NEW MOONS

TRANSCRIPTS OF THE PRESENTATIONS AT THE

SPECIAL SESSION OF THE

EIGHTH LUNAR SCIENCE CONFERENCE

ON

TOWING ASTEROIDS INTO EARTH ORBITS FOR EXPLORATION AND EXPLOITATION

16 MARCH 1977

JOHNSON SPACE CENTER

HOUSTON, TEXAS

COMPILED BY

DAVID R. CRISWELL

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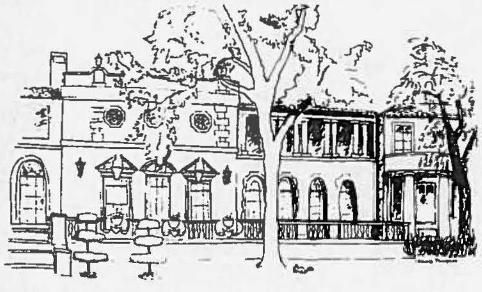

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N E W M O O N S

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FOR
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Presentations at the

Special Session of the
Eighth Lunar Science Conference

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Johnson Space Center
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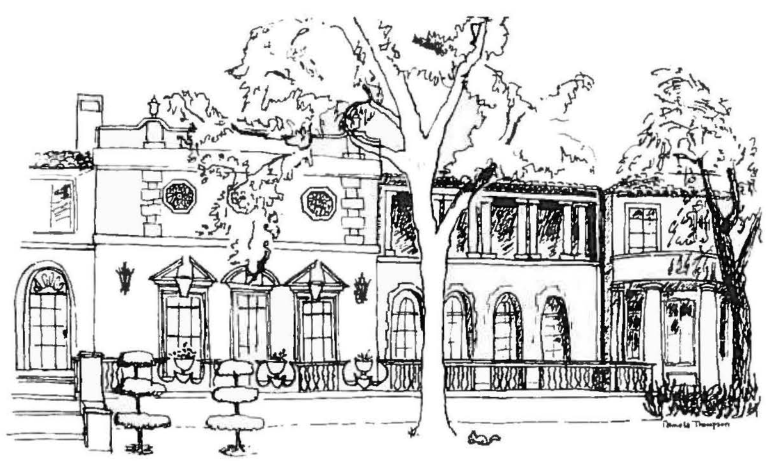

PREFACE

Space industrialization requires large scale sources of inexpensive mass in order to expand man's economic activities in space from the present "service" functions (directed solely toward the earth) to a self-sustaining and growing activity. The concept of asteroid retrieval to near earth space for industrial use and reforming asteroids into habitats has been discussed in both the technical and scientific fiction literatures. This special session was prompted in part by research at the second summer study on Space Manufacturing (June-July 1977, NASA Ames Research Center) which indicated the overall feasibility of conducting large industrial operations in earth/moon space. However, the key spark was a preprint by B. J. O'Leary (Princeton, Univ. and co-organizer of this session) which indicated that a new type of solar electric rocket engine (mass driver) could be used to tow a special class of asteroids into orbits about the earth. These special asteroids have orbits which come close to the orbital path of the earth. Extremely large quantities of mass could be provided very inexpensively if the concept is feasible.

There are basic questions that have to be identified for early evaluation of the concept. The Annual Lunar Science Conference provides an ideal opportunity for gathering very knowledgeable people to identify major potentials and problems of the concept and focus widespread attention toward exploring the concept. These questions include: (1) whether or not the mass drivers can be utilized as a new type of high-thrust reaction engine utilizing either solar or nuclear power; (2) can one actually make use of any available material from the asteroid mass during the tow to earth; (3) and, is there a large population of asteroids which is easily accessible? There is a growing realization that with the space transportation system coming into operation in 1980, it is reasonable to envision large scale construction in space, possibly involving many people, such as would be necessary for the space power systems. Potentially large economic returns could begin in the next decade and a half from space systems for the supply to earth of energy.

Detailed technical reports are now becoming available on asteroid towing, mass driver design, the general topic of space industrialization and utilization of non-terrestrial materials. Recent publications of particular interest include the following:

1. O'Leary, B. J. (1977) Mining the Apollo and Amor Asteroids, Science, 197, 363-366.
2. Gaffey, M. and McCord, T. (1977) Asteroid Surface Materials: mineral-ogical characterizations and cosmological implications, Proc. Lunar Sci. Conf. 8th, Vol. 1, 113-143, Pergamon.
3. Helin, E. F. and Shoemaker, E.M. (1977) Discovery of Asteroid 1976 AA, Icarus, 31, 415-419.
4. Arnold, J. R. and Duke, M.B. (editors) (1978) NASA Conference Publication 2031 - Summer Workshop on Near-Earth Resources, pp. 107 (price $5.50), Govern. Printing Office, Wash., D.C.
5. O'Neill, G. K. (1978) The Low (Profile) Road to Space Manufacturing, Aeronautics and Astronautics, March (in press).
6. O'Neill, G. K. (editor) (1977) Space Based Manufacturing from Non-Terrestrial Materials, Prog. Aeronautics and Astronautics, Vol. 57, pp.177,Amer. Inst. Aeronautics and Astronautics, New York.
7. Grey, J. (editor) (1977) Space Manufacturing Facilities, Proc. of the Princeton/AIAA/NASA Conference, 7-9 May 1975, pp. 338, Amer. Inst. Aeronautics and Astronautics, New York.

Publication is expected in 1978 of the proceeding of "The Third Princeton/AIAA Conference on Space Manufacturing Facilities" (by the American Institute of Aeronautics and Astronautics, New York) which was held 9-12 May 1977 and the collected technical papers of the 1977 NASA Ames Summer Study on Space Manufacturing (20 June-3 August 1977). Three summer study reports of particular relevance are:

Gaffey, M.J., Helin, E.F. and O'Leary, B. (1978) - An assessment of near-earth asteroid resources (in progress).

O'Leary, B., Gaffey, M. J., Ross, D. J. and Salkeld, R. (1978) The Retrieval of Asteroidal Materials (in progress).

Bender, D. F., Dunbar, R. S. and Ross, D. J. (1978), Round-trip Missions to Low Delta-V Asteroids and Implications for Material Retrieval (in progress).

The third report contains an analysis of an asteroid retrieval strategy employing gravity-assists by Venus and the moon during the return trajector. It is found that the ranges of orbital inclination above the ecliptic and apogee of the potential target asteroids are significantly increased over direct return to near earth space of an asteroid as presented by O'Leary (ref. 1 above).

The following pages are based on the transcripts of the recordings of the special session and are intended to provide a wider audience with an understanding of the motivations for retrieving asteroids to the vicinity of the earth and a qualitative feel for some of the major technical problems apparent to the speakers and the audience on 16 March 1977. I do wish to thank the participants for their very helpful cooperation in checking and modifying the original transcripts.

Dr. David R. Criswell
Associate Scientist
Lunar and Planetary Institute

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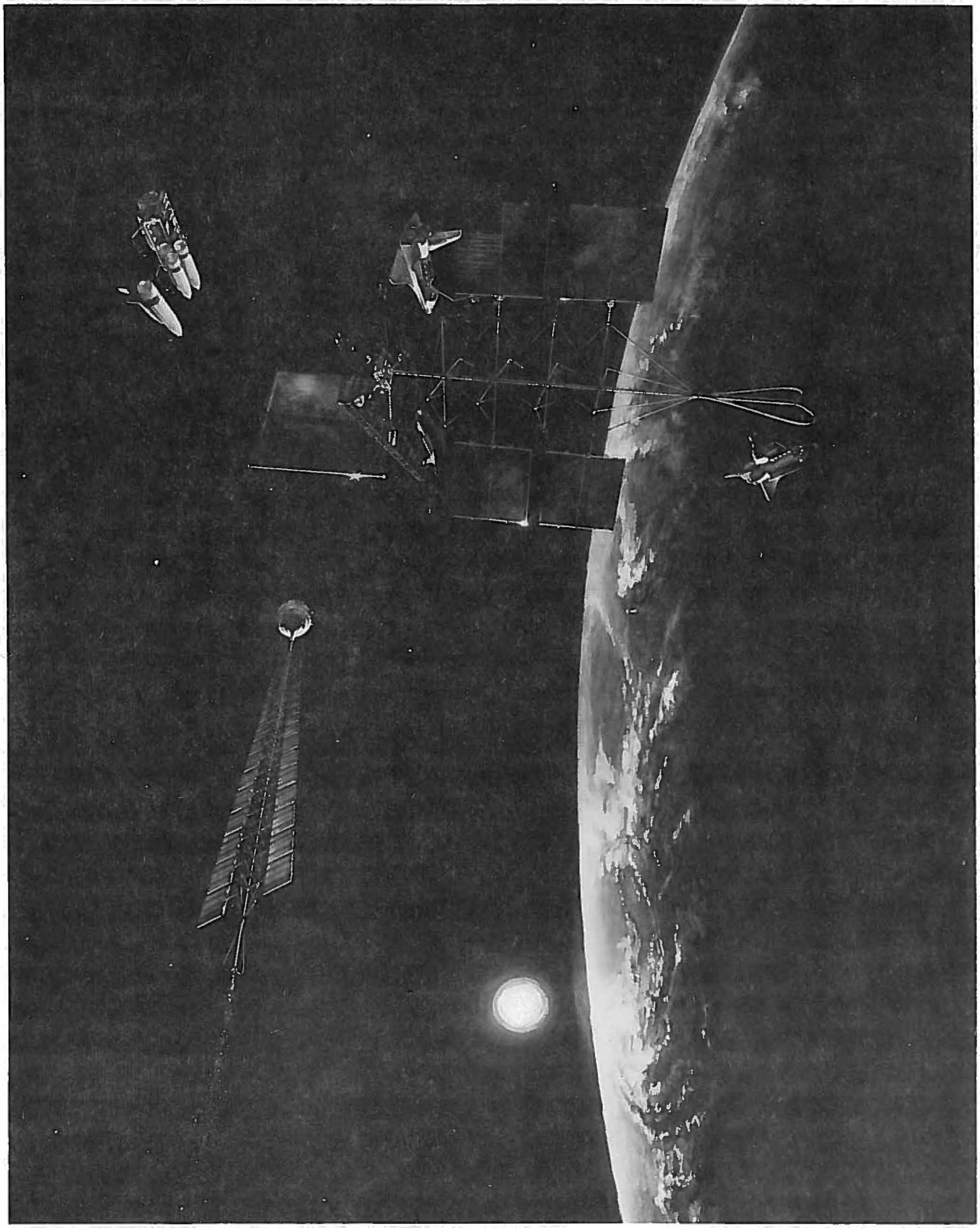
FIRST RETRIEVAL MISSION

- Beginning -

Orbital sunrise greets the start of the first mission to retrieve an earth-approaching asteroid. "Asteroid-1" is the central long structure in this painting. Crew and supporting equipment are located in the spherical unit. The propulsion unit is the long tubular structure enveloped by stiffening yard arms and guy wires. Solar cells running the length of the propulsion system convert sunlight into electricity which is used to power the propulsion system. During the mission these solar arrays are always oriented toward the sun to gather in the maximum power. A fine spray of material is shown being ejected from the propulsion unit. Acceleration of this material utilizing solar power and the subsequent ejection of the material or mass evokes the reaction force which accelerates "Asteroid-1" outward. In this particular scenario the reaction mass for the outbound flight is provided by grinding up the fuel tanks of the space shuttle flights needed to deploy the unit. This operation is depicted in the corner of the painting. On the return flight a large portion of the asteroid is ground up and ejected to evoke the reaction force. G. K. O'Neill first suggested this propulsion scheme as an alternative in some applications to chemical rockets, nuclear propulsion or ion-drives. He coined the name "mass driver" for this approach to in-space propulsion.

A second mass-driver unit is shown in the foreground being constructed out of material shipped from earth in the bays of four space shuttles. An orbital construction platform which is in permanent low earth orbit provides the power, supplies depot and the work volume within which construction proceeds. Although physically large, the total mass of one of the propulsion units is relatively small. Some mission scenarios would require mass-drives which could be deployed from earth by approximately 30 shuttle flights.

Ms. Denise Watt of Houston produced this and the following painting which incorporates some of the general qualitative features of mass driver systems as determined at the 1977 NASA/Ames summer study on space manufacturing. Public television station WGBH (Boston) commissioned the paintings for use in a documentary (The Final Frontier) on the possible future roles of NASA in space. Thanks are extended to Mr. Graham Chedd and Ms. Marion White, the director and co-director of the two part NOVA series.



ASTEROID INDUSTRIES

Creation of a new economy in space is the objective of retrieving an asteroid to high earth orbit. The scale of objects in this painting is approximately 100 times larger than in "First Retrieval Mission" where the space shuttle provided a familiar reference. The space solar power system occupying the mid-field of this painting is approximately five kilometers in width and 15 kilometers long and would be approximately 100,000 metric tons in mass. Such a station could produce on the order of 10 gigawatts of electric power. In the foreground is the retrieval portion of the first asteroid to be returned. This asteroid is the source of much of the mass necessary to shield the large habitat in the background and of the reaction mass for the second out-bound journey of the mass-driver shown just returning.

It is expected that the asteroids will provide a greater range of elements for use in space industrialization than would materials from the low latitude regions of the moon. While we do not presently have the detailed knowledge of asteroids that we presently have of lunar soils, it is still reasonable to assume that substitution of materials will make possible the construction of a large fraction of the massive structures from only asteroidal materials. In any case, the asteroidal material would be a valuable supplement to industrial feedstock derived from lunar ores.

INTRODUCTION

Professor Gustav Arrhenius (University of California,
San Diego/Scripts Institute)

When the Apollo program was proposed many years ago, the reaction from the scientific community was not the one that we like to think it was today. It was very mixed indeed and mostly negative in various degrees and/or marked with uneasiness. A distinguished British astrophysicist, for example, predicted that the moon would be just a dead slag heap in space and he added, without any scientific interest to speak of and certainly not worth spending American tax-payer's dollars on. Fortunately, the taxpayer was at the time in a somewhat more adventureous mood and the program went ahead, spurred on by a relatively small number of foresighted and enthusiastic eminent scientists here. They made it very clear to the public that on the moon we would find the most primitive material in the solar system that would give us the key to the most early events that dealt with formation.

Well, as it came out, John Paul Sautre and Kirkagard proved to be right in their existentialistic credo that man is not very capable in predicting relationships of a complex nature that we are mostly presented with. So, our enthusiasts were wrong, except that the whole enterprise proved to be eminently important and interesting; and the pessimistic Britisher proved to be right, except in his added comment that the slag heap would be without any scientific interest. It soon became evident then that we had to look elsewhere for the record of the earliest development of solar system and the question was where, since it was quite clear that the moon mercilessly smashes any material that is captured and falls into its potential well. It was strongly suggested that the answer to this question lay in the small bodies in the solar system - the parent bodies of meteorites and interplanetary dust - the comets and asteroids.

In the meantime, however, the element of social demands on the space program has grown dramatically and rightly so. It is no longer possible, if it ever was, to justify extensive new bold exploration only on the basis of man's quest for knowledge. Under these circumstances, it is with greatest interest and anticipation that I look forward to the program here tonig t presenting some remarkably advanced and, considering the circumstances, realistic engineering aspects of the problem and, as I see it, scientific adventure of the first order coupled with a new search for materials and energy resources from the existing moon and from the new moon yet to be brought into orbit.

GENERAL OVERVIEW OF THE DEVELOPMENT, DEPLOYMENT AND COST OF A MASS DRIVER TUG AND RETRIEVAL OF AN EARTH APPROACHING ASTEROID

Brian J. O'Leary
Princeton University

About eight years ago, my colleague and friend, Gerry O'Neill, reminded me that we here on earth sit at the bottom of a very deep gravity well. This point is obvious to all of us, yet sometimes we get geocentrically hung up. I think that it was this perception of O'Neill's, and an increasing number of others, that is leading to a rather exciting era of conceptual thinking of what can be done about using energy and materials in space which are easily retrievable from very shallow gravity wells. It may be a bit presumptious of me to say this, but these discussions may be the beginning of a sort of a second Copernican revolution against geocentric thinking. One must spend several hundred dollars to launch a pound of material into high earth orbits from the earth using the space shuttle. However, it should require on the order of a few cents to a dollar per pound to acquire raw material from an asteroid or from the moon. The best candidates for non-terrestrial materials are the moon and the asteroids. The goal is to be able to approach self-sufficiency in space, to be able to construct satellite power stations which are economically competitive with the existing electrical energy sources, and perhaps also to build permanent settlements in space. To date, the moon has been considered as a prime candidate for non-terrestrial materials. The launching device used is the mass driver which Henry Kolm will be talking about in greater detail this evening. I considered the asteroids, not the asteroids in the main belt where the energy of transfer of the material is generally comparable to that from the earth's surface, but the Apollo and Amor class which are earth-approaching asteroids. We now know of 37 such objects. We believe a small, but finite percentage, have rather favorable opportunities for low energy transfer of material into high earth orbit. They could then be used for space manufacturing or for direct return to the earth. Drawing on data largely generated by individuals who will be speaking later, I concluded that a competitive early program in space manufacturing could be started using the asteroid route, rather than the lunar route.

To give you an idea of how vast the resource out there is, this is a Viking photograph of Phobos about twenty kilometers across. One resolution element in that picture is about two hundred meters, which is equivablen to ten million tons of material (slide 1.1). That's enough to construct ten to forty satellite power stations. Slide (1.2). This is a graph of the short impulse delta v's to and from some asteroids in favorable opportunities around 1992 or 1993. The cost of any mission is approximately proportional to the square of the delta v that you are dealing with. These delta v's are comparable to those from the lunar surface, but several times less than from the main asteroid belt. This is one of the underlying reasons why carefully selected asteroidal resources are so attractive. John Niehoff will elaborate on accessibility of these asteroids. There is a scenario in which a one kilogram sample from asteroid 1943 could be returned in the early 1990's with the use of just one space shuttle flight. There is going to be a need to develop scenarios for low thrust missions, such as the kind that mass drivers would go on. Some excellent recent work (slide 1.3) which Tom McCord will be talking to you about later tonight, using earth based spectrophotometry of the asteroids suggests very close matches with ordinary chondritic meteorites and carbonaceous meteorites. This deduction gives a general range of compositions of materials that might be useful for space industrialization. The suggestion here is that the asteroids would appear to offer a wider variety of useful materials. In some cases there may become available free metals and in other cases, hydrogen,carbon and nitrogen, which is lacking in lunar samples.

Slide (1.4) indicates the current estimates as far as the population of these objects. Gene Shoemaker will be talking about this a little bit tonight. There appear to be on the order of a hundred thousand or more earth-approaching asteroids that are greater than one hundred meters across. These are objects that weigh more than ten million tons, so there's a very vast array of asteroids out there (slide 1.4). We only know of 37, but they're being discovered by scientists in a modest program at Mt. Palomar. Eleanor Helin and Gene Shoemaker and others are working on that program and discovering about two or three of these objects per year. Slide (1.5) shows estimates of what various scenarios for expanded search programs would be and you can see that the number of known Apollo/Amor asteroids could be doubled, tripled or quadrupled each year with some moderate step up in the search program. Such an activity would seem to be worthwhile from several points of view, no matter what view you might want to take on the scenario I am going to unfold in a minute. Certainly for scientific reasons, it would seem to make sense to expand this search. From the point of view of mission planning, it's important to have a recipe of mission opportunities which could come from the discovery and orbit determination of these asteroids.

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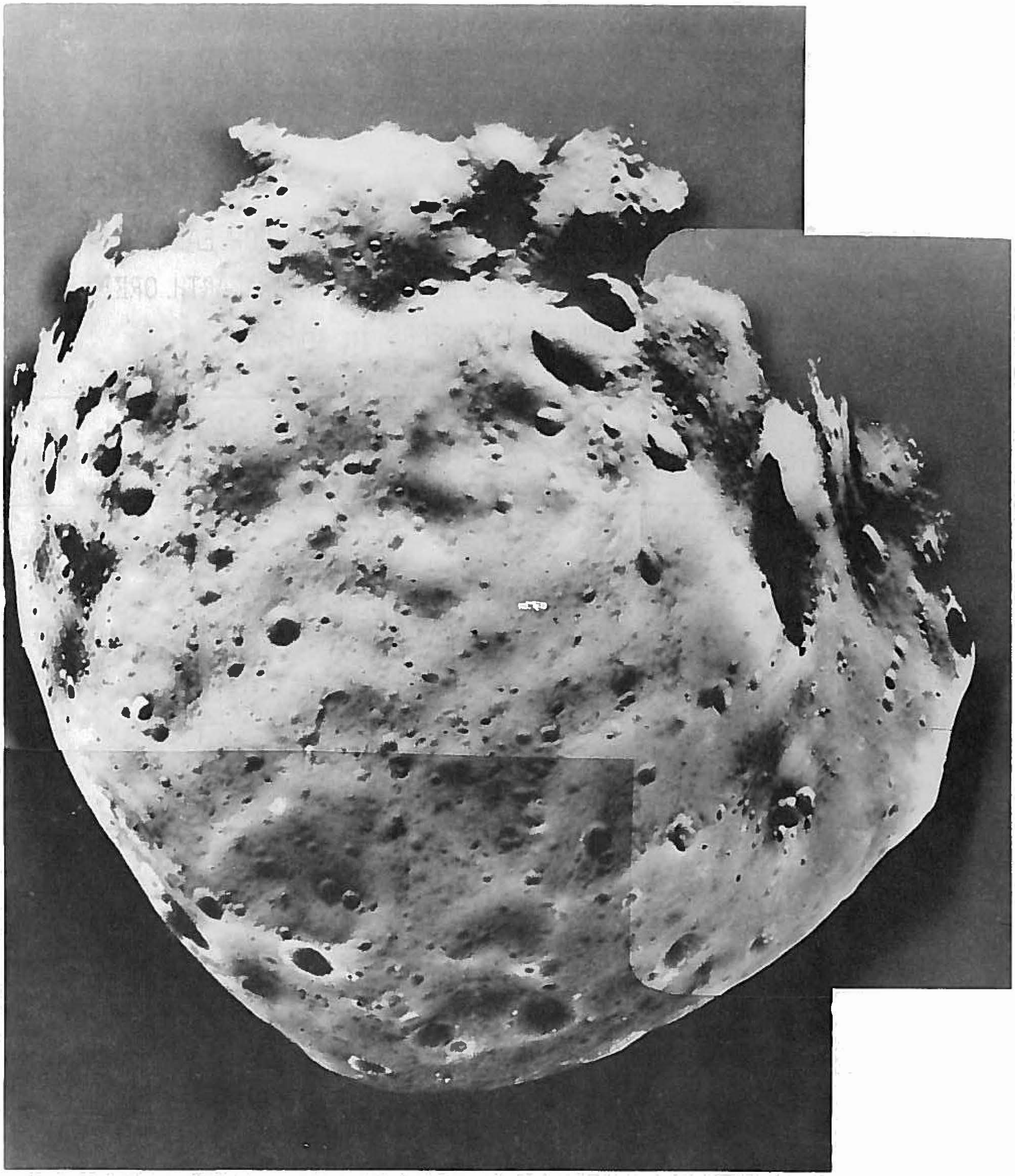


Slide 1..

ESTIMATED VELOCITY INTERVALS IN MISSIONS FROM LOW EARTH ORBIT TO THE MOON AND ASTEROIDS; AND RETURN TO HIGH EARTH ORBIT (SHORT-IMPULSE TRANSFERS IN km/SEC)

OBJECT	Δv_{OUT}	Δv_{IN}	Δv_{TOTAL}
433 EROS	6.5	2.7 - 3.7	10
1943	5.5	2.6 - 3.6	8
CONVENIENT MAIN BELT ASTEROID	13	8	21
MOON	5.6 - 6.2	2.3 - 3.4	9

APPROXIMATE CHEMICAL COMPOSITION OF
METEORITES AND LUNAR SOIL SAMPLES (%)

	Ordinary Chondrites	Carbonaceous Chondrites	Lunar Samples
Silicates	75 - 86	76 - 90	98 - 100
Water	0.2 - 0.3	1 - 21	0
Free Metals	8.3 - 19	0.1- 35	0 - 1
Carbon Compounds	0	0.5- 7.5	0
Nitrogen	0	0.01- 0.3	0

Slide 1.3

POPULATION OF APOLLO AND AMOR ASTEROIDS

> DIAMETER OF:

1 km	1,600±800
½ km	~6,000
100 m	~150,000

DISCOVERY RATE OF APOLLO AND AMOR ASTEROIDS

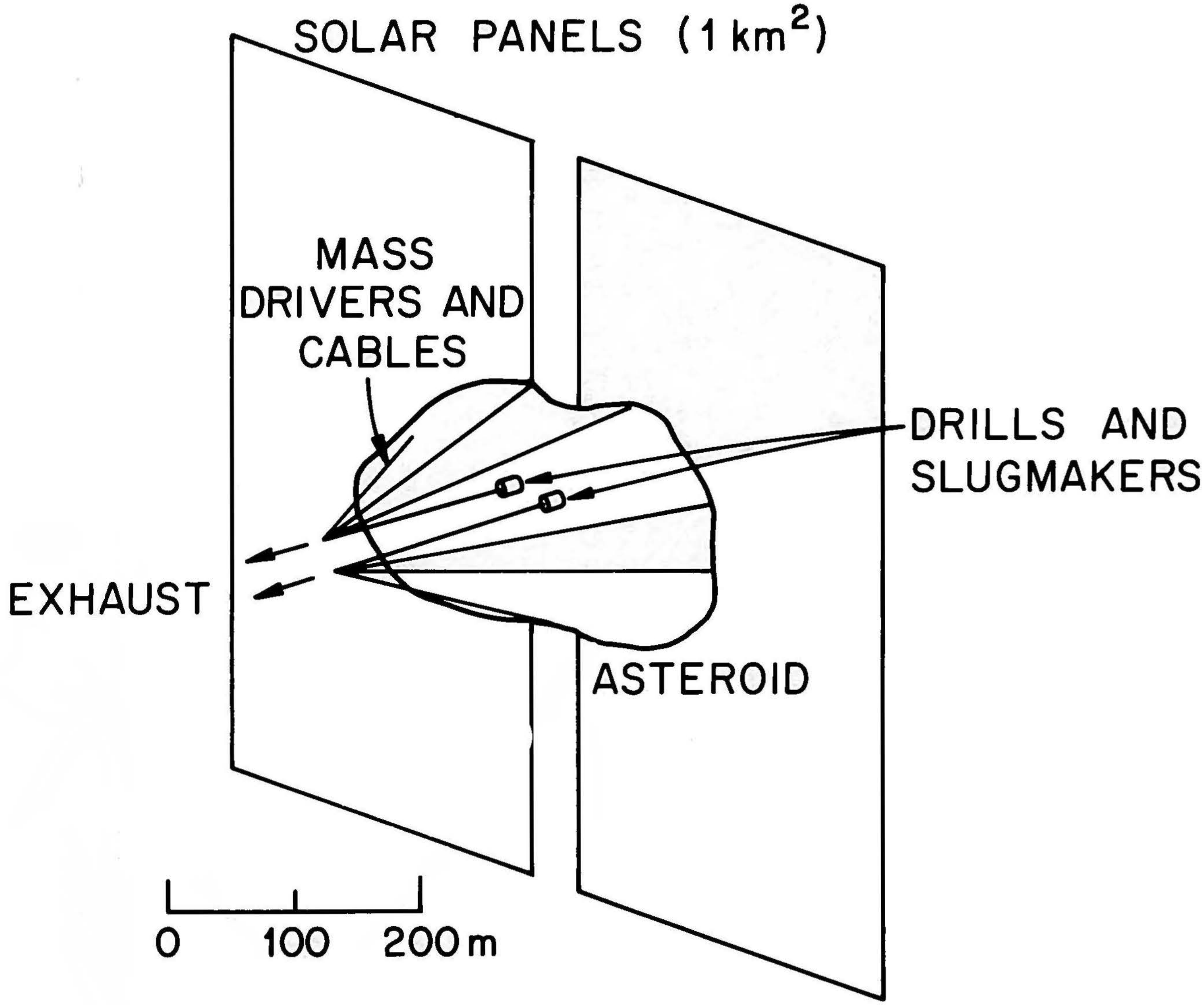
	Number
CURRENT 18-INCH PALOMAR SEARCH	2-3 PER YEAR
DEDICATED 48-INCH SEARCH	$\gtrsim$25 PER YEAR
DEDICATED 18-INCH IN ORBIT	100 PER YEAR
NUMBER OF KNOWN APOLLO/AMOR ASTEROIDS	37

Slide (1.6) is a little sketch I had done up on what the mass driver retrieval of an asteroid might look like. We would take a mass driver, assemble it in low earth orbit and use tankage from the space shuttle as reaction mass for boost into a transfer trajectory to the asteroid. This is some work that Henry Kolm will refer to tonight. The asteroid retrieval might involve a redundant system of two automated mass drivers which would rendezvous with the asteroid, and fasten it to it. The thrust would be aligned with the center of gravity of the asteroid and would use the asteroid itself as the source of reaction mass for the return flight. The asteroid would then be propelled into a convenient orbit for space manufacturing.

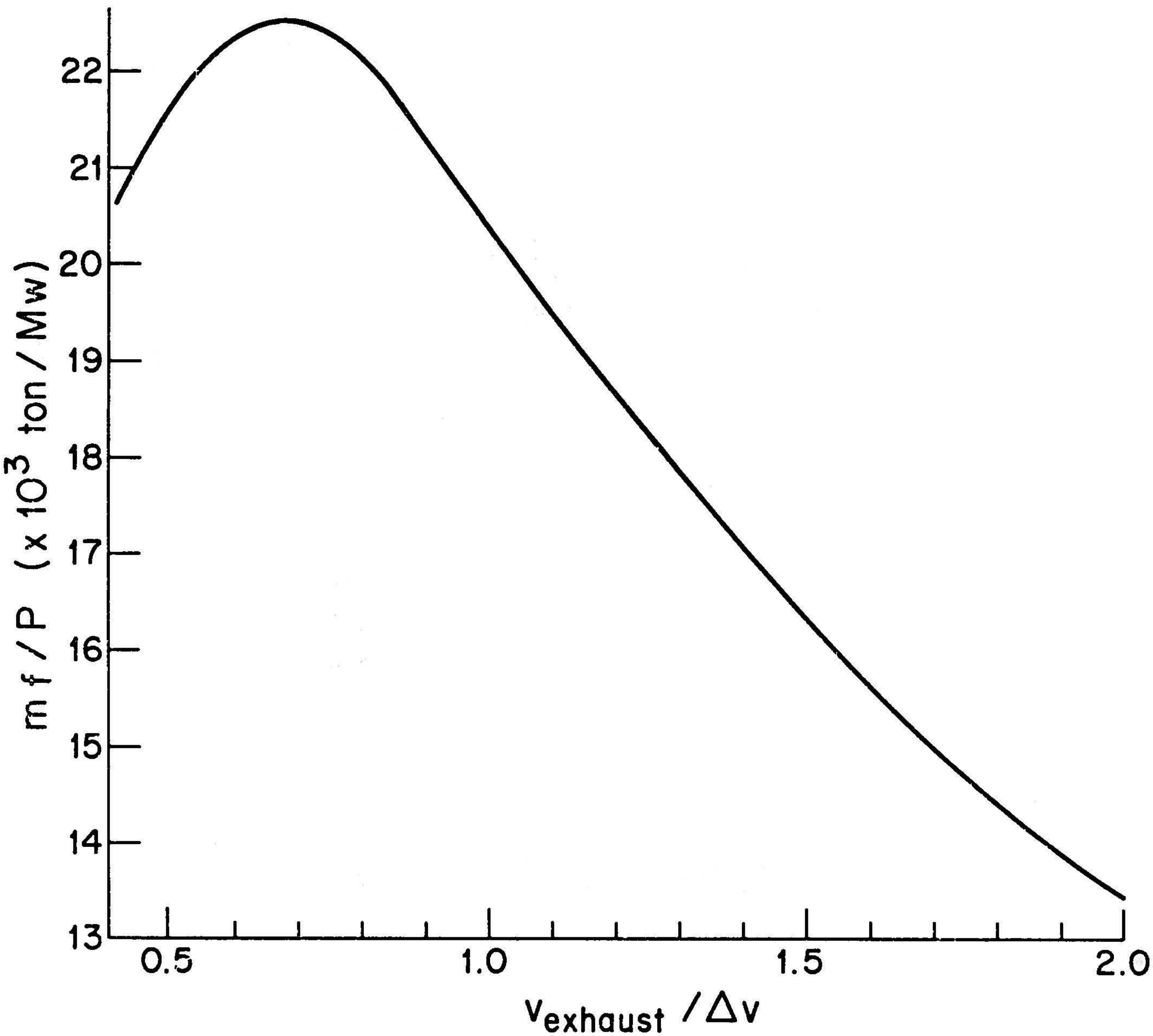
I went through an optimization study (slide 1.7) of just what the exhaust velocity ought to be. The goal is to get the most mass of the asteroid back per unit energy put into the mass driver system. The mass driver power plant rating drives the economics of this kind of system (slide 1.8). If we assume a delta v of three kilometers per second a value which I believe would be expected in several cases, then we can derive the parameters for a system which could retrieve a ten million ton or two hundred meter diameter asteroid. The parameters include throughputs, final mass, the power plant requirements (100 megawatts); the length of the solar power array for mass driver would be about one kilometer square. This would be the kind of development that would be commensurate with early demonstrations of satellite power systems on the one hundred megawatt level, or about one hundredth the size of a full scale satellite power station of the kind proposed by Peter Glaser and studied by the Johnson Space Center Study.

I made some assumptions which I consider to be fairly conservative. They do include development costs, many of which would be common to other mass driver applications. I estimate that such a mission may cost one billion dollars in this hypothetical case of retrieving the ten million ton (two hundred meter diameter) asteroid (slide 1.9). I might add that two hundred meter diameter is toward the lower end, but not at the lower end of the size range one would expect to pick up in the increased search program, which we all, I think, would agree is a reasonable thing to do. So, I think this is a fairly realistic asteroid size that we are dealing with. You can see the assumptions going into this study. There are two scenarios (slide 1.10). The first is to use a mass driver device as the tug to go to the asteroid and the second to use normal chemical propellants as an upper stage to get to the asteroid. The cost estimate for the mass driver system assumes a thousand dollar a kilowatt for the power plant, $400. a kilogram for the mass driver, and $240 per kilogram for Earth-Launch of the mass driver. These are very

Slide 1.6


SOLAR PANELS (1 km^2)
MASS DRIVERS AND CABLES
DRILLS AND SLUGMAKERS
EXHAUST
ASTEROID
0 100 200 m

Slide 1.7



m f / P (x 10^3 ton / Mw)
22
21
20
19
18
17
16
15
14
13
0.5
1.0
1.5
2.0
v exhaust / Δv

1.10

PARAMETERS FOR A MASS DRIVER OPTIMIZED FOR MOVING A 10^7-TON ASTEROID THROUGH A VELOCITY INTERVAL Δv = 3km/SEC OVER A PERIOD OF 5 YEARS AT A MEAN SOLAR DISTANCE OF 1 A.U.

Exhaust velocity	v_e = 2.0 km/sec
Mass Ratio	m_f/m_i = 0.223
Delivered (final) mass	m_f = 2.2 million tons
Reaction mass	m = 7.8 million tons
Throughput (5 yrs.)	$\dot{m}$ - 49.4 kg/sec
Thrust	$F = \dot{m}v_e$ = 99,000 newtons
Kinetic Power	$P = \frac{1}{2}\dot{m}v_e^2$ = 99 megawatts
Acceleration	a = 10,000 m/sec^2
Length	ℓ = 200 meters
Solar collector area	1 km^2

ESTIMATED OPTIMIZED COSTS OF RETRIEVAL OF
A 10^7 TON APOLLO/AMOR ASTEROID, Δv = 3 km,
DURATION = 5 YR, POWER = 100 MW, MASS DRIVER MASS = 700 TONS,
POWERPLANT MASS = 700 TONS

ITEM	COST	
	Mass Driver Tugs Developed	Current Orbital Transfer Vehicles
Powerplant @ $1000/kw	$100 million	$100 million
Mass driver @ $400/kg	280	280
Upgraded shuttle launch costs @ $240/kg	336	336
Orbital transfer to deep space:		
tug @ $1/kg (x 2)	3	
current vehicles @ $760/kg		994
($950/kg from the Earth's surface)		
Total cost	$719 million	$1710 million

ESTIMATED OPTIMIZED COSTS OF RETRIEVAL OF
A 10^7 TON APOLLO/AMOR ASTEROID, Δv = 3 km,
DURATION = 5 YR. POWER 100 = MW, MASS DRIVER MASS = 700 TONS,
POWERPLANT MASS = 700 TONS

ITEM	COST: Mass Driver Tugs Developed	COST: Current Orbital Transfer Vehicles
Cost/kg returned (5 yr.)	$ 0.32	$ 0.78
Cost/kg (amortized over 10 yr.)	0.16	0.39
Cost/kg for transport of lunar material (amortized over 10 yr.)		3.50

similar to the assumptions that have gone into the use of mass drivers for lunar applications. They should be reasonable; they may be off by a factor of two or three, but probably not much more than that. The unit costs of the returned material turn out to be quite inexpensive for a delta v of three kilometer per second. We are dealing with costs that are roughly in order of a magnitude less than those estimated for return of material from the moon. The reasons why the asteroidal case appears to be cheaper than the lunar case are: (1) if you set up a mass driver on the moon you have to soft land everything on the moon; that increases your costs by about a factor of two because you need chemical propellants to do the soft landing; and (2) there is another factor of two lost in the case of the moon versus the asteroids because of the fifty percent duty cycle of the availability of solar energy on the moon. Add to those factors the logistical considerations of a lunar base with manned support and with the need for having a very high accuracy guidance mass driver to propel propellants into space and then have a catcher for the material and for the transfer of the material to the manufacturing orbit. You are probably dealing something on the order of an order of magnitude difference in the lunar case and asteroid case even though the total delta v's may be comparable. Slide (1.10) gives you a general idea of the cost of returned asteroid materials for a program development amortized over a period of ten years. We expect costs somewhere in the range of 10¢ a kilogram to a dollar a kilogram depending on whether the mass drivers are developed as interorbital tugs and what kind of mission opportunities are available.

I would like to conclude by suggesting a program that, in a very optimistic vein, may come about as early as the 1980's. Of course, when you discuss these things you have to assume that people's philosophies are going to need to change somewhat; after all that's what made Apollo, and it is difficult to make a linear extrapolation of what NASA is now planning. If people think it's worth one to maybe three billion dollars to do this development and do a retrieval, then the program could be done on a fairly short time scale, (slide 1.11). Between 1977 and 1982 you could expand the search. One should do that anyway. It should not cost more than a few million dollars. We would also want to determine orbits, classify the compositions, identify mission opportunities, do a mission system study and so forth and so on. Mass drivers development in space is a larger cost item in comparison, but these are also the kinds of things you want to do if you commit to a full scale space manufacturing program (slide 1.12) of the sort that Gerry O'Neill and some of the rest of us have been studying. Included in the development costs are mass driver tests in low earth orbit and demonstration of satellite solar power.

POSSIBLE SPACE MANUFACTURING PROGRAM USING APOLLO AND AMOR ASTEROID RESOURCES

YEAR(S)	ACTIVITIES
1977-81	EXPANDED SEARCH, ORBIT DETERMINATION, COMPOSITION CLASSIFICATION, IDENTIFICATION OF MISSION OPPORTUNITIES, MISSION SYSTEMS STUDIES, SPACE MANUFACTURING FACILITY SYSTEMS STUDIES AND LOW EARTH ORBIT TESTING, SATELLITE SOLAR POWER TESTING, MASS DRIVER TESTS ON THE EARTH AND IN LOW EARTH ORBIT (COST $\lesssim$ \$1 BILLION).
1980-81	CHEMICAL ASSAY PROBE AND SAMPLE RETURN MISSIONS TO PRIME ASTEROID MISSION CANDIDATES (COST $\sim$ \$100m); MAKE GO/NO GO DECISION ON SPACE MANUFACTURING OF ASTEROIDAL MATERIAL.
1981-82	IF GO, LAUNCH ASTEROID MASS DRIVER TO THE PRIME TARGET(S) (COST $\sim$ \$1 BILLION), BEGIN TO LAUNCH AND CONSTRUCT A HIGH ORBITAL PROCESSING AND MANUFACTURING FACILITY (SMF) SIZED FOR THROUGHPUTS UP TO 10^6 TON/YR.

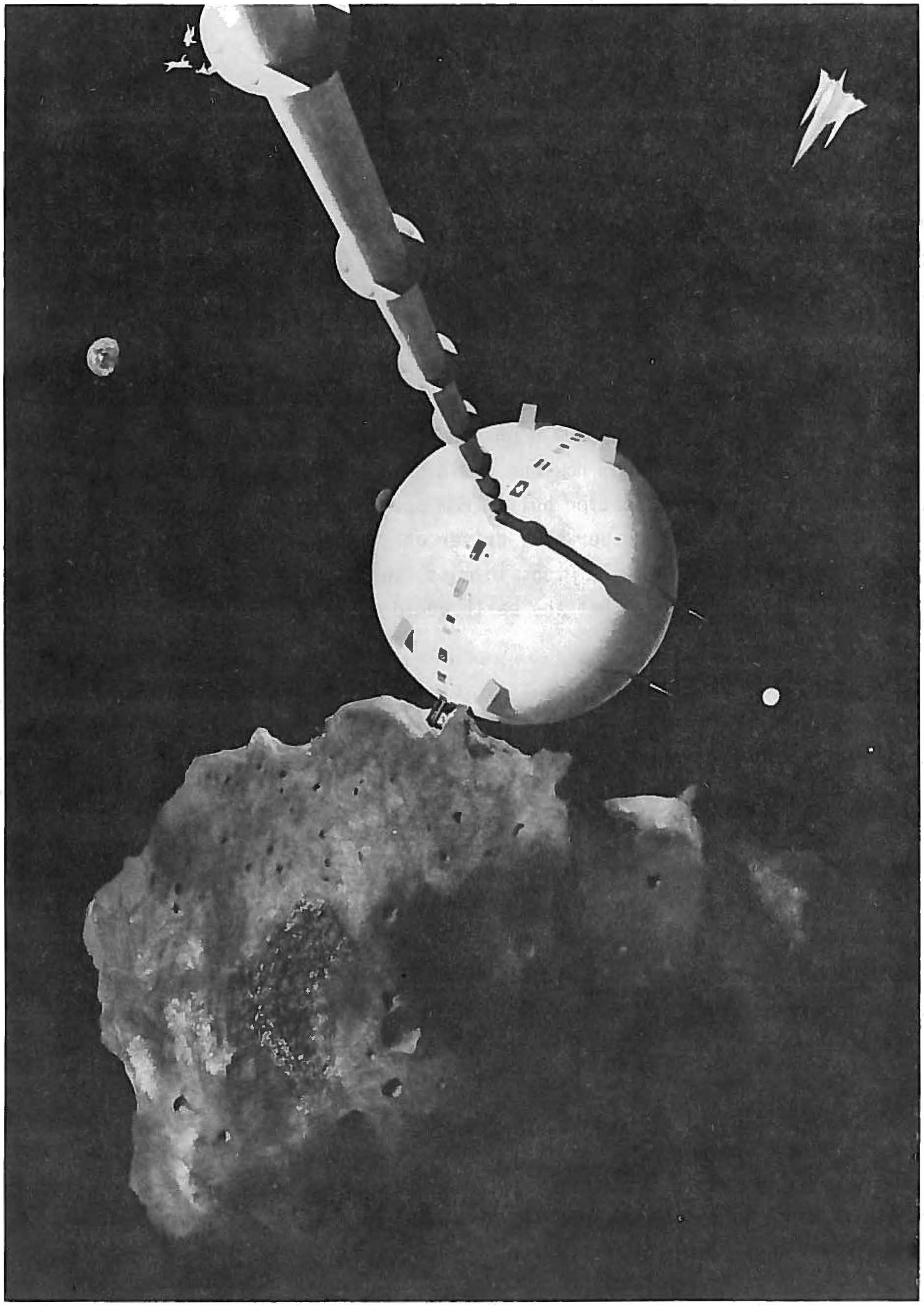
POSSIBLE SPACE MANUFACTURING PROGRAM USING APOLLO AND AMOR ASTEROID RESOURCES

YEAR(S)	ACTIVITIES
1981-85	DEVELOPMENT OF THE FIRST FULL SCALE SMF (COST $\sim$ \$15 BILLION).
1985-86	RECEIPT OF FIRST ASTEROID ($m_f \gtrsim 10^6$ TONS) AT THE SMF; BEGIN PROCESSING.
1986-87	CONSTRUCTION OF FIRST FULL SCALE (10,000 MW) SATELLITE SOLAR POWER STATIONS.
1987-1995	RETRIEVAL OF LARGER ASTEROIDS ($m_f \gtrsim 10^8$ TONS) FOR LARGE-SCALE PROGRAM OF SPACE MANUFACTURING.

The costs of these activities, over the next eight years, would be somewhere around a billion dollars or so. In the early 80's then you may send a probe and return a sample to a candidate asteroid. Or you may, as Dave Criswell suggest, decide to sidestep that step and just go out and get what you can and use it as reaction mass. Then you would make a go or no-go decision, possibly toward the end of the Carter administration or slightly thereafter. It would take a few years to bring the asteroid back. Meanwhile, one builds a chemical processing plant in space sized for the kind of throughputs you could sustain from the asteroids. The throughputs are somewhat comparable to that of the lunar case that we have been studying in summer studies. In principal, approximately twelve years from now one could have the first full-scale satellite power station or prototype station built from asteroidal material. That satellite power station could power a super-mass-driver or super-tanker-tug to get a larger asteroid on an order of 10^8 - 19^9 tons in mass. Such a large asteroid could provide all the satellite power stations that the earth would ever need, plus permanent space habitats.

In the final slide (slide 1.13) is a very pretty Chesley Bonnestell painting that appeared on the cover of Aeronautics and Astronautics a couple of months ago. This is a concept of an advanced mass driver hauling in an asteroid.

I would like to conclude that the studies I have done show that asteroid-retrieval seems to be cost effective compared to other resources. The asteroid approach perhaps opens up a lower cost, incremental road to a wide scale program in space manufacturing. The economics of a concept of Gaffey and McCord that you could recover asteroidal resources for metal resources to be used directly here on the earth looks quite as if you are retrieving asteroids with very low delta v's by use of a mass driver. There are also other ideas, such as growing food in space for use on the earth. There are also other ideas, such as growing food in space for use on the earth. Not least of all for this audience, is that such an undertaking would be scientifically very exciting. A carbonaceous sample would be very, very exciting to recover. The one billion dollar price tag I mentioned is simply for the mass driver retrieval mission; it does not include development costs, that my guess would be on the order of a few billion more. However, those development costs would be incurred in any space manufacturing program that is proposed. My recommendation then is to increase the search program drastically and immediately, to perform mission analysis and design studies, work out low thrust trajectories as soon as possible in realistic cases and to speed up development of the mass driver.



Slide 1.13

QUESTIONS AND ANSWERS

Q: "You implied that the space missions to retrieve the asteroids would be unmanned and certainly the time scale retrieval of one to two years to bring them back to earth orbit would seem to imply that. My question is what do you think the developmental costs and the necessary increased level in automation would be for this type of system to work? In other words, why are you leaving man out of the loop in this type of effort?"

A: "I don't necessarily mean to prejudice the case there; I was suggesting that it could perhaps be done unmanned. I think this needs a very careful study. If you sent men there and it took several years to get the asteroid back, then I would think you'd want to send the men back on another mass driver or other device on a Homann trajectory fairly quickly. But, I think that the technical challenges of such a program, at least in first glance, do not appear to be that insurmountable to be able to do it automated."

Q: "Would the presently planned space telescopes be adequate for the search that you are talking about?"

A: "Well, the space telescope that is being planned for the early 80's has a very small field of view ; what you really need are large field telescopes. One concept that we are looking at is a proposal for the Long Duration Exposure Facility to fly a Schmidt telescope with about an eighteen inch aperture. We would expect the discovery rate to go up to about a hundred new objects per year. You can get about twenty thousand sky fields that way and you can actually track an object in its orbit and perhaps classify it chemically in a rather general way by using different color filters. So, that seemed to be the most attractive thing, there are other suggestions about using existing Air Force infrared telescopes. If anybody has access to these data, let me know."

2.1

PROBABLE POPULATION OF EARTH APPROACHING ASTEROIDS AND FUTURE TELESCOPIC SEARCHES

E. M. Shoemaker and E. Helen

Revised transcript is not available.

A manuscript particularly relevant to this topic was prepared at the 1977 NASA/Ames summer study and is to be published in 1978 as a NASA SP.

Gaffey, M. J., Helin, E. F. and O'Leary (1978); An Assessment of near-earth asteroid resources (in press).

REMOTE DETERMINATIONS OF THE COMPOSITIONS OF EARTH APPROACHING ASTEROIDS

Prof. T. B. McCord & Dr. M. J. Gaffey
University of Hawaii

Recently, there has been a considerable increase in the activity of remote sensing of asteroids and this activity has ranged all the way from determining brightness of the asteroids to determining their sizes, albedos, culminating finally in the determination of what some of these objects are made of, their surface mineralogy.

There are several methods of acquiring information which can be used on determining surface mineralogy (slide 3.1). First of all, is spectrophotometry. There are absorption bands in the reflection spectra of asteroids and these absorptions can be interpreted in terms of specific minerals. Secondly, there is infrared radiometry which is used to determine diameters of the objects and using the brightness to get an albedo. And thirdly, the polarization method produces an albedo and with brightness, a diameter. The methods "b" and "c" can be checked one against the other. The albedo is the important piece of information which is used in improving compositional interpretations.

These are reflectance spectra of minerals and rocks (slide 3.2) measured in the laboratory. Reflectance is plotted vertically, and wavelength, horizontally. At half a micron, one micron, and in the visible spectra region you see for a variety of minerals some very intense absorption features. The bottom curve is the spectrum of the mineral pyroxene which exhibits the two absorption bands near 0.9 and 1.8 microns characteristic of this mineral. The positions of these bands are related to mineral chemistry. The middle curve (olivine) shows the broad asymmetric feature near 1.0 micron typical of this mineral. The spectral curve of nickel-iron metal (slide 3.3, lower right, curve #4) has no specific absorption features, but has a characteristic slope and shape. A laboratory mixture of a clay mineral with about 5% carbon (slide 3.3, lower left) is similar to that of carbonaceous chondritic assemblages types 1 and 2.

So, the point is that there are quite dramatic absorption features that occur in minerals and rocks when measured in the laboratory under the best of conditions. One can analyze these spectra and Mike Gaffey, my colleague, has become quite expert at deriving detailed quantitative information out of spectra. Here is a spectrum plotted in energy space rather than wavelength space (slide 3.4). One

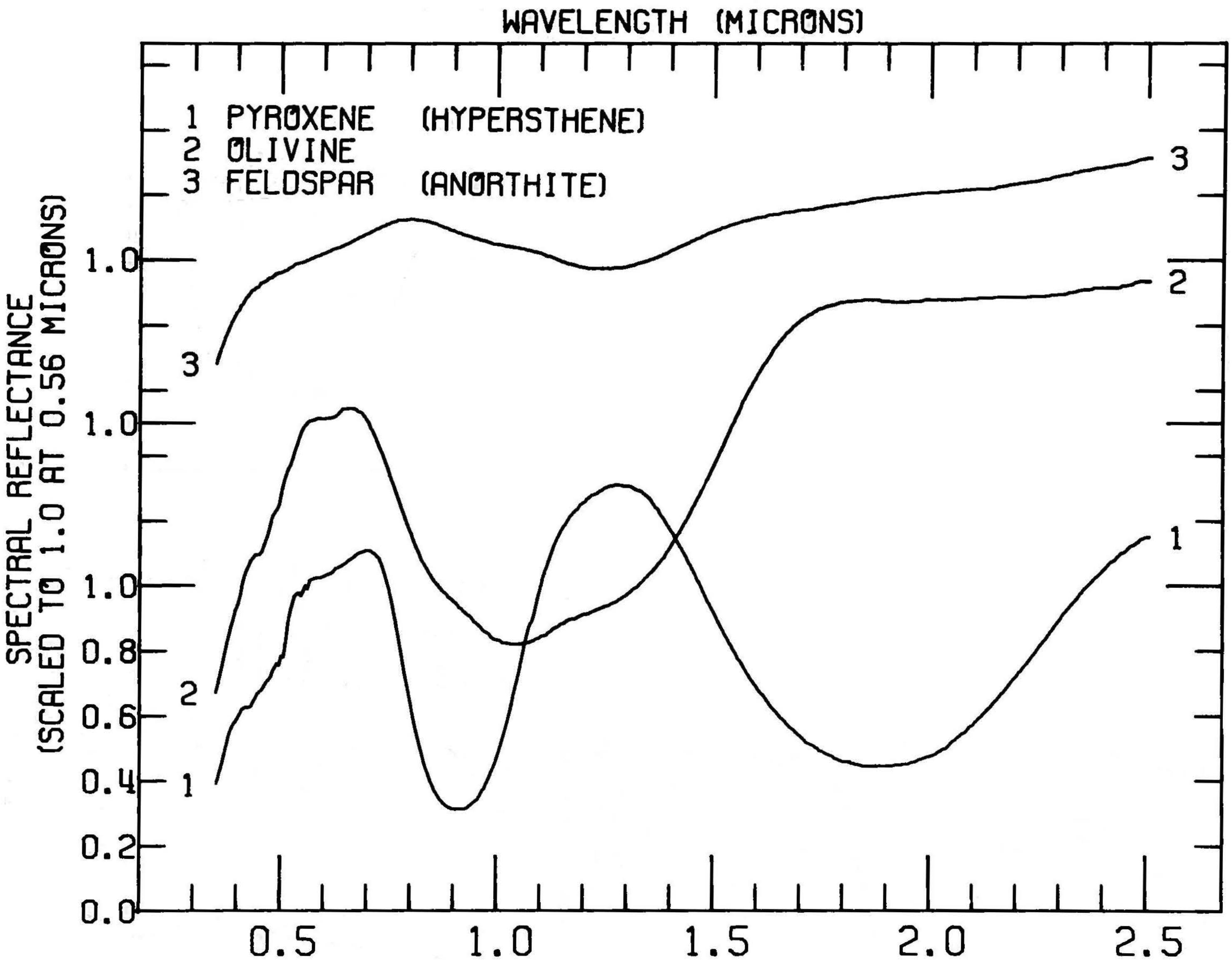
ASTEROIDAL DATA SETS:

A. SPECTROPHOTOMETRY

1. LOW RESOLUTION - UBVRIJHK FILTERS
2. INTERMEDIATE RES. - NARROW FILTERS
3. HIGH RESOLUTION - INTERFEROMETER

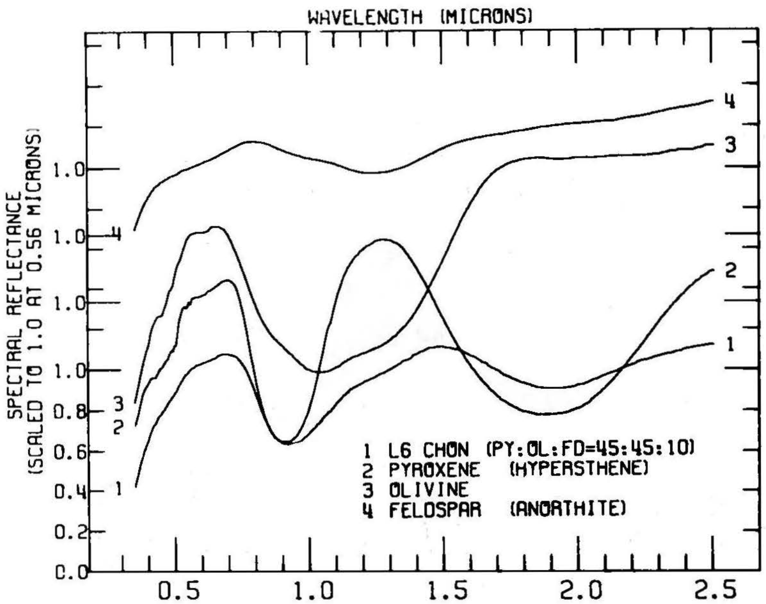
B. INFRARED RADIOMETRY

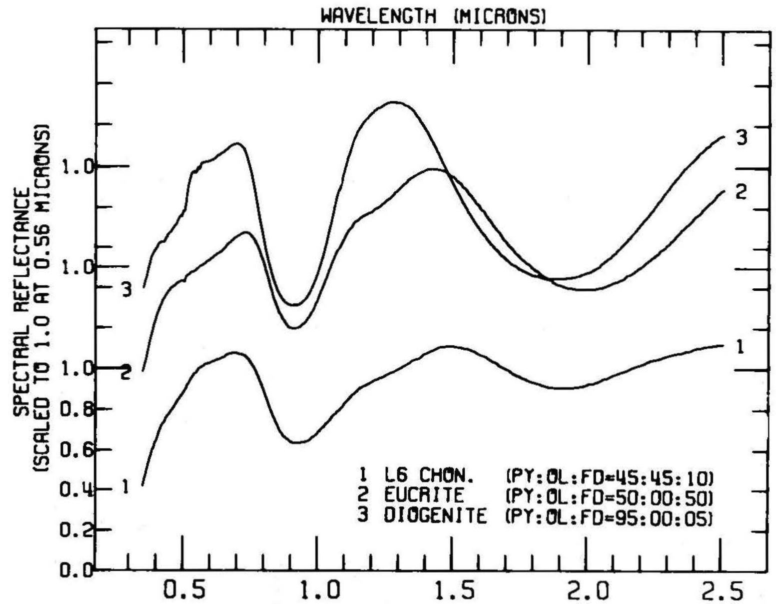
C. PHASE - POLARIZATION PHOTOMETRY

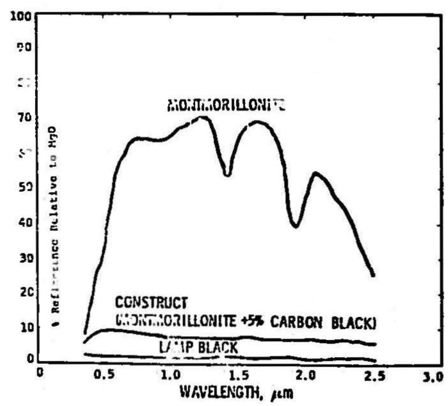


WAVELENGTH (MICRONS)
1 PYROXENE (HYPERSTHENE)
2 OLIVINE
3 FELDSPAR (ANORTHITE)
SPECTRAL REFLECTANCE
(SCALED TO 1.0 AT 0.56 MICRONS)
1.0
1.0
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3
2
1

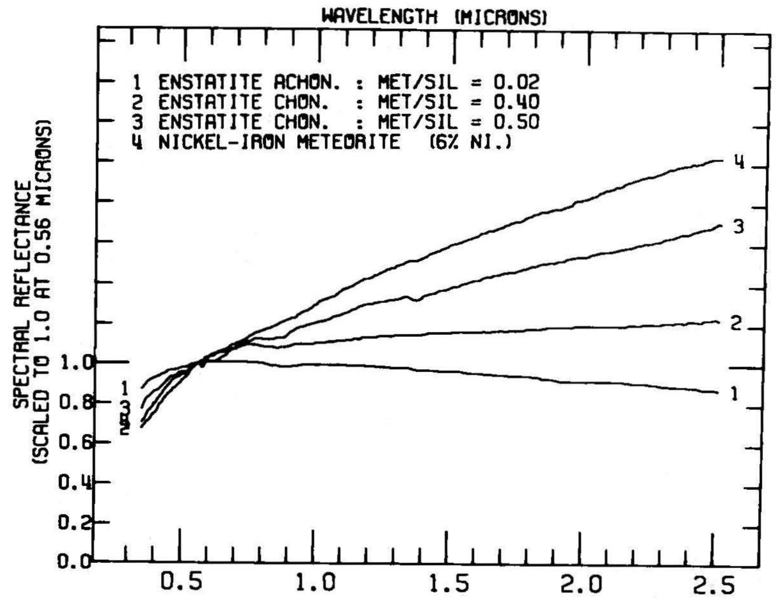
Slide 3.2



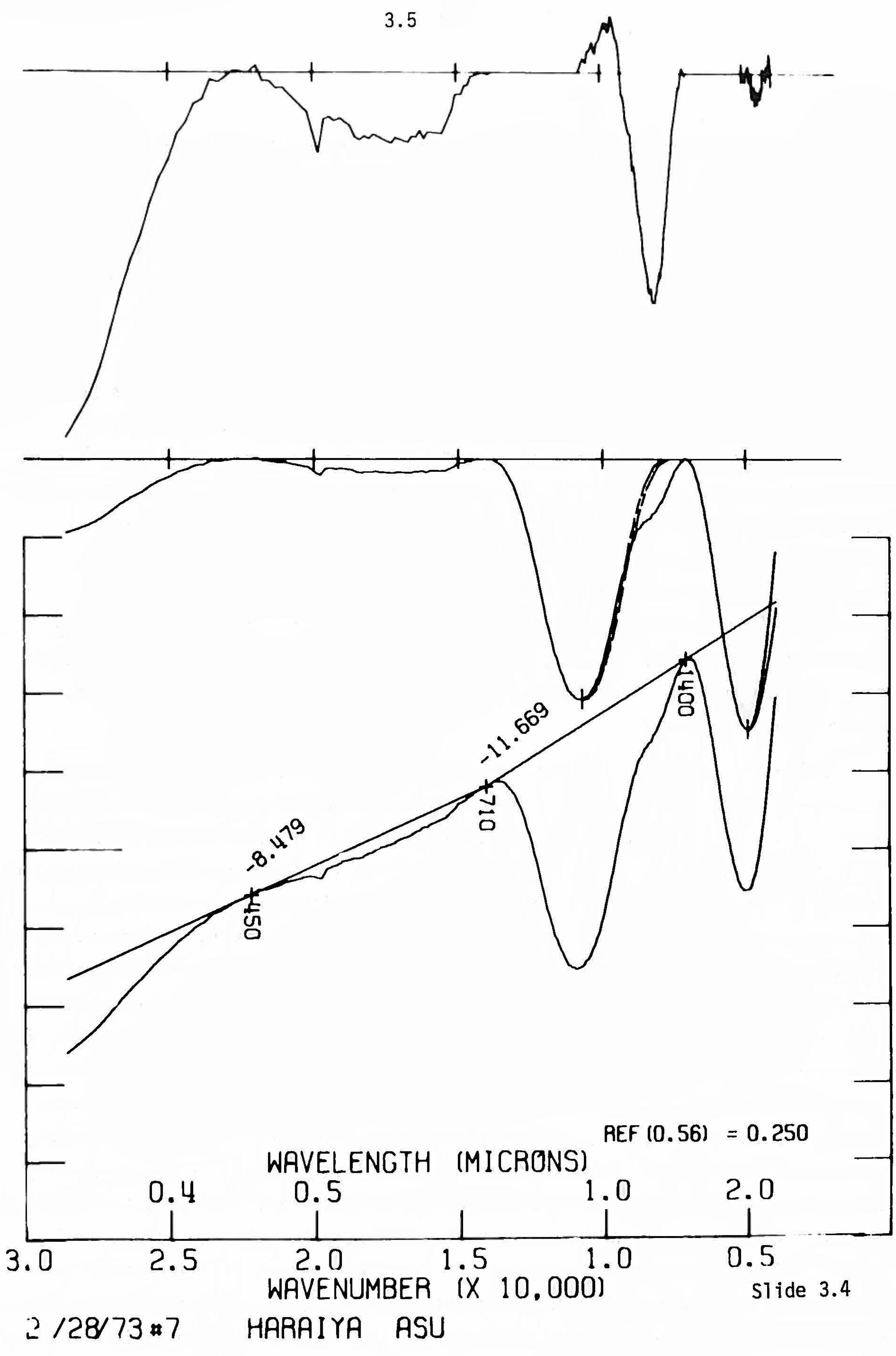




(Johnson and Fanale, 1973)



Slide 3.3

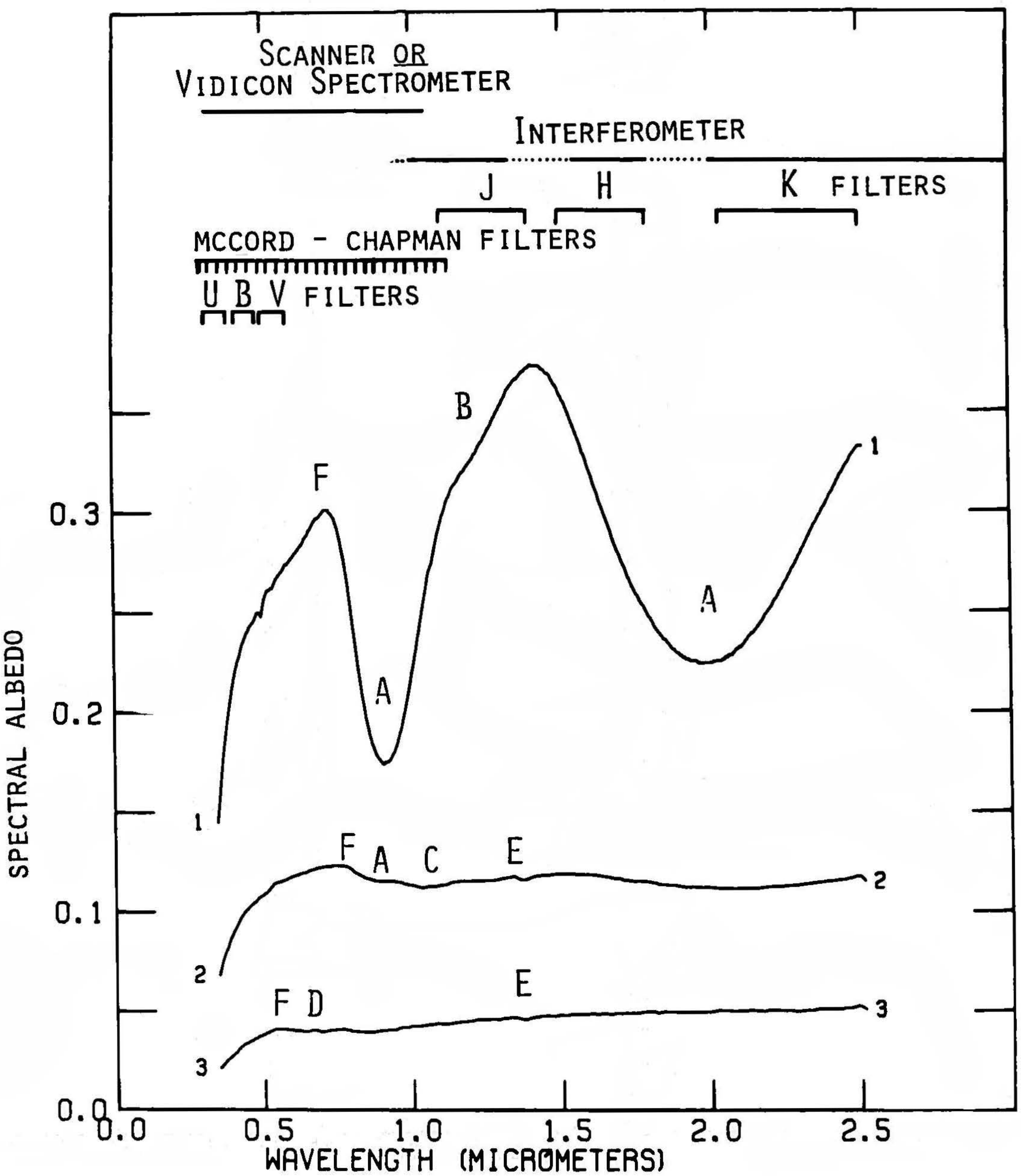

3.5
-8.479
-11.669
450
710
1400
REF (0.56) = 0.250
WAVELENGTH (MICRONS)
0.4
0.5
1.0
2.0
3.0
2.5
2.0
1.5
1.0
0.5
WAVENUMBER (X 10,000)
2 /28/73 #7 HARAIYA ASU

Slide 3.4

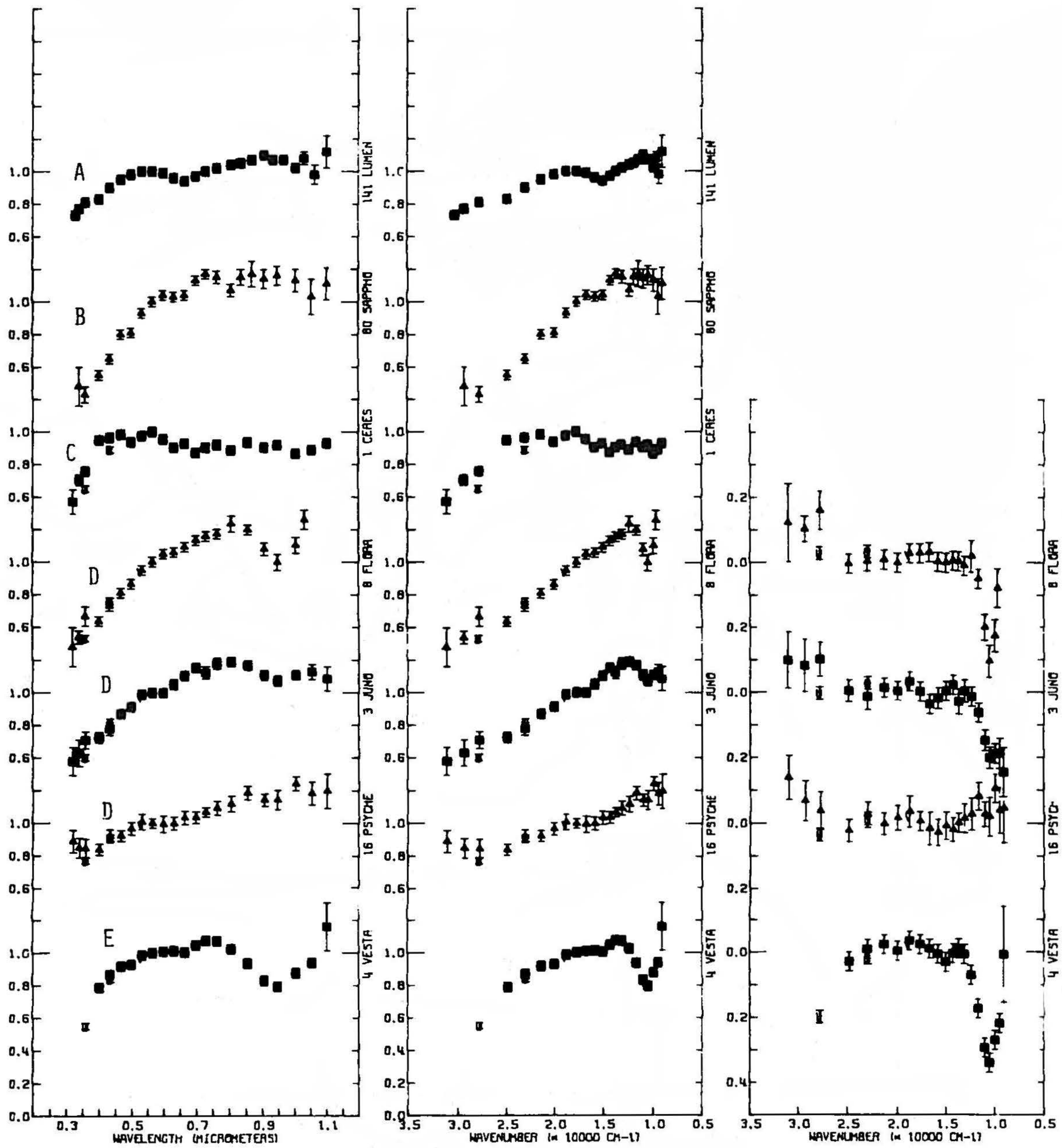
can make assumptions about the shape of the absorption bands, assumptions that are based on theoretical and laboratory analyses, and one can remove bands and then analyze smaller bands that are combined with stronger bands where we see a plot with a residual. In the top portion of the slide, the scale is expanded considerably to show where the feldspar band is enhanced.

On slide 3.5 you see a pyroxene-rich rock plotted with an example of different spectral resolutions associated with different measurements made of the spectrum of asteroids. UBV photometry, three broadband filters measuring near UV and visible portion of the spectrum, the multifilter spectrophotometry that Clark Chapman and myself have been doing over the last five to eight years, here 24 or 25 filters covering the regions which contain a number of these absorption features in this particular rock and in other kinds of materials. Broadband infrared measurements (J, H, K filters) are made by Johnson and Matson and others. Three asteroids have been measured using interferometry in the near infrared spectral region, but this works on only fairly bright objects. You get a feeling for the kind of spectral resolution necessary to analyze rocky surfaces for their compositions compared to the observational data sets.

Slide 3.6 presents examples of asteroid spectra; these are reflectance spectra of asteroids measured using ground-based telescopes. We have measured over 200 asteroids now and have published about 100 asteroid spectra. All of these measurements are in the region from 0.4 to 1.1 microns, a somewhat smaller region of the spectrum than I was showing for the laboratory measurements, but the same region as indicated for the 24 filter measurements in the previous slide. You see here a variety of curve shapes, curves with a more or less linear slope increasing to the red part of the spectrum, and curves with strong absorptions in the infrared. One can see combinations of these things and you see spectra that are more or less flat, except for a strong UV absorption. Now, these curves appear somewhat noisy to you, I imagine, but if you've looked at enough of them and measured them enough times, you'd find that these features repeat quite nicely and are interpretable. Some of these features I've pointed out to you are key features in understanding or determining the composition. There is a considerable amount, as I have said, of laboratory and theoretical work that have gone into understanding these asteroid spectra and it is because of this intensive background work that we are able to determine that a particular absorption band is due to the mineral pyroxene and, in fact, go so far as to determine its calcium


SCANNER OR
VIDICON SPECTROMETER
INTERFEROMETER
J
H
K FILTERS
MCCORD - CHAPMAN FILTERS
U B V FILTERS
F
A
B
A
1
1
F A C E
2
2
F D
E
3
3
0.3
0.2
0.1
0.0
SPECTRAL ALBEDO
0.0
0.5
1.0
1.5
2.0
2.5
WAVELENGTH (MICROMETERS)

Slide 3.5


A
B
C
D
D
D
E
141 LUMEN
80 SAPPHO
1 CERES
8 FLORA
3 JUNO
16 PSYCHE
4 VESTA
WAVELENGTH (MICROMETERS)
WAVENUMBER (× 10000 CM-1)
WAVENUMBER (× 10000 CM-1)

Slide 3.6

content and iron-to-magnesium ratio.

I point out here also that it is the features in the curves that we are interested in and not just the overall shapes of the curves themselves. One can measure in the laboratory a variety of materials and then search through a library of curves and attempt to overlay the asteroid curve or a number of the curves in a data library and come up with a match. The problem with that technique is that sometimes there can be very large differences in the spectra which are not terribly significant mineralogically, or there can be very small differences which are significant. One must consider the different features in a curve independently and analyze them in terms of what one knows from laboratory and theoretical work. In this way, one can produce an understanding of the mineral assemblage present, that is, the different kinds of minerals.

The results of the work so far are a paper that Mike Gaffey and I are about to submit for publication; it only took us three years to produce it and I sure am glad to get rid of it (slide 3.7). We have taken the 65 best spectra that we have for asteroids and have combined these with laboratory theoretical work to interpret or determine the mineral assemblages which we think are most likely to exist on the surfaces of these 65 asteroids. We have determined mineral assemblages in terms of these major components, namely, opaque materials, either carbon or magnetite, various iron silicate minerals (olivines, pyroxenes, feldspars) and in terms of metal, nickel iron. The breakdown is as follows: of these 65 asteroids, about 40% of them contain opaques, plus $Fe2^{+}$ bearing silicates; these are low-temperature assemblages, clay minerals and carbon, probably, and the equivalent meteorites could be Cl or C2 carbonaceous chondrites. The next group comprises about 15% of the objects measured; these are opaques, plus mafic minerals, such as olivene, and these would be equivalent to C3 carbonaceous chondrites. The third group is opaques plus mafic silicates, with magnetite rather than carbon and is equivalent to perhaps a C4 carbonaceous chondrite and these are about 10% of the 65. The fourth group, which is the other large group, is metal, that is, iron and nickel, plus mafic silicates, olivene and/or pyroxene. The relative abundances of metal and silicates vary throughout this group of asteroids. Then the fifth group, which has one member, so far. It is similar to a basaltic achondrite. The last group which is of perhaps most interest to this particular discussion is the ordinary chondrite-like assemblages, which we found for two near-Earth-passing asteroids and for essen-

ASTEROID SURFACE MATERIALS - SUMMARY

I. CLAY MINERAL (Fe^{2+}-Fe^{3+}) + OPAQUE

~80% OF MAIN BELT ASTEROIDS

~C1-C2 CARBONACEOUS CHONDRITIC MATERIALS
HYDRATED SILICATES + CARBON

LOW ALBEDOS (3-6%)

10 HYGIEA, 19 FORTUNA, 511 DAVIDA

II. MAFIC (Fe^{2+}) SILICATE + OPAQUE

~C3 (OLIVINE + CARBON)

80 SAPPHO, 221 EOS, 887 ALINDA

III. MAFIC (Fe^{2+}) SILICATE + OPAQUE

~C4 (OLIVINE + MAGNETITE)

1 CERES, 2 PALLAS

IV. METAL (NiFe) & METAL + SILICATE

MOST COMMON IN INNER BELT

METAL + OLIVINE: 3 JUNO, 354 ELEONORA

METAL + PYROXENE: 8 FLORA, 40 HARMONIA

METAL OR METAL + ENSTATITE: 16 PSYCHE, 140 SIWA

HEATED AND MELTED

V. PYROXENE-PLAGIOCLASE - 4 VESTA

~EUCRITE, HEATED AND MELTED

VI. OLIVINE (+ METAL?) - 349 DEMBOWSKA

~OLIVINE ACHONDRITE

VII. OLIVINE + PYROXENE + METAL - 433 EROS

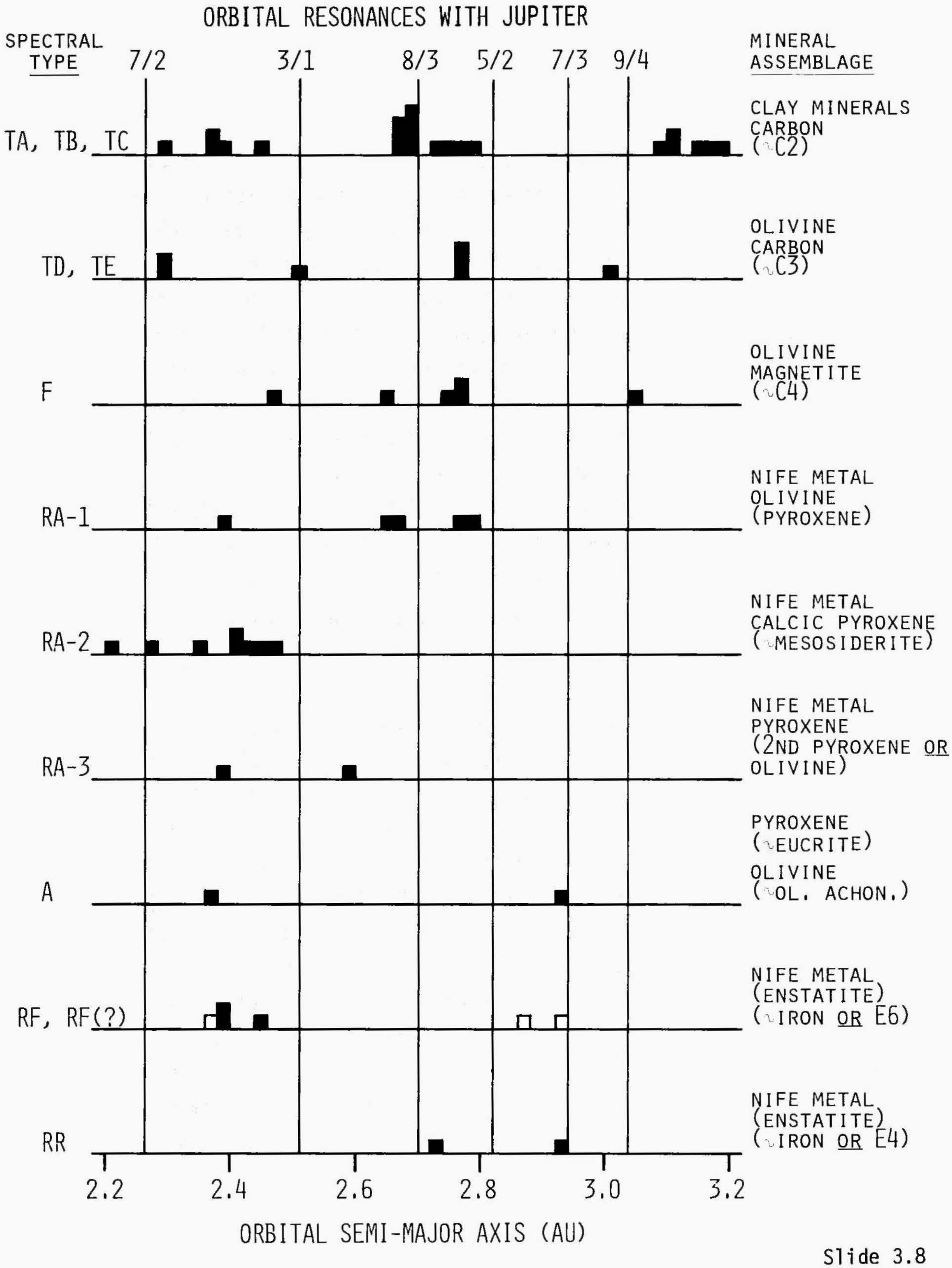
~ORDINARY CHONDRITE

RARE OR ABSENT IN MAIN BELT

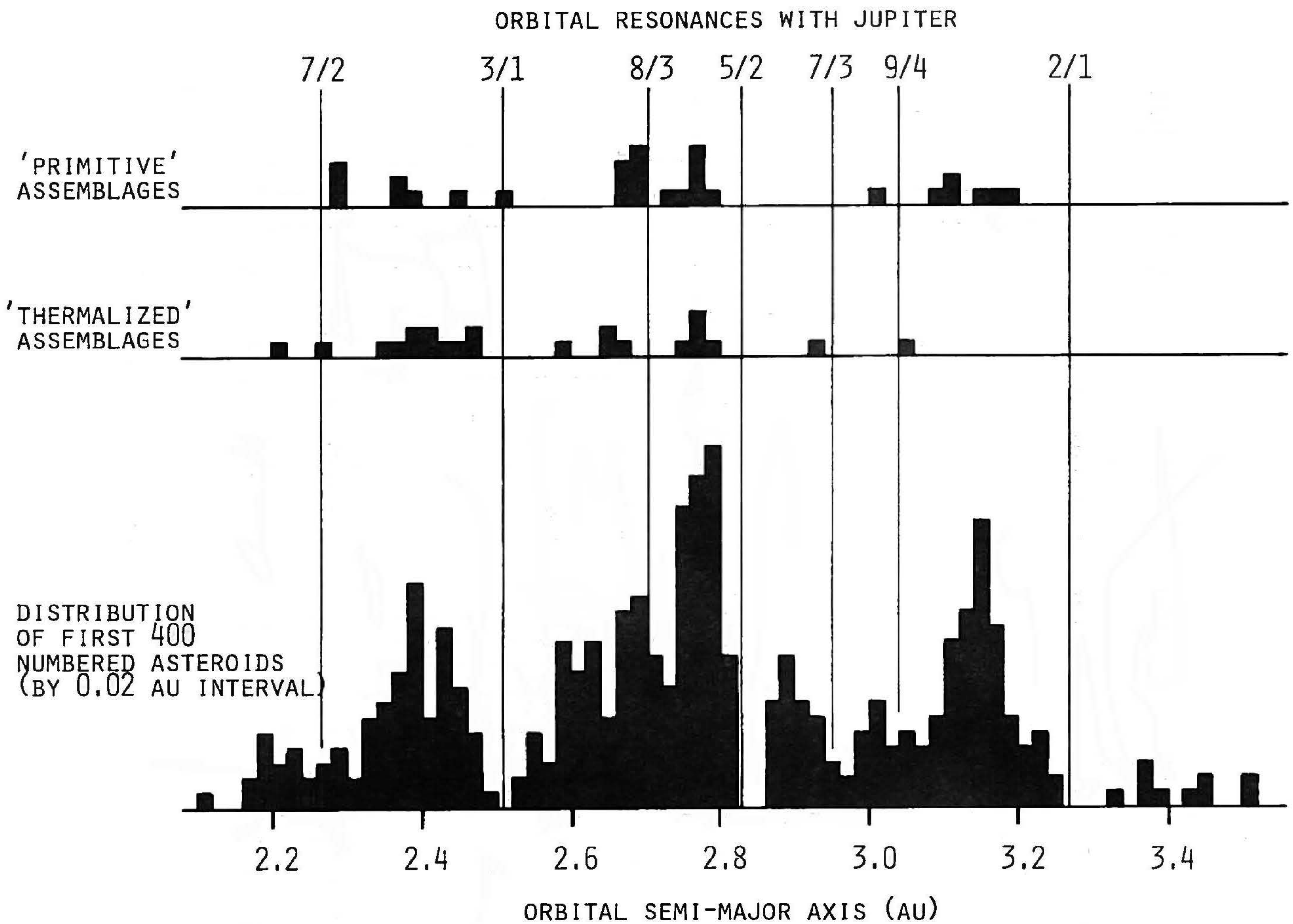
COMMON ON EARTH APPROACHING ASTEROIDS

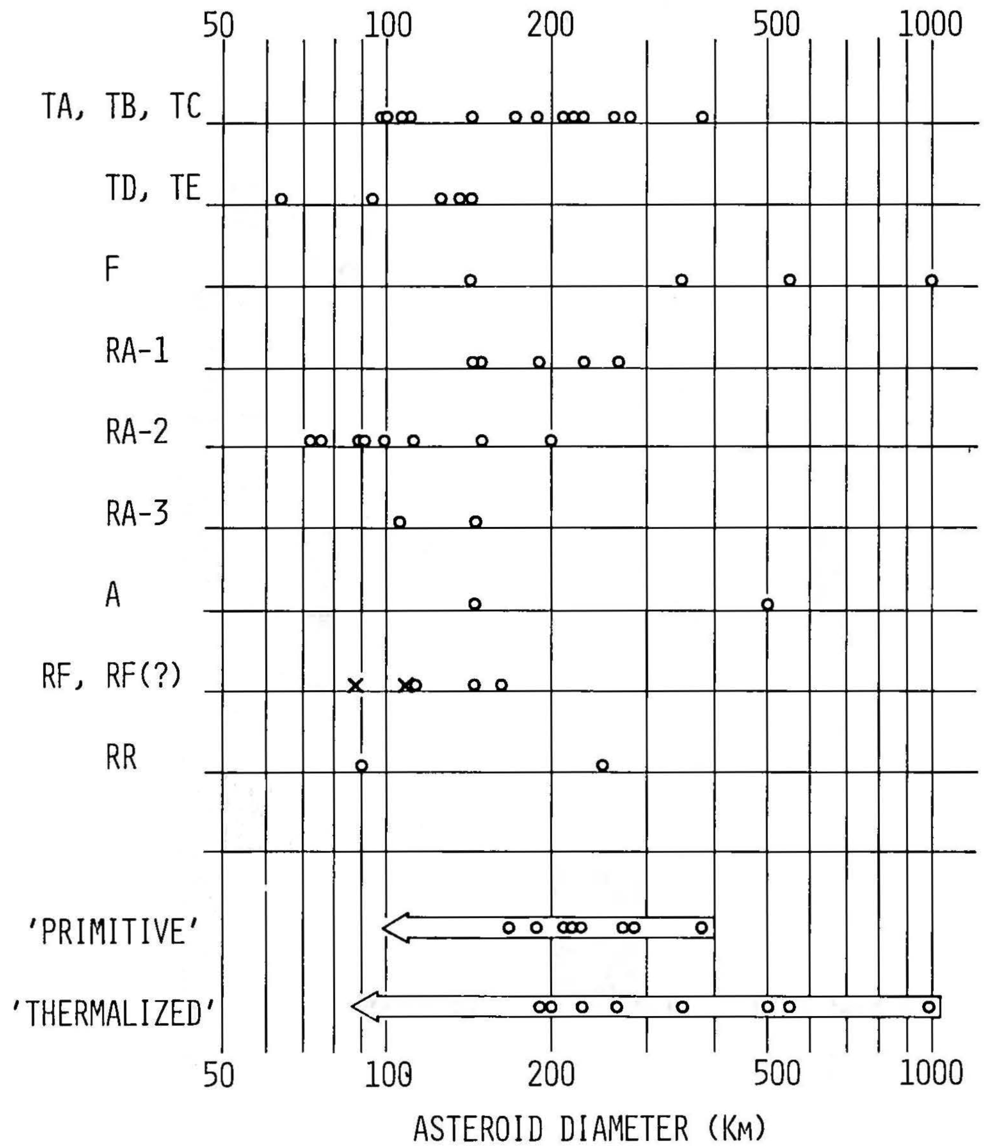
tially no other asteroids that we've looked at. This particular mineral assemblage is the most common in meteorite falls and yet is very uncommon, essentially non-existent as far as we've seen to date in the main asteroid belt, but has comprised two of the three close-passing asteroids that we have looked at so far and may comprise the third; the data aren't really good enough to interpret. Once you do a little statistics on these asteroids, according to their compositions and orbits one finds (slide 3.8) that objects which have had low-temperature histories, which are those objects containing clay minerals tend to be evenly distributed throughout the asteroid belt as we have looked so far. Objects that have had a high-temperature history and contain reduced metals tend to be concentrated more in the inner part of the solar system. A plot of mineralogy versus semimajor axis (slide 3.9) for grouped high- and low-temperature materials shows this pattern. Slide (3.10) is a correlation of composition with asteroid diameter. We find that the objects with higher temperature pasts dominate the largest size group.

All these measurements are made using ground-based telescopes and I would suggest that there is a future for this sort of work, especially for near-Earth-passing objects. It's not enough to find them; one must understand what they are made of before one can determine whether it's worthwhile going after them or not. I would also suggest that it is important to go to a number of these asteroids and actually sample them. After all, everything I am telling you may be wrong and it would be nice to find out before we mount a multibillion dollar expedition to bring one of these objects back. And, thirdly, I would not like to see us get locked into considering only near-Earth objects at this point. The amount of delta v or energy it requires to bring an object in seems not to be all that well agreed upon at the moment. There are many objects in the main asteroid belt, which contain large amounts of economically useful materials. Before we simply eliminate them, we should be sure, number one, that there are objects passing close to the Earth that require low delta v to use and that have the right kind of materials and, secondly, that it does indeed take a significant amount more energy to go to the objects in the main asteroid belt and use them.


ORBITAL RESONANCES WITH JUPITER
SPECTRAL TYPE
7/2
3/1
8/3
5/2
7/3
9/4
MINERAL ASSEMBLAGE
TA, TB, TC
CLAY MINERALS
CARBON
(∿C2)
TD, TE
OLIVINE
CARBON
(∿C3)
F
OLIVINE
MAGNETITE
(∿C4)
RA-1
NIFE METAL
OLIVINE
(PYROXENE)
RA-2
NIFE METAL
CALCIC PYROXENE
(∿MESOSIDERITE)
RA-3
NIFE METAL
PYROXENE
(2ND PYROXENE OR
OLIVINE)
A
PYROXENE
(∿EUCRITE)
OLIVINE
(∿OL. ACHON.)
RF, RF(?)
NIFE METAL
(ENSTATITE)
(∿IRON OR E6)
RR
NIFE METAL
(ENSTATITE)
(∿IRON OR E4)
2.2
2.4
2.6
2.8
3.0
3.2
ORBITAL SEMI-MAJOR AXIS (AU)

Slide 3.8


ORBITAL RESONANCES WITH JUPITER
7/2
3/1
8/3
5/2
7/3
9/4
2/1
'PRIMITIVE' ASSEMBLAGES
'THERMALIZED' ASSEMBLAGES
DISTRIBUTION OF FIRST 400 NUMBERED ASTEROIDS (BY 0.02 AU INTERVAL)
2.2
2.4
2.6
2.8
3.0
3.2
3.4
ORBITAL SEMI-MAJOR AXIS (AU)


50
100
200
500
1000
TA, TB, TC
TD, TE
F
RA-1
RA-2
RA-3
A
RF, RF(?)
RR
'PRIMITIVE'
'THERMALIZED'
50
100
200
500
1000
ASTEROID DIAMETER (KM)

Slide 3.10

QUESTIONS AND ANSWERS

Q: "What do you expect to be able to do with the space telescope with the amount of observing time you would expect to be able to get on it?"

A: "I'm not sure that it is really required, it would be helpful, but it would not represent an order-of-magnitude increase in our ability to do this sort of work."

Q: "What would the gravitational effects of the asteroids be? I know the asteroids have some kind of gravitational effect. What would the effect of it be compared to the pull of the moon? What tides would be produced? What would the Earth's movements be in relation to that?"

A: "Insignificant, because the mass difference between the Earth and the asteroids is so great that I would guess there would be very little effect or none at all."

Q: "What would happen if the asteroids went into the atmosphere and came down?"

A: "I think one would try to avoid such a situation."

M. Gaffey - "Tom, I think it's worth pointing out as Gene did for his survey, the magnitude of the effort to properly observe these Earth-crossing asteroids. After they are seen they are typically observable by our techniques for only one or two weeks. The magnitude of the observing program necessary to properly survey those is considerably larger than any of us are currently being funded to operate."

McCord - "Yes, there are several problems here. It's certainly a larger magnitude undertaking than Gene Shoemaker was talking about in that we have to measure at many wavelengths and have a very small amount of time and must measure at a great precision. So, to do this properly, one needs a rather large telescope dedicated to the program and some very sophisticated instrumentation to be able to obtain the proper precision to make the interpretations."

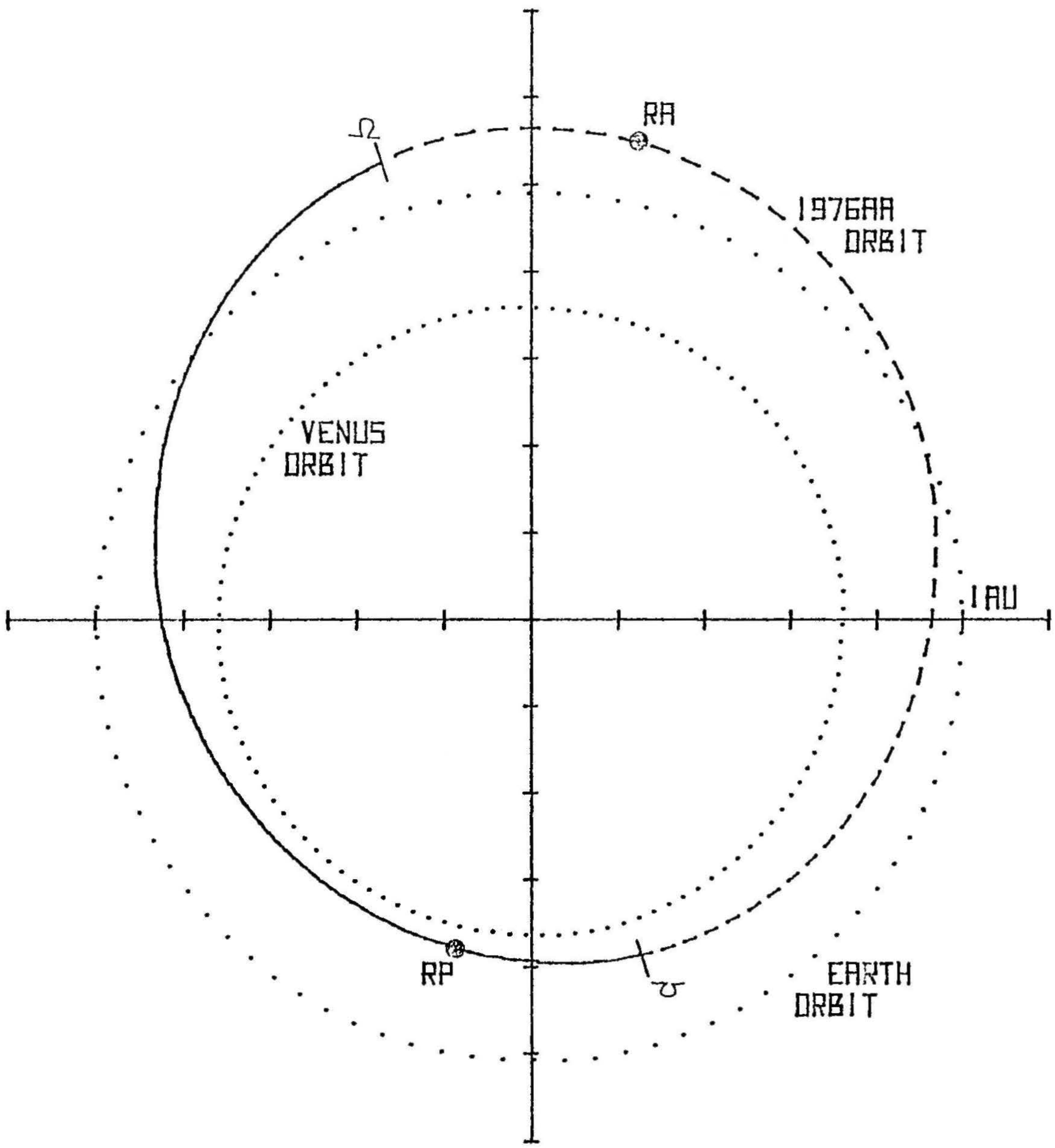
ASTEROID RETURN TRAJECTORIES

Mr. John C. Niehoff
Science Applications, Inc.

As an advanced planner providing technical support to the Lunar and Planetary Program Office for the past 15 years, I have watched the interest in asteroids and asteroid missions ebb and flow as our knowledge of where and what they are has evolved. I'm sure many of you remember Dr. Anders' comments at the Tucson Meteorite Conference in 1971. At that time he gave a reasoned argument for deferring planning of asteroid missions until the very credible existing ground-based asteroid observation program was given a chance to bear fruit. That program has, in fact, been so productive that some scientists (including several in the observations program) now feel that our base of knowledge justifies reinitiation of asteroid mission planning. Further impetus to an ateroid mission renaissance has come from the highly successful search program for near-Earth objects being conducted by Drs. Eleanor Helin and Gene Shoemaker. Their recent discoveries of several Earth-crossing asteroids have been of considerable interest to NASA as potential targets of low-energy automated or manned exploration endeavors.

I would like to first summarize the results of near-Earth asteroid sample-return mission opportunities (automated and manned), particularly those generated in the past year. Then, within the perspective of these data, I will present some preliminary results of requirements for returning an entire asteroid to Earth orbit. The renaissance in asteroid mission planning I spoke of began about a year ago with the discovery of 1976AA (Slide 4.1). As you can see, not only is this an Earth-crossing object, but it also comes very close to Venus with a perihelion of 0.79 AU. The object's aphelion is just beyond the Earth's orbit at 1.14 AU. This is the first Apollo object discovered with an orbit period less than the Earth's period of one year; specifically, 1976AA has a period of 347 days. Hence it approaches the Earth only once every 19 years. Although annual mission opportunities to 1976AA exist, optimum opportunities are also separated by 19 years.

Before examining mission requirements to 1976AA, let us first quickly review typical payload assumptions for automated asteroid sample-returns (Slide 4.2). As you can see, we're going to start out thinking very small with sample returns of only 1 kilogram. From this table you can see that approximately 780 kilograms of mass are required to support the return of such a sample. This includes the



ORBIT PARAMETERS:

PERIHELION........0.79 AU
APHELION..........1.14 AU
PERIOD............347 DAYS
INCLINATION.......19.1 DEG

ASTEROID 1976AA ORBIT PROFILE

Slide 4.1

PAYLOAD ASSUMPTIONS

Unmanned Asteroid Sample Return Missions

RETURNED SAMPLE	1 KG
DIRECT REENTRY CAPSULE	29
INTERPLANETARY BUS	250
ENCOUNTER SCIENCE PAYLOAD	150
LAND/LAUNCH/DOCK SYSTEM	350
TOTAL PAYLOAD	780 KG

Slide 4.2

sample cannister and reentry capsule, the interplanetary bus (spacecraft), the encounter science (including a 90-kg instrument allowance), and a sample collection/ retrieval system. Using these assumptions, the performance requirements of an automated sample-return mission to 1976AA can be assessed (Slide 4.3). The roundtrip time is 1 year, which is typical for this object because of the shape and size of its orbit. A one-month stay time, although arbitrary, is about as long as one can stay at the object without creating serious return transfer performance penalties. The launch, arrival, and return dates are for the optimum roundtrip opportunity which occurs in 1993-4. The total mission impulse requirement, assuming direct reentry upon returning to the Earth, is almost 14 km/sec. With cryogenic tug propulsion capability, it would take four Shuttle launches to accumulate sufficient mass in Earth orbit to undertake this mission. This is a severe launch requirement for returning only a 1-kg sample. The underlying cause of the large total impulse and consequent launch requirements is the relatively high inclination of 1976AA, i.e., over 19 degrees.

These results were discussed with Drs. Helin and Shoemaker with the hope that a more favorable object of lower inclination might provide more practical performance results. They suggested that we look at the earlier discovered Amor object, 1943, which has an inclination of less than 9 degrees (Slide 4.4). 1943 can come within 0.1 AU of the Earth with a perihelion of 1.06 AU and crosses the orbit of Mars to an aphelion of 1.8 AU. Its orbit period is 625 days. Launch opportunities to 1943 occur every 2-1/2 years. Low-energy, long roundtrip ($\approx$ 3 years) opportunities, favorable for automated missions occur every 12 years. The next one occurs in 1980, the one after that in 1992, and so on. The performance requirements for a 1992 automated roundtrip mission are summarized in the next slide (Slide 4.5). The total roundtrip time is just under three years with an extended staytime of almost six months before phasing between 1943 and the Earth is acceptable for a low-energy return. Launch occurs in May 1992 with the sample returning in May 1995. The total impulse requirement is 7.4 km/sec, just a little more than half the 1976AA requirement. This reduction comes directly from the reduction in inclination. The total mass required in Earth orbit to perform this mission can be delivered with a single Shuttle launch. In fact, the IUS(II) upper-stage configuration, planned for operational geosynchronous Shuttle-based missions could be used as the escape stage for this sample return. Except for the lengthy flight time, and launch year, this could be an attractive early asteroid sample return candidate.

PERFORMANCE SUMMARY

Unmanned 1976AA Sample Return

ROUND-TRIP TIME	365 days
STAY TIME	30 days
LAUNCH DATE	7/16/93
ARRIVAL DATE	12/18/93
RETURN DATE	7/16/94
TOTAL IMPULSE REQ'D	
(Direct Earth Reentry)	13.825 km/sec[a]
GROSS LAUNCHED PAYLOAD MASS	89,500 kg[b]
NO. OF SHUTTLE LAUNCHES REQ'D	4

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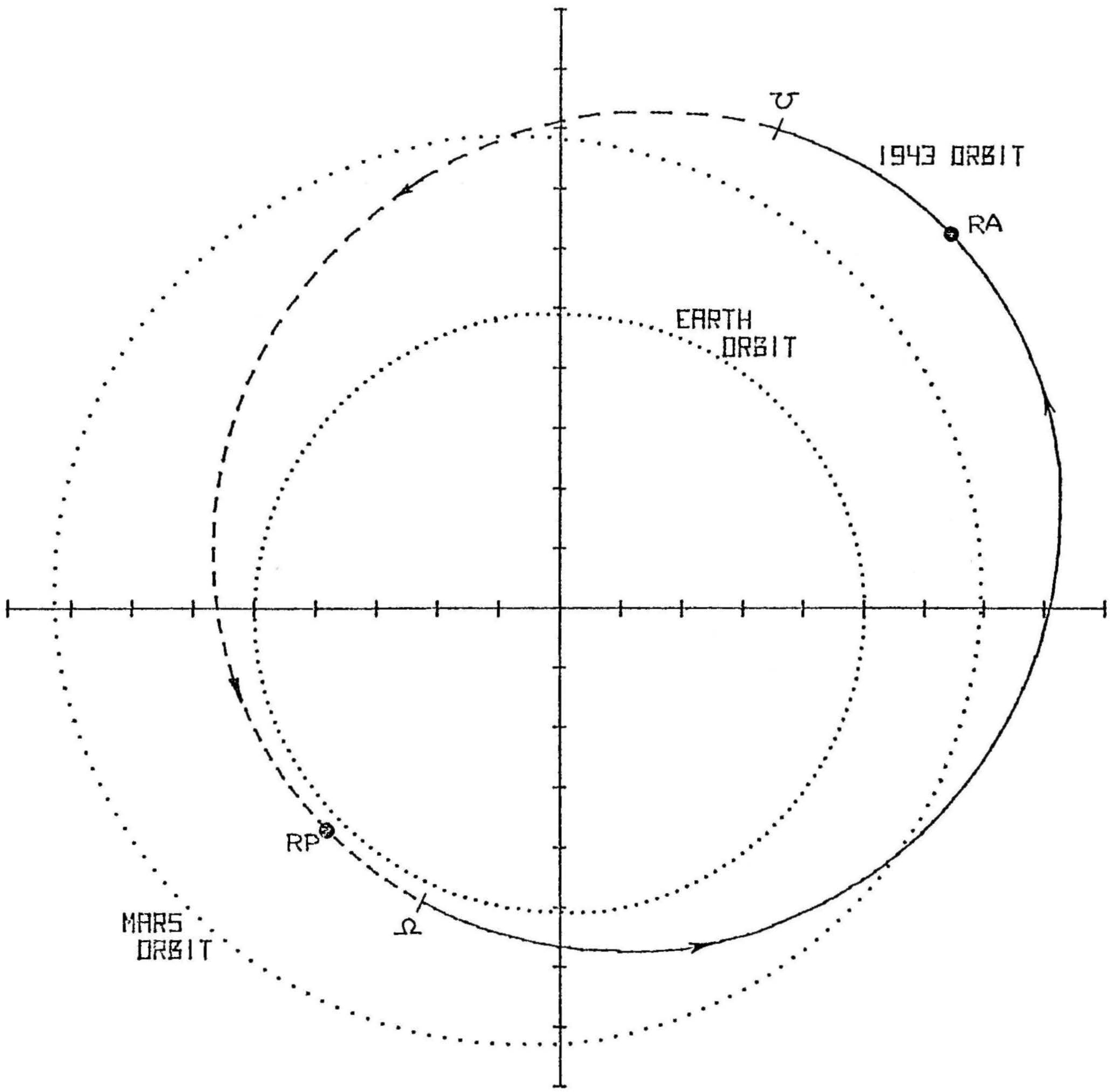
a. includes 0.275 km/sec maneuver and G/C impulse

b. assumes 3 Expendable Tug escape stages and space-storable interplanetary propulsion.

Slide 4.3



ORBIT PARAMETERS:

PERIHELION.........1.06 AU
APHELION...........1.80 AU
PERIOD.............625 DAYS
INCLINATION........8.70 DEG

ASTEROID 1943 (AMOR GROUP) ORBIT PROFILE

Slide 4.4

PERFORMANCE SUMMARY

Unmanned 1943 Sample Return

ROUND-TRIP TIME	1084 days
STAY TIME	177 days
LAUNCH DATE	5/26/92
ARRIVAL DATE	8/20/93
RETURN DATE	5/14/95
TOTAL IMPULSE REQ'D (Direct Earth Reentry)	7.410 km/sec[a]
GROSS LAUNCHED PAYLOAD MASS	29167 kg[b]
NO. OF SHUTTLE LAUNCHES REQ'D	1

---

a. includes 0.275 km/sec maneuver and G/C impulse

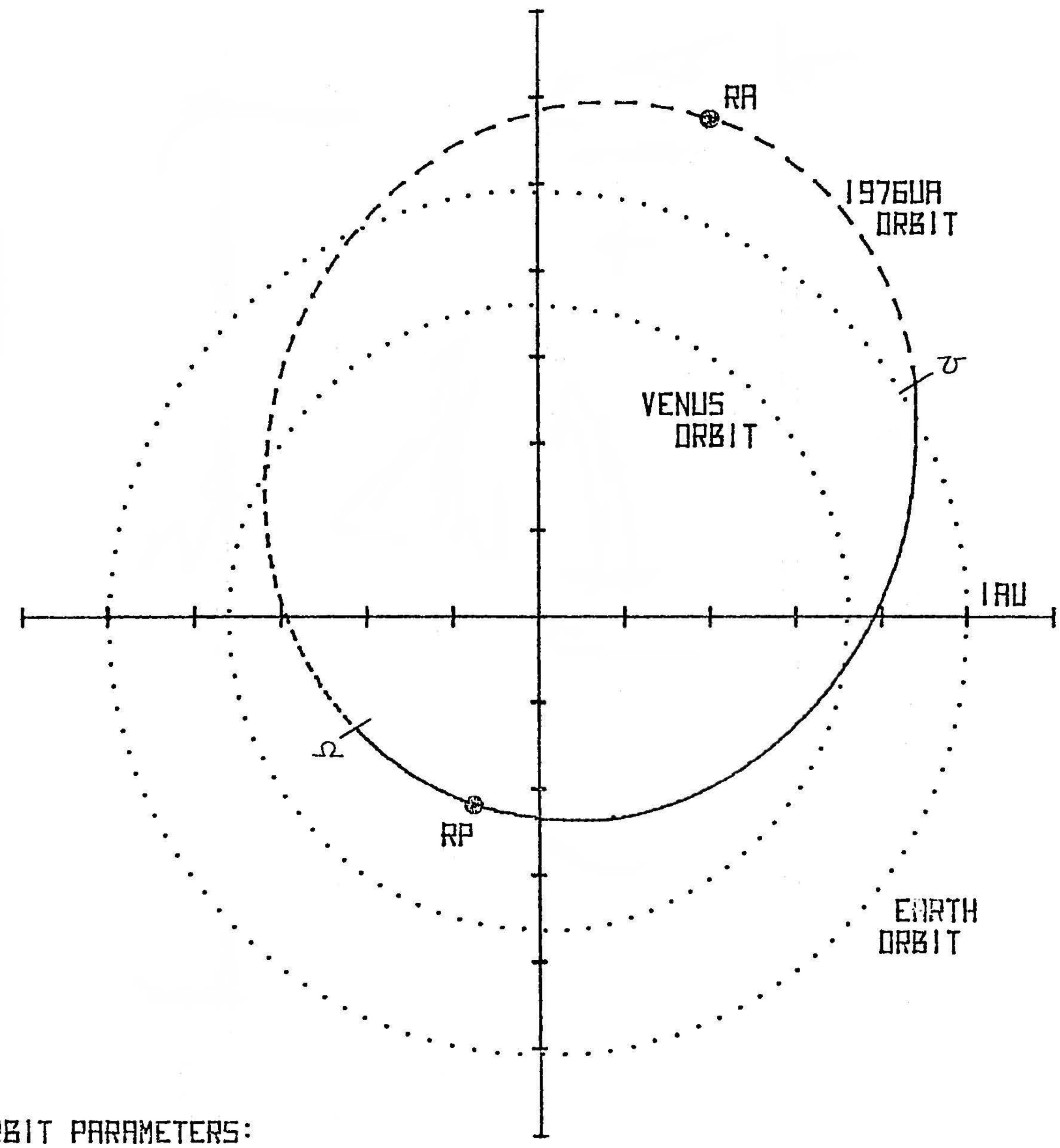
b. assumes Recoverable TUG/Kick escape stage and space-storable interplanetary propulsion.

Manned mission results for 1976AA and 1943 were also briefly studied, constrained to one-year trip times, with very different results. Assuming a three-man mission implementing cryogenic tug level propulsion technology it was found that 28 Shuttle launches would be required to meet 1976AA energy requirements, and 23 launches to do a 1943 mission. The short flight time requirement combined with 1943's large aphelion bring its requirements almost up to those of 1976AA even though it does have less than half the inclination. The large increase in launches for both missions result primarily from the very much increased support equipment required for manned missions.

Later during the past year another low inclination object was discovered by Dr. Helin, 1976UA (Slide 4.6). Not only is its inclination less than 6 degrees, but its aphelion (compared to 1943) is only about 1.2 AU. Hence, it was thought that this object might be an even better target, from the viewpoint of celestial mechanics, than either 1976AA or 1943. Unfortunately, its perihelion of 0.46 AU brings it well within Venus' orbit which requires large transfer energy reduction to achieve rendezvous, which must be added back for return to Earth. Preliminary investigations by Dave Bender at JPL revealed that even one-way missions to 1976AU had prohibitive performance requirements, so a roundtrip analysis was not attempted.

I'd like to now summarize these and other sample-return results with the purpose in mind of presenting implications these data contain for using the mass-driver concept to return complete asteroids to Earth orbit (Slide 4.7). The table shows basic orbit data and return transfer requirements of sample-returns to Eros, 1943, and 1976AA. The return impulses now include the Earth approach velocity which would have to be nulled by a mass-driver system. The Eros and 1943 requirements of 7.4 and 7.5 km/sec are quite similar as are their orbital data. 1976AA, with much higher inclination has a larger return impulse of over 12 km/sec. These values are at least a factor of 2 and in the case of 1976AA, a factor of 4 greater than the 3 km/sec which Dr. O'Leary used as an example at the outset of the meeting tonight.

If the comparatively favorable sample-return objects, Eros and 1943, apparently have quite high impulse requirements for the mass-driver asteroid return concept, an obvious question then becomes: "What objects are accessible to mass-driver return?" A preliminary answer to this question is the subject of the latter portion of this talk. A brief mass-driver performance analysis has just been finished using performance assumptions similar to those presented by Dr. O'Leary. These



ORBIT PARAMETERS:

PERIHELION.........0.46 AU
APHELION...........1.22 AU
PERIOD.............283 DAYS
INCLINATION.......5.88 DEG

Slide 4.6

ASTEROID 1976UA ORBIT PROFILE

SUMMARY OF BALLISTIC ASTEROID RETURNS

OBJECT	R_p (AU)	R_a (AU)	i (deg)	RETURN DATE	RETURN IMPULSE (km/sec)
EROS	1.13	1.79	10.8	JAN '82	7.416*
1943	1.06	1.80	8.7	MAY '95	7.530
1976AA	0.79	1.14	19.1	JUN '95	12.300

*Best Return Conditions Between 1975 and 1985

Slide 4.7

assumptions are summarized in the next slide (Slide 4.8). A 200-m object assumed to weigh 10^7 metric tons was used. The mass driver has an exhaust velocity of 2 km/sec which it can achieve with a 200-m rail and 1000-g acceleration. Return trajectories were constrained to a three-year trip time beginning at object aphelion with zero departure velocity. All initial object orbits were assumed to have zero inclination. Low-thrust transfers along with residual asteroid mass at Earth rendezvous and mass-driver performance characteristics were generated for 14 initial orbits with three initial aphelions (Slide 4.9). These results were cross-plotted onto a format of aphelion versus perihelion to assess mass-driver capability (Slide 4.10). The left diagonal line represents orbits with one-year periods, an arbitrary lower limit on the parameter set chosen for this cursory analysis. The right diagonal line represents circular orbits. Between these two limits preliminary contours of constant returned mass have been drawn, based on the low-thrust-mass-driver performance results. None of the three objects, Eros, 1943, and 1976AA, fall within the mapped region of this plot. To summarize these results, in order for the assumed mass driver to return at least 30% of a 10^7 ton asteroid to rendezvous with Earth (capture is assumed via lunar gravity assist), the object must not have an aphelion greater than 1.2 AU and its perihelion must be within 0.1 AU of the Earth's orbit. It must also be coplanar, i.e., have zero inclination.

To illustrate the performance penalty added by inclination of the returned object's orbit, I also investigated ballistic broken-plane return transfers from a circular 1.3-AU orbit (Slide 4.11). While these are oversimplified results, they give a qualitative feel for the effect of added inclination. Percent increase in performance required over coplanar return is shown as a function of where the plane change is made for initial inclinations of 5, 10, 15, and 20 degrees. It is obvious that asteroid inclinations much greater than 5 degrees will constitute considerable additional penalties on return performance of the mass driver.

These results are only initial estimates of performance requirements and considerably more work is needed to properly assess the potential of the mass-driver concept to asteroid returns. Some of the areas of future study are outlined in the last slide (Slide 4.12). These include refined definition of mass-driver low-thrust return trajectories. Henry Kolm is going to talk more about mass-driver designs, the application of them to asteroid recovery and the design implications which need to be studied. Another subject I haven't discussed is use of the Moon to actually help in capturing the returning asteroid. It may be able to reduce the characteristic ΔV as much as a kilometer and a half by using its gravity field to assist the Earth capture maneuver. Lunar-assisted capture, the resulting orbits, and subsequent

ASSUMPTIONS FOR MASS DRIVER PERFORMANCE ANALYSIS

- OBJECT*

DIAMETER	200 m
INITIAL MASS	10^{10} kg

- MASS DRIVER*

EXHAUST VELOCITY	2 km/sec
LENGTH (@ 1000g's)	200 m

- TRAJECTORY CONSTRAINTS

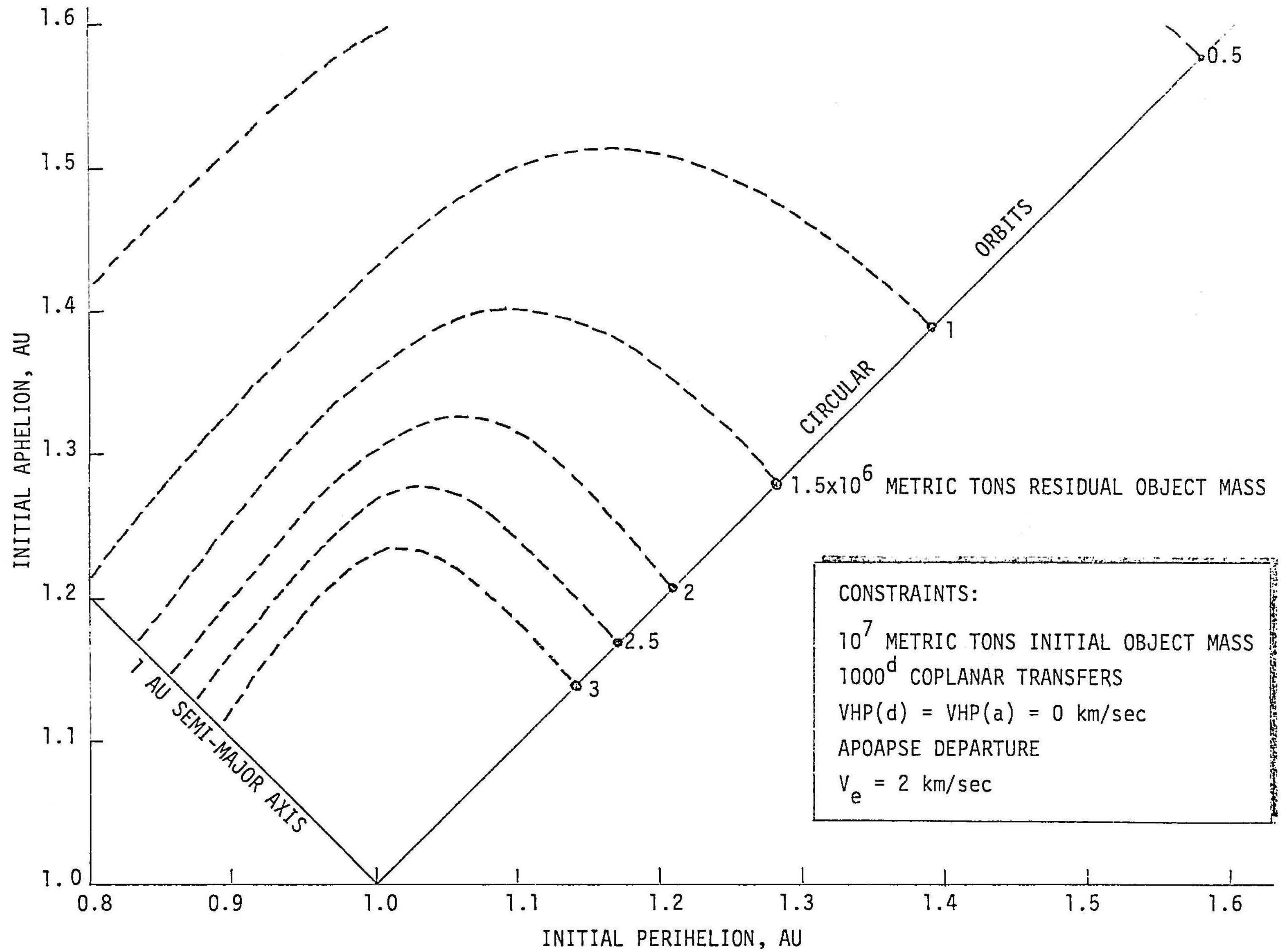
FLIGHT TIME	1000 days
DEPARTURE LOCATION	Aphelion
DEPARTURE VELOCITY	0 km/sec
EARTH APPROACH VELOCITY	0 km/sec
INCLINATION	0 deg

*After O'Leary (1976)

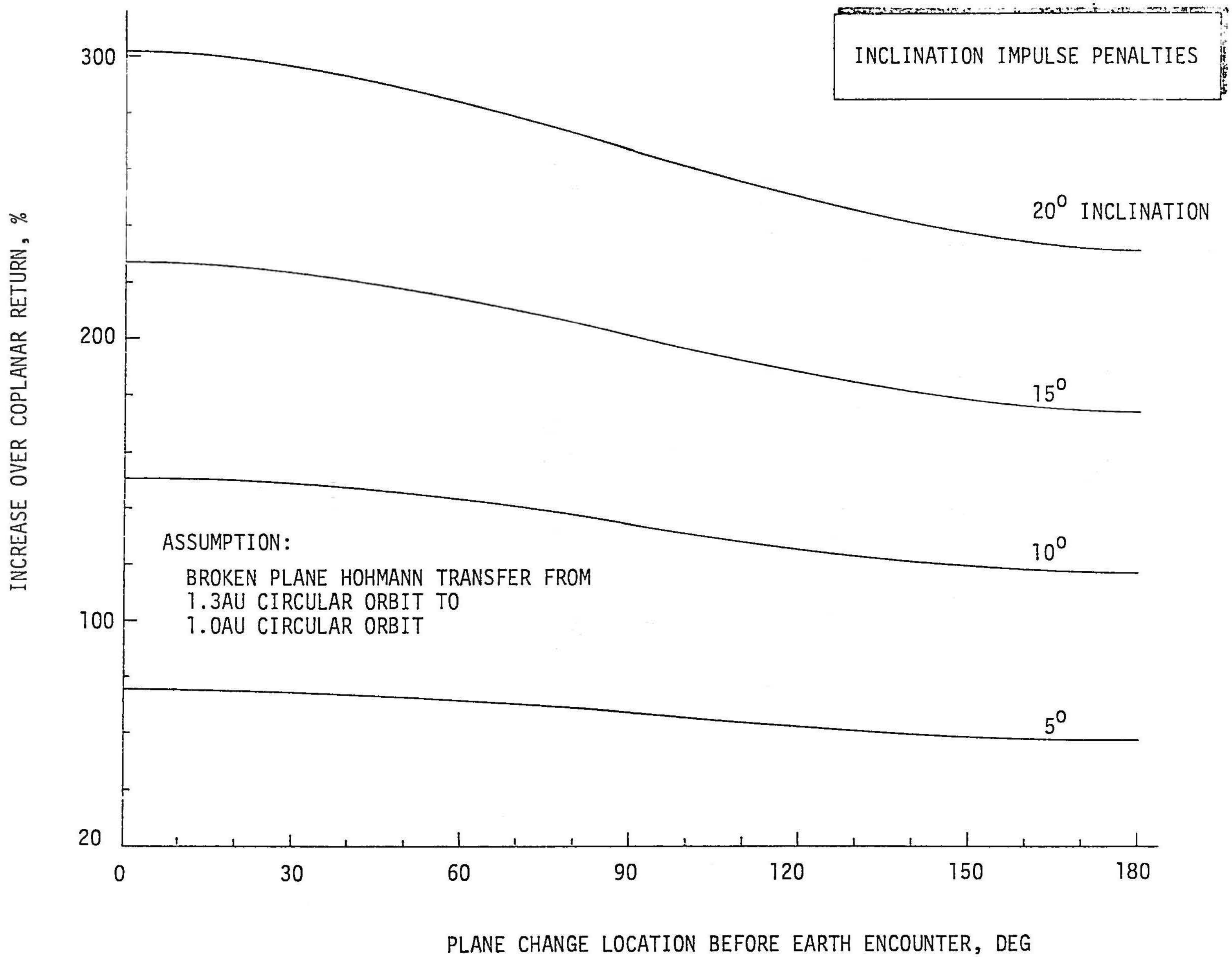
DATA SUMMARY OF MASS DRIVER ASTEROID RECOVERY PERFORMANCE*

INITIAL ORBIT		CHAR. ΔV (m/sec)	FINAL MASS (10^9 kg)	THROUGH-PUT (kg/sec)	KINETIC POWER (Mw)	MASS/PWR RATIO (Tons/Mw)
RA(AU)	RP(AU)					
1.2	0.8	4493	1.058	103.5	207	5109
	1.0	2436	2.958	81.5	163	18150
	1.2	3086	2.138	91.5	182	11745
1.4	0.6	7486	0.237	113.0	226	1048
	0.8	5167	0.755	107.0	214	3529
	1.0	4879	0.872	106.0	211	4126
	1.2	4115	1.278	101.0	202	6329
	1.4	4611	0.997	104.2	208	4785
1.6	0.6	12351	0.021	115.5	231	90
	0.8	7889	0.194	113.5	227	853
	1.0	6190	0.453	110.5	221	2049
	1.2	5167	0.755	107.0	214	3529
	1.4	5285	0.712	107.5	215	3312
	1.6	6390	0.410	111.0	222	1845

* For constrained 1000^d coplanar transfers with mass-driver assumptions per previous table.



ESTIMATE OF ASTEROID MASS DRIVER PERFORMANCE IN RP/RA SPACE


INCLINATION IMPULSE PENALTIES
INCREASE OVER COPLANAR RETURN, %
300
200
100
20
20° INCLINATION
15°
10°
5°
ASSUMPTION:
BROKEN PLANE HOHMANN TRANSFER FROM
1.3AU CIRCULAR ORBIT TO
1.0AU CIRCULAR ORBIT
0
30
60
90
120
150
180
PLANE CHANGE LOCATION BEFORE EARTH ENCOUNTER, DEG

AREAS OF FUTURE ACTIVITY

- REFINED DEFINITIONS OF LOW-THRUST RETURN TRANSFER REQUIREMENTS
- IMPROVED DESIGN DEFINITIONS OF MASS DRIVER SYSTEMS
- ANALYSIS OF EARTH CAPTURE CONCEPTS INCLUDING LUNAR GRAVITY-ASSIST
- EXPANDED SEARCH PROGRAM FOR NEW NEAR-EARTH OBJECTS
- IMPROVED PROGRAM FOR GEOPHYSICAL/GEOCHEMICAL CLASSIFICATION OF NEWLY DISCOVERED OBJECTS

Slide 4.12

orbit shaping with repeated lunar encounters would all be areas of fruitful investigation. I want to underscore the last two items in the table which the previous two speakers have also addressed. I think it is obvious that if we are really serious about returning asteroids to Earth we need more targets to choose from. An expanded search program is definitely needed and classification of what we find, geophysically and geochemically, is equally important. After all, if we expect a concept like this to be saleable we must obviously be able to tell people what it is they're getting. Thank you.

QUESTIONS AND ANSWERS

Q: Dr. John Wasson

"John, it seems to me like the problem with this last orbit that you have described is that it must be an orbit from which materials would be captured by the Earth very quickly relative to some of the more typical orbits and that, therefore, the chance of finding an object still in such an orbit or currently in such an orbit is much smaller than for some of the other orbits that you described."

A: John Niehoff

"That's a very good point and one which I'm glad you raised. I think the answer to that can be more eloquently given by George Wetherill than myself. George, if you would, I'd like to ask you to summarize an early discussion we had on this question."

A: Dr. George Wetherill

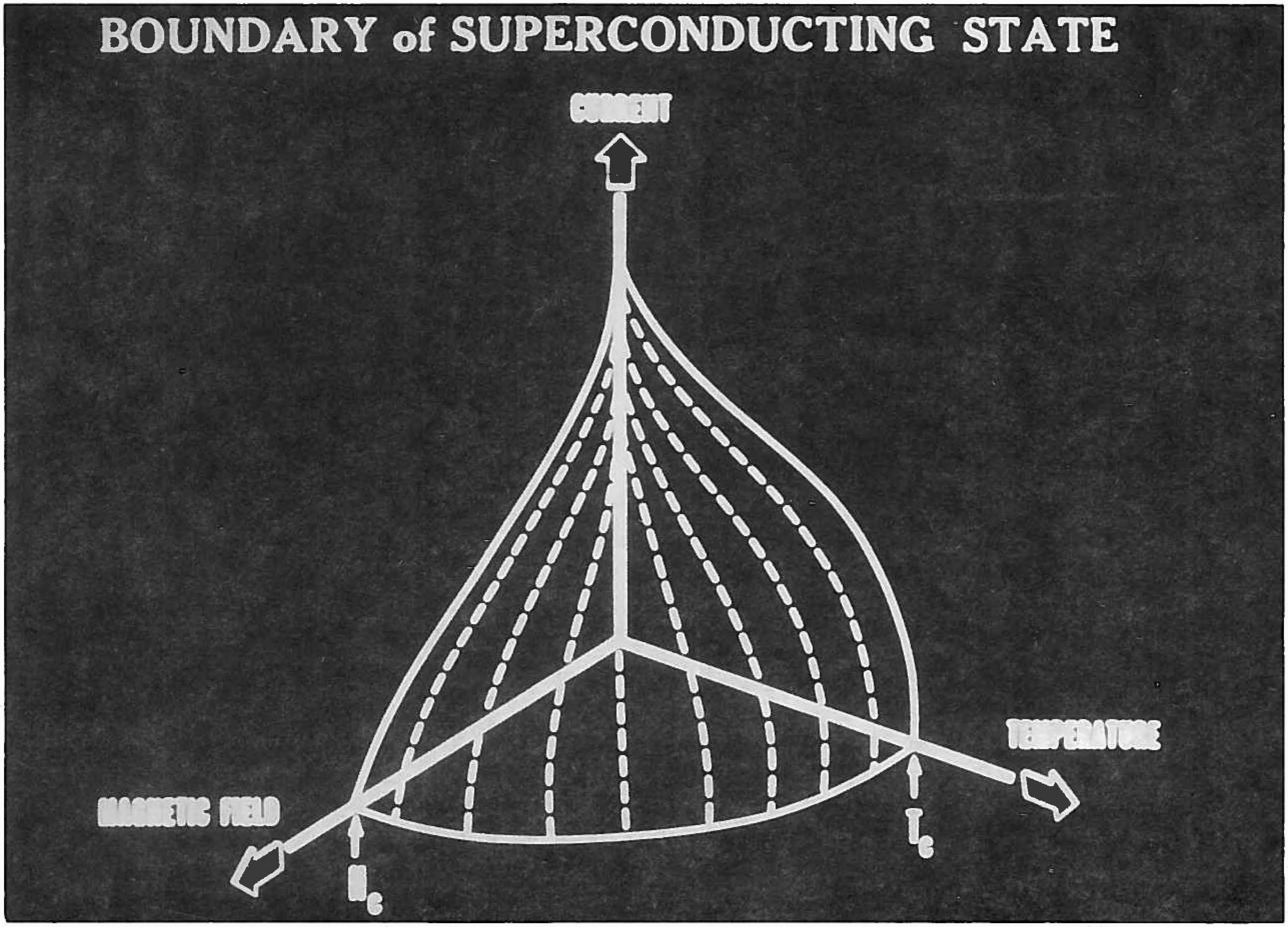
"I don't know how eloquent it is, but I think what you asked before was a slightly different question. [what object that comes close to the Earth and] What I said was - objects come even closer to the Earth and that they hit the Earth all the time. So, we know that some such objects which come very close to the Earth are still existing. One can calculate this type of thing - I hesitate to do it on the top of my head - they will be decreased in numbers as John said, but the lifetime would be more like perhaps 10 to the 5 years or 10 to the 6 years as opposed to 10 to the 7th year, so it wouldn't be catastrophic reduction, but there would be less such objects."

ELECTROMAGNETIC MASS DRIVERS

Professor Henry Kolm
Massachusetts Institute of Technology

Mass drivers today are at about the stage of the Wright Brothers' first airplane fit for public demonstration in about 1911. During the same year, Kammerlingh Onnes discovered superconductivity at Leiden University in Holland. It is interesting to reflect on how little has happened with superconductivity since 1911 compared to how much has happened to Orville Wright's airplane. It has been known since 1911 that certain materials can carry a current without any resistive loss as long as the temperature, magnetic field, and the current density remain below certain limits. These conditions can be represented by an onion in the three-dimensional space of current, field and temperature, as shown in slide (5.1). In 1911 this onion was too small to be practical. It was only in about 1960 that the so-called "hard" superconducting alloys were discovered, which brought the onion to practical proportions. The present capability of available superconductors can be expressed in comprehensible terms by saying that if the twelve gauge copper wire which can supply 20 amperes to a house outlet were made of currently available superconducting material, it would carry about 50,000 amperes. Modern superconducting materials are made either by depositing many thin layers of niobium-tin on a stainless steel ribbon, or else by swaging many fine filaments into a mass of copper or aluminum and braiding such composites into a cable, so that there are over a thousand superconducting filaments in the entire structure, which is typically between one and two millimeters in diameter.

The impact of superconductivity on electrical engineering is comparable to the impact of the wheel on mechanical engineering: it provides frictionless transportation of electricity just as the wheel provided frictionless transportation of matter. When the wheel was invented, it involved formidable technological obstacles, and it must have taken many centuries before it was accepted as a practical device. Not only was it necessary to develop the technique for making round wheels and to invent lubrication, there was not even an obvious application for the wheel; nobody had built highways. Superconductivity has been facing analogous obstacles since 1911. The possibility of using superconducting magnets to levitate and propel a railway train, for example, evokes more amusement than serious interest on the part of railway engineers. Nevertheless, the cryogenic engineering art has advanced to the point that we manage to ship liquefied gases not only across the ocean, but

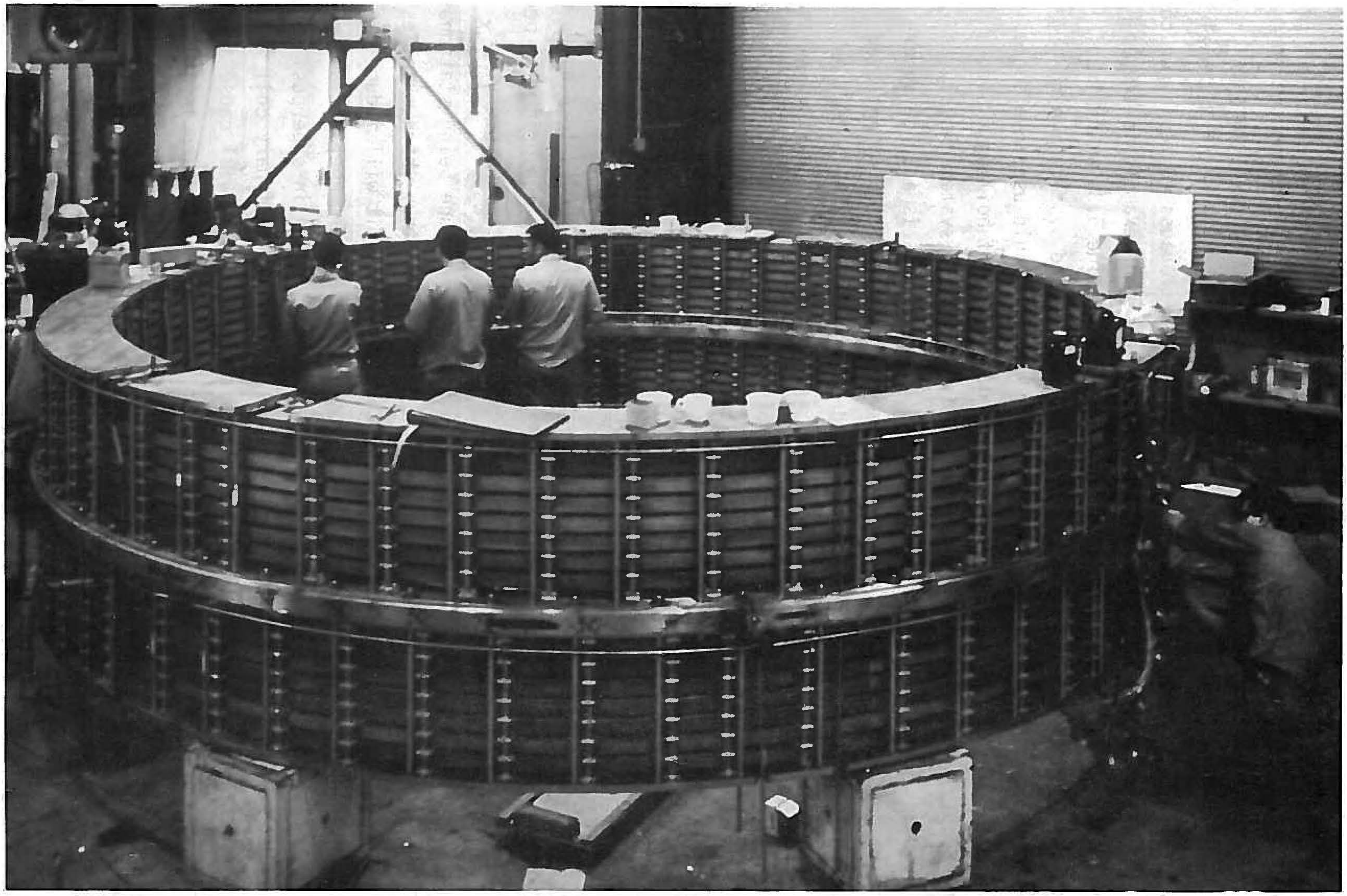

BOUNDARY of SUPERCONDUCTING STATE
CURRENT
TEMPERATURE
MAGNETIC FIELD
H_c
T_c

Slide 5.1

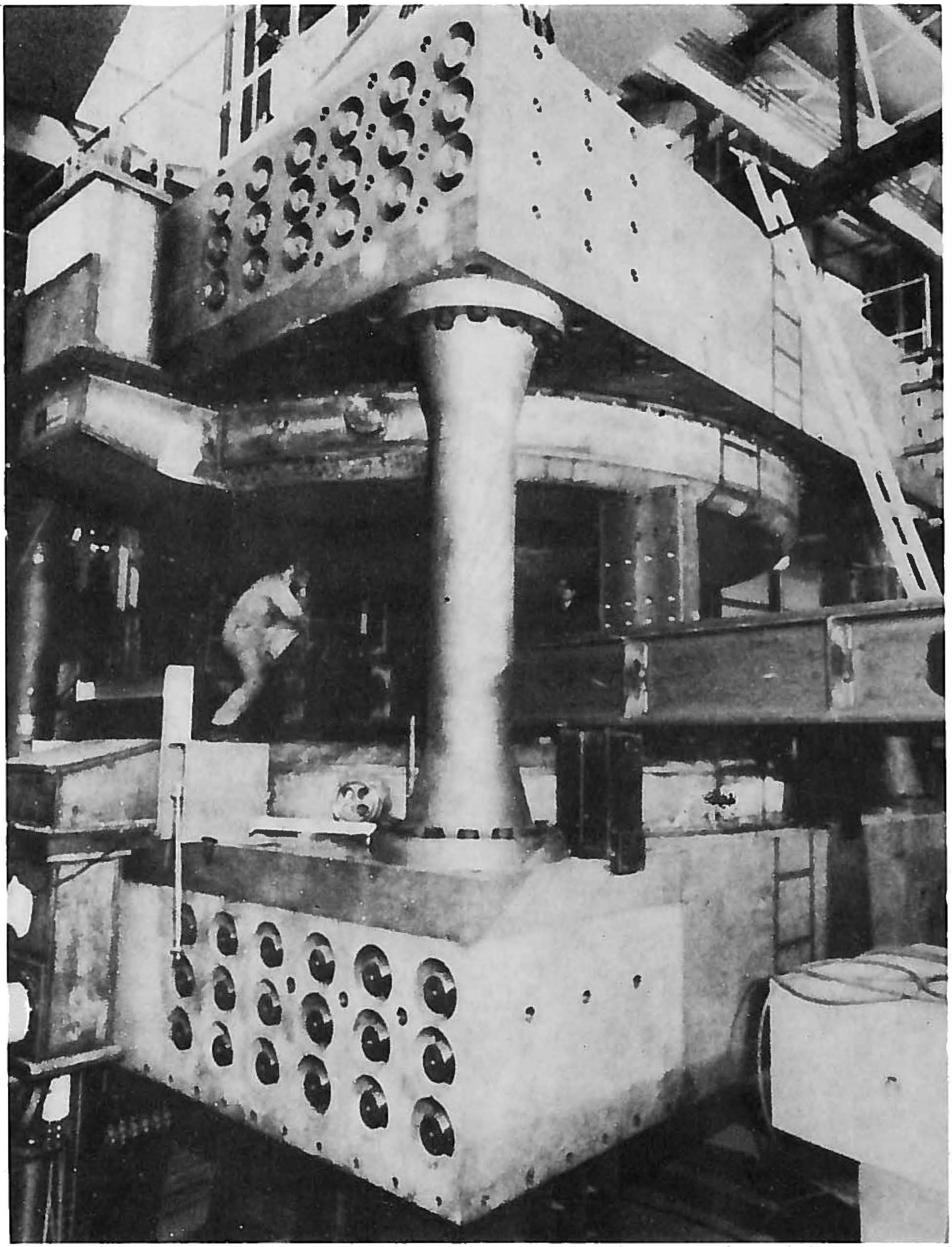
throughout the entire solar system. A number of very large superconducting magnets have been operated for at least ten years. Three notable examples are a 14 foot diameter hydrogen bubble chamber magnet at the Argonne National Laboratory in Chicago (slide 5.2) which generates 30 kilogauss (3 tesla) which is 50% more than the saturation field of iron. The second example is the so-called omega magnet at the CERN laboratory in Geneva (slide 5.3) which is of particular interest because it is refrigerated by a closed system of high-pressure, super-critical helium, the sort of system one would use in a space vehicle. The use of helium does not imply large buckets of boiling fluid, as many people still think; helium can be used in a closed system exactly as freon is used in a kitchen refrigerator. The third example is a large superconducting homopolar dc motor known as the Fawley Motor (slide 5.4) operated in England to replace a 3 megawatt dc motor driving a large water pump. An ac superconducting motor has also been built at MIT, with liquid helium contained in its rotating armature, and a larger copy of it is in operation at Westinghouse. There is no shortage of examples to support the argument that superconductivity is practical today.

In relation to mass drivers, superconductivity would provide first of all the non-contact levitation and guidance forces needed to achieve the required speeds. It also provides the light-weight magnetic dipoles needed to achieve significant acceleration. I want to explain the basic levitation principle because it is not a matter of intuitive experience, even to electrical engineers.

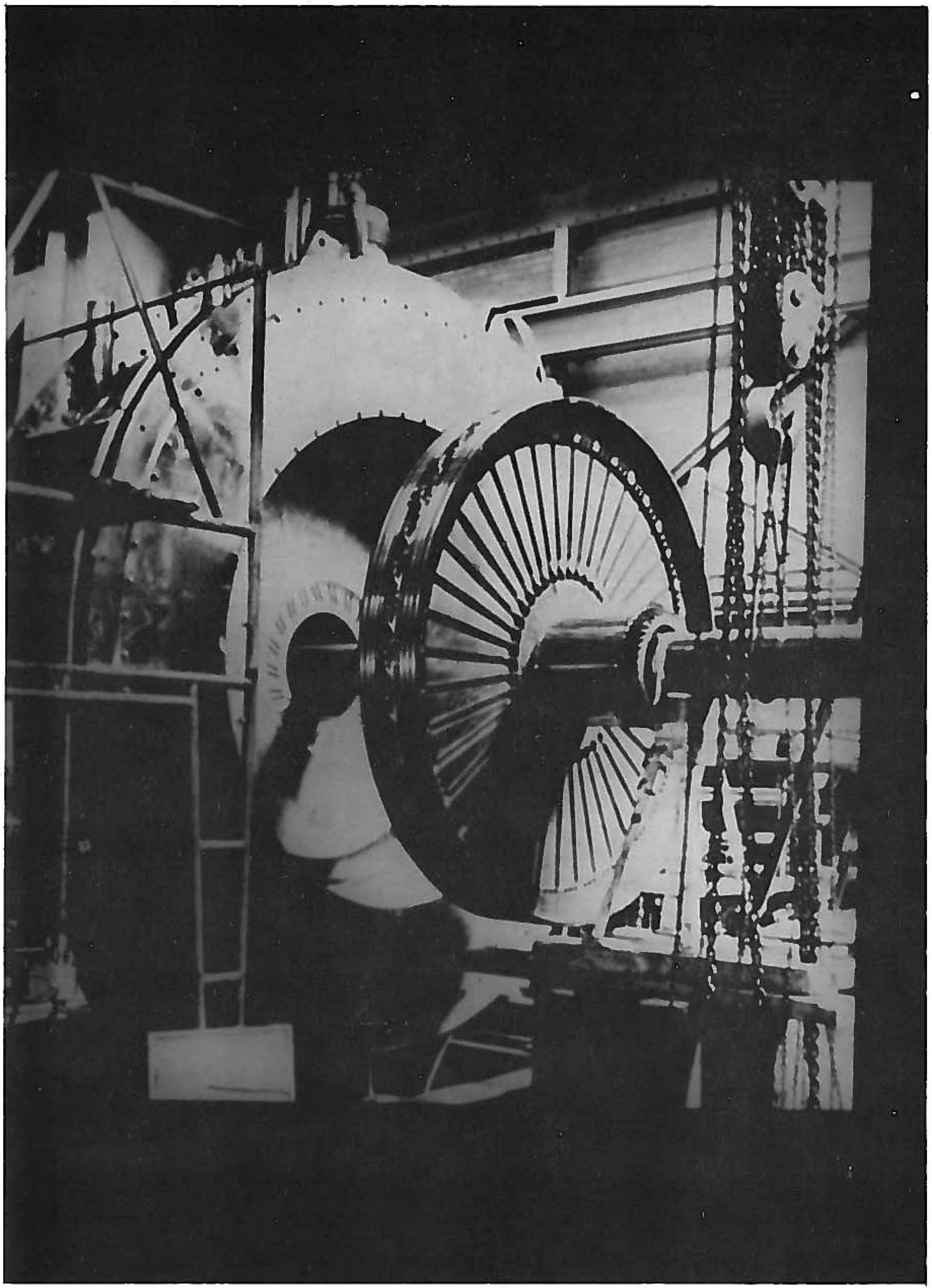
Consider two coils, as shown in slide (5.5), the lower one being stationary and short-circuited, the upper one being connected to a battery which supplies a dc current. If the upper coil moves past the lower coil, it will induce a current in it which is proportional to the rate of change of magnetic flux linkage. This current will flow as long as the two coils are in superposition, and will exert a repulsive force on the moving coil. The stationary coil will have an effect which is exactly like that of a cobblestone: it will cause the moving coil to rise as it passes over. Now, if the cobblestone were infinitely hard, the passage of a wheel over it would be lossless in the sense that all the energy invested in approaching it is returned as one leaves. Unfortunately, however, the stationary coil is not superconducting and therefore the cobblestone is not infinitely hard. The induced current decays as the moving coil passes, and thus resistance dissipates some of the energy we have invested; the passage therefore involves drag or friction. Note, however, a very important point: the



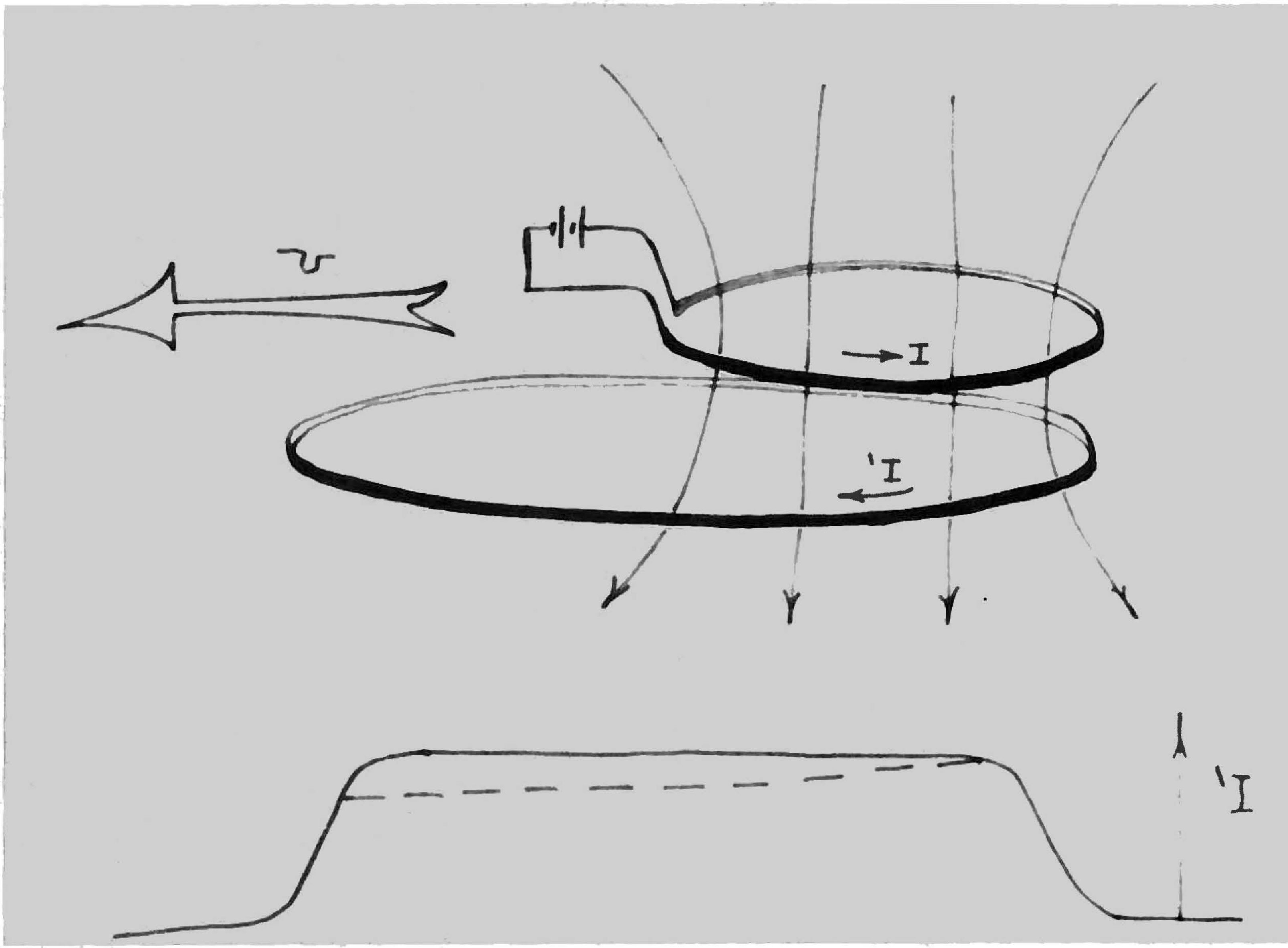
Slide 5.2



Slide 5.3



Slide 5.4

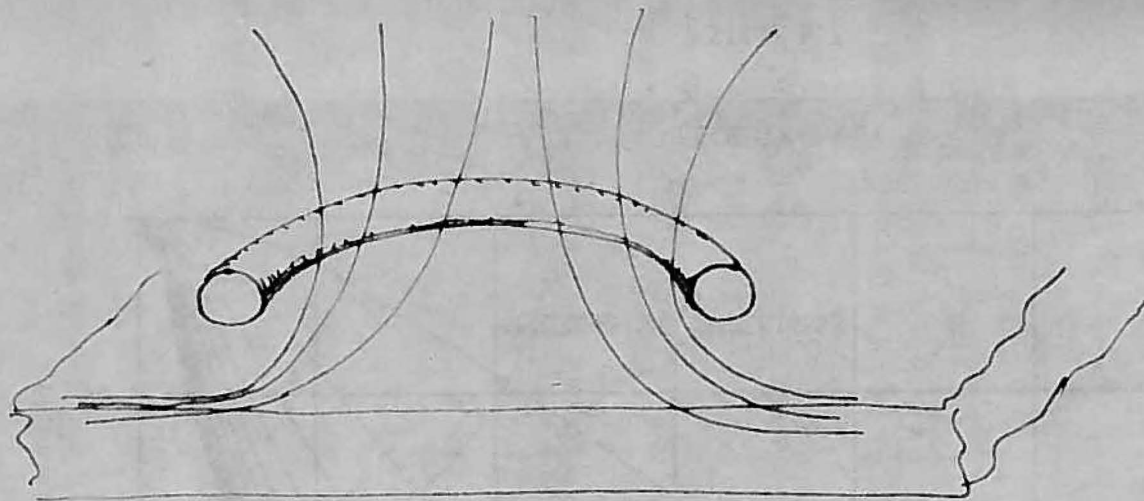


Slide 5.5

loss does not come out of the current flowing in the upper coil, the superconducting vehicle coil; the loss comes in the form of a mechanical drag, exactly as in the case of an airplane wing. We can thus think of magnetic levitation as the electromagnetic analog of flight: it produces lift at the expense of drag exactly like an airfoil. Having used this loop analogy to provide conceptual understanding, we can now transfer our thinking to a current loop passing over a continuous sheet, for example an aluminum guideway, as shown in slide (5.6). We can think of the same phenomenon in a different manner. If the coil were standing still, its magnetic flux would pass freely through the aluminum sheet. As the coil begins to accelerate, it induces a circular eddy current which flow in such a direction as to oppose the penetration of magnetic flux into the aluminum. Opposition becomes more effective the faster the coil moves, until finally the magnetic flux penetrates only a very small distance into the aluminum, a distance called the "skin depth". The lift force is thus produced by a cushion of magnetic flux which is repelled by the aluminum surface. The family of curves in slide (5.7) indicates how the lift force increases with increasing thickness of the aluminum plate at low velocity. The plate has to be relatively thick to effectively expell the magnetic flux, and therefore take-off occurs sooner in the case of a thicker plate. At high velocity the induced eddy currents are confined to a very small skin depth, and therefore the thickness of the plate no longer matters.

Slide (5.8) shows a family of curves indicating how the drag force depends on velocity and thickness of the levitation surface. Drag passes through a peak at a certain velocity, and this peak moves to higher velocities as the plate becomes thinner. Beyond the peak, drag decreases continuously, which leads to a unique property of electromagnetic flight: less energy is needed to travel a given distance the faster one travels. Thus, magnetic flight at very high speed involves very low drag and a very thin guide surface, a clear indication that electromagnetic flight is destined for space transportation.

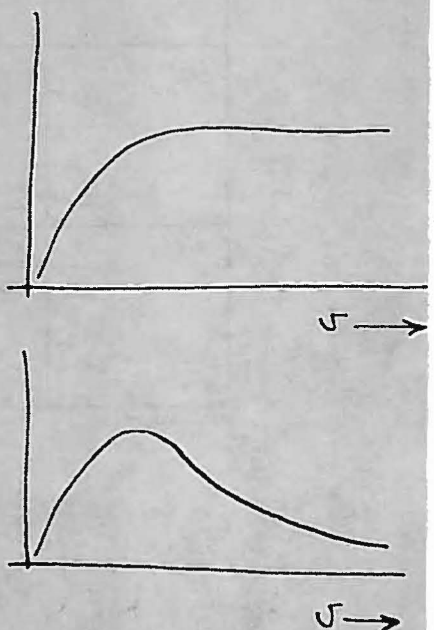
At MIT we built a transportation system which combines electromagnetic flight with linear synchronous propulsion. It is called the "magneplane", and is illustrated in slide (5.9). The vehicle contains several saddle-shapped superconducting magnets and flies above a circular aluminum trough. Along the center of this trough there is a slot in which are located meander-shaped propulsion windings. These windings simply generate a travelling magnetic field, which moves along the guideway. If the vehicle were simply a metal cylinder, it would



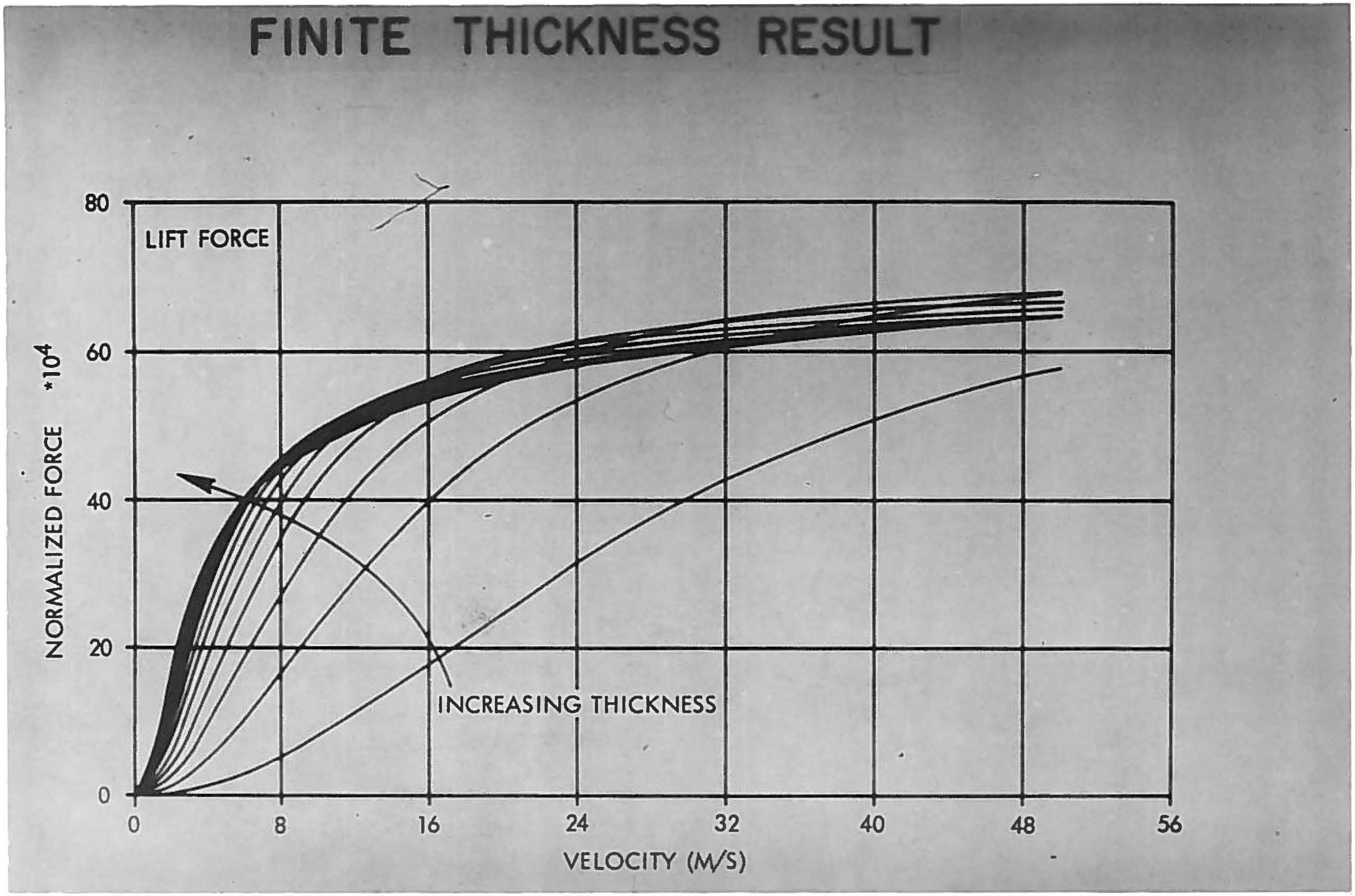
LIFT $\sim H_T N_N = 60$ psi for $10\ \text{kgauss}^2$

DRAG $\sim H_N^2$

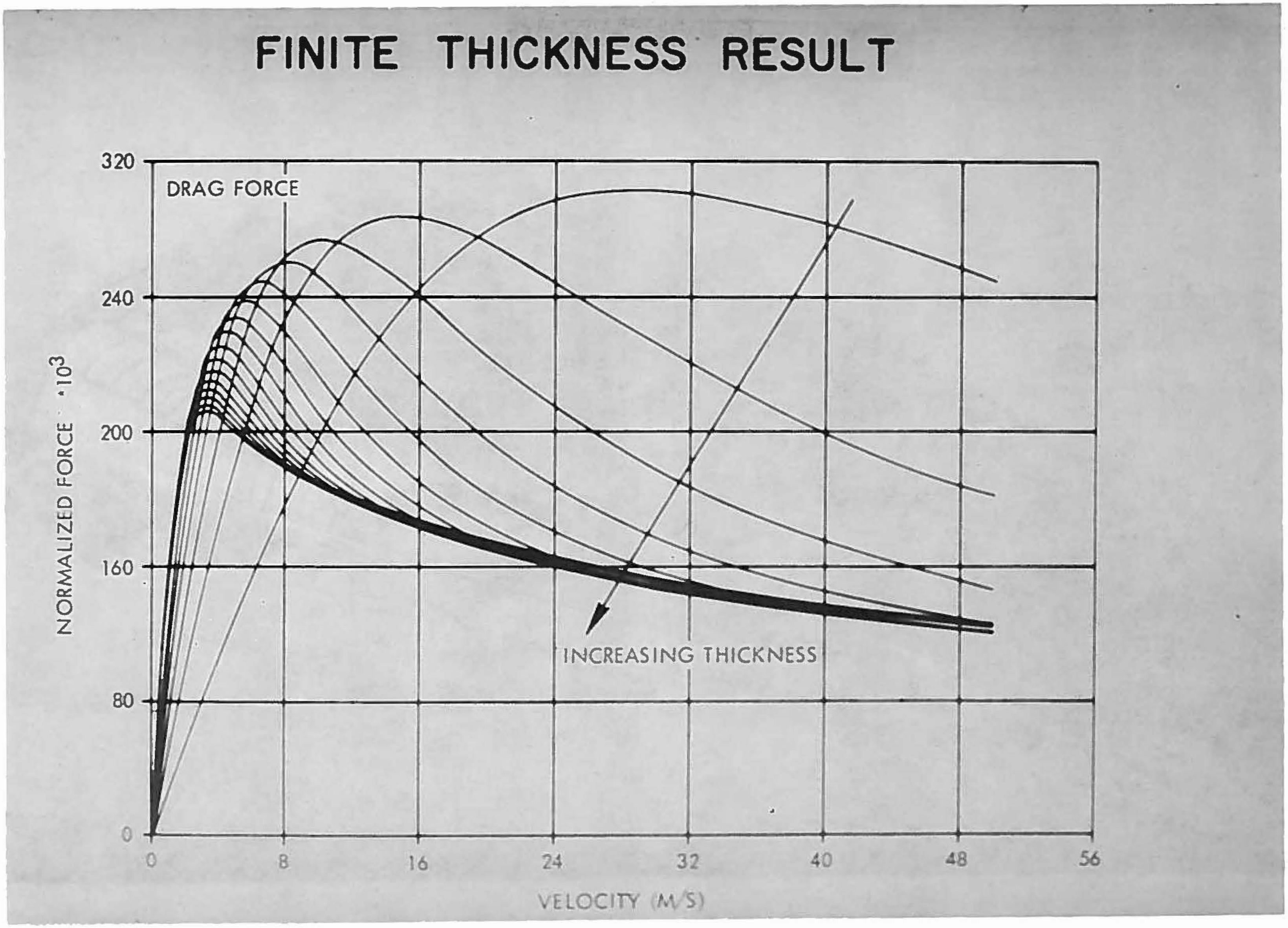
$$\frac{\text{LIFT}}{\text{DRAG}} \sim \frac{H_T}{H_N}$$



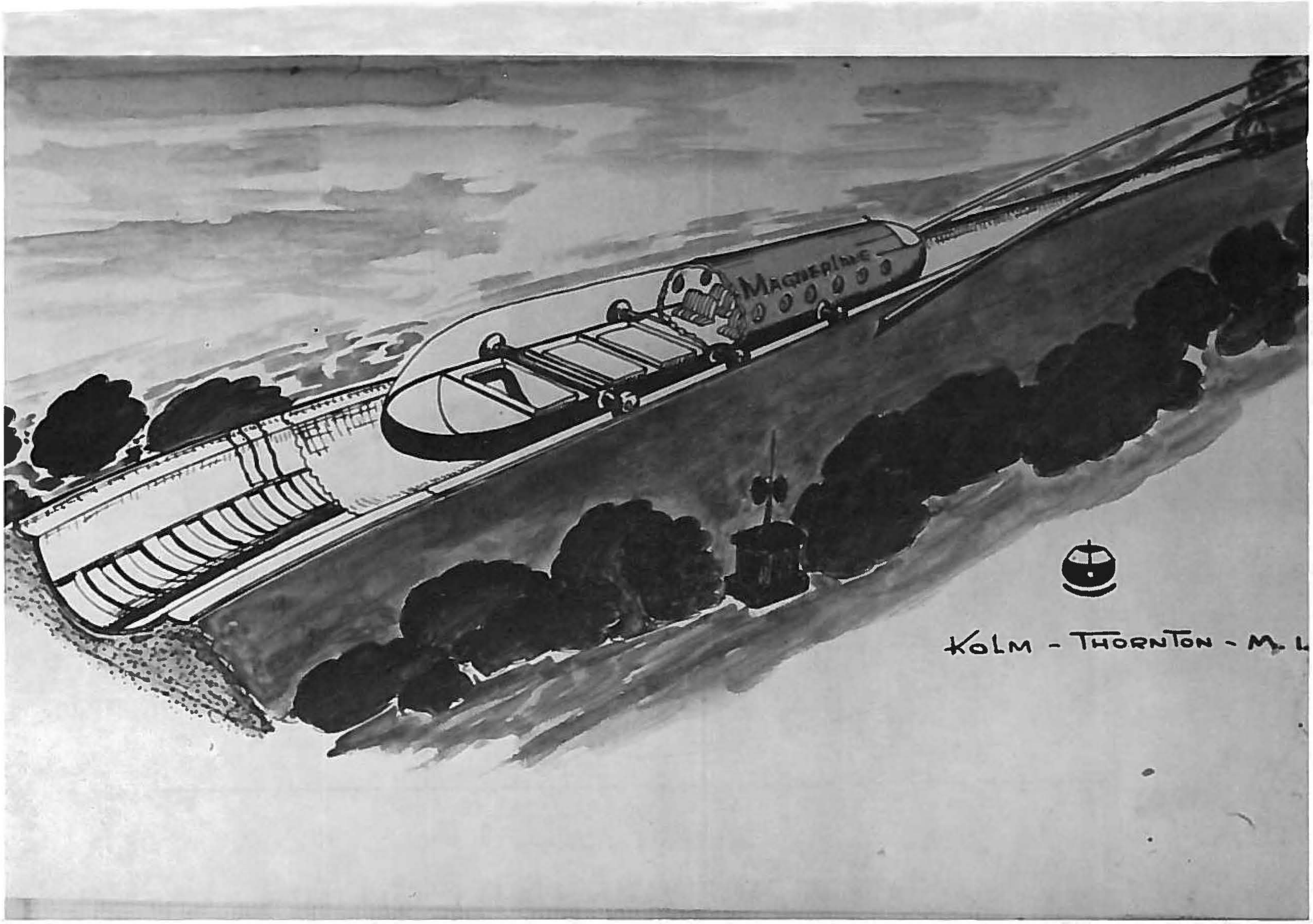
Slide 5.6


FINITE THICKNESS RESULT
LIFT FORCE
NORMALIZED FORCE *10^4
80
60
40
20
0
INCREASING THICKNESS
0
8
16
24
32
40
48
56
VELOCITY (M/S)

Slide 5.7


FINITE THICKNESS RESULT
DRAG FORCE
NORMALIZED FORCE ·10³
320
240
200
160
80
0
0
8
16
24
32
40
48
56
VELOCITY (M/S)
INCREASING THICKNESS

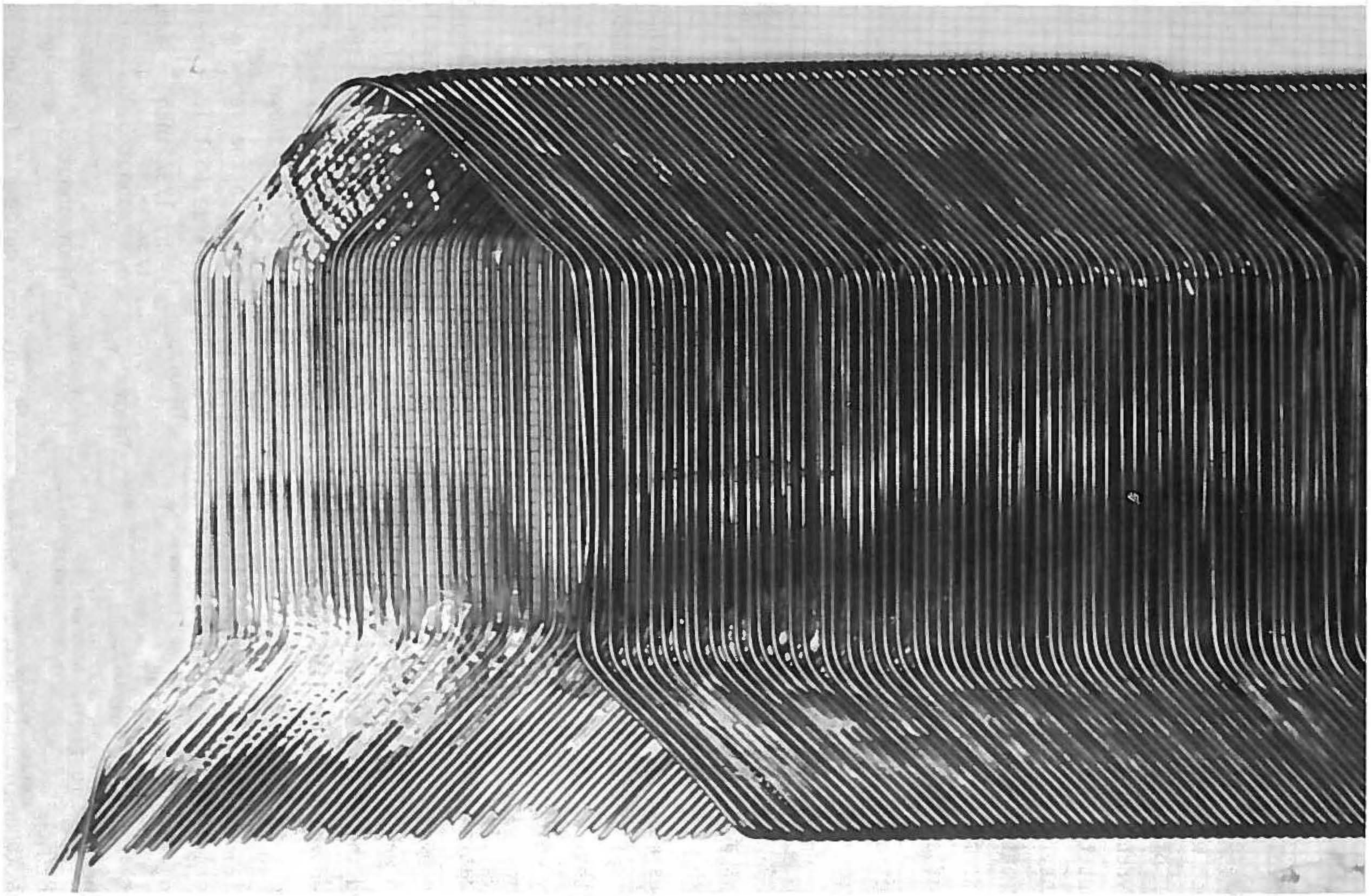
Slide 5.8



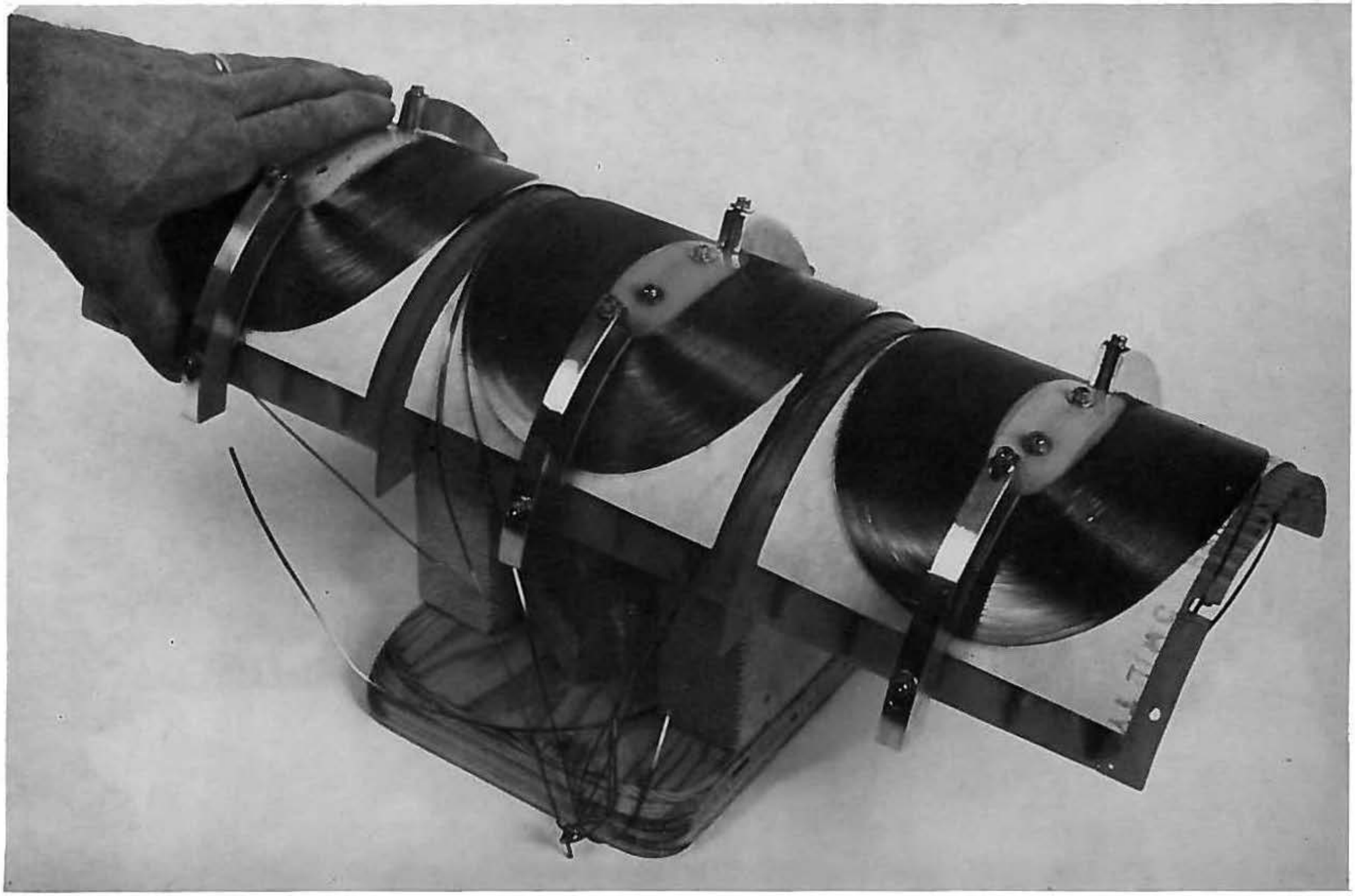
Slide 5.9

be dragged along by this travelling wave due to induced eddy currents, and the system would represent a linear induction motor. Since the vehicle is equipped with magnets, it is locked to the travelling magnetic wave in the manner of a surfboard, and represents what is known as a synchronous motor. Synchronous motors are significantly more efficient than induction motors, but they have never been used before for such propulsion systems because they have to remain exactly synchronized. If a synchronous motor is pulled out of synchronism it loses all its thrust and just sits and hums. A dc motor is a synchronous motor which is synchronized mechanically by means of commutator switches attached to the rotor.

Magnetic rockets or launchers, or magnetic guns, represent an old dream. An electric rocket launcher was built in Germany during World War II, based on linear induction. Unfortunately, the induced currents tended to melt the projectiles, and the scheme was abandoned in favor of chemical rockets. During the forties a magnetic catapult was built in the U. S. for launching aircraft, known as the Westinghouse Electropult. It used a mechanically commutated synchronous motor, far more efficient than the German induction motor. However, the weight of its armature was too great and it failed to compete with compressed air and steam catapults. The availability of very large superconducting dipoles having low weight and negligible energy consumption makes the linear synchronous motor a very efficient and practical device. In the case of the magneplane, synchronization is achieved by transmitting position information from the vehicle to wayside power conditioning units which control the frequency and phase of the travelling wave. This process is far simpler than transmitting high current from the ground to a vehicle, particularly at speeds above 300 mph. The propulsion system used in the magneplane model is simply a wire which meanders back and forth across the guideway. There are 36 such wires in parallel, as shown in slide (5.10). The three saddle-shaped superconducting magnets in the vehicle which interact with these propulsion windings are shown in slide (5.11). They are made of four layers of superconducting wire, about 1/16 by 1/32 inch square, which carries over 300 amperes, generating a magnetic field of about 3,000 gauss several inches from the vehicle. This performance surpasses by a large factor the best permanent magnets available. Slide (5.12) shows the magneplane model vehicle as it begins its acceleration down a 400 foot test guideway, located on the grounds of the Raytheon Laboratory in Wayland, Mass. To be sure, this



Slide 5.10



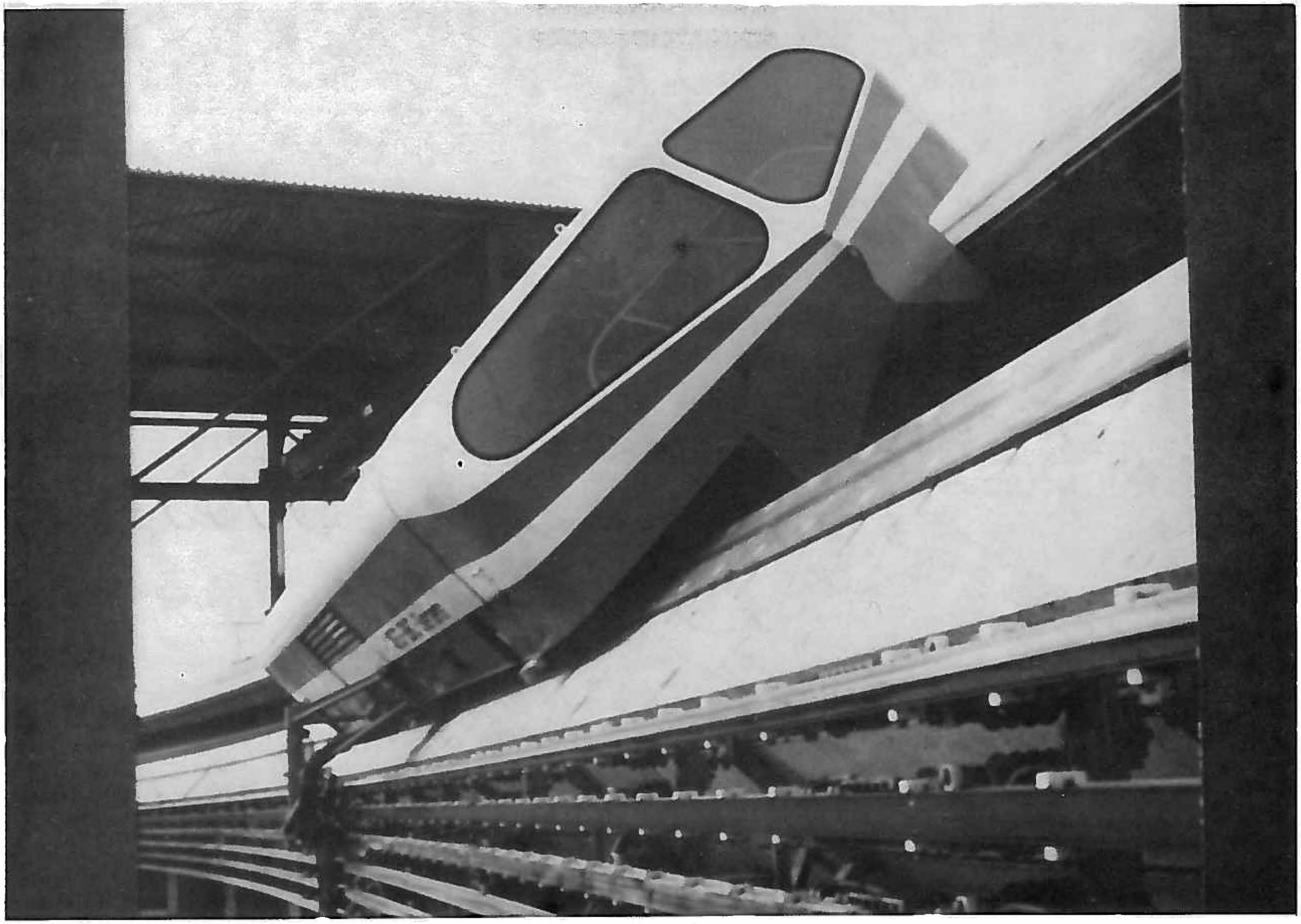
Slide 5.11

Slide 5.12

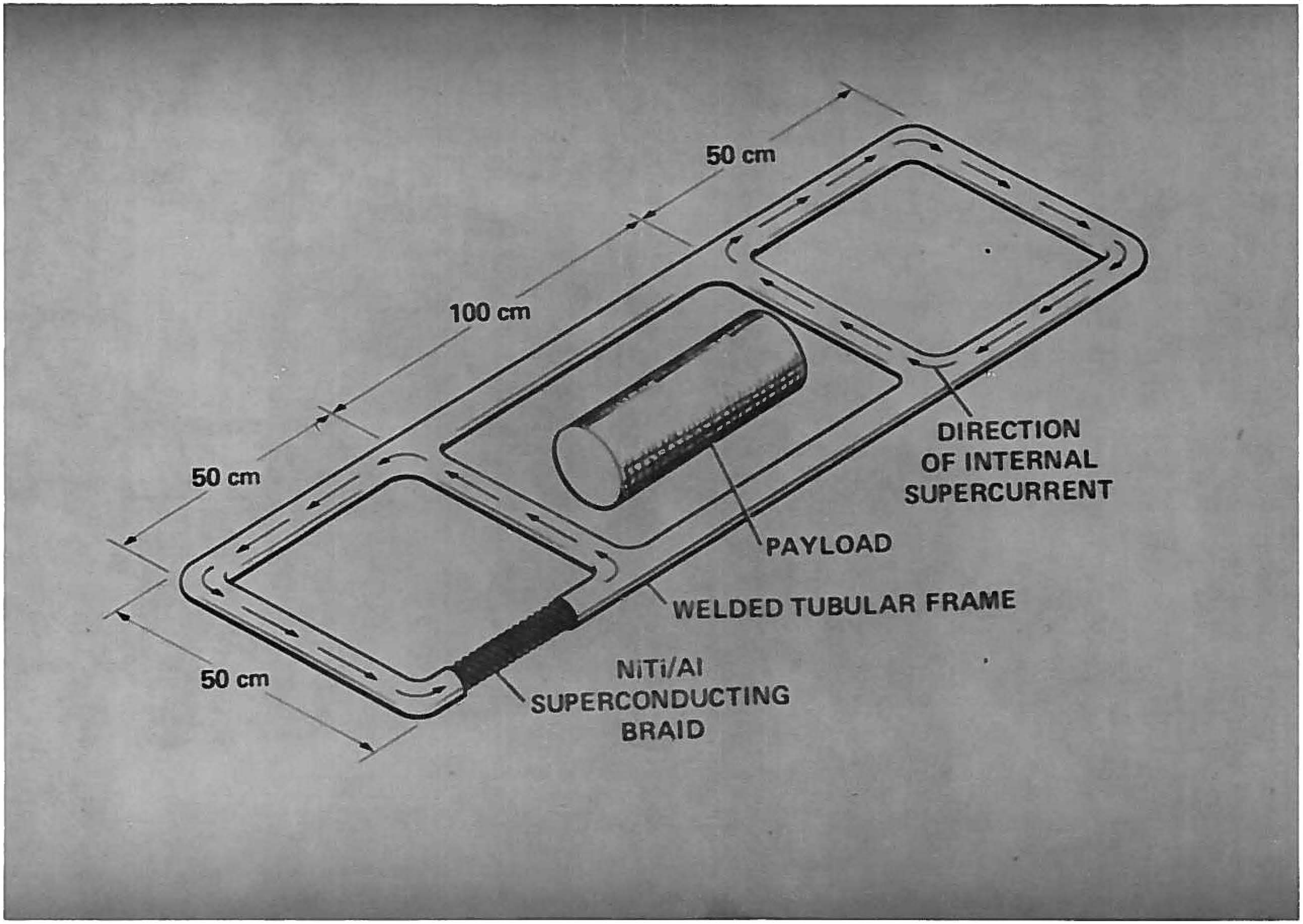
magneplane model only achieves slightly over 1 g acceleration and a velocity of only 60 mph, but it does contain essentially all the systems involved in a lunar mass driver. The magneplane model operated successfully for about 100 test runs, and the superconducting vehicle coils even survived being accidentally catapulted off the end of the guideway and onto the lawn. Unfortunately, the venture was less successful politically. All U. S. research in advanced transportation was terminated by the Office of Management and Budget in February 1975. However, research in this area is being continued very seriously in Germany and Japan. Slide (5.13) shows a 280 meter diameter test ring built at the Siemens Laboratory in Erlangen, and slide (5.14) shows a superconducting magnet test vehicle mounted on this ring track. This installation represents only a component test bed, and is not a complete integrated system like the MIT magneplane.

My involvement in mass drivers began when Gerry O'Neill recognized the applicability of much of the magneplane work to the lunar mass driver and invited me to participate in the 1975 Ames summer study. The first system we studied was a flattened and double-sided version of the magneplane geometry, largely because the performance of such a configuration could be calculated using magneplane software. The vehicle, shown in slide (5.15) is roughly the size and heft of a bicycle frame, made of stainless steel tubing, 0.5 m wide by 2 m long. It contains two square superconducting loops at its ends and carries a cylindrical payload in its center section, held by a yoke which will permit the payload to continue its trajectory when the vehicle is deflected laterally. The vehicle will fit into a guideway structure shown in slide (5.16), having propulsion windings above and below and cylindrical guide surfaces along both edges. A block diagram of the overall installation is shown in slide (5.17). A summary of the study has been published in Aeronautics and Astronautics, October 1976 issue; two detailed technical papers describing the mass driver are to appear in Progress in Aeronautics and Astronautics. In the lunar launcher, according to our reference design, 20 kg payloads will be released at half second intervals at a launch velocity of 2.4 km/sec. The cycle time for each individual bucket would be about 100 sec, and each bucket will run about two hours before being taken out of service for re-cooling and re-charging its current. Re-cooling would simply involve contact with a refrigerator, and re-charging would be accomplished by induction. The service process would take about 3 minutes.

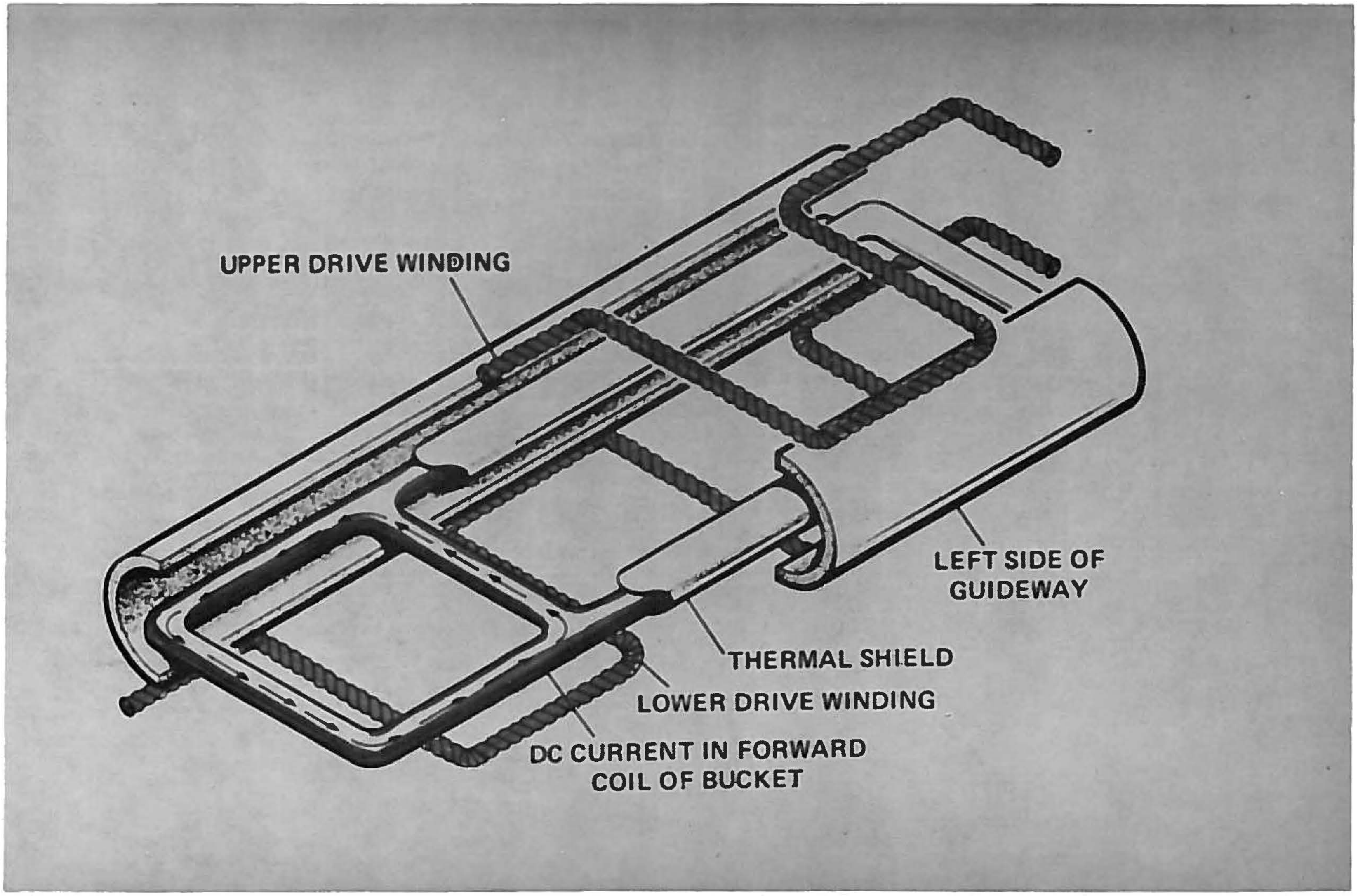
Slide 5.13



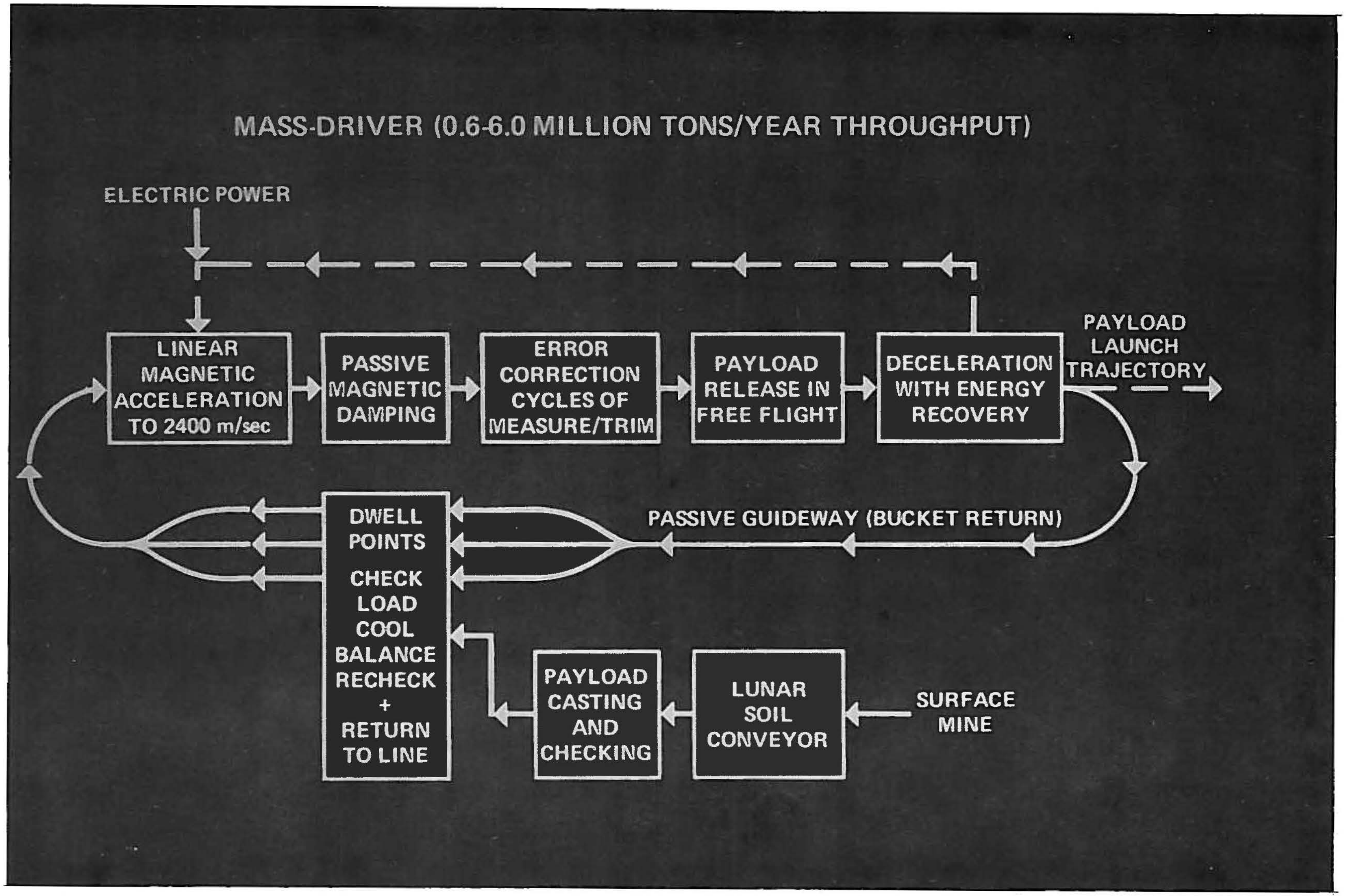
Slide 5.14


50 cm
100 cm
50 cm
50 cm
DIRECTION
OF INTERNAL
SUPERCURRENT
PAYLOAD
WELDED TUBULAR FRAME
NiTi/Al
SUPERCONDUCTING
BRAID

Slide 5.15


UPPER DRIVE WINDING
LEFT SIDE OF GUIDEWAY
THERMAL SHIELD
LOWER DRIVE WINDING
DC CURRENT IN FORWARD COIL OF BUCKET

Slide 5.16

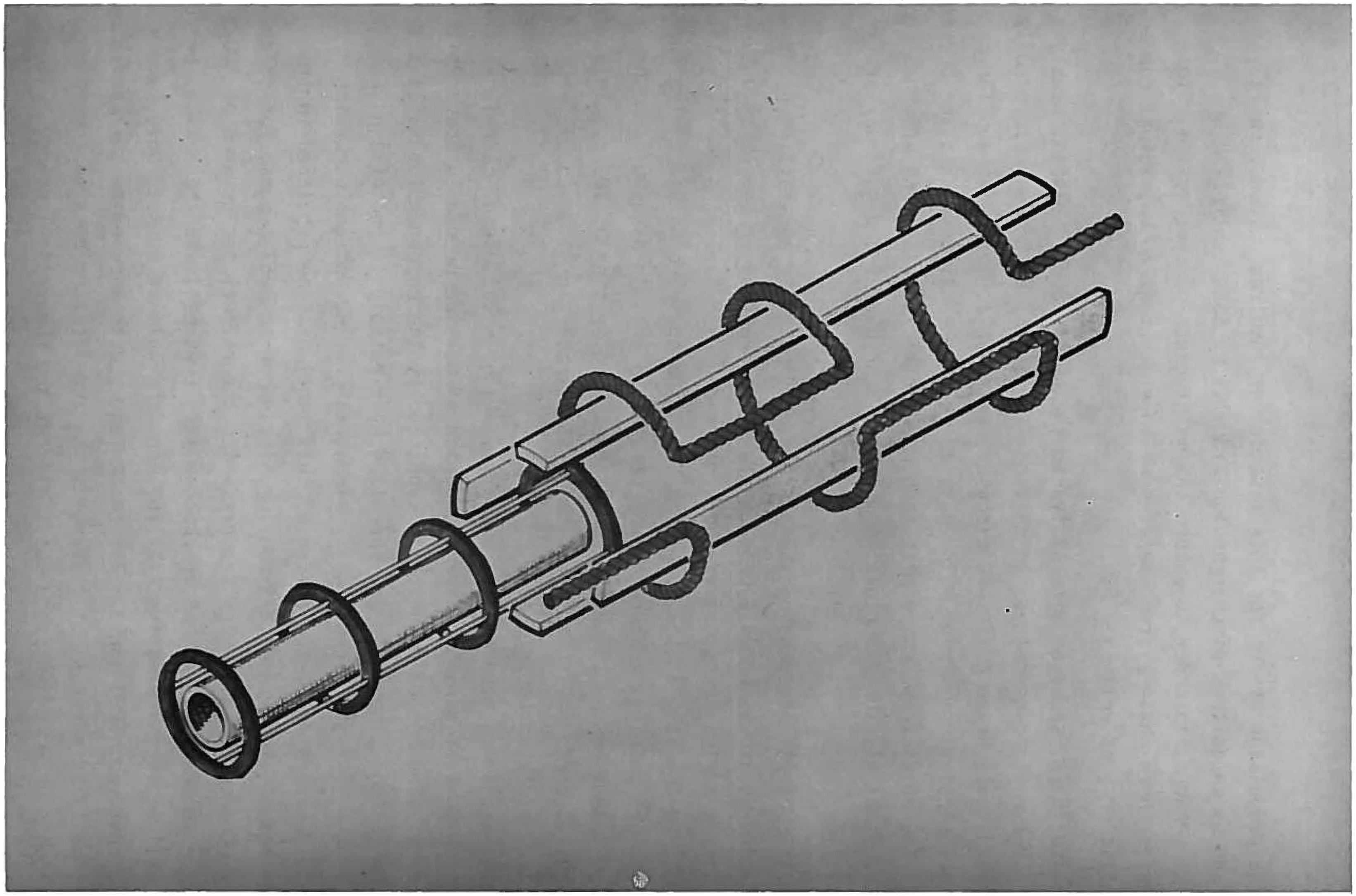

MASS-DRIVER (0.6-6.0 MILLION TONS/YEAR THROUGHPUT)
ELECTRIC POWER
LINEAR MAGNETIC ACCELERATION TO 2400 m/sec
PASSIVE MAGNETIC DAMPING
ERROR CORRECTION CYCLES OF MEASURE/TRIM
PAYLOAD RELEASE IN FREE FLIGHT
DECELERATION WITH ENERGY RECOVERY
PAYLOAD LAUNCH TRAJECTORY
PASSIVE GUIDEWAY (BUCKET RETURN)
DWELL POINTS
CHECK LOAD COOL BALANCE RECHECK + RETURN TO LINE
PAYLOAD CASTING AND CHECKING
LUNAR SOIL CONVEYOR
SURFACE MINE

Slide 5.17

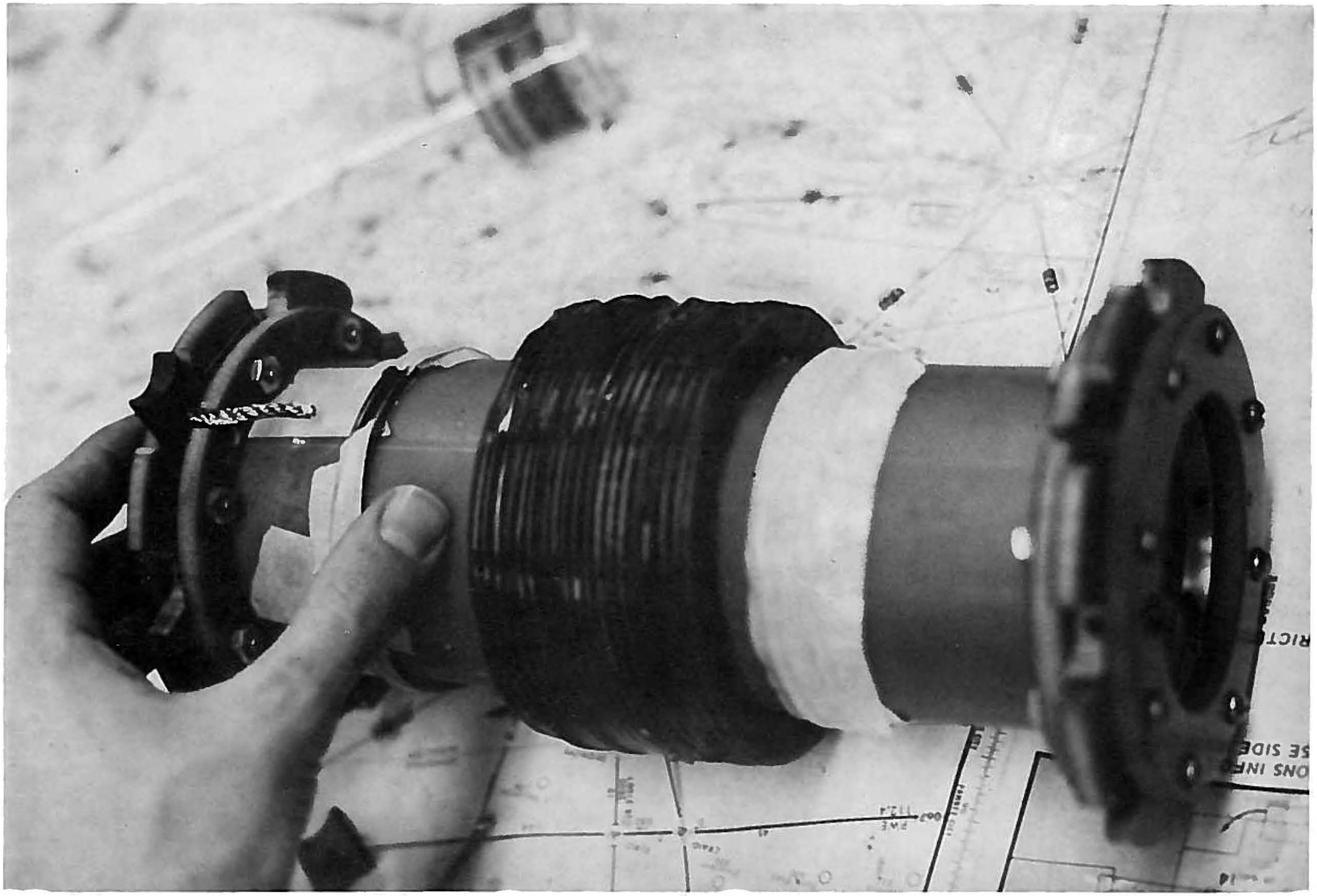
The propulsion system for this mass driver involves guideway coils energized by capacitors discharged individually by SCRs controlled by position sensors, in order to ensure the maintenance of synchronism. This full wave, three phase system operates at an electrical to mechanical conversion efficiency of well over 90%.

Slide (5.18) shows an alternative to the planar configuration, namely a coaxially symmetric geometry. In this configuration, both the vehicle coils and the guideway drive coils are circular, guidance forces being applied by longitudinal aluminum strips. The payload is now contained within the bucket coils. The coaxial system permits tighter electric coupling and also has the advantage that all the structural members of both bucket and guideway are in pure tension.

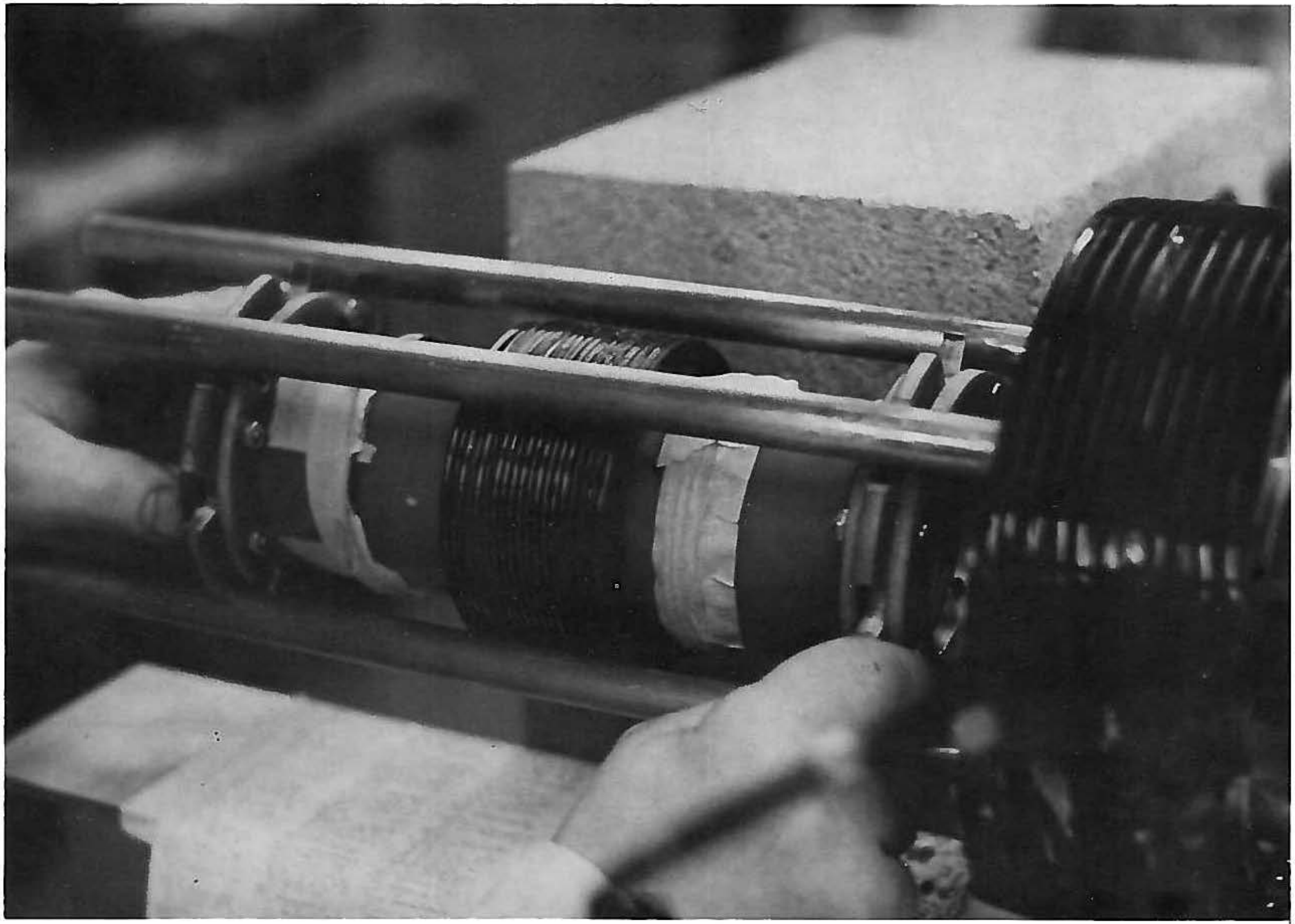
G. K. O'Neill is spending the present academic year as visiting professor at MIT, and we are using this opportunity to collaborate in the construction of a basic cyclindrical mass driver model, intended as a table-top demonstration device to be operated at the Princeton Symposium on Space Manufacturing in May. Although this model is a student project started only in January on a shoestring budget, it should come close to producing an acceleration of 100 g. This model uses short buckets having a single coil, illustrated in slide (5.19), guided and energized by carbon brushes sliding along four copper tubes, shown in slide (5.20). The vehicle coil is made of aluminum wire, which is capable of carrying superconducting current densities for the period of 0.1 sec needed to traverse the 2 m test track. The copper drive coils supported by the copper guide rails are shown in slide (5.21). The coils are energized by electrolytic photoflash capacitors, triggered by SCRs and crowbarred by diodes to prevent voltage backswing. A complete description of the design of this model will be published in the Proceedings of the Princeton Symposium, including an HP67 program for calculating the performance of axial mass drivers. The theoretical performance of 100 g implies a velocity of 160 mph in about 6 ft. Even half the theoretical performance will be very impressive. At 160 mph, the half kg bucket would have a kinetic energy of 1000 joule. The track required to decelerate the bucket by friction will be three times as long as the accelerating section. Even so, it will only be able to dissipate about half of the theoretical energy. The remainder, if any, will have to be absorbed by a stack of lead bricks.



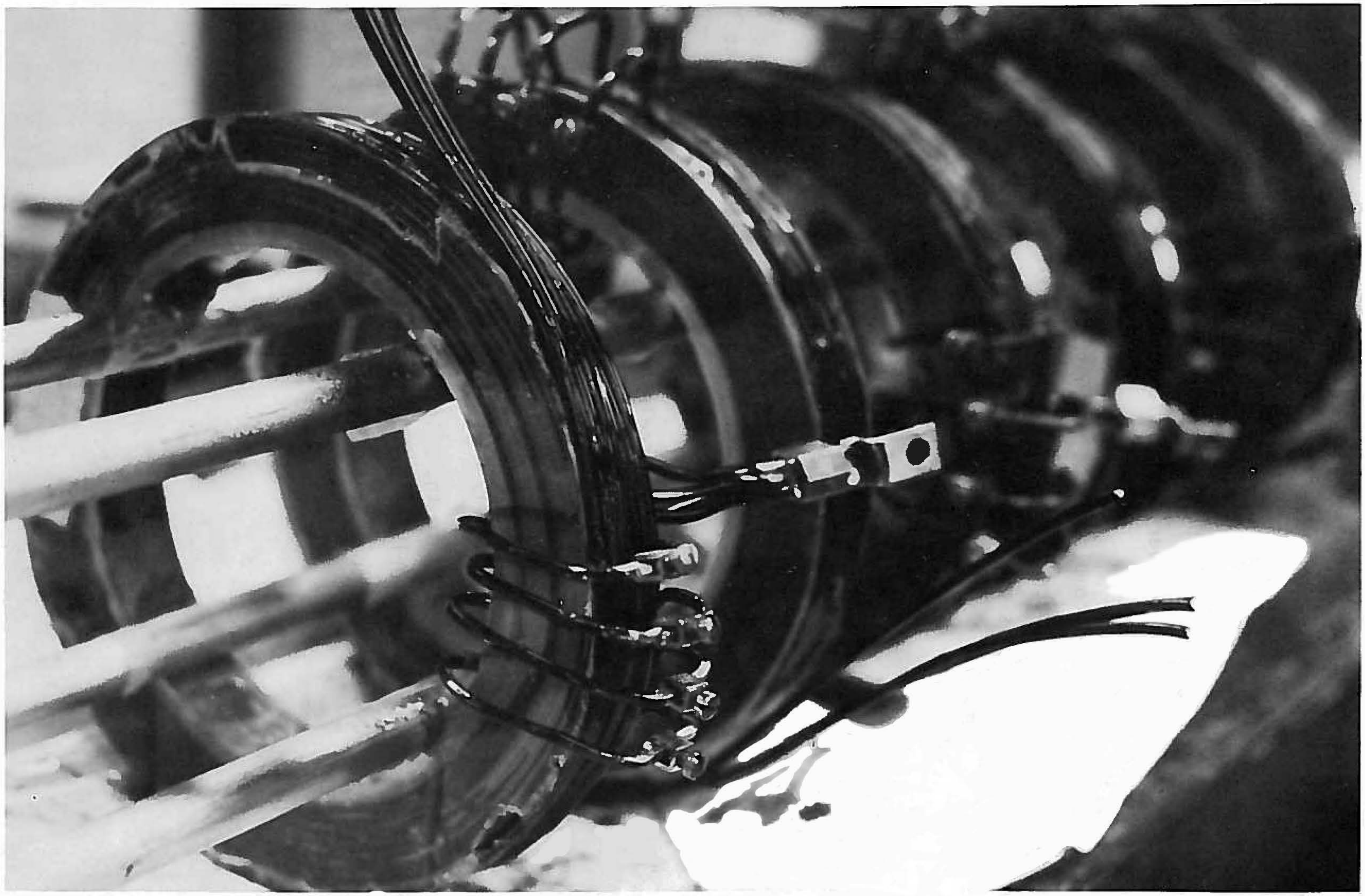
Slide 5.18



Slide 5.19



Slide 5.20



Slide 5.21

If four students can build a terrestrial mass driver in three months on a budget of about 2 k$, it may not be too wild an extrapolation to predict that NASA can build a lunar version in three years on a budget of perhaps 200 M$, excluding delivery and installation.

* The MIT mass driver was completed and demonstrated repeatedly at the 3rd Princeton Conference on Space Manufacturing in May 1977. Accelerations of 40 g were achieved in this prototype unit.

QUESTIONS AND ANSWERS

Q: "Right at the end you touched on a problem. What happens to the slugs after they come out the end of the asteroid mass driver; you're talking about throwing away 80% of the mass of the asteroid?"

A: "Well, we're obviously going to have to avoid any catastrophic space pollution problems."

Q: "I tend to worry more about the decceleration phase when you're bringing it back. I presume you're going to throw things toward us."

A: "Well, it depends on what the payload is; it may be that for very high velocity applications the slugs would only be a few grams each. In which case they will probably burn up in the atmosphere.

Comment: "If you eventually get to the point of chemical processing of material before it goes into the mass driver, you could use waste products like liquid oxygen. This eliminates the contamination problem.

TECHNOLOGY CHALLENGES IN DEPLOYING AND USING MASS DRIVER SYSTEMS

H. P. Davis
Johnson Space Center

I would like to make a brief point on each of four subjects relative to the concept of mass driver retrieval of extraterrestrial objects. The first slide (6.1) illustrates these four items: (1) launch of the elements of a mass driver, which is measured in the hundreds of tons, (2) the construction in space of these kilometer-scale structures, (3) the availability of aluminum from and the loss of payload consequent to placing the Shuttle external tank into orbit, and (4) some constraints relative to mass driver exhaust trajectories.

Assembly of the mass driver is assumed to be in a repeating orbit that will give us a twice per day launch opportunities; this orbit is sufficiently high to reduce to manageable levels the orbit drag make-up propulsion that will have to be provided during the construction interval. We are now planning to have a suborbital separation of the Shuttle external tank with targeting for that tank into the Indian Ocean. The energy that we place into the orbiter after main engine cut-off, or MECO, is performed with the limited capability orbital maneuvering system (OMS) and results in a relatively low apogee. Going to higher altitudes than, perhaps, 200 kilometers requires that we resort to carrying additional OMS propellant tanks in the payload bay and consume some of what is perhaps the most precious commodity of the Shuttle flight--the payload bay length. Direct injection to a higher apogee orbit is possible and would be advantageous from a performance point of view and therefore would conserve payload bay length. The problem with these more energetic orbits is that the tank comes down somewhere between Hawaii and the western U. S. coast. If you wish to take the tank to orbit, that problem goes away. The data indicated on slide (6.2) is payload capability of the Shuttle system to this favorable altitude orbit for space construction with and without carrying the external tank into orbit. Keep in mind that the case of <u>not</u> carrying the external tank into high apogee orbits is not now planned operationally because of the tank disposal constraints. About two metric tons loss of Shuttle payload capability (less than 10%) is consequent to injecting the tank into orbit.

EARLY OPERATIONAL CONSIDERATIONS

- LAUNCH OF MASS DRIVER ELEMENTS
- CONSTRUCTION OF MASS DRIVER VEHICLE
- ALUMINUM AVAILABILITY FROM SHUTTLE EXTERNAL TANKS
- EXIT VELOCITY CONSTRAINTS AND CONCERNS

Slide 6.1

LAUNCH CONSIDERATIONS

- 31° INCLINATION, 477 KM, REPEATING ASSEMBLY ORBIT
- BASELINE SHUTTLE PAYLOAD
  DIRECT INJECTION WITH RENDEZVOUS, NO OMS KIT
  - 25 TONS WITHOUT ET
  - 23 TONS WITH ET
- SHUTTLE-DERIVED HLLV
  - APPROXIMATELY 75 TONS WITHOUT ET
  - APPROXIMATELY 73 TONS WITH ET

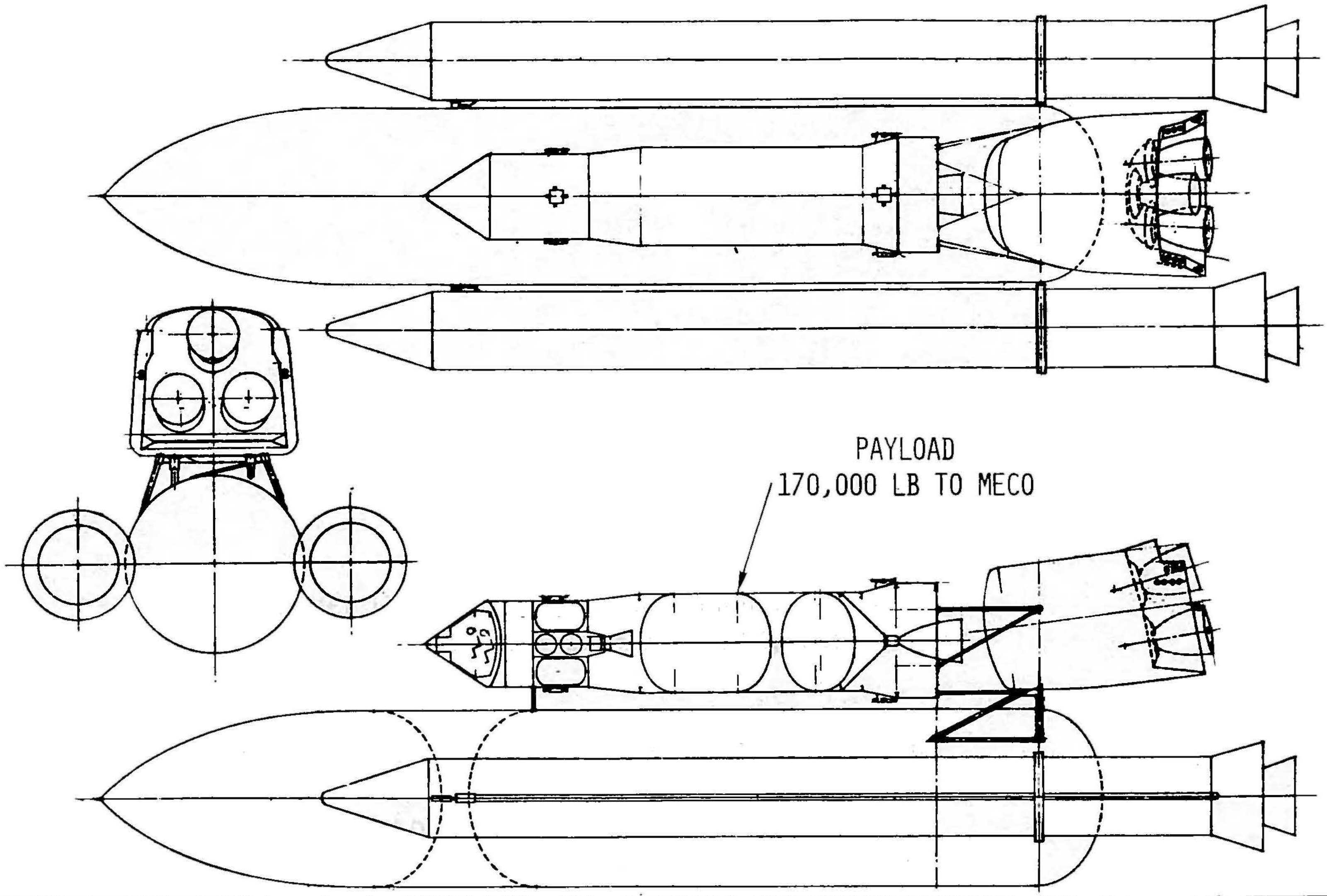
Slide 6.2

The Shuttle can be transformed in a "heavy lift launch vehicle" (HLLV) (slide 6.3) by removing the forward portion of the Shuttle Orbiter and replacing it with an expendable payload housing. The aft section of the orbiter with the three main engines is enclosed in a reentry body fitted with an inexpensive ablative entry system. The entry body that returns the avionics and the three main engines is not an orbital vehicle, but follows a ballistic path to reentry about halfway around the Earth. If we fly the typical Shuttle "Mission One," a due east launch, the entry body would be given about a 12 foot per second (4 meters per second) impulse beyond MECO. That small energy addition would place the entry body neatly down on the west coast of Australia, where we would pick it up with a truck, bring it to a ship and then return it on surface transport to the launch site. If we use a derivative of the Shuttle in this way, the number of Shuttle flights that John Neihoff mentioned to do the various energetic missions can be reduced by a factor about 2-1/2. So, there may be, if we have the mission requirements, the capability to do very energetic missions using chemical propulsion. We may be able to fulfill these demands for launch services by a rather straightforward derivation from the current Shuttle system.

The mass driver (slide 6.4) is a very long structure; it's perhaps four to five kilometers in length to do the type of missions discussed in the previous papers. The mass that Dr. Gerard O'Neill has estimated for this mass driver is in the order of 200 tons for the synchronous mission. Dr. Brian O'Leary, if I recall, estimated about 700 tons for the asteroid retrieval mission device. The mass driver is outside the scope of a single launch of any launch vehicle. Construction in space is thus required for acquiring the use of a mass driver. If you are constructing a 200 metric ton mass driver, (presuming that it can be built for that mass) a total of about thirteen flights of the Shuttle are needed. Using the heavy lift derivative of the Shuttle, only four flights are required to acquire the mass in orbit to do the construction.

The construction process itself is a subject of great interest to us; there are any number of reasons for NASA wanting to develop, quite

SHUTTLE DERIVATIVE WITH 2 BASELINE SRBs



6.5

Rockwell International
Space Division

27SSV56195

Slide 6.3

CONSTRUCTION

- REQUIRES SPACE CONSTRUCTION OF APPROX. 5 KM LONG STRUCTURE FOR $V_e = 7.1$ KM/SEC, $V_c = 5.8$ KM/SEC

- MASS APPROXIMATELY 200 TONS SCALED FROM O'NEILL FOR 180 TON PAYLOAD

- FOR AN "OVERHEAD" FOR CONSTRUCTION OF APPROX. 50% REQUIRES 13 FLIGHTS TOTAL OR 4 FLIGHTS OF HLLV

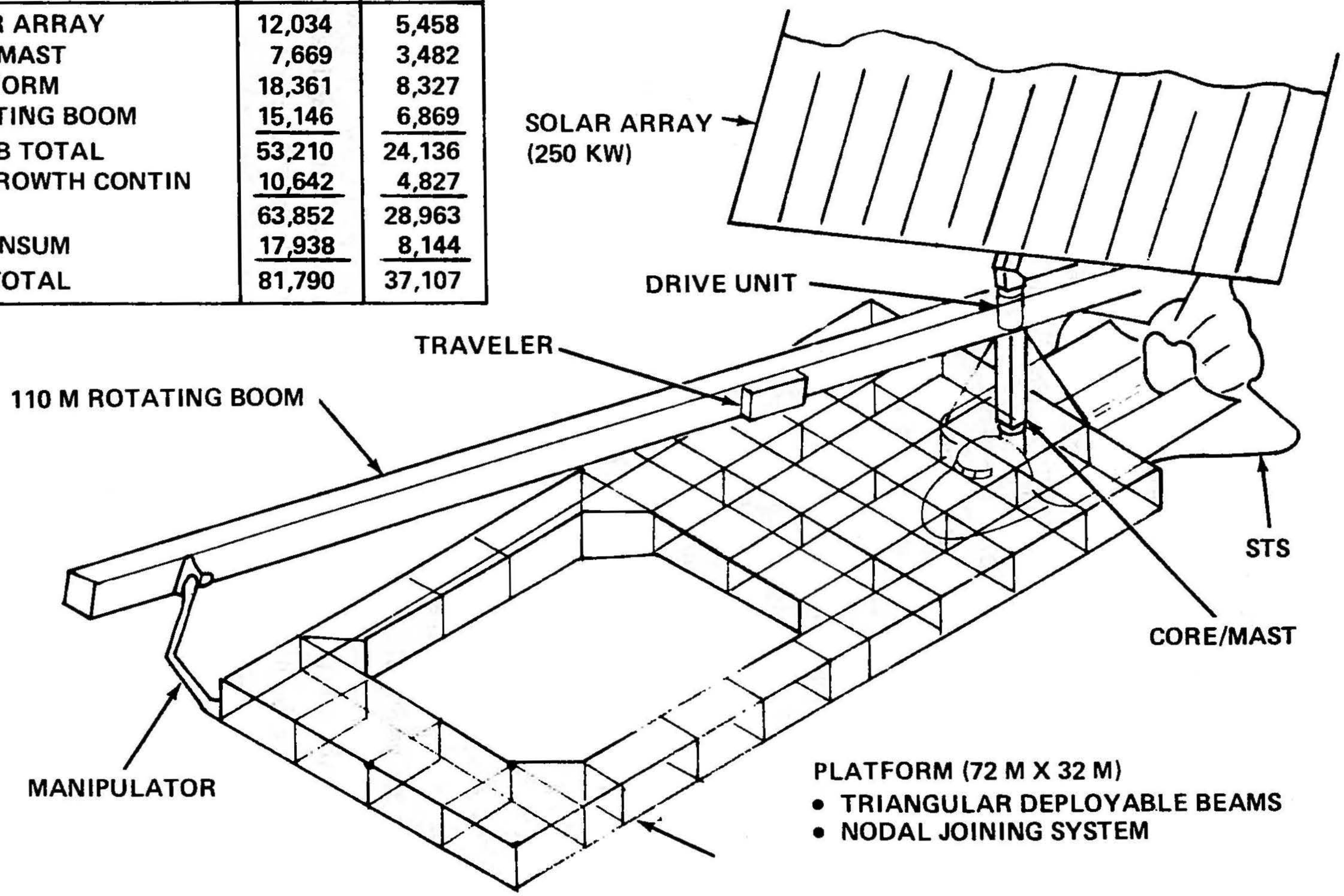
Slide 6.4

early in the Shuttle's operational span, the ability to build or construct large linear structures in space. The next two charts illustrate one of the concepts that we have had under study for about a year--this one by Grumman (slide 6.5) that we have termed "Orbit Construction Demonstration Article." The term "article" is not a very elegant phrase--it has its derivation, back in the early Apollo Lunar Module program days, when that was the term we used to describe the test articles of vehicle assembly level--the large Lunar Module test items. The OCDA weighs 35 to 40 tons. It has a platform dimension, a workbench top, if you will, of about 32 meters in the minor dimension and 82 meters in the major dimension. The hole in the middle is a very important feature, in that this gives us the means of generating linear or parabolic structures by means of fabrication devices to make the structures from coils of stock materials. The 110 meter boom shown here and illustrated further on the next charts is a material handling system to serve the same purpose as an overhead crane in a factory. It has a "traveler" on the boom, and on the traveler is a device related to and derived from the Shuttle Orbiter "remote manipulator system" now under development by the Canadians. The electrical power supply--obviously necessary to support the construction process and also to provide power for extended stay times of the Shuttle Orbiter docked with the workbench--is a 250 kilowatt array. The array is derived directly from the Solar Electric Propulsion Stage (SEPS) technology that has been under study for some years.

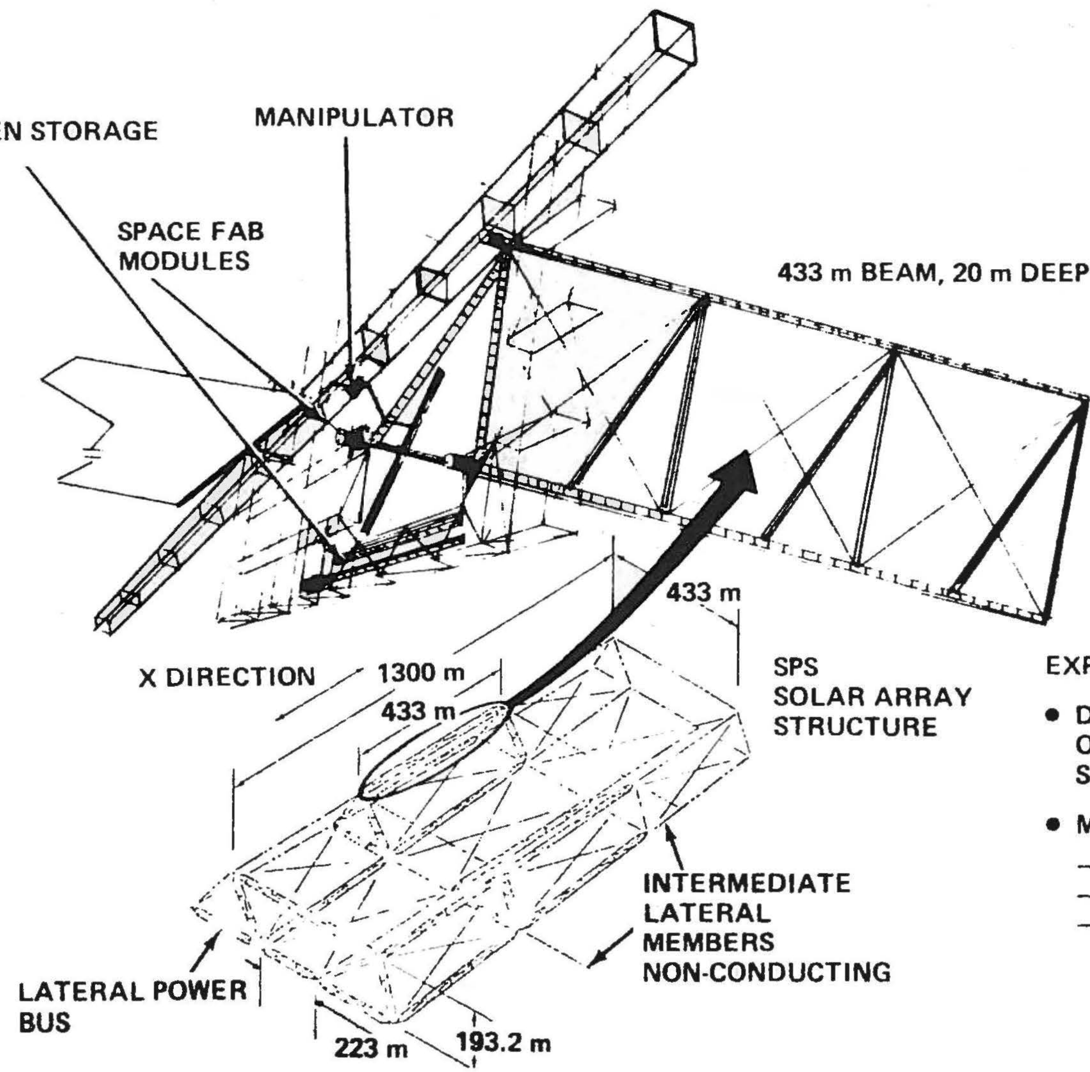
Utilization of the OCDA, once it is built, checked out and used for small scale experiments may include (slide 6.6) the fabrication of a beam having a 20 meter dimension across the battens. This beam was selected for this study to be 433 meters in length. There is really no need to stop at that length, it can be of essentially arbitrary length in the weightless environment. The Orbit Construction Demonstration Article appears to be fully competent to carry out the construction of linear structures in space of mass driver scale and to do so at a quite rapid production rate. There has been some studies done of the productivity rate on beam builder machines. I do not recall the precise numbers, but as I recall, several meters per minute is the goal for the construction rate of

SELECTED OCDA – DESIGN DEFINITION

	MASS	
	LBM	KG
• SOLAR ARRAY	12,034	5,458
• CORE MAST	7,669	3,482
• PLATFORM	18,361	8,327
• ROTATING BOOM	15,146	6,869
SUB TOTAL	53,210	24,136
20% GROWTH CONTIN	10,642	4,827
	63,852	28,963
CONSUM	17,938	8,144
TOTAL	81,790	37,107



FOLLOW-ON EXPERIMENT (20 M BEAM FABRICATION)



EXPERIMENT OBJECTIVES

- DEMONSTRATE PRODUCTION OF LARGE BUILDING BLOCK STRUCTURE
- MEASURE
  - PRODUCTIVITY
  - BEAM ALIGNMENT
  - JOINT INTEGRITY

Slide 6.6

entire structures. You have to consider, in judging the reality of these high production rates, that you are operating in the absence of weather and you are operating in the absence of gravitational forces. By proper automation and tooling, we believe that very high productivity rates for space construction will be with us in a very few years after the onset of the Shuttle.

Dr. O'Neill has considered the availability of aluminum (slide 6.7) from the Shuttle expendable tank for use in pelletized form as propellant for the mass drivers. The weight statement on the external tank and conversation with the people in Michoud (Louisiana) who are building the external tank has determined that there are about 28.6 tons of aluminum available in each tank of five different alloys. Now, you are going to have to work out some means of separating out the insulation, the steel bolts, the steel structure that supports the two solid rocket boosters to the tank in order to obtain the total content of aluminum available. One might estimate a yield of that aluminum of perhaps 50% to 70% of the total. I doubt that we will be able to have a complete 100% yield of the materials. The mass driver is conceptually quite insensitive to the type of mass it accelerates as long as we understand the magnetic properties of the pellets, as I recall from conversations with Professor Kolm. It is conceivable that we could even use a larger fraction of the dry weight of the tank than the 28.6 tons of aluminum, provided the differing magnetic properties of the propellant can be accommodated. Now, (slide 6.8) the number of tanks required to support a mass driver mission of the sort that Dr. O'Neill has described assumed that we had a 1,050 metric tons of propellant available to yield a payload of about 180 metric tons from low orbit to geosynchronous orbit. If we are to fly that class of mission with the mass driver, we would have to accrue some external tanks in addition to those available from the Shuttle flights for the construction of the mass driver itself. If you recall, we used in the teens for the number of Shuttle flights to build the mass driver and we need 37 to 50 tanks to accrue the necessary number of aluminum projectiles to feed the mass driver for both its inbound and outbound journeys. Acquiring these extra tanks may pose operational complexities or added cost.

*Exhaust velocities considerably larger than 6 km/sec appear possible for the mass-driver system. Thus, the payload to escape velocity may be much greater than 180 tons (DRC).

SHUTTLE EXTERNAL TANK

ALUMINUM CONTENT

	ALUMINUM TYPE	WEIGHT, KG
LO_2 TANK	2024	709.9
	2219	4915.7
INTER TANK	2024	1953.2
	2219	1807.1
	6061	2.3
	7075	1935.5
LH_2 TANK	2024	1657.0
	2219	12517.1
	6061	1.8
INTERFACE EQUIPMENT	1100	7.7
	2219	531.1
	6061	16.8
	7075	1149.0
PROPULSION AND MECHANICAL SYSTEM (EST.)		1383.5
TOTAL ET ALUMINUM		28,607.9 KG
ET INERT DRY (TANK SERIAL NO. 7 AND SUBSEQUENT)*		33,756.5 KG

*REFERENCE: ET MASS PROPERTIES STATUS REPORT, JANUARY 15, 1977

Slide 6.7

EXTERNAL TANKS REQUIRED FOR PROPELLANT

- o ASSUMED 1050 TON PROPELLANT LOAD, PER O'NEILL
- o 28.6 TONS/ET AVAILABLE @ 100% YIELD
- o 37 TO 50 TANKS REQUIRED, DEPENDENT UPON YIELD
- o EXTERNAL TANKS FROM OTHER MISSIONS REQUIRED

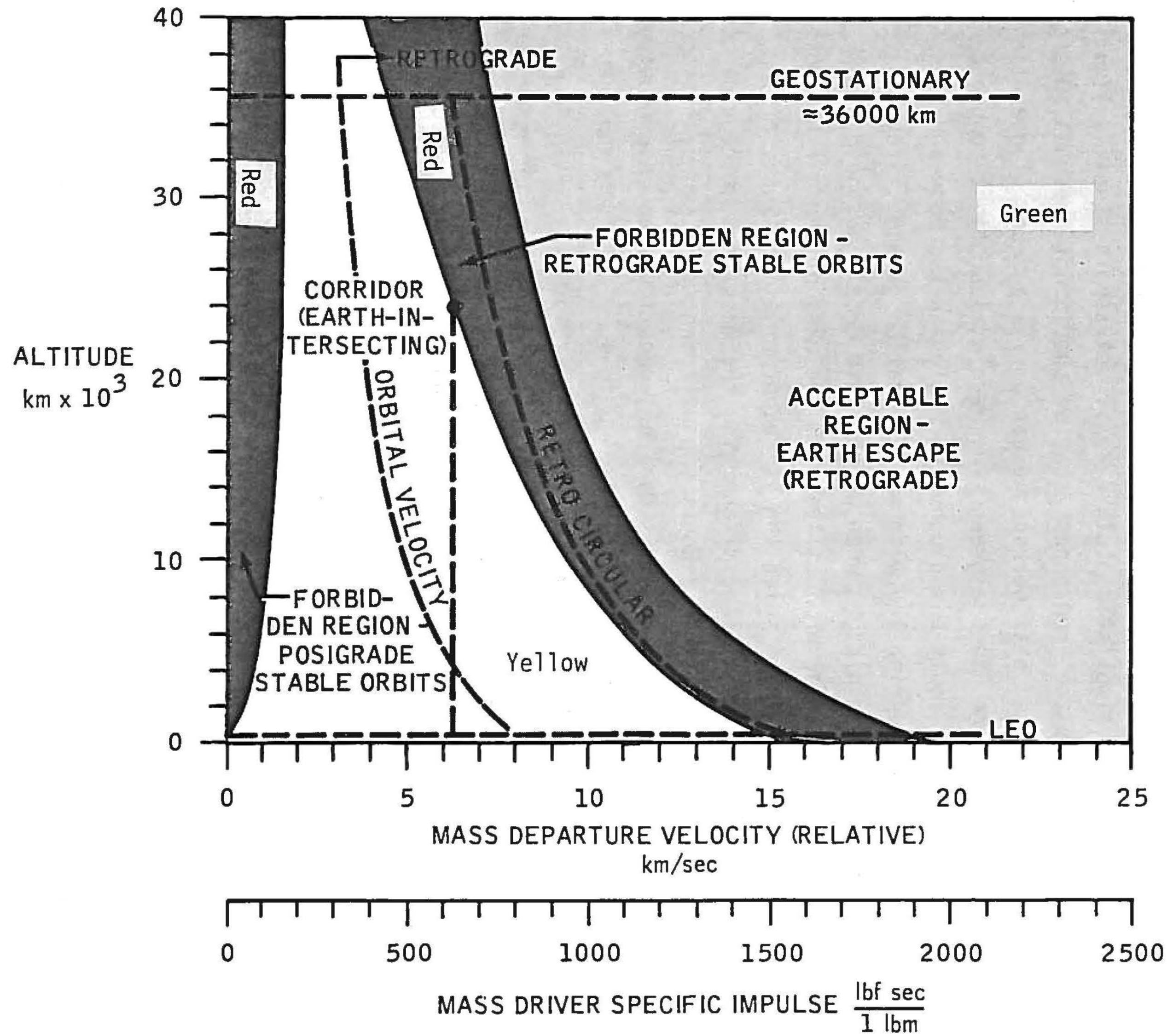
Slide 6.8

The last point I would like to make (slide 6.9) was brought up by a question to the previous speaker: That is, we are going to have to file an "environmental impact statement" on this device and we must be a bit careful as to where we discharge projectiles. I have attempted to put forward here a quite simplistic picture to illustrate in "traffic light" fashion where we have the "red zones" that we should not trespass, where we have a "caution zone" that perhaps we can derive a means of operating within and where we are "in the green"--we have a clear light to proceed. Now, these zones are simply based upon the Keplerian two body equations using a tangential steering law with no inclination change. Steering is going to complicate the picture when we get into detail on the orbital mechanics of the departing projectiles from the mass driver. A 6 kilometer per second exhaust velocity selection is inappropriate because, at the synchronous altitude you will be discharging the mass into retrograde circular orbits. So, in approximately 12 hours you will meet your own pellets coming at you at twice orbital speed. This does not constitute an insurmountable problem, but we will probably have to fly up to some altitude and then step down the power to the mass driver to fly up to synchronous altitude within the "corridor." We would also have to do orbital tracking during descent of the pellets to the Earth-- intersecting trajectories to be very sure that we do not have people beneath that might be annoyed by having 25 caliber projectiles impinging on them at high relative velocity. If we are willing to use the mass driver at a thousand g's and we are willing to build a 10 or 15 kilometer long track, perhaps we can get sufficient velocity into the pellets for their trajectory to be Earth escape in the retrograde direction. This may pose a different form of orbital problem heliocentric debris. I have not considered anything other than the geocentric problem. I think a little bit of care on how we do our early mission planning for the mass driver is imperative to give due consideration to where these 20 to 35 millions of 25 millimeter projectiles are going. Thank you very much.

NASA-S-77-10545

MASS DRIVER DEPARTURE VELOCITY ZONES

LOW EARTH ORBIT TO GEOSTATIONARY ORBIT
TANGENTIAL STEERING



Slide 6.9

QUESTIONS AND ANSWERS

Q: "Have you considered the whole concept from the view of material strength. After all, it is not only a matter of high g's, but it seems to me that a third derivative of the thrust of the mass driver is going to be very, very high. So, for three years all of this device will be subjected to a legion of people hammering continuously; wouldn't the whole thing just tear up?"

Davis - "I have made no reviews of the structural design of the mass driver, although that is clearly a most important area. The numbers I have used were simply scaled from Dr. O'Neill's work."

Q: "It is also not only the device, but the whole asteroid can just be torn apart."

D. Criswell - "I think the acceleration levels you are talking about for asteroidal retrieval will be on the order of a micro g."

Q: "Oh, but it's a third derivative, don't forget it will be continuous, right?"

D. Criswell - "I would imagine you can take care of that with shock absorbing."

A: "At about 3-1/3 rounds per second?"

H. Kolm - "Think of the airplane you came here in--it probably had more highly stressed turbine blades than that mass driver would."

A: "I am very curious how well aligned this 5 kilometer mass driver has to be. If this is in space environment, say it is getting sheltered by the sun, shadowed by the sun, doesn't the mass driver tend to flex and does that present any problems?"

H. Kolm - "The mass driver structure itself would be statically in a very simple equilibrium because it's all in tension, however, the dynamics we haven't looked at yet. It would have the same problems of a flag, you know, a flag should actually fly straight, but it is known to flutter. The dynamic analysis needs to be done, of course, but the mass driver as a static problem seems to be very manageable.

B. O'Leary - "People should distinguish between what Hugh Davis is talking about and what we were talking about earlier--the asteroid retrieval mission. These are two different applications for the mass driver. One of them (transfer from low earth orbit to escape velocity) being one that would require large exhaust velocities, something on the order of greater than 6 kilometers a second. That's the one that requires the long mass driver. The other use is the asteroid retrieval itself, where the asteroid pellets are spit out at considerably lower velocities and where the pellets then go into heliocentric orbits. With some kind of reasonable thrust vectoring strategy, you're not dealing with navigational hazards in the vicinity of the Earth in the second case. That's why I stressed two scenarios in my presentation - one was using mass drivers to get to the asteroid and the other is just using conventional upper stages to get the asteroid retriever system to the asteroid.

LUNAR VERSUS ASTEROIDAL RESOURCES

Professor Jim Arnold
University of California, San Diego

I think that Dave Criswell set this up as an adversary situation, or rather I think he hoped to. Obviously, lunar and asteroidal resources are alternatives from the start; are two possibilities. I deny that I am in the position, of saying that the search for asteroid resources is bad and the search for lunar resources are good; they are really two aspects of the same program. I hope that I will be regarded as virtuous, standing up here without any slides or viewgraphs at all. Such an informal presentation might not be entirely out of place. I'll ask you though to imagine that I am not so peculiar and anomalous as I seem and that there actually are a series of viewgraphs going up on there. In the first one, I'm going to discuss the advantages of lunar resources. This one is all white space, except for one word, which is my first thought, and the word is "knowledge". We know a great deal about the moon; we know its position, we know its orbit, we know its composition in part, and we have samples. About 10 to 20% of it has been surveyed and we know a great many other things about it as well.

The second imaginary viewgraph would also have one word and that word would be "location". We don't have to bring it into high earth orbit. It's in high earth orbit and so, presuming that we want to use it somewhere nearby, we don't have to wait for a favorable opportunity and so on.

My third and last imaginary viewgraph has four words on it, the words are "Use on the moon". Historians never seem to write about the important history of now. In my view, that what's going on at this symposium tonight is a part of human history and a very important part. In the few years in which such ideas have been active, we have been looking at particular schemes whose virtue are chiefly derived from imagination and drive of the people who made them. We want very much at this stage to keep our prospectives broad and look at a wide range of possibilities. In that spirit, I'd like to bring to your attention the possibility that the best use we can make of the earth's resources will not be in free space at the absolute top of the potential well, but perhaps on the surface of the moon itself. In the 1960's when people were thinking of follow-ons for Apollo, there was some very large schemes for lunar bases and all sorts of colorful airbrush pictures which focused on that theme. It since has become very unpopular, but perhaps we should remind ourselves not only does the moon has for all useful purposes an infinite mass, but that it also has a very large area. The area of the moon is just about equal to that of Columbus' new world, of North and South America. That's a lot of territory. If one wants to build anything, if one wants to make anything, if one wants to grow anything, the availability of that real estate, which does not have to be built, is an important advantage. It's also not obvious to me in this very early stage of our thinking that the presence of one sixth g is a disadvantage. It may very well turn out that that's quite an optimal amount of gravity. It is not enough to make lifting and jumping and carrying terribly difficult, small enough that mass drivers can be designed at MIT which can throw things off the planet, but at the same time large enough so there's a definite direction down and so that one's structures can remain where they are put without trimming of orbits and so on.

I don't want to suggest that anything that I've said is decisive. I want only to say that these are things that need to be thought about. In closing, I would like to talk a bit about the nature of the resources on the moon and about the nature of man's need for resources. We have soil containing iron and aluminum in abundance, with a little bit of the iron in metallic form. We have all the oxygen (tied up in the oxides) that we want. I'm not at all sure that we know how best to get these things out, but they are there as they are surely in the asteroids. We have plenty of plain dirt, which is also necessary. The other thing which people need in enormous quantities is water. Up to now every indication has been that there is very little water indeed on the moon. One of the reasons I am so passionate about the Lunar Polar Orbiter is because I believe that the old ideas of Watson, Murray and Brown are sound and that we can indeed find water (ice) in considerable quantities in the permanently shadowed regions near the lunar pole. My estimates, in the paper I am trying to write between phone calls to Washington on the subject, run something like 10^{16} to 10^{17} grams as the most likely amount. The uncertainties are very great and we need to go and look. Still, there may well be these quantities of ice. If there are not, that certainly greatly increases the relative attractiveness of the asteroidal resource. If there are, then these two things are more comparable.

A few words about the other elements that one might need. Obviously, if one needs something like mercury in small amounts, that can be brought from the earth, not extracted in space. The other things besides metals and oxygen and water that one needs in fairly large amounts are carbon, nitrogen, sulphur and phosphorus for life. The carbon and nitrogen in the lunar material are not negligible in quantity. The typical lunar soil has roughly 100 parts per million of each. Our requirements for them in a closed biological system are far smaller than our needs for an active reservoir of oxygen. These quantities appear to me to be sufficient. It would obviously be desirable to have a carbonaceous chondrite composition with its abundant water and carbon in amounts running up to a few percent. If water does exist on the lunar poles, the amounts of carbon and nitrogen there may also be large.

Summing up the lunar materials are a known quantity, except for ice and a few other things. They appear adequate with that single very large exception to do most of what we want since we have the actual materials in our laboratories. That, in my view, means at the present time we are riding two horses: one is the asteroids and the other is the moon. Thank you.

QUESTIONS AND ANSWERS

Q: "As Tom McCord points out, most of the near-earth asteroids are ordinary chondrites; how does that change your viewpoint as opposed to carbonaceous chondrites?"

A: "The ordinary chondrites actually do have some bound water, as I think you know; it's roughly a few tenths of one percent. The solar wind hydrogen in the lunar soil is 50 ppm's, so .05% water equivalent is in the lunar soil; that would still give the chondrites an advantage. The ordinary chondrites have one advantage over the type 1 carbonaceous chondrites in that the metal is already free. We haven't spent much time tonight about the cost of processing, but certainly having iron in metallic form is an advantage. Other than those two remarks, I don't think there's much to say. Finally, let me switch sides for a moment: there's got to be carbonaceous material in earth crossing asteroids."

Q: "In our statistics there are only two."

A: "Right. Exactly. Someday when there are statistics of 100, the worst case we would expect to find would be the one in which carbonaceous materials were about as abundant in the earth crossing asteroids that we are interested in as they are in the collections in the museums. Everything indicates that the bias in the collections is against the carbonaceous materials. Thus, I would expect that by the time you have 100 you would have at least a few. However, if you've really been listening tonight, the number of objects have the right delta v without discrimination would not be many. If we and the further bias which Wetherill, if I can misquote him, was saying might be a factor of 10 depleting the best objects, by the time you got 100 objects you still might not have one good one."

Q: "In the recent literature I have seen from Brian O'Leary and Gerry O'Neill and others the retrieval of asteroids and construction of space colonies from lunar material are the means for the providing of inexpensive electrical power to a society here on earth. How would you see the colonization of the lunar surface providing a similar or related end as opposed to the means?"

A: "I think it would not be unfair to O'Neill if I suggested that perhaps his first idea was to make the space colonies and his second idea was - "How can I figure out a way to support them?" I'd feel a little more comfortable making that remark if he were here, but I think that these are his motivations as I understand them and they would be my own, as a matter of fact. I cannot answer your question except to say that I think the real plus, speaking for myself, the real plus in O'Neill's schemes is not the power which it would provide, but the establishment of those colonies. I don't think that what was thought in the sixties when we were thinking about such things as manned colonies on the moon was very imaginative and I am not feeling very imaginative tonight, but give us a couple of years."

"NEW MOONS" - SCIENTIFIC AND ECONOMIC VALUE OF A 1980's SPACE PROGRAM BUILT ON RETRIEVAL OF EARTH APPROACHING ASTEROIDS

Dr. David R. Criswell
Lunar Science Institute

Why retrieve asteroids (slide 8.1)? First, it may give a high advantage in cost. Retrieval costs for large tonnages on the order of many megatons are estimated to be the order of a few billion dollars. Launching from earth an equal mass of material would require on the order of 500 to 10,000 billion dollars. Secondly, this approach very likely minimizes the time, steps, and complexities necessary to bring large quantities of mass near the earth. Finally, all the material that you can bring back is useful either as reaction mass, or as radiation shielding for workers in large colonies, to work as raw material to make feedstock for industrial processes, and to serve as a base.

A retrieval mission would have high visibility (slide 8.2). This would be the appearance of a mass driver system at a 200 kilometers slant range. It is dusk and the mass driver and solar cell array are leaving low earth orbit on the way to the asteroid. The pellets used as reaction mass can be seen as meteorites at least for a short time to convince everyone on earth that the project is on-going. The globe circling meteorite shower could be visible for several days during the outbound trajectory. Eventually, one reconfigures the exhaust velocity, and the pyrotechnics would stop.

The mass driver concept uses the shuttle very intensively and has a great potential of dramatically lowering the cost of space solar power systems, as compared to terrestrial launch of all materials. It appears to provide a very good split between unmanned and manned operations. An unmanned mode would be used to retrieve the asteroid from deep space. Manned industrial processes could be started subsequently in near-earth space.

There is a somewhat subtle legal and social point. The asteroids have evoked at this point in time few emotional precepts, attachments or legal constraints. Space Law is a very active subject now in the United Nations. This results in part from the literal "high visibility" of the moon. However, the presently invisible, but highly numerous asteroids have not come under consideration for legal restriction on their use.

WHY ASTEROID RETRIEVAL?

1. 10^7 tons for 1-2B$ versus 500-10,000B$ from earth.

2. Minimum time and steps.

3. All material is useful (reaction mass, shielding, to make feed-stock).

4. High visibility.

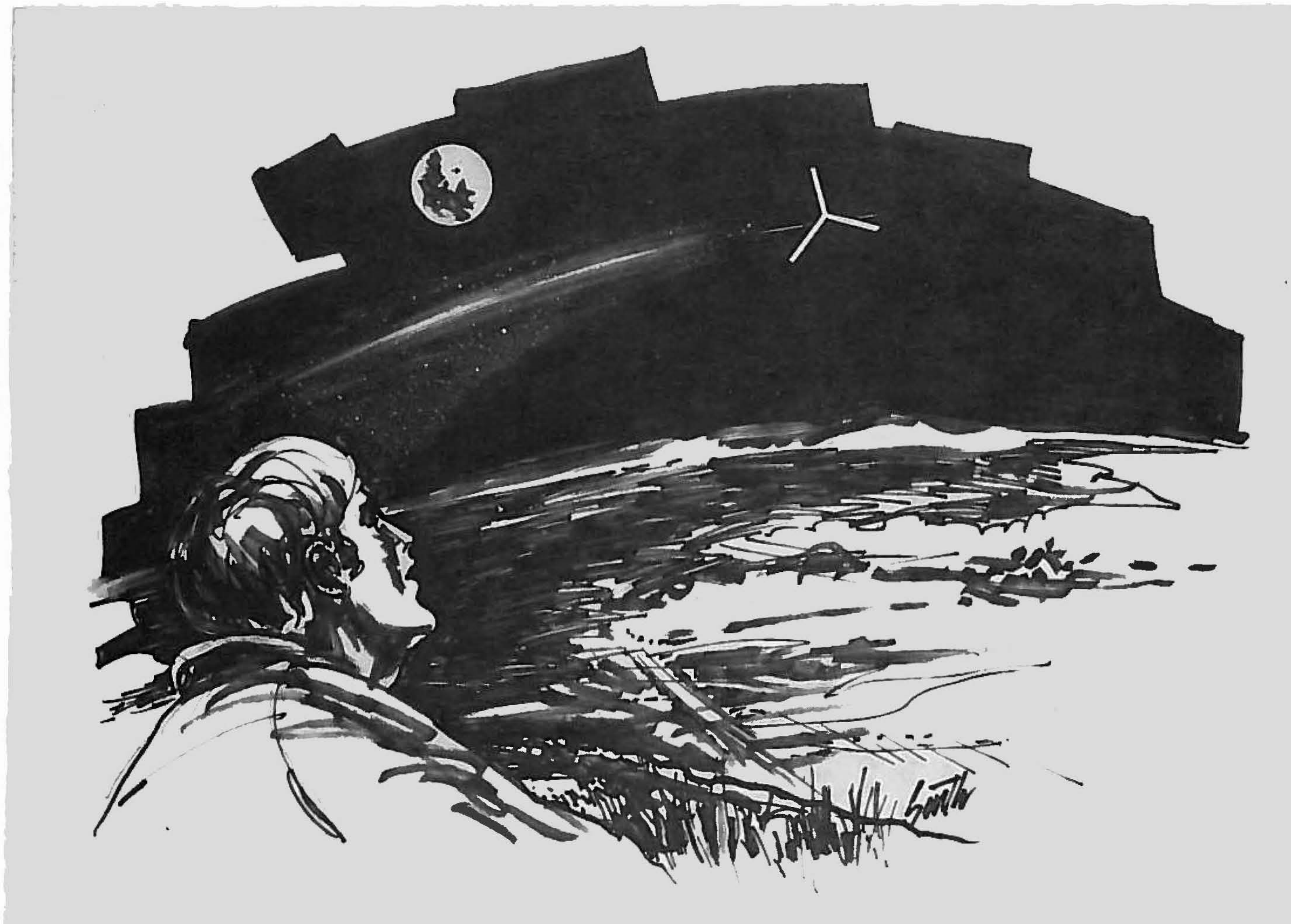
5. Uses the space shuttle intensively.

6. Reduce costs of Space Power Systems.

7. Good split of unmanned (retrieval) and manned (utilization) operations.

8. Asteroids have evoked few emotional precepts or legal constraints.

9. Fully challenges the capabilities of NASA and its contractors.



Slide 8.2

Asteroid retrieval fully, but does not overly, challenge the capabilities of NASA and it's contractors. It's an adequate challenge (slide 8.3). Let us take the view into perspective. In slide 8.4 we see a 100 meter asteroid. It is approximately the size of two astrodomes or the mass of twenty super tankers. It is connected to a mass driver system which is on the order of 200 meters long. The exhaust pellets trail out the right side. Solar panels are arrayed toward the sun. By adjusting the length between the solar cells and the mass driver, one controls the center of mass of the entire system's two degrees of thrust alignment. The major problems are rendezvous and survey capabilities which would have to be developed, despin of an asteroid the size of the Astrodome, and docking and stabilization of the asteroid which may possibly be a very friable structure against even the 10^{-6} acceleration. In the cruise phase, three basic things - mining, analyzing and contouring of the internal volume of the asteroid must be accomplished.

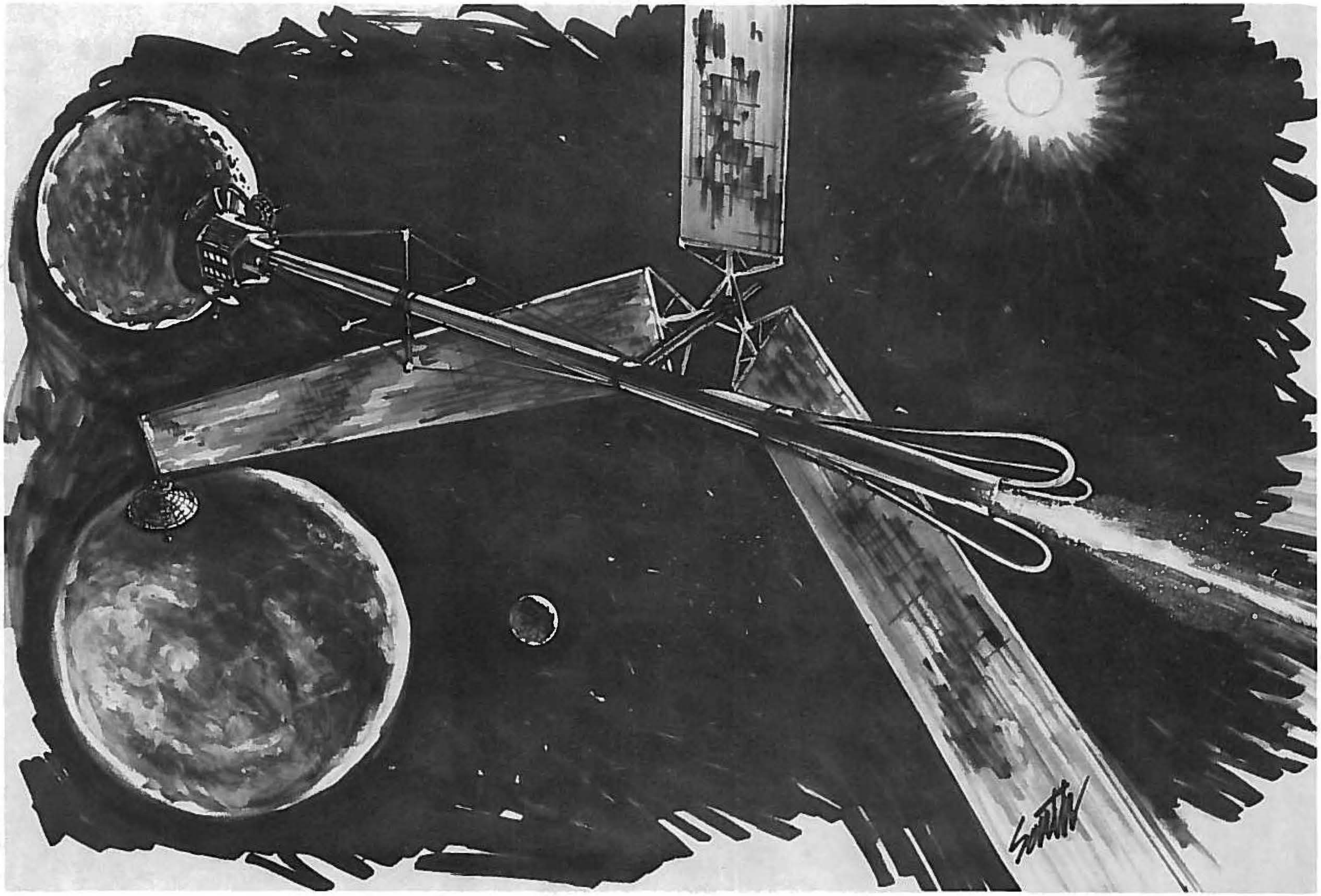
The mining machine (in slide 8.5) has a personality all its own and must possess impressive capabilities. However, it can be designed as industrial grade equipment and not be restricted to a spindly high stress technology. Thus, the system is unlike Viking which was taken to its limits as far as strength, weight, power, and everything else was concerned. You can plan for the capabilities of moving material with the power available in the mass driver system. You can talk about caterpillar or heavy equipment capabilities. The early mass driver system would ingest about ten kilograms of asteroid a second. That's about the equivalent of 4 or 5 water pitchers of mass per second.

Utilizing an asteroid, offers in my mind a very clean separation between the developmental aspects that a government can do and the things that private industry or public utilities can do (slide 8.6). In terms of our present economy the development costs of 2 to 4 billion dollars seem very reasonable as front end money. One can do analysis of the composition of the asteroid in the cruise phase of three to five years. During that phase one can start preparing the equipment necessary to start processing the asteroidal material and deploying the habitats for workmen. Therefore, this approach minimizes or carefully defines in the cruise phase the risk associated with the total investment needed for industrial operations. As importantly, the duration of that investment and the capitalization of major industrial requirements on recovery of the body to earth - space are minimized.

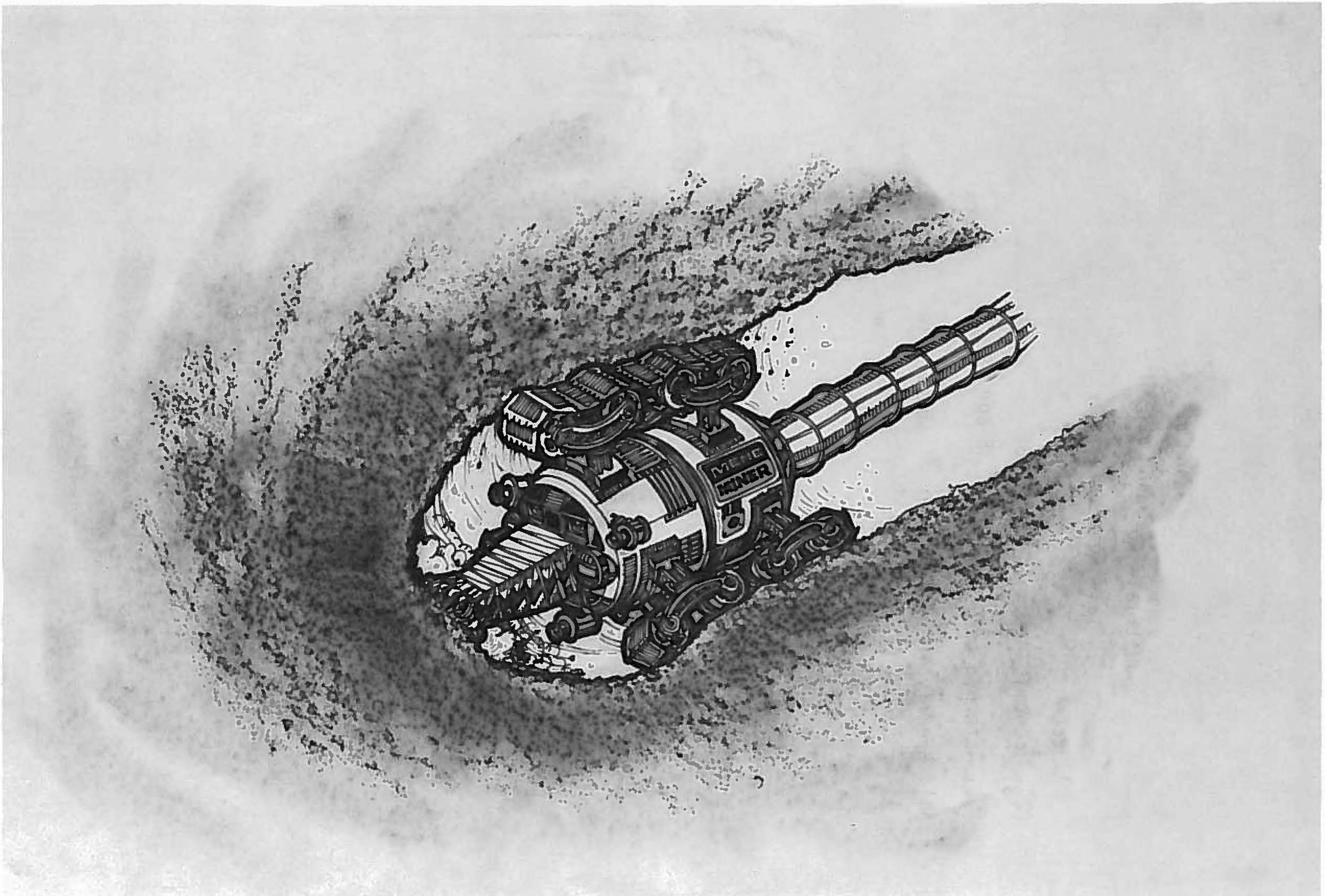
ADEQUATE CHALLENGE

100 meter asteroid -	size of two Astrodomes
	mass of 20 super tankers

1. Rendezvous and survey
2. Despin
3. Docking & stabilization (10^{-6}g)
4. Cruise phase
   (a) Mining (b) Contouring (c) Analyzing



Slide 8.4



Slide 8.5

Habitation/Utilization

(1) Program defines RISKS and minimizes INVESTMENT DURATION and TOTAL INVESTMENT for industrial organizations much larger than NASA.

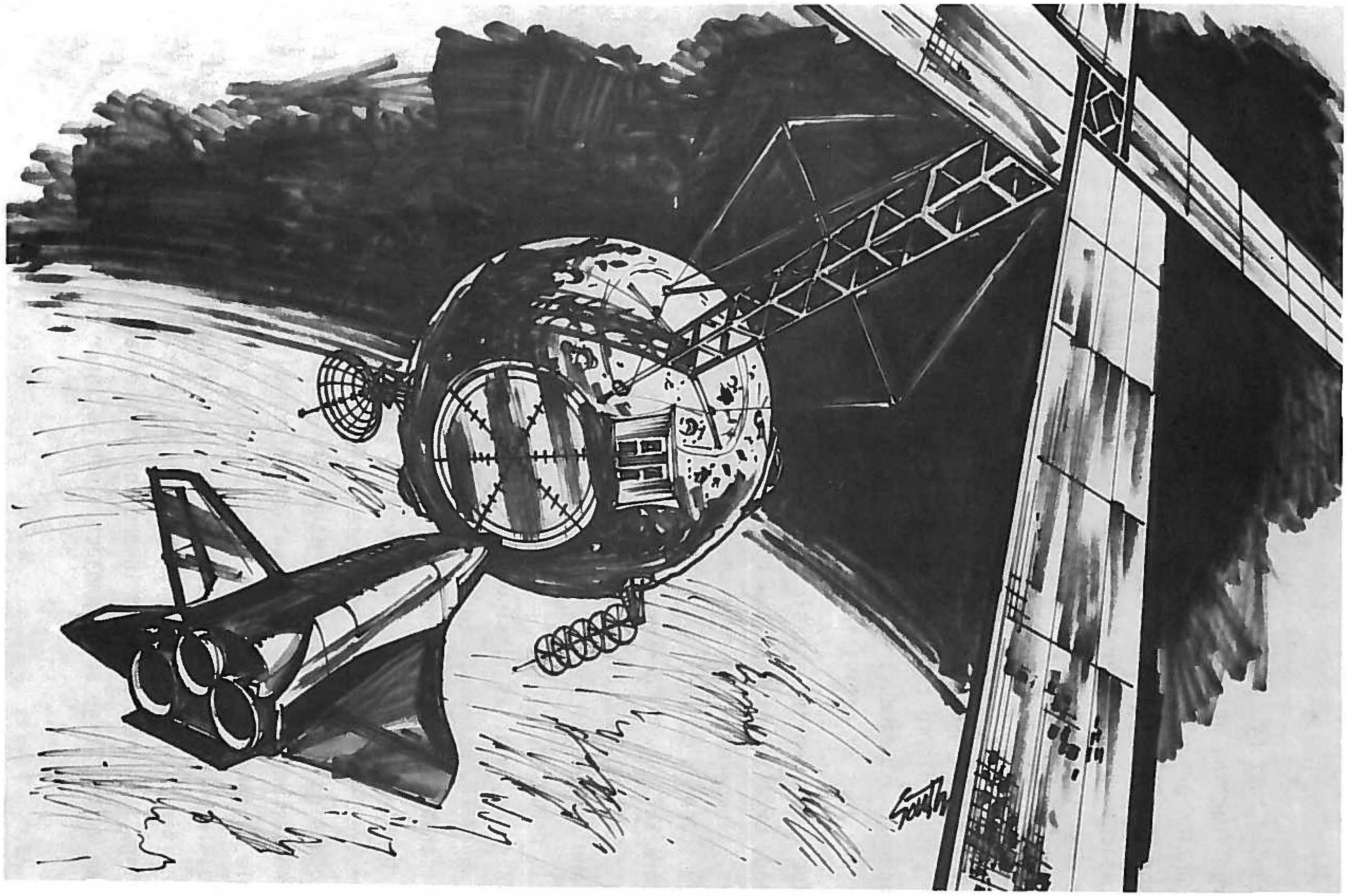
(2) Economic return from 50 SSPS could be 100B$.

(3) Asteroid provides radiation free living volumes.

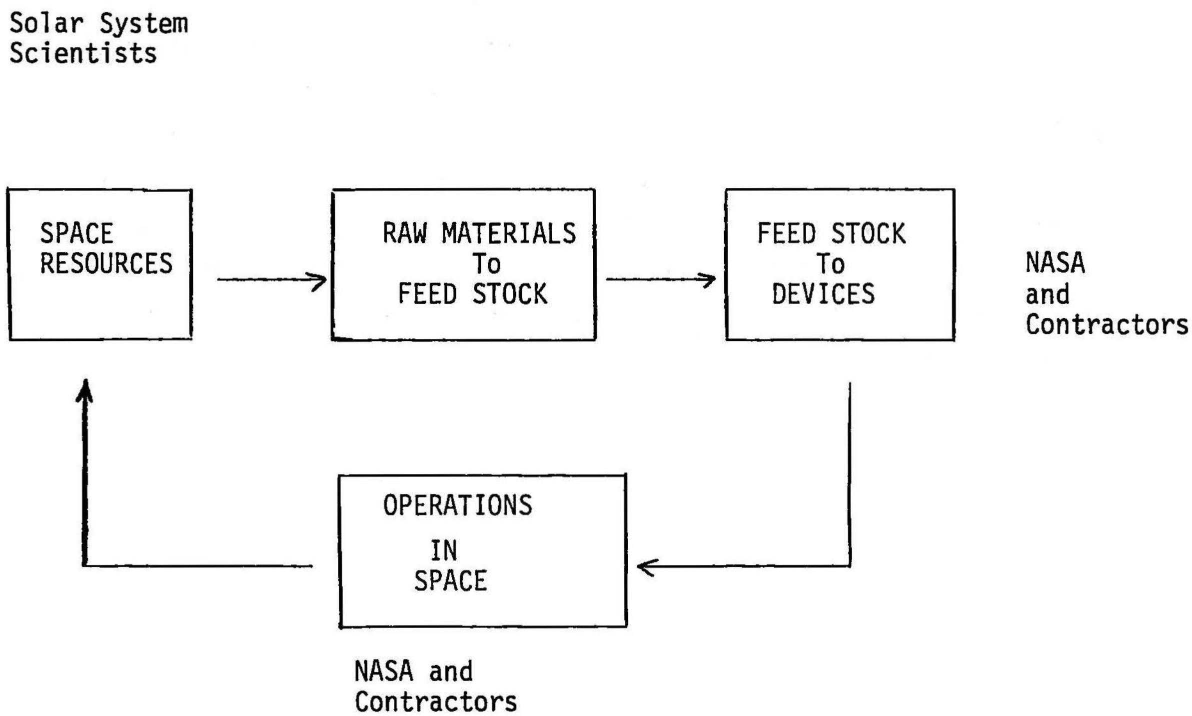
(4) Greatly increased scale of space science activities.

Assuming that by substitution of materials you can use virtually all or a large fraction of the recovered mass of the asteroid you can envision the production of up to 50 space solar power systems from the 2 million to 10 million tons of asteroid brought back. If you assume a worth of those power stations on the order of $500 per kilowatt, that leads to a market value of the final product on the order of 100 billion dollars. The asteroid, itself, in the initial phases, might provide radiation free living volumes (slide 8.7) in the volumes contoured out during the cruise phase and a greatly increased scale of space science activities because there would be activities in space comparable to the order of ten to possibly fifty billion dollars a year concerned with industrial operations. Thus, there would be a much higher base for any sort of activities than would occur for science activities alone.

Slide (8.8) depicts a basic development problem. There are people who understand, or at least know how to start studying the availability of space resources. These are people in the lunar sciences community and in the broader planetary sciences community. NASA and the aerospace companies and their contractors know how to convert feedstock to devices that do things, such as Saturn V's, Vikings and buildings. NASA and it's contractors also know how to analyze and conduct operations in space. However, there is a gap which is very serious in promoting the realization or even judging the realization of what you can do in space; what is missing is experience available to NASA for judging the conversion of raw materials to industrial feedstock. There has been no need in the terrestrial environment for NASA or aerospace companies to get involved with material processing. The possible needs are only now being discussed which would encourage Owens-Illinois, United States Steel, or a large copper company to worry about processing extraterrestrial materials. This is a very key problem because it's a problem dealing with the creation of mental facilities to think about reasonable engineering techniques for processing non-terrestrial materials into industrial feedstocks. It takes some time to develop the mental facilities. This identification and evaluation of detailed processing schemes is one of the major things that must be faced in the analysis of any situation of what you do downstream with a large scale project, such as lunar mining or asteroid retrieval.



Slide 8.7


Solar System
Scientists
SPACE
RESOURCES
RAW MATERIALS
To
FEED STOCK
FEED STOCK
To
DEVICES
NASA
and
Contractors
OPERATIONS
IN
SPACE
NASA and
Contractors

Slide 8.8

What might asteroid retrieval mean to the man in the street. Apologies are in order to all lunar sample researchers for not calling this Rocky's Gem and Metal Shop (slide 8.10). If one divides the total amount of lunar samples that have been brought back by the total expenditure, the lunar samples cost about a half a million dollars a gram. However, with asteroid retrieval the opportunity exists to sell pieces of the primordial solar nebula (condensed) to the man in the street for $4.95 a kilogram. If one can return 2 to 5 million tons of asteroid, it could be chopped up and the first mission paid for by selling half of the asteroid as souvenirs of man's first "New Moon".


Stony's
GEM and
MINERAL SHOP
LIMITED SELECTION
LUNAR SAMPLES
$500,000/Gram
SPECIAL
JUST DOWN
PRIMORDIAL
SOLAR
CONDENSATE
$3.95/Kg!
PARKING IN REAR
SALE

Slide 8.9

PANEL AND AUDIENCE DISCUSSION SESSION

B. O'Leary - I would like to make a couple of remarks, essentially in the form of responses to what some of the speakers said. It's important, at least in terms of using solar powered mass drivers, to concentrate on the best possible delta v opportunities for the Apollo and Amor asteroids, rather than the main belt asteroids. The reason is that the Apollo and Amor asteroids are in an area of higher solar flux. Solar fluxes are on the order of 5 times greater near one astronomical unit than out in the asteroid belt. When you combine that factor with the delta v's for the most favorable possible opportunities, then one is dealing with factors on the order of 20 to 30 to 40 difference (less) in the total amount of mass that would have to go into the mass driver power plant to retrieve an Apollo or Amor asteroid under the most favorable opportunities versus the main belt asteroid. That is the reason why I'm concentrating on the Apollos and Amors".

Q: "A number of speakers emphasized how we have to get more geochemical information about these asteroids before we can go out and retrieve asteroids. Yet, I gather from what Brian says and from my understanding of O'Neill's work, that what they mostly want to do with this material is make something that looks like adobe bricks out of it or some kind of construction material. Is that the idea? Can you give us some more specific information about how to utilize materials? What do you want to know about the chemistry?"

B. I'Leary - "I think the major implication that O'Neill and I have been developing in the terms of the lunar scenario, and I think it also applies to the asteroidal scenario is the economic return from building satellite solar power stations. One would have to build a chemical processing plant in a stable high orbit, which would process the lunar and/or asteroidal material into silicon for the solar collectors, and the metals into metal framework for the power station. I think that is really the basic thing that we're after at this point."

Q: "Is the greatest percent of the mass used just in making the blocks, the cinder blocks or something like that, or is most of the mass going into really highly refined silicon and metal and so forth?"

B. O'Leary - "What fraction ends up as shiny metals and refined silicon is just one of the many preliminary studies that were done recently. A lot more study is still needed. I think Dave Criswell could maybe address that."

D. Criswell - "Actually, in the 1976 Ames Summer Study the major projected use of the mass initially is in radiation shielding for the long term habitations; it dominates by at least a factor of ten."

Q. "You're saying that it does not make any difference what most of the mass is chemically. True?"

D. Criswell - "That's right. The major use of the mass in most of these models is simply for cosmic ray shielding and the chemical composition does not matter to first order."

Q: "So, maybe you don't care what the composition of the asteroid is."

D. Criswell - "That is a major point I am trying to make. The other is that substitution of materials allows great latitude in final construction of power stations and other items. This attitude becomes less defensible as the cost of launching material from earth decreases. Costs of acquiring material in space and processing it for the production of industrial feedstock must be continually compared to the costs of acquiring similar feedstock or semi-finished goods from the earth. Clearly, economics of scale are significant. At this point in time, the launch costs utilizing the shuttle and the shuttle derivatives of 100-250$/Kg should make the space acquisition of bulk materials very attractive."

J. Arnold - "Well, if I may point out, however, you need water, you need oxygen, you need iron and aluminum, the availability of these materials and the cost of processing, which is an open thing is very important even if it's only 10%. I can't imagine the very, very large end cost involved. No sane or prudent manager would commit say 4 billion dollars to a project that was a small first step toward asteroid retrieval, but then refuse to commit tens of millions of dollars to finding out what the compositions were."

Q: "At the Tucson Minor Planet Conference in March of 1971 and also at the NEIAA lecture at UCLA in April of 1972, Professor Herrick suggested the exploration and exploitation of a minor planet, which in your tables I found conspicuous by it's absence. The asteroid is 1620 Geographus. I realize the Geographus has an inclination which may have kept you from considering it. But, there are some interesting facts about it which I think I'd like to point out. In March 1983 Geographus is going to make a close approach to the earth, of .09

astronomical units. Again in August 1994 it's going to come within .03 astronomical units. Now, the thing that makes this interesting is that it's close approach to the earth takes place at the longitude of the ascending nodes or very close to it. That brings it down as a possible minor planet to be considering here. It just so happens that in 1973 I studied this particular minor planet. The delta v required to move Geographus out of it's orbit at aphelian to intersect the earth was .5 kilometers per second. I don't know how that compares with Eros or 1943. I wasn't doing a comparative study. I wonder if rather than the favorable press that Eros and all the other minor planets have had if you could throw this into one of your computer programs."

J. Niehoff - "I think I can answer your question. One simple way of looking at the problem is just to see what the encounter velocity would be at the node and it turns out that Geographus is the next most favorable object after the ones that we have discussed among the Amors and the Apollo classes. So, it's in there very close and you're certainly right. Now, of course, just to have a close crossing at the node doesn't mean it's easy to get rendezvous with. It's good for a flyby -- very good for that, but rendezvous is a different game."

Mike Gaffey - "The MIT study group, which I have been working with for about two and a half years now, would basically like to second what Jim Arnold said. We should keep as many options open for as long as possible. Tonight we have considered the mass driver as a mass mover in the solar system. I'd like to point out that there is another possible transport system, which is a low mass solar sail. Eric Drexler (Grad. Student - MIT) has calculations indicating these systems may be capable of moving approximately 10^6 metric tons over a 10 kilometer per second delta v in a year. The type of sail he is talking about is relatively insensitive to wear and problems of damage, such as micrometeorites and it also has the advantage that if something goes wrong with one sail, you can rapidly deploy a second sail. You can get it from one point to another very rapidly. I was talking about a 200 to 400 angstrom metal film laying over a grid as the carrying stress elements. I say, we would like to keep the options open and just to prove that we're not prejudiced against mass drivers, I'd like to point out that Eric Drexler was one of the students who helped construct the MIT mass driver. Jonas Garbus, is also working on both projects. What is required is a sail 60 kilometers in diameter which is spinning at one tenth of a g, and using a radial cable structure as the main structure pattern with a circular cable structure for the tangential elements. The sail would be completely in stress. There would be no compressional elements in the system."

J. Arnold - "That gives me a chance to make a comment on comparing costs. Costs are naturally now dominated by the mass driver costs, because mass drivers are big things. The driver costs for the devices that are now being built are this year's designs. Again, I think if we keep options open, whether it's Mike Gaffey's scheme or another one, just judging by the whole history of the space program from sputnik to shuttle, those costs are likely to go down and I would think that other costs would then come to dominate. I think we can probably drive the costs of bringing things to earth down a great deal. I am not for a moment suggesting that we can drive them down far enough. I think it might well turn out that the costs of either bringing the asteroids back or bringing material off the moon might drop with development to the point where the choice will be made on other grounds."

J. Oberg - "I'd like to remind the people here that there is a study group (L-5 Society) which produces a monthly publication that tries to devote itself to promoting some of these far out ideas. The monthly newsletter is published by the L-5 Society in Tucson, Arizona. There is a local L-5 Houston chapter which plans to talk about all of these ideas at meetings about once every month or two."

B. O'Leary - "I was going to follow up on Jim Arnold's remark. Even if the total cost of doing something doesn't change fast enough to change the way the program goes, the set point of choice between two different ways of doing things has certainly shifted a couple of times in our past. The dimensions of solar sails reminded me that perhaps these inclination problems with the asteroids will not be as serious with solar sails as they are with reaction propulsion schemes of any kind."

H. P. Davis - "Well, I listened to a JPL briefing this afternoon on the Haley Comet rendezvous mission using the solar sail. If memory serves, they were talking about an inclination change of about 162° at three-tenths AU over a period of a year. The trick there is that you go in toward the sun and do your inclination changes there and come back out, going the other way and rendezvous with the comet. The point I was getting at was not primarily that the technique will necessarily be applicable to the asteroids. I think it is in principle.

Rather, I was trying to second Jim Arnold's point. Both from a scientific standpoint of learning what there is to be had and from the engineering standpoint that knowledge which doesn't exist today will exist before these big decisions have to be made as to whether you go this way, that way, or the other way in mechanizing each of these mammoth endeavors. Gathering that engineering knowledge by a series of logical steps is something we ought to devote ourselves to. We are able to do some of that through the solar sail program at JPL and the other things that are going on."

B. O'Leary - "I agree with Jim completely. The scenario that unfolded tonight was based on just one study and you can consider it a straw man."

Comment - "A study of this kind stimulates the thinking that will bring alternative concepts into being because if somebody doesn't push this thing in one direction or another, we'll never find out what is the right way to go."

A: "I think some people are still concerned with the problem of the pellets adding a significant fraction to the meteorite population of the earth solar system area and one possibility would be to use extra energy to grind the material into powdered or colloidal sized particles which would then be either harmless or removed by the solar wind. How possible would this be in terms of the energy involved?"

J. Arnold - "I am having some trouble in understanding your question. We have an atmosphere as far as the protection of ourselves is concerned. There are pellets coming in probably every second into the earth's atmosphere right now which are meteors, what's the problem?"

Q: "There will be future traffic, interplanetary traffic,between the inner planets and if you are adding millions of particles of many kilograms each to this area, eventually you are going to have collisions between the particles and the traffic."

A: "I don't know. Maybe George Wetherill would like to comment. There are a hundred thousand objects crossing the orbit of the earth, we were told earlier in the evening, which are a hundred meters across. If you break one of them up into pellets, b-b shot, or whatever, you will, of course, make an enormous number of them. But you saw in the slide the very rapid increase in the naturally occurring number with decreasing size. I can't offhand estimate the number of pellet sized objects in the region of the earth, but as the phrase goes, it must be astronomical. Do you have a number?"

B. O'Leary - "I did a rough calculation and apparently for the first retrieval and that's the one that I really want to think about, the number of pellets is still in the noise of natural objects in that size range, in heliocentric orbits. There's a problem when you get near the earth or when you go from the earth, as Hugh Davis pointed out. That is the class of orbits that are geocentric and that would be a real navigational hazard. There are some ways around the problem besides doing thrust vectoring strategies of various sorts. Dave Criswell mentioned earlier tonight that one could put a small oxygen processing plant on the mass driver. I think this would be after the first asteroid retrieval. Then one would use liquid oxygen as a reaction mass. That approach eliminates the hazard problem."

Q: "Would it be possible to use an electrostatic system which would impart an electrical charge to dust particles and then in a manner directly analogous to ion rockets accelerate the dust particles as reaction mass?"

H. Kolm - "The answer to that is electrostatic forces are a couple of orders magnitude smaller than the magnetic forces you can generate having superconductors. That's been worked out. I'd like to make the remark that there is too much prejudgment of missions on the basis of demonstrable cost effectiveness. Now, if you go back into the history of human progress, there aren't many things that would have been undertaken if they had to have passed the test of demonstrable cost effectiveness. This sounds like an accounting department basically. You wouldn't have built all the cathedrals of medieval Europe on that basis. You wouldn't have put a man on the moon on that basis. You wouldn't have developed half the technology which we now find essential. Nobody in his right mind, for instance, would have supported airplanes for commercial purposes even in the twenties when Lindberg did his thing because it was obvious that airships were the future thing and similarly with mass drivers and all the rest of it. To me, the mass driver is an inevitable development for the same reason that the wheel was. Also, when used in space travel, it gives us the same kind of autonomy that the mule gave the prospector. You know, the electromagnetic mass driver is a mule in the sense that it can survive on nothing but what it finds along the way - namely solar energy and occasional mass. It is inevitable that the liquid propelled rocket will not satisfy that criteria and that is a more valid criteria than cost effectiveness."

T. McCord - "Well, I think this issue of cost effectiveness is a very well put point, particularly when we are talking about missions that are in the future on the scale of the ones we are talking about tonight. It's reminiscent, I think, of what Aviation Week had recently of the Catch-22 of the space program. Everything that is proposed to be done is subjected to a very stern test of its cost effectiveness. Unless it has demonstrable cost effectiveness, it is not supported. In the event that you are able to demonstrate with absolutely no residual doubts that it is cost effective, then it's clearly a job for industry to do on a private capital basis. I think that is a good point to make."

D. Criswell - "I want to thank the speakers and the audience for participating in a very interesting special session. Good evening."