Lee S. Valentine

The first paper was "Hyperboloidal Deployable Solar Space Mirrors, Antennas and Structures." In this presentation, Terrance Waters describes a method to use Hyperboloidal structures that are readily deployable in space to minimize spacecraft mass or maximize structural efficiency for a given mass.

This paper certainly caught my attention. It caught some structure people from Carnegie Mellon's attention as well. And they're going to take a careful look at this paper, and try to make sure the assertions made herein are correct.

Of course to make an ideal material you need ideal things to make it out of Ideal structures are the same way. Lines should ideally be perfectly dimensionless except in one direction. We're forced to contend with physical atoms and physical voids and unfortunately out structures can't be made in this perfect way. So we're going to have to take a careful look and see whether these assertions are actually correct.

The second paper I'd like to talk about is by Tom Taylor, "Partial Gravity Habitat for Space Tourism." Tom has the use of five Shuttle tanks, provided that certain specifications are met. He would like to use these tanks to construct an orbital hotel. We would like Tom to put windows in his hotel because we do not see windows as it's presently designed. But Tom has thoughtfully provided for some, not quite micro gravity, but not full Earth gravity- just enough to keep things in their places and I think that this is probably, if not a necessity in early space hotels, at least a useful feature.

Tom has, as John pointed out, a successful record at starting space companies, which actually make money, albeit currently the government as the prime customer.

I'll entertain any questions that are forthcoming.

Audience question (Hank Smith): Just picking up on that last remark, are there ways that a space company can make money without the government as its customer?

Oh yes, indeed. In fact most profitable space companies make money with you as the customer. That's the way AT&T makes its money and GTE makes its money.

Audience question (Hank Smith): And my employer, Bell Atlantic...

And your employer, Bell Atlantic, exactly so.

Audience question (Hank Smith): That would be communications satellites, for instance.

Yes, there are currently really two ways that people make money in space other than using the government. One way is communications, and that is nearly all the income, and the second way is by providing remote sensing data and that's a relatively small portion. What we're at this conference to talk about are other ways to do things that cover the entire gambit of the human experience.

If there are no more questions, that will end the summary of this session.

V. BIOMEDICAL AND SOCIAL CONSIDERATIONS

Chairs: Logan Smith, Space Studies Institute and Richard Satava, DARPA
Summary: Logan Smith

We are much indebted to Dr. Richard Satava from DARPA who gave the excellent presentation, "The Role of Robotics and Virtual Reality for Medical Mission Support." Dr. Satava talked about DARPA's work with telepresence and tele-robotic surgery, which finally shows signs of catching up with Dr. Waldo's work in the Heinlein novella.

Tele-robotic surgery is the practice of surgery by remote installation. It has, indeed come a long way.

Dr. Satava's first paper is concerned with recent developments. Harnessing the increases in computational power and miniaturization of components that have allowed the field to advance to the stage where actual cardiac and laparoscopic GI surgery has been performed in France. The sensors employ tactile feedback, which in effect guides the surgeon in the appropriate force and motion. Virtual reality is now being used to image not only for surgery but to image anatomy for the training of medical students and also practice in surgical techniques being done on three-dimensional images by residents and medical students. This has also been done, and I've been following literature on that, in my field of ophthalmology. In our case it may save undue pain and suffering to an innumerable numbers of pigs' eyes I used to go harvest for practice.

Finally, virtual endoscopic procedures are being studied. What they do is make a three-dimensional CT or MRI image of a body system such as the gastrointestinal system, and then the computer makes a virtual reality image of the GI system which allows the physician to view the system as if it were a true endoscopic procedure, but without the certain amount of discomfort the patient might otherwise have.

The second paper, "Yale Telemedicine," was presented by Dr. Satava's associate, Brett Harnett. This was a review of telemedicine projects that Yale University has been performing in the real world. By the use of satellite communications and the Internet, Yale has sponsored expeditions to South America and mostly to the Balkans to diagnose illness and make decisions about possible treatments.

Yale is also sponsoring what they call a house program. A nurse or physician extender can go visit a housebound patient, hook up sensors to the patient and feed data by use of a laptop over a modem back to the medical center where it can be reviewed. The physician can interview the patient over the Internet in real time. I think that's quite a feat and I predict that it will become much more common in the coming years.

Steve Garber of the NASA History Office gave the next talk. Switching gears a bit; "Why Does the Space Shuttle Have Wings? A Historical Case Study in the Sociological Determinants of Space Technology" is a social analysis of decision-making. Looking back through NASA he points out that the Shuttle was designed just a few years after the beginning of the space age, and was designed largely by aeronautical engineers and aeronautical engineers design things with wings. Also, he said, this is a type of style. Instead of an evolutionary design, which the Russians have always believed in, the NASA style was more to be revolutionary and leapfrog to the next thing.

He stated that there were three options really in the design of a reusable spacecraft. One was a ballistic capsule, such as a big Apollo capsule, one was a lifting body, and one was a winged vehicle. The ballistic capsule, of course, is well understood aerodynamically, but was not revolutionary.

The lifting body was well understood and used in a number of experiments by NASA in the '60s. Most recognizable was the one that was shown at the beginning of the series, "The Six Million Dollar Man" television show.

The winged vehicle was more complex and the heat problems were more complex, but this was selected due to some of the goals of the Shuttle. The goals of the Shuttle were its reusability/lower cost and cross range capability. This largely involved launching out of Vandenberg in a polar orbit for a military mission. In space when it came around one orbit of the Earth, the launch pad had moved 1100 miles as the Earth rotated. They needed to have some cross range capability to be able to land back at the same place. The payload was supposed to be at least 50,000 pounds, which was, once again in retrospect, driven by military requirements, and then it had to be human rated, which added much to the complexity and redundancy to the systems. It was a very interesting talk.

The next talk went a little farther afield that a strict biomedicine one. It began with a part of space travel that has not been covered so much by the engineers, as Mr. Burrough pointed out last night in his remarks after dinner. The psychology of space travel is certainly something that has not been very well considered.

The paper, "The Arts in Space Settlements; Artistic Evolution Out of New Experiential Perspectives," was by Roger Davidson, who is a composer and musician. He was discussing the different types of art, which may result from the experiential perspective of space. I think we would know that it's not really the type of art we see in space atlas- just pictures of moons and planets. But I really can't conceive of that myself, not being artistic, so he did a good job of laying out the fact that things will be different when our whole perspective may be changed just by the fact that people live in space.

The next presentation, "Functional Neuromuscular Stimulation of Hand Muscles for Telerobotic Feedback" by David Odrobina related to the earlier papers on telemedicine. This is a novel system that David has been working on for the last five years at the University of Buffalo. He has been working on the problem of getting feedback from telepresence operations. Dr. Satava's system does this in one way. When one pushes down on the hemostat, or a needle, there is a mechanical system that pushes back against the effector as feedback so you get tactile feedback in that way. At the University of Buffalo, the tactile feedback they're working on is achieved by neuromuscular stimulation, with non-invasive electrodes. Electrodes are embedded in a sleeve placed on the arm so that when there's feedback, or pressure backwards, the electrodes stimulate the extensor muscles that will actually move the fingers back. They have been able to demonstrate in an experimental hook up with a robot finger that when they extend the robot finger to straighten it out, the system will stimulate the flexor muscles and one does have feedback that allows one to sense the position of the finger. Whether or not the gain on that will be enough and the speed will be enough to actually give you the ability, say to do surgery, or to tighten a bolt or insert something on the Hubbell space telescope or the International Space Station, remains to be seen. It's certainly fascinating.

Mr. Harnett talked about Yale's program of telemedicine to Everest in the expedition in 1999. His program monitors every member of the Everest expedition with medical monitors. Monitored parameters are sent to the base camp, then to a satellite then via the Internet back to Yale. Each person's position and health status is known at all times. This is an amazing advance in telemedicine.

Richard Satava presented the final paper of this session. "Medical Support for International Space Station and Mission to Mars" concerned the future of training for long-duration spaceflight. Dr. Satava discussed the lack of proper facilities to train future astronauts and made suggestions for proper preparation for the day when long-duration missions will be a reality.

That concludes the summary of the Biomedical and Social Considerations Session.

VI. ROBOTICS

Chair: Red Whitaker
Summary: Richard Blomquist

I am representing Red Whitaker, who many of you know quite well. He is a very dynamic ex-Marine who is sure to keep the speakers in his session on schedule. He has an easy smile, which is fortunate; if he has a bad temper, I get the feeling that he could probably kill someone with two fingers. I happen to be one of his graduate students.

Audience Laughter.

I am quite interested in the topics discussed in this session. Each presentation is related in some way to my life's work. I will recap each paper in a different order than they were presented following the schedule that appears in the program.

The first speaker was David Lavery of NASA Headquarters. He has been a friend to Carnegie Mellon Robotics for many years, providing help and guidance, and enabling us to carry out many different types of robotics projects. One of these projects is the Dante mission to explore volcanoes. Another is the Nomad Rover. This last winter, Nomad spent time in the Antarctic conducting automated meteorite search tests, which we hope to follow up next year using more capable operating strategy and a little bit more experience in how to perform autonomous geology.

Dave Lavery mentioned at the beginning of his talk the mantra of NASA, which is: better, faster, cheaper, meaning that in designing rovers to go to other planets, NASA is abandoning the mindset that a planetary rover measuring meters in length, depth, and height, and costing billions of dollars is a bargain. The new thinking is that a rover perhaps the size of a microwave oven, weighing perhaps 15 kilograms, and costing somewhere on the order of 100 million dollars is the preferred way to go.

Mr. Lavery also mentioned in his talk the future of Mars exploration and the driving force for us to have a presence on Mars. There is some political will for us to go to Mars right now, and it's great to take advantage of that. The driving force originates in the discovery of material in a Martian meteorite that may be organic, suggesting the existence of life on Mars at some time in the past. If life is there, we definitely must endeavor to find the signs of it,.what form it is in, and so on. Many of the Mars missions in the future will help us answer the questions surrounding life on Mars; beginning with a series of robotic missions launched every couple of years. We will have to wait 15 or perhaps 20 years for a human to investigate in person.

No one knows where the Pathfmder Sojourner rover is right now. It may have wandered off far from the lander, only to be found by some future explorers. Dave Lavery contributed a great deal to the preliminary development of the Sojourner rover and I know he is excited about the opportunity to some day see someone go to the surface of Mars and find Sojourner. On the bottom of the Sojourner there is a plaque with the names of many of the people who helped with the original work on the rover; the astronaut who finds it will turn it over and see Lavery's name.

The next speaker was Wayne Zimmerman of the Jet Propulsion Laboratory. He is heading up the robotics work for the Mars '98 and the Mars '01 missions. He showed us a picture of the Mars Pathfinder lander, Sojourner, and the robotic are mounted on the rear of the rover, which I was personally tickled about. I think he showed the arm for my sake, since I designed it. I thanked him afterwards.

He also showed us the development of some of the robotics arms that are going to be on landers in the future. His presentation revealed the process NASA engineers use to design, build, and test mechanisms. The design must pass the scrutiny of many reviews; it must be capable; and, it must meet many sometimes-conflicting requirements.

The operation of the Mars '98 arm is very slow. The joints are powered by motors with extremely high gear ratios, largely because the arm is meters long, and the ground reaction torques must be counteracted with lightweight, high torque motors running on little power. The slow motion is acceptable, because the arm can work constantly, slowly digging a ditch up to 11.2 meters deep.

Think about it. If you were digging for a very long time using your fingernails you could eventually make a deep hole; that is the basic operational scenario for this arm.

The next person to speak was myself. I am from Carnegie Mellon University. I spoke about the Solar Blade Nanosatellite Project, a project involving the development of the first solar sail ever to fly in space.

First of all, I mentioned capability of a solar sail; the effect of solar pressure on an object and what a solar sail can theoretically do, including missions to the outer planets, asteroids, or comet rendezvous' and station keeping between the Earth and the Sun for solar storm warning In fact, for the solar storm warning scenario, solar sails that are on the drawing board right now would allow us to increase warning time for solar storms by a factor of two or three.

I also mentioned that the design of our solar sail, which will be about 2.5 kg and have about 80 square meters of sail area, is a demonstration vehicle for solar sailing. The cool thing about this design is that it is scalable, and it will provide an opportunity to understand the operation and development of solar hails for space. The design is a heliogyro, a helicopter-like vehicle. It looks like a Dutch windmill with long, thin blades that pitch with respect to the Sun to provide a pressing capability.

Next on the list is Joe Parrish from NASA. He talked about the Ranger Telerobotic Shuttle Experiment, and mentioned what having a robotic servicing capability in space can do for us. He mentioned that 65% of EVA activity is spent in set-up and that sort of thing. We need to be able to give our astronauts a more efficient way of working in space. If a robotic servicing module can set up tasks for the astronauts, and, in fact, replace some of the tedious tasks they need to do, we can be much more efficient.

A number of the presentations in this conference talked about large space structures, which we cannot easily send astronauts to build. In the future, we will be able to take advantage of robotic that will enable us to construct and service these large structures without having to rely exclusively on expensive and risky EVA activity.

Originally, the Ranger telerobotic Shuttle will operate in the Shuttle, but Joe mentioned that the real market for telerobotic EVA is for things like geosynchronous spacecraft. The design of geosynchronous spacecraft is such that we do not limit the life of the spacecraft by the reliability of parts, but rather by the amount of propulsion on board. Once the propellant runs out, the spacecraft loses its positioning capability and its orbit degrades. If we can send robotic servicing models to replenish propellant supply, we can greatly extend the life of these geosynchronous spacecraft.

We also had a talk from Paul Tompkins and Ashley Stroupe, who are both from Carnegie Mellon University. Their talk actually changed to just focusing on the work of searching for volatiles on the lunar poles. They talked about work that we have done at Carnegie Mellon University in developing a rover that will be able to drive around on the surface of the Moon. For those of you who attended the whole conference, you were able to hear a talk by James Arnold at one of the luncheon sessions about the possibility of ice being on the Moon, specifically in permanently dark regions in the north and south pole areas where the temperatures are low enough to prevent ice sublimation. Over a period of billions of years, ice from comets that impacted the lunar surface might have accumulated in these cold traps, providing us an excellent resource for lunar colony development, for propellant development, and so on.

The design of the rover is basically a four-wheeled vehicle; two wheels are steer able and two wheels articulate to allow proper registration on the surface. It also has an articulating solar panel that helps control rover internal temperatures. Radioisotope heating units inside the body maintain temperature and help the rover survive the long lunar night. The key here is that the fluctuation in temperatures from sunlit regions to shadowed areas is so great that temperature control cannot be done solely by passive means. By articulating the solar array, the thermal properties of the rover are dramatically changed, and the rover's temperature follows.

We also heard a talk from Mr. Shanai, which was similar to a talk he gave earlier about hybrid technology for computers. His work is extremely exciting because future spacecraft concepts requires us to miniaturize, miniaturize, miniaturize. I know that for solar sails, the smaller the components, the easier it is to make the solar sail, which is similar for many other nanosatellites.

We also received a talk about the AERCam Shuttle experiment, which Dave Lavery describes as the Death Star. Basically, it is a rapidly developed experiment that is capable of maneuvering in space around another object like the Space Shuttle or the International space Station and taking photographs. It can manipulate itself in such a way that its motion can be automated.

These are the talks of this session. I think it is quite exciting what robotics capabilities will allow us to do in the future. It looks like robotics work is healthy and proceeding in a way that will generate amazing results in the next two years.

Any Questions?

Audience Question: (Paul Fernout) I was wondering if you could comment on the combination of technologies, such as newer launch technologies with solar sail capability, launching a small payload with a solar sail.

Well, definitely, is you're able to make the solar sail small enough. Here's the key about a solar sail, you actually want to make it cover a large area when it gets up to space, but you want to make it extremely light. You may end up having weird shaped spacecraft, or weird shaped capsules that are shipped into space. But, in the future we may be able to rapidly shoot something up into space. Once it gets up into space you can open up the solar sail and then you're off. You're not dealing with any propulsion systems, so basically you can have a rapid way of going to an asteroid or a comet, where you just point this gun or whatever it is that's going to shoot the capsule into space. The solar sail deploys and then it's off and running It can be extremely light, very small and especially since the initial development of a cannon such as this won't be able to put up too much mass, this is a perfect place to start with something as small as a nanosatellite, a solar sail, or something like that. You could have cheap and rapid deployment of spacecraft to a number of different targets throughout the solar system.

Audience: Before you mentioned the Mars missions that were going to land on the planet every two years. Would you comment on how far along they are in the development of the one that's supposed to land there, scoop up the soil samples and bring them back to Earth?

That's a difficult question because it has changed. The original development was that they were going to have two chances to do that; one in 2003 and one in 2005 and then have a choice of going to one of the two spots and retrieving the samples. They're going to scale down their plans a little bit. They're doing a lot Unfortunately, since it has changed I do not know what the time frame is. There's probably someone in the audience that can answer that much better than I can.

Audience: I believe it is 2005.

Somewhere around there.

John Lewis: I'm glad I did not see a demonstration of Red Whitaker killing with two fingers. In fact in 1981 I received an application from a perspective graduate student that was a graduate of the Air Force Academy. I read his application with careful attention. He had a perfect academic record "A" in every single course except one, which was hand-to-hand combat. I decided for that combination of reasons he was my new student. Laughter. The student's name is Tom Jones. He is a member of the Astronaut Corps. He's flown the Shuttle three times and he 's going to fly the space station assembly flight towards the end of the year. So, if you get into an argument with him, you're safer than you thought. Laughter.

VII. TRANSPORTATION

Chair: Leik Myrabo

First up was Dr. Edward Belbruno. Edward's goal in this paper, "A Ballistic Capture Transfer to L4, L5," was to demonstrate the practicality of ballistic capture transfer to L4 & L5, with exceedingly small, almost insignificant Delta V's. These highly specialized transfer trajectories were largely planned for unmanned spacecraft payloads -- i.e., missions for which the trip time is less unimportant than a low (or approximately zero) Delta V. Edward noted that a basic component of this class of transfers is the operationally tested WSB, or Fuzzy Boundary, lunar transfer.

Edward showed several examples of his unconventional trajectories and explained the orbital mechanics. This sophisticated science/art has only come into existence over the past few years, and could enable a substantial increase in payload delivered for a wide variety of space missions. I enjoyed Ed's presentation, in particular his explanation of how these exotic trajectories were designed.

Next up was Derek Tidman. His paper, "Slingatron Engineering and Early Experiments," was an update of latest developments on his Slingatron launch concept. Derek's presentation revealed a couple of new features that were not a part of the original mass-accelerator concept, which had a circular geometry. This new approach is now based on a spiral geometry, and employs an injection gun to insert the projectile into the gyrating guide tube. Derek provided further engineering design details on the guide tube's support structure, gyrating drive system, bearings, feasible Delta-Vs, as well as a description of his new experiment to measure the sliding friction coefficient of high velocity projectiles.

This launcher looks like it will be quite a complex apparatus, when built to the projected full-scale dimensions. However, Derek's overall objective is to greatly cut the launch costs to space by first building a substantial infrastructure on the ground, and then reusing that facility for thousands of launches. In essence this is an "infrastructure rich" approach, which lies in sharp contrast with the "infrastructure poor" approach of today's chemical rocket launcher systems.

Next up was Douglas Witherspoon, with UTRON, Inc. Doug asked me to mention that he initially came to UTRON to work with Derek Tidman. Clearly, from the title of his paper alone, "A Low-Cost Space Launcher Using Hypervelocity Combustion Light Gas Gun," we can assume that Doug is also interested in developing an "infrastructure rich," low-cost access to space. His paper mentions a target of $100 per pound to LEO.

The launch concept employs a chemical combustion-driven, light gas (e.g., hydrogen) gun with distributed 142 injection behind the projectile as it accelerates down the barrel. This CLGG gun-launched projectile would leave the barrel at, say perhaps 4.2 km/sec, and then employ a chemical rocket "kick booster" to accelerate the payload into an orbit of 200 km. Again, the basic idea is to invest in a formidable ground-based launch facility, capable of propelling hundreds to thousands of payloads into low Earth orbit. The cost of building this facility would then be amortized over a large number of users, in a commercial launch business. Doug showed an artist concept of such a gun launch facility built up the side of a mountain, and then presented engineering design details on projectile acceleration rates, gun Delta-Vs, barrel material strengths, pressure limitations, gun lengths, and combustion rates.

Finally, Doug showed a very interesting picture of an experimental CLGG device: a 45 mm gun demo sponsored by BMDO and the Army SMDC. On the combustion system for this device.... Doug are you here? What kind of electrical system did you use to ignite this gas mixture?

Doug Witherspoon: We purposely didn't show that. We weren't allowed to It's nothing particularly exotic.

Would it be an exploding wire, or distributed spark plugs?

Doug Witherspoon: I can't say.

Next up was Marshall Miller's paper, "Analysis of a Fuel Cell Powered Lunar Rover," which was given by Chris Faranetta. Chris received an email from Marshall who indicated that he was not feeling well and would not make the conference. Marshall's paper presented an end-to-end analysis of a fuel cell powered lunar rover vehicle, which was assumed to operate from a lunar base that refuels the vehicle with gaseous hydrogen and oxygen. The analysis incorporated a dynamic vehicle model called AVTE to simulate hybrid vehicle driveline performance, using vehicle and power component parameters as inputs. A separate fuel cell model enabled the calculation of total power supply weight and volume, for a variety of vehicle ranges and drive cycles designs. The end-to-end design process was iterated until consistent results were attained.

I was up next and gave an update on beamed energy (laser and microwave) propulsion research, "Highways of Light" sponsored by the Air Force Research Laboratory, and NASA Marshall Space Flight Center. The first half of the presentation covered the spin-stabilized, beam-riding, free-flights of 25-35 gram laser-boosted aluminum Lightcraft at the High Energy Laser Systems Test Facility, located on White Sands Missile Range, NM. I described the outdoor flight test setup showing a simple launch stand, and then explained the need for a 4-ft X 8-ft plywood laser beam stop held up at 120-ft altitude -by a crane. Basically, this plywood intercepts any stray laser radiation that misses the Lightcraft in flight; we don't want to accidentally blind any infrared sensor satellites in LEO. If a gust diverts the craft from the centerline of the vertical laser beam, the pulsejet engine automatically vector its thrust to re-center the craft on the beam. Several time-lapsed photos of the vehicle in flight were shown, as well as videotape coverage of these short 3-4 second flights. The most recent altitude record of 100-ft was set in August 1998.

Next I covered the latest developments on the 20-m diameter microwave Lightcraft concept - including the new design for a 1-km diameter, rechargeable solar power satellite in LEO capable of transporting this 6-12 person craft into orbit, around the world, or directly to the Moon. The SPS would be constructed 55 pie-shaped segments made from 1/16-inch thick silicon carbide (ceramic matrix composite thin films), and would be coated with efficient solar cells On one side, and 1.9 billion little 35-GHz microwave antennas on the opposite side. The "bicycle wheel" SPS design and construction methodology builds upon the work of Flint (Ref. 1997 SSI Conf. Proceedings), but adds two super conducting cables about the perimeter, sized to store the 320 megawatts of power generated during one complete orbit around the Earth: i.e., about two-thousand gig joules total. When needed, the gyro stabilized satellite, spinning at about 1-rpm, would download this stored electrical energy to "beam up" the microwave Lightcraft in a flight lasting less than 3-5 minutes. To coarsely point the transmitter, the two super conducting cables can torque the SPS in the Earth's geomagnetic field.

Finally, I mentioned that a number of experiments are being carried out in the RPI Hypersonic Shock Tunnel to further develop the engine technology for this microwave Lightcraft concept: a) tests on the directed energy Air Spike, and b) the external MHD slipstream accelerator.

The next paper, "Combined Propulsion for a Small Reusable Launcher," was given by Vladimir Balepin, who introduced his concept for a combined airbreathing/rocket engine cycle consisting of a thermally integrated deeply cooled turbojet (DCTJ) and a liquid rocket engine. Vladimir called this the KLIN engine cycle, and he envisions it for use in a vertical takeoff, single stage to orbit (SSTO) launch vehicle. Basically, "thermal integration" means that the rocket's liquid hydrogen fuel is used to super cool the inlet air for the turbojet engine, to greatly increase the turbojet's pressure ratio and thrust. He believes that the "extremely high" thrust-to-weight ratio of this KLIN engine can enable a substantial reduction in the gross take-off weight of a small, reusable SSTO launcher. Such a KLIN cycle launcher would transition from the combined airbreathing/rocket mode, into a pure rocket mode at about Mach 6.

Vladimir is making plans for an experimental demonstration of the KLIN cycle based upon an expander cycle rocket engine of the RL 10 family. At low altitudes, he suggests that icing in the turbojet's inlet can probably be avoided (without affecting the engine's cycle efficiency) by injecting a small flow rate of liquid oxygen (4-6% of the inlet air mass flow rate) in front of the LH2 precooler -- which takes the inlet air temperature below the triple-point. The nonafterburning DCTJ is expected to give a 2% increase in thrust for a 1% oxygen addition to the inlet air. Vladimir envisions the DCTJ units should be custom designed turbo machines that exploit a lightweight compressor optimized for low temperature operation.

This KLIN booster engine concept seems like an interesting near term opportunity, and I hope Vladimir is successful at getting its performance demonstrated in an adequate test program -- within the next few years. The data will speak for itself.

The final paper in the session, "A Survey and Recent Developments of Lunar Gravity Assist," was given by Paul Penzo. He first introduced the basic mechanics of lunar gravity assist (LGA), and then highlighted the numerous applications where it has been successfully applied since the Apollo mission in 1964. Such LGA missions included redirecting an Earth-sun libration point satellite to a comet encounter, and enhancing payloads with a lunar energy boost.

Paul concentrated most of his presentation on more recent missions and studies benefiting from LGA including, lunar capture assist, repositioning GEO communications satellites, boosting spacecraft to Earth escape, and launching small spacecraft as secondary payloads then releasing them into almost random orbits. He showed several exotic trajectories

of the last category, explaining how they may depart and maneuver in space with gravity assists from both the Moon and the Earth - for a wide variety of missions. Paul has developed one such application for application in 2002, using piggyback flights on Ariane 5 launches of comsats to GEO. By the conclusion of his talk, Paul left no doubt that the Moon has been and will continue to be important in space exploration.

That concludes the summary of the Transportation Session.

SUMMARY OF THE EVENING PANEL DISCUSSION: SPACE POWER AND THE ENVIRONMENT

Chair: Christopher Faranetta

Following a brief introduction of each participant and the topic, each of four panelists made a 5-10 minute presentation outlining their positions on the topic. The discussion was then opened to the audience for comments and questions. An abstract of each panelist's presentation is included below:

Robert Gent, Astronomical League:

The science of astronomy faces three serious threats. The International Dark-Sky Association describes these problems as light pollution, radio frequency interference (RFI), and space debris. The sky glow from light pollution already threatens the very survival of both professional and amateur astronomy. In addition, radio astronomy is now critically threatened by telecommunication, navigation systems, and other radio signals transmitted from space. While not as critical to astronomers as other issues, space debris is a matter of significant concern. Launch of space-based reflectors to illuminate cities at night poses a potential and new threat to astronomy. Solar power stations sending powerful microwave beams to Earth may virtually shut down all ground based radio astronomy. Any future proposals should be reviewed by environmental groups and astronomers to assess potential negative impacts on astronomy and the environment.

Margo Deckard, Space Frontier Foundation:

The standard of living of a nation is directly related to its per capita energy use, and the world is filled with rapidly growing nations that need more energy. The US Department of Energy projects that worldwide demand for energy will double in 20 years, and double again in the next 20. It is clear that current energy sources are not going to be adequate or environmentally clean enough to meet this need. The Sun supplies the Earth with an abundance of natural energy. Space Solar Power (SSP) is a means of collecting that energy and beaming it down to the Earth wherever it is needed.

Products in today's market must pass the social test. Passing this test for SSP means that it must follow good stewardship practices with a controlled, well-understood and limited environmental impact. This process can not be just scientific, it must also deal with public perception issues.

Failure to address the environmental issues related to the large-scale development of space solar power could result in a polarized situation with popular environmental groups and ecologists on one side and the SSP supporters on the other. This polarization could make the adoption of SSP very difficult, unnecessarily expensive, or impossible.

Guy Pignolet, CNES:

Pignolet discussed the potential effects of space power systems on the environment (natural, social, legal, etc.). He looked at the problem from the non-developer's end first. Would the environment even allow the construction of large space illumination or space power systems when the democratic and economic concerns appear to be so short-sighted? Next, even if ours has the potential to become a truly space-faring species, is it responsible and mature enough to be given now advanced global tools? He submitted that the question of positive and negative effects is a false, poor dimensional question, which will eventually dissolve in the "overview" co-evolution; that the technology is ready for a nice job, that some individuals are ready to see that it would happen with harmony, but that our social and political environment is, by and large, not ready yet to handle the question properly. We have space, let's take time.

Vladimir Syromiatnikov, Space Regatta Consortium:

This presentation was devoted to the practical experience gained from the first space experiments to reflect sunlight to the night side of the globe. In accordance with the mail subject, special attention was given to the professional and public reaction to the experiments. Syromiatnikov also provided a brief assessment of the potential impact of space illumination on the environment.

SUMMARY OF THE EVENING SESSION AND ROUNDTABLE DISCUSSION: VIEW FROM 1999

Chair: George Friedman

Many aspects of Gerry O'Neill's vision remain valid today; yet there is still much to do.

These elements of O'Neill's high frontier are as valid today as when he defined them over twenty years ago:

- The exploitation and colonization of space is essential to humanity's material future as well as its sense of purpose and freedom.
- Space resources should be employed rather than expensively lifting them from Earth, with the highest initial priority given to space power beamed down for use on Earth.
- Human colonization sites should emphasize rotating space habitats rather than the surfaces of the planets and moons of the solar system.
- Efficient transducers of sunlight to kinetic energy should be developed to transport mass and to provide propulsion within the inner solar system.

Despite the accuracy of the high frontier vision, its pace of development is disappointingly slow. There is much to be done, beginning with a critical examination of these tempting illusions that we share with most idealistic space enthusiasts:

The illusion that US space policy and funding can be extrapolated from the early years of the Sputnik to Apollo era and that the cost of lifting mass to orbit will be substantially reduced.

The illusion that manned space missions are analogous to the exploration and colonization of the western hemisphere.

The illusion of rationality -- that good ideas will be implemented merely because they are good, and that it is not necessary to sell them to decision makers.

The illusion of a catalytic ignition, followed by exponential growth, where humanity's machines and humanity itself self replicates into the universe.

The illusion that science fiction is an accurate predictor of the pace of technology and the future of the human race.

There have been favorable trends and emerging technologies; we must recognize them and seize the opportunities:

The cold war is over. This diminishes the "space race" priority, but more resources are now available to improve the lot of humanity. Our challenge is to sell the high frontier to the public and governments as an excellent long-term investment in the well-being of all citizens of earth.

SSI and its sister organizations have been increasingly effective in getting this message to Congress and the general public.

The concept of space solar power, after an unfortunate setback in the 1980's, is once again receiving substantial funding. The National Science Foundation has sponsored a special conference to evaluated promising SSP technologies and systems concepts.

Cheap Access to Space is enjoying increasing attention from both governments and private entrepreneurs. A factor of ten cost reduction is reasonable employing conventional rocketry and another factor of ten should be attainable employing advanced techniques such as mass drivers and laser beam rider propulsion.

Advances in microelectronic and micromechanical systems over the past decades permit the far more efficient utilization of payloads and telerobotics for a great variety of missions and new man/machine tasking strategies.

Our knowledge of the resources of near-Earth space -- especially earth orbit crossing asteroids (ECA's) -- has vastly improved over the past ten years. Not only do the ECA's promise a far greater variety of crucial material than the lunar surface, many of them are more reachable from an energy expenditure standpoint. The logistics of building habitats now favors construction at the site of the asteroids, rather that transporting material from the Moon to L5.

The mass driver (linear motor) is an inspirational concept to free ourselves from the traditional restrictions of rocketry, but it should be extended to include the mass catcher (linear generator) in order to complete the problem of mass transport, propulsion and momentum transfer within the inner solar system.

Sending people into space is our most difficult task. The use of telerobots -- when practical --is far easier. Easier yet is the transmission of energy. Easiest of all is communication, the transmission of information. Our technology plans and investment strategies should be mindful of this ladder of difficulty; it the past they have not.

There is far more good news than bad O'Neill's vision still lives. We must keep the faith and sell our story.