

N91-22142

A REMOTELY MANNED SPACE STATION MARVIN MINSKY DRAFT 4/1/90

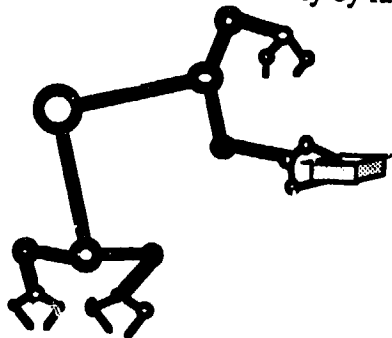
## PROPOSAL FOR A REMOTELY MANNED SPACE STATION

Marvin Minsky, MIT

The United States is in trouble in space. The costs of the proposed Space Station Freedom have grown beyond reach, and the present design is obsolete. The trouble has come from imagining that we have only two alternatives: manned vs. unmanned. Both choices have led us into designs that do not appear to be practical. On one side, we simply do not yet possess the robotic technology needed to operate--or assemble--a sophisticated unmanned space station. On the other side, the manned designs that are now under way seem far too costly and dangerous, with all of its thousands of EVA hours. We'd accomplish more at far less cost--by proceeding in a different way. Here is what we ought to do to achieve this third alternative

- Design a space station made of modular, Erector set-like parts.*
- Develop mechanical telerobots to be remotely-controlled from Earth.*
- Train earth-based workers to build the station in space using simulators.*
- Launch a small preassembled spacecraft with a few of the telerobots.*
- Ferry the telerobots into orbit, along with stocks of additional parts.*
- Instruct the trained terrestrial workers to remotely assemble a larger station.*
- Launch materials for additional power, and life-support systems.*
- Finally, send human scientists and explorers.*

The initial cargo would begin with a conventional pre-assembled system for propulsion, power, and communication. The novel aspect is to equip the station with three or more remote-controlled mobile mechanical hands that can move themselves from place to place. These manipulators--call them "telerobots"--are controlled by human operators who use "power gloves" and "control suits" to translate their movements into the corresponding telerobotic acts. Each telerobot, in turn, provides a sense of "telepresence" to its operator by returning visual, auditory and tactile sensations, using head-mounted visual and manual force-display technology. Simple such systems already exist, and better versions could be developed in a very few years. In less than a decade, the project would be years ahead of what's being planned now. If we use a suitably modular design strategy, we should be able to use these telerobots to maintain and repair one another--as well as other components of the space station. Our proposed "tree-robot" design has but a few types of components, each made on scales that differ in size only by factors of two.

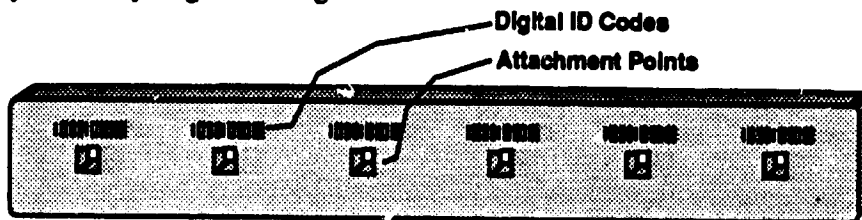


A Binary-Tree Telerobot

The initial cost of such a space station could be very modest, because it lets us postpone costs of safety and life-support systems until manned operation becomes desirable. The first human operators will work on Earth; later they'll be on the station itself--and then, before long, they can work on the Moon.

## THE MICRO-MODULAR SPACE STATION

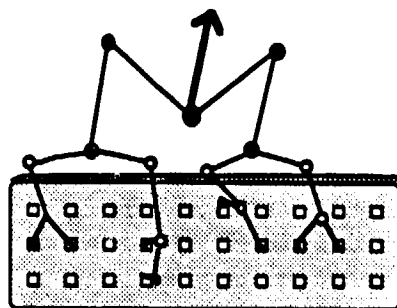
The use of remotely manned telerobots will let us re-think all our old concepts of space technology. Now we can aim toward making even the smallest structural components so modular that, in effect, the entire station can be built with elements like the kinds used in construction toys like Erector™, Meccano™, FischerTechnic™, LEGO™, or TinkerToy™. Every surface of each component should be studded at regular intervals with standardized "attachment-points" each labelled with a unique, machine-readable identification mark. This policy has many large advantages:



A typical structural component

- It enables a computer to keep track of all spaceborne materials.
- It permits re-use of the same parts for different purposes.
- It simplifies simulation, assembly, and design.
- It reduces the total inventory mass of material and spares.
- It simplifies training for assembly operations.
- It simplifies subsequent development of autonomous robotic operations.
- It facilitates both telerobotic and manned mobility.
- And it simplifies converting lunar or asteroidal materials into useful components.

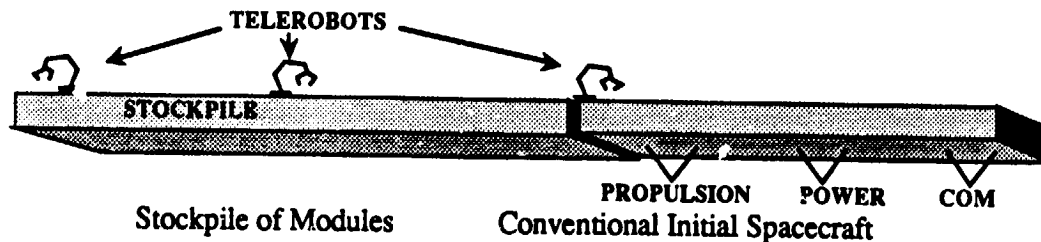
The use of micro-modularity will make it easier to design and debug both the structures themselves and the skills involved in assembling them. The availability of attachment-points will make it easy for the telerobots to move from place to place.



Telerobot traversing a beam.

## STAGES OF DEVELOPMENT

The initial configuration should begin with a conventional spacecraft equipped with power, propulsion, and communication facilities--and bearing a stockpile of modular parts. Then a much larger station can be remotely assembled in space.



### **I. PREPARATION FOR INITIAL LAUNCH:**

- *Develop the modular components and connectors for space structures.*
- *Develop the modular components and connectors for the telerobots.*
- *Develop the telepresence communication systems for the sensors and actuators.*
- *Use two Telerobots to assemble a third, under neutral buoyancy conditions.*
- *Start training workers on Earth in operational and maintenance skills.*
- *Establish minimal-delay satellite communication network.*

### **II. INITIAL LOW EARTH ORBIT CONFIGURATION.**

The initial unmanned station in LEO is equipped with conventional packages for power, orbital maneuver propulsion, and satellite communications. Its principal payload should consist of three or four telerobots and a stock pile of parts. All further construction will be done by telerobots controlled by workers on the ground, who will reconfigure and extend structures as necessary. Because it is both desirable and feasible to move slowly at first, the initial power requirements will be small; the telerobots should need less than 1KW of power.

### **III. DEVELOPING LEO SPACE ASSEMBLY OPERATIONS.**

- *Assemble and test larger structures.*
- *Operate instruments for scientific research.*
- *Practice Telerobot disassembly and repair.*
- *Launch materials for life-support systems and living quarters.*
- *Launch materials for commercial prototypes.*
- *Experiment with tethered and free-flight transfer operations.*

### **IV. BEGIN LARGER SCALE OPERATIONS.**

- *First manned residence and industrial operations.*
- *Astronauts practice local, delay-free control of telerobots.*
- *Introduce semi-automatic assembly operations, using planning programs.*
- *Assemble and test larger life-support and residence systems.*

### **V. BEGIN LUNAR OPERATIONS.**

- *Proceed with similar procedures to assemble a lunar base.*
- *Experiment with refining lunar materials.*
- *Begin preparing interplanetary or asteroidal exploration vessel.*

## THE CONCEPT OF MICRO-MODULARITY

In contemporary NASA jargon, the term "module" is applied to any self-contained system, even one so large as an entire space shuttle payload. Here we shall use the term "micro-module" for the idea that every structure should be composed of standardized parts --like those of children's construction sets --wherever this is feasible. Even simple containers should be assembled from smaller plates and beams, except for imperative reasons. This policy may sometimes cause small increases in spaceborne mass, but will usually yield large economies when the same parts are later reconfigured for other applications.

**ATTACHMENT-POINTS.** Every micro-module should be covered with Attachment-Points, marked with unique and precisely located machine-readable optical identification patterns. We must also provide suitably standardized connectors for assembling larger structures. Each connector device must be easy to apply, test, remove, and firmly lock. Re-usable rivets might suffice, but we should also seek a reversible welding technique.

**SPECIFICATION REGISTRY.** Adopting a uniform attachment-point identification scheme would enable us to maintain an international register in which every object launched into space could have a unique ID. Whenever a new structure is needed, a CAD system could then locate required components, even considering those in other, already assembled systems. These spatial ID markings could also be used to locate remote instrumentation devices. For example, passive vernier strain gauges could be located at appropriate points, because optical scanners could easily read them--at no additional hardware cost.

**AUTOMATING TELEROBOTIC OPERATIONS.** What if we wish a telerobot automatically grasp and assemble a certain set of objects? We cannot automate many such functions today, because our present-day robotic technology is not mature enough to do such things reliably. In particular, the technology of Machine Vision is still too weak. But adopting micro-modularity, we could do this today, by exploiting the precisely located ID markings of our micro-modular components to access data bases that precisely specify the spatial shape of every registered micro-module. That knowledge-base would make it easy to build software to reliably locate and assemble the needed parts. Such programs could be made extremely robust by testing the match, at every step, between the sight, and the feel, of the actual scene with what our simulators predict. At the first sign of discrepancy, the system can stop and revert to remotely-manned operation.

**MOBILITY.** How would our telerobots move from place to place? This would be very hard to do in a conventional spaceship, where each change in location poses new mooring problems. But if every surface of the micro-modular spaceship is studded with attachment-points, the telerobots can exploit these for mobility. At each point, then, a Simulator could plan ahead, locating ID-points for further steps, so that the telerobot can move by grasping one attachment-point after another: each new one being verified, both by vision and actual touch. At the same time, the simulator would also confirm the suitability of every new attachment-point for anticipated loads and strains.

**CONCURRENT SIMULATION.** Adopting micro-modularity would simplify full-scale simulation of the entire station, under both actual and hypothetical conditions. The goal should be to maintain a data base that holds, and constantly verifies, the location of every known component--including all available knowledge about the physical states of every part: their stresses, velocities, temperatures, fatigue histories, etc. Such a system could be used both to plan and debug each new construction, and also to train the telerobot operators, to support them with anticipatory feedback (to reduce the apparent time-delay), and to automate routine procedures.

## TELEROBOTS SHOULD BE MODULAR, TOO

The telerobots themselves should be made of only a few pre-assembled components, with each skeletal element equipped with its own motors and sensors--so every unit is easily replaceable. The motors need not be very strong, but each joint must include a fail-safe brake that locks when local power fails. A single docking connector should complete both mechanical and electrical connections. Supplying power and signals has always been hard, in designing terrestrial robot arms. But this should be somewhat simpler in space, where the power required is so much less. Because a typical motor needs less than one watt, it might suffice to run a simple two-wire bus throughout the tree, treating every sensor and motor as a single, separate network node.

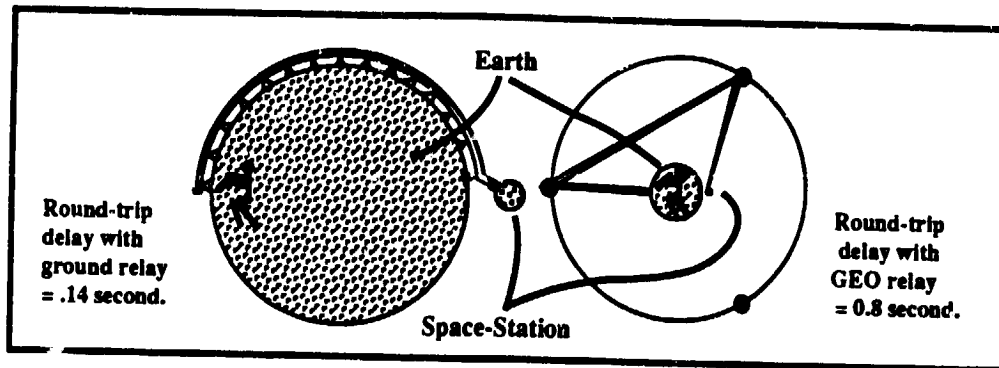
Such telerobots would be dependable, because the tree-like design has enough "redundant" degrees of freedom to be usable in spite of occasional joint failures--provided that they lock when they fail. Earth-based manipulators, have always been designed with as few joints as possible--because gravity demands such relatively massive motors and beams. Indeed, to develop the tree-robots on Earth, we may have to test them in neutral buoyancy conditions.

A more radical approach to mobility would equip each joint module with an independent communication system and power supply. A one-watt motor with 25% duty cycle can run a full day from a single size D rechargeable cell. NASA's free-flying teleoperators will be impractical for large scale work because they consume too much reaction-mass. But self-contained telerobots could propel themselves by the ballistic exchange of reaction-mass objects--including batteries. If an object is projected slowly enough, its trajectory can be verified before it exceeds the reach of the throwing arm; in any case, such objects could be retrieved by tethers. For larger scale operations, we could surround the entire workspace with a tethered tetrahedral skeleton, tensioned by the momentum flow of masses exchanged between vertices.

## TELEPRESENCE AND TIME DELAY

Why have telerobots not have been used more in space? This seems largely because of a widespread belief that no one can work effectively through systems involving time-delays. But I am convinced that this is wrong--if the feedback delays are large enough! People are telerobots, too, because our bodies and brains must always cope with internal time-delays of the order of 0.2 seconds between sensation and action. You cannot hope to catch a ball by "keeping your eye on it." Because of your reaction-time, your brain must anticipate its trajectory, at least for that final interval. This critical subject is discussed at more length, in this essay's Appendix.

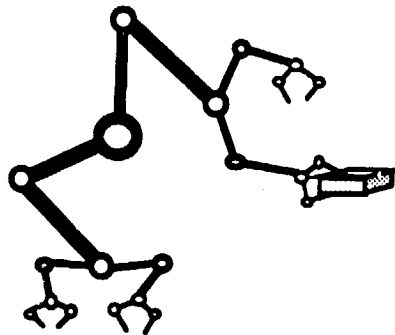
Transmitting a round-trip signal between Earth and a low-orbit satellite would take at least 1/7 second, and would require a very expensive equatorial belt consisting of a dozen or more earth-based communication stations. A more economical system would relay signals between Earth and three geosynchronous relay satellites. This would involve a longer delay of nearly 1 second.



With suitable training, remote operators should be able to learn to perform useful work at "one-fifth real-time" speeds--and eventually faster, when some of the effects of delays are reduced by exploiting computer-supplied "anticipatory feedback" and "supervisory control" modes of operation. In the appendix to this paper, we argue that this mode of work is not entirely unlike that done by people who operate large construction-cranes--systems that impose similarly slow reaction times.

### PRODUCTIVITY ADVANTAGES

A common objection to these ideas is that these time delays will force the work will proceed too slowly. But simple arithmetic refutes that view. Each pair of remotely manned mobile hands should be able to accomplish as much as a space-borne astronaut. For, even in the unlikely case that space-suited workers could tolerate 6 hours per day of EVA operation, it is hard to imagine this yielding more than the equivalent of two to three hours of earthside work. Consequently, we must compare 20-hour human weeks against 168-hour telerobot weeks--and even this is conservative, because anticipatory feedback computer enhancement should at least double final efficiency. So, even proceeding at 1/10 speed, each telerobot could accomplish a human equivalent of work--at perhaps one percent of the other's cost, and an infinite gain in safety.



What would such systems cost, in mass? Each telerobot need not weigh more than about 10 Kg. in contrast, each human EVA operator needs on the order of 2500 Kg, when we include not only the person's own weight but also that of the spacesuit, consumables, and life-support equipment, as well as the mass needed for reinforcement of pressurized living quarters--to say nothing of ferrying astronauts home. Remotely-manned operations offer a hundred-to-one advantage in cost.

## THE US SPACE PROGRAM IS A HOSTAGE TO SAFETY

Our manned space expeditions have been wonderful accomplishments, but were expensive, risky, and limited. And although it is claimed that humans on board made it possible to do emergency repairs, the actual record is not so impressive. The Apollo 13 crew was unable even to examine the damage. The Skylab parasol repair involved a mechanically simple task; yet the crew was able to restore only a portion of the lost function. STS crews have also managed only rather simple repairs. And as for automated unmanned missions, some of them did indeed work remarkably well, but mainly because of conservative plans, with almost everything planned out years in advance.

Today, though, Space seems tedious. A hidden cost has been overlooked: neither manned nor unmanned ships permit extensive repairs in flight, hence we're forced to depend far too much on maintaining reliability. Trustworthiness, not resourcefulness, has become the program's centerpiece--and the name of that game is constrained design. This makes us pay a crippling price--*of having to freeze our plans years in advance*. That's what we did in the early years, when we simply had no alternative. But now this has restricted us to obsolescent technologies, and institutionalizing a sluggishness that virtually bars us from challenging Space. Nothing new can be tried any more.

This problem has grown in the past few years because of our increasing concern for human safety. The Challenger disaster substantially delayed the entire space program, to reduce the chance of one accident. Prior explorers were careful, indeed, but not to any so drastic degree. Our astronauts now play the roles, not of leaders, but of "hostages", because we will do virtually anything to protect their safety. This is no mere concern of NASA alone, but part of a broader phenomenon in which people demand outlandish constraints on every aspect of daily life. Even in medicine--the technology of life itself--we have become so concerned with guarantees that we won't dare to save a hundred lives at the risk of losing any of them. This poses for NASA a dreadful dilemma: a perception that the public will support nothing less adventurous than manned exploration--but will never forgive any accident. This new cultural context provides no way to provide NASA with the "liability insurance" it needs. Manned flight is too risky and expensive, while unmanned operation is too inflexible and unsensational. Like many physicians in recent years, this dilemma has led NASA virtually to retire from practice, albeit without admitting it.

We might escape from this double-bind by adopting this alternative--of remotely manned operation. Using that way to go into space, we can prepare each expedition by using earth-based workers to do what would be, in space, much more dangerous, costly, and difficult. Because the initial station is unmanned, yet still able to exploit the intelligence of its remote operators, we can use it to try more experiments and develop new technologies. Using remotely manned operation, we can achieve our goals while gaining versatility--with at least a tenfold reduction in cost. As for safety, *no one gets injured when no one is there*. Nor should we reject this as a step away from manned exploration. On the contrary, it would speed up developing what we'll need for more ambitious voyages.

## THE ISSUE OF POPULARITY

When they hear this proposal, most people say, "I agree that this might be a good idea, but I'm sure that the Public won't buy it". But it seems to me that this belief is based on a wrong perception.

The public WILL buy it. Those objections might have been valid in the 1960s, but now they're out of date. In fact, the real problem is the opposite: *the public has grown weary of two decades of dull and non-productive man-in-space activity*. These days, few people learn the names of astronauts; today, it is Robots that are "in", like Artoo-Deetoo, HAL and Terminator. The youngsters adore Transformer™ toys, and spend their fortunes on new interactive game cartridges--new virtual realities to spark their personal game-machines. It started out with those TV games--old Breakout, Pong, and PacMan stuff, and then evolved from Zaxxon and Megaroids to Mario Brothers. This year, a million PowerGloves work in our children's homes, just waiting for their owners to manipulate some things in space. Those skeptical critics are out of date!

A remotely-manned space program will give the public a chance to share in the fun. Using simulators, we can post competitions to recruit people talented at assembling tricky systems and mechanisms. Soon there could be thousands of telerobot operators, working in local communities. Then Space will seem accessible, no longer only for strangers in far away places. This program will be more exciting in any case, because the new constructions and experiments can be more adventurous, and can proceed so much more rapidly, than could any involving risk of life. New structures and experiments will be completed much more frequently, attracting more active public interest. For reasonable fees, even non-technical persons will be able personally to experience the operation of actual telerobotic systems, first in far-away places on Earth, next in near-space, and finally, right there on the moon. Many people can thus get involved in active exploration roles.

Furthermore, the new telepresence simulation technology will contribute to new forms of entertainments for the public at large--of the kinds called "virtual realities". Imagine teams of players on moons (whether real or imaginary) engaging in strange new contest-games--building, or fighting, or playing games--or simply exploring and making friends. Among the many individuals engaged in these new practices, popular "stars" will start to emerge, as in all domains of human enterprise--and as our old heroes fade from mind, we'll adopt new idols of different kinds.

Acknowledgment: I wish to thank Robert E. Maas for many suggestions; also Dale Amon and Nathan Ulrich. The basic idea of tree-robots was first proposed by me in the 1960s, and later developed independently, and in much more detail, in Hans Moravec's *Mind Children*, (Harvard University Press, 1988)

\* \* \* \* \*



## Appendix on TELEPRESENCE and TIME-DELAY

*How could we start a new program based on such an immature technology? The project would have to wait too long before such telerobots become available.* People have said this for two decades. There has actually been substantial progress in systems that "reflect" the joint-forces back to the human operator. The general experience has been that people can perform gross operations at normal speeds, but delicate operations may take 5 to 10 times longer to perform. This is partly because previous manipulators were so clumsy, having only plier-like grippers; more dexterous multi-fingered hands are now in development. Also, previous teleoperators lacked tactile feedback at their fingertips--and small improvements in this domain will yield major gains in performance.

*Conventional manipulators have only 5 or 6 degrees of freedom, but you propose dozens of joints. How could we possibly depend on such complex new gadgetry? Increased complexity does not imply less dependability.* Additional (redundant) degrees of freedom are actually desirable! A person with an injured joint usually can manage things; even if one can't walk normally, one may still be able to limp. Terrestrial robots have never been designed to exploit this possibility, because it has been so hard for them to support their own weight against gravity. But redundant design is more feasible for low-torque work in low-gravity space, where it will actually increase reliability--if every joint has been equipped with fail-safe brakes.

*Won't time-delays make it impossible for people to use remote manipulators.* This is the most common objection to remotely-manned space operations. People often cite instances in which time-delays cause difficulties. Let me paraphrase some examples from my E-mail files:

"In a certain experiment, a TV camera and remote driving set-up was installed on a Go-Kart, with a five second time delay between the camera's transmission and the driver's video display. The driver then had to negotiate an obstacle course of moderate difficulty. Nobody was able to successfully negotiate the course."

To this, Paul Dietz replied, "*I don't think this proves anything, except that a 5-second delay means you cannot operate a Go-Kart at normal speed. Need I remind you that teleoperation of a lunar rover was accomplished years ago by the Soviets?*" In a similar vein, Joe Dellinger rejoined, "*I remember reading an article describing how they train pilots of Oil Tankers. They sit them in a very small very slow motor boat in a small pond, and put HUGE delays on all the controls, like 30 seconds. The article said that at first the pilots would crash the boat against the walls, etc. etc, but with a little more practice they would learn to pilot it exactly where they wanted to go without thinking.*" And Dellinger went on to add, "*Mammalian nerves carry signals faster than "more primitive" life's did, and yet 100 foot long dinosaurs whose nervous system probably took half a second to carry a signal from their hind feet to their head and back evidently walked around on irregular terrain at respectable speeds without tripping over their own feet.*"

When first you learn to drive a car, you find that it takes time to change direction--but soon you learn to anticipate. Similarly, at first it seems hopelessly awkward to operate a large boat, an airplane or a construction crane, or for pianist at first to play a pipe-organ. Eventually, though, most people learn. It seems to me strange to hear such concern with telepresence time-delays, when all around us we see successful control of delay-constrained systems. In most cases, all we'll need to do is--*slow down*.

"Some international phone calls introduce short (1/2 second) delays into your conversation, and this makes your standard speech protocols break down. It causes collisions in which both sides hear a dead area, start to speak, and then collide again with each other. I've found these conversations to be very fatiguing."

"It is difficult to work with computers over a heavily used INTERNET trunk that imposes large delays. It is frustrating to get several characters ahead and then find that I've made a typo. If I were working with a process where each action had an effect on the following ones, I could be far off track by the time I got feedback that I'd made a wrong action!

Again, we merely need to slow down. Those telephone calls would work quite well, if both parties were willing to "over and cut". That typist would have no trouble at all, when typing at a slower rate. We ought to remember that humans, too, are telerobots connected to brains. We all adhere to a cultural myth that mind is directly connected to world. A sounder view would recognize that human sensory-motor loops are not instantaneous, but take some time--of the order of  $T = 1/6$  second. Therefore, when we introduce, not a *delay*, but an *additional delay* of magnitude  $D$ , we should expect our performance speed to be reduced by the factor  $T/(D+T)$ . Thus, a one-second *additional delay* should permit one to work at  $1/7$  real time--for example, when operating devices on an earth-orbiting space station, as seen through a geosynchronous relay satellite system.

In any case, so far as large-scale space operations are concerned, the additional telepresence delays should present no trouble at all--because we have to slow down in any case. For example, to rotate a 10 meter beam, one would normally apply very small accelerations, because spaceworthy structures have flimsy parts that cannot tolerate earth-scale stress. Large-scale work can *only* be done in slower than normal "real time".

*But we can't always slow down. What about work that must be done in "real time".* The phrase "real time" should not be used to mean "instantly"--because *no* system can react without delay. That expression should refer, instead, to the sorts of things that a person can do in the order of 0.15 seconds. Consider, for example, that popular party-trick of suspending a dollar bill by holding the top about one inch above and between a victim's fingers. When you release the paper and it falls, no one can catch it. Human reactions are simply too slow. But many such problems will be simpler in space--if we think of vacuum and lack of gravity as assets instead of antagonists. That dollar bill's fall is determined by G--but no such bound applies in space, so our telerobot operator will find no problem in catching it. "Real time" can go slower in space!

"Suppose that a tele-operator turns a valve that releases coolant from a reactor. The operator on Earth waits for one second, then realizes the mistake and turns the valve back. One second's worth of coolant loss may not be so important on Earth, but on the Moon, that coolant may be irreplaceable."

This problem has little to do with time-delay. Even an astronaut right at the scene would lose some of that coolant. One answer lies in imposing appropriate protocols--for example, to slow down and institute safety checks, such as "*do you really want to do that*" dialogs. But every computer user has learned that no such schemes ever keep working for long. It is easy to talk about slowing down--but can we train people to work both slowly and reliably? This problem, again, is not one peculiar to teleoperation. Human attention is hard to maintain through any slow and uneventful task. We see the results right here on Earth, with oil tankers running aground. The problem is one of vigilance. Indeed, in the case of remotely-manned operation, we could always shorten sessions and rotate crews, because so many terrestrial workers are available, whereas that option is rarely open in space--and there is no way to maintain perpetual discipline among a limited staff of weary, overworked astronauts. We just can't expect to find a way to make people maintain constant vigilance. Ultimately, this problem can be solved only by more automation.

*Even if people could be made to slow down, won't things then take too long to be practical?* The cost-advantages of remotely manned operation would seem overwhelming because, as we argued earlier, even if the work proceeds 10 times more slowly, the on-location productivity of each telerobot will rival the equivalent of a full EVA work-week--at a hundred-fold smaller cost of launch.

*Why do certain ranges of time delays seem especially disturbing?* We have encountered peculiar difficulties in dealing with telepresence time-delays in the range between 0.05 and 0.5 seconds. For example, most people suffer a peculiar experience when they try to speak coherently through acoustic feedback systems that return an echo a fraction of a second later. This often results in a devastating stutter, in which the subject repeats many syllables. We see similar phenomena with delayed visual feedback. For example, when you try to write on a graphics screen, through a system with the same order of time-delay, you find yourself stuttering now with your hand--by repeating the loops in some characters. I have the impression that these aberrations are most disturbing for small delays, but they are not so apparent with larger delays--such as those we'll encounter when working in Space. I suspect that this could be because our brains have evolved specialized ways to deal with internal delays of those magnitudes: then these "stroboscopic phenomena" might arise from sub-systems of the brain having corresponding time constants. Consider that one would expect various parts of the brain to contain machinery specialized for comparing what actually happens, after each motor action, with what was planned or expected to happen. Schemes of that sort would seem quite indispensable, for providing information both for controlling, and for learning about, coordinated sensory-motor activities. Now each such mechanism can be presumed to engage some type of memory buffer and some variety of time-gated comparison scheme, both actuated at intervals comparable to that of that particular brain-system's sensory-motor loop-delay. (If such comparisons proceed at regular intervals, they might be detectable as local brain-wave frequencies.) Consequently, we might well expect "stuttering" types of disturbances whose magnitudes peak when those sensory cues are delayed by those singular intervals. But these special effects ought to weaken in strength with larger delays, and perhaps disappear entirely, when larger delays force workers to switch over to other, more deliberate modes of operation. If this is right then, paradoxically, we might get better performance using the 1-second GEO relay system than with the faster, more expensive 1/7-second earth-based relay alternative.

## Space Travel for the Next Millenium

Theodore Taylor

Transcript of invited talk for Vision-21 Symposium

For some eight years there were about two dozen of us at General Atomic at San Diego who were literally packing our bags to go off and explore the solar system. Maybe one way of summing up what we saw in our immediate future was our goal for 1970—which was Ganymede. We saw a way of getting from Earth anywhere in the solar system fast in spacecraft that were roughly one-third engine, one-third propellant and energy source, and one-third payload. We designed a lot of vehicles, and they all came under what we called the Project Orion. The project started the night of the announcement of Sputnik 1. It was an effort by a few of us to, as it were, recover our lost face because the Russians had been putting zoos in orbit and we were struggling trying to get something up there. We said "What do we really want to do?"

I want to come back to that question a couple of times in what I'll have to say, that question of "What do you really want to do and what is in the way of doing it?" And, if there is nothing in the way, then do it. The basic idea of Orion actually evolved out of a thought that Stan Ulam, the co-inventor (along with Edward Teller) of the H-Bomb, had (apparently) the day after the trinity explosion at Alamogordo. He was thinking of propelling things at ICBM velocities. This was in 1945—"Getting up to those speeds takes a huge amount of energy. This is the most energetic think we've got, what we saw yesterday. Is it crazy or not to think of a series of explosions that come from nuclear explosives that are carried on some kind of a thing that, somehow, explode behind it and it goes up to whatever speed is of interest?"

I've always been a space buff, ever since I can remember. And it didn't take an awfully lot of thrashing around that night in October 1957 to say that Stan was right, that that was the way to go. There followed a lot of things that were unbearably exciting and particularly unbearably difficult to give up when the project died about eight years later in 1965. I just want to say a few things about that. Mostly in the context of what we thought was a very real vision of our future. Most of us working on the project were in our late 20's, early 30's. I was 32 when it started; I was 40 when it died. And we saw our future very clearly—go out there and explore it.

It took us about six months to find money beyond a rather plush General Dynamics in those days. They gave us the resources to get going and put together a fairly persuasive proposal on what to do. At that time NASA didn't exist yet and it wasn't at all clear who was in charge as far as space activities were concerned. To make a long story short, Roy Johnson, who was the first director of ARPA--what was then the Advanced Research Projects Agency in the Pentagon--took hold very hard the first time we went in to see him. He had just hired Herb York as his Chief Scientist and Herb was an old friend from Los Alamos days, and so on. So we started a formal project for ARPA in July of 1958—a million dollars for one year.

That one year was packed with excitement, and I think some real accomplishments. One of those accomplishments was the successful flying of the first object that, as far as I know, has ever flown that way—and also the last that has ever flown that way. It was a one meter diameter model which had five charges, of about 2 pounds each, of high explosive inside. It fired them out sequentially—5 of them—and it got up to about 200 feet and a little parachute opened and the thing came down.

A key thing happened as we got going. This was very soon—a few days—after Sputnik was announced. Freeman Dyson, who was at the Institute for Advanced Study at Princeton and with whom a number of us had worked on a whole variety of things at General Atomic, heard about this and it took him about five minutes to decide "this is it". He took a leave of absence from the Institute and came to General Atomic, and made a huge difference in what happened there. I can't resist saying that at a point when it wasn't clear what was going to happen to us, he had to make a decision; and that was whether to continue to be a very good theoretical physicist, or to switch and

become what might be recognized eventually as the greatest engineer, ever.

Well, he was one of the key people in that project for about eight years. The idea is basically fairly simple. The idea is to carry several thousand nuclear explosives inside, stacked up about half way to the end of that thing (they weren't H-bombs, they were fission bombs). And then to fire those sequentially, typically at a rate of about one a second, at a point about a diameter and a half from the bottom from the center. The nuclear explosives were not spherical A-Bombs. They were shaped charges. You can show on the back of an envelope that if you try to enclose a nuclear explosion in anything with any structure it will blow it to pieces.

So, we focused on the explosive charge itself, trying to conserve momentum and direct as much momentum as we could through the solid angle that was subtended by the bottom plate, which we called the pusher plate. This was a metal plate—we finally wound up settling on aluminum. So the explosion would go off and slam this plate upward with a speed of something like 15 or 20 meters per second. Then the problem was how to connect that with the structure. From the very beginning we designed for at least a half dozen people up front in this thing. It was always, always—without exception—a manned space vehicle. So, we had to cushion the shock and there is an analogue here which I think is accurate. It is sort of like a car riding along on a rough road. First you need tires. The tires were toroidal gas-filled assemblies on top of the aluminum plate. Then there had to be something which was the analogue of wheels connected to shock absorbers. That was a structure just above those toroids connected with some long nitrogen filled shock absorbers. Then, at the top of the shock absorbers, things had been smoothed out so that the ride was cushioned. Just pretty much like a car.

Above that, depending on the way in which this shock absorber—tire system was driven, you'd either get pulses of a peak of something like 4 g's up front or—this is what we finally settled on—you could drive it at resonance so that you'd squeeze the pusher plate up—nto the tires and the shock absorbers. And then as it bounced you'd stop it and return it. Since you're talking about 2000 pulses to get into orbit, we were sure that some of them would fail, so we had to arrange that the pusher plate would be stopped and pulled back every time there was a failure to restart the cycle. That took a lot of doing.

What we focused on principally for most of those years was something that would take off from the Earth's surface; it was 135 feet in diameter, gross weight 4000 tons; payload through a very difficult mission, brought back to Earth orbit (we wouldn't bring it back down to the ground) about 1000 tons. The idea was that we'd mount this on some towers a couple of hundred feet high, probably from Jackass flats or Yucca flats in Nevada. And then start off with some very low yield explosions, because the air mass between the explosions and the bottom of the vehicle acts like propellant in a way that's a little bit like a ram jet. So while you're in the sensible atmosphere the yields are quite low. It turned out that to get up and out of the atmosphere took about two hundred kilotons of total yield. In those days most people, certainly people in the business of nuclear weapons, weren't particularly concerned about fallout. The reason that we didn't worry about it, in the beginning at least, was because 200 kilotons was to be compared with several *megatons* of fission (half fusion/half fission) in the big H bombs we were setting these off all over the place, mostly out in the Pacific. The Soviets by that time were, too. So we said, another 200 kilotons for each flight? Who cares?

The performance of this thing was 4000 seconds nominal specific impulse, about 40 kilometers per second effective exhaust velocity, which depended critically upon how well we could shape the charges. It began to look less and less crazy the more we looked at it. By the end of that first year a lot of people were taking it very seriously. It was all secret—some vague descriptions of it were made public, but it was generally not much in anyone's consciousness except for maybe 50 or 75 people in the United States. We kept going and got more and more persuasive that this wasn't crazy and, in fact, was something that could be done. About 1962 NASA asked us to do some mission studies. NASA had not become involved in the project, even

after NASA was formed, because basically nobody in NASA knew anything about nuclear explosions. And this was at the heart of what we were doing. But we did start some mission studies that were very important and gradually moved away from some of the really outlandish versions of this that we started out with. In particular, we did start worrying about fall-out. What we settled down to was a 34 foot diameter set of modules (the shock absorbers) about half the charge (propellant systems as we called them—we had a tendency to call them bombs but they were shaped pulse units) and then the payload.

The idea was to put each of these parts, in sequence, on top of Saturn V and put them in orbit. Then assemble the whole thing. The number of packages depended upon what you wanted to do. Our favorite mission by that time was the round trip to Mars in 250 days: roughly 30 kilometers/second mission velocity. We dropped the specific impulse to about 2500 seconds and what we wound up with was a departure weight from orbit of about 500 tons. Then two components of the payload—roughly fifty/fifty: 70 tons to be left at Mars and 70 tons brought back, with a crew of 8 to 12 people. It looked as if that was going to happen in about 1962.

Then along came the Nuclear Test Ban Treaty with the Soviet Union, which forbade any nuclear explosions except underground. We reacted to that with a proposal that was actually made by Neils Bohr, who was invited to be the principal person at the dedication of General Atomics' very fancy laboratory in La Jolla. Marshall Rosenbluth and I spent a whole night to—4 o'clock in the morning—hearing Bohr as best we could (because his English was terrific, but he mumbled. I don't know anybody who ever had ease in listening to Bohr talk, whether it was in Danish or in English.) In any case, he poured out this passionate feeling about having tried to get Stalin and Churchill and Roosevelt, before we built the bomb, to agree that it would never be built. And he failed. When he heard about Orion we couldn't tell him about it in any detail because it was secret and he was a Danish citizen. But he decided that it did make sense. So he decided that what we should do is go to the Russians and say "let's do this together". Now this was opening up the door to the Solar System really wide open, but it was also to get rid of all our bombs. So that double attraction got Bohr very strongly promoting the idea of a joint project with the Soviets.

When the Test Ban Treaty came along we proposed exactly that. But we said that there are still some loose ends in this and we have to do some testing. If we can't do it in space we will do it on the ground. Not repeated flight tests underground, but there are some key questions remaining after a lot of experimentation, mostly with high explosively-driven lead plasmas that we used to mock up the conditions of stagnating debris—the propellant we call it—against the bottom of this thing. The key question was, "what's to prevent heating up and essentially destroying the whole ship?" And the answer was very simple—pulse. Pulse everything. If a glowing ember ever pops out of the fire place, you don't pick it up and put it back in the fire place—you just flick it. And the reason is you can deliver the same momentum in a very small fraction of the time of actual continuous pushing. And during that time, heat flow is strongly inhibited at these very high temperatures (about 100,000 degrees Centigrade) by a build-up of an opaque layer of whatever it is that it is slamming up against. That opaque layer is very protective. Just like moistening your finger to test a hot iron—the same general idea.

So, pulsing and controlled ablation came to be the answers in great detail to the question "Why doesn't this whole thing burn up?" That concept needed some testing with a nuclear explosion and we proposed in detail how to do this underground. For about three weeks in 1965 there was a joint decision by the Defense Department, the Atomic Energy Commission and NASA to proceed for three years in what we call an Engineering Practicality Demonstration Program. And assuming it was successful, and we presumed it would be, then to go to the Russians and say "let's do it together". There actually was for three weeks a decision to do that!

Then the whole thing started becoming unravelled. I counted 13 sort of fancy committees that were called together to review all of this in detail—the Air Force Advisory Committee, several committees of NASA, a couple of ad hoc ones, Congress looked at it— and nobody recommended

stopping it; and more than three quarters of them recommended going full blast. But, a large part of the aerospace engineering community, some in the government, some not, said "Look we've got to learn how to walk before we run. This is really running, and running fast. That's great, but we've got to walk first".

For example, proceed with the nuclear rocket. I think the people in the nuclear rocket program felt threatened by Orion. So the net result was that the first person to really be convinced that this was really kind of crazy to proceed with, was Jim Webb. And, so NASA fell out of bed. Very quickly the Defense Department did. Harold Brown was very nervous about this thing and I think was greatly relieved when NASA decided to pull out. The AEC interestingly hung on a little bit longer, but then they finally dropped out and so the project died.

I'm not describing this in a little bit of detail because of any strong urge to revive Orion, in that form, at least, but because I think it's important to know what it feels like to be planning, in the next 10 years, to go out and explore space in a huge scale. And that is an experience that few people have actually had. What comes from that is a vision of a future. And that vision I'm finding is coming back with some important changes right now.

I want to spend a few minutes talking about that vision. What I'm going to do is to just sort of tersely present some features of the world which this modified vision (it has some connections with Orion) consists of. I don't expect to be persuasive. I think most of what I have to say is provocative--some of you may find it very provoking--but I feel this so strongly that I think I need to get it out.

These are not predictions. Neils Bohr said many things that are very wise. One of them was "You can't predict the future, especially when it hasn't happened yet." So, these are possible features of the rest of the 90's and the early parts of the next century.

The first is that I see coming a global consensus about how the rest of a vision like this may actually come to reality. I see that happening because of the enormous urgency that it does happen before the end of the 1990's. Pretty much world-wide, there is a sense of what to do and how to do it to avoid what could be extermination of the human species--nuclear war, a big one, or, whether we have a nuclear war or not, to ruin our habitat, just ruin it, if we continue what we are doing now globally. So, number one in this vision is a consensus about what to do about all this in a lot of detail. Much of this work has been done, but there's a lot that remains to be done. And I think it had better be pretty clear before the end of the century what this is going to be--we've got 9 years.

The second is it has to be clear to most human beings that having large families is not, as it has been traditionally among most parts of the world where large families still appear, not a way to achieve security. This has to get out: that in fact more children, like more nuclear weapons, make you not more secure but less. I think there has to be coupled with that something that's technical (bio-technical) and that is a really satisfactory method of birth control. For starters, I'd focus on males, just because there's been much less focus than on females.

The next characteristic of this vision is that the threats of wars, particularly indiscriminate wars of retaliation with weapons of mass destruction, will be much less than they are today. As far as nuclear weapons are concerned, for years now I've been a staunch promoter of abolition altogether, as soon as possible. A lot of that can be verified by all kinds of measures, but not perfectly. We can't do anything perfectly, but we need a global taboo that it is absolutely repugnant human behavior to be any part of acquiring or maintaining nuclear weapons of any kind. I think that needs to shift over to biological and chemical weapons as well. This whole idea of deterrence by maintaining a situation in which a country can flat-out murder a large population of people that have nothing to do with the decision to proceed with an attack--I find that monstrous. And I think that there's a very good chance that public pressure world-wide will bring that about. I

don't see that coming universally from government leaders. I certainly don't see it coming from the leadership of the United States. There have been—some people say somewhat half-hearted attempts by Mikhail Gorbachov and later Rajiv Ghandi, who is now out of power of course, to press for that, but a lot of that has been ignored and laughed at. I think it is dead serious and we had better DO IT.

Unfortunately, abolishing nuclear weapons but pressing for and expanding nuclear power seems to be incompatible. The reason I say that is that right now in about 40 countries in aggregate there are about 100,000 tons of spent power reactor fuel. The plutonium in that fuel can, counter to popular wide spread opinion, be used for making efficient, light-weight or heavy-weight nuclear warheads of all kinds. The total quantity of that plutonium is about 1000 tons, which is roughly five times the total amount of plutonium in all the world's 60,000 nuclear warheads. So how is it that we are going to arrange things so that a couple of countries, let's say the United States and the Soviet Union, continue to maintain 200, 500, 2000 minimum deterrent (so-called) nuclear weapons in a world in which the hardest part of making the nuclear weapons has been done in 40 countries with these huge numbers and somehow say "it is good for us but not good for you"? "You can't have them, we can have them!". That doesn't fly if you talk to a few Indians or Pakistanis or Brazilians or Argentines or Mexicans or Iraqis or Iranians or whoever that don't have them or even some people that do but secretly (like Israel). And the idea that somehow the two superpowers (or really five) can continue to behave as though they are much safer with nuclear weapons than without them but nobody else can do the same. How do you enforce that in a world that is awash with plutonium? That's one problem I've never seen addressed in such a way as to say it really is solvable.

What I see happening is that for a lot of reasons, but the main one of which is the weapon connection, we'll find that we're not mature enough yet as a species, and may not be for a very long time, to handle wide scale use of nuclear power.

The focus of what we must do, and do vigorously, has to be ways to find how to live in harmony with our environment and with each other to the extent that we can. And yet meet basic human needs in ways that are pretty much accessible to most of a population of a little over five billion and probably seven, eight, nine billion. And then I would hope we would taper off and maybe come back down a little bit.

Now, what about space? Number one on my list is that as soon as it can be arranged between those countries that are now active in space that all activities in space are internationalized without exception. And I include a lot of what goes under the name of military activity, which I think is very healthy, that has to do with keeping an eye on what's going on down below. I guess I could sum up one version of the Open Skies Proposal as far as surveillance and so on is concerned—satellites and other means—is to go back again to Orion days when Harrison Brown made an impassioned plea that we continue to expand what we can do in space with satellites but that we take every bit of raw data and every bit of processed data and put them in a sack—it turned out to be a very big sack—and put it on the front steps of the U.N. Building every Tuesday afternoon at 4 o'clock. No secrets. No secrets in space activity. Why? Secret activity in space is extremely threatening, and I see no way for that to change. We've got so much to do to clean up the messes which we have left behind that secrecy is something that maybe would be taboo also. In other words, superglasnost.

So far as how things in space get done is concerned, if one accepts the idea that everything is basically internationally organized and carried out, then that calls for intimate cooperation between countries that choose, have the resources, have the will, to do whatever it is: go to Mars, go to Mercury, get out to the major planets. The value of doing some things in a big way, particularly connected with surveillance, in space is that there's a strong connection with arms control and disarmament, and that is verification of disarmament and arms control treaties. Trevor Gardner, who basically started the U.S. missile program, hawkish as he was, proposed an international set



of arms control satellites. He proposed this strongly in 1960, 1961, and pretty much until he died in the late sixties.

Now, how to get into space and to how to move around in it? A great deal has been said, some of it I think absolutely fascinating at this conference, about all kinds of different ways to go beyond what we have done; beyond in the way of developing not just propulsion systems but whole transport vehicles and the infrastructure to support them and everything else. I just want to pick out two tasks which I think it's clear we can accomplish in such a way that those who wish to can participate in space activities on a huge scale. The first is how to get into orbit.

There is a kind of holy grail out there, and I have no idea how to take hold of it, tied up in free radical chemicals. If we could store atomic hydrogen in some stable way that we were quite sure couldn't explode, we've got a good solid 1700 to 2200 seconds of specific impulse. That's enough for all the high thrust things that I could think of doing—landing on the moon, getting up from the Earth, doing a soft landing on any place that we want to land on: Mars, Venus, Mercury (particularly) and all the moons, and so on. So we can carry along high thrust chemical propellant that's really up to the job.

Now until that time happens, I'd like to revive something. I was just talking to people here at the conference who are of the same mind: we ought to go back to what was being proposed in the late fifties, the early sixties. And that is, pick out some launch vehicle. I would argue for that launch vehicle being hydrogen and oxygen, from the ground up. That's not a new idea. There was a serious set of firm proposals to build single stage hydrogen oxygen launch vehicles to go into low Earth orbit and you can go through the arithmetic, anyone can do that, to overcome gravity and drag losses and so on. You can put somewhere around ten to fifteen percent of the launch weight into low Earth orbit. Of that weight maybe a third will be tanks, structures which are now in orbit. By tethering and all kinds of other things they become now a resource to be used in space. Trying to get the main weight of boosters back down for refurbishing is silly if you can get them up there and leave them there to use for other things.

Now, there are some missions in which what you really want to do is go very fast up to escape velocity and not orbit. For that, one very real possibility is a two-stage hydrogen oxygen rocket. The first stage moves things along at about 6 kilometers a second, and the second stage adds another 6 kilometers a second and there you are just barely hanging on—maybe at a libration point. But you've gone, in effect.

But now, how about moving around once you're up there? You don't need high thrust. I think that it's quite clear that the big winner is going to be solar electric propulsion. And that will do everything that we might want to do at low cost, very fast, out to about the first one third or so of the asteroid belt. From beyond Mars, all the way into the sun. What might this look like? Well I was astonished to see a diagram downstairs of Geoff Landis' bicycle wheel solar array which I think is a specific embodiment of how to go. This is just like a bicycle wheel—it's got spokes and it's got the analogue of a rubber tire on the outside, two kilometers in diameter. In that roughly three square kilometer interior are very thin film photovoltaic cells that are (at Earth orbit) picking up about 1350 watts per square meter. It seems to me quite fair to talk of those thin film cells, whatever they are, in the near future having efficiencies of 20 percent.

That electric power then goes into ion thrusters. That's not my field. I keep picking up things from people, particularly from the Soviets, about how efficient and light-weight those can be. You'd like to get into the ballpark of several kilowatts of input energy per kilogram of thruster. Now you can certainly do that for the solar cells. In fact, it's quite credible for a structure that is stable to deliver 10 kilowatts per kilogram of solar cells. I am not saying we know how to make the structure. Back to the bicycle wheel you see, the ship itself is the analogue of the rubber tire around the wheel. It rotates—this is a one kilometer radius—to give the ship and its contents about a quarter "g". Now that means it rotates once in about 90 seconds. And the payload: the people, the



shielding from solar flares or whatever, is all out there. I am sure that a lot of people here could decide within less than a day, where to put the propellant tanks for the ion thrusters. My guess is that the best place to put them is at the hub. The thrusters, at least most of the thruster capacity is also at the hub; but able to point over the best part of 180 degrees on either side so that the solar array faces the sun but the thrust is whatever direction you want.

What kind of performance can one get? Well, if you really look at what's out there now in terms of the weight of substrate on which these solar cells can be deposited, it's a thickness that can easily be less than mil--a thousandth of an inch. The penalty for going to very high specific impulse is lower accelerations, so it takes longer to get up to speed. But, if you'd settle for, let's say going out to Mars or, what I get much more excited thinking about, going in to Mercury (I think Mercury is a lot more interesting than Mars, but that's a separate question) to pick up about 15 kilometers a second you can do that in a week, two weeks. Your talking about roughly a milli-g, maybe a couple of milli-g's.

If the exhaust velocity is somewhere equal to or maybe twice the mission velocity, then you're talking about mass ratios of maybe two. And a division of weight between roughly four-thirds payload, two-tenths essentials, for the space craft that are not really connected with the payload. And then the rest is tanks and engines and the photovoltaic system. One can see these things not being very mission oriented. All they need is propellant and you go wherever you want. Reusable. How long? Who knows? But I think we could find out very quickly how long thin film photovoltaic cellswill keep operating more or less the way they are supposed to. You can fill them full of holes--one percent hole--and you've lost one percent of your electric power. At ten percent holes, which is a lot of holes, you have to worry about short circuiting and other things. I don't want to trivialize the problem, but it's not clear at all that there is any really severe, basic problem in doing this from an engineering point of view, and certainly not as far as the basic science is concerned. Rule of thumb: mission velocity about half the ion beam velocity.

That is fine out to somewhere between Mars and Jupiter. What do you do about the major planets? Orion could do it. I think there are a lot of side things about Orion. The one I worry about the most is the potential for destructive use of anything that carries 5000 nuclear explosives, which is what it takes to make a fast round trip to Ganymede, Titan, what have you. But, I think the answer is probably some form of nuclear power. Maybe thermonuclear power. It may be stretching things a little bit to consider thermonuclear power from Helium-3 and deuterium (which produces no neutrons, which is a big help.) But whatever that it is, a point of departure for thinking about nuclear propulsion beyond the asteroid belt is a constraint that for fission power or fusion power in which there are lots of neutrons, they go to clean cold starts way out there. Then they go back and forth and pick up payload; we can certainly get on our way to Pluto at very high speed. The problem is what do we do when we get there? We can break various ways. You've thought about that a number of things at this conference.

But, then how do you get back? And I think the answer is probably going to have to be nuclear. Another possibility is laser beams, generated from ferociously potent solar panels, let's say at Mercury where you get six times the insolation that you do on Earth. Unless we can somehow get around the laws of optics, you are stuck with roughly a kilometer aperture for something with a wavelength like sodium light--which may turn out to be possible. Then you can just beam energy out there. Something like that thing with pulses may be sort of close cousin to Orion in its original form, where you'd pulse energy on to it.

I am not suggesting that exploring the major planets and going clear out to Pluto is something not to think about; it's way off in the future. It may be much closer than we think. It was very close with Orion. But it takes some doing to put things together and if people really get serious about it we'll find ways to explore safely, without weapons connections and all that, out beyond Saturn.

Let me mention one other thing which may be a direct use of space—not exploration—on which everything else can ride. And that is disposal of the actinides, the 200 thousand tons of irradiated reactor fuel that the world is going to have at the end of this decade. We have a hundred thousand tons already and we'll get a hundred thousand more in the next ten years. You can visualize space disposal of nuclear wastes in a little detail, as has been done before, some years ago. Frank Rom told me about this yesterday.

You set criteria on the launch process that the payload cannot break—no matter what! Just to get a little specific, if you add up the total amount—total quantity of actinides in all this 200,000 tons of nuclear fuel, the answer is about 3 million kilograms of, mostly, plutonium. Suppose you use 200 launches to get rid of all this stuff. You're talking 5,000 kilograms plutonium per launch. You have to use dry fuel reprocessing. That's a whole other story—you can't have a lot of low level waste, and that's not easy, but you can do it. The weight of the plutonium is doubled with things like tungsten and cadmium, for example, that capture high energy fission neutrons and thermal neutrons so that it cannot sustain any kind of a chain reaction. Having done that with this package, that corresponds to 200 launches to get rid of everything. You've got something a little bit less than a meter diameter. It's pretty hot—I don't mean thermally (what I've looked at says that you can get the heat produced by this easily out without going to very high temperatures). But you do have to seal it with some 10 or 12 centimeters of tungsten around this sphere, which is now 6 feet across.

The next thing you have to do is make it buoyant so it floats. The ideal launch is if you go straight up off an island somewhere out in the ocean, so that if the engine stops, or blows up, or starts going off course, it falls back down roughly a little off to one side from where it lifted off and falls in the ocean. So it has to float. And how do you do that? Well, you add titanium honeycomb and then big heavy case around the whole thing. You wind up with a total weight of about 50 tons for this package, of which 30 tons is the shielded nuclear waste. That's what you want to deliver out to just barely hanging on by its skin of its teeth. Then you connect with that with a solar propulsion system brake with 30 kilometers a second and drop it right in the sun.

Now there may be terrible flaws with all this. But there's a chance it could turn out to be the only acceptable thing to do with this stuff. I think we can find out whether that's the case in a very short time—before the end of the decade. Then what have we got? The launch vehicles for each of these packages is the 2 stage hydrogen oxygen rockets—maybe we can do better than that. Each vehicle is a little bit smaller than Saturn 5. And 200 of them! We really settle down, which I think we should have done long ago, to pick a vehicle and use it over and over—and I don't mean re-use it, but use the same type of launch vehicle as though you really meant big business. Not go to the moon and then sigh and wonder what to do with the leftover Saturns and so on... we can't do that again! So there just may be something which, of itself, would call strongly for good launch vehicles into high orbit—or low orbit for that matter—and high performance solar electric propulsion. Then everything else rides on that. And a few of these things don't pick up these packages—they go off and go to Mars! Or go to Mercury, or whatever.

All this may sound like Pollyanna. All I can say about that is two things. First, I'd far, far prefer to be pursuing a kind of world that may turn out to be too good to be true than to keep drifting, as we are, toward a world that is just too awful to contemplate. The second thing I want to say is as a guiding principle on how to get to something like this vision of a stable, harmonious future—lots of things going on in space—is to give you the motto of the Pugwash movement. Pugwash was organized originally by Albert Einstein and Bertrand Russell. The first meeting was in the town of Pugwash in Nova Scotia. The drive was to make sure that no matter what happened, at least some American and Soviet scientists would keep talking to each other. Einstein died before that first meeting, but Russell came up with this motto: and you think about it, it's a way to sort of keep steady. Simply: "Remember your humanity and forget the rest!"

Thank you.