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AFFORDABLE IN-SPACE TRANSPORTATION PHASE II

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AN ADVANCED CONCEPTS PROJECT

October 16–17, 1996
Technical Interchange Meeting

EXECUTIVE SUMMARY

Office of Space Access and Technology, NASA Headquarters
Advanced Concepts Office, NASA Marshall Space Flight Center
National Aeronautics and Space Administration

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University of Alabama in Huntsville

5-25620

SECTION 1

1.0 Introduction

The Affordable In-Space Transportation (AIST) program was established by the NASA Office of Space Access to improve transportation and lower the costs from Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) and beyond (to Lunar orbit, Mars orbit, inner solar system missions, and return to LEO). A goal was established to identify and develop radically innovative concepts for new upper stages for Reusable Launch Vehicles (RLV) and Highly Reusable Space Transportation (HRST) systems. New architectures and technologies are being identified which have the potential to meet a cost goal of $1,000 to $2,000 per pound for transportation to GEO and beyond for overall mission cost (including the cost to LEO).

A Technical Interchange Meeting (TIM) was held on October 16 and 17, 1996 in Huntsville, Alabama to review previous studies, present advanced concepts and review technologies that could be used to meet the stated goals. The TIM was managed by NASA-Marshall Space Flight Center (MSFC) Advanced Concepts Office with Mr. Alan Adams providing TIM coordination. Mr. John C. Mankins of NASA Headquarters provided overall sponsorship. The University of Alabama in Huntsville (UAH) Propulsion Research Center hosted the TIM at the UAH Research Center. Dr. Clark Hawk, Center Director, was the principal investigator. Technical support was provided by Christensen Associates. Approximately 70 attendees were present at the meeting.

This Executive Summary provides a record of the key discussions and results of the TIM in a summary format. It incorporates the response to the following basic issues of the TIM, which addressed the following questions:

1. What are the cost drivers and how can they be reduced?

2. What are the operational issues and their impact on cost?

3. What is the current technology readiness level (TRL) and what will it take to reach TRL 6?

4. What are the key enabling technologies and sequence for their accomplishment?

5. What is the proposed implementation time frame?

See Appendix A for the TIM Agenda and Appendix C for the AIST Program Terms of Reference.

SECTION 2

2.0 Vehicle Systems Overview

Lead:
John C. Mankins

Rapporteur:
David L. Christensen

Speakers:

Garry Lyles	Advanced Space Transportation Program (ASTP)
John Mankins	HRST Overview
Leslie Curtis	AIST Phase I Study Results
Melissa Van Dyke	AIST Phase I Study Results
John Cole	NRA Schedule and Funding
Gordon Woodcock	Cost/Operations/Manufacturing

Participants:

Alan Adams
David K. Bonnar
Ben Donahue
Bill Escher
Dave Gerhardt
Joe Hastings
Roger Heatherly
Joe Howell
Homer Pressley
Cecil Stokes
Glenn Zeiders

2.1 Session Overview

What is specifically meant by a cost goal of $1,000 - $2,000 per pound of payload for the design reference mission including missions to GEO and beyond? The projection is that there will be an AIST price composed of two principal constituents, the first being recurring cost which is technically driven and the second being other costs which are financially driven. The recurring technically driven cost is the number with the minimal technological solutions and improvements including, for example, operations, consumables, the actual cost of the operational hardware; i.e. the fleet, cost of spares, etc. It does not include the cost of capital, profit, and those things associated with the capitalization approach, the degree of government involvement, and financing. Clearly these are interrelated, but there is a need to distinguish between the two.

Affordable In-Space Transportation
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EXECUTIVE SUMMARY

TABLE OF CONTENTS

		Page
Section 1	1.0 Introduction	1
Section 2	2.0 Vehicle Systems Overview	2
Section 3	3.0 Panel Discussions	12
	3.1 Solar	12
	3.2 Magnetohydrodynamics	15
	3.3 Breakthrough Physics	19
	3.4 Nuclear Propulsion	24
	3.5 Tethers	35
	3.6 Beamed Energy Transportation	42

Tables, Figures and Appendices

Table 1	AIST Design Reference Missions	3
Table 2	AIST Design Reference Missions-General Types	4
Table 3	Solar Summary-Design Reference Missions	12
Table 4	Mission Applicability-Nuclear Propulsion	25
Table 5	Known Tether Flights	35
Figure 1	Accelerator Configurations Under Consideration	16
Figure 2	Thermal Storage Concepts	17
Figure 3	Mission Versatility	27
Figure 4	LANTR Engine Concept Capability	28
Figure 5	Reusable Mars Transportation System	29
Figure 6	Nuclear Electric Propulsion (NEP) Vehicle	30
Figure 7	"Open Cycle" Gas Core Rocket	32
Figure 8	"Gasdynamic" Mirror Fusion Rocket	34
Figure 9	Electrodynamic Tether Thruster Performance	37
Figure 10	Electrodynamic Tethers Orbital Inclination	37
Figure 11	SSTO Performance	38
Figure 12	LEO Tether Transfer System Dimensions	39

Table of Contents (continued)

		Page
Appendices		47
Appendix A	AIST TIM Agenda	A-1
Appendix B	Vehicle Systems Overview Charts	B-1
	AIST Cost Definition	B-1
	AIST Vehicle Systems	B-1
	"What Must Be...?"	B-2
	"What Must Be...?" General Issues	B-2
	AIST System "Must Be's"	B-3
	AIST Strategic Design Issues	B-5
	AIST System Strategic Design Ideas	B-6
	National AIST Strategies	B-6
Appendix C	AIST Terms of Reference	C-1
Appendix D	AIST Participants	D-1

There should be a brief, concise statement based on the principal of what should be included and where, in order to get a good consistency in analyzing the technical approaches.

The scope of AIST has been broadened to try to encompass a much larger range of NASA's own programmatic objectives in AIST as well as service to the potential commercial market place, the LEO to GEO market. *That was the subject of AIST Phase I; but it did not capture many of NASA's own programmatic objectives for affordable in-space transportation.*

2.2 Design Reference Missions

A series of design reference missions have been identified for AIST Phase II, ranging from a telecommunication transport of relatively small and medium sized payloads to MEO and GEO (on the order of 30 flights per year) ranging through the Mars mission (both Mars transfer vehicles and Mars excursion vehicles). See Tables 1 and 2.

	Payload Type			*Payload "Specification"*		
DRM	S/C	Cargo	Crew	Mass	Destination	Mission Notes
1	Yes	Yes		3–10 MT	MEO/GEO	Telecomm (30+/yrs)
2		Yes	Yes	> 20 MT	MEO/GEO	SSP (300+/yrs)
3	Yes			3–10 MT	NEA/MBA	Aster. Rendez. (1/2 yrs)
4		Yes	Yes	10–20 MT	LLO	LTV (< 3–5/yrs)
5		Yes	Yes	10–20 MT	L. Surf.	LEV (~1 ×/LTV)
6	Yes	Yes	Yes	10–50 MT	MO	MTV (1 Mission/2 yrs) TBD Flts/HB.)
7		Yes	Yes	10–50 MT	M. Surf.	MEV (1–10 ×/MTV)

Table 1 AIST Design Reference Mission

- *STV Class*
  - LEO ⇄ MEO — Commercial, DOD, Earth Obs.
  - LEO ⇄ GEO — Many flights/year
  - LEO ⇄ LLO — NASA
  - LEO → DS — Few flights/year
- *MTV Class*
  - LEO ⇄ MO — ~ 1 "Mission"/2 years; TBD flights @ NASA
- *LEV/MEV Class*
  - Orbit ⇄ Surface — NASA; Variable flights/mission

Table 2 AIST Design Reference Missions-General Types

In summary, there are three basic classes of transportation problems in these seven design reference missions. There are those problems that are essentially space transfer vehicle type problems, either LEO to MEO, LEO to GEO (largely dominated by commercial, DOD and Earth observing type payloads), LEO to low Lunar orbit, and LEO to deep space (essentially NASA type payloads).

Also, there are the stand-alone transfer vehicle problems such as the Mars transfer vehicle, which presents major problems.

Lastly, there are the landers, the Lunar and Mars excursion vehicle problems.

2.3 Types of Vehicles

Chemical

Looking at chemical propulsion, one has to consider pulse detonation wave approaches with the basic issue being the energy coming from chemical bonds as opposed to nuclear forces or to external forces, either solar or momentum or beamed energy.

In trying to get a sense of consequences of taking a particular technology to its limit, we considered a reusable cryogenic stage (LOX-Hydrogen propellant combination). What if it had zero probability of catastrophic mission failure and had an essential infinite life; i.e. the same vehicle could be used, with regular maintenance, over the entire 20 year time frame. For LOX-Hydrogen bell nozzle type stages, the cost was reduced by 22%, if the system was perfect in terms of its hardware. Even so, chemical transportation vehicle costs to GEO for a 3,000 pound payload is on the order of $3,300 per pound. This illustrates the nature of the problem in that the chemical powered stages are not economically feasible.

Another interesting feature of the LOX-Hydrogen space transportation system was that the LEO costs were 55%, two-thirds (37%) was for transporting the propellant to LEO.

Chemical (HEDM)

Regarding chemical powered launch vehicles, it has to be understood that the ETO system can not be put to any significant risk. This is true of HEDM, a high energy chemical bond type system. On most of the concepts, there is no real threat to the ETO system. The system may fail in operation but it is not going to do anything to the RLV or HRST while it is getting to LEO. This is simply not true with some HEDMs.

Neither personnel nor payloads can be put at risk and that includes the effluents from the HEDM based systems. Highly chemically reactive species can not be introduced into orbits where they might interfere with or damage sensors. In most cases, the cost of propellant is essentially trivial. This may not be true with HEDMs. The cost of propellant in the HEDM based system may be significant, therefore, it must be made acceptable.

Chemical Pulse Detonation Wave (PDW)

Pulse detonation wave must achieve long life and high reliability if it is a reusable type system or it has to have a very low manufacturing cost. In addition to achieving whatever performance goals the PDW engine approach might achieve, it must satisfy all the same constraints that apply to other chemical systems--either exceptionally reliable and long life reusable systems, or exceptionally low manufacturing cost for expendable systems.

Tethers

Tethers included both momentum exchange and electrodynamic rotating systems; i.e. rotovator type systems, and in-space catapults.

The momentum transfer tethers need to have a very long life. For all cases of momentum transfer, the reboost associated with the in-space infrastructures has to be consistent with the time constraints requirements for AIST; i.e. two to four weeks of service times. If, for example, one is using electric propulsion for reboost, there has to be sufficient power to reboost in a time which is meaningful to serve the traffic model.

For the electrodynamics case, that being an electric propulsion scenario, it needs megawatts of power in order to get the utilization or capacity to be competitive with nuclear electric, nuclear thermal or solar thermal. It also has to be very low cost due to orbital operations issues. There are limitations on the electrodynamic tether approach, therefore, it conceivably can only serve a relatively small fraction of the design reference mission set. It has to be used, therefore, in conjunction with other systems with added costs, or it can only be used for a small fraction of the total design reference mission set. Either way, for those concepts to win, they must have a very low cost.

Solar

In identifying sub elements, we looked at solar energy as the force for the transfer vehicle system where there was solar thermal, solar electric, solar cells, and solar wind.

Solar Thermal

For solar thermal, if the system is going to be reusable, there has to be fast round trip times. The system must have high thermal energies on the order of megawatts thermal and therefore, has to have very large concentrators in order to get the short round trip times required. This leads to very high temperature materials and in doing everything necessary in order to obtain acceptable thrust to weight ratios.

Solar Electric

The same basic issue applies to solar electric in that there must be megawatts of electrical energy in order to accomplish the Design Reference Mission with the round trip times required. This requires very large on-board power and perhaps very large solar arrays. There must be efficient thermal management strategies at the system level so that the total vehicle mass and hardware costs are not excessive.

Solar cells have very limited design reference mission applicability and therefore any solution involving solar cells would have to be exceptionally low cost because only one or two would be flown over the entire period. There would be none of the advantages of the larger traffic models associated with the LEO to MEO and LEO to GEO missions.

Solar Wind

The solar wind concept is still to be determined because we could not figure a way to make it work; i.e. basic feasibility must be determined.

Magnetohydrodynamics (MHD)

MHD was based upon the source of the plasma which is accelerated using the MHD device, and MHD with the plasma coming from chemical, electric, or thermal sources including solar thermal.

Nuclear

Nuclear concepts include nuclear thermal, nuclear electric, gas core as a special version of nuclear thermal, fusion, and antimatter based approaches.

Nuclear is very similar to solar thermal, but in general, there are two additional constraints. The system has to satisfy nuclear safety, disposal and basing issues associated with the transfer vehicle and it has to satisfy any related constraints or operational cost constraints associated with meeting those objectives of nuclear safety, disposal and basing.

Nuclear Thermal

Based on cost factors, it appears that the nuclear thermal systems need to be very long-lived and of very high reliability. You can not afford to have them failing due to high cost and because of safety consequences if there should be a nuclear failure in Earth orbit.

Nuclear Electric

The same two issues that are associated with solar electric are true for nuclear electric. Namely, there has to be a high power level and high thermal management efficiency to get the round trip times and utilization of capacity.

Nuclear Gas Core

Gas Core has to satisfy nuclear safety. Technical risks, development and technologies, per se, have not been addressed. Instead, we have tried to stay at a very high systems level and identify barrier thresholds.

Nuclear Fusion

It is not known how to make fusion economical for the design reference missions. If the threshold barrier, whatever it may be, could be surmounted, then it would become feasible, with the possible exception of Mars transfer vehicle options and for the longer term where there was, in fact, not the design reference mission 6 or 7, but some high end Mars transportation scenario.

Antimatter

We did not know what to do with antimatter against our design reference missions.

Beamed Power

In considering beamed power, laser electric, laser ablation, laser thermal, laser fusion, and RF-electric were all identified.

There are international issues associated with basing that are unique to terrestrial based electromagnetic beamed power. There are those issues that are special to this case that must be resolved. With laser electric, there has to be high levels of on-board power for the same reasons as the other low to intermediate thrust scenarios have to have high power. There has to be very high reliability at an affordable price in the laser system for reasons of opportunity, cost, etc.

The same kind of issues apply to laser fusion. One very special issue involving laser fusion is the fact that it has to satisfy issues associated with air traffic control and transmission of the high energy beam through the Earth's atmosphere and through near Earth space associated with various substances like iridium, etc.

Breakthrough Physics

Breakthrough physics, including inertia cancellation, gravity manipulation or cancellation, worm holes, and natural space warps of some sort were all seen as different versions of magic to be exploited.

Aero Assist (Braking)

Aero Assist (braking) is a means of changing the momentum, velocity and direction of vehicles and therefore should not be neglected.

Gravity Assist

Gravity Assist is another technique which can not be neglected, especially for the deep space missions whether robotic or manned Mars transfer vehicles.

Catapults

There is the possibility for surface catapults such as the Lunar based mass driver as a fundamental approach to the space transportation problem.

2.4 Summary

Having identified all the different types of vehicle systems, we prepared a chart which plots technical maturity versus the level of infrastructure investment associated with each concept. AIST's strategic goals are $1,000 - $2,000 per pound for taking payloads out through the main asteroid belts. This is an extremely aggressive affordability objective. In order to achieve this goal, there must be a high payload ratio for all materials transported to LEO. If, out of every ten pounds, four pounds are payload and six pounds non-payload, either propellant or vehicle, at the HRST type launch costs of $200 per pound, the cost contribution due to Earth orbit transportation is $500 per pound of payload regardless of the destination beyond LEO.

This is a fundamental starting point, and to be affordable, one can not take a hit larger than $500 per pound for the transportation from Earth to LEO. Also, the number of people involved has to be a consideration. There can be no more than 200 people (both hands-on and non hands-on) per 100,000 pounds of payload per year, regardless of where that 100,000 pounds of payload is going. This is based upon 2000 man-hours per year at an average cost of $60 per hour. The idea is to try to keep the cost contribution due to all the people involved below $250 per pound of payload.

The total then, before going anywhere, is already $750 per pound of payload. Lastly, the cost contribution to the total cost per pound of payload due to vehicle hardware has to be kept in check by setting a goal of $250 per pound of payload transportation cost due to vehicle hardware associated with that mission.

These three primary hurdles total $1,000 per pound of payload. Whatever technology (technology development requires resources--people, dollars, and time) the system exploits, if it can not accomplish these goals, it does not have a reasonable shot at accomplishing the AIST objective.

Looking at the macro-economics, there is a question of the utilization of capacity, the market opportunity, and the costs of failing to serve the market efficiently. Of particular interest are the two high traffic cases in the design reference mission, namely LEO to MEO and LEO to GEO services for constellations that are commercial or defense oriented, and the emerging market opportunity if the costs are low enough for solar powered satellites. This is for a very high traffic model and very high through-put. If the transportation system is slow (long trip time to reach MEO or GEO), then a very large fleet size will be required. A great deal of hardware will have to be expended for reusable systems in order to meet the market needs.

Therefore, for the LEO to GEO case or LEO to MEO case, the trip time can not be greater than two to four weeks round trip. This is consistent with a fleet size of two transfer vehicles serving a 30 mission per year scenario going to MEO or GEO. This imposes severe constraints on the viability of some of the low thrust advanced propulsion options.

In order for a concept to accomplish the AIST design goals, it has to be packaged to fit inside of some existing Earth to orbit transportation system, both in terms of its initial launch and subsequent operations. It can not contribute significantly to Earth orbiting debris and it must accommodate a wide range of the design reference missions. That is translatable into a significant range of delta velocities as well as payload masses. Also, where there is a strategy that entails a reusable system, that system must be able to account for the cost of failure. For example, what if there is a fleet of two vehicles that are reusable and only one is lost? Do you shut down for two, three, or four years and therefore lose the entire commercial market or cause a massive collapse in the US competitiveness? The system must not be inherently fragile with regards to the cost of a system failure during the operational scenario.

2.5 Conclusions

Very advanced conventional systems must have an extremely low cost. The cost contribution to the hardware must be extremely low, either through exceptionally low cost manufacturing of an expendable system or very long life and low maintenance, high reliability, reusable systems. Even then, as we saw in the case of the LOX-Hydrogen system with potentially infinite vehicle life, with essentially zero probability of vehicle failure, the cost was only down to $3,300 per pound of payload, a reduction of only 22%. Also, the ETO cost contribution must be driven down in order for the chemical system to be economically feasible.

There needs to be a better understanding of the strategic trades or different technologies in vehicle concepts between expendability, focusing on low cost manufacturing and reusability, focusing on very low cost contributions due to the system even if it was only manufactured once. We must characterize and understand the trade between using kick motors or not using kick motors, in particular as a function of the space transfer vehicle propulsion technology.

There is a turnover in the increasing capability of the propulsion system of the main transfer vehicle at which point it does not pay to use the Apogee Kick Motor (AKM). In the case of the reusable cryogenic stage, it turned out that the cost of the AKM and the cost of the propellant for the AKM, along with transporting it and its propellant to Earth orbit ended up making a contribution between 15% and 20% to the total cost, once the cost of the transfer stage hardware was eliminated and infinite life of the system was achieved. So, as you drive down to lower cost, using a kick motor becomes a significant cost contributor.

This issue has to be treated not just against Isp but also in terms of the consequences of number of engine starts, the life of the system, the probability of failure at start, etc. There are several system issues to take into account in thinking through that trade of using or not using a kick motor.

See Appendix B for additional charts.

SECTION 3

3.0 Panel Discussions

3.1 Solar

Lead:
Ed Cady

Rapporteur:
Leslie Curtis

Participants:

Joe Bonometti	Leonard Pearlman
John Brophy	L. Denise Stark
Bill Dean	Hal Strumpf
Dave Goracke	Melissa Van Dyke
Brian Landrum	Daniel J. Vonderwell

We went through the design reference missions, looked at solar thermal, solar electric and solar sails and wind to see which of these could reasonably satisfy these missions. (Table 3)

DRM	Solar Thermal	Solar Electric	Solar Sails & Wind
LEO-GEO	Yes	No (Time)	No
LEO-GEO	Yes	Yes	No
NEA	Yes	Yes	No (?)
LTV	Yes	Yes	No (?)
LEV	No	No	No
MTV	Yes (?)	Yes	Yes (Time)
MEV	No	No	No
TRL (1996)	3-4	4-5	2
TRL (2005)	E-6/R-5/6	E-6/R-5/6	3 (Size)
Infrastructure	E-VL/R-M	E-VL/R-M	Very High

Table 3 Solar Summary - Design Reference Missions (DRM)

None of the excursion vehicles could be met because the thrust levels are too low and we are not sure, due to the size, whether we can scale up to something like this with solar thermal. The technology readiness levels, generally, today are: 3-4 for solar thermal and 6 for expendable by 2005. Reusable takes significant effort as does solar electric. Due to the size of the solar cells, we are not sure we can even get to level 3. We have a concept in mind but that will be about the level.

The infrastructure ratings are based on the following code: low, very low, moderate, high, very high. There is a moderate infrastructure requirement for reusable systems due to the need for refueling in orbit. Otherwise, infrastructure is very low for expendables. Infrastructure is high for solar cells if they have to be fabricated (kilometer size) on orbit.

Infrastructure investments are: low maturity-high investment for solar sail and wind and moderate for reusables. Both solar electric and solar thermal are in the range of 3-5 TRLs.

Reusable solar thermal upper stages that have a payload a little less than 3 metric tons were looked at. This is the small end of the scale and is a stage we had designed already. Basically, the payload fraction here is about 0.3 which is not particularly good. The reason is that you have to put 30% more propellant into the stage for the return trip. That comes directly at the expense of payload to orbit. If you multiply the payload number by $2,000 per pound, you get $10 million. You take off the propellant supply cost, assuming that you have to truck up 15,000 lbs of tank, propellant, etc. to your RLV. At $200 per pound, the launch cost for the 18,000 lbs would equal $3,600 per pound. So, you are left with about $4 million for vehicle cost. If you have five flights, that is $20 million, about $6,600 per pound which is not unreasonable.

It might be possible to build a reusable solar thermal stage for a five mission reuse for $20 million. It looks as if you can get there with modest reusability. We chose five missions because at a month out and a month back, that is a year's worth of exposure. With inflatable reflectors and having to operate these engines at 1000 or so hours of operation, we felt that was a good goal.

Solar electric propulsion for two sizes of payloads resulted in electrical requirements up to 70 kilowatts with huge photovoltaic arrays for these classes of payloads. We can do it, but, when you get this much array power, you have to have cheap photovoltaics or just that cost is going to swamp you. Tall poles include the engine life and the number of cycles on it. I am not sure that anything close has yet been demonstrated. But, this would be relatively easy to do with a development program. The collectors have to go back and forth through the Van Allen Belt and micro-meteoroids, etc. for a year. A photovoltaic array will be required just for housekeeping power and that has to be protected.

For solar electric, you have to get down to $100/watt probably with radiation-hardened arrays in order to come anywhere near reaching the cost goals, even with reusables. That is an order of magnitude less than the costs are now. (They run $1,000-$2,000/watt now.)

One of the burdens on solar electric is that the array costs are probably the dominant cost of the vehicle and these are the things that have to be controlled. If the solar cells are large, they have to be fabricated in space since we do not know how to deploy something a kilometer or more across. We do not know what to do about solar cells yet.

Solar thermal and solar electric stages meet all missions except the excursion vehicles. Solar cells probably cannot meet these missions. The reusable five-flight vehicle may be achievable at $20 million and would give you $2,000 per payload pound. If you look at $1,000, you cannot make it due to the cost of resupply and getting the propellant up. The vehicle cost is too much. Expendable Solar Cell Orbital Transfer Vehicles require 100 watt solar arrays with six month trip times to meet the cost. You probably cannot meet a one month trip time even at $10/watt at this cost.

We felt that it would take about $100 million in propellant handling equipment to go on the RLV in order to resupply this vehicle or any other vehicle that needs resupplying. All of the reusable vehicle components have to have a dedicated program. We have to shift our emphasis from expendable vehicles to reusable vehicles. That will require more work and more testing.

3.2 Magnetohydrodynamics (MHD)

Lead:
Jim Chapman

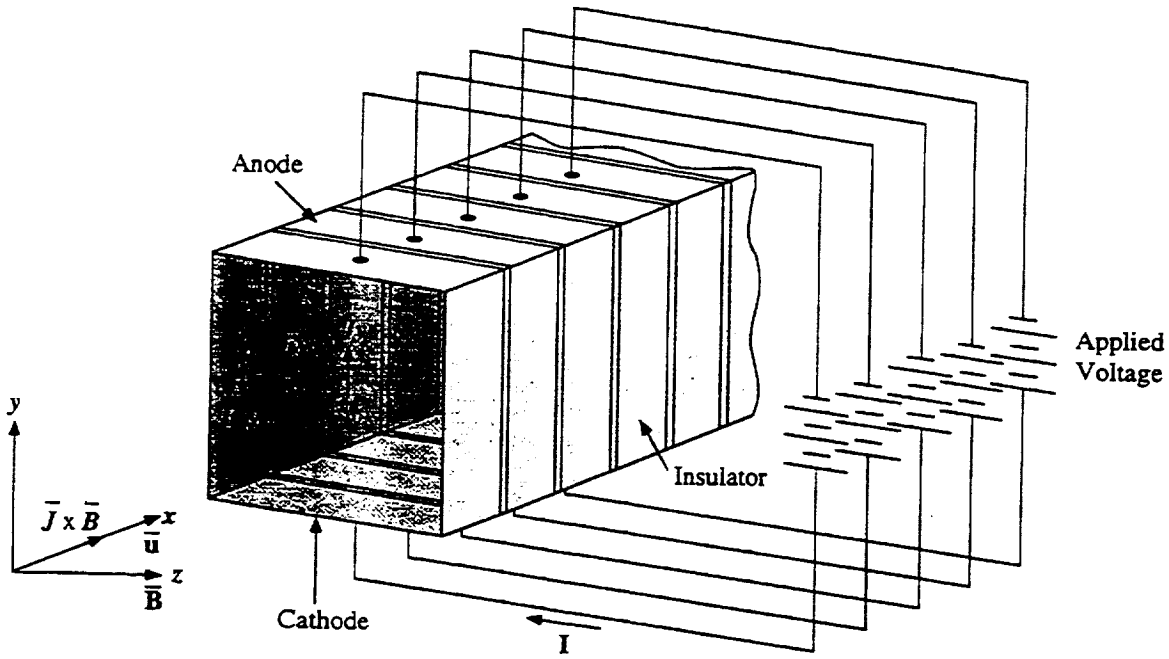
Rapporteur:
Tony Robertson

Participants:

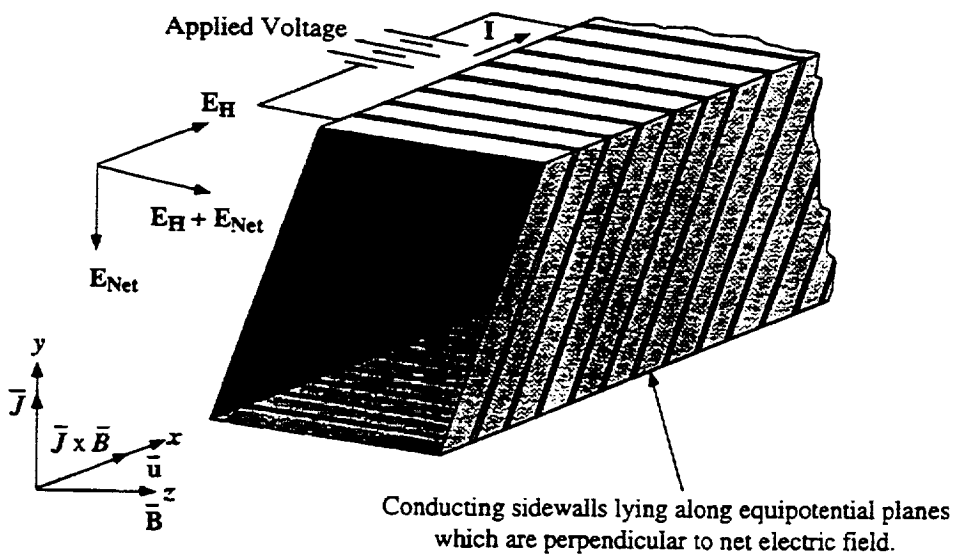
John Cole
Jonathan Jones
Ying-Ming Lee
Jack Lehner
Abel Lin
Ron J. Litchford
Dave Micheletti
Roy J. Schulz
John Stekly

The types of accelerators that might be considered are the segmented Faraday, which is most common experimentally and for which a separate power source is necessary for each pair of electrodes and the diagonal connection which can use a single power supply. (See Figure 1) The wall angles are reasonable for low pressure operation. The MHD accelerator replaces the gasdynamic nozzle in the propulsion system. All the gas expansion to the ambient pressure at altitude is taken in the MHD accelerator, and weight is saved by combining these functions. This presents problems with a diagonal connection, however, as the optimum current differs along the duct length due to the area divergence.

We looked briefly at rail guns. The rail gun could be used either from the LEO vehicle to propel payload into GEO as the projectile or the rail gun could be used on the payload to provide sufficient thrust to get it to GEO. It is doubtful if either one of these is worthy of very much consideration.



Segmented Faraday Electrode Accelerator



Diagonal Conducting Sidewall MHD Accelerator

Figure 1 Accelerator Configurations Under Consideration

In electric propulsion applications, there probably needs to be energy storage, particularly if you use solar or beamed power. We considered briefly how that might be done. One idea is to use the coil on a superconducting magnet to both store the energy and provide the magnetic field for MHD propulsion. Other possible storage means are batteries, capacitors, and flywheels. There are a large number of flywheel concepts, but we are talking about it generically. In Jonathan Jones's concept, presented in the working group, he had a reservoir of water where thermal energy could be stored by heating it up when you're not thrusting. (Figure 2)

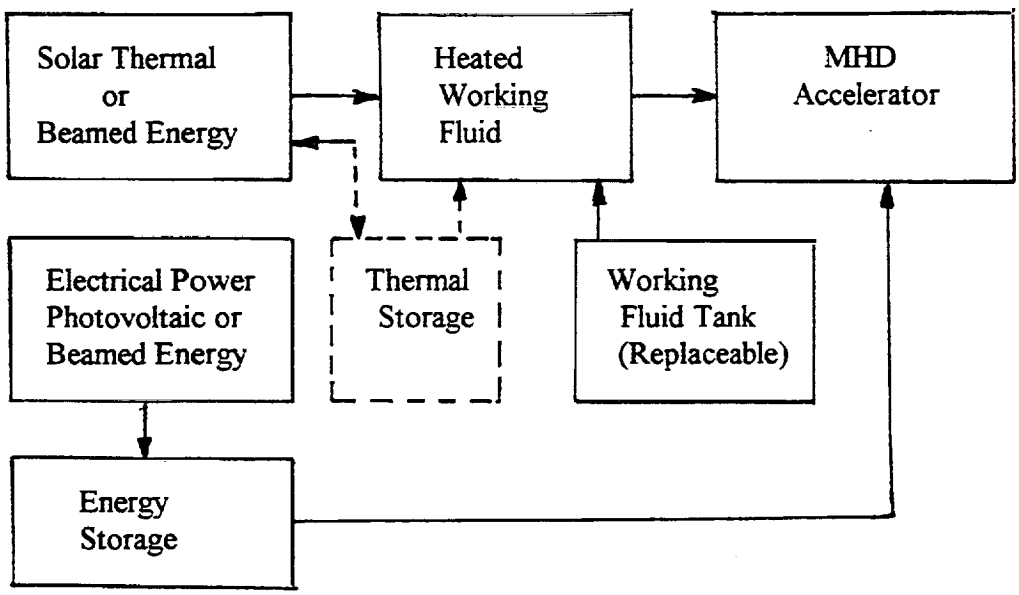


Figure 2 Thermal Storage Concept

Our group overlapped some of the other groups particularly the nuclear group. One of the most attractive concepts is one we call the gas cooled reactor. The concept we considered used argon as a cooling medium. Use of other gases is possible, of course. In this concept, argon was heated to 2200 degrees Kelvin. That could be used in a closed cycle MHD with extraction of electrical power amounting to 38% of the sensible weight of the gas at the entrance being already demonstrated. The argon would then be recycled through a heat exchanger which would transfer heat to the propellant and then be compressed for reuse. There are also open cycle variations of this that need to be developed, but none of them provide quite as much electrical power as that generated by the closed cycle MHD generator. Our reusable concept was to include a reloadable fuel assembly for the reactor and propellant.

The solar thermal or beamed energy system requires lenses to focus the energy to heat the working fluid for the MHD accelerator. An electrical power supply of some type would also be needed to provide the electrical power for the acceleration of the gas.

What does it take to get MHD propulsion to TRL-6? One of the things that needs to be done is systems analysis and integration. That would permit estimating the cost and performance for systems and provide the kinds of numbers that are desired for this study. There are also some component and system laboratory demonstrations needed. MHD has never been used in the power densities envisioned for this space propulsion application. High power densities in the temperature, pressure regime of space propulsion need to be demonstrated.

The key research areas systems analysis is needed to optimize the system with respect to the measure of merit. The cost per pound, LEO to GEO, would be the measure of merit. The analysis should include comparison of the working fluids including looking at equilibrium ionization versus non-equilibrium. You may be able to relax the temperature requirements particularly if it is possible to go to a non-equilibrium accelerator. That is, you may be able to use a lower temperature and selectively give energy to the electrons.

Regarding energy recovery and efficiency, the final measure of merit in this system is not efficiency, but it has a high influence on the cost-per-pound. We would begin with some systems work and laboratory experiments. Shortly thereafter, we would develop a conceptual design and initial testing. We are not suggesting a space-borne test in this time frame, but laboratory tests of the system. One of the problems with a laboratory test is the need for a big vacuum chamber or some way to simulate the exhaust pressure.

We felt there were no major operational issues with the MHD system, but it is a relatively minor part of the overall propulsion system. We did put a couple of minor things in, one being that the exhaust of the accelerator is going to be an ionized gas and RF transmission though it is a problem. We do not think that is a large problem because this is a relatively small ionized volume and there are probably ways to work around it. The major operational issues, we think, are the resupply of the propellant and the unique problem of the power supply to provide electrical power.

The MHD accelerator costs are comparatively small. They could almost be considered insignificant compared with the overall propulsion system. The delivery of the propellant and the working fluid is a major cost driver and largely influences the cost per pound. The power supply, storage and controls for the electrical supply are major cost drivers and need to be done very cleverly in order to arrive at reasonable costs. One of the opportunities is combining the magnet and thereby eliminating some of the complex power conditioning equipment. That is, you can control the current and voltage of the power taken off the magnet to be that which you need for the accelerator.

Regarding nuclear and beam options, we think policy and legislation are critical cost drivers. The beamed power system probably requires extensive infrastructure for the ground base stations to generate the power and the beam. The MHD was shown at less than an average infrastructure requirement with a TRL of 4. Beamed power is at a lower TRL and a higher infrastructure requirement.

3.3 Breakthrough Physics

Lead:
Robert Frisbee

Rapporteur:
George Schmidt

Speakers:
Robert Frisbee
Alan Holt

Participants:

Whitt Brantley
Clark Hawk

3.3.1 Background and Overview (R. Frisbee)

The following propulsion breakthroughs are needed to realize revolutionary advances in space transportation:

(1) Eliminate or drastically reduce the need for rocket propellant. This implies discovering fundamentally new ways to create motion, presumably by manipulating inertia, gravity, or by any other interactions between matter, fields, and spacetime.

(2) Dramatically increase vehicle speeds to make deep space travel practical. This implies determining and achieving the actual maximum speed limit for motion through space or the motion of space-time itself. If possible, this means circumventing the light speed limit.

(3) Discover fundamentally new on-board energy generation methods to power such revolutionary propulsion devices. Since the above two breakthroughs could require breakthroughs in energy generation to power them, and since the physics underlying the propulsion goals is closely linked to energy physics, this third goal is included in the program.

What if we could actually generate and control things like worm holes or manipulate gravity? Some of the system level impacts, going all the way from fairly modest improvements in vehicle performance; or knocking a few percent off the weight of the vehicle; on up to being able to completely eliminate the on-board rocket propulsion; get rid of the rocket equation; get endless amounts of energy out of the zero point vacuum energy; all are very highly speculative at this point. There might be the potential to improve safety and the cost associated with safety. Having large amounts of chemical propellants, nuclear power systems, etc., introduces some very real safety concerns when you have crew. You have to include crew safety, crew rescue, abort and escape mechanisms.

There are a number of general research areas which we could start pursuing. These include things like getting energy out of the zero point, fluctuation of the vacuum, different types of hyper-field or hidden variables experiments. The ones that are probably going to be focused on near-term are the super-conductor and the spinning super-conductor gravity screening experiments. This area has extremely low technology readiness levels. There is a lot of theoretical work but a severe shortage of experiments to demonstrate the theory. Once you try to prove some of these concepts, the next step would be to try and demonstrate it as a propulsion application. For example, go just beyond a research curiosity stage into something that looks more like an engineering application leading to a small prototype and then a full-scale prototype testing. How can we bring this all together? We can start by addressing some of the concepts which are being considered for breakthrough physics.

Antimatter can be used in two ways; as the primary energy source for the propulsion system where all the energy comes from antimatter annihilation or as a means to trigger fission or fusion explosion. This concept is being pursued by Jerry Smith at Penn State University.

If you use antimatter/antiprotons as the primary energy source, someone is going to have to build something capable of producing at least milligrams per mission of antiprotons. That is an extremely large infrastructure. Congress balked at the super-collider. This would probably dwarf that, which doesn't mean that it might not lend itself at some future date to some multinational infrastructure because of the potential benefit. A potentially more near-term and much more affordable approach would be to use the Penn State concept. It turns out that it can

use antiproton production rates as we see today, ten to the minus twelve grams typically, or about ten to twelve antiprotons per year. At this point, in terms of what we have for resources, time and energy, the best we could do was a hand-waving guess or estimate and say that the hardware costs of the stage might compare with what we've seen in a gas core fission rocket.

Historically, gas core fission and fusion have been thought to have been competitors. Each camp thinks the other's concept is impossible to do but they both fill similar performance requirements. For example, they are both able to go from Earth to Mars in three or four months.

High Energy Density Materials (HEDM) concepts involve advanced chemical propellants. Typically, they are based on taking a solid propellant matrix and imbedding some high energy species in the solid that prevents the HEDM material from wandering through the solid, recombining, reacting and doing other unpleasant things. An example would be to put atoms of hydrogen in a solid molecular hydrogen matrix or molecules of ozone or atoms of oxygen in a solid molecular oxygen matrix. HEDM systems do have the potential for both high thrust and high specific impulse. Some relatively near-term HEDM systems might get you as high as 600 seconds specific impulse. If you had something like metallic hydrogen or pure atoms of hydrogen, it would be even better. Without needing any hydrogen matrix, you might get up as high as 2000 seconds. The problem is, there does not seem to be any easy or obvious physical way of achieving this system.

The other potential problem with HEDM is that even with fairly good performance (a 600 second chemical rocket), because it has a relatively good stage dry weight, you can only get performance comparable with what you might see from nuclear thermal rockets. But, again, the issue is that it is too much like an existing chemical rocket. Also, storing something like hydrogen at liquid helium temperatures introduces some very non-trivial thermal control problems. That may really impact the dollar per kilogram of stage dry mass that you are paying for the hardware.

Penn State has completed building an electro magnetic trap called a Penning Trap. It is being tested this year and during 1997. It will be filled with some antiprotons and taken to Kirtland Air Force Base. They are then going to implode a uranium pellet, shoot antiprotons into it and see if it works. Then, in a couple of years, they are going to try it with both a fission and fusion pellet, again to see if they can demonstrate a reasonable amount of reaction.

In the HEDM area, the Air Force's Phillips Lab at Edwards Air Force Base has an on-going program which has already demonstrated being able to take solid ethylene, which is normally a gas, freeze it and run liquid oxygen through a hybrid liquid-solid rocket motor. This year, Orbitec has an SBIR and is building a solid oxygen/liquid hydrogen hybrid rocket motor.

The technology readiness levels may have been overstated. They may be a little less than zero. That would be like testing in a vacuum chamber and these are probably going to be open air tests. Hopefully, in a couple of years, they will be able to do solid hydrogen in liquid helium plus liquid oxygen. In each case, when they show it can be done with the pure propellant, they will attempt to start introducing high energy species, different atoms, etc.

We need a fairly long-term but relatively low level plan, partly because it takes time to get grants through the mill to researchers. The idea would be to have a series of annual research workshops, new research opportunity announcements, possibly every other year, and then also reviews. Maybe there could be University grants with periodic Blue Ribbon Panel peer reviews of the on-going work. This helps give credibility to the program because high level people would be evaluating the work.

Concerning near-term activities, we identified the option of briefing the National Research Council Advisory Board, the Committee on Advanced Space Technology.

Another approach would be to set up a review process involving NASA, the National Science Foundation (NSF), the Department of Defense, and the Department of Energy, as well as members from academia and industry. This could include private consultants and major corporations. Finally, we will try to initiate the new research announcements. Another approach is a method that the Air Force is using, known as a Broad Area of Interest Announcement. This allows potential researchers to submit something as small as a one page abstract to determine interest and eliminate wading through large proposals.

We may have a workshop every year to review researchers' work and to get everyone together, from those who review proposals to those doing the planning. The research opportunity announcements could be every other year and the Blue Ribbon Panels could be every three to four years. Part of the idea for the Blue Ribbon Panels is to determine if a program is making progress.

What we really have is three or four different parts to the program. The first, primary part would be basic research where theories and experiments would be worked out. Part two, then, would involve taking the do-able experiments and designing small-scale model experiments, ultimately leading to full-scale experiments. There are theoretical models of how to generate gravity manipulation but in some cases, they are simply not feasible in any reasonable engineering sense. Therefore, our selection criteria, in part, would be to determine which ideas ultimately lend themselves to a technologically adaptable and solvable problem.

3.3.2 Cost and Operations (A. Holt)

Most of the things that we put together for costs and operations issues are really things that apply to all the systems. Keeping the initial experiment costs low is obviously an objective, particularly in the area of breakthrough physics, because we have to have some success before we can get much in the way of significant funding. We do have the spinning super conductor which is getting some funding, but beyond that, it is going to be difficult. Therefore, we have to look at existing facilities and apply piggy-backing and small prototypes. We also have to accommodate surprises because we will likely try to get something into a small-scale process as quickly as we can. We are going to find that we really do not understand the physics and all the performance parameters like we thought we did. We will have to then go back and do some iterations while trying to keep the cost down. Once we do get past that stage, it will still be difficult even if we have something that looks good. The next question is, "Is it cost effective?". Is it something we can really implement and how are we going to get managers and crews and other people to a point where they have confidence that we can actually use something like this and do it safely? We can utilize existing vehicles. The X-33 planned to use the SR-71 to do some propulsion testing so you can look at a vehicle like that or you could look at the X-33 itself, if it is available at that point.

Since we are designing a new approach, we should consider manufacturing techniques to make sure that what we end up with is not something that is so unique that it is going to cost us two billion dollars every time we try to built it. The cost could be fairly high initially, but if we approach it right, we can address that.

For energy requirements, if we do get to the zero point energy in a situation where we are actually using the energy from the vacuum, we would have solved a lot of problems. Initially, we will probably have to rely on conventional power systems on the ground, maybe some chemical propulsion for some tests and maybe a nuclear power system at some point.

For the kind of vehicle we are looking at, the surface itself not only has to provide protection but probably plays a role in the propulsion system, maybe even in the energy system itself, so we want to combine functions as much as we can. The goal for maintenance and refurbishment might be to get things to the point where it is the surface that wears out and that determines when we have to have maintenance and refurbishment. By commonality, using the same forms, we save a lot of costs, except when we go for deep space or unique functions and then we would probably have to look at something unique.

Initially, it is not clear whether we can operate these kinds of systems without some hefty power supplies, maybe some nuclear components. In any case, even zero point energy may have some radiative aspects to it that we are not familiar with. That would have to be taken into account. You want to design your vehicle for ease of access for both internal and external maintenance,

again, to keep costs down. Guidance and control could be a challenge. You are dealing with a lot of non-linear physics. Therefore, you may need either some high powered digital computer applications or some combinations of analog calculations. There may be a sensitivity to environmental conditions that other vehicles are not sensitive to and that has to be taken into account to keep costs from climbing. In the meantime, between failure and maintenance, obviously, we can have the high performance system that can do all sorts of things; for example, take us to Mars and even the stars. However, if there is failure every week or every month and we have to return for costly maintenance, the system will have to be developed until it can be made usable.

Even if there are monumental breakthroughs, it does not eliminate the other considerations that everyone else has to deal with. Conclusions can not be given at this time because we are just getting started.

3.4 Nuclear Propulsion

Lead:
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Rapporteur:
Bill Emrich

Participants:

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Ward Dougherty	Travis Knight
Harold Gerrish	Sarah McIlhenny
Keith Goodfellow	Morgan White
Steve Howe	

The nuclear propulsion team examined six candidate concepts ranging in technology maturity form highly developed to those conceptual in nature. The concepts included: (1) the solid core nuclear thermal rocket (NTR); (2) nuclear electric propulsion (NEP); (3) the gas core nuclear thermal rocket (GCR); (4) nuclear fusion propulsion (fusion); and (5) the antimatter or mass annihilation rocket (MAR). The team members, selected from NASA, JPL, academia and industry, were tasked with evaluating each of the above concepts in five particular areas: (1) concept cost drivers; (2) operational issues; (3) technology readiness levels (TRL); (4) key research areas; and (5) a proposed implementation time frame. The team was also asked to

evaluate the suitability of each concept to perform seven different design reference missions (DRMs) outlined by John Mankins of NASA Headquarters. The DRMs, ranging from near Earth orbit to interplanetary missions, and the applicability of the various nuclear propulsions concepts is shown in Table 4. Also included is the concept's ability to utilize extraterrestrial resources for fuel, oxidizer or reaction mass. This summary table represented the consensus view of the team members.

Mission Applications	NTR/ LANTR	NEP	GCR	Fusion	Antimatter
LEO ⇌ MEO/GEO DRM#1 (SC/Cargo)	✓				
LEO ⇌ MEO/GEO DRM#2 (Cargo/Crew)	✓				
LEO → Deep Space DRM#3 (Robotic SC)	✓	✓	✓	✓	✓
Moon: DRM#4 -LTV Cargo	✓	✓	✓		
Crew	✓		✓		
Moon: DRM#5 -LEV Cargo	✓				
Crew	✓				
Mars: DRM#6 -MTV Cargo	✓	✓	✓	✓	✓
Crew	✓	✓	✓	✓	✓
Mars: DRM#7 -MEV Cargo	✓				
Crew	✓				
"In-Situ" Resource Utilization (ISRU)	Hydrogen (NTR) Hydrogen & Oxygen (LANTR)	Argon (Ion) Hydrogen (MPD)	Hydrogen	Hydrogen (Reaction Mass)	Hydrogen (Reaction Mass)

Table 4 Mission Applicability - Nuclear Propulsion

Nuclear Thermal Rocket (NTR)

The solid core NTR was acknowledged by the team to be at the highest maturity level with 20 rocket reactors designed, built and tested during the Rover/NERVA programs and ~$1.4 billion dollars spent on this technology through January, 1973. Since then, significant advances have continued in chemical propulsion resulting in lightweight, high heat flux nozzles and high pressure turbomachinery, as well as, lightweight graphite/epoxy "composite" LH_2 propellant tanks, all of which are needed in an operational NTR stage. The two key technology development areas prior to initiating DDT&E are fuels and effluent treatment system (ETS) design allowing an economical, "environmentally acceptable" ground test facility (GTF) for full-power operation and performance validation of the NTR engine before flight testing. Significant advances have been made by the Russians in the development of a tricarbide fuel since the Rover/NERVA days. Russian rocket reactor tests conducted at Semipalatinsk facility in Kazakhstan have verified the fuel's capability to operate in hot hydrogen at ~3100 degrees Kelvin (K) for over an hour. This temperature is ~500 K higher than the best achieved in Rover/NERVA! Furthermore, by reducing the fuel operating temperature from ~2800 K to ~2600 K (Isp~925 s to ~890 s), the engine's operational lifetime can be extended by a factor of three--from 10 to ~30 hours. Extending engine lifetime for a reusable NTR stage is important to reducing the hardware costs to the few hundred $/lb per mission required by an AIST system.

In regards to the GTF development schedule and cost, NASA's current focus on a small 15 thousand pounds force (klbf) NTR engine, in contrast to the 50 to 250 klbf engines tested in the Rover/NERVA programs, is expected to substantially reduce both since the GTF capacity will scale with engine size/exhaust throughput. Outfitting the "Contained Test Facility" at the Idaho National Engineering Lab (INEL) with an ETS for a 15 klbf engine has been estimated to cost ~$150 million dollars and ~$30 to 40 million dollars if testing is done at Semipalatinsk as part of a collaborative U.S./Russian development program. Because the HTR TRL is estimated at ~5, DDT&E would be primarily oriented toward developing an actual flight engine rather than a "battleship" ground test article already demonstrated in the NERVA program. A detailed development schedule and cost requiring ~7 years and $1.5 billion dollars for a 15 klbf flight engine was provided by Lewis Research Center to the Marshall Space Flight Center in support of the Advanced Space Transportation Program (ASTP) in the spring of 1996. Recurring costs were estimated at ~$100 million dollars per engine. A small single engine stage could be used for LEO-to-GEO orbit transfer missions, as well as, for "deep space" robotic science missions (e.g., fast transit orbiter missions to the outer planets). Clustering several (~2 to 3) of these small engines would also increase mission versatility (Fig. 3) allowing both piloted and cargo lunar and Mars missions.

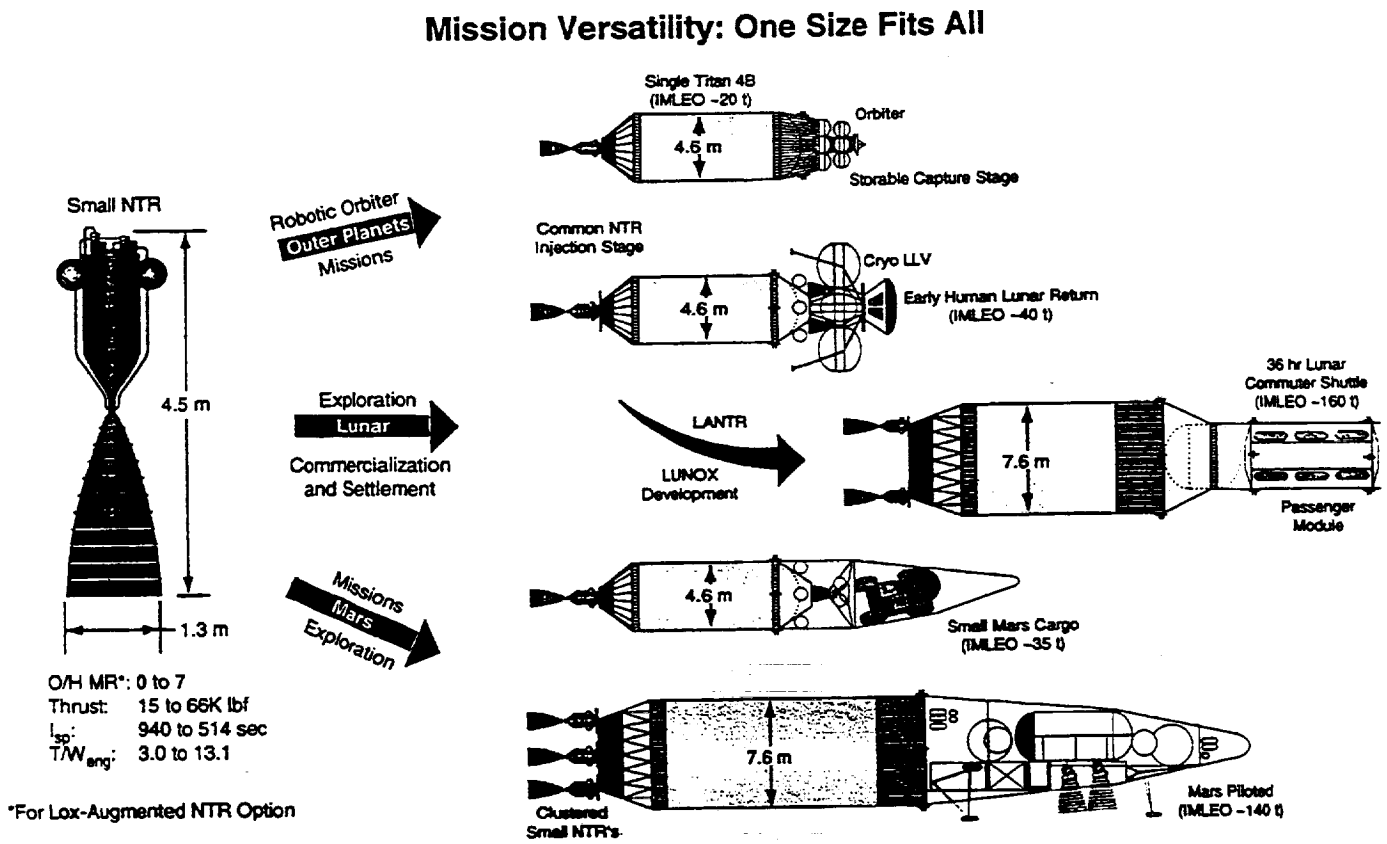
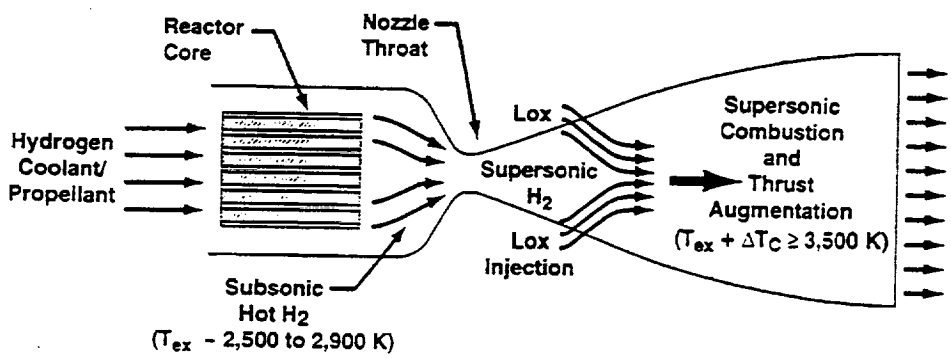


Figure 3 Mission Versatility: (Small 15 klbf NTR/LANTR)

The major operational issues with NTR propulsion are the need for additional cooldown (cd) propellant to remove fission product (FP) decay heat from the engine's reactor core and shielding mass to protect crew and/or cargo from the neutron and gamma radiation fields emanating from the engine. Because the NTR is a high thrust system, engine burn times are typically short (varying from a few minutes to ~0.5 hour) and the FP inventory/decay heat is small and quantifiable. The cd propellant penalty is ~3% of usable propellant consumed during the burn and limited access to the vehicle outside the protected shield zone is also possible after an appropriate period to allow radiation fields to decay.

In terms of mission applicability, the NTR is the only nuclear propulsion concept identified by the team capable of satisfying the entire spectrum of DRMs including Moon/Mars ascent/descent propulsion, and "in-situ" resource utilization (ISRU). Although the conventional, "all LH_2" NTR provides the highest performance (Isp), the availability of solar wind implanted hydrogen in the lunar soil is very small compared to abundant lunar oxygen (LUNOX) chemically bound in the lunar regolith. Substantial quantities of hydrogen may, however, be available on the Moon if reports of ice at the lunar south pole prove to be correct. Beyond the Moon, water exists on Mars and probably in the asteroids and the Galilean moons of Jupiter--Europa, Ganymede and Callisto. An enhanced NTR concept, proposed by NASA Lewis and Aerojet in 1994, and known as the "LOX-augmented" NTR (LANTR) can potentially utilize both hydrogen and oxygen. The LANTR concept (Fig.4) utilizes the large divergent section of the NTR nozzle as an "afterburner" into which oxygen is injected and supersonically combusted with reactor-heated hydrogen emerging from the LANTR's choked sonic throat--"scramjet propulsion in reverse". By varying the LOX-to-LH_2 mixture ratio (MR), the LANTR engine can operate over a wide range of thrust and Isp values while the reactor produces a relatively constant power output. In addition to thrust augmentation, the increased use of high-density LOX in place of low-density LH_2 reduces hydrogen tank volume and boil-off as well as stage size. The payload delivery capability of the space transportation system is also dramatically increased once extraterrestrial sources of hydrogen and oxygen are available at destination for the return trip home.



	I_{sp} (sec)				
Life (hrs)	5	10	30	Tankage Fraction (%)	T/W_{eng} Ratio
T_C (°K)	2,900	2,800	2,600		
O/H MR = 0.0	941	925	891	14.0	3.0*
1.0	772	762	741	7.4	4.8
3.0	647	642	631	4.1	8.2
5.0	576	573	566	3.0	11.0
7.0	514	512	508	2.5	13.1

*For 15K lbf LANTR with chamber pressure = 2,000 psia and ε = 500 to 1

Figure 4 LANTR Engine Concept Capability

The LANTR concept with ISRU has the potential to "revolutionize" cislunar and interplanetary space travel. "Commuter flights" to and from the Moon with 1-way transit times of ~24 hours could become commonplace. At Mars, reusable biconic shaped LANTR-powered ascent/descent vehicles, operating from specially prepared landing sites, could transport modular payload elements to the surface while supplying orbiting transfer vehicles (see Fig. 5) with propellants needed to reach refueling depots in the asteroid belt. From there, the LANTR-powered transfer vehicles could continue on to the "water-rich" moons of the Jovian system, providing a reliable foundation for the development and eventual human settlement of the Solar System.

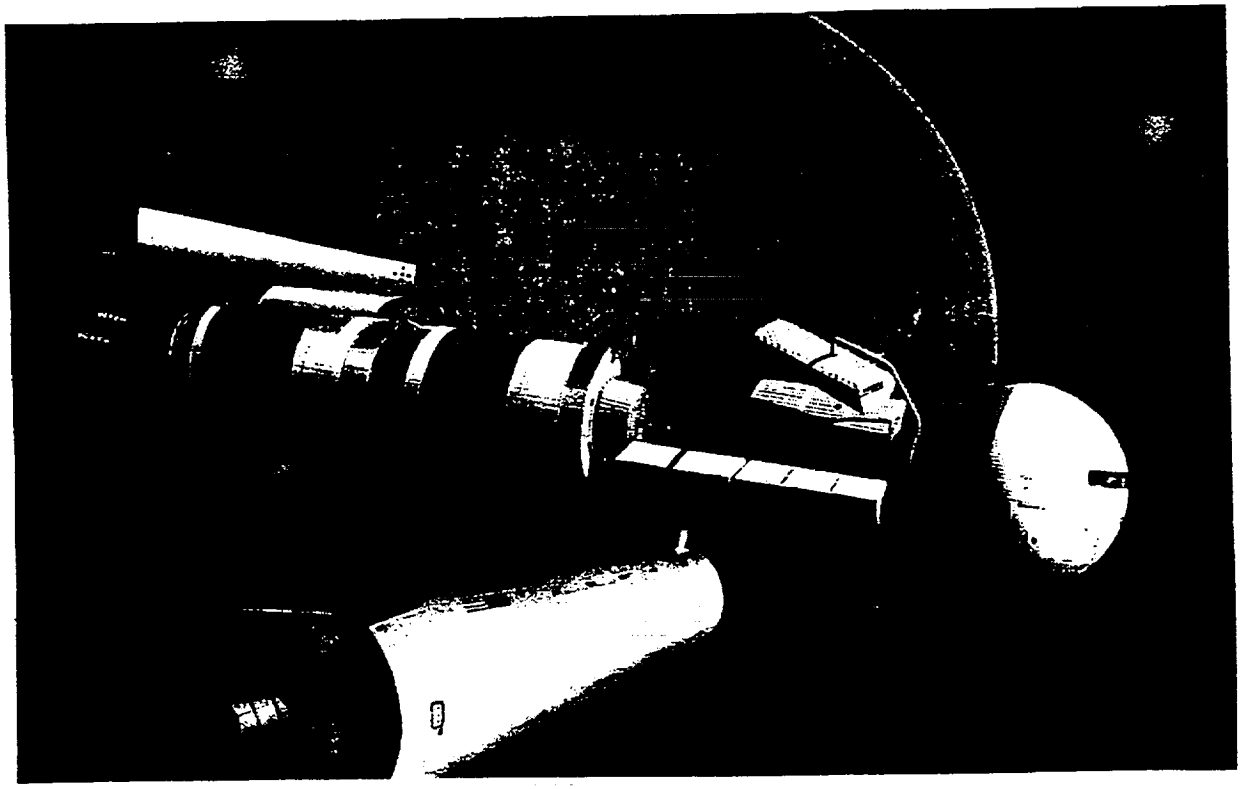


Figure 5 Reusable Mars Transportation System
Architecture using LANTR-Powered Landers and Transfer Vehicles (Vehicle Designs by Stan Borowski of NASA's Lewis Research Center/Artwork for NASA by Pat Rawlings of SAIC)

Nuclear Electric Propulsion (NEP)

Next in line in terms of technology maturity is NEP. In contrast to the NTR, which uses its reactor as a source of thermal energy to heat the hydrogen coolant/propellant, NEP uses its reactor to generate electrical power to energize fuel efficient electric thrusters. (Fig. 6) Significant development on low power (kWe-class) ion thrusters is presently underway in the New Millenium program and although cancelled in 1994, approximately $500 million dollars was also spent by the SP-100 Program on fuels and technology development for a 100kWe-class fission power reactor system. The team examined NEP vehicle systems in both the low and high power operating regimes. At the low power end (~100 kWe), the specific mass is ~30 kg/kWe but is expected to drop to ~10 kg/kWe at a power level of ~2 Mwe assuming a "SP-100 derived" reactor and advanced liquid metal potassium Rankine power conversion technology. Thruster power level and lifetime are also issues for NEP systems. Although electric thrusters operate at high Isp, they are low thrust devices and typically must operate for long periods of time. For example, the New Millenium 3 kWe ion thruster is being lifetested for ~8000 hours. Thrusters with power levels in the 100's of kWe range and capable of operating for 10's of thousands of hours will be required for most of the DRMs shown in Table 4. (See page 25)

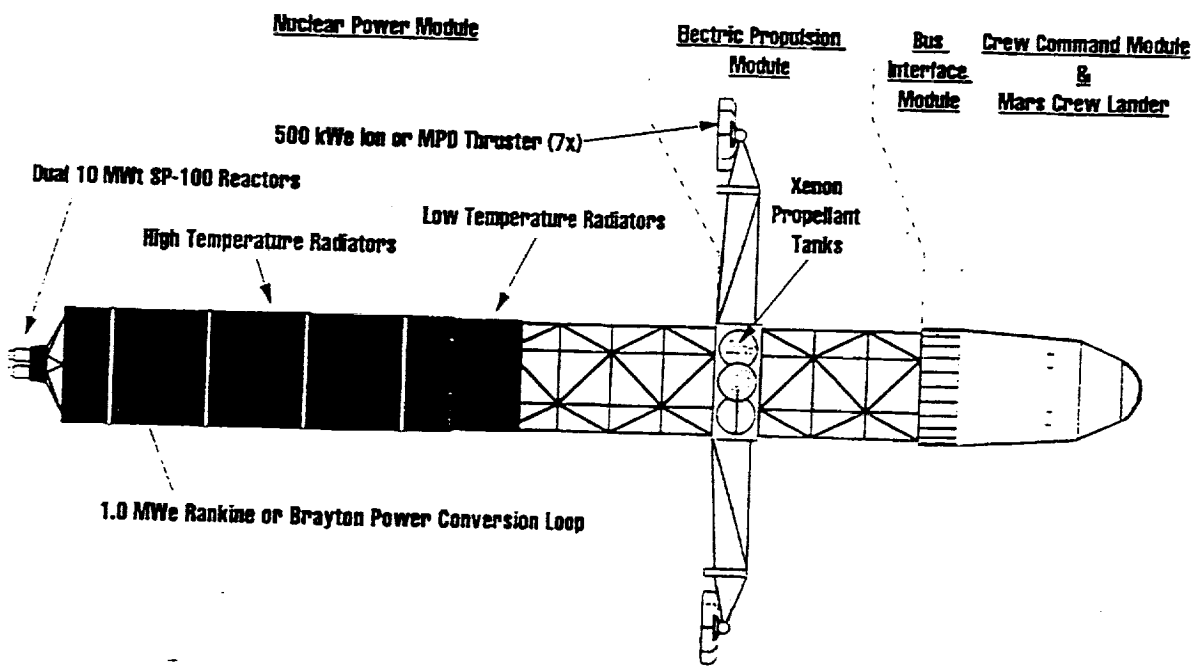


Figure 6 Nuclear Electric Propulsion (NEP) Vehicle

The TRL, as well as the DDT&E phase duration and cost for both low and high power NEP systems was also discussed by the team. Based on the SP-100 Program, the TRL was estimated to be ~4 with the DDT&E phase requiring ~$500 million dollars and ~7 years. The TRL for the 2 Mwe NEP system was estimated at ~3 with ~$2 to 3 billion dollars and ~10 to 12 years required to reach a flight operational stage. The need for and cost of an integrated NEP system ground test facility (GTF) was discussed at some length. Because of the long operational times, vacuum pumping requirements for high power thrusters and overall system complexity, the GTF cost was estimated at between $0.5 to 1.0 billion dollars. Ground testing only the individual subsystems was proposed as a way of reducing the overall DDT&E cost with the first fully integrated NEP system test being that of the flight article. This approach, while appearing less costly on the surface, was thought to be higher risk with the potential to be even more costly should the in-flight test article fail and be irretrievable for post-flight examination and corrective measures.

With its high Isp, NEP is usually thought of as ideal for "cargo-type" missions where high payload fraction and not trip time is considered important. However, if the AIST study goal of ~$1000 to 2000 dollars per pound to "GEO and beyond" is to be met, trip times also must not be excessive. For reusable LEO to GEO missions, trip times on the order of ~2 to 4 weeks are required to insure that the fleet capacity is high and vehicle hardware costs of ~$200 to 300 dollars/lb per mission are achievable. Data provided by Keith Goodfellow of JPL for low power (~200 kWe) NEP systems indicated trip times of ~100, 157 and 240 days for GEO payloads of 3, 10 and 20 tons, respectively. At the 1.5 Mwe power level, trip times were still 80, 89 and 98 days for the three payload categories indicating either the need for higher power levels or the acceptance of longer trip times. From an operational standpoint, there is also the concern that the long duration outward spiral to GEO of NEP systems at multi-megawatt power levels will increase the radiation exposure of space assets at lower altitudes. Beyond GEO, NEP is a definite candidate for deep space robotic science missions and potentially lunar cargo missions although piloted missions are out of the question because of unacceptably long trip times. For piloted missions to Mars, NEP systems can provide trip times comparable to that of the NTR because of the much longer distances involved. High altitude parking orbits, like that of Deimos, are often assumed for NEP mission architectures to reduce the piloted trip time. Access from and to Deimos orbit implies added propellant and a larger MEV because of the higher delta V requirements.

Gas Core Nuclear Thermal Rocket (GCR)

To overcome the material temperature limitations of the solid core NTR, an advanced "second generation" engine, the GCR, has been proposed which operates with its uranium fission fuel in a gaseous rather than solid state. Nuclear heat generated in the ionized gas or "plasma" would be released in the form of thermal radiation and captured by hydrogen propellant flowing around a vortex of fissioning uranium plasma. (Fig. 7) High values of thrust (~50 klbf) and specific

impulse (Isp~3000 s) have been discussed in previous conceptual design studies which showed the potential for fast (~3 to 6 months) round trip missions to Mars. Numerous small scale experiments were also conducted during the 1960s and early 1970s which demonstrated key aspects of a GCR such as gaseous fuel criticality, hydrodynamic confinement and radiative heat transfer. Using advanced weapons codes capable of simultaneously modelling nuclear, hydrodynamic and radiative heat transport effects, Los Alamos National Laboratory is currently studying confinement/uranium loss from various "open cycle" vortex flow geometries.

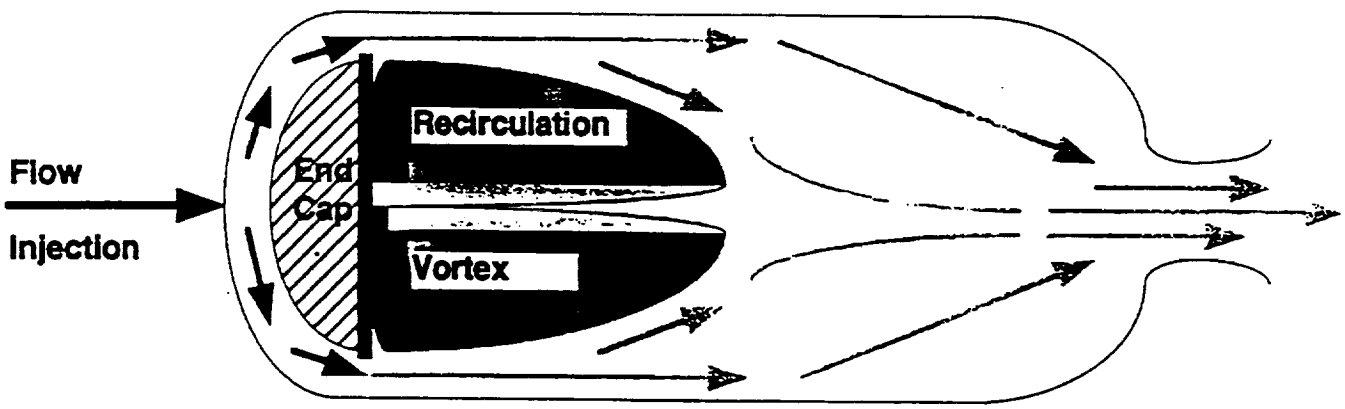


Figure 7 "Open Cycle" GCR

The TRL for the GCR was estimated by the team to be at ~2 to 3 with a series of "small-scale" integrated nuclear tests being necessary to prove concept feasibility before pushing on to the DDT&E phase estimated at ~15 years or more and ~$3 to 5 billion dollars. Substantial technology development is also required in the areas of high pressure LH_2 turbopumps and high heat flux transpiration-cooled nozzles to satisfy the 500 to 1000 atmosphere chamber pressures and nozzle exit temperatures in excess of 10,000 K! Because of the need for a thick moderator mass, heavy pressure vessel and external space radiator to dissipate excess waste heat deposited in the moderator by neutron and gamma radiation, GCR engines are expected to be heavy and expensive. Their primary mission applications for the GCR will probably be limited to reusable cislunar and interplanetary missions with deep space robotic missions a possibility if smaller, less costly GCR engines can be developed. A key operational issue associated with open cycle concepts is the potential loss of expensive enriched uranium fuel and radioactive fission products in the hydrogen exhaust potentially contaminating local space and its assets.

Nuclear Fusion Propulsion

Beyond the GCR, still higher values of Isp (~10^4s to 10^6s) could be possible using fusion-based propulsion systems. In contrast to fission, which generates its energy via neutron-induced splitting of heavy uranium-235 atoms, nuclear fusion produces energy by fusing together nuclei of various light elements, like the hydrogen isotopes deuterium (D) and tritium (T), and the helium isotope He^3. Creating and sustaining the conditions for a power-producing fusion reactor here on Earth is a daunting challenge. Fuel must be heated to super high temperatures (~150-600 million K) at high enough densities and for long enough times to cause substantial fusion reactions to occur and useful energy to be released. Rocket designs utilizing magnetic fields, high power lasers and particle beams, and electrostatic potential wells for particle confinement have all been studies in the past. Propulsive thrust would be generated by using a magnetic nozzle to direct energetic plasma particles from the fusion reactor rearward from the spacecraft at very high Isp or by adding reaction mass (e.g., LH_2) to the plasma stream to provide a variable thrust and Isp capability.

While fusion propulsion may hold the promise for a future "solar system-class" space transportation system, its current TRL is low (~2 to 3). Even terrestrial fusion experiments have yet to achieve the condition of "breakeven" (fusion power output = input power) despite multibillion dollar investments made in major facilities worldwide over the last three decades. With the added requirements of high power density and low mass, alternative fusion reactor concepts such as the compact toroid "field reversed" mirror configuration and the linear "gasdynamic" mirror concept (Fig. 8) presented by Prof. Terry Kammash (University of Michigan), are potential candidates. The DDT&E duration and cost was estimated to be at least 25 years and $10 billion dollars given the numerous complex technologies required to support fusion reactor operation. Also, because fusion systems will be extremely heavy (many 100's of tons) and expensive, their primary application will be in powering reusable, transfer vehicles on fast transit missions to Mars and beyond. From an operational standpoint, fusion propulsion systems will likely be limited to high orbit departures and arrivals (because of their low thrust-to-weight ratio) necessitating the need for an efficient high thrust propulsion system, such as LANTR, to economically ferry both crew and cargo to and from the fusion-powered transfer vehicle. A higher operating orbit also reduces the exposure of space assets at lower altitudes to the large flux of energetic 14.1 MeV neutrons that would emanate from DT-fueled engines, which produce ~80% of their power output in this radiation form.

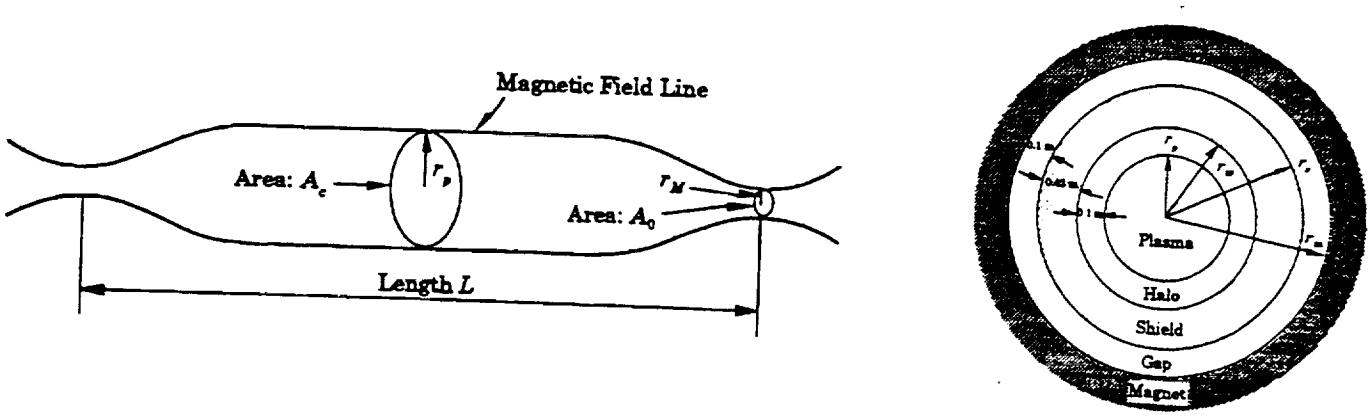


Figure 8 "Gasdynamic" Mirror Fusion Rocket

Antimatter or Mass Annihilation Rockets (MAR)

The routine production of antiprotons at high energy physics facilities like Fermilab and CERN, and the recent momentary creation of an antihydrogen atom (consisting of an antiproton and positron) has provided motivation for considering them as an energy source for future propulsion systems. While synthetic antihydrogen is definitely "high test" fuel (e.g., ~2 milligrams of equal parts antihydrogen and hydrogen has the equivalent energy content of 13 tons of LOX and LH_2 propellant), it requires enormous energy and cost (estimated at ~$5 to 10 million dollars per milligram) to produce here on Earth, and will be difficult to store and manipulate in a practical propulsion system. When annihilated with normal hydrogen, it also liberates approximately a third of its energy in the form of two 200 MeV gamma rays necessitating massive amounts of dense shielding to protect crew and equipment. These operational issues have in no way dampened the spirits of antimatter rocket enthusiasts who have proposed concept analogues to the solid core, gas core and fusion propulsion systems discussed above. Antiprotons have been considered as a catalyst in a hybrid pulsed microfission-fusion propulsion system proposed by Penn State University (PSU). Although the TRL for a MAR is low (~2), the recent development of a portable Penning trap by PSU will allow transport of up to ~10^9 antiprotons and is expected to accelerate studies and experiments on the potential use of this exotic high energy density fuel.

3.5 Tethers

Lead:
Les Johnson

Rapporteur:
Chris Rupp

Participants:

Robert Hoyt
Ronnie LaJoie
Saroj Patel

The groundwork has been laid for tether space transportation systems. NASA has developed tether technology for space applications since the 1960's. Important recent milestones include retrieval of a tether in space (TSS-1, 1992), successful deployment of a 20-km-long tether in space (SEDS-1, 1993), and operation of an electrodynamic tether with tether current driven in both directions—power and thrust modes (PMG, 1993). A list of known tether missions is shown in Table 5

NAME	DATE	ORBIT	LENGTH	COMMENTS
Gemini 11	1967	LEO	30 m	spin stable 0.15 rpm
Gemini 12	1967	LEO	30 m	local vertical, stable swing
H-9M-69	1980	suborbital	500 m	partial deployment
S-520-2	1981	suborbital	500 m	partial deployment
Charge-1	1983	suborbital	500 m	full deployment
Charge-2	1984	suborbital	500 m	full deployment
ECHO-7	1988	suborbital	?	magnetic field aligned
OedipusA	1989	suborbital	958 m	spin stable 0.7 rpm
Charge-2B	1992	suborbital	500 m	full deployment
TSS-1	1992	LEO	<1 km	electrodynamic, partial deploy, retrieved
SEDS-1	1993	LEO	20 km	downward deploy, swing & cut
PMG	1993	LEO	500 m	electrodynamic, upward deploy
SEDS-2	1994	LEO	20 km	local vertical stable, downward deploy
Oedipus-C	1995	suborbital	1 km	spin stable 0.7 rpm
TSS-1R	1996	LEO	19.6 km	electrodynamic, severed
TiPS	1996	LEO	4 km	long life tether, on-orbit (11/96)

Table 5 Known Tether Flights

Tether Applications for Space Transportation

Various types of tethers and systems can be used for space transportation. Long non-conducting tethers can be used to exchange momentum between two masses in orbit. Shorter electrodynamic tethers can use solar power to 'push' against a planetary magnetic field to achieve propulsion without the expenditure of propellant. Below are descriptions of the main types of tether space transportation systems

Electrodynamic Tethers

A conducting tether, terminated at the ends by plasma contactors, can be used as an electromagnetic thruster. A propulsive force of $\mathbf{F} = I\mathbf{L} \times \mathbf{B}$ is generated on a spacecraft/tether system when a current, I, from an on-board power supply is fed into a tether of length, **L**, against the emf induced in it by the geomagnetic field, **B**. This concept will work near any planet with a magnetosphere (Earth, Jupiter, etc.) This was demonstrated by the TSS-1R mission – the Orbiter experienced a 0.4 N electrodynamic drag thrust during tether operation

An electrodynamic upper stage could be used as an orbital tug to move payloads in LEO after launch from an RLV or other launch vehicle. The tug would rendezvous with the payload and launch vehicle, dock/grapple the payload and maneuver it to a new orbital altitude or inclination within LEO *without the use of boost propellant.* The tug could then lower its orbit to rendezvous with the next payload and repeat the process. Such a system could conceivably perform several orbital maneuvering assignments without resupply, making it low recurring cost space asset. The performance of a 10 kW, 10 km tether system is illustrated in Figures 9 and 10.

'Hanging' Momentum Exchange Tethers

The effectiveness of momentum exchange tethers to boost payloads to higher orbits from an RLV or other launch vehicle stems from the fact the RLV must reduce its altitude after payload release in order to return to Earth, while at the same time the payload it ejects must increase its altitude to reach the desired orbit. In other words, momentum must be removed from the RLV and added to the payload. Tethers provide a method to make this exchange.

Operationally, this can be accomplished by the deployment of the payload upward on a long (~20 km) tether from the RLV (Figure 11). Libration begins and the momentum is transferred from the heavy RLV to the payload. Upon release, the RLV experiences a deboosting force and the payload is inserted into an orbit with apogee many times the tether length higher than previous. This was demonstrated inadvertently when the electrodynamic tether broke on the TSS-1R flight, sending the endmass into a new orbit. The technology for this type of momentum exchange utilizing a tether exists today and has been successfully demonstrated 3 times with the Small Expendable Deployer System (SEDS) since 1993.

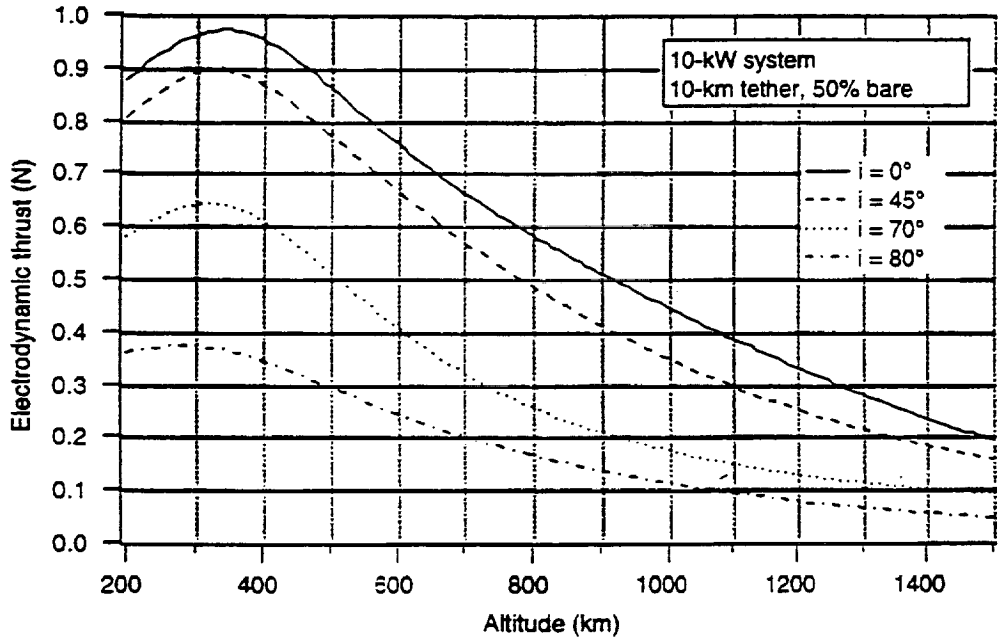


Figure 9 Electrodynamic tether thruster performance

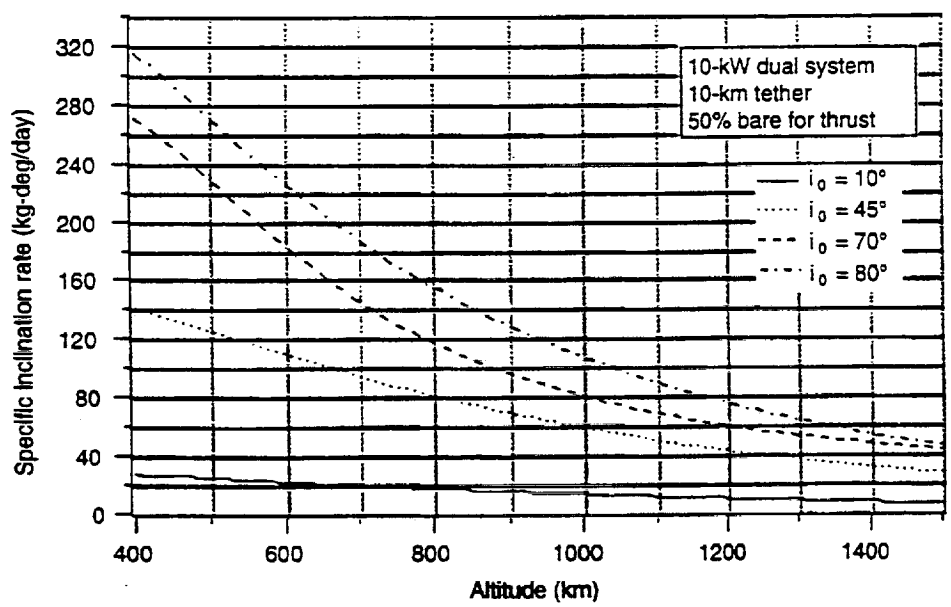


Figure 10 Electrodynamic tethers orbital inclination.

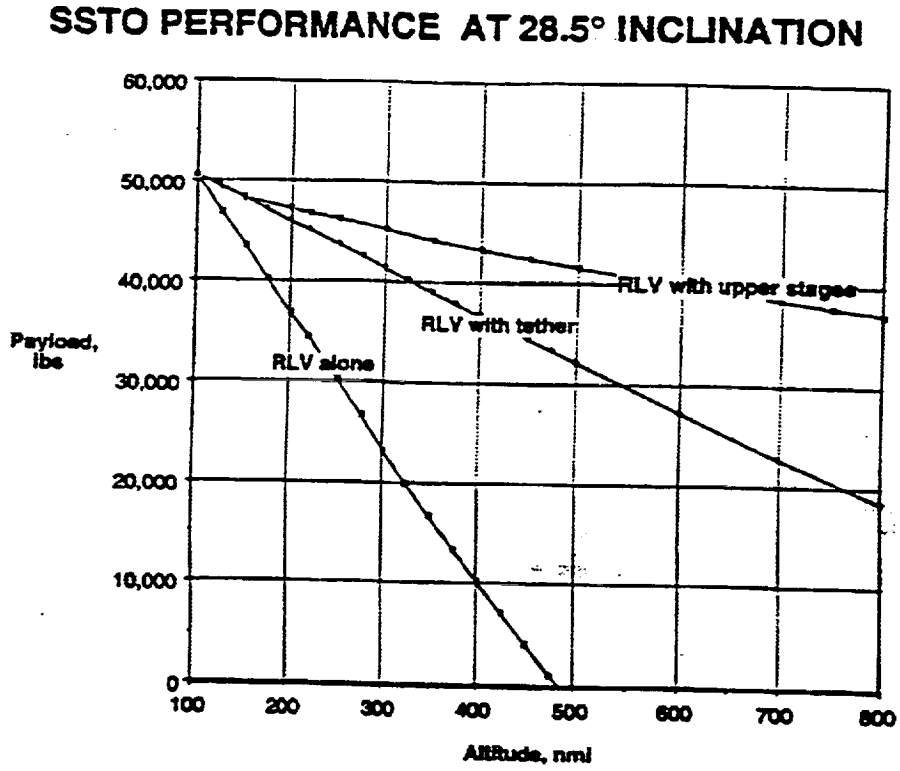


Figure 11 SSTO Performance.

Rotating Momentum Exchange Tethers

A spinning tether system can be used to boost payloads into higher orbits with a Hohmann-type ΔV. A tether system would be anchored to a relatively large mass in LEO awaiting rendezvous with a payload delivered to orbit by the RLV or some other launch vehicle. The uplifted payload meets with the tether facility which then begins a slow spin-up using electrodynamic tethers (for propellantless operation) or another low thrust, high Isp thruster. At the proper moment and tether system orientation, the payload is released and 'slung' to its new orbit. A network of such systems could be developed to "hand off" a payload until it reaches geostationary orbit.

As an example, the length of an idealized system for transferring a 1,000 kg payload from LEO to a higher orbit is illustrated in Figure 12. The maximum acceleration is limited to 10 g.

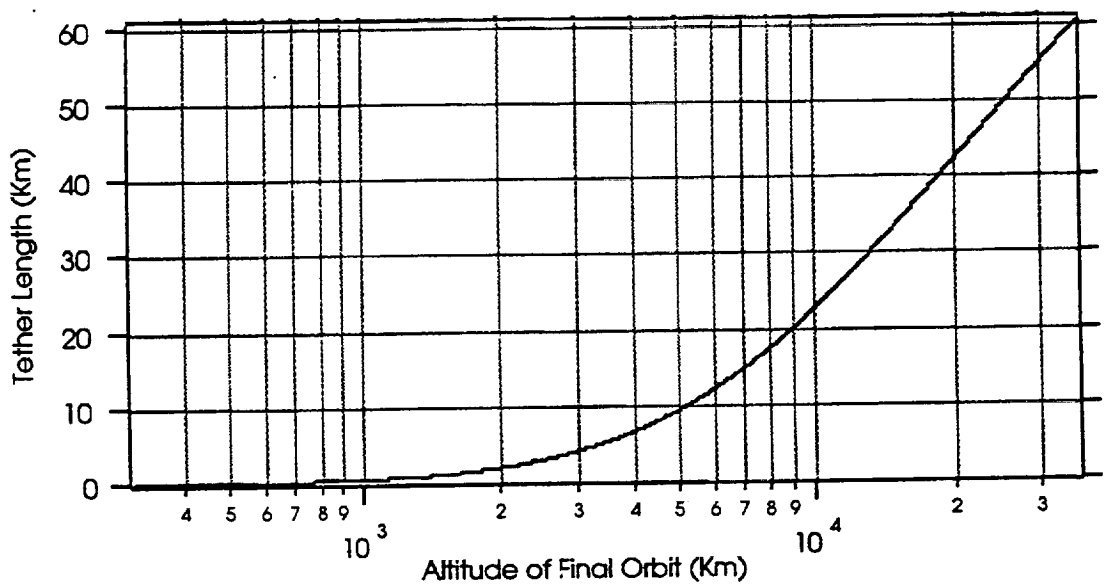


Figure 12 LEO tether transfer system dimensions.

Other Tether Transportation Applications

In addition to those applications already discussed, tethers can be used in other configurations for space transportation. Among these are:

1. Lunar Rotovator: A rotating tether facility placed in orbit around the moon takes advantage of the lunar atmosphere to 'dip' downward to the surface and deposit/grapple payloads. Used in conjunction with a multistage rotating tether system this could make routine access to the lunar surface cost effective.
2. Electrodynamic Catapult: A linear motor accelerates a payload along a long conducting tether 'guide' to achieve a delta-V of 30-100 km/s. The concept is basically a space-based rail gun launcher.
3. Tether Launch Towers or Space Elevators: Long tethers (>100's of km) suspended in orbit transfer payloads via space elevators.

Tether Technology Readiness Levels

Electrodynamic

TRL 7 Achieved with TSS-IR and PMG missions

'Hanging' Momentum Exchange

TRL 7 Achieved with SEDS-1,2 and TSS-IR missions

Rotating Momentum Exchange

TRL 4 Achieved; TRL 5 can be met with application of Automated Rendezvous and Capture (AR&C) technology and development of long-life tethers. TRL 6 requires space demonstration

Catapult

TRL 2 Achieved; Requires concept study and subscale laboratory demonstrations

Rotovator

TRL 2 Achieved; Requires concept study and subscale laboratory demonstrations

Space Elevators

TRL 5 Achieved for crawlers, Long life tether development required; TRL 6 Achieved for deployer and scaled tether with SEDS and PMG missions.

Tether Technology Implementation Cost Drivers and Reduction Method Proposed

1. Control laws are unique to a specific mission; Invest in automated process
2. Lightweight long life tethers; Develop highly survivable tethers (SBIR in-process)
3. Rendezvous and docking with moving target; Automate and build upon on-going AR&C work
4. Solar arrays; Use industry standard arrays and invest in advanced technologies
5. Tether for catapult; Invest in advanced materials
6. Accumulation of ballast mass on-orbit; Use "thrown away" on-orbit masses (ETS, MIR, Progress, etc.)
7. Extremely long tether fabrication; Utilize mass production techniques
8. Tether crawler development for space applications; Evolve current research.

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3. Johnson, Les, et al, "Electrodynamic Tethers for Reboost of the International Space Station and Spacecraft Propulsion", AIAA 96-4250, 1996.

4. Lorenzini, Enrico, Smithsonian Astrophysical Observatory. Technical input to the NASA MSFC LEO-to-GEO Momentum Transfer Tether Study, 1996.

5. Tethers In Space Handbook, Second Edition, 1989.

3.6 Beamed Energy Transportation

Speaker:

Sandy Montgomery

A "Beamed Energy Transportation (BET) technology workshop was held at MSFC October 3-4, 1996. It included a summary review of recent component technology advancements relevant to the development of new technology launch vehicles and space transfer systems utilizing high average power laser beams and/or microwaves. Potential applications and benefits of a beamed energy system were also discussed. The goals and organization of the NASA Beamed Energy Transportation (BET) development plan were discussed. The results of the workshop are included as a part of the TIM Executive Summary.

Overview

There are unique economical considerations in comparing a beamed energy architecture to conventional propulsion means. Probably the highest is the utility nature of a system designed to provide high quality power to distant facilities. The same system designed to support propulsion has inherent potential for supporting basic energy needs of the payload (or target) and as a communication medium. Past studies have focused on economical analyses of battery charging for COMSATS and providing power to a lunar base. (Ref. 1, 2)

Component Technology State-of-the-Art

High average power Free Electron Lasers (FELS), high power diode arrays, and microwaves were identified as having the appropriate operational efficiency needed in a continuously operating utility. However, demonstrated power levels for these are quite low. For beam production in the early phases, gas dynamic lasers appear to be the only alternative - despite their unsuitability for long run times and/or high duty cycles. Possibly, a non-coherent diode array such as that being developed by Lawrence Livermore National Laboratories (LLNL) for laser pumping could be stacked like bricks to produce one kilowatt per centimeter squared. The cost would be $10-$100/Watt today, but that price could drop to $1/Watt with economics of scale. Research into phase-locking techniques for higher efficiency was discussed as well. Government and industry expertise in coherent and incoherent lasers, beam direction and propagation, target interaction, power conversion to propulsion, project management, and overall system and mission analysis were presented at the workshop. Microwaves were only marginally represented. John Cole, the MSFC Space Transportation Research Manager and Sandy Montgomery, the MSFC Beamed Energy Transportation Manager, opened the workshop by presenting brief overviews of their programs. Emphasis is on the pursuit of enabling technologies, not the further refinement of existing technologies. Both stated the importance of demonstrations.

Concepts Identified

Two of the most attractive beamed energy missions identified in the workshop were the airbreathing launcher and the orbital transfer vehicle. Realistic levels of laser power and momentum coupling restrict the launch mission to relatively small payloads. In this area, a near term demonstration seemed most feasible. On the other hand, orbital transfer missions appear to promise greater mid-term benefits. The observation that "there are no major technical barriers to beamed power" (referring to physics, not engineering) was debated and accepted. It was noted that politics and economics would be leveraging factors.

Technology Discussions

SELENE is an "Electric Utility for the Space Industry" and a commercial power beaming venture of the City of Ridgecrest, California, Lawrence Berkeley Laboratory, the California Space Authority, and the Western Commercial Space Center (WCSC). Their discussions with Intelsat indicated waning interest in battery charging because their current spacecraft have delicate thermal balances and technical obsolescence is the most common life-limiting factor today. Much higher power satellites in the 100 kW category will represent an emerging market by 2005, and reduction of GEO launch costs to $20 k/kg would be of great interest. There is interest from other parties in GPS power augmentation and in power beaming to LEO for all-weather radar and satellite deboost.

An aerostat-based relay optics concept to dramatically increase the coverage without incurring the propagation and cost penalties associated with orbiting space relays was presented. Such a relay might be used with a simple plastic block thruster to provide propulsion maneuvering and boost/deorbit capabilities for LEO and MEO (Iridium-type) satellites. A LEO/MEO system might find commonality with an orbital debris removal capability.

Laser propulsion experiments for the Lightcraft Technology Demonstrator (LTD) airbreathing engine were presented. The baseline device uses the plug nozzle after-body to produce a ring line focus of an incident pulsed laser beam, and the resulting air breakdown and blast wave act on the annular shroud to produce thrust. Ballistic pendulum tests using the Pulsed Laser Vulnerability Test Stand (PLVTS) carbon dioxide laser at White Sands measured coupling coefficients up to 20 dynes/watt and predicts up to 50 dynes/watt can be expected. Static tests using the multi-MW 3.6m MIRACL are planned in the near future.

A Laser-Powered Heat Exchanger Rocket for Ground-to-Orbit Launch was presented in which hydrogen is laser heated in a microchannel heat exchanger.

Laser-photovoltaic interaction test results were reviewed that led to the decision to drop the induction Free Electron Laser from the SELENE program. High I^2R losses will produce unacceptable performance losses with any laser pulse format departing significantly from CW operation.

Advantages in promoting solar thermal and solar electric propulsion as evolutionary stepping stones to laser electric systems were discussed. A resistojet was recently replaced by an arcjet in an on-going spacecraft program. It was a low risk evolutionary change that promised a good return on investment.

LEO-based COMSATS are the most expensive because of the large numbers required by their poor coverage and rapid attrition. GEO requires the fewest satellites, but it is expensive to get there, and more power is needed for transmission. MEO, therefore, appears to be optimum. Damage to photovoltaics caused by the radiation are expected to be resolved soon, causing the communication satellite market to move to MEO.

Micro-satellites launched by power beaming with large lasers might be used to dramatically reduce the cost to LEO and MEO, however, microsats can not give decent data rates over long distances. Such capability has not been developed because of the practical lower limit to the size of conventional rockets. Laser launchers could open an entirely new market.

Real potential mass markets in space - aside from military - are tourism, transportation, and communication. Space manufacturing is another potential market in space. It is unique in that payloads have to be returned as well as delivered. The concept of providing a cheap capability to test out new technology components in a space environment was mentioned which also had the same property. Space manufacturing and crystal growing could be a potential mass market but it will be difficult to compete with improved silicon production techniques on the ground.

Conclusions

Specific comments from attendees at the meeting included:

1. Use MIRACL to perform launch experiments/demos with several different concepts. Encourage participation by Phillips Laboratory and Wright-Patterson.
2. Concentrate on horizontal wire-guided or tracked tests for airbreathing engine.
3. Push an on-orbit demo, perhaps piggy-backing. Get laser and microwave operating communities involved.
4. Try to tie in more closely with commercial user community.
5. It is valuable to tie in with the Orion orbital debris removal concept. Consider using a liquid layer over a black surface to increase coupling. Benefit from DoD interest in SAR, surveillance, ASATs, etc.
6. Orbit transfer offers a good opportunity if the view problem can be solved. None of the other possibilities (chemical, etc.) are cheap.
7. Need to show technical feasibility with demos. Perform market analysis and cost

comparison with other techniques. Need good systems analysis. Piggy-back the solar people. Produce a catalog of available lasers.

8. Perform solar parameter tests. Pursue the heat exchanger rocket. Use diode laser to power an airplane.
9. Orbital transfer has to be electric (ion or Hall) with a laser. Definite niche for launch of micro payloads.
10. Consider air-cooled PVs for beam-powered aircraft. Use replication to fabricate LTD nozzles.
11. Need a cheaper way to build big lasers.

Summary

These synopses contain many pertinent observations relating to the technical and cost drivers for Beamed Energy Transportation. The operational issues and their impact on cost were not discussed to a large extent at the workshop. It is noted that a range safety program was initiated and was basically completed for the Orogrande GBL site at White Sands and a similar process will begin this year for the US Naval Air Warfare Center at China Lake. An early SELENE study located a number of good candidate sites located around the world. As suggested by Dr. Glenn Zeiders, component technologies are in the 4-6 range for entry beamed energy applications. System technologies are needed, but not expected to be a show-stopper.

It was noted, in conclusion, that a typical buy-in price for a small launch is $15 M for 1000 pounds using Pegasus, but the ride can be shared, so $15 K/lb is realistic. The AIST goal of $100-200/lb is a great improvement over that, but one which may be an appropriate goal for research. The BET program is releasing a NASA Research Announcement next year to identify key research requirements, the sequence for its accomplishment, and an implementation schedule. Also, the three year program will include high value demonstrations of systems capable of meeting two beamed energy goals:

I. Earth-to-LEO transport of 1-100kg payloads for < $100/lb.

II. LEO/MEO/GEO orbital transfer of 500-2500kg payloads for < $1,000/lb.

After the meeting, a review of current US laser resources was prepared. This and other references and discussions can be found in the conference proceedings.[3]

References

1. Dr. Andrew Meulenberg, "Application of Laser Power Beaming to Commercial Communications Satellites", SELENE Advocacy Briefing and Progress Review, Washington, D.C., July 16, 1992.

2. Dr. Jeffrey H. Smith, "Lunar Power Systems Analysis, Laser Beam Power Feasibility Study", Proceedings of the Review of SELENE FY91 Program Results & FY92 Program Kickoff, Marshall Space Flight Center, AL 35812, December 10-11, 1991.

3. Dr. Glenn W. Zeiders and E.E. Montgomery, Proceedings of the Beamed Energy Transportation (BET) Annual Technology Workshop. George C. Marshall Space Flight Center, AL 35812, October 3-4, 1996.

Appendices

Appendix A	TIM Agenda
Appendix B	Vehicle Systems Overview Charts
Appendix C	AIST Terms of Reference
Appendix D	Participants

Appendix A

AIST TIM Agenda
October 16, 1996
UAH University Center

7:30	Speakers Breakfast Exhibit Hall A	
8:30-9:00	Welcome Remarks Overview of TIM	C. Hawk A. Roth J. Mankins
9:00-9:30	Advanced Space Transportation Progs	G. Lyles
9:30-10:00	HRST Overview	J. Mankins
10:00-11:00	AIST Phase I Study Results	L. Curtis
11:00-11:30	AIST Phase II Study • Objectives • Scope • Groundrules & Assumptions • Reusable Propulsion Concepts • NRA Schedule & Funding	J. Mankins J. Cole
11:30-12:00	Cost/Operations/Manufacturing	G. Woodcock
12:00-1:00	Lunch	
1:00-4:00	Concept Breakout Sessions (Panel Discussions) • Solar (Room 126 A) • MHD (Room 126 B) • Breakthrough Physics (Room 137) • Nuclear (Room 126 C) • Tethers (Room 146) • Vehicle Systems (Exhibit Hall A)	 Ed Cady L. Curtis J. Chapman R. Frisbee S. Borowski B. Emrich Les Johnson Chris Rupp John Mankins Bill Escher
4:00-5:30	Status Report on Concepts Meeting	Chairmen
6:00	Mixer & Dinner at Bevill Center	

Appendix A

AIST TIM Agenda
October 17, 1996
UAH University Center

7:30	Speakers Breakfast	
8:30-9:00	Announcements/Expected Results	C. Hawk J. Mankins
9:00-12:00	Concept Breakouts (Panel Discussions)	
	• Solar (Room 126 A)	Ed Cady L. Curtis
	• MHD (Room 126 B)	J. Chapman
	• Breakthrough Physics (Room 137)	R. Frisbee
	• Nuclear (Room 126 C)	S. Borowski B. Emrich
	• Tethers (Room 146)	Les Johnson Chris Rupp
	• Vehicle Systems (Exhibit Hall A)	John Mankins Bill Escher
12:00-1:00	Lunch	
1:00-3:00	Wrap- up Panel Discussions • Results • Conclusions • Recommendations	Chairmen
3:00-3:30	Action Items	C. Hawk
3:30	Adjourn	

Appendix B

Vehicle Systems Overview Charts

AIST Cost Definition

AIST Price = Recurring Cost* (Technical) + Financially Driven Costs

AIST Goal: ~ $1,000/$2,000 per Pound to "GEO and Beyond"

Includes Cost of Capital, "Profit," Amortization of DDT&E, etc.

*Operations, Support, Fleet Cost, Hardware Spares Cost, etc.

AIST Vehicle Systems

- *Concept Teams*
  - Solar (thermal, electric, sail, wind)
  - Nuclear (thermal, electric, gas core, fusion, antimatter)
  - Tethers (momentum, electrodynamic, rotavator, catapult)
  - MHD (MHD-chemical, MHD-electric, MHD-thermal)
  - Beamed power (laser electric, laser ablator, laser thermal, RF-electric, laser fusion)
  - "Breakthrough" physics (inertia cancellation, gravity cancellations "warp drive," worn holes)
  - Chemical (HEDM, PDWE)
  - Aeroassist
  - Gravity assist
  - Surface based catapults

A wide variety of propulsion technologies could be considered.

"What Must Be...?"

- High payload ratio (> 0.4) to min. ETO cost percent
  - → Overall (not per ETO)
  - ≅ Mass payload ÷ total mass ETO → ≤ $500/lb
- Low ops personnel costs (< 200 folks*)
  - ≤ $250/lb allowable
- Low vehicle hardware costs
  - ≤ $200–$300/lb per mission
- "Short" trip times/high use of capacity*
  - – e.g., ~ 2–4 weeks LEO-GEO, LEO-MEO

*Per 100,000 lb/year total payloads and "ops cost" from MKT

"What Must Be...?"

General Issues

- Must be "Packageable" (volume) to fit in "Existing" ETO vehicle
- Minimum space "Junk" (i.e., debris) contribution
- Should accommodate a wide range of ΔV's (across DRM's)
- Reusable systems (especially) must account for the cost of failure

AIST System "Must Be's"

Solar

- Thermal
  - Reusable ⟶ very large concentrators (e.g., MW'st)
    ⟶ very high temperature materials
  - Acceptable T/W
- Electric
  - Short trip times ⟶ very large arrays (e.g., MW'st)
    or high levels of onboard power
  - High-efficient thermal management strategies, > accept T/W
- Sails
  - Must be ultra low cost due to very limited DRM application
- Wind
  - TBD – unknown how to make it work

Nuclear

- Must satisfy nuclear safety/disposal/basing requirements
- Must satisfy constraints at acceptable cost

- Thermal
  - Must be long lived, high reliability
- Electric
  - Must have high levels of power (e.g., MW's)
  - Must have high efficient thermal management
- GCR
  - Must really satisfy safety, etc.
- Fusion
  - ? Unknown how to make economically draft MTV option
- Antimatter
  - ? Unknown how to make economically draft MTV option

AIST System "Must Be's"

Tethers

- Must be very high reliability

- Momentum
  - Must be very long life
  - Reboost must satisfy $\Delta\tau$ goals (high power)

- Electrodynamic
  - Must have high onboard power (e.g., MW's)
  - Must be very low cost (due to orbit ops limits)

- Rotating
  - Must be very long life
  - Reboost must satisfy $\Delta\tau$ goals (high power)

- Catapults
  - Must be very long life
  - Reboost must satisfy $\Delta\tau$ goals (high power)

Beamed Power

- Must resolve initial basing issues

- Laser Electric
  - Must have high power levels onboard (e.g., MW's)
  - Must have high reliability at affordable cost

- Laser Fusion
  - Must have high reliability at affordable cost

- RF Electric
  - Must have high power levels onboard (e.g., MW's)

- Laser Thermal/Ablator
  - Must satisfy air control (safety issues) (inclusion of space systems risks)

AIST System "Must Be's"

Chemical

- HEDM
  - Must not put ETO "at risk" (or payloads or pads)
  - Propellant cost must be "acceptable"

- PDWE
  - Must achieve long life/high reliability for reusable systems or low manufacturing cost for expendables
  - Must have very low cost contributions due to hardware (low cost manufacturing or reusability/reliability)
  - Must drive down ETO cost contribution

- Very Advanced "Conventional"
  - Must have very low cost contributions due to hardware (low cost manufacturing or reusability/reliability)
  - Must drive down ETO cost contribution

AIST Strategic Design Issues

- Must quantify/understand the strategic trade between

Expendable	*or*	*Reusable*
(Low cost manufacturing)		(Low cost contribution due to manufacturing)

- Must characterize/understand the trade between AKM or NO AKM as a function of "STV" prop. tech (i.e., Isp)
  - Must also treat number of engineer starts, probability of failure at start (vs. tech. investment)

AIST System Strategic Design Ideas

- Examine the limits on small NTR propulsion
  - Especially for LEO-MEO-GEO applications
- Increase performance margins to increase life, reduce failure probability, reduce maintenance
  - May entail operating systems in low stress modes
- Consider continuing R&D investments (improvements over time, e.g., in reusability)

National AIST Strategies

- Create a "large" Virtual Market Place (common systems, etc.)
- STV Class Transport
  - Higher performance prop./"smaller" vehicles
  - Reusable systems/long life
  - Low cost ops/autonomy
  - High "utilization of capacity"
  - "Zero" non-productive in-space infrastructure
- LEV/MEV Class Transport
  - Derive from low cost ETO systems
  - Derive from STV systems
  - ISRU
- MTV Class Transport
  - High levels of vehicle systems modularity

Appendix C

AIST Terms of Reference
June 1, 1996

Geo and Beyond at $1,000-$2,000 per pound

Introduction and Background

To develop and encourage revolutionary commercial utilization of space beyond low Earth orbit (LEO) — including geostationary Earth orbit (GEO) and beyond — and to provide an affordable means to continue NASA space science and exploration missions, the transportation costs to destinations in space must be radically reduced. The Reusable Launch Vehicle (RLV) program is planning to demonstrate technology to allow US industry to develop a new generation of space launch systems. These systems will be capable of delivering payloads in the 20,000 to 40,000 pounds class to LEO for prices of approximately $1,000 to $2,000 per pound. In addition, post-RLV advanced concepts are being identified (e.g., in the Highly Reusable Space Transportation (HRST study) and technologies developed (i.e., in the Advanced Space Transportation Program (ASTP) that may enable ETO costs of $100-$200 per pound or less. Many missions require transportation beyond LEO, with costs of more than $20,000 per pound using current technology systems (e.g., Titan IV with a 11,500 pound payload to GEO @ $22,000/pound). New upper stage concepts for RLV or new in-space transportation systems must be developed in order to significantly reduce the cost of in-space transportation.

An initial assessment of Affordable In-Space Transportation (AIST), conducted during FY 1995, discovered that none of a selected set of six nearer-term concepts can approach these aggressive goals for an initial challenge of transport between LEO and GEO. At the same time, increased interest has emerged in transportation beyond GEO, especially relating to future low-cost exploration missions.

An additional advanced concepts study project AIST is needed (1) to identify or invent new, radically innovative system, concepts, architectures and technologies that have the potential to meet a goal of $1,000 per pound for transportation to GEO and beyond, (2) to analytically examine these concepts and architectures to assess relative performance and issues, and (3) to define a roadmap for further studies and experiments.

Objectives and Scope

The principal objective of this study is to conceptually define 4-6 approaches to in-space transport of both satellites and other payloads, and people, beyond LEO. The study will address:

(1) A range of payloads including: (a) payloads up to the 10,000 pounds class to GEO destinations, (b) payloads in the 1,000-3,000 pounds class to GEO and beyond, and (c) payloads up to 50,000-100,000 for exploration missions.

(2) A common transportation cost goal across payloads of all types of $1,000-$2,000 per payload-pound.

(3) Safe transportation of people to and from all destinations, focusing on inner solar system destinations.

Other aspects of the study include: Both expendable (but "restartable") and reusable in-space systems will be considered. Various approaches for ETO will be considered. Advanced upper stages concept will be considered as well as advanced in-space systems. Transportation services based on these concepts should have the potential to be viable in the long-term as privately financed and operated business that would entail significant commercial potential.

For the system concepts that exhibit good potential, the identification of technology development requirements will be made. The government's role in any system will be limited to technology research, technology developments and risk-reducing demonstrations. Potential secondary commercial (space or non-space) applications or NASA space applications will be identified.

Technical Scope

Requirements

The study will develop requirements from a wide variety of sources. It will use input from the Interagency Requirements Working Group to develop nearer-term payload requirements for an in-space transportation system. The Commercial Space Transportation Study (CSTS) results will be used as a source for mid- to long-term commercial space requirements. Payload destination, mass, configuration, environment, and interface requirements will be identified for use in this study. For this study, specific transport missions — including various payloads — will be examined. A typical payload mass and destination will be used to provide comparisons between system concepts.

The AIST study will also coordinate with other relevant advanced concepts study projects including Space Solar Power, Solar System Resources Exploration and Development, Highly Reusable Space Transportation, and others as appropriate.

Architectures

The study will be leveraged off of the 1981 Advanced Propulsion Systems Concepts for Orbital Transfer Study, the 1994 Reusable Launch Vehicle Upper Stage Study, and the FY 1995 AIST study. The study will include examination of various architectural approaches to achieve delivery of payloads and people to/from GEO and beyond. A variety of ETO strategies may be considered.

Propulsion System Approaches

The focus of the study will be on advanced concepts. (More traditional propulsion system approaches were considered during the initial FY 1995 AIST study and were found to be incapable of meeting AIST goals.) Propulsion system reusability will be evaluated as a characteristic baseline. The following systems and combinations of systems may be examined: Solar Thermal, Solar Electric, Chemical with an Aerobrake, Advanced Momentum Transfer Approaches (e.g., Tethers), Chemical (Solids, Storables, Cryogenic propellants, Hybrids), Beamed Power, Nuclear and other approaches using more than one propulsion system. From an initial review of the various propulsion systems 4-6 most promising system concepts will be identified for further study.

Operations and Servicing Strategies

Reduction of operations costs is one key to providing an affordable in-space transportation system. Some appropriate degree of reusability will be considered as a baseline to determine cost and benefit limits for specific approaches. Systems may involve: no servicing, servicing with an in-space infrastructure, or servicing with a ground-based infrastructure. Cycle limitations, infrastructure costs, and ETO downmass constraints will be considered for transportation systems concepts (where applicable). Also, the potential for providing integrated power and propulsion to the payload/spacecraft will be examined for the transportation systems studied.

Additional System Applications

Identification of opportunities for secondary commercial applications (space or non-space related) of AIST technologies will be made in this study. The potential for evolutionary capability of various system concepts will be considered. (This evolutionary capability may include delivery of payloads for Lunar, Asteroid, or Mars missions.)

Cost Estimation and Economics

Preliminary estimates of system element costs and uncertainties will be made consistently across the study. Top level cost comparisons between the system concepts will be conducted. Broad economic analyses will be conducted. Follow-on studies will define costs and uncertainties more precisely and will explore the identification of uncertainties, and the relationships between concepts, technologies, costs.

Programmatics and Schedule

Project Approach

The AIST project will be conducted as an integrated study, with supporting studies and analyses identified and implemented as required for specific developing concepts. The project approach will include:

- Team formation
- Assessments of past studies
- Selection and definition of 4-6 promising top-level architectures and system concept options
- Parametric analysis of performance for various options (Including cost estimation)
- Assessment of the potential markets and economics
- Identification of needed technologies and opportunities

Meetings and Workshops

The project will be conducted using the Internet and through regular by-invitation working meetings. A single major workshop will be held during Winter 1996-1997.

External Activities

(Industry Participation)
Industry will be involved through direct contracting to involve key individuals in the aerospace systems houses.

(Related Government Studies)
The project will be coordinated with the Highly Reusable Space Transportation (HRST) advanced concepts study project and with the Reusable Launch Vehicle (RLV) program (especially the Upper Stage portion of the RLV program). Coordination with in-house, contracted studies, and Air-Force studies of various advanced in-space transportation concepts will also be done.

Schedule

The study will begin in June, 1996 and will require approximately 12 months to complete.

Participants

A list of specific people and institutions and their responsibilities, will be developed and provided in the project plan, and updated during the course of the study. Participants will include:

- NASA HQ (the Office of Space Access and Technology (OSAT)
- Marshall Space Flight Center (as study lead)
- Lewis Research Center (addressing studies of nuclear thermal propulsion, electric propulsion and related concepts)
- Jet Propulsion Laboratory (addressing studies of very advanced concepts, and fusion propulsion options)
- Aerospace (including companies, consultants and advisors, and professional associations)

Other government organizations may also participate including: the Department of Defense and the Departments of Energy, Commerce, and Transportation (through the Interagency Requirements Group).

Appendix D

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