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Alternate Propulsion Energy Sources
An Introduction

What follows is a paper prepared for the Air Force by Dr. Robert L. Forward on energy sources for space propulsion. It contains a quick look at a wide variety of exotic propulsion methods.

Dr. Robert Forward is familiar to many space enthusiasts. A physicist and author, he is famous for his radical ideas in physics and technology, many of which involve space propulsion and transportation concepts.

To say Forward is ahead of his time is an understatement. One could compare him to Leonardo Da Vinci or Jules Verne in the sense that he envisions ideas that are often beyond the technology of his era. However, the comparison would be more apt if one imagined Da Vinci describing the Space Shuttle in his papers instead of prototypical parachutes, submarines or helicopters. Forward is the ideal person to report on advanced propulsion systems.

The purpose of the contract under which this paper was written was to make an initial examination of propulsion energy sources, and then to make recommendations on whether or not the Air Force should do follow-up studies of any of them. Forward holds tightly to the contract's purpose: examining propulsion energy sources, not propulsion technology. Note as you read that such far-reaching concepts as laser light sails, tether orbital transfer, launch loops, and micropellet fusion are not recommended for follow-on work because they are only(!) engineering problems, and not new energy sources.

Forward really hits his stride when he gets to the section on anti-matter--a particular specialty of his. Needless to say, he recommends further work in this area. In fact, since this contract was completed, Forward has done considerable work on anti-matter propulsion both for the government and on his own (see the references below).

Interested readers may wish to follow up the many references given by Forward in this paper. A list of names is given of individuals in the advanced propulsion field who contributed ideas. Many of these people, like Freeman Dyson, will be familiar to the reader. References to a number of specific papers are also included.

Despite the wide variety of ideas covered here, there were many propulsion energy sources that were excluded for reasons given in the paper. These excluded concepts are listed without elaboration near the beginning of the paper. The list is fascinating by itself, as many of the concepts are a complete mystery to me. What is a "scissors launcher," or a "cryogenic oscillator"? And what about "Alfven propulsion"?

(Note: the format of this paper has been compressed to put two facing pages together on the same page, so when the text refers to an illustration "on the facing page" it refers here to the illustration or diagram below the text.)

<u>Further Reading by Robert Forward:</u>

Mirror Matter: Pioneering Antimatter Physics, by Robert L. Forward and Joel Davis (1988, John Wiley & Sons, Inc.). As Ed would say, everything you want to know about antimatter--or mirror matter as Forward prefers to call it--is right here in this book. And if it's not, then it's probably in the newsletter that Forward publishes:

<u>Mirror Matter Newsletter</u>, self-described as "an informal, aperiodically issued newsletter on the scientific, medical, and technological applications of stored antimatter." Forward provides the newsletter free to those with a serious interest in antimatter. Write to Robert L. Forward, Editor, P.O. Box 2783, Malibu, CA 90265-7783. I am uncomfortable recommending this publication to a wide audience since, as far as I know, the costs of distributing it free to readers come out of Forward's pocket. However, no set of references on antimatter would be complete without it.

Also recommended for reading enjoyment are Forward's fiction books *Dragon's Egg* and its sequel, *Starquake* (both published by Ballantine Books). The books describe an alien civilization living on the surface of a neutron star, and its interaction with the human race.

Tom Brosz
December 29, 1989

AFRPL TR-83-039 AD:

Phase I Report
for the period
3 March 1983 to
23 May 1983

Alternate Propulsion Energy Sources

June 1983

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SECTION I

INTRODUCTION

The Phase 1 activities were defined by the Statement of Work. A condensed version of the Phase 1 SOW follows:

> **Phase 1: Technical Assessment**
>
> The contractor shall conduct a thorough literature search and carry out an intense technical assessment of the latest concepts in science and engineering that show promise of leading to a major advance in available energy sources for space power and propulsion in the next century. In general, the contractor shall study any physical concept that might derive energy from the space environment, as well as any unconventional methods of storing energy in a compact form that may have applicability to space power and propulsion. The best of these shall be investigated in Phase 2.

A literature search combined with a large number of personal contacts with people involved in the field of advanced propulsion insured that as many new concepts as possible were uncovered. Although some time was spent on detailed analysis when the concept warranted it, most of the activities in Phase 1 were of the data collection type rather than data analysis.

SECTION II

PHASE 1 ACTIVITIES

The ten weeks of the Phase 1 technical effort involved writing 71 letters, taking 7 trips, interviewing 62 people, visiting 17 facilities, giving 7 lectures to a total of 350 people, and reading uncounted numbers of reports, papers, and other documents. This effort resulted in the uncovering of 62 propulsion energy concepts, of which 26 were well defined enough to allow a technical assessment. A list of the 62 propulsion energy concepts uncovered plus the results of the 26 technical assessments are given in the Appendix. The facilities visited and the individuals interviewed are given below.

FACILITIES

The following facilities were visited during Phase 1 of this contract:

Princeton Engineering Department
Institute for Advanced Study, Princeton
Princeton Physics Department
MIT Physics Department
Jet Propulsion Laboratory
Lawrence Livermore Laboratory
Hughes Research Laboratories
Rockwell Space Systems Division
R&D Associates
United Technology Research Center
G-T Devices
BDM Corporation
Air Force Office of Scientific Research
NASA/Lewis Research Center
Fermi National Accelerator Laboratory
California Institute of Technology

INTERVIEWS

The following people were interviewed during Phase 1 of the contract. The subjects discussed are listed after the name of the individual.

Dean George Mueller, Princeton - plasma propulsion
Prof. Arnold Kelley, Princeton - MPD thrusters
- charged particle radiators
- multineedle field emitter
Freeman Dyson, Inst. Adv. Study - microwave sails
- monopole catalysis
- laser pushed lightsails
- relativistic pellet beam
Prof. William Happer, Princeton - spin polarized atomic hydrogen
- "black" potassium ion beams
Dean Robert Jahn, Princeton - MPD thrusters
- psychokinetics (PK)
Dr. Eugene F. Mallove - advanced propulsion library
- solar sails
- rotary catapult launcher
- mechanical scissors launcher
Dr. Gregory Matloff - solar sails
- perforated sails
Dr. Philip K. Chapman, MIT, ADL - rotating tethers
Prof. Daniel Kleppner, MIT - spin-polarized atomic hydrogen
Dr. K. Eric Drexler, MIT - lightweight solar sails
Keith Henson, Analog Prec. - solar sails
- dust-filled radiators
Dr. Philip Garrison, JPL - advanced propulsion
Dr. Robert Frisbee, JPL - advanced propulsion
Dr. Jonas Zmuidzinas, JPL - metastable helium
Dr. Paul Massier, JPL - antimatter propulsion
Dr. Duane Dipprey, JPL - antimatter propulsion
Dr. Giulio Varsi, JPL - solar sails
Dr. William Carroll, JPL - solar sails
Dr. Duncan Steel, Hughes - laser cooling of neutral beams
- Lyman alpha laser
Dr. A. Jay Palmer, Hughes - laser cooling of neutral beams
- solar sustained plasmas
Dr. Thomas O'Meara, Hughes - lightweight lenses
- coherent optical adaptive techniques
Dr. Lowell Wood, LLL - x-ray lasers
- micropellet fusion rockets
Dr. Roderick Hyde, LLL - dynamic towers
- micropellet fusion rockets
Dr. David Morgan, LLL - antimatter propulsion

Dr. George Chapline, LLL - antimatter production
Dr. Alan Holt, JSC - hyperfield resonance drive
Gary Hudson, GCH - chemically initiated fusion
Keith Lofstrom - launch loop
Dr. Eric Jones, LANL - interstellar propulsion
G. Harry Stine - inertialess drives (Dean drive)
Anita Gale, Rockwell - advanced propulsion
Dr. Myron Tapper, Rockwell - metastable helium
Robert Budica, Rockwell - advanced propulsion
Martin Willinski, R&D Assoc. - advanced propulsion
- beamed microwave power
- fission fragment rocket
Dr. Leik Myrabo, BDM - laser propulsion
Dr. Benjamin Adelman, science writer - advanced propulsion
Dr. David Brin, UCSD - tether power and propulsion systems
Prof. Gregory Benford, UCI - antimatter production
Ron Oglevie, Rockwell - flywheel energy storage
Ronald Newlon, Martin-Marietta - cryogenic oscillator
Dr. Brice Cassenti, UTRC - antimatter propulsion
A. E. Mensing, UTRC - nuclear lightbulb engine
Michael Fowler, UTRC - laser thermal propulsion
Dr. Jerry Meltz, UTRC - lasing the ionosphere
Dr. Derek Tidman, GT-Devices - plasma pushed railguns
Dr. S. A. Goldstein, GT-Devices - impact fusion
Dr. Leonard Caveny, AFOSR - advanced propulsion
James Muncy, Congressional Staff - advanced propulsion
Morris Hornik, SSI - mass drivers
Dr. S. Nakanishi, NASA/LRC - microwave free-radical thruster
William Kerslake, NASA/LeRC - rail accelerators
Dr. George Zweig, LANL - quark catalyzed fusion
Dr. Vernon Sandberg, LANL - advanced propulsion
Dr. Peter Gram, LANL - muon catalyzed fusion
Dr. David Buden, LANL - nuclear reactor propulsion
- high temperature prime power engines
- high temperature radiators
Fred Sparber - oscillating proton reactionless drive
- stimulated K capture
- electron excited nuclear radioactivity
Dr. James MacLachlan, Fermilab - antiproton beam cooling
- lithium lens focusing
Dr. Carlos Hojvat, Fermilab - antiproton production
Lt. Col. Roger Dekok, AF Hdq - space weapons
Capt. Stan Rosen, USAF - advanced propulsion
Robert Salkeld, SDC Consultant - advanced propulsion
William Stump, Eagle Engineering - advanced propulsion

CONCEPTS RECEIVING PRELIMINARY PHASE 1 TECHNICAL ASSESSMENT

During Phase 1 many concepts were uncovered in the literature search and the survey of experts in the field of advanced propulsion. Of these, 26 were selected for preliminary technical assessment. They are listed on the facing page. In addition, there were many other concepts previously known or uncovered that were not felt to show sufficient promise of leading to a major advance in available energy sources for space power and propulsion in the next century. These concepts are listed below. As used in this list, the word "drive" implies a mechanism that violates one or more of the laws of conservation of mass-energy, linear momentum, or angular momentum. The concepts are not on this list because they violate conservation laws, but because of the lack of hard evidence to base any assessment on. (Indeed, the real breakthrough in propulsion will come when we can find a way around the momentum conservation laws, just as the last breakthrough came when Einstein and Fermi found a way around the law of conservation of mass by demonstrating how to convert mass into energy.)

CONCEPTS UNCOVERED THAT DID NOT RECEIVE PRELIMINARY TECHNICAL ASSESSMENT

negative matter
antigravity
gravity shielding
gravity propulsion
space warps
time machines
spin annihilation drive
momentum annihilation drive
inertia cancellation drive
inertia redistribution drive
microwave phase drive
oscillating proton drive
water flow drive
electromagnetohydrodynamic drive
hyperfield resonance drive/warp
unbalanced rotor (Dean) drive
tachyons
quantum dynamic energy
black hole thermal energy source
Alfvèn propulsion
fission fragment rocket
radioisotope sail
sodium heat engine
stimulated K capture
e-beam activated nuclear radioactivity
solar heat collector prime power
flywheels
fusion ramjet
psychokinetics (PK)
induced dipole microwave thruster
rotary launcher
scissors launcher
high speed pellet beam
magnetic levitator and thruster
cold-gas turbine thruster
cryogenic oscillator

CONCEPTS RECEIVING PRELIMINARY PHASE 1 TECHNICAL ASSESSMENT

METALLIC HYDROGEN
FREE-RADICAL HYDROGEN
METASTABLE HELIUM
MASS DRIVERS
LIGHTWEIGHT LENSES
SOLAR PUMPED PLASMAS
BEAMED MICROWAVE THRUSTERS
IONOSPHERIC LASER
LASER HEATED THRUSTERS
LASER ELECTRIC THRUSTERS
SOLAR SAILS
PERFORATED LIGHT SAILS
LASER SAILS
MICROWAVE SAILS
TETHER POWER SYSTEMS
TETHER PROPULSION
DYNAMIC STRUCTURES
HIGH TEMPERATURE RADIATORS
NUCLEAR FISSION PULSE
IMPLODED MICROPELLET FUSION
MONOPOLE CATALYZED FUSION
QUARK CATALYZED FUSION
MUON CATALYZED FUSION
ULTRACOLD NEUTRON FISSION
METASTABLE EXCITED NUCLEI
ANTIPROTON ANNIHILATION

CHEMICAL ROCKETS OPERATE NEAR THEIR THEORETICAL LIMIT

After decades of intensive development, engineers have produced rocket designs using chemical propellants that are close to their ideal performance limit. On the facing page is an example taken from the FY81 JPL study. The Space Shuttle main engines use liquid oxygen/liquid hydrogen fuel. The 460 sec specific impulse of these engines are within 98% of the specific impulse obtained on a test stand and within 87% of the ideal specific impulse. There are some chemical fuel combinations that have a slightly better theoretical ideal specific impulse, but even if all the engineering problems are solved, the gain in specific impulse is only about 10% or so. To obtain significantly better performance it will be necessary to change to more exotic fuels, or new methods of propulsion that don't use rockets.

During Phase 1 we looked again at some of the more exotic "chemical" fuels such as metallic hydrogen, free radicals, and metastables. In general we agree with the conclusions of the FY81 JPL study on these three concepts as well as other, previous surveys,[1-3] except that we have uncovered a proposed concept that might overcome the short lifetime limitation of metastable helium.

1. "Advanced Propulsion Concepts - Project Outgrowth", AFRPL-TR-72-31, F.B. Mead, Jr, Air Force Rocket Propulsion Lab, Edwards AFB, CA 93523 (1972)

2. "Frontiers in Propulsion Research", JPL TM 33-722, D.D. Papailiou, Jet Propulsion Lab, Pasadena, CA 91109 (1975)

3. "Advanced Propulsion Systems - Concepts for Orbital Transfer Study", Final Report on Contract NAS8-33935 with NASA/Marshall Space Flight Center by Dr. Dana G. Andrews, Boeing Aerospace Company, Seattle, Washington 98124 (July 1980 to July 1981).

CHEMICAL ROCKETS OPERATE NEAR THEIR THEORETICAL LIMIT

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12657-2

	SPECIFIC IMPULSE		
	IDEAL	TEST STAND	ACTUAL (VEHICLE)
SOLIDS		340	306 (IUS)
MONOPROPELLANT			
N_2H_4	269	264	
BIPROPELLANTS			
O_2/RP −1	461	380	
O_2/H_2	528	470	460 (SHUTTLE)
TRIPROPELLANTS			
F_2/Li $-H_2$	703		
METALLIC HYDROGEN	~ 1700		
FREE RADICALS			
$H + H \rightarrow H_2$(100%)	2130		
METASTABLES			
$He^* \rightarrow He$(100%)	3150		

REF: JPL 715-151(1982)

METALLIC HYDROGEN

Metallic hydrogen is a postulated high energy propellant that releases its energy when the atomic metal is converted into gas molecules. It is estimated to have a specific impulse of 1700 sec and a specific density of 1.15 (solid molecular hydrogen has a specific density of 0.088.) Very high pressures will be needed to produce the metal form of hydrogen. The present estimates[1] are pressures of 1.9 to 5.6 Mbars. Theoretical studies[2] indicate that the metal will be a liquid at all pressures. There has been theoretical speculation that once formed, the metal state may be metastable and remain in the metal form after the pressure is released. Other theoretical estimates seem to cast doubt on any metastable state.

During the Phase 1 survey, it was found that most of the experimental research on producing metallic hydrogen has ceased. The only active work seems to be at the University of Amsterdam[1] using a diamond-anvil cell. Their maximum pressure seems to be 0.5 Mbar.

With little active research on producing metallic hydrogen, and with the theoretical estimates of the required pressures being almost an order of magnitude more than the presently achievable pressures, it seems that the FY81 JPL assessment of the status of metallic hydrogen still stands.

Recommendation: Wait for new high pressure machine concepts that can produce megabar pressures.

1. "Low-Temperature Equation of State of Molecular Hydrogen and Deuterium to 0.37 Mbar: Implications for Metallic Hydrogen", J. van Straaten, R.J. Wijngaarden, and Isaac F. Silvera, Phys. Rev. Let. **48**, 97 (1982)

2. "Absence of Crystallization in Metallic Hydrogen", A.H. MacDonald and C.P. Burgess, Phys. Rev. **B26**, 2849 (1982)

METALLIC HYDROGEN

- ADVANTAGES
  - HIGH THEORETICAL DENSITY (1.15 g/cm^3, SOLID H_2 = 0.088 g/cm^3)
  - $I_{sp} \sim 1700$ s
  - USE AS A SOLID (LIQUID) PROPELLANT
- PRODUCTION VERY DIFFICULT
  - $P \sim 1 - 10$ MBAR, $T < 4$ K
  - PRODUCTION STILL DEBATABLE
- STORAGE
  - ONCE FORMED, MAY BE METASTABLE ON RELEASE OF PRESSURE
- REQUIRES PROOF OF CONCEPT EXPERIMENTS
  - EXISTENCE HAS NOT BEEN SATISFACTORILY DEMONSTRATED
  - PRODUCE AND CONFIRM EXISTENCE (STATIC RATHER THAN DYNAMIC PRESS)
  - DETERMINE T, P LIMITS IF METASTABLE

PRODUCTION OF FREE-RADICAL HYDROGEN

Free radicals are single atoms of elements that normally form molecules. Atomic hydrogen is a free-radical form of hydrogen that can be used as a propulsion energy source since it releases energy when the hydrogen atoms combine to form hydrogen molecules. The ideal specific impulse from this reaction is calculated to be 2130 sec. Although it is relatively easy to produce large quantities of atomic hydrogen by electron bombardment, it has proven difficult to store it in high concentrations. Rosen[1] did a complete survey of the work up to 1973, and showed[2] how to use it as a propellant. The FY81 JPL study covers the work since then. Because of the recent interest in using spin-polarized atoms for fuel in fusion reactors, the research on this field has increased, especially at Princeton and MIT. MIT recently reported[3] storing 0.8×10^{17} atoms/cc for four hours at 0.3 K using a 10 T magnetic field trap, but the lifetime is inversely proportional to the storage density. No really good concepts exist for high density storage.

Recommendation: This work is receiving support from the fusion field. Propulsion oriented funding should wait for better ideas to attain high density storage.

1. "Current Status of Free Radicals and Electronically Excited Metastable Species as High Energy Propellants", Final Report on JPL Contract 953623, Gerald Rosen, Drexel University, Philadelphia, PA (December 1973 revision of August 1973 report).

2. "Manufacture and Deflagration of an Atomic Hydrogen Propellant", Gerald Rosen, AIAA Journal **12**, 1325 (1974).

3. "Magnetic Confinement of Spin-Polarized Atomic Hydrogen", R.W. Cline, et al, Phys. Rev. Lett. **45**, 2117 (1980).

PRODUCTION OF FREE-RADICAL HYDROGEN

- PRODUCE IN SITU IN A SOLID H_2 MATRIX BY PARTICLE BOMBARDMENT
  - CONCENTRATIONS $M_H \sim 0.003$ ACHIEVED AT < 0.1 K FOR H_2 DOPED WITH 2.5% (WT) TRITIUM
- ALTERNATIVE METHODS NEEDED TO ACHIEVE USEFUL CONCENTRATIONS ($M_H = 0.26$)
  - VERY HIGH MAGNETIC FIELD (1 - 10 MG) TO KEEP MOBILE H SPIN ALIGNED DURING IN SITU PRODUCTION
  - VERY LOW TEMPERATURES (< 0.05 K) FOR EFFICIENT TRAPPING DURING IN SITU PRODUCTION
  - PREPARE AS BOSE - EINSTEIN CONDENSED GAS

METASTABLE HELIUM

Metastable helium is the electronically excited state of a helium atom. It releases energy when the helium atom decays into the ground state. The ideal specific impulse is calculated to be 3150 sec (about six times that of oxygen/hydrogen). Metastable helium atoms are easily produced by electron bombardment, either in a gas (helium-neon lasers use the state) or by sending high energy electrons into liquid helium. The theoretical lifetime of the metastable state is 2.5 hours, but typical lifetimes in containers is less than a second. Because of the short lifetime, metastable helium is usually not considered to be a suitable propellant, and the FY81 JPL study came to that conclusion. Recently, however, Dr. Jonas Zmuidzinas (of JPL), suggested some techniques that might suppress the normal spin-orbit decay of the metastable state. If this decay mode were suppressed, then according to theory, the next mode of decay is by double-photon emission, and this lifetime is 8 years.

It is known experimentally that metastable helium atoms can combine with another helium atom to form a metastable helium molecule. Dr. Zmuidzinas, in an unpublished paper[1] has proposed using optical pumping to stabilize these molecules. He also has found theoretical evidence that indicates that these metastable helium molecules may spontaneously form into a solid. He is receiving funding from AFRPL to carry out some experiments to test his predictions. If solid metastable molecular helium doesn't exist, Dr. Zmuidzinas has another possible method to suppress the normal spin-orbit decay. This technique involves irradiating the metastable helium atoms with properly phased coherent laser radiation to inhibit the spin-orbit decay mode.[2]

1. "Stabilization of $He_2(a\ ^3\Sigma_u^+)$ in Liquid Helium by Optical Pumping", J. Zmuidzinas, unpublished (1976)

2. "Dynamic Stabilization of Metastable Atoms", J.S. Zmuidzinas, Applied Physics B28, 107 (1982)

METASTABLE HELIUM

- TWO FORMS
  - ATOMIC $He^* \equiv He\ (2\ ^3S_1)$
  - MOLECULAR $He^*_2 \equiv He + He^* = He_2\ (a\ ^3\Sigma^+_u)$
- EASILY MADE BY 24 keV ELECTRON BEAM IN LIQUID HELIUM
  - 500 He* PER ELECTRON
- HIGH ENERGY CONTENT SUITABLE FOR PROPULSION
  - $He^* \rightarrow He + 19.8$ eV (114 kcal/gm)
  - I_{sp} = 3150 sec (IDEAL)
- PRESENT LIFETIMES SHORT
  - 0.2 sec IN EXPERIMENTAL DEWAR (WALL EFFECTS)
  - 2.5 hour THEORETICAL MAXIMUM (SPIN-ORBIT DECAY)
- LIFETIME 8 years IF SPIN-ORBIT DECAY SUPPRESSED
- THREE APPROACHES
  - STORAGE IN STRONG MAGNETIC FIELDS
  - FORMATION OF FERROMAGNETIC SOLID PHASE OF He_2^*
  - COHERENT LASER PUMP INHIBITION

ESTIMATES ON HE IV

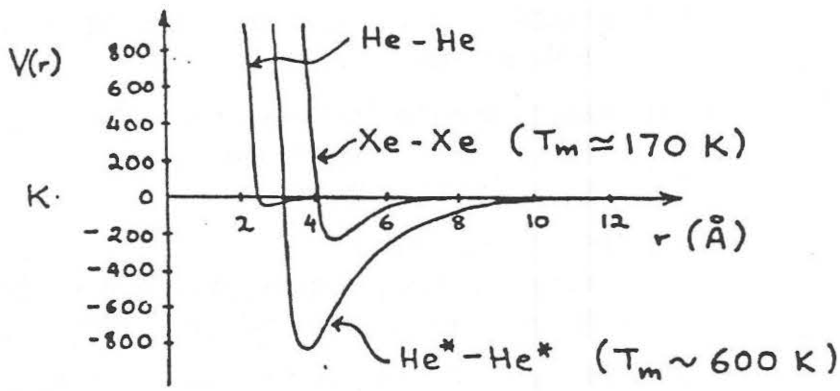
Helium IV is the name given by Dr. Zmuidzinas to a solid consisting of excited metastable helium molecules or atoms. The theory on which the existence of this state is based is a paper[1] which calculates the potential energy curves for the various states which arise from the combination of two triplet metastable helium atoms. The curves all show potential minima, which indicates binding. Even the state where the two metastable states have their spins aligned with an applied magnetic field shows a weak binding. In the diagram on the facing page, Dr. Zmuidzinas compares the potential energy curves of helium to helium, xenon to xenon, and metastable helium to metastable helium. Since xenon has a solid phase that melts at 170 K, Dr. Zmuidzinas predicts a melting point of 600 K for a spin-aligned form of metastable helium atoms. He also assumes that the potential energy curves for the molecular form of metastable helium will look similar to the curves for atomic metastable helium, and therefore predicts it will also form a room temperature solid. Since the spins are aligned, there is good reason to believe that it might be a ferromagnetic solid, which will have an internal magnetic field that will keep the spins aligned, suppressing the spin-orbit decay mode.

Recommendation: It is recommended that metastable helium be one of the concepts selected for investigation in Phase 2. IF all the physics breaks the right way, this concept could provide a new, high-energy, chemical propellant many times better than any existing chemical fuel. The approaches proposed are ingenious and seem to be based on reasonable principles of physics, but they do not seem to have been published in the open literature where they would have received the critical analysis of peer review. Study of this concept should be delayed until the later part of the Phase 2 technical effort since the AFRPL supported experimental work at JPL should start producing preliminary experimental data in August 1982.

1. "Penning and Associative Ionization of Triplet Metastable Helium Atoms", B.J. Garrison, W.H. Miller, and H.F. Schaefer, J. Chem. Phys. 59, 3193 (1973).

ESTIMATES ON HE IV

- ASSUME He_2^* - He_2^* AND He^* - He^* POTENTIALS SIMILAR
- COMPARE WITH HE - HE AND XE - XE POTENTIAL



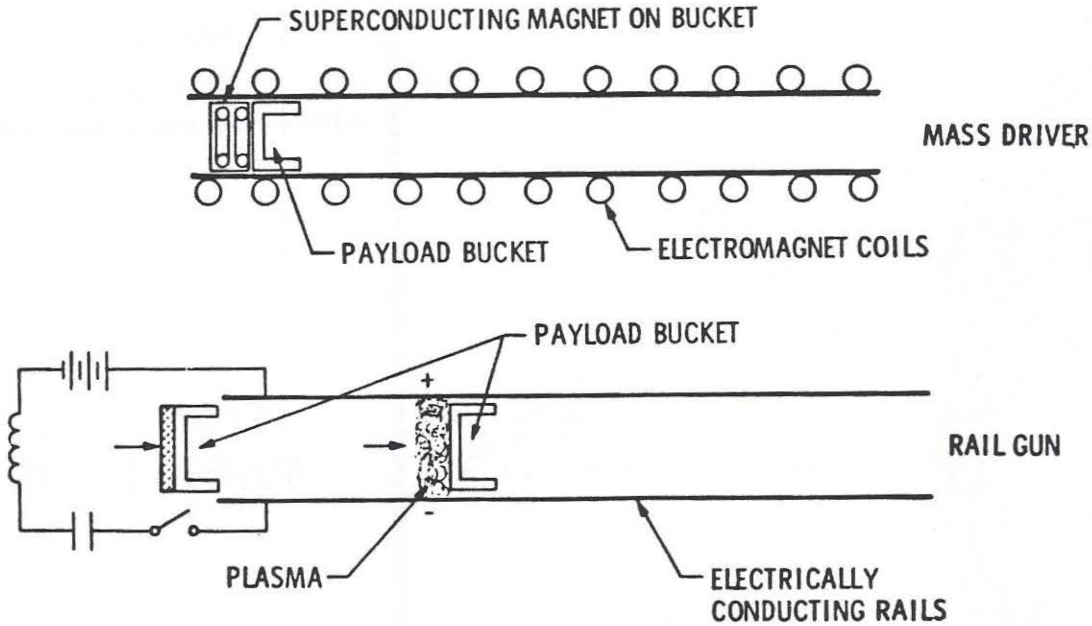
⇒ HE IV CLASSICAL SOLID WITH MELTING TEMPERATURE ~ 600 K

RAIL GUN/MASS DRIVER

There are many types of rail guns or mass drivers. The mass expelled ranges from micrograms of foil to multiton payloads. The driving mechanism is usually electromagnetic but can be electric arc, externally applied plasmas, or any other method of applying a kick to the projectile. Since these systems have the potential of achieving higher exhaust velocities than are obtainable from chemical reactions, they are certainly potential candidates for an advanced propulsion system, although they should always be compared in performance with other electric propulsion systems using the same prime power source.

Recommendation: Because of the extensive amount of work being supported by DOD and DOE in this field, much of which is classified and unavailable to this contractor, and because the concept is a propulsion mechanism rather than a propulsion energy source, it was decided not to invest a large amount of time in Phase 1 on this concept. The concept warrants continued support by the propulsion community but it is not recommended for further study in Phase 2 of this particular contract.

RAIL GUN/MASS DRIVER



LIGHTWEIGHT LENSES AND COLLECTORS

Many of the propulsion energy concepts uncovered in the Phase 1 survey involve the collection or beaming of radiant energy. This usually involves the use of transmitting, focusing, reflecting, or collecting optics. For space applications it is desired that the mass per unit area of these optics be kept low, while the optical properties remain optimum for the mission. A partial list of some lightweight lens concepts follows:

O'MEARA PARA-LENS: A large Fresnel phase plate lens suitable for transmitting, focusing, or receiving laser light. The lens has chromatic aberration. Consists of radial spider-web-like mesh, with alternating layers of nothing and thin plastic with thickness chosen to add a half-wave of phase to the laser light. If focal length is long, can ignore lens motion and fabrication errors of many centimeters.

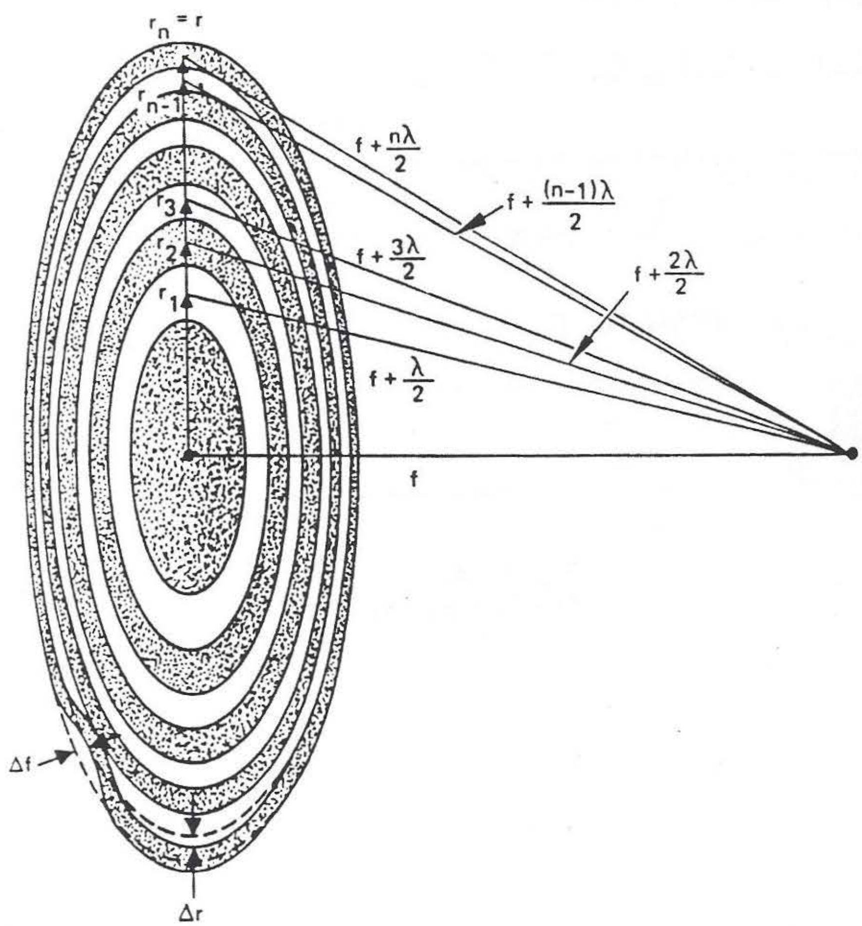
PALMER AEROSOL LENS: Two medium power lasers can interact with an aerosol (actually a vacusol) of optically non-linear drops or beads to form a three dimensional holographic-like Fresnel lens. Probably the lightest-weight lens that can be made.

INFLATED FRAME MEMBRANE LENS/COLLECTOR: See example in the Solar Thermal Rocket figure on a later page.

BALLOON COLLECTOR/LENS: See example used as the collector in the Laser Electric Propulsion figure on a later page.

PLASTIC FILM TRANSMISSION HOLO-LENS: See example used as the relay optics in the Laser Electric Propulsion figure on a later page.

Recommendation: As a generic topic for future space propulsion applications, it would be desirable to maintain funding for engineering research and development for lightweight optics in general. Except for specific proposals that will be made in the Perforated Sails section, most of the research is engineering oriented and probably not suitable for recommendation for studies in Phase 2 of this contract.



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O'MEARA PARA-LENS

LASING THE IONOSPHERE

One of the more exotic of the propulsion energy source ideas uncovered in Phase 1 of the contract is the concept of using large, lightweight lenses on a spacecraft to make the ionosphere lase. In this manner the relatively low energy densities in a large volume of the ionosphere could be collected and dumped through the output laser lens into the spacecraft, which could then use the energy for propulsion.

It is known that certain regions of the upper atmosphere of Mars are superradiant (emitting coherent laser light without the benefit of lenses) in the infrared. Thus, there is reason to speculate that there might be layers in the earth's atmosphere that are inverted enough to lase if mirrors were used to enhance the stimulated emission, but not so inverted that they are superradiant, in which case the mirrors are ineffective in collecting the energy. This concept has been independently invented by at least two people. J.D. Barry of Hughes[1], and G. Meltz of United Technology[2]. Meltz has a proprietary twist that might be worth additional analytical study. Even if not suitable for earth, this concept may be useful around other planets that have more cooperative atmospheres.

The HILAT satellite is scheduled to be launched June 1983 into a 830-kilometer altitude orbit with an 82.2 degree inclination. It will make radio, visible, and UV observations of the ionosphere, aurora, and airglow. The data from this spacecraft may be useful in any studies of ionospheric lasing.[3]

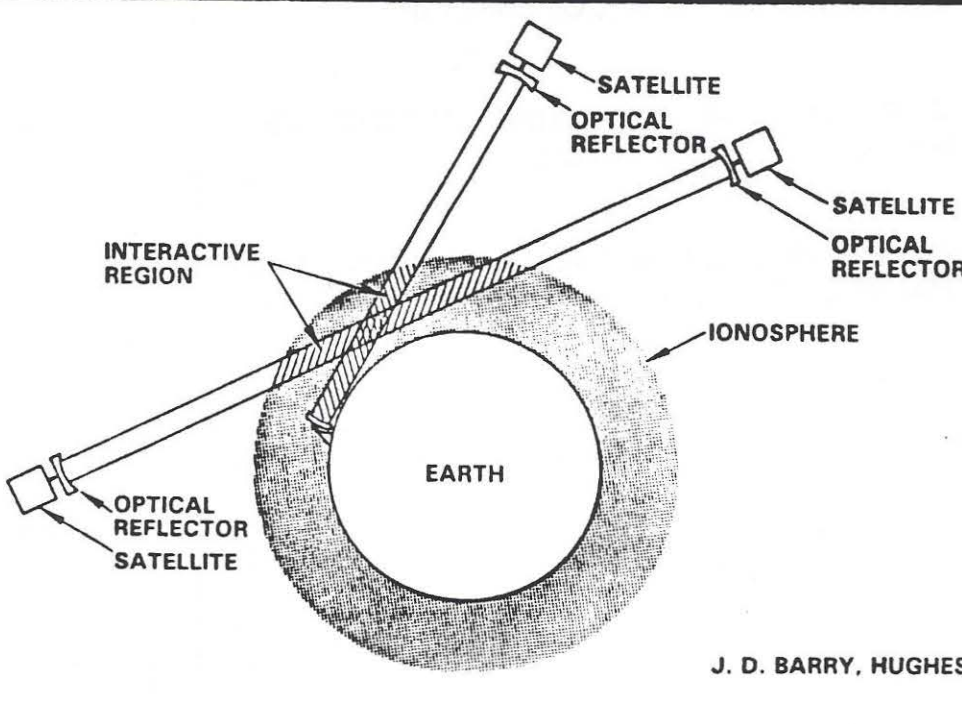
Recommendation: Possibly worth a small paper study or two. The problems are more analytical and engineering rather than basic physics. Might pay to wait for the results of the HILAT program. Not recommended for study in Phase 2 because there are better candidates, but certainly could be included or substituted for another topic if desired.

1. "Auroral Energy Source", (internal undated document [1981?]), J.D. Barry, Hughes Aircraft Co., EDS Group, P.O. Box 902, El Segundo, CA 90245.

2. "LITA", (proprietary document [1977?]), G. Meltz, United Technology Research Center, East Hartford, Conn 06108.

3. "The HILAT Program", (news summary), EOS, Trans. AGU 64, 163 (1983)

LASING THE IONOSPHERE



J. D. BARRY, HUGHES

SOLAR SUSTAINED PLASMAS

Although much research has gone into dc, ac, rf, microwave, and laser excited plasmas for use in lasers and propulsion, it seems that little research is being supported on the use of concentrated sunlight to produce and sustain plasmas. The space environment is full of sunlight, 1.4 kilowatts per square meter or 1.4 gigawatts per square kilometer. We need to find good ways to collect that light and turn it into electricity or thrust. Assuming good lightweight collectors can be developed, we need good converters. In a number of research facilities research is being carried out on dense alkali vapor plasmas that are nearly "black" and can absorb a large fraction of the solar spectrum. (As two examples, Prof. W. Happer of Princeton has made a 1/3 atmosphere beam of potassium ions, and Dr. A.J. Palmer at Hughes Research Labs has used sunlight to heat a cesium plasma to 3000 K.) These hot plasmas can be used in a closed cycle MHD electric generator to produce prime power, or used open or closed cycle to drive high power metal ion lasers, or passed out a nozzle to produce thrust. Although alkali metals are easy to ionize, it is also possible to ionize lighter elements such as hydrogen, especially if it is seeded with small amounts of alkali metals.

Recommendation: It is recommended that solar pumped plasmas be one of the concepts selected for investigation in Phase 2. The energy source is available (given reasonable engineering advances in collector optics) and the feasibility experiments involve basic research in plasma physics on a scale that is compatible with the probable budgets available for Phase 3 activities.

SOLAR SUSTAINED PLASMAS

HUGHES

HUGHES AIRCRAFT COMPANY
RESEARCH LABORATORIES

- CONCENTRATED SUNLIGHT CAN HEAT CESIUM PLASMA TO 3000°K
- PLASMA ABSORBS > 80% OF SUNLIGHT
- HOT CESIUM PLASMA CAN RUN CLOSED CYCLE MHD ELECTRIC GENERATOR
- NOZZLE EXPANDED HOT ALKALI PLASMAS CAN PROVIDE THRUST OR DRIVE HIGH POWER LASERS

REF: A. J. PALMER, HUGHES
MAY 1983

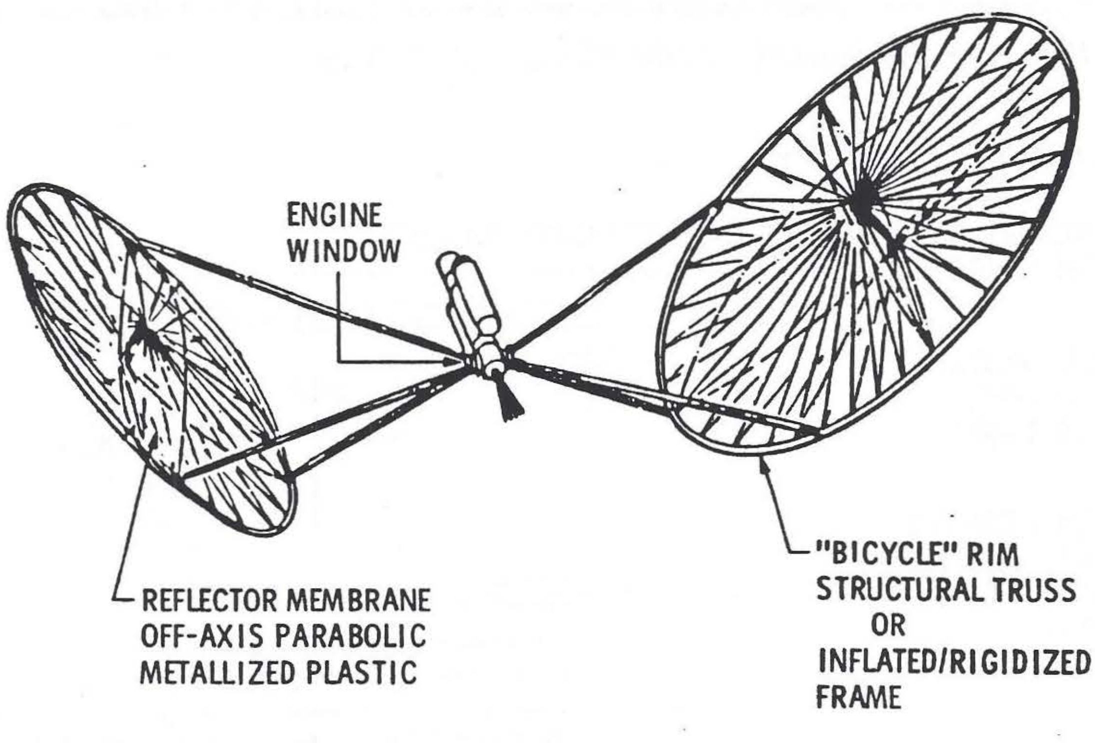
SOLAR THERMAL ROCKET

An example of a rocket using a solar sustained plasma is shown on the facing page. The figure is taken from the FY81 JPL report and shows a solar heated hydrogen rocket designed by Rockwell under an AFRPL contract.[1] Quoting from the abstract of the report.

"A specific impulse of 872 seconds was achieved by passing hydrogen through a heat exchanger placed at the focal spot of a large parabolic dish solar concentrator mirror. With a windowed chamber type of thruster and a particle-laden hydrogen flow, the specific impulse was 1041 seconds. Inflatable construction techniques were determined to be optimum for large concentrating mirrors based on ease of deployment and low specific mass."

1. "Solar Rocket System Concept Analysis" AFRPL-TR-79-79, Final Technical Report on Contract F04611-79-C-0007, by F.G. Etheridge, Rockwell Space Systems Group, Downey, CA 90241 for AFRPL, Edwards AFB, CA 93523.

SOLAR THERMAL ROCKET



LASER THERMAL PROPULSION

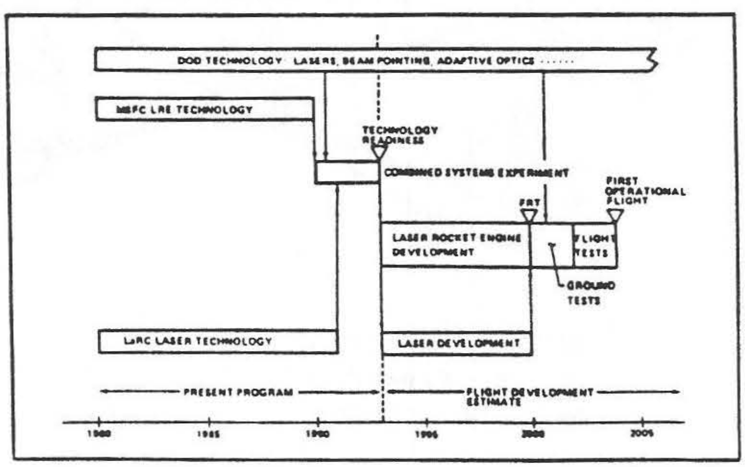
Laser Thermal Propulsion is a concept for obtaining propulsion energy by beaming laser energy to the spacecraft to heat a working fluid. Since the energy source is separate from the reaction mass, the reaction mass can be chosen to have a low molecular weight (hydrogen), and the specific impulse can be tailored to the mission by varying the amount of laser energy supplied per gram of reaction mass.

Recommendation: Laser thermal propulsion can give high specific impulse and high thrust and is a definite candidate for an advanced propulsion system. Because work on the propulsion aspects of this concept is well underway at NASA/Marshall and NASA/Lewis,[1] and work on the high power lasers and the pointing and tracking optics is well underway on a number of DOD and DOE high power laser programs, very little time was spent on this concept in Phase 1, and it is not recommended that this concept be studied further in Phase 2.

1. "NASA's Laser-Propulsion Project", L.W. Jones and D.R. Keefer, Astronautics & Aeronautics, 66 (September 1982).

LASER THERMAL PROPULSION

- ENERGY SOURCE SEPARATE FROM REACTION MASS
- HIGH I_{sp} AND HIGH THRUST
- LASER ENERGY TO THRUST CONVERSION MAJOR RESEARCH QUESTION
- R&D WELL UNDERWAY AT NASA/MSFC AND NASA/LeRC
- PROGRESS AIDED BY LARGE DOD AND DOE HIGH POWER LASER PROGRAMS



JONES AND KEEFER, A&A, 66 (SEPTEMBER 1982)

LASER ELECTRIC PROPULSION

Another form of beamed laser propulsion is to use the narrow beamwidth capability of coherent light to beam the laser energy to the spacecraft. Instead of trying to use the laser light directly by heating a working fluid, however, the idea is to convert the laser light to electricity first, then use the electricity to power an electric thruster. Studies of this concept were done in 1975.[1] This report was briefly reexamined in Phase 1 of this contract. The concepts discussed in those studies are still valid, and any mission analysis involving beamed laser power should consider this option.

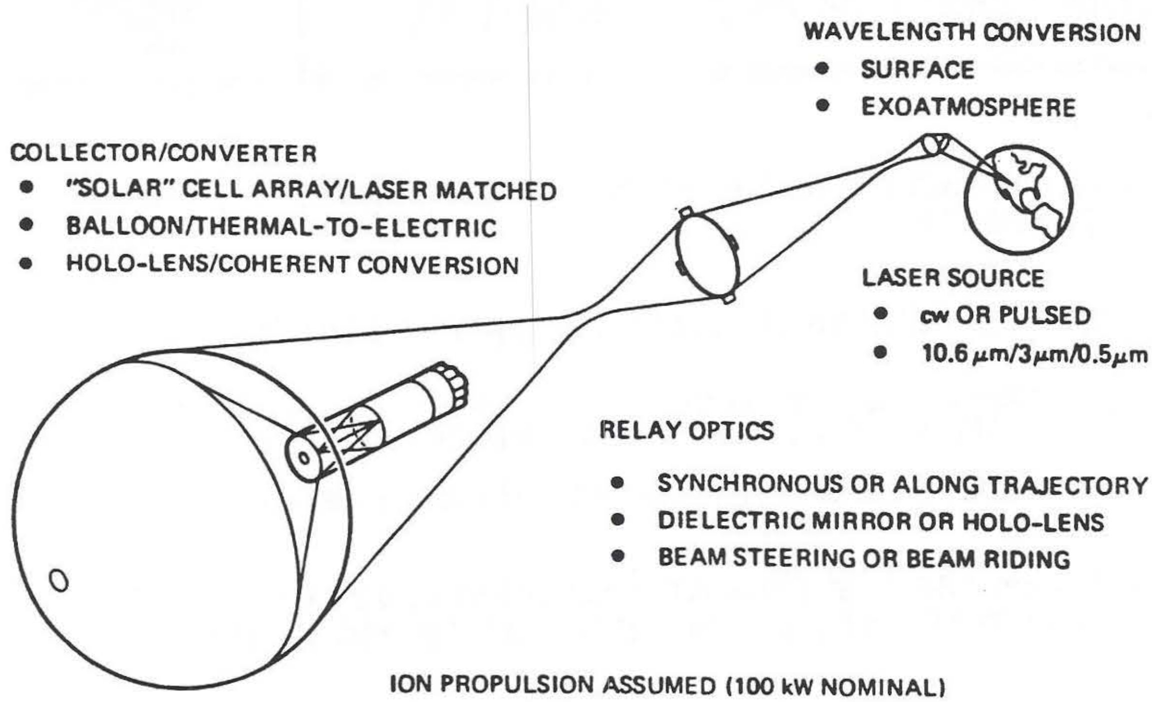
The advantage of laser electric propulsion over laser thermal propulsion is that the electric ion thrusters are well known, tested devices, and the laser to electric photovoltaic conversion process is well known, scalable, and should reach conversion efficiencies of greater than 50% (42% efficiency has been demonstrated in the lab). Also, the laser light collector does not have to be of optical quality since it will be distributing the laser light to a large area of photovoltaic cells.

Recommendation: It is recommended that further studies be made of the laser electric propulsion option, and that research be carried out on optimizing the efficiency of multilayer semiconductor cells for specific laser frequencies. It is not felt, however, that further study of this concept is needed in Phase 2 of this contract.

1. "Advanced Propulsion Concepts Study - Comparative Study of Solar Electric Propulsion and Laser Electric Propulsion", Final Report on JPL Contract 954085, by R.L. Forward, Hughes Research Labs, Malibu, CA 90265 for Jet Propulsion Lab, Pasadena, CA 91109 (June 1975).

LASER ELECTRIC PROPULSION

HUGHES
HUGHES AIRCRAFT COMPANY
RESEARCH LABORATORIES



ION PROPULSION ASSUMED (100 kW NOMINAL)

MAY 1983

BEAMED MICROWAVE THRUSTERS

If studies are going to be made of beamed laser power propulsion, then some thought should be given to beamed microwave power propulsion. The basic concept proposed here is to assume that we will use the existing thruster designs that use microwave power to create and heat a plasma to produce thrust. Instead of generating the microwaves on board, however, the microwaves will be beamed to the spacecraft and sent directly to the thruster. The advantage of this approach is that the high mass penalty of the prime power source and the microwave generator will be replaced by the (hopefully) more modest mass of the collector for the microwaves. It is very likely the thruster designs will have to be modified to optimize the total system performance (i.e. making them operate at high microwave frequencies if possible).

The initial reaction of most people to this concept is that the antennas will be too large. They are large, but the weight penalty for the spacecraft is not too bad if you are willing to make the transmitting antenna large. For example: A 10 kilometer transmitting array at 30 GHz can send power to a 100 meter collecting array at geostationary orbit distances. These antennas are large, but the concept should not be rejected out of hand if good microwave powered thrusters exist.

Another factor that might make this concept more viable would be the construction of a large Solar Power Satellite in GEO. If the microwave transmitter array on the SPS were designed with propulsion as well as prime power in mind, by making the transmitting array large enough and giving it a multiple electronic beam steering capability, then the power that isn't needed on earth could be used for microwave powered tugs moving between LEO and GEO and out toward the moon.

Recommendation: Because the problems to be solved here are mostly those of microwave antenna design and systems engineering, and good microwave thrusters suitable for use with this concept are not yet available, it is not recommended that this concept receive further study in Phase 2 of this contract.

BEAMED MICROWAVE THRUSTERS

- BEAM MICROWAVE ENERGY TO MICROWAVE EXCITED THRUSTERS
- USE PRESENT MICROWAVE THRUSTER DESIGNS
  - MODIFY THRUSTER DESIGN (i.e. HIGHER FREQUENCY OPERATION) TO OPTIMIZE TOTAL SYSTEM PERFORMANCE
  - TRADE POWER SUPPLY WEIGHT FOR COLLECTOR WEIGHT
- 10 km TRANSMITTER AT 1 cm WAVELENGTH (30 GHz) CAN REACH 100 m COLLECTOR AT 36,000 km (GEO)
- 1 km TRANSMITTER AT 3 cm WAVELENGTH (10 GHz) CAN REACH 30 m COLLECTOR AT 400 km (LEO)

SOLAR SAILS - PRESENT STATUS

In 1977 a JPL team designed a number of solar sails that would use near term thin film and structures technology to construct a high-performance spacecraft that could reach the very difficult target of the retrograde Halley's Comet.[1] Although many thought that its predicted performance was better than that of a comparable Solar Electric Propulsion System, the SEPS was chosen for the mission because the technology was more mature. (The SEPS was later cancelled by Congress.)

The solar sail has a major drawback in that it cannot be launched below about 1000 kilometers. The air drag is larger than the solar thrust. A concept to be discussed later, Perforated Solar Sails, may overcome this problem.

Although improved technologies and designs exist that would make a modern solar sail design far exceed an electric propulsion system for many missions, there seems to be no research being supported on these advanced concepts. One small group of engineers[2] is attempting to launch a small sail using private funding. Other than that, no activity in solar sail research was found in the United States, and only paper studies in Europe.

Recommendation: It is recommended that more research be supported in this field. Since the work that needs to be done is more engineering and systems design rather than basic physics research, it is not recommended that further studies be carried out on Phase 2 of this contract with the exception of the proposed research on perforated sails.

1. "Solar Sailing - The Concept Made Realistic", L. Friedman, et al., AIAA Paper 78-82, AIAA 16th Aerospace Sciences Meeting, Huntsville, AL (1978).

2. World Space Foundation, Box Y, South Pasadena, California, 91030

SOLAR SAILS PRESENT STATUS

- 1977 JPL DESIGN - 5T, 850 m SQUARE, 2 μm KAPTON (6 g/m^2) PREDICTED TO OUTPERFORM SOLAR ELECTRIC PROPULSION TO HALLEY'S COMET
- 1979 DREXLER DESIGN - ROTATING TRUSS FRAME WITH TRIANGULAR PANELS 30 nm (300 Å) ALUMINUM FILM PANELS, 0.1 g/m^2, 0.01 g IN ONE SOLAR FLUX
- NO RESEARCH BEING DONE BY ANYONE AT PRESENT TIME
- FABRICATION PROCEDURES EXIST THAT CAN MAKE
  - IMPROVED UNFURLABLE SAILS - 500 nm ALUMINIZED KAPTON (<1 g/m^2)
  - ULTRALIGHT ALUMINUM FILM SAILS — 300 - 30 nm (0.5 - 0.1 g/m^2)
- LIMITS TO PRESENT SOLAR SAIL CONCEPTS
  - ALUMINUM FILM BECOMES TRANSPARENT BELOW 20 nm (0.05 g/m^2)
  - ATMOSPHERIC DRAG PROHIBITS OPERATION BELOW 1000 km
- POTENTIAL SOLUTION: PERFORATED SAILS
  - MAINTAIN RELFECTIVITY WHILE REDUCING MASS
  - MAY HAVE LOW DRAG IN MOLECULAR FLOW REGION

NOTE: $1 \frac{g}{m^2} = 1 \frac{T}{km^2}$

PERFORATED SOLAR SAILS - CONCEPT

It is well known that a microwave reflector does not have to be made of solid metal in order to be a good reflector of microwaves. Many radar dishes, in order to reduce weight and wind loading, are made of wire mesh with holes smaller than the wavelength of the microwave radiation. In the same manner, it should be possible to reduce the weight of a solar sail by fabricating it with holes smaller than a wavelength of most of the light in the solar spectrum. It is also probable that the air drag of a perforated sail will be less than that of a solid sail, especially at high altitudes where the air is in the molecular flow regime. Whether perforated sails can be launched at the upper range of the Shuttle orbital altitude is an unanswered question that can probably only be resolved by a Shuttle flight test.

Techniques exist in the laboratory to make a thin perforated sail. Focused ion beams have already demonstrated the capability to make holes down to 0.1 microns, well below solar light wavelengths. Crossed holographic gratings have already been developed in photosensitive resists and used to make arrays of square posts with 0.2 to 0.5 micron spacing. The use of a positive rather than a negative resist would produce a square grating with similar sized square holes.

Recommendation: Little is known about the optical properties of thin films containing structures such as holes and posts. Even less is known about their thermal properties. It is recommended that more research be done in these areas.

PERFORATED SOLAR SAILS CONCEPT

- LARGE RADARS USE PERFORATED REFLECTOR DISHES
  - WEIGHT REDUCED
  - WIND LOADING REDUCED
  - REFLECTIVITY SAME IF HOLES SMALLER THAN RADAR WAVELENGTH
- TECHNIQUES EXIST TO MAKE THIN PERFORATED FILMS
  - FOCUSED ION BEAMS CAN MAKE HOLES DOWN TO 0.1 μm
  - CROSSED HOLOGRAPHIC GRATINGS IN RESIST PROVIDE MASKS FOR ALUMINUM MESH WITH 0.2 - 0.5 μm SPACING
- POTENTIAL FOR IMPROVED THERMAL PROPERTIES
  - THIN ALUMINUM OXIDE LAYER TO PREVENT AGGLOMERATION
  - MICROSTRUCTURES ON BACKSIDE TO IMPROVE EMISSIVITY (A STACK OF SHINY RAZOR BLADES LOOKS BLACK FROM EDGE-ON)

PERFORATED SOLAR SAILS - POTENTIAL PAYOFF

If perforated solar sails can be made, then there are significant performance potentials to be gained.

IF the physics cooperates, it may be possible to manufacture and launch perforated solar sails from low earth orbit.

IF the mass of an unfurlable plastic-backed sail can be lowered to 0.1 metric tons per square kilometer by using perforation techniques, then it will have the low mass and performance of an aluminum film sail with the ruggedness and unfurlabilty of a plastic-backed sail.

IF a perforated aluminum film sail can be made with a 10:1 reduction in mass over a non-perforated film sail, then new missions become possible, such as creating new geostationary orbits that are not on the equator. One such concept is described on the next section.

Research on the optical properties of thin films containing microstructures on the backside may allow us to make a film that is highly reflective on one side and highly emissive on the other side. This would allow us to operate much closer to the sun (where the accelerations are higher).

PERFORATED SOLAR SAILS POTENTIAL PAYOFF

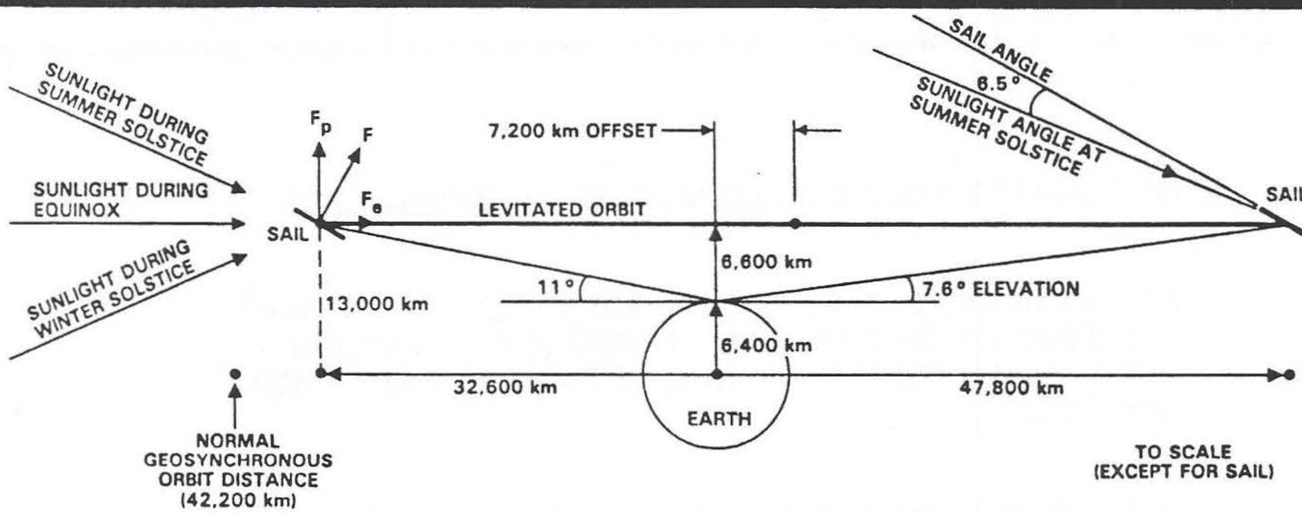
- PERFORATED SOLAR SAILS MAY BE LAUNCHABLE IN LEO
- 10 km DIAMETER SAIL WITH MASS/AREA = 0.1 T/km^2 CAN TAKE 5T OF PAYLOAD TO GEO (OR ESCAPE) IN THREE DAYS (AND THEN CAN RETURN FOR ANOTHER PAYLOAD)
- 10 km DIAMETER SAIL WITH MASS/AREA = 0.01 T/km^2 CAN PLACE 1T OF COMMUNICATIONS PAYLOAD INTO GEOSYNCHRONOUS "ORBIT" CONTINUOUSLY VISIBLE FROM POLAR REGIONS!
- THERMALLY OPTIMIZED DESIGNS CAN OPERATE AT 50 SUNS OR 0.14 AU (MERCURY IS AT 0.39 AU). ACCELERATE AT MANY g's

POLAR LEVITATED GEOSTATIONARY ORBITS USING PERFORATED SOLAR SAILS

On the opposite page is a diagram showing one of the potential applications of an ultrathin perforated solar sail. At the present time, the only geostationary orbits are those along the equator at 35,800 kilometers altitude (42,200 kilometers from the center of the earth). Although geostationary spacecraft can be seen at the Arctic and Antarctic Circles (depending upon the local horizon topography), they cannot be used near the poles.

If a spacecraft were supplied with a lightweight sail, it could use the sunlight to supply a constant force in the poleward direction. This would levitate the usual equatorial orbit out of the equatorial plane and the spacecraft would orbit about a point determined by the relative magnitude of the earth gravity forces and the solar light pressure forces. (There would also be a tangential force which would displace the orbit on the side opposite the sun. This effect was noticed on the Echo satellite.) By choosing the proper sail angle, the new orbit could be kept synchronous with the earth's rotation, providing a true geostationary communications capability to the polar regions.

POLAR LEVITATED GEOSTATIONARY ORBITS USING PERFORATED SOLAR SAILS



SAIL PARAMETERS

- MASS – 2T (1T PAYLOAD)
- DIAMETER – 9 km
- m/A – 0.013 T/km^2

ORBITAL PARAMETERS

- ORBITAL RADIUS – 40,200 km
- ORBITAL OFFSET – 7,200 km
- ORBITAL LEVITATION – 13,000 km
- ORBITAL PERIOD – 24 hours
- POLAR ELEVATION – 9.3° ±1.7° (WORST CASE)

PERFORATED SOLAR SAILS - SUGGESTED RESEARCH PROGRAMS

The research tasks that need to be done to check the feasibility of the perforated sails concept are straightforward. They are listed on the facing page. The optical properties study and the aerodynamics study both involve basic physics research on a scale compatible with the probable budgets for Phase 3. If the optics studies show that the sail mass can be reduced by an order of magnitude or more without significant loss in reflectivity, and especially if the aerodynamics study shows that the sail can be launched at the upper range of shuttle altitudes, then the more engineering-oriented thermal, mechanical, and mission studies can proceed.

Recommendation: It is recommended that perforated sails be one of the concepts selected for investigation in Phase 2. Since the research work that needs to be done is already fairly well defined, it is recommended that this be the first topic to be studied in Phase 2. A program plan for Phase 3 work on perforated sails can probably be produced early in July, in time for early incorporation into FY84 planning.

PERFORATED SOLAR SAILS SUGGESTED RESEARCH PROGRAMS

OPTICAL PROPERTIES STUDY

- FABRICATE 10 TO 5000 nm ALUMINUM FILMS WITH HOLES OF VARIOUS SIZES
- MEASURE REFLECTANCE, TRANSMITTANCE, ABSORPTANCE AND EMITTANCE vs WAVELENGTH AS FUNCTION OF HOLE SIZE, HOLE PATTERN, AND ALUMINUM OXIDE THICKNESS

AERODYNAMICS STUDY

- MEASURE DRAG OF PERFORATED FILMS IN MOLECULAR FLOWS SIMULATING CONDITIONS AT SHUTTLE ALTITUDE (SHUTTLE EXPERIMENT?)

THERMAL PROPERTIES STUDY

- DESIGN MICROSTRUCTURES TO INCREASE EMISSIVITY OF FILM BACKSIDE
- FABRICATE AND TEST FILMS WITH MICROSTRUCTURE UNDER SIMULATED SUNLIGHT
- MEASURE AGGLOMERATION POINT AS FUNCTION OF STRUCTURE TYPE AND ALUMINUM OXIDE THICKNESS

MECHANICAL PROPERTIES STUDY

- DESIGN TRUSS SUPPORT FRAMES AND PERFORATED FILMS FOR BEST STRENGTH/LIGHTNESS
- FABRICATE AND MEASURE MECHANICAL STRENGTH OF FILMS

MISSIONS STUDIES

- (AS FILM AND SUPPORT STRUCTURE DATA BECOMES AVAILABLE)

LASER PUSHED LIGHTSAILS

The concept of pushing a lightsail with a laser was invented the year that the first laser was demonstrated.[1] The basic formula that determines the acceleration a of a sail of mass m for a given incident power P is

$$a=2P/mc,$$

where the factor 2 comes from the double momentum transfer of the reflected photons and c is the velocity of light. From this formula it is easy to calculate that 1.5 gigawatts of laser power are needed to accelerate one kilogram of payload and sail at one earth gravity. This is not much push for that amount of power and reflects the high specific impulse of the concept. Laser pushed lightsails seem to be best suited to light payloads and relativistic mission speeds.

A recent survey[2] of this concept for interstellar missions was prepared in 1982. The basic conclusion was that if you design the system to use a very large transmitter lens (1000 kilometers minimum) and have the laser power available, then a number of interesting interstellar missions can be performed.

Recommendation: Because this concept seems to be limited to interstellar missions, it is not recommended that further study be carried out in Phase 2.

1. "Pluto - The Gateway to the Stars", R.L. Forward, Missiles and Rockets **10**, 26 (2 April 1962).

2. "Roundtrip Interstellar Travel Using Laser Pushed Lightsails", R.L. Forward (accepted for publication in J. Spacecraft and Rockets, 1983).

LASER PUSHED LIGHTSAILS

- **1.5 GW PUSHES 1 kg AT 1 GEE**
- **PAYLOADS NEED TO BE LIGHT**
- **I_{sp} BEST SUITED FOR INTERSTELLAR MISSIONS**
- **CAN ACCOMPLISH INTERSTELLAR MISSIONS**
  - NEED LARGE TRANSMITTER LENS (1000 km)
  - 65 GW TO FLY 1T PAST α CENTAURI IN 50 YEARS
  - HIGHER POWERS CAN ALLOW RENDEZVOUS AND RETURN
- **WOULD BENEFIT FROM PERFORATED SAIL RESEARCH**

MICROWAVE SAILS

One of the more exotic concepts uncovered in Phase 1 of the contract is the idea of a microwave driven sail. This is an extreme version of a perforated sail where the wires in the mesh are kept small while the mass per unit area is lowered by increasing the hole size and increasing the wavelength of the microwave power proportionately. This concept uses the same acceleration versus power equation as the laser pushed lightsail - 1.5 megawatts can push (levitate) one gram at one earth gravity.

One application of this concept is to levitate a very lightweight mesh in the upper atmosphere with a few megawatts of modulated transmitter power and use the mesh as a passive microwave relay.

An interesting application of the microwave sail was suggested by Freeman Dyson. The idea is to drive the mesh at high accelerations to initiate an interstellar flyby mission. Dyson's original analysis was augmented with the following results.

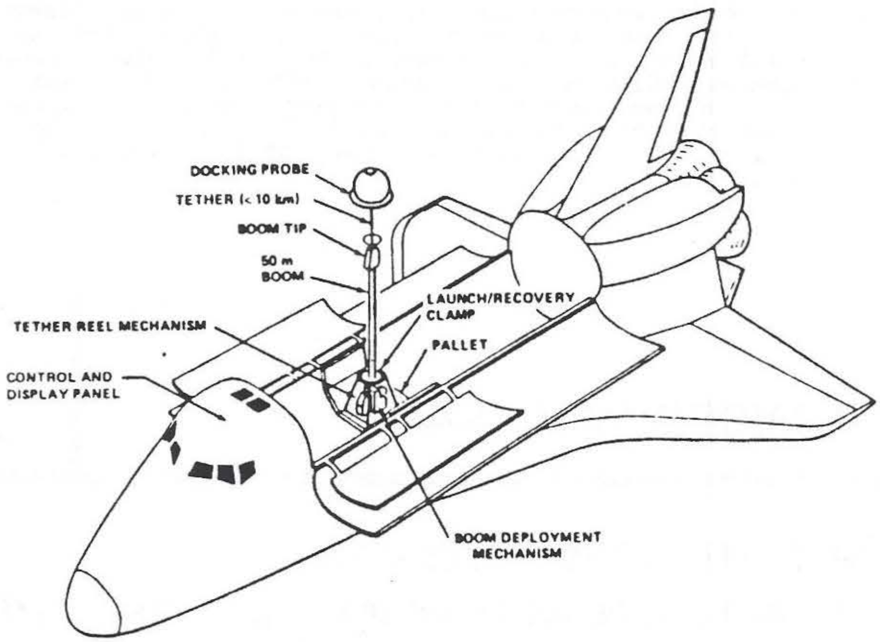
A single Solar Power Satellite is used to produce 10 gigawatts of X-band microwave power. The microwave sail is three kilometers in diameter but only weighs 30 grams because it is made of 0.1 micron wire. The microwave power is transmitted by a 10,000 kilometer Fresnel mesh lens, and accelerates the sail at 180 earth gravities. At that acceleration the mesh will reach one-third the speed of light in one day at 30 AU distance. At c/3 the sail will reach alpha Centauri in 13 years. The mesh payload will be a few grams of microcircuits placed at the vertices of the mesh structure. They will use the wires in the mesh for antennas and interconnection. The 10 gigawatts of power beamed from the solar system through the transmitter lens will be 400,000 kilometers wide at alpha Centauri. The total incident microwave power on the 3 kilometer sail/probe is 10 watts. This power is enough to power the microcircuits which can use retrodirective phased array techniques to return a beam modulated with the information that their photodetectors and other miniature sensors have collected during their 25 hour flythrough of the alpha Centauri system.

MICROWAVE SAILS

- MESH OF FINE WIRES (HOLES $< \lambda/2$)
- MASS/AREA DROPS WITH INCREASING WAVELENGTH
- 1.5 MW CAN PUSH (LEVITATE) 1 GRAM AT 1 GEE
- "SPACE MIRROR" — MICROWAVE LEVITATED PASSIVE RELAY
- SPS POTENTIAL SOURCE OF 10 GW AT 10 GHz
- ORBIT RAISING?
  - 10 GW PUSHES 700 kg AT 0.01 GEE
- "STARWISP" — INTERSTELLAR FLYBY PROBE
  - 10 GW PUSHES 30 g (3 km) SAIL AT 180 GEES
  - REACH c/3 IN 1 DAY AT 30 AU
  - ARRIVE α CENTAURI IN 13 YEARS
  - ACTIVE MICROCIRCUITS AT MESH VERTICES
  - DATA BACK USING RETRODIRECTIVE REFLECTOR MODE
- REFLECTIVITY MEASUREMENTS NEEDED ON MESH

SHUTTLE TETHER EXPERIMENT

In 1987 NASA is planning to fly the first space tether experiment, it will be a joint program with Italy. An 500 kilogram satellite designed to measure the characteristics of the upper atmosphere will be lowered 100 kilometers down from the normal 250 kilometer Shuttle altitude to 150 kilometers. At this altitude the spacecraft would normally come down in a fraction of an orbit because of the drag, but the tether is acting as a propulsion system to transfer energy from the Space Shuttle to the smaller satellite.

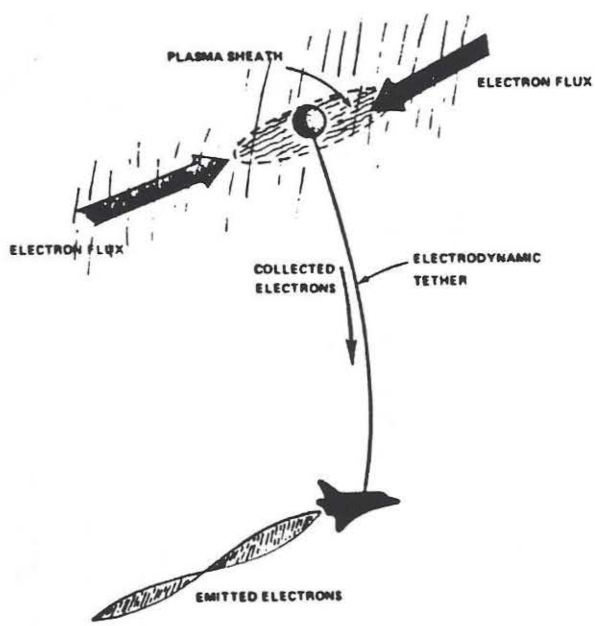


ELECTRIC POWER FROM A MOVING TETHER

The tethered satellite system also offers a new means for extracting energy from the ionosphere. The basic idea[1], shown on the facing page, is to launch a satellite upward on an electrically insulated conductive tether. The motion of the conductive tether through the earth's magnetic field lines will generate voltage differences between the two ends of the tether of several thousand volts. In a normal eastward orbit, the placement of the satellite above the orbiter results in electron collection by the satellite and a need for electron emission from the Shuttle which can be supplied by the electron gun tested on one of the earlier flights. Power levels of 10 kilowatts are expected from the prototype system.

Recommendation: Obtaining kilowatts of power by simply throwing out a wire sounds very interesting until you realize that the electrical energy gained is taken from the motion of the Shuttle. This may be a useful concept to keep in mind to generate power to operate instruments or to decelerate at a planet, but it is definitely not a propulsion energy source and should not be studied in Phase 2 of the contract.

1. "The Tethered Satellite System - Facility Requirements Definition Team Report", Report under NASA Contract NAS8-33383, Center for Atmospheric and Space Sciences, Utah State University, Logan, Utah 84311.

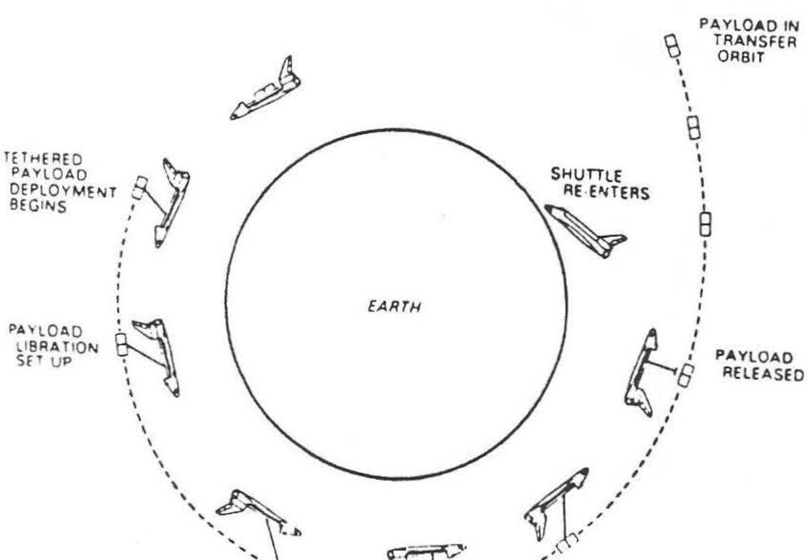


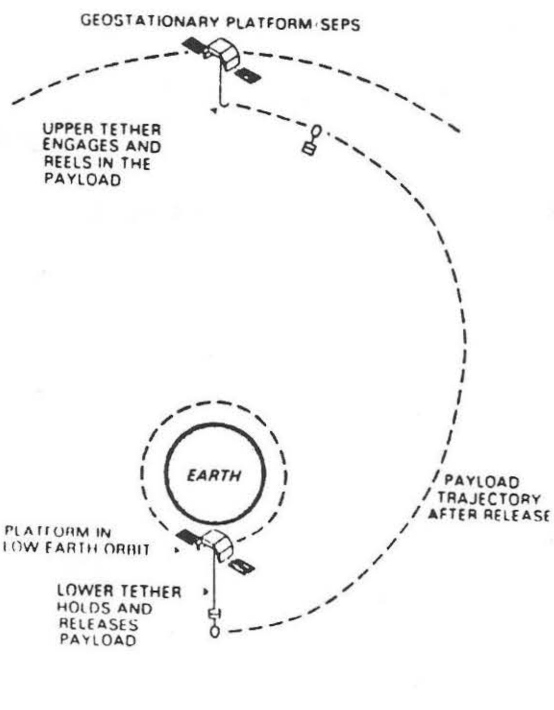
TETHER TRANSFER FROM LEO TO GEO

As is shown schematically on the facing page, once the NASA planners have become comfortable with the tether concept, the Shuttle tether system can be used to transfer the Shuttle momentum to the payload, launching the payload into a transfer orbit while the Shuttle returns to earth. Later, more advanced systems operating from large platforms can transfer payloads from LEO to GEO and back. This can be done with **no expenditure of fuel** as long as the amount of mass dropped inward down the earth's gravitational potential well equals or exceeds the amount of mass sent upwards.

Recommendation: The idea of using tethers to transfer energy and momentum has not received much attention in propulsion research. It is recommended that those involved in the more traditional forms of propulsion take a serious look at this concept since the engineering problems of deploying and using tethers will have been solved by 1987. If there are potential propulsion applications for this concept, the mission planners should be ready to take advantage of the developed technology. Since the problems to be solved are mostly engineering ones, it is not recommended that tethers be studied in Phase 2 of the contract.

1. "Tethers Open New Space Options", I. Bekey, Astronautics & Aeronautics, 32 (April 1983).





DYNAMIC STRUCTURES

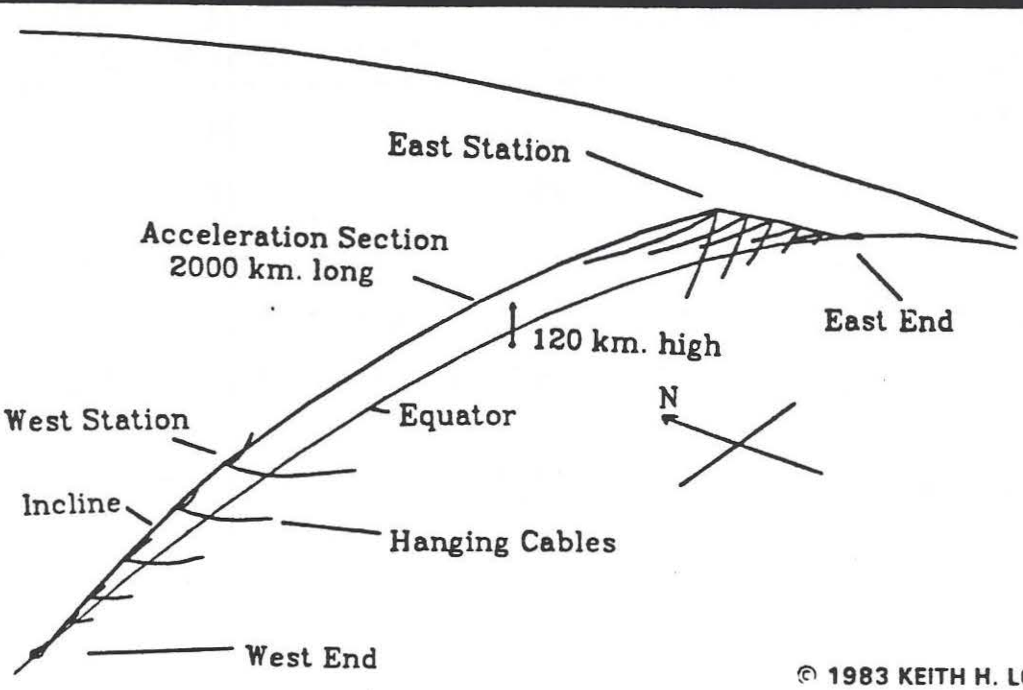
Another exotic concept that was uncovered in Phase 1 was the idea of dynamic structures. It is known that the compressional strength of materials is not strong enough to build a tower into space, and that the tensile strength of materials is not strong enough to drop a skyhook down from geostationary orbit. By using dynamic structures, where energy and momentum is transferred by means of macroscopic interactions with moving masses instead of through the molecular structure of the materials, it is possible to construct active structures that can exceed the performance of passive structures.

LAUNCH LOOP - It is well known (and often demonstrated by careless gardeners), that the momentum of the flow of water through a garden hose is enough to lift the hose off the ground and send it up in the air. The Launch Loop works by the same principle, except that the water is replaced by a high speed cable driven by electromagnetic motors on the ground at both ends. In a manner similar to San Francisco cable cars, vehicles slip-couple electromagnetically to the moving cable, ride to the top, and gain enough speed to go into orbit.
VERTICAL TOWER - The launch loop does not have to be horizontal. It can work vertically and be used to construct a tower out to geostationary orbit.
ORBITAL RING - An extreme version of the launch loop has the system circling the earth in low earth orbit. "Jacob's Ladders" hang down from the ring to the top of convenient mountains, allowing you to climb into orbit.
ROTATING SKYHOOKS - Although no material is strong enough to lower a cable down to the earth's surface from geostationary orbit, it is possible to build a cable 4000 kilometers long and put it into a 2000 kilometer high orbit and set it spinning so that the ends come within 50-100 kilometers of the earth's surface six times an orbit. A sub-orbital flight takes you up to the lower end of the cable. You attach on and a half-rotation later you are on the upper end of the cable with enough energy to send you into an escape orbit.

What is amazing about these studies is that all these concepts seem to be feasible using ordinary materials, although some designs perform much better using superconductors. They all have large capital investments, large circulating powers, and significant potential for damage if the control fails.

Recommendation: These concepts should not be neglected by the propulsion community, but the problems to be solved are usually engineering, system, and money problems, and are not recommended for study in Phase 2 of the contract.

LAUNCH LOOP

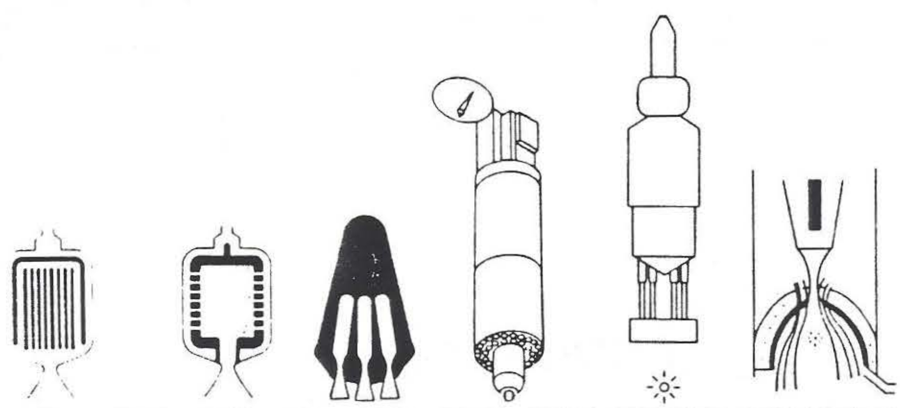


NUCLEAR PROPULSION CONCEPTS

When nuclear energy was first found, it was hoped by the propulsion community that this new energy source would be the long-sought-for replacement for chemical fuels. Unfortunately, the physics and politics of nuclear reactors prevented that dream from being realized. Even the most optimistic designs failed to achieve an increase in specific impulse that was an order of magnitude larger than the best chemical launch systems.

Although fission reactors have not produced a new propulsion system, and were deliberately not studied in Phase 1 of the contract, there may be other techniques for releasing or utilizing nuclear energy. We looked for these in Phase 1 and found a few things that we think deserve further attention by others, and one that we recommend for selection for further study in Phase 2.

NUCLEAR PROPULSION CONCEPTS



	SOLID CORE	PARTICLE BED	GAS CORE	ELECTRIC	PULSE, FISSION	PULSE, FUSION
THRUST, kN	70	230	445	$<10^{-2}$	3500	970
I_{sp}, s	860	1000	2040	6120	2550	6330
M_{pp}, Mg	2.6	3.2	57.0	*	94	200
T/W, ENGINE	2.7	7.3	0.8	$<10^{-4}$	3.8	0.5
P_t, MW	300	1100	4460	0.05-0.40	43820	30150

* α = 50-30 kg/kW

NUCLEAR REACTOR PROPULSION - HIGH TEMPERATURE RADIATORS

In our cursory examination of nuclear reactor propulsion, which was covered in great detail in the FY81 JPL study and the 1980 Boeing study, it was evident that the design of the high temperature radiator was the major driver in the system design. It was also noticed that there are a number of ideas for constructing a lightweight high temperature radiator, but they are all paper studies and very little experimental work was noticed. Admittedly radiator design is not propulsion, but without the radiator the nuclear propulsion systems will never fly.

Recommendation: It is recommended that the propulsion community give serious thought to the design, space demonstration, and test of some of the more advanced forms of light weight, high temperature radiators. The concepts are not propulsion energy sources however, and are not recommended for Phase 2 studies.

NUCLEAR REACTOR PROPULSION
HIGH TEMPERATURE RADIATORS

- RADIATOR MAJOR DRIVER IN SYSTEM DESIGN
- CONCEPTS EXIST ON PAPER
  - DUST RADIATOR
  - PARTICLE RADIATOR
  - LIQUID DROPLET RADIATOR
- NEED SPACE DEMONSTRATION AND TEST
- APPLICABLE TO SOME SPACE WEAPONS

IMPLODED MICROPELLET FUSION PROPULSION

The original Orion concept obtained propulsion by dropping small fission bombs out the back of the rocket where they were exploded behind a "pusher plate" to obtain thrust. The Orion concept was/is technically feasible, but environmentally undesirable and politically unthinkable. The solution is to switch to "clean" micropellet fusion bombs.

Fusion is being attempted in two ways. One is by containment of the deuterium-tritium fusion fuel in the form of a hot plasma in some kind of magnetic bottle. The other is to compress the cold D-T fusion fuel to high densities and pressures by impacting a tiny pellet of the fuel with either laser beams, electron beams, ion beams, or high speed BBs. To date, none of these approaches have worked, although some neutrons have been released. If imploded micropellet fusion is found to be feasible in the laboratory, then, even if it never becomes commercially viable as a prime power source, it still may be viable as an advanced propulsion concept. No matter what the implosion method may be, the resultant fusion reaction will produce nearly identical plasmas that can be contained and directed into thrust by a magnetic nozzle.

Recommendation: The Department of Energy is funding the research to develop the implosion technology. It is recommended that the propulsion community fund further research on those areas specifically related to the propulsion application. These would be detailed design studies for the magnetic nozzle, lightweight radiators, lightweight tritium breeders, and lightweight versions of the implosion method that finally works. The studies that need to be done are mostly engineering and optimization studies and it is not recommended that further study on these concepts be done in Phase 2 of this contract.

IMPLODED MICROPELLET FUSION PROPULSION

- FUSION OF D-T IN MICROPELLET BY IMPLOSION WITH
  - LASER BEAMS
  - ELECTRON BEAMS
  - ION BEAMS
  - HIGH SPEED PROJECTILES
- RESULTANT PLASMA CHANNELED BY MAGNETIC NOZZLE
- DOE FUNDING IMPLOSION TECHNOLOGY
- RESEARCH NEEDED ON PROPULSION APPLICATION
  - MAGNETIC NOZZLE DESIGN
  - LIGHTWEIGHT RADIATORS
  - LIGHTWEIGHT T BREEDER
  - LIGHTWEIGHT IMPLOSION METHOD

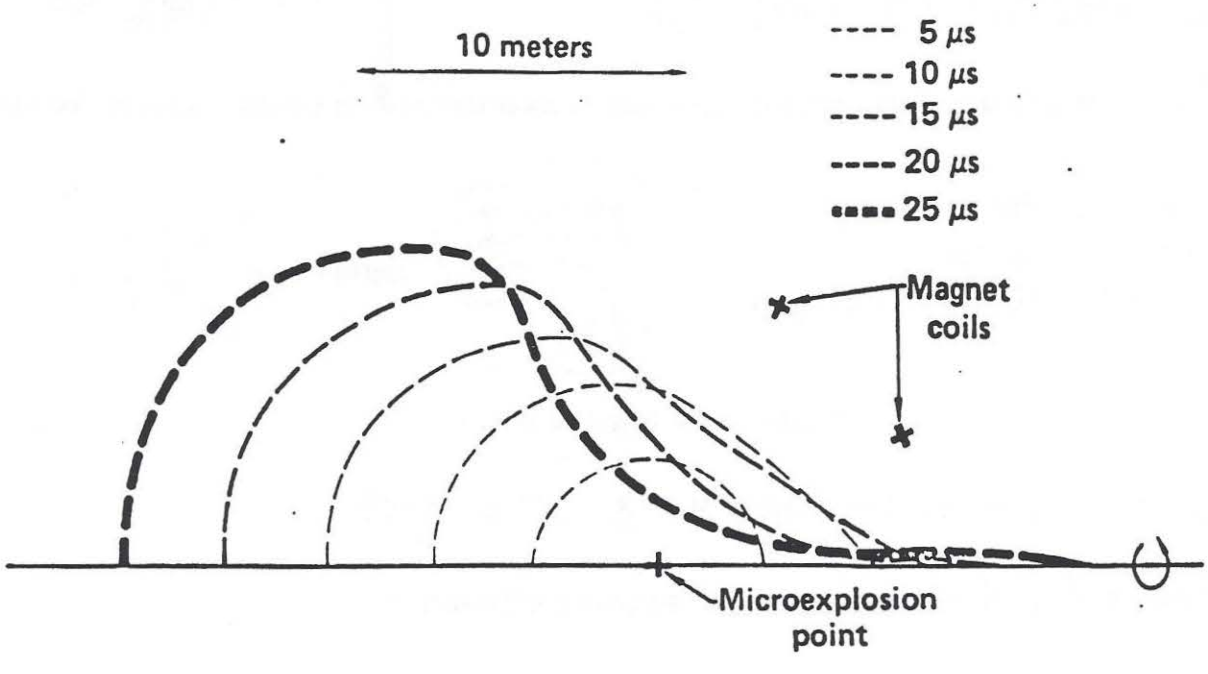
PELLET EXPANSION

Although laser imploded D-T micropellet fusion has not been demonstrated in the laboratory, we already have detailed engineering designs[1] for a rocket engine that can convert those isotropic miniature explosions into directed thrust. The version shown on the facing page is a magnetic nozzle formed by two superconducting magnetic rings (the diagram is to be imagined as axially symmetric). The various dotted curves show how the magnetic fields from the two coils first contain, then direct the plasma coming from the microexplosion point. The paper not only discusses the interaction of the plasma with the magnetic field, but the design of the shielding for the superconducting magnetic coils that not only stops the gamma rays and neutrons, but uses the neutrons to breed the tritium needed for future pellets. The design also includes weight and size estimates for the lasers, mirrors, auxiliary systems, and heat-pipe radiators.

In a visit to Lawrence Livermore Lab during Phase 1 of the contract, it was learned that a single superconducting magnetic coil might be preferable to two coils, since the two coil system requires that each coil be shielded from the backscattering from the other as well as the microexplosion point, and the shielding weight penalty overcomes the reduced conversion to thrust of the more crudely shaped nozzle.

1. "Prospects for Rocket Propulsion with Laser Induced Fusion Microexplosions" R. Hyde, L. Wood, and J. Nuckolls, AIAA Paper 72-1063 (Dec 1972).

PELLET EXPANSION



MAGNETIC MONOPOLES

Magnetic monopoles are hypothetical particles that have only one magnetic pole, either north or south, not both as magnets do. They were first predicted by Dirac to explain the quantization of charge. Later theories not only predict their existence but also predict they are extremely heavy. A very recent, very complete bibliography[1] was uncovered in the Phase 1 survey.

Magnetic monopoles could have a significant effect on future propulsion since they can catalyze proton decay, releasing most of the proton energy. Once one magnetic monopole has been trapped, then it can be used in a magnetic accelerator to produce more magnetic monopoles.

One experiment to detect magnetic monopoles has produced a positive result[2], but no further events have been seen to date.

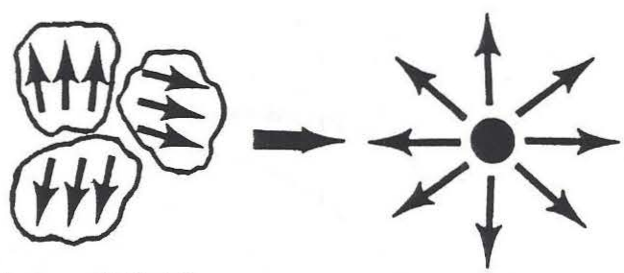
Recommendation: If and only if more magnetic monopole events are found, and especially if a magnetic monopole is captured, then it is recommended that all other studies on this contract be halted and further study be concentrated on this concept.

1. "Magnetic Monopole Bibliography 1981-1982 (and previous versions)" R.E. Craven and W.P. Trower, Fermilab-82/96 (March 1983).

2. "First Results from a Superconductive Detector for Moving Magnetic Monopoles", Blas Cabrera, Phys. Rev. Let. 48, 1378 (17 May 1982).

MAGNETIC MONOPOLES

- Made early in the universe
  - Small ~ 10^{-29}cm
  - Heavy ~ 10^{16} GeV (10^{-8}g)



Domains with trapped field

- One possibly seen at Stanford (PRL 48, 1378-81, 1982)
- Not consistent with fractionally charged particles
- Can catalyze proton decay

$$p + M \longrightarrow e^{+} + \pi^{\circ} + M + 800 \text{ MeV}$$

- Search continuing at Stanford and elsewhere

FRACTIONALLY CHARGED PARTICLES

Fractionally charged particles and quarks are hypothetical particles that have electric charges that are fractions of the charge of an electron. Quarks are particles predicted by one of the more accepted theories of quantum electrodynamics. They have charges that are multiples of 1/3 of an electronic charge. Some negatively charged quarks can replace an electron in a deuterium molecule and catalyze D-D fusion which can be used for propulsion.

Fractionally charged particles have been reported to have been observed on a number of occasions on small niobium balls levitated in a specially constructed superconducting chamber that is capable of measuring forces due to the electric field effects of a small fraction of a charge.[1] DOE is presently funding two experiments[2] based on ink-jet techniques to process multi-kilogram amounts of finely ground material to extract large quantities of fractionally charged particles.

Recommendation: If and only if significant quantities of fractionally charged particles are found, then it is recommended that all other studies on this contract be halted and further study be concentrated on this concept.

1. G.S. LaRue, J.D. Philips, and W.M. Fairbank, Phys. Rev. Lett. 46, 967 (1981).

2. "Detection and Enrichment of Fractionally Charged Particles in Matter", C.D. Hendricks, LLL and G. Zweig, LANL, DOE Advanced Energy Projects 24 and 25, DOE/ER-0150, U.S. Department of Energy, Division of Advanced Energy Projects, Office of Energy Research, Washington, DC 20545.

RACTIONALLY CHARGED PARTICLES

- A few possibly seen at Stanford (PRL 46, 967, 1981)
- Not consistent with monopoles
- Can initiate fusion

$$2d + Q^{-4/3} \longrightarrow T + p + Q + 4.0\ \text{MeV}$$
$$\longrightarrow He^3 + n + Q + 3.3\ \text{MeV}$$
$$(10^{16}\ \text{BTU/year/mole})$$

- DOE funding extraction studies

MUONS

Muons are elementary particles with a mass of 106 MeV and a lifetime of 2.2 microseconds. Sometimes called "heavy electrons", they carry one unit of electronic charge. They can act as a fusion catalyst by replacing an electron in a hydrogen molecule. Because of their large mass, the muon orbits are so tight that the two nuclei come close enough together that the nuclei have a finite probability of fusing. Despite their short lifetime, the muons can catalyze many reactions.

The catalytic capability of the muon has been known for decades, but dismissed since elementary calculations showed that the muon could not catalyze enough reactions to compensate for the energy cost of creating it. During Phase 1 of this contract it was learned that DOE funded experiments to measure the actual (rather than the calculated) efficiency of muon-catalyzed fusion reactions were underway at LANL.[1] The experiments are still in progress and the experimenters are reluctant to release data prematurely. The reaction is not simple. "Enhancements" have been observed in the D-T-muon reaction, while He^3, a natural byproduct of tritium decay, has been observed to scavenge muons and remove them from the reaction chain. The experiments have been carried out at high temperatures and pressures and it has been observed that high temperature increases the reaction yield by factors of 3 or more.

Recommendation: Considering the difficulty of obtaining muons (they have to be obtained from decaying pions), and the difficulty of obtaining the fusion fuel (tritium is radioactive), and the marginal ideal efficiency, it is doubtful if this line of research will lead to a alternate propulsion energy source. The research effort is still young, however, and should be encouraged. In addition to the present DOE research, studies should be done on the effect of using He^3 filters in the target, using magnetically polarized muons and targets, and developing more efficient muon generators. If a breakthough occurs in any of these areas then it is recommended that all other studies on this contract be halted and further study be concentrated on this concept.

1. "Measurement of the Efficiency of Muon-Catalyzed Fusion", S.E. Jones, EG&G Idaho/LANL, DOE/ER-0150, U.S. Department of Energy, Division of Advanced Energy Projects, Office of Energy Research, Washington, DC 20545.

MUONS

- "Heavy" electron
  - Mass = 106 MeV
  - Lifetime = 2.2 μsec
- Can catalyze 100 or more fusions
  - $\mu^- + T + D \rightarrow He^4 + n + 17.6\ MeV + \mu^-$
- LANL starting to measure efficiency at high pressure
  - Resonances observed
  - He^3 scavenges muons
  - High temperature increases yield by 3 or more
- Work needs monitoring and encouragement
  - He^3 filters
  - Polarized targets
  - Efficient muon generators

ULTRACOLD NEUTRONS

Neutrons that have a very low kinetic energy are moving very slowly and consequently have a very large quantum mechanical wavelength. For example a neutron with a velocity of 1 meter per second has a wavelength of 0.4 microns, about that of light. This quantum-nuclear wave can interact coherently with all nuclei within a wavelength. If the nuclei in a nearby wall are repulsive, the neutron will find itself repelled without approaching the wall. If the nuclei are reactive, the reaction will have a very large cross section. Thus, very slow (ultracold) neutrons can be used to initiate a nuclear fission reaction at will, just by pumping them into some neutron sensitive material such as uranium or lithium when the reaction is desired. No "critical mass" is required.

Ultracold neutrons were first made in quantities by using a cold neutron moderator made of cryogenically cooled hydrogen. Later, other techniques such as rapidly moving turbines and vibrators were proposed[1] and later used[2] to create significant amounts of ultracold neutrons. Both magnetic bottles (which work on the nuclear magnetic moment of the neutron) and total internal reflection bottles (which interact with the coherent quantum wavelength of the neutron) have been used to contain the neutron longer than its 15 minute beta decay lifetime (it decays into an electron and a proton).

Recommendation: The finite lifetime of the neutron limits this concept as a propulsion energy source. There are theoretical indications that the dineutron (a two neutron deuteron) or a tetraneutron (a four neutron alpha particle) may be stable against beta decay. If any evidence for these particles is discovered, then it is recommended that all other studies on this contract be halted and further study be concentrated on this concept.

1. "Ultracold Neutrons and Their Potential Value in Gravitational Research", R.L. Forward, RR-267A, Hughes Research Labs, Malibu, CA 90265 (Oct 1964).

2. "Ultracold Neutrons", R. Golub, et al., Sci. Am., **240**, 134 (June 1979).

3. "Ultracold Neutrons", V.I. Luschikov, Physics Today, 42-51 (June 1977).

ULTRACOLD NEUTRONS

- **Slow (cold) neutrons have large wavelengths**
- **Can be slowed**
  - — cold moderators
  - — mechanical turbines, vibrators, etc.
- **Can be trapped**
  - — magnetic bottles (Bonn)
  - — total internal reflection (USSR)
- **Can initiate fission**

  $n + U^{235} \rightarrow$ fragments $+ 172$ MeV

  $n + Li^{6} \rightarrow T^{+} + He^{++} + 4.8$ MeV (10,000 barns)
- **Neutron has finite lifetime ($\sim$15 min)**

GAMMA RAYS

Ever since the Mössbauer effect was discovered, there have been speculations about constructing an x-ray or gamma-ray laser. There are many low-lying nuclear states that are not in their ground state, but do not have enough energy to emit a massive particle and are limited to emitting electromagnetic energy such as x-rays and gamma-rays. Some of these states last for very long times, but only a few of them can be formed into a molecular crystal that exhibits the Mössbauer effect where the natural nuclear reaction linewidth is maintained by the acoustic phonon selectivity of the crystal.

Conceptually, it should be possible to make a fuel out of elements that had long-lived metastable nuclear states, then release that energy on demand by forming the conditions for a gamma-ray laser. The recent review paper[1] on this subject was studied during Phase 1 and this concept does not look like it will produce a feasible alternate propulsion energy source. First, the amount of energy released per nucleon is very low for a nuclear reaction, only 0.01 to 0.15 MeV, while the longest lifetimes for a Mössbauer emitter are less than an hour.

Recommendation: Although investigation of this concept involves basic physics research, the potential for payoff in the propulsion field is so slight that it is not recommended that further study be given to this concept in Phase 2.

1. "Approaches to the Development of Gamma-Ray Lasers", G.C. Baldwin, J.C. Solem, and V.I. Gol'danskii, Rev. Mod. Phys. 53, 687 (1981).

GAMMA RAYS

- Store energy in long-lived metastable nuclear states
- Gamma ray laser releases energy on demand
- Recent review paper (RMP 53, 687-744, 1981)
- Energy release per nucleus low 0.01 – 0.15 MeV
- Lifetimes short
  - ^{107}Ag τ = 44.3 sec
  - ^{103}Rh τ = 3360 sec (~ 1 hour)

THRUST FROM ANTIMATTER ANNIHILATION

The concept of using antimatter as the energy source for a space propulsion system has been in the literature for decades, with the first paper covering the subject in some detail being that by Sanger[1]. The fuel is conceptually simple to use; you merely mix equal amounts of matter and antimatter together to obtain total conversion of both masses to energy with an energy release of 1.8×10^{17} J/kg of antimatter. In Sanger's time, the only known source of antimatter was the antielectron or positron, which interacts with electrons to produce 0.511 MeV gamma rays. Sanger tried to invent electron-gas mirrors to direct these short wavelength gamma rays to produce a photon rocket.

The antiproton is much more suitable for propulsion systems. The annihilation of an antiproton by a proton (or neutron) does not produce gamma rays. Instead the usual product of the annihilation is from three to seven protons. On the average there are 3.2 charged pions and 1.6 neutral pions.[2] The neutral pions have a lifetime of only 90 attoseconds and almost immediate convert into two high energy gamma rays. The charged pions have a normal half-life of only 26 nanoseconds, but because they are moving at high speed (94% the speed of light), their lives are lengthened to 70 nanoseconds. Thus, they travel an average of 21 meters before they decay. This time and interaction length is easily long enough to collect the charged pions in a thrust chamber constructed of magnetic fields and direct the isotropic microexplosion into directed thrust. Even after the charged pions decay, they decay into energetic charged muons, which have even longer lifetimes and interaction lengths for further conversion into thrust. Thus, if sufficient quantities of antiprotons could be made, captured, and stored, then present known physical principles show that they can be used as a highly efficient propulsion fuel.[3]

1. "The Theory of Photon Rockets (in German)", E. Sanger, Ing. Arch 21, 213 (1953).

2. "Antiproton Interactions in Hydrogen and Carbon Below 200 MeV", L.E. Agnew, et al., Phys. Rev. 118, 1371 (1960).

3. "Antimatter Propulsion", R.L. Forward, J. British Interplanetary Soc. 43, 391 (1982)

THRUST FROM ANTIMATTER ANNIHILATION

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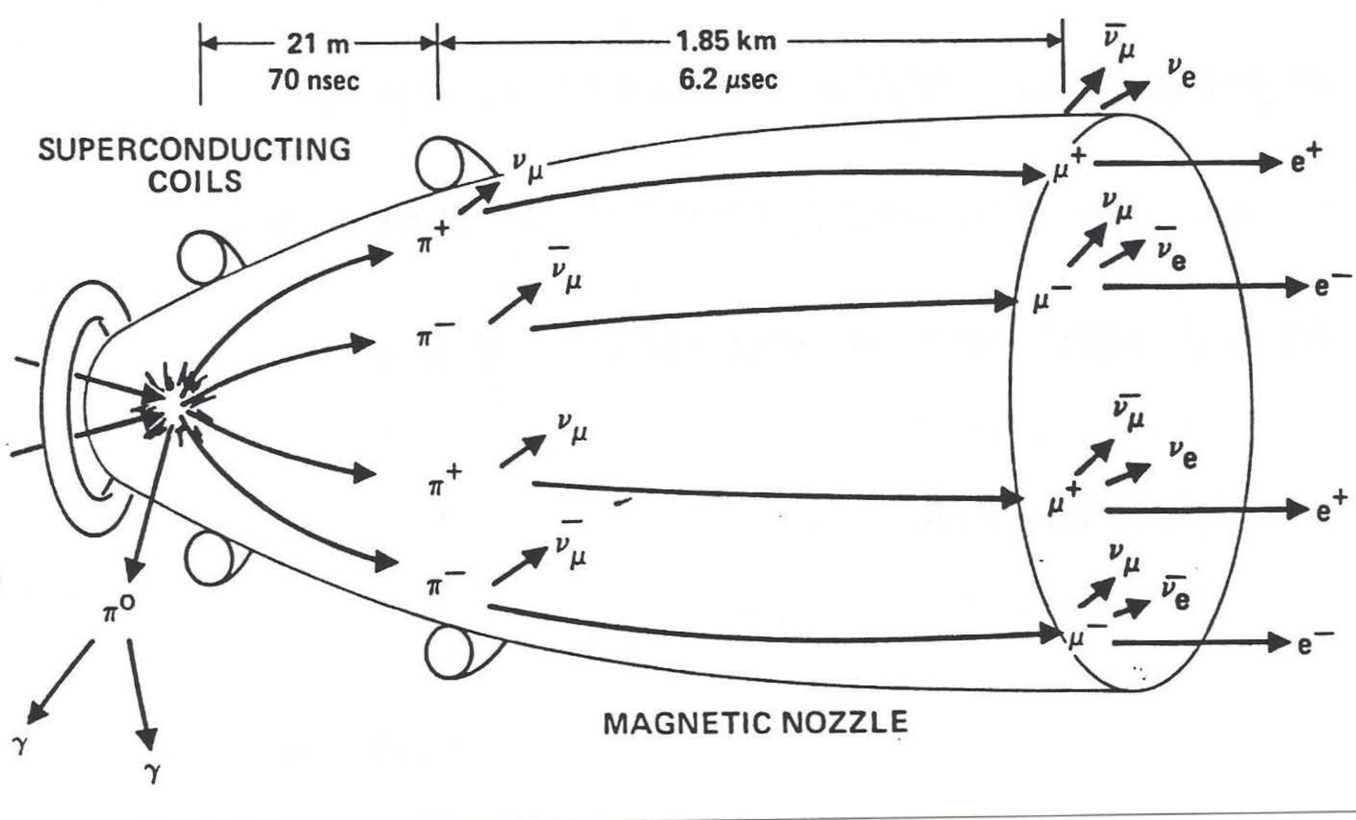

ANTIMATTER PROPULSION (SPECIFIC IMPULSE OPTIMIZATION)

When antiprotons interact with protons (hydrogen), the resultant annihilation products are high speed pions, two-thirds of which are charged and can be directed into thrust with magnetic fields. The average energy is 400 MeV which translates to an exhaust velocity of 94% of the speed of light. Thus, pure antimatter rockets are best suited for relativistic missions. In an important paper[1], Dipprey showed that the best way to use the antimatter is not to use equal amounts of matter and antimatter. Instead, the antimatter should be used to heat a much larger amount of propellant. The analysis comes to the conclusion that except for extreme relativistic spacecraft speeds (>0.5 c), the reaction mass needed is always four times the spacecraft payload mass, or an overall ratio of launch mass to payload mass of 5:1. The mass of the antimatter needed increases at the square of the mission "delta V", but is always a negligible fraction of the total mass. Dipprey's work has been expanded by Cassenti[2], who basically confirmed the 5:1 mass ratio and showed that heating liquid hydrogen with antimatter reaction products should produce an efficiency of about 44%.

In an interview with David Morgan of Lawrence Livermore Labs carried out on Phase 1 of this contract, it was learned that it may be difficult to transmit the energy of the charged pions to hydrogen because of the long interaction length and the short pion lifetime. This interaction needs to be calculated. Morgan also suggested the use of heavy nuclei instead of protons. The antiprotons would be attracted to the heavy nucleus and annihilate with one of the protons or neutrons. The pions would immediately transfer their energy to the rest of the nucleons, lowering the specific impulse and increasing the efficiency for subrelativistic missions. This approach has the advantage that the energy in the neutral pions is not lost, but the disadvantage that the energetic neutrons generated will be lost and will add to the shielding problem. This interaction needs to be calculated and perhaps checked by experiments with antiprotons interacting with heavy nuclei.

1. "Matter-Antimatter Annihilation as an Energy Source in Propulsion", D.F. Dipprey, Appendix in "Frontiers in Propulsion Research", JPL TM-33-722, D.D. Papailiou, Editor, Jet Propulsion Lab, Pasadena, CA 91109 (15 March 1975).

2. "Design Considerations for Relativistic Antimatter Rockets", B.N. Cassenti, J. British Interplanetary Soc., 35, 396 (1982).

ANTIMATTER PROPULSION

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DO NOT USE EQUAL PARTS MATTER AND ANTIMATTER

USE MILLIGRAMS OF ANTIMATTER TO HEAT TONS OF MATTER

OPTIMUM RATIO (FOR ANY SPEED LESS THAN c/3)

PAYLOAD MASS	1
REACTION MASS	4
ANTIMATTER	< 0.1

D. F. DIPPREY, JPL TM 33-722 (1975)

MATTER-ANTIMATTER PROPULSION (NOZZLE DESIGN)

The plasma created by the interaction of antiprotons with protons will be too hot to be contained and directed by thrust chambers and nozzles made of solid material. Fortunately, most of the particles generated are charged and can be contained and directed by strong magnetic fields. One example of a design for a magnetic field rocket engine is shown on the facing page.[1] With dimensions in the order of meters, it is about as large as a Shuttle main engine. Note the path of a particular positive or negative pion traced out in the diagram. Even though the pion starts out from the annihilation point in a direction that is opposite to the desired thrust direction, its direction is reversed by the converging magnetic field lines and it is redirected into the proper direction to provide thrust. The magnetic fields required are high, 50 T (500,000 gauss), and will require superconducting magnetic coils that are adequately shielded from the gamma rays and neutrons generated by the reactions.

A design for a magnetic field nozzle that has considered the shielding problems is the design previously described in the section on Imploded Micropellet Fusion Propulsion.[2] As seen in the drawing entitled Pellet Expansion, this engine has dimensions of tens of meters, and only consists of two superconducting rings, both well shielded from the 14 MeV neutrons that emerge from the fusion microexplosion. After discussion with the authors of this concept it was determined that this engine design would handle annihilation produced plasmas as well as the fusion produced plasmas that it was designed for. With only two coils to form the shape of the magnetic nozzle, this engine design is not as efficient at converting the isotropic explosion into thrust, but the shielding problems are significantly reduced. In fact, unpublished work by Hyde and Wood indicates that using just one superconducting loop to form a crude doughnut-shaped "nozzle" may save enough in shielding and radiator weight to compensate for the low (65%) thrust conversion efficiency of the design. Further studies on the design of magnetic nozzles are needed. Such nozzles might also be useful if other high energy propellants such as metallic hydrogen, atomic hydrogen, or metastable helium are found.

1. "Concepts for the Design of an Antimatter Rocket", David L. Morgan, Jr., J. British Interplanetary Soc. 35, 405 (1982).

2. "Prospects for Rocket Propulsion With Laser Induced Fusion Microexplosions" R. Hyde, L. Wood, and J. Nuckolls, AIAA Paper No. 72-1063 (Dec 1972).

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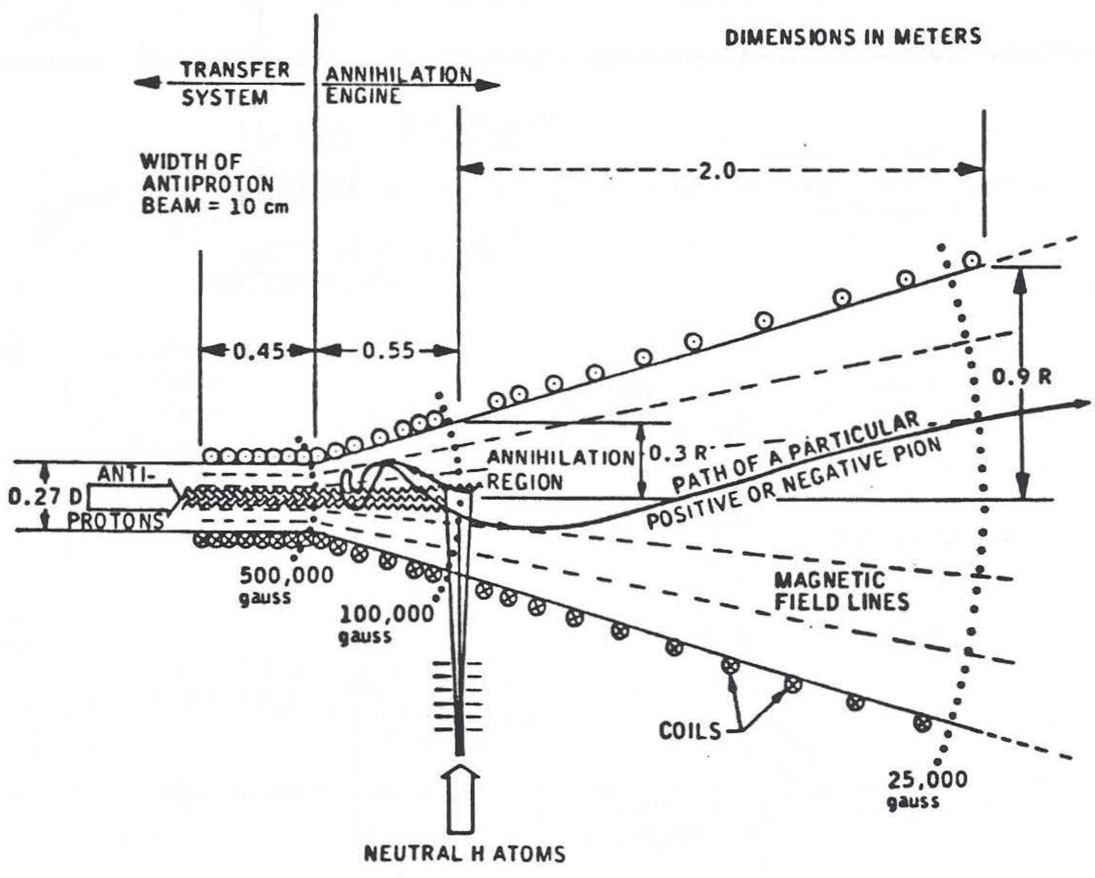
MATTER-ANTIMATTER PROPULSION



MAKING ANTIPROTONS AT FERMILAB

Antimatter in the form of antiprotons is being made and stored today, albeit in small quantities. The two major producers are IHEP in the USSR and CERN in Switzerland. The United States Fermilab has started construction of their antiproton facility and expects to be in operation in 1985. One way to make antiprotons is to send a high energy beam of protons into a dense tungsten target. When the relativistic protons strike the dense metal nuclei, their kinetic energy, which is many times their rest-mass energy, is converted into a spray of particles, some of which are antiprotons. The accelerator at CERN has generated 3.5 GeV antiprotons with a 26 GeV proton beam and has stored as many as a trillion antiprotons for up to four days in their magnetic ring "racetrack" antiproton accumulator.[1] At Fermilab in the United States one of the planned antiproton facility designs is shown on the facing page.[2] An 80 GeV beam of protons hits a tungsten target to produce a cloud of particles, including antiprotons. A magnetic field focuser and selector separates the 6 GeV relativistic antiprotons from the resulting debris and directs them to a particle decelerator that reduces their velocity to subrelativistic speeds. The slowly moving antimatter is then captured and cooled in an antiproton beam magnetic storage ring and cooler.

When the antiprotons are generated, they have a wide spread of energies about their nominal energy of 6 GeV. After they have been captured and decelerated down to 200 MeV, their average energy is less but the spread is still the same. Two techniques for reducing the velocity spread have been successfully demonstrated. In the stochastic cooling scheme, the radio noise generated by fluctuations in the beam are detected. This noise is amplified, phase shifted, then transmitted across the diameter of the ring to a kicker that suppresses the fluctuation. In the electron cooling scheme a beam of monoenergetic electrons is inserted in the ring with the antiprotons. Those antiprotons moving too slowly will be sped up by the electrons and those moving too fast will be slowed down. These cooled antiprotons could then go through another stage of deceleration and cooling to bring them down to speeds suitable for capture, control, and cooling by other techniques.

1. "The Search for Intermediate Vector Bosons", D.B. Cline, C. Rubbia, and S. van der Meer, Scientific American **247**, No. 3, 48 (March 1982).

2. "CERN Builds Proton-Antiproton Ring; Fermilab Plans One", Search and Discovery Section, Physics Today **32**, No. 3, 17-19 (March 1979).

MAKING ANTIPROTONS AT FERMILAB

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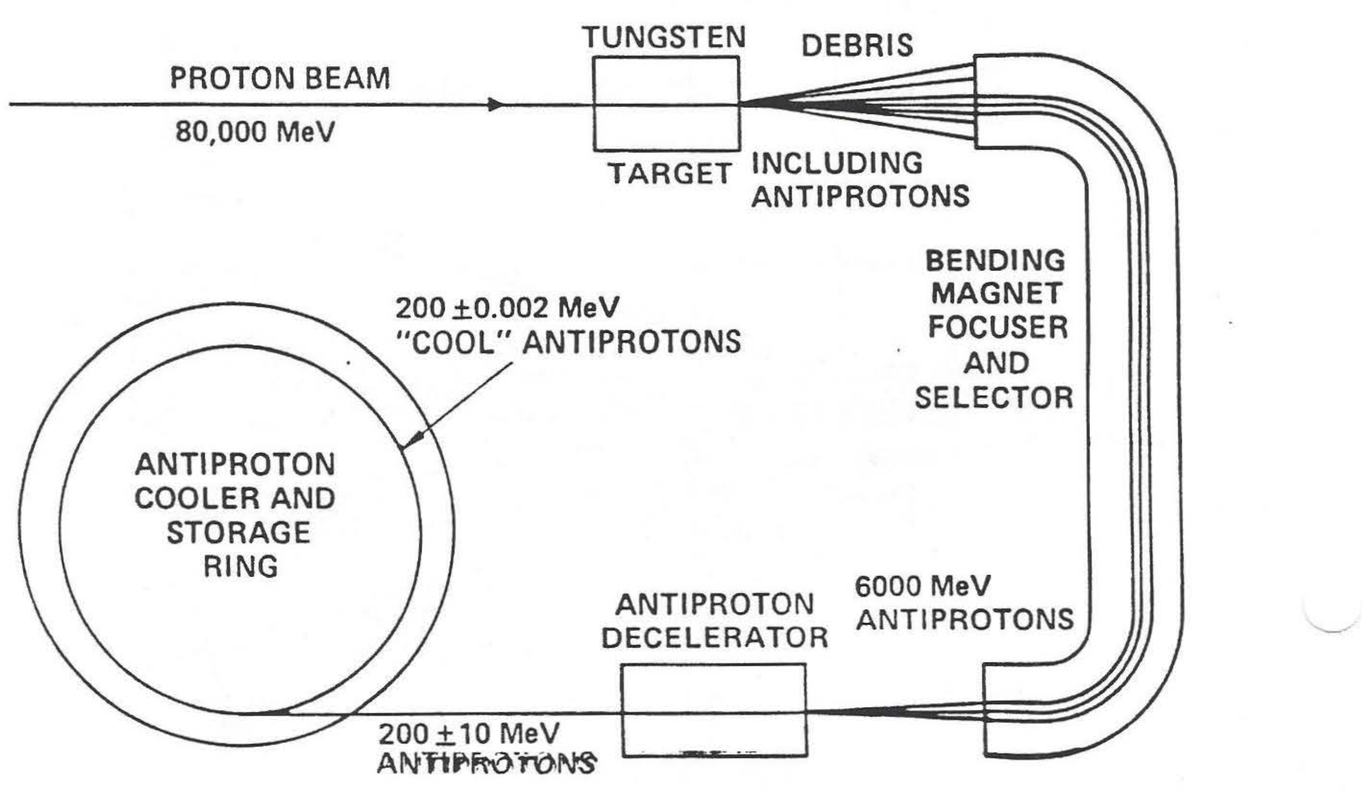


COMPARISON OF ANTIPROTON PRODUCTION FACILITIES

The characteristics of the three antiproton production facilities in the world are shown on the facing page.[1] The CERN and IHEP data describe operational systems, while the FNAL (Fermilab) data describe the characteristics of their latest plans for the facility they expect to have operational in 1985. (Note that some of the numbers have changed since their 1979 plans described on the previous pages.) In general, the higher the proton energy, the more efficient the proton is at generating antiprotons, so the IHEP and FNAL beams generate more antiprotons per proton, while the CERN facility partially makes up for that with higher beam currents. The major factor in system efficiency is the efficiency of the antiproton collector. The CERN collector has the best angular acceptance (it can capture a 100 mrad beam from a 1 mm target), while the IHEP can capture a wider spread in momentum (velocity). Still, both of these capture efficiencies are very low and only a small fraction of the antiprotons that are generated are ever captured.

The number of antiprotons generated by each proton increases with increasing energy in the incident proton. An analysis carried out in Phase 1 showed that the energy cost to make an antiproton decreases with increasing proton energy despite the fact that it costs more energy to make the higher speed proton. The incident proton energy to antiproton rest mass energy per steradian of angle at the central peak of the antiproton output beam was estimated to vary from 0.3% for the 26 GeV CERN energies, to 3.5% for the 70 GeV IHEP beam, to 7% for the 120 GeV beam of the planned Fermilab facility. The efficiency increases to 12% for a 200 GeV beam and 23% for a 400 GeV beam. (Don't forget that these percentages must be multiplied by the actual half-width in steradians of the output antiproton beam. This data is not readily obtainable from the literature and is one of the pieces of information that needs to be collected in the Phase 2 work.)

1. "Antiproton Source for the Accelerator-Storage Complex, UNK-IHEP", T. Vsevolozskaja, et al., FN-353, Fermilab translation of INP, Novosibirsk preprint 80-182 (1981)

COMPARISON OF ANTIPROTON PRODUCTION FACILITIES

	CERN (EUROPE)	FNAL (USA)	IHEP (USSR)
PROTON ENERGY (GeV)	28	120	70
PROTONS/CYCLE ($\times 10^{12}$)	10	3	7
CYCLE DURATION (sec)	2.6	2	7
ANTIPROTON ENERGY (GeV)	3.5	8	5.5
ANGULAR CAPTURE (mm - mrad)	100π	20π	60π
MOMENTUM CAPTURE ($\Delta P/P$)	$\pm 0.75\%$	$\pm 3\%$	$\pm 3.2\%$
ANTIPROTONS/CYCLE ($\times 10^{6}$)	25	70	320
ANTIPROTONS/PROTON ($\times 10^{-6}$)	2.5	23	46
ACCUMULATION RATE ($10^{6}\ \overline{p}$/sec)	10	35	47

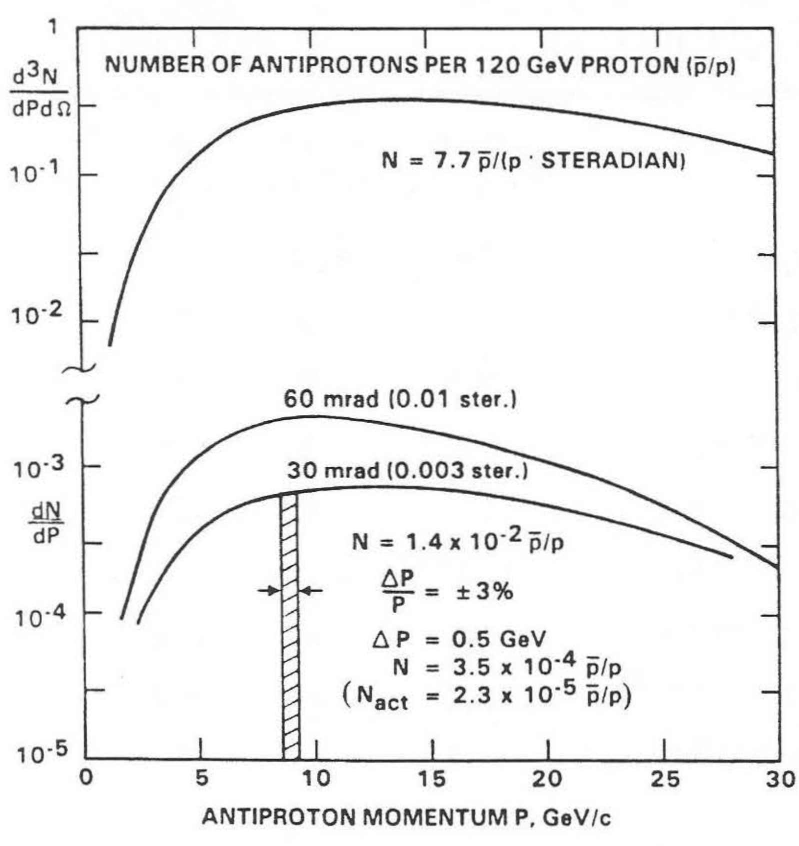
PRESENT ANTIPROTON CAPTURE EFFICIENCIES

The present capture efficiencies of the antiproton facilities are abysmally low. The situation is best summarized by the figure on the facing page derived from a very recent Fermilab publication.[1] The upper part of the figure shows the total number of antiprotons generated per GeV of antiproton momentum per steradian of solid angle at the central portion of the antiproton beam. Integrating the curve over the antiproton momenta shows that each proton produces 7.7 antiprotons per steradian. If the beam half-width is a steradian, then each proton is producing 7.7 antiprotons. The half-width of the beam is not given in the paper and was not readily obtainable from phone contacts with Fermilab sources. In the paper, the number of antiprotons per GeV of antiproton momentum is estimated assuming that the antiproton collector can only accept those antiprotons with an angular spread off the axis of 30 mrad (0.0028 steradians). When this curve is integrated over the antiproton momenta we find that there are only 0.014 antiprotons per proton in this narrow angular acceptance. Then, of this small angular spread the Fermilab collector is only able to capture those with a momentum (velocity) spread of ±3% or 0.5 GeV around 8.9 GeV. Thus, ideally, they only expect to capture about 3.5×10^{-4} antiprotons per proton, with an estimated actual efficiency of 2.3×10^{-5} antiprotons per proton (the reason for the excess loss is not clear at the present time. Further investigation is needed in Phase 2.)

Data is also given in the paper for a 60 mrad angular acceptance. If the antiproton beam had a flat angular distribution, this curve should be four times higher than the 30 mrad curve. It actually is about three times higher, showing that the efficiency is dropping off with increasing angle away from the center of the antiproton beam. It is suspected that this is due to the 45 mrad acceptance angle of the particular lithium metal magnetic lenses that exist in the Fermilab design, but it is not obvious from the paper.

At the present time there does not seem to be any fundamental reason for the present low capture efficiencies. Multiple thin targets surrounded by wide angular arrays of multiple lenses with different velocity acceptances should allow for capture of a high percentage of the generated antiprotons. At the present time it is guessed that the efficiency of capture could be raised to 5% or more. This is merely a guess and needs to be backed up with more detailed analysis in Phase 2.

1. "Calculation of Antiproton Yields for the Fermilab Antiproton Source", C. Hojvat and A. van Ginneken, Nuc. Inst. and Methods 206, 67 (1983).



PRESENT ANTIPROTON CAPTURE EFFICIENCIES

ANTIMATTER CONTROL - ELECTRIC FIELDS

After the antiprotons have been generated, captured, and cooled, it is possible to think of storing them in that form. It has already been demonstrated at CERN that they can be stored for days in a magnetic storage ring. Standard rings are heavy, and although lightweight superconducting storage rings should be looked at as potential "fuel tanks" for storage of antimatter fuel, it is probable that other techniques will be better. One approach would be to combine the antiprotons with antielectrons (positrons) to form antihydrogen atoms. A recent CERN preprint[1] (not yet available) indicates that this has been or will be done. This beam of electrically neutral antihydrogen atoms can then be further slowed and stopped by a number of techniques. One technique is called resonant radiation cooling and capture. A laser with photon energy just less than the transition energy is used to excite an atom which then re-emits the photon. The energy difference each cycle comes from the energy of the atom, stopping it and cooling it down.[2] The resonant light pressure can also be used to create a trap for the antihydrogen by using three orthogonal laser beams or a resonant cavity.

Since hydrogen is slightly diamagnetic, it can be directed by hexapole magnetic channels and trapped by a magnetic bottle made of superconducting rings.[3] Actually, the best storage means may be to convert the atomic hydrogen atoms into hydrogen molecules, direct and cool them with laser beams from molecular hydrogen lasers, and store them as small particles of antihydrogen ice using a simple electrostatic levitation and servo system as shown on the facing page. If the temperature is kept below 1 K, the sublimation pressure is so low that the antihydrogen ice will last for years. The antiprotons are extracted by irradiating the ice with ultraviolet, driving off the positrons, extracting the excess antiprotons by field emission with a high intensity electric field, then directing them to the thrust chamber.[4]

1. "Enhanced Electron-Ion Capture and Antihydrogen Formation", H. Poth, A. Wolf, and A. Winnacker, CERN EP preprint (to be submitted to Z. Phys.)

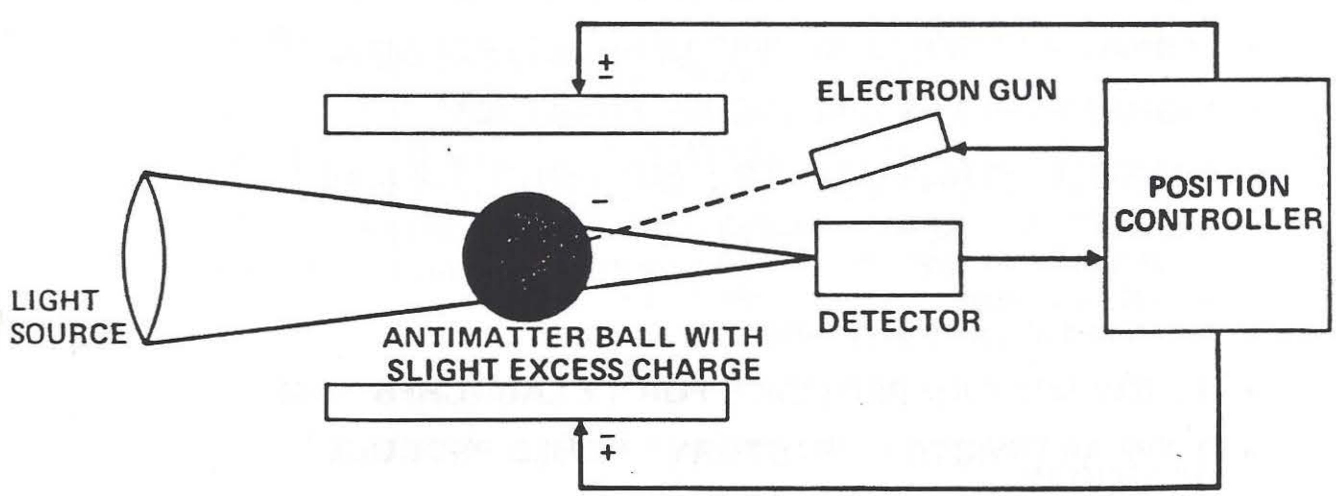
2. "Cooling and Capture of Atoms and Molecules by a Resonant Light Field", V.S. Letokhov, et al. Sov. Phys. JETP 45, 698 (1977).

3. "Possibility of Accumulation and Storage of Cold Atoms in Magnetic Traps", V.S. Letokhov and V.G. Minogin, Optics Comm. 35, 199 (1980).

4. "Concepts for the Design of an Antimatter Annihilation Rocket", D.L. Morgan, Jr., J. British Interplanetary Soc. 35, 405 (1982).

ANTIMATTER CONTROL
ELECTRIC FIELDS

HUGHES
HUGHES AIRCRAFT COMPANY
RESEARCH LABORATORIES



ANTIPROTON ANNIHILATION PROPULSION - POTENTIAL PAYOFF

To scope the problems and potentials of antiproton annihilation propulsion, it is informative to calculate the mass equivalent of the energy in specific mission scenarios and typical prime power sources. For example, the kinetic energy in a large orbiting space vehicle (the Space Shuttle in LEO) is equivalent to 25 milligrams of matter. When the Space Shuttle takes off, the three main engines generate 7 GW each for about 500 seconds for a total energy output of about 0.1 grams (not counting the solid booster contribution). Thus, assuming 25% launch efficiency it should only take 0.1 grams of antimatter fuel to launch the Shuttle (along with 300 tons of lead or bismuth as reaction mass).

A large prime power plant (Hoover Dam or a modern nuclear plant) generates 5 GW of power, while the designs for the Solar Power Satellites go up to 10 GW. A 10 GW power plant produces the equivalent of 3.5 kilograms of energy per year. If a reasonable fraction of that energy could be converted into antimatter and stored, then one such plant could provide enough antimatter for the present space program. Actually, if antiproton annihilation turns out to be a viable propulsion technique, then it would not be desirable for safety or environmental reasons to have the antiproton production facility or its power plants on the earth. The facility should be out in space, powered by sunlight (probably solar thermal rather than solar photovoltaic) where the high vacuum and low gravity aids in the design of the proton accelerators and the antiproton collectors. For the far future, ten 100 GW antiproton factories could produce a gram of antiprotons per day, which could power high speed space vehicles throughout the solar system and on to the stars.

The real problem is the low efficiency of the antiproton sources. CERN has an estimated "wallplug" to antiproton rest mass efficiency of 2×10^{-10}.[1] The wallplug to proton kinetic energy is only 2×10^{-3}. Fermilab has built a superconducting magnet "Energy Saver" accelerator with improved efficiency. It would be valuable to determine the ultimate that could be obtained.

Recommendation: IF a 200 GeV (or higher energy) accelerator could be designed with a 10% wallplug efficiency, and IF the antiproton capture efficiency can be increased to 5%, then the use of antiproton annihilation begins to look feasible for propulsion. Only crude guesses can be made at the present time at the various efficiencies. More investigation needs to be done in Phase 2.

1. Letter from S. van der Meer, CERN (28 April 1983).

ANTIPROTON ANNIHILATION PROPULSION POTENTIAL PAYOFF

- ORBITING 75T SHUTTLE CONTAINS 25 mg ENERGY
- 10 GW SPS PRODUCES 3.5 kg ENERGY/YEAR
- CERN "WALLPLUG" TO $\bar{p}$ EFFICIENCY 2×10^{-10}
- FERMILAB "ENERGY SAVER" USES SUPERCONDUCTORS
- HIGHER ENERGIES GIVE HIGHER EFFICIENCY
- POSSIBLE "WALLPLUG" TO $\bar{p}$ EFFICIENCY 1.2×10^{-4}
  - WALLPLUG TO 200 GeV PROTONS $\epsilon = 10\%$
  - 200 GeV PROTONS PRODUCE 25 $\bar{p}$ $\epsilon = 12\%$
  - HIGH-EFFICIENCY $\bar{p}$ COLLECTORS $\epsilon = 5\%$
  - ANNIHILATION ROCKET EFFICIENCY $\epsilon = 20\%$
- 10 GW SPS CAN PROVIDE $\bar{p}$ FOR 17 LAUNCHES/YEAR
- 1 TW ANTIPROTON "FACTORY" COULD PRODUCE GRAM/DAY

MAY 1983

ANTIPROTON ANNIHILATION PROPULSION - PROBLEMS TO OVERCOME

The efficient generation, collection, storage, and utilization of antiprotons for advanced propulsion is a long way in the future. But the goal of obtaining what many have called the "ultimate fuel" make it worth looking at the subject closely before giving up and leaving the topic to future generations. On the facing page are the problems that must be overcome to obtain propulsion using antiproton annihilation. (This scenario assumes the antiprotons will be generated by high speed protons and will be stored as antihydrogen ice. Other methods of generation or storage will involve changes in the problems to be solved.) It is interesting to note that many of these problems have already been studied. Some of them have been solved, and some of them look solvable based on the results of present research in these areas.

Recommendation: It is recommended that antiproton annihilation be one of the concepts selected for investigation in Phase 2. The plan will involve examining all the problems listed on the facing page. First we will attempt to determine if any of the problems are "show-stoppers" in that there seems to be no solution to the problem and no way around it. If no intractable problems are found, then one or two of the more critical problem "bottlenecks" will be selected for more intensive study, and an investigative team will be formed to propose a suitable research program for Phase 3.

ANTIPROTON ANNIHILATION PROPULSION PROBLEMS TO BE OVERCOME

- GENERATE ULTRARELATIVISTIC PROTONS (DONE)
- CREATE RELATIVISTIC ANTIPROTONS (DONE)
- CAPTURE RELATIVISTIC ANTIPROTONS (DONE - INCREASE EFFICIENCY)
- COOL RELATIVISTIC ANTIPROTONS (DONE - STOCHASTIC COOLING)
- SLOW ANTIPROTONS TO SUBRELATIVISTIC SPEEDS (DONE)
- COOL SUBRELATIVISTIC ANTIPROTONS (DONE - ELECTRON BEAM COOLING)
- CONVERT ANTIPROTONS TO ANTIHYDROGEN (DONE?)
- COOL ANTIHYDROGEN BEAM (LYMAN α LASER?)
- CONVERT ANTIHYDROGEN ATOMS TO MOLECULES (?)
- COOL ANTIHYDROGEN MOLECULES (H_2 LASER?)
- TRAP ANTIHYDROGEN MOLECULES (MAGNETIC FIELDS?)
- CONDENSE TO ANTIHYDROGEN ICE (?)
- STORE ANTIHYDROGEN ICE (ELECTROSTATIC SUSPENSION)
- EXTRACT ANTIPROTONS (e^- BOMBARDMENT, E-FIELD EXTRACTION)
- REACT WITH NORMAL MATTER (HYDROGEN, HEAVY ATOMS)
- DIRECT INTO THRUST (MAGNETIC NOZZLE)