PROJECT LONGSHOT
... a Mission to Alpha Centauri

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Curtis West
Sally Chamberlain
Neftali Pagan
Robert Stevens

United States Naval Academy
Aerospace Vehicle Design Project

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Introduction

For centuries, mankind has gazed skyward wondering "What is it like out there?" In the 1960's, man took the first step in answering this question by exploring near-Earth space through programs such as Mercury and Gemini, culminating with trips to the Moon with Apollo. The expanding technology of the 1970's and 1980's brought more ambitious exploration of the solar system with Voyager and Magellan. Man is currently taking one step further in space exploration by designing the Hubble Space Telescope to gather information about heavenly bodies at tremendous distances. But no program has been developed to explore other solar systems. Project Longshot has been proposed to meet this need.

Longshot's destination is Alpha Centauri, the closest star to the Sun. Enroute, it will collect data to extend the astronomical baseline, which will allow astrometrists to measure stellar distances more accurately. Once in the Centaurus system, Longshot will provide information about the planetary structure and environmental properties of the trinary star system. Longshot will also provide an opportunity for engineers to develop advanced technologies to solve the tremendous propulsion and communication problems associated with interstellar travel. Finally, Project Longshot will offer mankind the chance to further his quest for knowledge about the universe in which he lives.

Chapter 2:

Mission Model

MISSION MODEL

Alpha Centauri, being the closest star system to our own solar system, is a logical choice of stars to visit. Although relatively close compared to other stars, 4.3 light years is an enormous distance to travel with the limited energy resources man has at this time. More information on Alpha Centauri is shown in fig. 1.

Longshot will be a fully autonomous probe designed using current technologies and technologies that can reasonably be expected within thirty years. The destination is Alpha Centauri A. A mission to Alpha Centauri A will be of great scientific value , advancing knowledge in fields of astrometry, trinary star systems, and possibly finding planets. The mission profile will be the following:

1. Assemble modular components on earth.
2. Launch components to LEO.
3. Launch three communications relay stations prior to constructing the the space probe with seven to nine year intervals between launches. They will be launched at a slower velocity so they will ultimately be passed by Longshot in transit and will be in position for transmission when Longshot reaches its destination.
4. Assemble components at space station.
5. Escape the earth and sun in the ecliptic plane using a single impulse.
6. Change declination to aim toward Alpha Centauri A and initiate the boost phase to accelerate to the coast velocity.
7. Drift at coast velocity, 1/10 the speed of light, for 41 years.
8. Rotate spacecraft 180 degrees and decelerate to reach desired orbit injection velocity around Alpha Centauri A.
9. Enter circular orbit around Alpha Centauri A, deploy instruments, and begin to transmit data to relay stations.

TECHNOLOGY

Because the 4.3 light year distance is large and the spacecraft is expected to live a half century, their are three areas where advances in technology are needed. These areas are propulsion, data processing for autonomous command and control functions, and reliability. To get to Alpha Centauri within 50 years, a specific impulse on the order of one million seconds is required. Project Longshot intends to use the high energy output of proton-antiproton annihilations to statisfy this requirement. Since the distance from earth to the space probe is so large, positive control from

FIGURE 1

ALPHA CENTAURI INFORMATION

Alpha Centauri is a trinary star system consisting of two large stars orbiting around the barycenter, and a third, smaller star, Proxima Centauri orbiting around the other two at a greater distance away.

Distance: 4.34 light years
Radial velocity: 14.5 mi/s in approach
Orbital period: 80.089 years
Eccentricity of true orbit: .52
Distance between two large stars: 11 to 35 AU

INFORMATION ON THE A AND B STARS

star	magnitude	type	mass (solar mass)	diameter (solar diam.)
A	-.04	G2V	1.10	1.07
B	1.17	dK1	.85	1.22

From Burnham's Celestial Handbook (Reference 1)

FIGURE 2

MISSION PROFILE

ESCAPE

Escape earth and sun in ecliptic plane. Navigate with star trackers and IMU.

BOOST

Change plane. Thrusters direct Longshot toward target. Navigate with star trackers. Accelerate at .1 g for one year.

COAST

Coast velocity, .1c is reached. Propulsion unit is shut off. Thrusters keep Longshot directed toward Alpha Centauri. Spacecraft drifts for forty-one years.

DECELERATION

Gravitational force of Centauri system is detected. Rotate spacecraft 180°. Start propulsion unit. Navigate with star trackers and IMU.

TERMINAL

Longshot enters circular orbit around Alpha Centauri A. Propulsion unit is shut down and detatched. Instruments are deployed for data collection.

the earth will be impossible due to time delays. Longshot must be completely autonomous, requiring advances in the field of artificial intelligence. Since not many man made dynamic systems last more than 50 years, the reliability of Longshot's components over its lifetime is a key concern, so Longshot's components will all be either double or triple redundant systems.
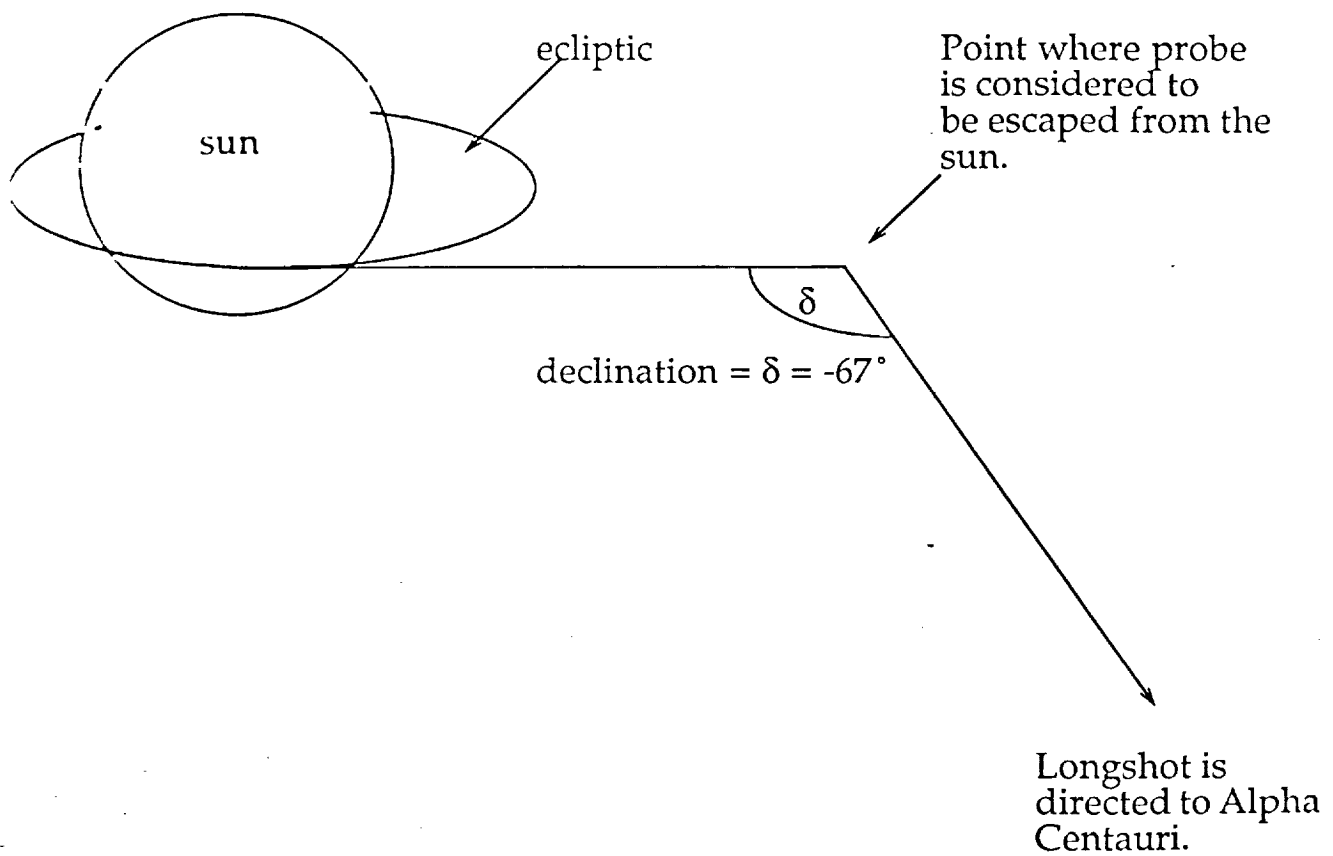
TRAJECTORY

ESCAPE

The energy required to travel 4.3 light years in forty years is enormous; on the order of 10^{11} kilowatt-hours. This is equal to the electrical energy produced in the United States for two weeks.[1] Although this amount of energy dwarfs the amount of energy required for a solar escape in comparison, even a solar escape is too demanding on conventional chemical rockets (See Appendix A for an analysis of various solar escape options). The costs of using huge chemical rocket staging to escape the sun outweigh the costs of using the antiproton drive to perform this relatively minute task. To escape the earth and the sun in a single impulse would require an escape velocity of about 53 km/s. Because the antiproton drive can attain this velocity in a short time, a little over an hour, it will be fired when the earth's velocity vector is in the direction of the right ascension of the Centauri system. Using the earth's velocity for the solar escape, Longshot will be fired just before summer solstice so it will be escaping at a 170 degree right ascension in the solar coordinate system (See AppendixB-2 for coordinate system calculations). Once the probe has escaped the solar system, i.e. the sun's gravitationl field is no longer a significant influence, a declination change of -67.6 degrees with respect to the ecliptic will be performed using hydrazine-thrusters. This declination change directs Longshot toward the target system where the boost phase of the trajectory begins as shown in fig. 3. No overshoot declination change is required to account for the velocity left over from the escape because this velocity is small compared to the enormous coast velocity that will be reached later in the trajectory.

BOOST PHASE

The boost phase is simply the interval of time that Longshot accelerates approaching coast velocity. Limitations may be placed on useful probe accelerations. If the speed of light could be reached instantaneously, the

FIGURE 3

SOLAR ESCAPE PLAN

ecliptic

sun

Point where probe is considered to be escaped from the sun.

δ

declination = δ = -67°

Longshot is directed to Alpha Centauri.

probe would arrive at Alpha Centauri in 4.3 years from the time of ignition. If the probe accelerates at 1 g for a year, the probe would reach 90% of the speed of light, arriving at Alpha Centauri in a little over five years. Had project Longshot been a manned mission, a 1 g acceleration would be appealing since it simulates the gravity on earth. Longshot is unmanned, however, and not much time would be gained by accelerating any more than 1 g, so this acceleration will serve as an upper bound. The lower limit is determined by propulsion capabilities and desired mission time. An acceleration of less than .01 g would slowly nudge Longshot to Alpha Centauri in 500 years, much too long for the mission. Therefore Longshot will thrust at the maximum acceleration that the drive will allow. An acceleration of .1g is expected from the antiproton annihilation drive. At this acceleration, there is the option of having a long boost phase of 3 years followed immediately by the deceleration phase which will get to the destination in about 6 years, but this would be at the price of high fuel consumption. Accelerating at .1 g for a short time, say two months, might provide a tempting mass ratio, but would require 210 years to coast along to the destination. Figure 4 shows the relationships of various burn times. To better understand the relationship between mass ratio and travel time, these characteristics were calculated for various burn times (see Appendix B-3) and plotted in fig. 5. Because of the relativistic velocity that must be attained and the nature of proton-antiproton propulsion, the mass ratio relationship with velocity changes is different from the one most conventional chemical rocket engineers are accustomed to. The mass ratios shown in figure 6 are those of the initial mass to final mass and those of the annihilated mass to final mass for various ζ values. The parameter ζ is the fraction of annihilated energy ejected in massless particles, and varies from zero, the most practical case, to one, which would represent a photon rocket. Notice that for ζ =0 the initial to final mass ratio remains at a relatively constant value of five for velocities up to about .5c, but the amount of antimatter mass that must be annihilated increases drastically with longer burn times and higher coast velocities. This is a major concern since it is desirable to conserve as much antimatter as possible.[2] A burn time of one year will accelerate the probe to 1/10 the speed of light using a minimum of antiprotons and still getting to the Centauri system within 45 years.

COAST PHASE
    Once the coast velocity is determined to be .1c by accelerometers and
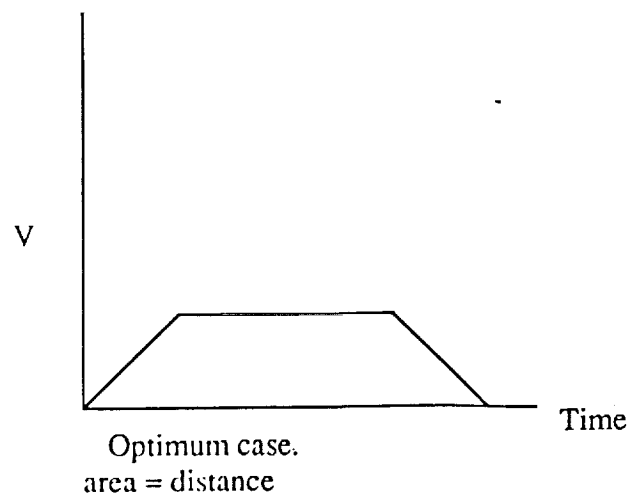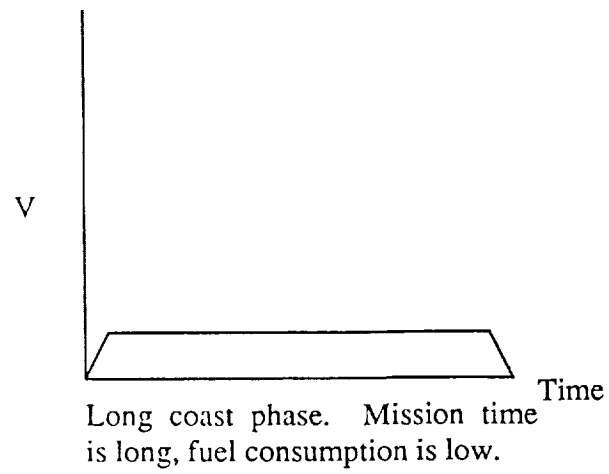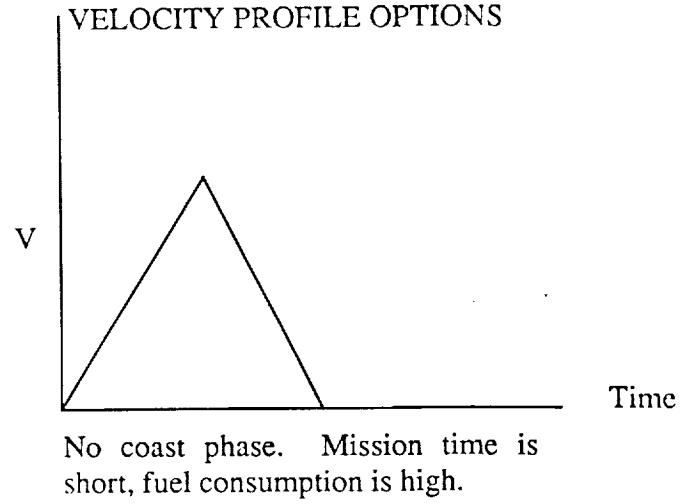
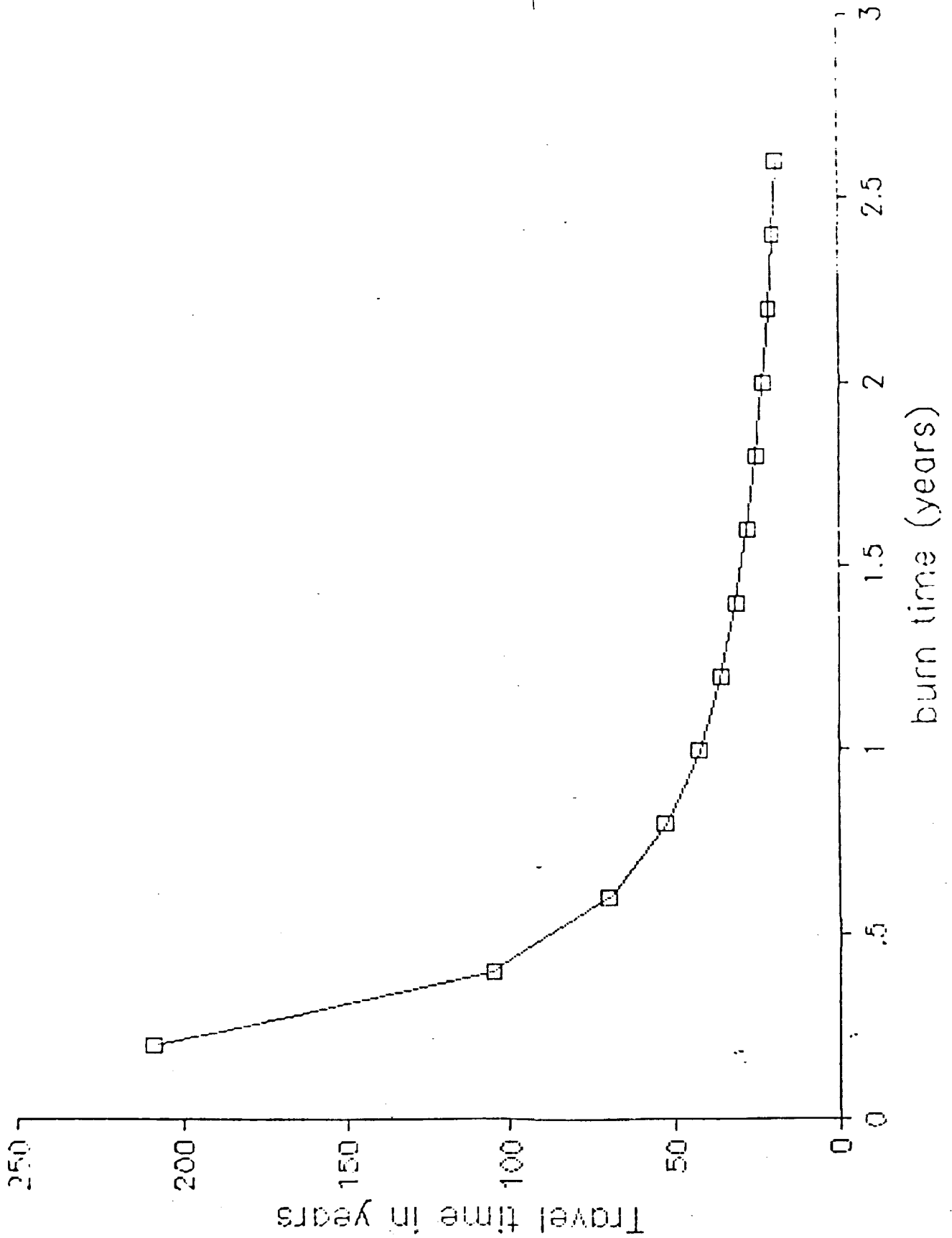# FIGURE 4
VELOCITY PROFILE OPTIONS

No coast phase.   Mission time is short, fuel consumption is high.

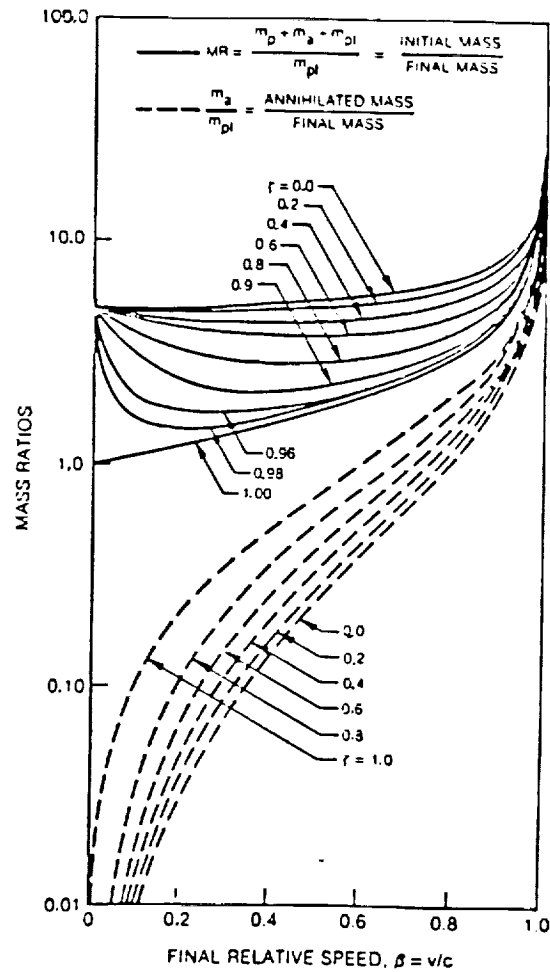Long coast phase.   Mission time is long, fuel consumption is low.

Optimum case.
area = distance

FIGURE 5

Total travel time vs. burn time

FIGURE 6
MASS RATIO VS. COAST VELOCITY

From Robert L. Forwards report, "A Program for Interstellar Exploration" (Reference 6)

the clock (discussed in the Navigation section), the propulsion system will automatically shut down. The coast phase is initiated. Star trackers are the key source of navigation in this phase since the accelerometers have nothing to measure at constant velocity. The only propulsoin taking place is the occassional burst of the hydrazine thrusters to nudge the probe directly toward Alpha Centauri.

Forty one years after the initiation of the coast phase, the accelerometers will detect the gravitational pull of the Centauri system. When the gravitational pull and the star trackers indicate that Alpha Centauri is 1/20 of a light year away, which is the distance required to decelerate to the approach velocity, Longshot will initiate the next phase of the trajectory, the deceleration phase.

DECELERATION PHASE

The hydrazine thrusters will be fired to rotate the probe 180 degrees from its original flight path and stabilized. Star tracker data must be updated to account for the rotation and allow for further navigation toward the target star. Guidance will now direct the probe 1 AU from the center of Alpha Centauri A in the plane containing the star and the probe. Since it is best for the probe to orbit in conditions similar to those experienced in its home solar system, a distance of 1 AU was chosen as the circular orbit radius about Alpha Centauri A, which has similar characteristics to the sun. The two primary stars travel in an elliptic orbit about their common barycenter in a fashion shown in fig. 7. Notice the planets are always diametrically opposed with a pericentron distance of about 11 AU. Figure 8 shows where Alpha Centauri A was in 1985, and where it will be in 2050 (the approximate arrival time of Longshot) with respect to the barycenter. At this point in the orbital cycle of the two stars, A and B are about 20 AU apart. The effect of the gravitational field due to Alpha Centauri B is negligible when considering the orbit about A. The force due to B is only 1/280 that of A for the worst case of being between the two stars.

The gravitational force ratio of Alpha Centauri B to A on the probe at a distance of 1 AU from A when the two stars are 20 AU apart is given by:

$$F_B/F_A = \frac{M_B/r_B^2}{M_A/r_B^2} = \frac{1.1/19^2}{.85/1} = .0035$$

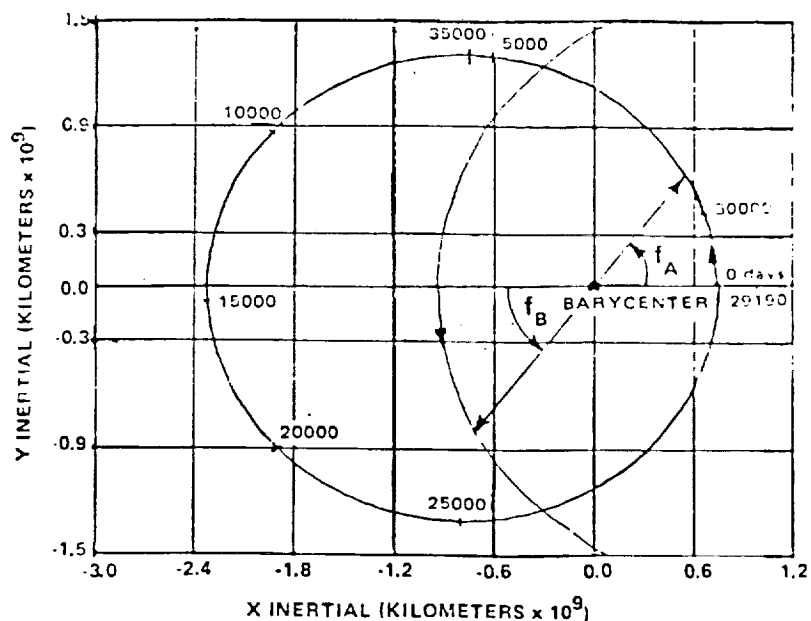FIG 7. Alpha Centauri A & B Orbital Plane.
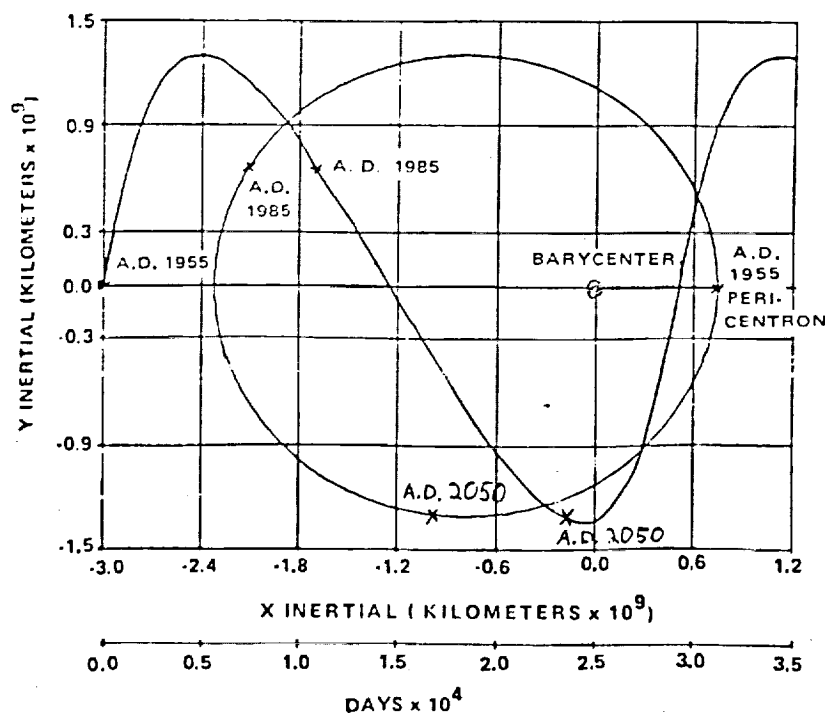

FIG. 8. Alpha Centauri A Position & Time.

From W.D. Kelly's report (Reference 7)

where the force of gravity is given by $F=GM/r^2$.

The velocity of Alpha Centauri A at this point in the orbit is 19 km/s with respect to the barycenter. Longshot must decelerate to 42.9 km/s relative to this star to orbit at 1 AU from its center. Thus Longshot must decelerate to 62 km/s relative to the barycenter (see calculations in Appendix B-4). To attain this orbital velocity, the awaiting antiproton annihilation drive will finally begin firing for the second and final time. The deceleration phase will last for 1 year, which is the same amount of time as the boost phase time since the same approximate change in velocity is required to bring the probe to approach velocity, only in the opposite direction. Longshot will shut down its main drive again when the velocity is determined by the accelerometers to be the approach velocity. The massive propulsion unit will be ejected from the remainder of the probe since it is no longer needed. After the ejection, Longshot will be in the desired circular orbit around Alpha Centauri A. The instruments will then be deployed for data collection.
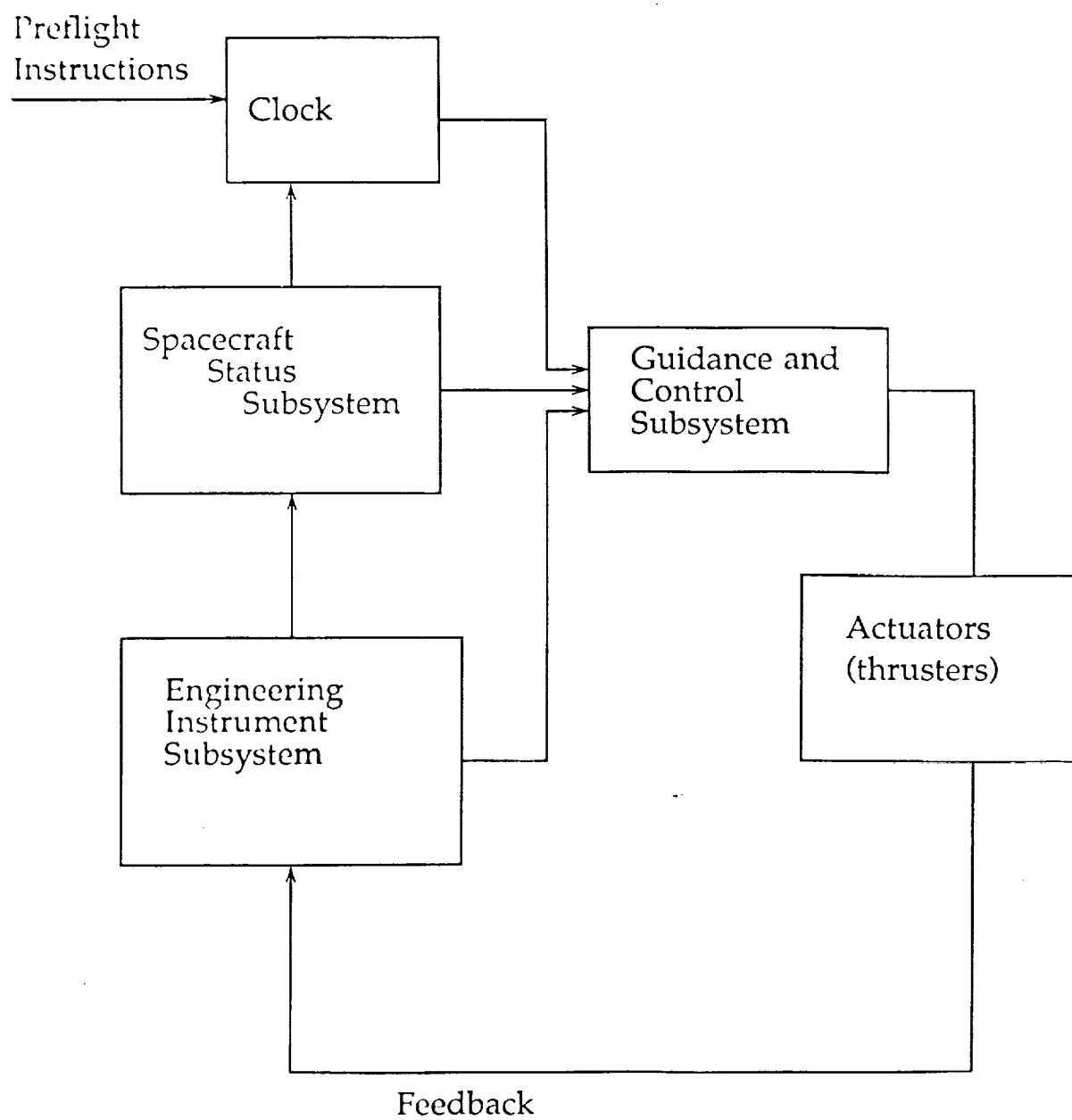
NAVIGATION

The first satellites put into space by man relied on information sent to it by earth to determine position. This is a reasonable method of guidance and control for spacecraft close to earth, but this is not feasable for an interstellar space probe at distances measured in light years. The navigation, guidance, and control systems of Longshot must be fully autonomous. The probe must compare navigation measurement data received from the external star trackers to preprogrammed instructions, and respond to errors in position or velocity using the guidance subsystem. Figure 9 shows a chart of the flow of guidance and control data in Longshot. The chart shows that the system's control functions are all internal, meaning no updated information or commands are received from earth.

There are three phases of the trajectory with which the guidance subsystem will be concerned : escape, midcourse, and terminal guidance. Escape guidance deals with the time from the initiation of the earth escape until solar escape is reached. Guidance and control aspects in this phase of the trajectory are especially important because small errors will create large trajectory dispersions that the midcourse and terminal guidance and control phases must handle. Furthermore, it takes much more fuel to correct errors later on in the trajectory. An Inertial Measurement Unit, IMU, will be used to guide the space probe while the probe is accelerating

FIGURE 9

FLOW OF GUIDANCE AND CONTROL DATA IN LONGSHOT

Preflight
Instructions

Clock

Spacecraft
Status
Subsystem

Guidance and
Control
Subsystem

Engineering
Instrument
Subsystem

Actuators
(thrusters)

Feedback

to escape. The IMU provides three functions. It provides a non-rotating frame of reference so the acceleration may be compared to that frame. Second, it provides information to the guidance subsystem on the orientation of the coordinate frame with respect to the spacecraft. The IMU also measures the acceleration of the spacecraft. The IMU in Longshot will be similar to those used in other long range missions. It will consist of three orthogonal accelerometers mounted on a stable member of the craft to measure accelerations for velocity determinations, and gyroscopes to detect angular deviations. Using the IMU to determine Longshot's position and velocity will start it on an accurate course toward Alpha Centauri.[3]

While Longshot is coasting, i.e the propulsion unit is shut off, accelerometers and gyroscopes will be of little use. Two star trackers will provide enough information required for guidance in this phase. One star will be 900,000 light years away to provide a relatively fixed reference point, and the other star is the target star Alpha Centauri A. Two more pairs of star trackers using different stars as a reference will be incorporated for triple redundancy. Each tracker will have a large field of view (6 degrees by 6 degrees) and will be equipped with solid state detectors sensing stars with magnitudes ranging from -1 to +6. These detected stars will be compared to preprogrammed celestial data and the error will be sent to the guidance subsytem which will order the thrusters to make appropriate corrections. A star tracker is shown in figure 11. For terminal phase guidance, the velocity must be reduced to 62 km/s relative to the barycenter of the Alpha Centauri system. Once again the IMU will measure the velocity changes and angular deviations to orient the probe in its desired circular orbit around Alpha Centauri A.

Footnotes
1. R. L. Forward, "A Program for Interstellar Exploration", p 617
2. R. L. Forward, "A Program for Interstellar Exploration", p 402
3. Bate, Fundamentals of Astrodynamics, p 191 - 192
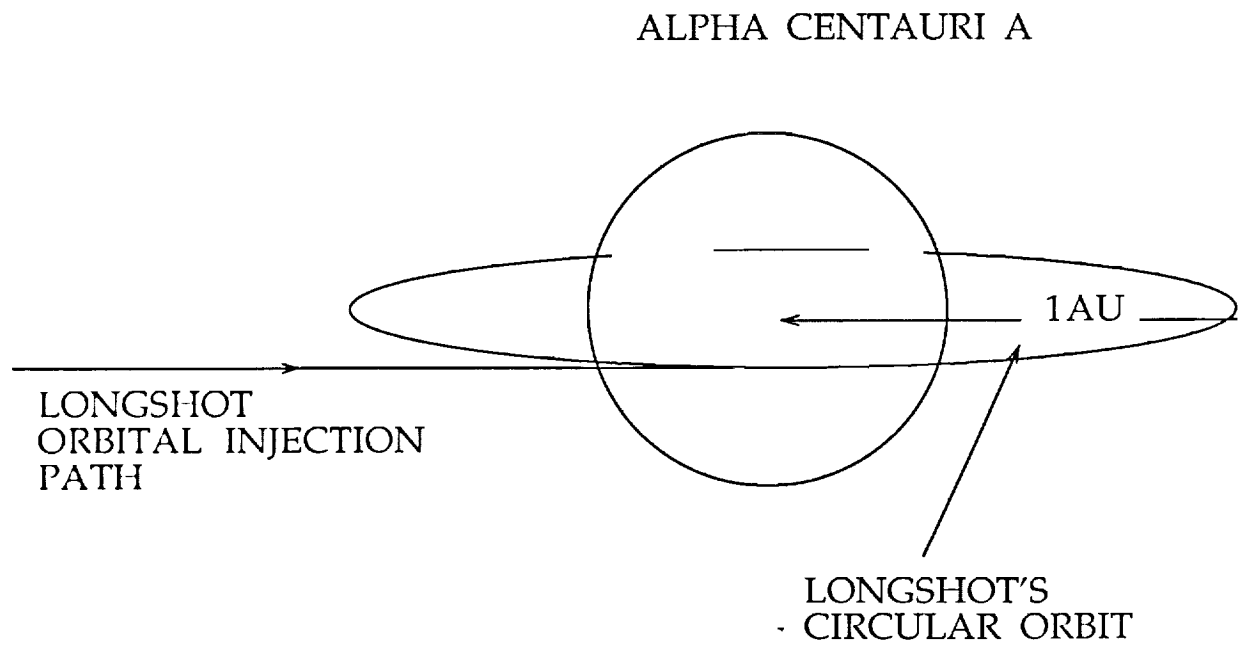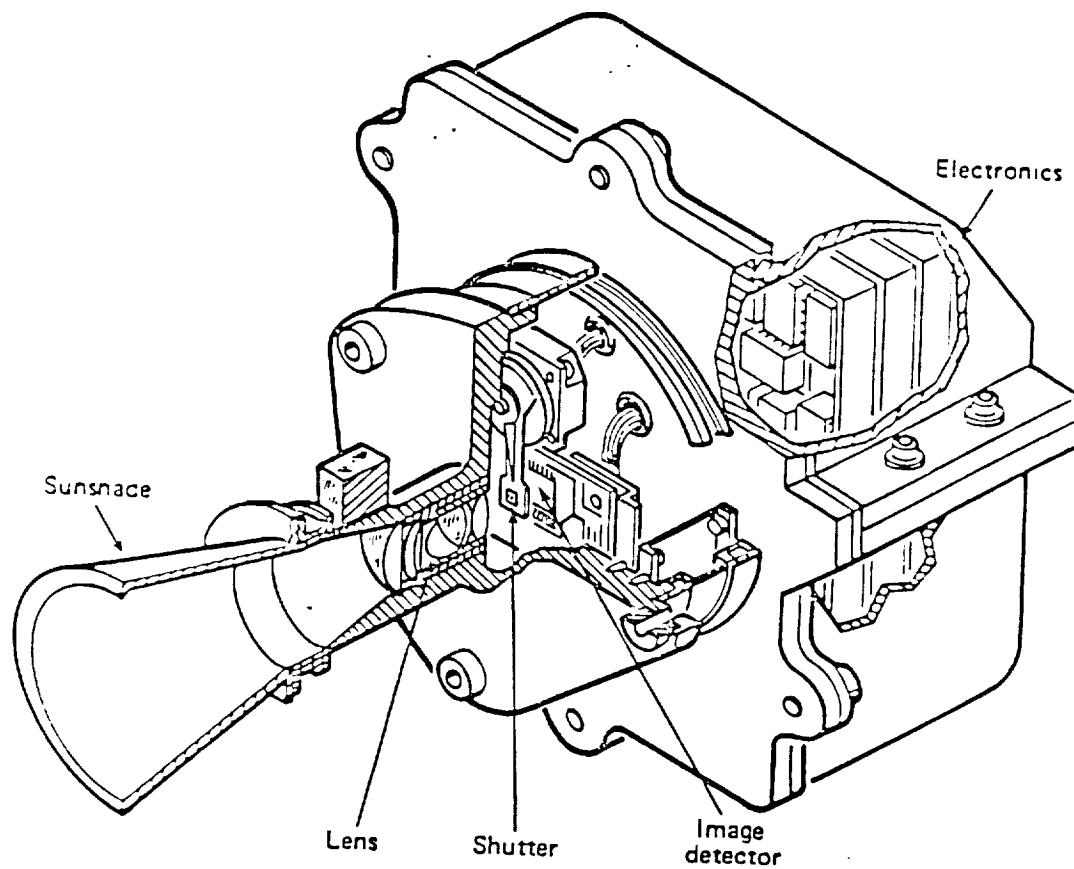
FIGURE 10

ORBITAL INJECTION

ALPHA CENTAURI A

1AU

LONGSHOT
ORBITAL INJECTION
PATH

LONGSHOT'S
· CIRCULAR ORBIT

FIGURE 11
STAR TRACKER HEAD

Electronics

Sunspace

Lens Shutter Image detector

From APL notes

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Chapter Three:

Propulsion

Propulsion Subsystem

The propulsion of Project Longshot presents a unique problem. Thus far in space exploration, distances have been of the order of less than 1 AU. The majority of propelled space flight has been mainly earth-orbiting platforms. For these systems a chemical propulsion system is sufficient. Consider the mass ratio equation:

1)
$$R = \frac{m_v + m_p}{m_v} = e^{\Delta V/v} = e^{\Delta V/gIsp}$$

R=mass ratio $\qquad$ m_v=vehicle mass

I_{sp}=specific impulse $\quad$ m_p=propellant mass

For a typical earth payload, ΔV would be of an order of magnitude of 10^3 m/s. Most chemical propellants have I_{sp} less than 10^3 sec. This gives apropellant to total vehicle mass ratio of less than ten for most earth missions.

When a mission to another star system is considered, the limitations imposed by chemical propulsion become much more apparent. The distance from earth to Alpha Centauri could be traversed in 40 years at 0.1c. For a mission ΔV of 0.1c (3×10^7 m/s) a chemical propellant with $I_{sp}=10^5$ sec would require a mass ratio of 10^{44}. Obviously chemical propellants are insufficient for interstellar travel, if a mission is to be accomplished within one human lifetime.

3.1

Propulsion systems Considered

Therefore another means of propelling the spacecraft is necessary. There are various possible methods of propulsion under study at the current time. Included are passive and active means of propulsion. Passive methods include solar sails and laser pumped lightsails, as well as field propulsion. Active means considered include nuclear fusion and antimatter annihilation propulsion.

Solar sails and laser-pumped light sails were not considered for this project because of the long interstellar distance involved. The solar radiation pressure at 1 light year from the sun would be negligible. With this small a pressure to work with a functional sail would have to be tremendous. With each increase in the size of the sail comes an accompanying increase in weight, requiring more force. Solar sails just won't work for the mission to Alpha Centauri. Laser- pumped sails run into the same problem -- distance. An earth-based laser to push the spacecraft would have to be thousands of times more powerful than anything seen to date, and must be able to operate over a long period of time. Sailing is out of the question to Alpha Centauri.

Another method of passive propulsion available is field propulsion. There exist extremely weak magnetic fields within the solar system that a spacecraft could potentially "ride" a field line to another star. This area of propulsion is not very well defined and was not considered for this mission. However, information provided by Project Longshot about the interstellar magnetic field could provide a clearer picture of just how these fields could be used to carry a spacecraft to another star.

As for active methods of propulsion, nuclear fusion and antimatter annihilation involve similar concepts. The nuclear fusion propulsion system considered was Pulsed Fusion Microexplosion. It involves using high-energy particle beams to induce fusion in fuel pellets and exhaust the fusion products through a magnetic nozzle. Pulsed Fusion was not selected because of the large fuel mass required for an Alpha Centauri mission.

With all of the other forms of propulsion considered, antimatter annihilation shows the most promise as an interstellar means of

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propulsion. It must be remember that much of what is known about antimatter is only in its theoretical infancy. Antimatter propulsion will require large advances in technology before it becomes reality. Therefore, what is presented is a what-if scenario of an antimatter annihilation propulsion system.

Fundamental Concepts of Antimatter

To understand the nature of antimatter propulsion it is first necessary to understand some fundamentals of antimatter. Antimatter, or mirror matter as it is sometimes called, is very much like the matter that makes up most of the universe as we know it. Every particle of matter has an antimatter equivalent. An antiproton is a proton with negative charge and opposite spin. An antielectron, or positron, is a positively charged electron with opposite spin. When a particle and its antiparticle combine, they annihilate each other, converting all their rest mass to energy. This has been verified experimentally, and physicists have a good knowledge of the process. The goal of antimatter propulsion is to take this knowledge and transform and expand it to a useful means of propulsion.

The most promising antimatter reaction for propulsion purposes is the proton-antiproton annihilation reaction. When a proton and an antiproton combine, there are several transition states before pure energy is released. The reaction sequence is as follows:

2) $$ p+ + p \rightarrow \pi^0 + \pi^+ + \pi^- \rightarrow \mu^+ + \mu^- + \nu $$
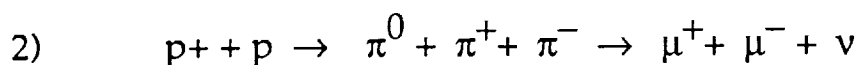
The proton and antiproton combine to form charged and neutral pi-mesons or pions. The neutral pions almost instantaneously decay into high energy gamma rays. The charged pions have lifetimes of 26 nsec which lengthens to 70 nsec when relativistic time dilation is taken into consideration. It is this fact that drives one design for an antimatter engine. The charged pions decay into charged muons, neutrinos, and antineutrinos. These particles turn into electrons, positrons, and more neutrinos and antineutrinos, which in turn annihilate to release gamma rays.

The idea of using antimatter for propulsion presents several problems. First, antimatter is extremely difficult to produce. Once the antimatter is made, it must be converted into a storable form and put in some sort of

3.3

storage vessel. From its stored form the antimatter must be converted into a reactable form and brought into contact with matter. Once the reaction occurs, the energy released must be converted into propulsive thrust for the spacecraft. The rest of this section will deal with some possible solutions to these problems, and how they will be implemented in Project Longshot.

Antimatter Production

Antimatter production is one of the major stumbling blocks to antimatter propulsion. The current method for production of antiprotons is to strike a high atomic number target metal with a high energy proton beam. The collision of the protons with the metal releases a shower of particles, some of which are antiprotons. The antiprotons can be magnetically focused out of the shower and collected in a storage ring. At this point in the process the efficiency is around 10-4. One antiproton per ten thousand collisions makes antiproton production extremely costly. If antimatter propulsion is to be a reality, antiproton production efficiencies must be improved.

When the antiprotons are created they have very high energies, around 10 GeV. These relativistic antiprotons must be slowed, or "cooled," to a state where they can be stored. This can be accomplished through the use of lasers to slow the antiprotons and collecting them in a storage ring. "Cool" antiprotons is a deceptive name, as the antiprotons will still have energies around 100 MeV.

Antimatter Storage

If the antiprotons are sufficiently cooled they can then be combined with positrons to produce antihydrogen atoms. This has not yet been accomplished in the laboratory, but the potential exists for the production of antihydrogen in the next few years. Antihydrogen can be cooled cryogenically to make balls of antihydrogen ice. This concept of storing antimatter in the form of antihydrogen ice is the most promising method. A ball of antihydrogen ice can be levitated in a vacuum by a magnetic field. Experiments to validate this approach have not been conducted with actual antimatter, but tests with hydrogen ice have shown that it could work.

To react antihydrogen with matter it is necessary to extract the ice from storage and separate the antiprotons. Using an electron beam to annihilate the positrons off the surface of a small ball of antihydrogen ice it would become possible to move the charged antihydrogen ball using electric fields. The antihydrogen would then be re-energized and focused into a beam of antiparticles. It is this antimatter beam that is the heart of the antimatter propulsion concept. Two methods will be presented for using this beam of antimatter to provide propulsion for Project Longshot.

Antimatter Propulsion Concepts

The first concept considered for antimatter engine design comes from a paper by David L. Morgan. His design uses magnetic fields to direct the reaction products of the annihilation reaction. This in effect creates a magnetic nozzle which could be used to propel the spacecraft. A beam of antiprotons is directed longitudinally through the nozzle and comes into contact with a perpendicular beam of hydrogen atoms. The perpendicular alignment would provide almost 100% annihilation of incoming antiprotons. The charged pions, as mentioned earlier, have a lifetime of 70 nanoseconds. In this time they travel an average of 21 m before they decay. These energetic charged pions could be directed out of the nozzle by magnetic field line as shown in the figure below. Momentum transfer is from the charged particles to the vehicle through the field.
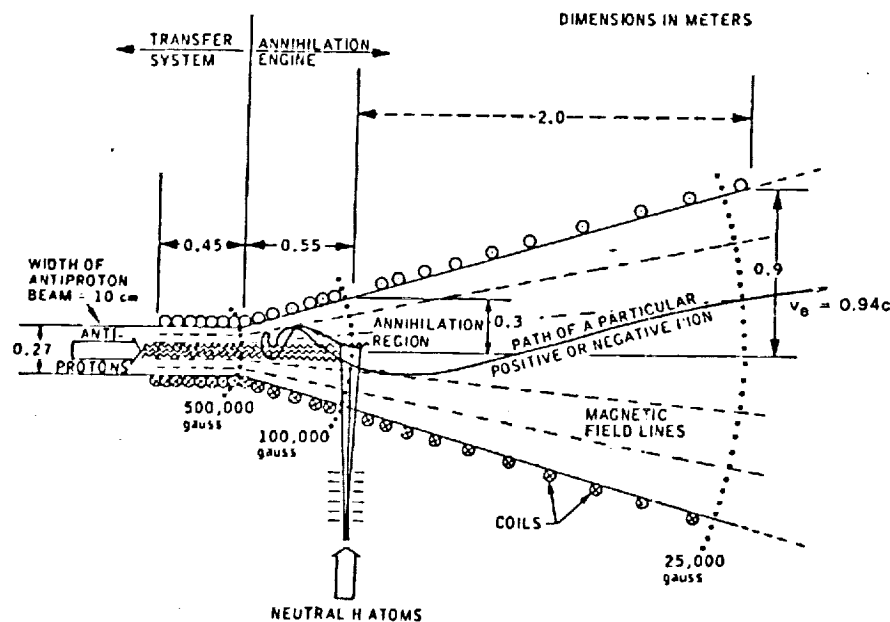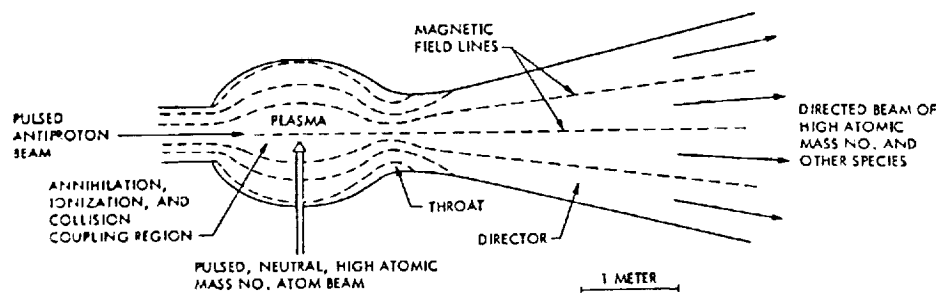

Morgan Engine (ref. 2)

3.5

This engine concept was desirable because it was easiest to understand and also was the most efficient. However, closer inspection reveals serious limitations in the Morgan engine.

The most serious limitation of the Morgan engine is its low thrust. The example given is a 2 m diameter nozzle, yet it only produces 70 N of thrust. This is hardly enough to propel a spacecraft the size of Longshot. Scaling offers little hope for the Morgan engine. Increasing the size of the nozzle by a factor of R will increase the thrust produced by a factor of R^2. Along with this increase comes an increase in mass of roughly R. By increasing the size of the engine by R, a net thrust-to-weight increase of R is achieved. To propel Longshot with a Morgan engine would require an extremely large nozzle.

The most feasible variation of antimatter propulsion is a magnetically contained plasma engine. Below is a diagram of what a this engine would look like:

MAGNETIC FIELD LINES

PULSED ANTIPROTON BEAM

PLASMA

DIRECTED BEAM OF HIGH ATOMIC MASS NO. AND OTHER SPECIES

ANNIHILATION, IONIZATION, AND COLLISION COUPLING REGION

THROAT

DIRECTOR

PULSED, NEUTRAL, HIGH ATOMIC MASS NO. ATOM BEAM

1 METER

Pulsed Plasma Engine (ref. 2)

This engine would use a heavy element plasma as its working fluid. By annihilating a small amount of antimatter with a large amount of plasma, the annihilation reaction will serve to heat the plasma. The reaction will be confined by the magnetic field until the field is opened at one end, allowing the energetic plasma to escape the nozzle. The pulse will last approximately 7 ms for all the annihilation energy to be transferred to the working fluid. Total pulse time is estimated at 17 ms. An engine of this kind will produce an estimated thrust of 550 kN at a hopeful specific impulse of 10^6 sec. No detailed design exists for this method, but current work with magnetically-confined plasmas indicates that this is a workable concept.

The mass ratio properties of antimatter propulsion make it a particularly desirable concept. Recall equation 1 above but now consider the antimatter situation. All the energy in antimatter propulsion is supplied by the antimatter, not the working fluid. This transforms eq. 1 as follows:

m_r = mass of working fluid

2) $$R = \frac{m_v + m_r + m_e}{m_v}$$

m_e = mass of energy source

(matter + antimatter)

The mass of the energy source will be twice the mass of antimatter. The exhaust energy is given by the following relation:

3) $$\varepsilon \, (m_e c^2) = \frac{1}{2} \, (m_r + m_e) \, v^2$$ ε = efficiency

If the two previous equations are combined:

4) $$m_e = \frac{m_v v^2}{2\varepsilon \, c^2} \, (e^{\Delta V/v} - 1)$$

For minimum antimatter ($m_e/2$) this equation will be a minimum when $v = 0.63\Delta V$. Therefore:

5) $$R = e^{\Delta V/v} = e^{1.59} = 4.9$$

From the above calculations it becomes apparent that the mass ratio for antimatter propulsion will never exceed 5:1. This makes antimatter especially appealing because the total mission mass will not necessarily go up with increased ΔV. The graph on the following page shows this relationship more clearly:

(ref. 1)

3.8
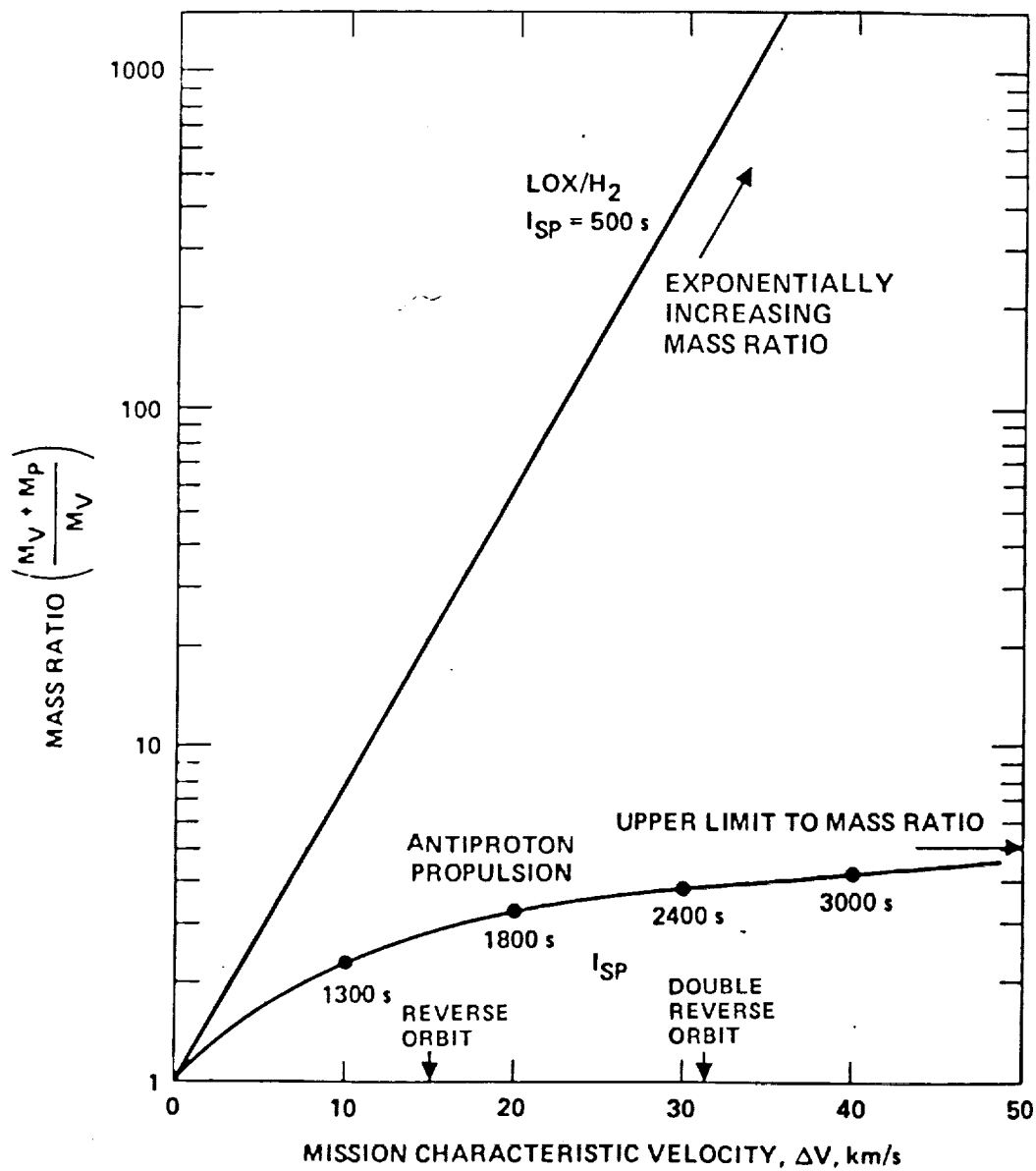
Where some missions, such as Longshot would be impossible with chemical propulsion, they are possible with antimatter propulsion.

Recalling the definition of I_{sp}:

$$I_{sp} = \frac{F_{net}}{mass\ flow}$$

One can see that this definition loses meaning in the case of antimatter propulsion. What mass flow should be used in the definition? Because in antimatter propulsion, the energy source is independent of the working fluid, there is a discrepancy. It is better to consider the exhaust velocity as the governing factor in the problem. Because the mass ratio will never exceed five, an exhaust velocity can be tailored to a particular mission velocity by:

$$v = \Delta V \ln R = 1.589\ \Delta V$$

Since exhaust velocity is controlled by the amount of antimatter addition, optimization for a particular mission velocity is achieved by choosing an appropriate amount of antimatter. For the case of 0.1c, an appropriate exhaust velocity would be 4.76×10^7 m/sec. This would be a highly energetic plasma.

Of course, the theory behind antimatter propulsion is still in its infancy. To make this a viable means of propulsion, much effort is needed in antimatter research. By learning more about antimatter and its properties, man will be better able to harness this incredible source of energy.

3.9

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Chapter Four:

Power

POWER SOURCE

A nuclear fission reactor will provide the power required to operate the probe. The reactor must supply enough power for the instruments, the computer, the communication equipment, and the antimatter drive. This includes the power necessary to operate the laser communication system, and to keep the antimatter magnetically isolated. The reactor must be compact-sized, have a low specific mass, long life, and high reliability.

As with other components in this spacecraft, reliability will be a prime driver in the design. It must be able to operate for more than 50 years. The mission will end when the reactor can not supply enough energy to communicate with the Earth.

A nuclear fission reactor was chosen due to the power requirements and the duration of the mission. The distances involved preclude the use of solar panels. The mission duration eliminates the possibility of using radioisotope thermoelectric generators (RTG) or fuel cells. Figure 1 shows the typical regimes of applicability of different power systems.

Figure 2 contains the basic components of a generic space nuclear power system. It includes a nuclear energy heat source, a thermal transfer subsystem, an energy conversion subsystem and a heat rejection subsystem. The system chosen for this mission will use fission of enriched uranium as nuclear heat source. Heat pipes will be used to transfer heat from the core to the energy conversion subsystem, and from the energy conversion subsystem to the heat rejection subsystem. A thermionic subsystem will convert heat into electricity. Radiators will discard the excess heat.

The fission process takes place in the reactor core. The core contains the nuclear fuel, and appropriate amounts of moderators and reflectors.The nuclear fuel is enriched uranium, a fissile material. The uranium is assembled in hexagonal-shaped rods that minimize its volume. Mass and volume can also be saved by using isotopes with lower critical mass. For example, the critical mass of uranium^{233} is one third of the critical mass of uranium^{235}. Figure 3 shows the most efficient core configuration. The moderator is a low mass material that slows down the neutrons. The reflector scatters the neutrons back into the core. The rate of the reaction in the core must be controlled using control drums. These contain neutron absorbers, and they are the only moving parts required in the reactor core.

The working fluid will be liquid lithium at 1500 K. Lithium was selected because of its heat capacity and operating temperature. Higher operating temperatures increase the efficiency of the system. Heat pipes are the prefered method of heat transfer. These are used where high thermal tranfer rates are needed and precise temperature control is required. The two phase fluid flow inside a heat pipe attains high thermal conductance. Additionally, heat pipes are simple, and self-contained. Heat pipes eliminate the need for a bulky pressure vessel, which reduces weight. Finally, heat pipes can start up from a frozen state. This eliminates the need for coolant preheating and increases the reliability of the system.

The heat will be converted into electricity using a thermionic conversion system. This device will be located outside the reactor core. This will reduce system degradation due to neutron irradiation of the electrical insulators.

The thermionic converter is a static energy conversion device. It consists of a hot emitter surface, typically at 1800 K, from where electrons are emitted to a cooler collector surface. The collector is typically at 1000 degrees Kelvin. Figure 4 shows the operating principles of the thermionic converter. The thermionic converter is like a heat engine that uses the electrons as the working substance.

The temperature of the collector is very important here. According to Steffan-Boltzman Law, for a fixed amount of radiated energy, the size of the radiator is inversely proportional to the fourth power of its temperature. Therefore, the highest possible collector temperature is desired. But if the collector temperature is too high, some electrons will be emitted back into the emitter plate. A design trade off between heat rejection optimization and converter performance must be made. Figure 5 shows the relation between temperature and the size of the radiator.

Heat pipes will also carry the excess heat from the thermionic collector to the radiators. These pipes operate at a lower temperature, using potassium as a working substance. If necessary, some of this heat may be diverted for housekeeping uses. This includes keeping all the spacecraft components operating at their optimum temperatures. Figure 6 shows some possible radiator configurations. In designing these radiators, we must locate them so that their emissions do not interfere with the scientific instruments.

The choice of a reactor as main power source introduces other requirements into the design of the spacecraft. We need an adequate radiation shield to protect the payload from the large amounts of neutrons and gamma rays that are emitted during the fission process. Sensitive electronics will experience noise, electronic upset, or even burn out if not adequately protected

Fortunately, this is an unmanned mission. As such, it has less restrictive radiation dose criteria, although extreme caution will be necessary in the vicinity of the Earth. A full $4\pi^2$ shield will not be required for this mission. The vacuum of space makes it possible to use a shadow shield, which protects the payload, but leaves a major portion of the reactor unshielded, such as shown in figure 7. This represents a major savings in mass. This shield will use lithium hydride to attenuate the neutrons. Tungsten will absorb gamma rays. The shield must also have an active heat rejection system. With shadow shields, particular care should be taken to ensure that no radiation scattering sources exist. In addition to a shadow shield, the instruments will be located at the end of a long truss. This will use the inverse square law of the distance to further reduce irradiation of the payload.

This system will be required to produce 300 Kw of electrical power. It must also be compact sized, and have a long lifetime. Based on existing technologies, and assuming some advances in the field of reactor and power conversion systems design, we expect the reactor to have the following characteristics.

Reactor output	3.0 MWt
Electrical output	300 KWe
Lifetime	55 years
Total mass	10700 Kg

We arrived at these estimates by scaling up contemporary reactor designs. Table 1 has a more detailed breakdown of these estimates.
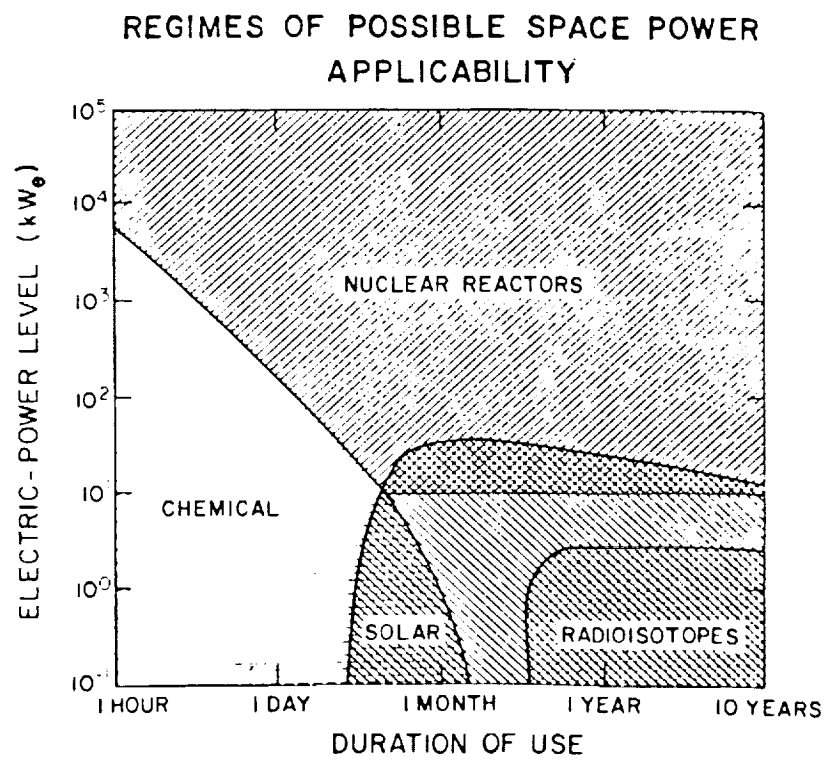
REGIMES OF POSSIBLE SPACE POWER
APPLICABILITY

Figure 1 [Ref 2]

GENERIC SPACE NUCLEAR POWER SYSTEM

ELECTRICAL ENERGY OUTPUT

REJECTED THERMAL ENERGY

THERMAL ENERGY-TO-ELECTRICAL ENERGY CONVERSION

DIRECT THERMAL ENERGY UTILIZATION FOR HEATING, COOLING OR IN HIGH THRUST PROPULSION SYSTEMS

THERMAL ENERGY

PRODUCTS OF NUCLEAR PROCESSES

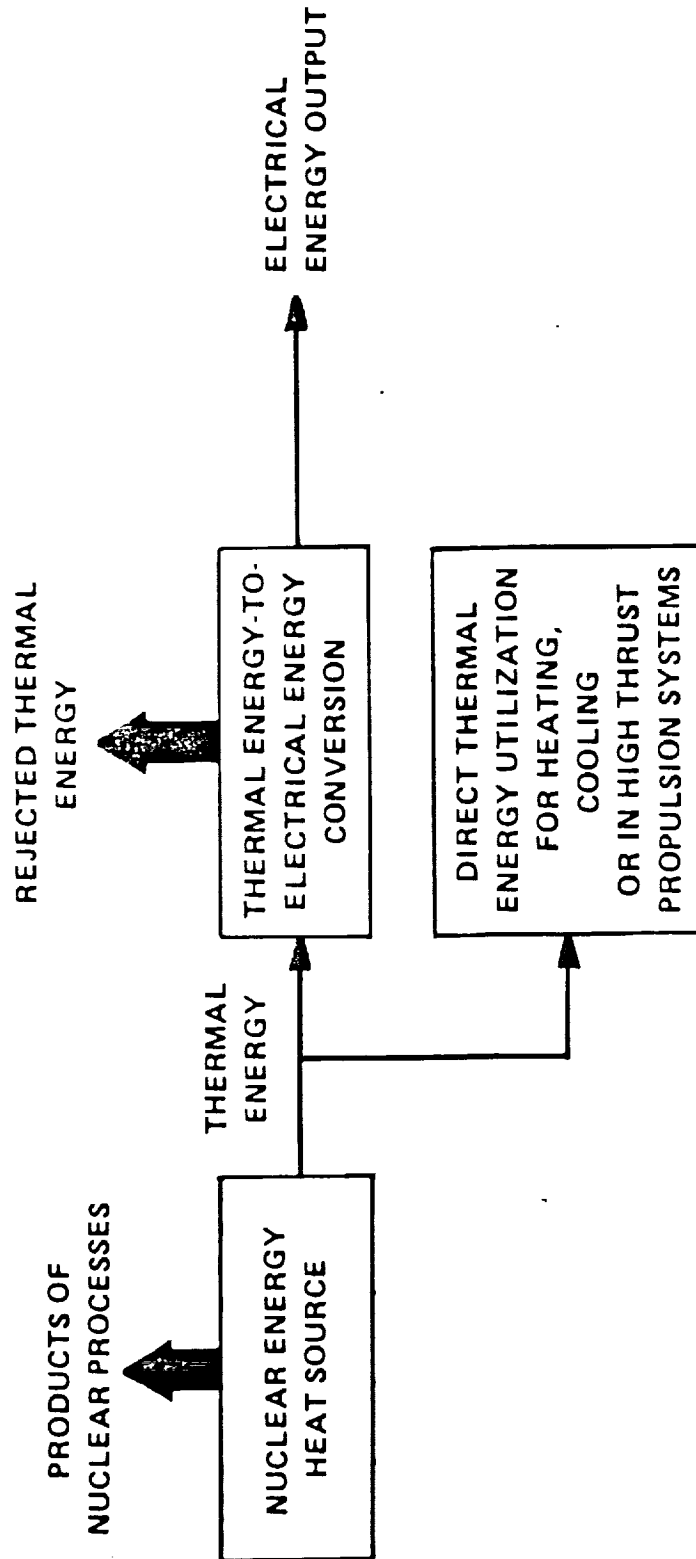| NUCLEAR ENERGY HEAT SOURCE |
|---|

Figure 2 [Ref 2]

Figure 2

×

4.5

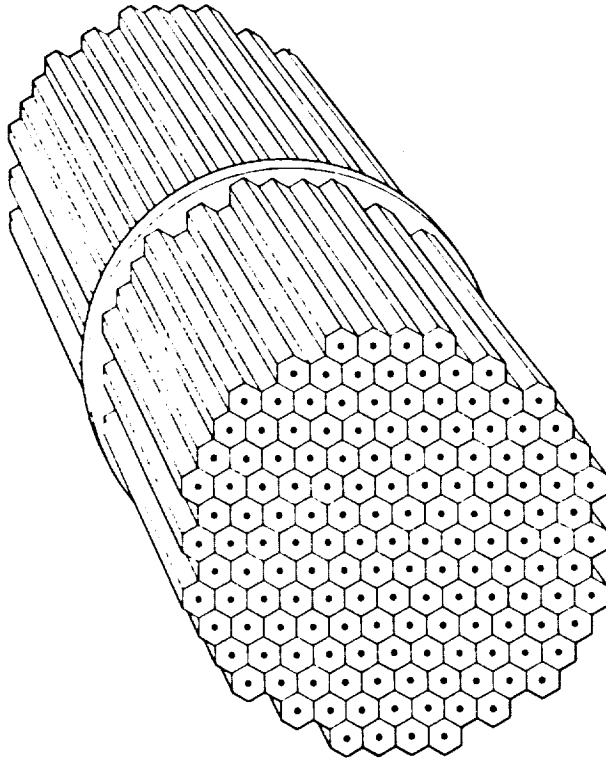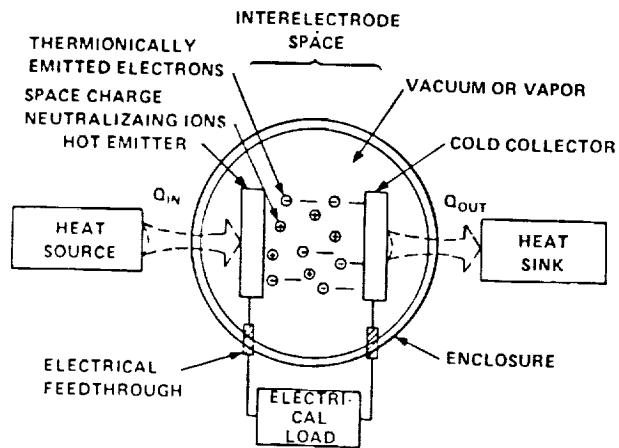# REACTOR CORE

Figure 3 [Ref 1]

THERMIONIC CONVERTERS

TYPICAL OPERATING REGIME

EMITTER TEMPERATURE:	1600–2000 K (2420–3140°F)
COLLECTOR TEMPERATURE:	800–1100 K (980–1520°F)
ELECTRODE EFFICIENCY:	UP TO 20%
POWER DENSITY:	1–10 W/cm^2

MATERIALS

EMITTER MATERIALS:	W, Re, Mo
COLLECTOR MATERIALS:	Nb, Mo
INSULATOR MATERIALS:	Al$_2$O$_3$, Al$_2$O$_3$/Nb CERMET
ELECTRODE ATMOSPHERE:	Cs AT 1 Torr

Figure 4 [Ref 2]

4.7

TEMPERATURE-MASS RELATION
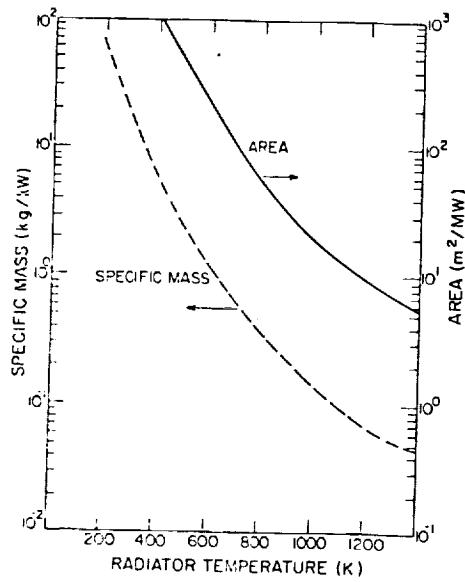
Figure 5 [Ref 2]
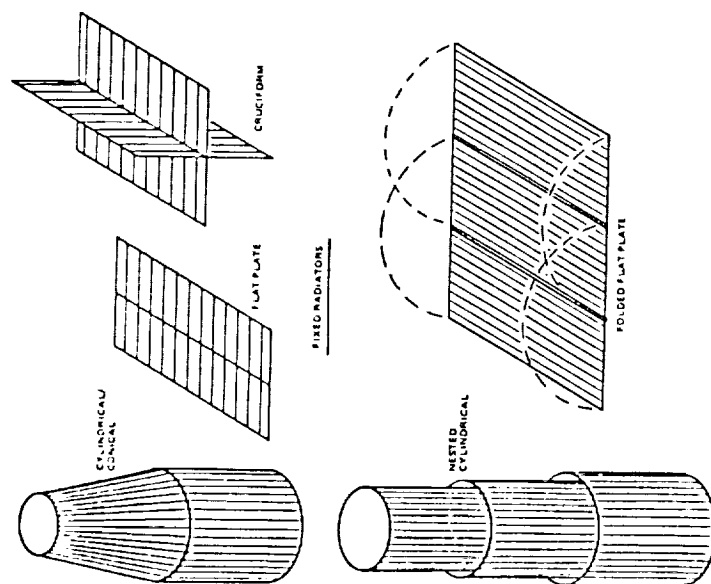
4.8

RADIATOR CONFIGURATIONS

CRUCIFORM

FLAT PLATE

FIXED RADIATORS

FOLDED FLAT PLATE

CYLINDRICAL CONICAL

NESTED CYLINDRICAL

Figure 6 [Ref 2]

4.9

SHIELD CONFIGURATION

α = CONE HALF-ANGLE

PAYLOAD

LITHIUM HYDRIDE NEUTRON SHIELD

TUNGSTEN GAMMA SHIELD

CORE

REFLECTOR
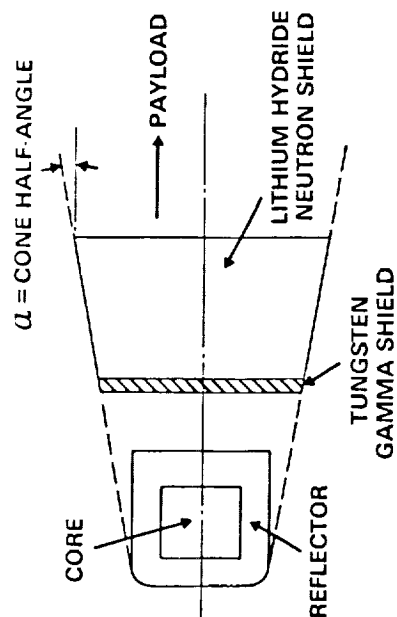
Figure 7 [Ref 2]

REACTOR CHARACTERISTICS

	SP-100	Longshot
Reactor ouput (MWt)	1.6	3.0
Electrical output (KWe)	100	300
Efficiency (%)	6.3	102
Lifetime (yrs)	7	55
Masses(Kg)		
Reactor	450	4000
Shield	790	800
Heat pipes	460	1000
Conversion system	250	700
Thermal insulation	290	400
Radiator	100	200
Structure	300	3000
Power control	130	200
Total mass	2770	10800

1. see reference 1 page 101
2. Assumes improvements in energy conversion devices.
3. Mission requirement.
4. Shadow shield only.

TABLE 1

SHIELD DESIGN CONSIDERATIONS

1. Ability to attenuate radiation

2. Minimum mass

3. Resistance to radiation induced thermophysical damage

4. Stability at elevated operating temperatures

5. Ease of fabrication

6. Availability

7. Cost

KEY DESIGN FACTORS
FOR POWER CONVERSION SYSTEMS

Efficiency

Mass

Reliability

Peak Operating Temperatures

Heat Rejection Temperatures

Working Fluid Properties

Lifetime

Vibration and Torque

Power Range

Modularity

Startup and Shutdown

Power Processing

Radiation Hardening

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Chapter Five:

Scientific Investigations

SCIENTIFIC INVESTIGATIONS

Very few details are known about the Centaurus system, other than it is a trinary star system. Astronomers do not know how the gravitational and magnetic fields of these three stars interact with each other or if there are any planets in the system. The underlying purpose of Project Longshot is to answer some of these basic questions. Additionally, it will provide astrometrists with over a four light-year baseline, allowing them to make parallax measurements of stars, which, when combined with Earth-based and Earth-orbiting astronomical measurements, will yield more accurate measurement of interstellar distances. Longshot will conduct astometry, infrared radiation, ultraviolet spectroscopy, photopolarimetry, particle, magnetic field and radioastronomy investigations.

Given the current 2-AU baseline to calculate trigonometric parallax, astrometrists can accurately measure distances no further than about 100 pc. Project Longshot, with its 272-kAU baseline, can extend the accurate measurement of distances out to about 1.3 Mpc. This new distance scale will make a serious impact on future astronomical observatories. The Hubble Space Telescope, for example, will require accurate distances from optical astronomy to realize its full potential. Two optical telescopes, located on either side of the probe, having viewports through the protective shield, will collect this astronometrical data while Longshot is in transit from Earth to the Centaurus system. The data will be stored in the onboard computer, and will be the first information to be transmitted once the probe arrives in Alpha Centauri. Once transmitted, the data will be discarded from memory to make room for more data [References 1 and 2].

If the Centaurus sustem is similar to our solar system, in having planets, Longshot should receive infrared radiation from these planets by both thermal emission of the planets themselves and the reflection of solar radiation from their surfaces. The surface emissions would occur mainly in the far infrared wavelengths, since the planet's surface temperatures are relatively low, while the reflected solar radiation would mainly encompass the near infrared and visible wavelengths. Since the effectiveness of the bands of atmospheric gases of the planets vary with the chemical composition and temperature of the gases, an infrared radiation investigation will give information about the existence of

their atmospheres. The instrument used to conduct the investigation will consist of a telescope for collecting the infrared radiation, two interferometers for measuring spectral data in the near (1.4 - 10 μm) and far (15 - 200 μm) IR regions and a radiometer for measuring the total reflection over a band of wavelengths.

Like the infrared radiation investigation, the primary purpose of the ultraviolet spectroscopy investigation is to determine the composition and structure of Centauran planets' atmospheres, if any. Atmospheric gases emit radiation in the far ultraviolet radiation region (500 - 1700 Å) due to the resonance scattering of solar ultraviolet radiation or excitation by bombardment with energetic particles. Resonance scattering causes a decrease in the transmitted energy from the incoming sunlight at certain wavelengths. Thus, when entering or leaving a planet's shadow, a spectrometer aimed at the sun can analyze the ultraviolet spectrum and determine the atmospheric composition from which wavelengths are missing. Atmospheric excitation by bombardment with energetic particles produces an airglow, which can then be analyzed to determine atmospheric composition.

A secondary objective of the ultraviolet spectroscopy investigation is to conduct a survey of other stellar sources of extreme ultraviolet radiation. Extremely distant solar bodies emitting very weak UV radiation, which might not be strong enough to reach Earth, might be detected from the Centaurus system. Thus, new solar systems may be discovered.

The ultraviolet spectrometer aboard Longshot will operate in both the solar occultation and airglow modes as appropriate. In the solar occultation mode, it will look directly at the sun and measure the changing atmospheric absorption. In the airglow mode, it must be extremely sensitive to measure weak far-ultraviolet emissions. For the UV spectrometer to operate correctly in both of these modes without interfering with other instruments on the probe, a mirror must offset the solar occultation field of view from that used during the airglow mode.

The primary objectives of the photopolarimetry investigation are to determine the physical and chemical properties of atmospheric particles of planets having atmospheres, or planet surfaces of those having either no atmospheres or non-light scattering atmospheres. Sunlight radiates unpolarized over a very broad band of wavelengths. When it is scattered by atmospheric particles or a surface, it becomes polarized. A photopolarimeter can determine both the extent and plane of polarization by measuring the scattered light intensities through three plane-

5.2

by measuring the scattered light intensities through three plane-polarizing filters oriented 60° apart. Longshot's photopolarimeter will make its measurements in ten wavelength bands, ranging from the ultraviolet region (2350 Å) through the near infrared region (7500 Å). It will consist of a telescope, a photomultiplier tube, three motor driven wheels to select the wavelength band, polarization plane and field of view, and various electronics.

Longshot's particle investigation is comprised of three separate investigations dealing with cosmic ray particles, low-energy particles and plasma particles. Galactic cosmic rays are charged particles, primarily protons, which travel at nearly the speed of light, and therefore have kinetic energies on the order of a billion electron volts. There are also other lower energy charged particles. A cosmic ray particle instrument sorts these particles according to charge, mass and energy, while measuring variations in their number at different times, places and anisotropies, or directions of arrival. For electrons, the measured parameter is energy, while for nucleii of heavier atoms that have been stripped of their electrons, energy, elemental composition and streaming patterns are measured. Data from this investigation will provide information about cosmic ray sources and the medium through which the particles travelled. Longshot's cosmic ray particle detector consists of three sets of particle telescopes: the high energy, low energy and electron telescopes.

The low energy particle investigation is basically the same as the cosmic ray particle imvestigation, except it deals with much lower energy particles (0.1 - 1 MeV). Study of these particles can provide information about the flow velocities and temperatures of hot plasmas, planetary magnetospheres and the interplanetary environment. Longshot's low energy particle detector consists of two subsystems: the low energy magnetospheric particle analyzer for monitoring the magnetospheric environment, and the low energy particle telescope for studying the interplanetary environment.

The plasma particle investigation deals with plasma particles which have much lower kinetic energies than both cosmic ray and low energy particles (10 - 6000 eV), and are much more abundant. Due to their large numbers, this investigation measures collective, instead of individual, particle properties, such as the plasma's velocity, direction, density and pressure. The plasmas that will be studied include the Centauran solar wind and planetary magnetospheres. Longshot's plasma particle detector
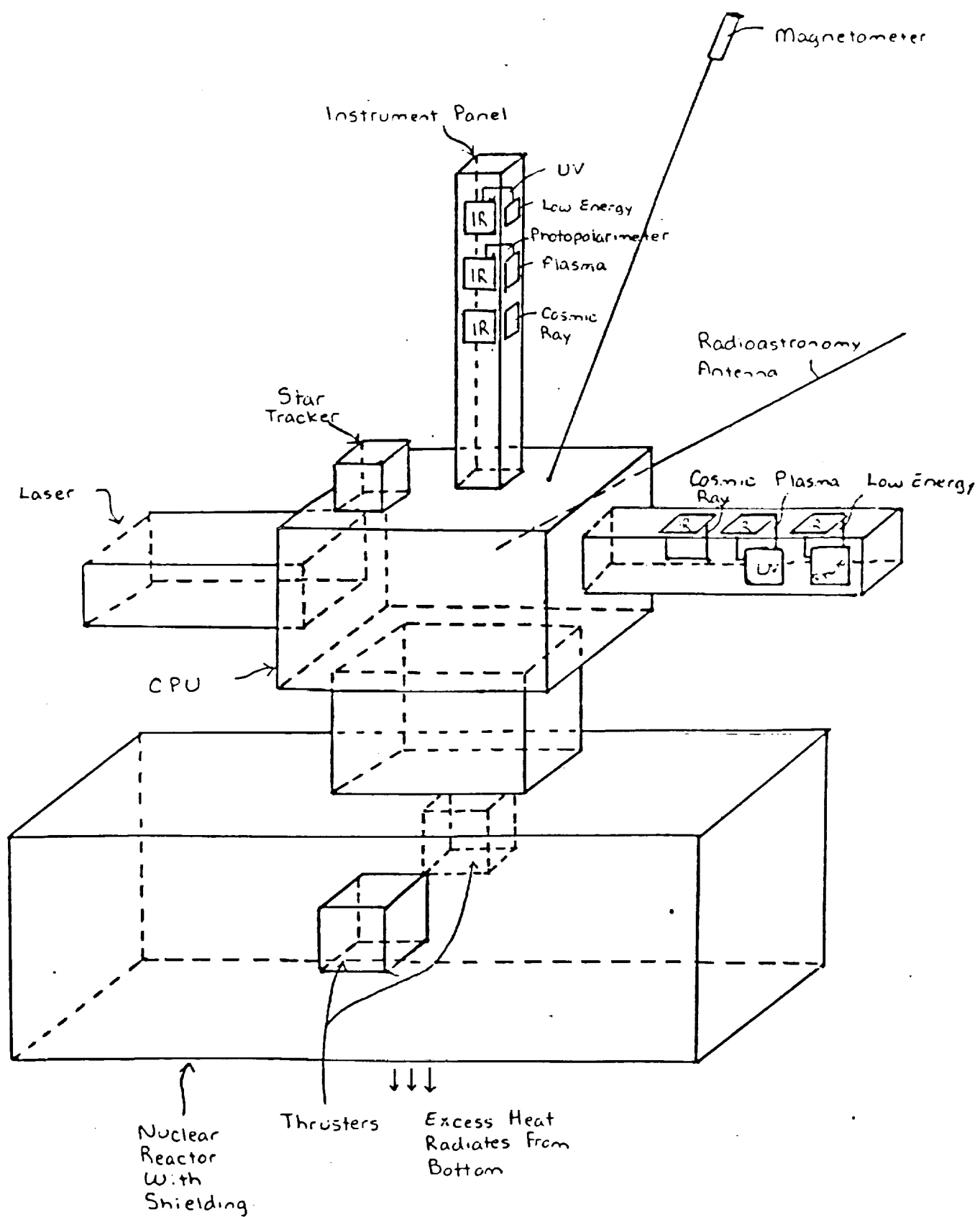
consists of two Faraday cup plasma sensors, oriented such that their fields of view do not overlap.

If the Centaurus system is similar to our own, magnetic fields will be abundant. Planets may have their own magnetic fields, while the charged particles making up the solar wind may bring other magnetic fields. Since there will probably be a large difference between the magnitudes of the relatively strong planetary magnetic fields and the relatively weak interplanetary magnetic fields, Longshot's magnetometer consists of both a high- and low-field magnetometer system. Each system has two triaxial fluxgate magnetometers, so the magnetic field intensity along three orthogonal axes can be measured simultaneously to yield a more direct vector measurement. All four magnetometers are located on a long beam to ensure the magnetic field of Longshot will not interfere with the measurements.

The final scientific investigation deals with radioastronomy. It is known that planets such as Jupiter and Saturn have radio emissions, so it is logical to assume that Centauran planets may also emit radio signals. The primary objectives of this investigation are to locate sources of planetary emissions at kilometric (300 kHz), hectometric (3 MHz) and decametric (30 MHz) wavelengths, and to try to explain their orgin. A secondary objective involves the search for extraterrestrial intelligence (SETI). SETI scientists can not afford to pass up an opportunity to extend their listening radius by over four light-years. Longshot will have two ten-meter antennae, oriented 90° apart, dedicated to the radioastonomy invesitgation.

The scientific investigations mentioned above were chosen assuming Alpha Centauri is similar to our own solar system, since there is no other model to follow. These experiments were chosen to be as widely encompassing as possible, and were modelled after those flown aboard the Voyager probes to Jupiter, Saturn and Uranus, as set forth in Reference 3.

Figure 1 shows the deployed configuration of the scientifc payload of the Longshot probe. Enroute to Alpha Centauri, the payload will be housed in a shell to protect it from radiation and high velocity collision with minute particles. Central to the instruments themselves is the main computer. This central processing unit must be fully autonomous, capable of choosing what data is meaningful, which would be transmitted back to Earth, and what information is redundant. A computer satisfying the mission requirements of longevity, self-correction and true artificial intelligence does not currently exist. However, 5 kW of power have been

Magnetometer

Instrument Panel

UV

Low Energy

Protopolarimeter

Plasma

Cosmic Ray

IR
IR
IR

Star Tracker

Laser

Radioastronomy Antenna

Cosmic Ray   Plasma   Low Energy

UV

CPU

Nuclear Reactor With Shielding

Thrusters

Excess Heat Radiates From Bottom

↓↓↓

Preliminary Design of Scientific Module

Figure 1

5.5

reserved for its operation in the calculaton of the power requirements of Longshot.

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3.   NASA. Voyager to Jupiter and Saturn. NASA SP - 420. 1977.

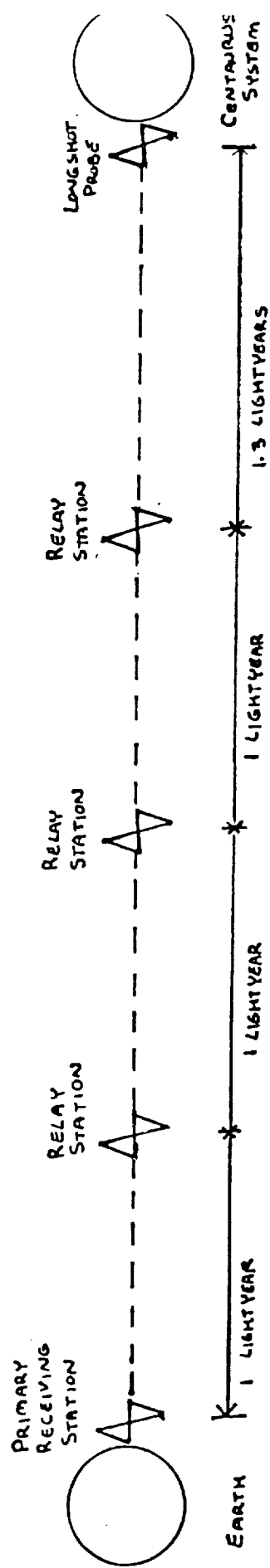# Chapter Six:

Communications

COMMUNICATIONS

There are several problems that the communications system aboard Longshot must overcome for the mission to be successful. These problems include the amount of space loss due to the extremely long distance between the Centaurus and our own solar systems and the very high power required to transmit over such a distance. To effectively reduce the amount of distance over which the signal must be transmitted, a series of three relay stations will be used, in addition to the Longshot probe and the primary receiving station orbiting the Earth (see Figure 1).

These communication platforms will be launched at several year intervals, starting immediately after Longshot is launched. The relay stations will not travel as fast as the probe. They will continue to move, collectively, toward Alpha Centauri, thereby being able to receive ever-weakening signals from the aging probe. Each relay station would take advantage of state of the art technology and would thus be better able to receive weaker signals. In addition, their power supplies would not be wasted, as their communications payload would not be activated until about one year prior to Longshot reaching Alpha Centauri. A timing mechanism aboard the platform, powered by a RTG, will "turn on" a nuclear reactor once the predetermined allotted time has elapsed.

Two types of communication systems were analyzed to determine which would fulfill the Longshot mission the best: a conventional radiofrequency communication system and a laser communication system. From the radiofrequency link budget calculated in Appendix C, for a bit error probability of 10 e-5 and a bit rate of 100 bps, the required effective power is 1.23 MW. For a bit rate of 1 kbps, the power requirement is 12.3 MW. Using the laser communication link budget (see Appendix D), the required power is only 15.3 kW and 153 kW respectively. From these results, it is definitely more advantageous to use a laser communication system. Low bit rates were chosen for this mission since it is assumed that data will be transmitted continuously for long periods of time, i.e. several years. In addition, pictoral data will not be collected, so a lower bit rate will be adequate.

The relay stations mentioned earlier will have the same basic power requirements as the Longshot probe after it reaches Alpha Centauri. Each platform will have the same design, consisting of a 20 m diameter receiver aperature, a 1 m diameter transmitting telescope similar to that on the

6.1

Longshot Probe

Centaurus System

Relay Station

1.3 Lightyears

Relay Station

1 Lightyear

Relay Station

1 Lightyear

Primary Receiving Station

1 Lightyear

Earth

6.2

Communications Link From Alpha Centauri To Earth

probe, associated electronic equipment, an attitude control system and a nuclear reactor to fulfill the power requirement of 20 kW for the entire relay station.

Several laser types were analyzed to determine which would be the best for the Longshot mission. From a summary of laser sources (Table 1), it was decided that the GaAs laser would be the best laser. It can be directly and easily modulated, easily combined into arrays, is reliable, and has a very long life of 50,000 hours (5.7 years). This laser is also relatively efficient. Its wavelength of 0.8 - 0.9 microns lies in a reasonably good position in regard to the wavelengths emitted by G - type star (not near the emission peak between 0.4 - 0.5 microns -- see Figure 2), so it would not be very difficult to detect the signals from the Longshot probe. Future technology will increase the average power output from the milliwatt to the kilowatt range. Since laser beams have a very narrow beamwidth, it is imperative that Longshot know its own location and orientation, as well as that of the next closest relay station, prior to the transmission of data from Alpha Centauri. Star trackers will be used to accomplish this. Ion thrusters attached to the sides of the nuclear reactor component of the probe will provide adequate attitude control to ensure correct orientation.

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Summary of laser sources.

| Laser Type	Wavelength	Average Power Output	Efficiency	Characteristics
Nd–YAG (neodynium–yittrium aluminum garnet) crystal	1.06μ 0.532μ	0.5–1 w 100 Mw	0.5–1% 0.5–1%	• Requires elaborate modulation equipment • Requires diode or solar pumping • 10,000 life hours • Frequency doubling loses efficiency
GaAs (solid-state diode)	$0.8-.9\mu$	40 Mw	5–10%	• Small, rugged, compact • Directly and easily modulated • Easily combined into arrays • Nanosec pulsing • 50,000 life hours, reliable
CO_2 (gas laser) carbon dioxide	10.6μ	1–2 w	10–15%	• In IR range (poor detectors) • Discharge tube • Modulation difficult • 20,000 life hours, existing technology
HeNe (helium neon)	0.63μ	10 Mw	1%	• Gas tube, power limited, inefficient • Requires external modulation • 50,000 life hours

TABLE 1 (ref. 1)
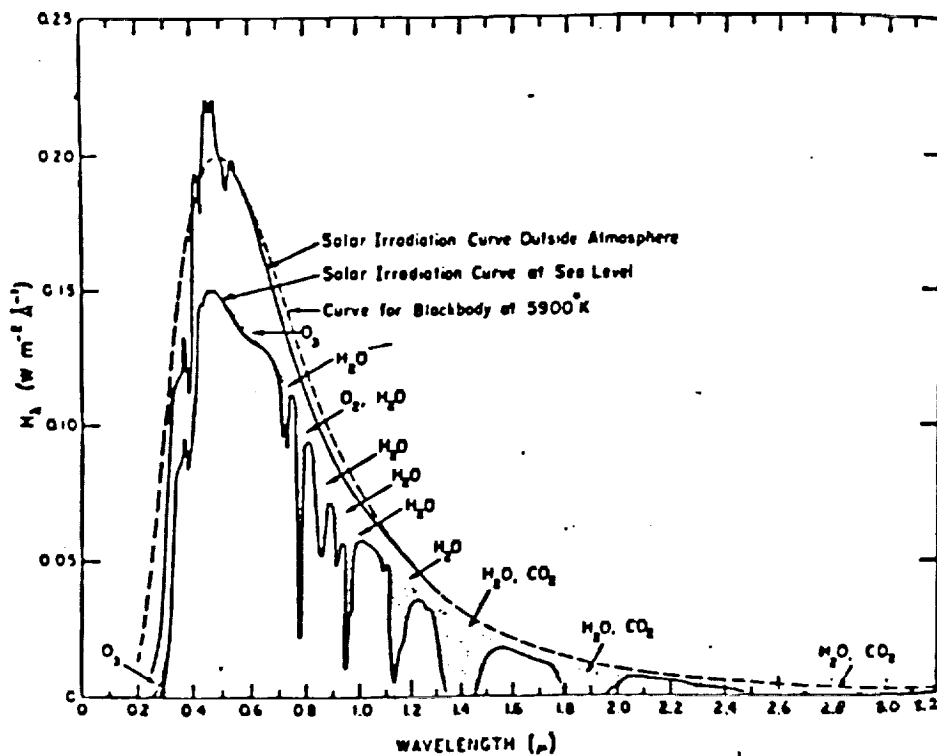
FIGURE 2 (ref. 2)

Chapter Seven:

Summary

TECHNOLOGIES

A mission such as Project Longshot is impossible based on existing technologies. We have identified those areas which require further investigation in order to make this feat possible.

In the area of propulsion, interstellar travel demands high thrust and high specific impulse. Before antimatter annihilation becomes the choice, we must be capable of production and storage of large amounts of antimatter for prolongued periods. As alternatives to antimatter annihilation, passive systems which use laser propulsion or solar sails may be proposed in the future.

Navigation presents a particuarly interesting challenge. We must accurately determine our position in order to obtain valid astrometric data. We can not orient ourselves using stars whose position we will be expected to determine later in the mission. We must use stars whose position is accurately known, or those so far away that they remain fixed as far as the spacecraft is concerned. New algorithms and durable equipment, such as star trackers, accelerometers, and spectrometers, must be developed for this purpose.

The duration of the mission requires reliable hardware. The on-board computers, and sensors must operate for more than 50 years. Additionally, the probe must be autonomous. Artificial intelligence will eliminate the need for command telemetry.

Communicating from 4.34 light years is a definite challenge. Powerful and efficient lasers must be developed for this. Present SDI research has included powerful Argon laser research. Longshot would require expanding this research into the field of solid lasers.

All the equipment on board must resist stellar radiation sources and exposure to the interstellar medium. The characteristics of this medium that the probe must travel through are largely unknown. The mission would benefit greatly if it is preceded by an exploration of this medium.

Finally, the spacecraft must have a reliable, compact, and lightweight power system. This requires advances in nuclear reactors, energy conversion devices, and radiators. A more efficient and reliable power conversion system is a must. Or perhaps, a reliable Rankine conversion system could do it more efficiently. Advances in heat rejection would also be necessary to further reduce the mass of this system.

CONCLUSION

Project Longshot will give us the first close look at a star other than our sun. It promises exciting advances in astrometry, and will expand our search for extraterrestrial intelligence. A mission of this magnitudes will require a propulsion system with high thrust and high specific impulse, such as antimatter annihilation. A nuclear reactor will provide the power required for this mission. A reliable laser communication system will relay all the vital information back to Earth. It will require advances in nuclear reactor design, solid lasers, artificial intelligence, and propulsion. It is a definite challenge, but the knowledge gained from studying the Centaury system could prove invaluable.

Appendix A:

Solar Escape Proposals

APPENDIX A

SOLAR ESCAPE PROPOSALS USING CHEMICAL ROCKETS

Guidance and velocity accuracy during escape are key factors in directing Longshot to its destination. Errors early in the trajectory will cost large amounts of antimatter to get back on course. Because velocity adjustments are impossible with the annihilation drive, and the magnetic nozzle can not be directed, a solar escape using conventional chemical rockets was studied. Presently, most chemical rockets provide known velocities and may be directed with greater liklihood of success than the new annihilation drive. Three solar escape plans were analyzed to try to minimize time and mass of fuel required (thus the size),

1. Escape the sun and perform an inclination change in one maneuver.
2. Perform parabolic escape in plane without changing inclination until the escape is considered complete.
3. A low thrust escape in plane to conserve fuel mass.

Earth escape requires a velocity of 10.9 km/s from a 150 nm. parking orbit. Inclination changes in earth orbit would be of little value because once the probe has escaped the earth it is still in the ecliptic plane for all practical purposes. The worst inclination escape case placing Longshot out of the ecliptic would only put it a distance of .01 AU perpendicular to this plane. An escape in the plane inclined 28.5 degrees from the equator will be sufficient.

Once the gravitational force of the earth is no longer significant, Longshot is a satellite of the sun travelling at 29.8 km/s, the velocity of the earth relative to the sun. The energy requirements for solar escape dwarf those for earth escape. This aspect of the trajectory must be analyzed carefully since the ratio of initial mass to final mass will be great and must be minimized. Ultimately, Longshot needs to be in a plane -67° from the ecliptic and a direction 170 ° right ascension from Aries (see coordinate calculations in Appendix B-2).

To perform an escape and inclination change in one impulse maneuver will require a velocity change of 41.28 km/s (see calculations in Appendix B-1). This requires a mass ratio of four if ion propulsion is used and assuming its specific impulse is 3000 seconds.

Another possibility is to escape the sun in the ecliptic plane, then change to the plane containing Alpha Centauri once the probe is considered to be

outside the effective solar gravitational field. This simple ecliptic plane escape only requires a change in velocity of 12.3 km/s.

The other idea using the same planar escape would be to use low thrust methods to lower the fuel consumption required to give large accelerations. Using lower accelerations will spiral Longshot away from the sun taking more time and requiring a greater velocity change, but providing a better original to empty mass ratio. A fuel with a higher specific impulse would be used in this case. Because low thrust escape requires more time and greater velocity changes and a single impulse escape requires more fuel, a combination of both methods is considered for escape. The spacecraft could use low thrust to a particular orbit and then escape using less velocity change from that orbit. The graph in figure A-1 shows the velocity required to reach a particular distance from the sun in AU, the velocity required to escape the sun from that orbit, and the total velocity change required for the entire maneuver. Note that if low thrust is used to get Longshot to 10 AU from the sun, the velocity change for the single impulse escape is significantly reduced and so is the required fuel mass.

The required mass ratios are still too large for conventional propulsion methods (where $I_{sp} < 1000$ sec) for any of the escape proposals (see graph in fig. A-2). Ion propulsion with a specific impulse of about 3000 seconds will give a mass ratio of about 1.5 for a parabolic escape. This seems to be the only viable option for a solar escape among the "conventional" propulsion systems.

Thus far, solar escape using the proton annihilation propulsion has not been mentioned. Although difficult to direct, this system is the only one with a specific impulse high enough to escape the sun with an acceptable mass ratio. The earth and solar escape could be accomplished in one large impulse if the thrust produced is capable of generating a reasonably large acceleration (about .1 g). Because the products of the drive decay quickly, they do not pose a threat by being 150 nm above the surface of the earth. The sun could be escaped in an hour and ten minutes, an insignificant amout of time compared the the trajectory time. Hopefully, the future will give scientists a greater degree of certainty of velocity and direction accuracy in the antimatter annihilation drive.

A.2

FIGURE A-1

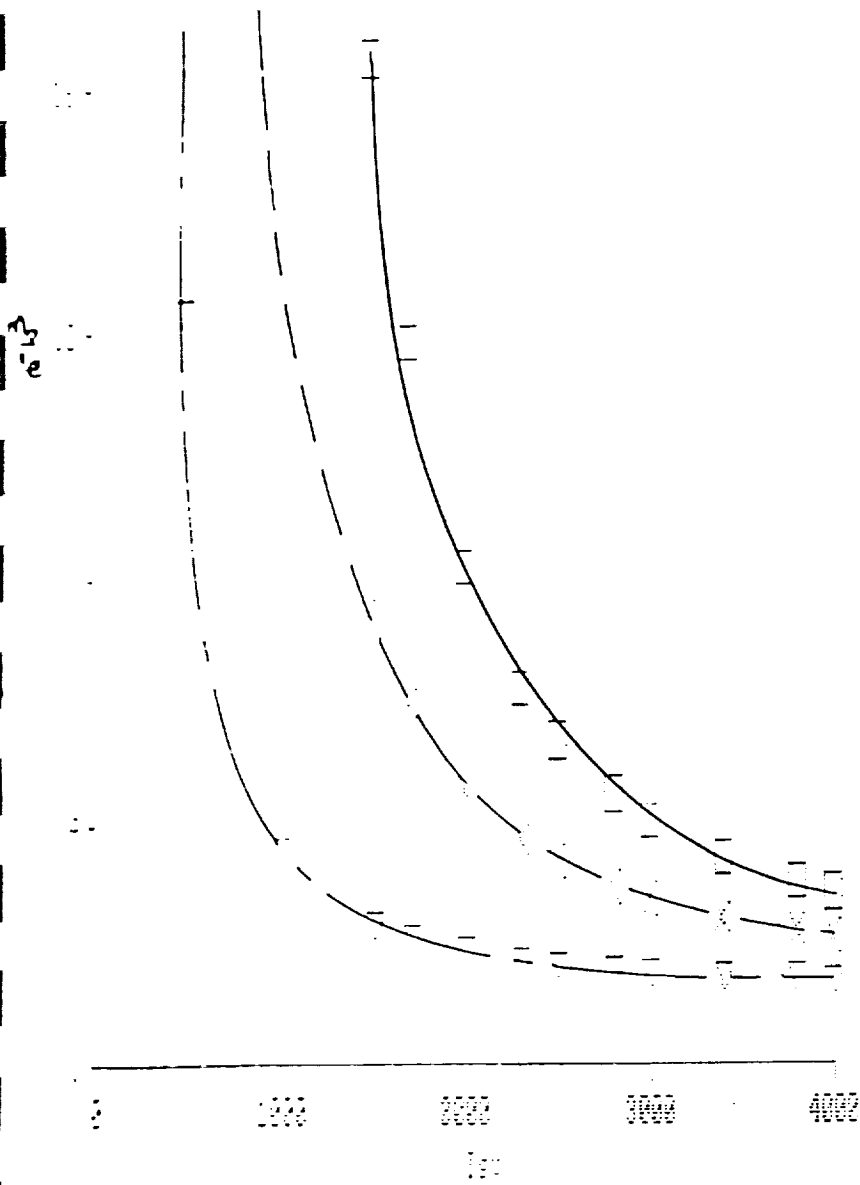Velocity vs. departure orbit's semi-major axis

Legend:
- $V_{low\,thrust}$
- V_{esc}
- V_{total}

V

a (AU)
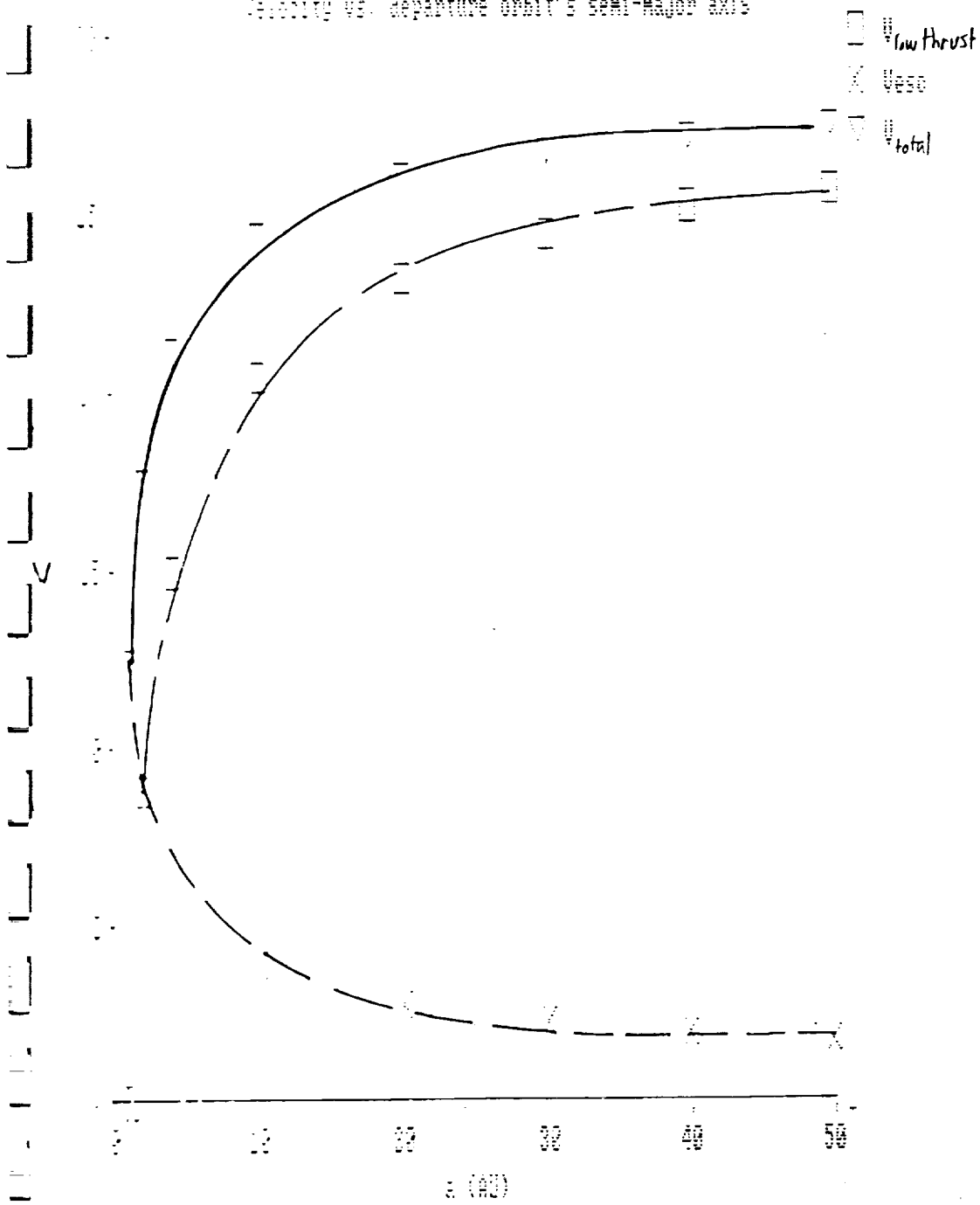
FIGURE A-2

Mass ratio vs. Isp

——————— V=41.3 km/s

——— — ——— V=29.8 km/s

——— · ——— V=12.3 km/s

Appendix B:

Mission Calculations

APPENDIX B-1

CALCULATIONS FOR SOLAR ESCAPE OPTIONS

The velocity required to escape the earth from a 150 nm parking orbit is:

$$V_{esc} = \sqrt{2\mu_\oplus/r} = \sqrt{2(3.986 \times 10^5)/6656} = 10.9 \text{ km/s}$$

The velocity required to escape the sun from 1 AU is:

$$V_{esc} = \sqrt{2\mu_s/r} = \sqrt{2(1.327 \times 10^{11})/149.5 \times 10^6} = 42.1 \text{ km/s}$$

The velocity of the earth relative to the sun is:

$$V = \sqrt{\mu_\oplus/r} = \sqrt{(1.327 \times 10^{11}/1.495 \times 10^8)} = 29.8 \text{ km/s}$$

So, the velocity of Longshot relative to the sun after it has escaped earth is given by:

$$V_{1/s} = V_{1/\oplus} + V_{\oplus/s}$$

Therefore to escape the sun in the ecliptic plane, Longshot must increase its velocity by:

$$42.1 - 29.8 = 12.3 \text{ km/s}$$

For an escape and an inclination change in a single maneuver, Longshot must have a velocity increase of 41.28 km/s in a direction $\beta = -70.5$ degrees with respect to the ecliptic.
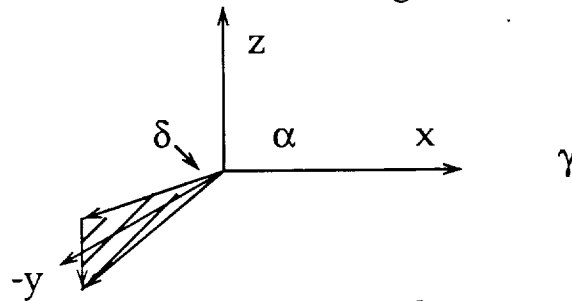

$\delta = -67.6$
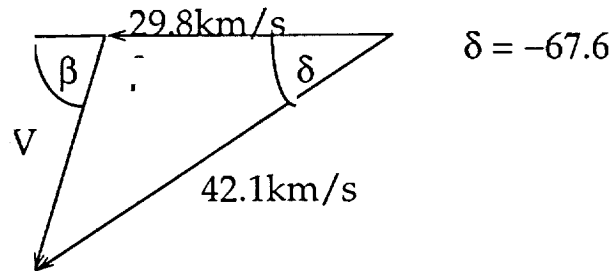
$$V^2 = 42.1^2 + 29.8^2 - 2(42.1)(29.8)\cos(67.6)$$
$$V = 41.28 \text{ km/s}$$

DETERMINATION OF DIRECTION OF ALPHA CENTAURI WITH RESPECT TO THE SUN

The declination and right ascension of Alpha Centauri with respect to the earth are respectively: $\delta = -60.77$ degrees

$\alpha = 219.6$ degrees

The position matrix of Alpha Centauri with respect to the earth is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{Bmatrix} \cos\delta\ \cos\alpha \\ \cos\delta\ \sin\alpha \\ \sin\delta \end{Bmatrix}$$

To get the coordinate system in the ecliptic coordinate system, a rotation matrix must be incorporated. The equatorial coordinate system must be rotated by the obliquity angle, 23.5 degrees. This rotation is represented by:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(23.5) & \sin(23.5) \\ 0 & -\sin(23.5) & \cos(23.5) \end{bmatrix}$$

So the position matrix of Alpha Centauri with respect to the sun is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(23.5) & -s(23.5) \\ 0 & s(23.5) & c(23.5) \end{bmatrix} \cdot \begin{Bmatrix} c(-60.77)c(219.6) \\ c(-60.77)\ s(219.6) \\ s(-60.77) \end{Bmatrix}$$
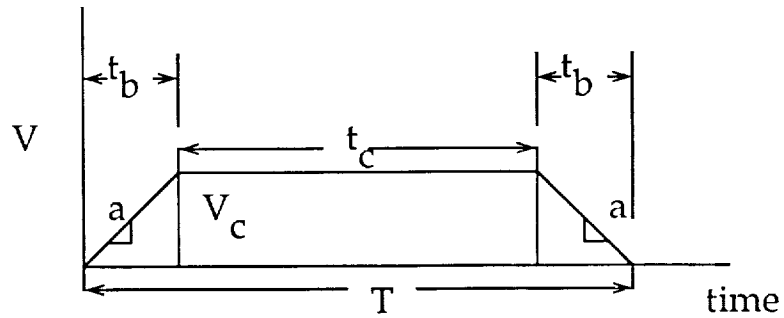
So the declination and the right ascension with respect to the sun are:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{Bmatrix} -.3763 \\ -.0625 \\ -.9244 \end{Bmatrix} \quad \text{so} \quad \delta = -67.6° \quad \alpha = 170.57°$$

CALCULATIONS OF MISSION TIME FOR VARIOUS BURN TIMES AT A CONSTANT ACCELERATION

a = acceleration = .1 g
d = distance = 4.3 light years
T = midcourse time
t_c = coast time

t_b = burn time

the coast time is :
$$t_c = T - 2t_b \quad (1)$$

Notice the area under this curve is the distance to Alpha Centauri (4.3 light years) and the area of the trapezoid is given by:
$$d = A = 1/2(V_c(t_c + T))$$

So, the coast time is :
$$t_c = 2d/V_c - T \quad (2)$$

Subtracting (2) from (1) gives:
$$0 = 2T - 2t_b - 2d/V_c$$

So the time of the mission is given by:

$$T = \frac{(2d/V_c + 2t_b)}{2} = d/V_c + t_b$$

DETERMINATION OF ORBITAL APPROACH VELOCITY

The masses of Alpha Centauri A and B in solar masses are respectively:
$$M_A = 1.1\,M_s \qquad M_B = .85\,M_s$$

Eccentricity = e = .52
Orbital period = T = 80.09 years
Using the following relationships, the velocity of the target star, Alpha Centauri A, will be determined.

$$\mu_{AB} = G(M_1 + M_2) = 2.74 \times 10^{11}\ km^3/s^2$$

$$p = (1+e)(1-e)a = (1.52)(.48)a$$

$$a = (T\sqrt{\mu/2\pi})^{2/3} = \left[\frac{(80.09 \times 3.15 \times 107)\sqrt{2.74 \times 10^{11}}}{2\pi} \right]^{2/3}$$

$$a = 3.537 \times 10^9\ km = 23.66\ AU$$

Therefore, $p = 2.58 \times 10^9$ km
So the specific angular momentum, h, is:

$$h = \sqrt{\mu p} = \sqrt{2.74 \times 10^{11}}(2.58 \times 10^9) = 2.66 \times 10^{10}$$

$$h = rv = 2.66 \times 10^{10}$$

When Longshot approaches Alpha Centauri A, it will be about 2050. Alpha Centauri A will be 1.4×10^9 km from the barycenter. The velocity of A with respect to the barycenter is:

$$v = h/r = 2.66 \times 10^{10}/1.4 \times 10^9 = 19\ km/s$$

The velocity required for a circular orbit around A at a distance of 1 AU with respect to the star is:

$$V_{1/A} = \sqrt{\mu/r} = \sqrt{2.74 \times 10^{11}}/1.495 \times 10^6 = 42.88\ km/s$$

The relative velocity with respect to the barycenter for approach is:
$$42.88 + 19 = 62\ km/s$$

So Longshot needs to decelerate to 62 km/s relative to the barycenter of Alpha Centauri to orbit A.

Mass Ratio vs. Isp for various velocity changes
V=41.3km/s V=29.8km/s V=12.3km/s

Isp s	m_0/m_f	m_0/m_f	m_0/m_f
500	4518.32	135.04	12.28
1000	67.22	20.86	3.50
1500	16.53	7.53	2.31
1700	11.88	5.97	2.09
2000	8.20	4.57	1.87
2300	6.23	3.73	1.72
2500	5.35	3.37	1.65
2800	4.43	2.96	1.56
3000	4.07	2.75	1.52
3400	3.45	2.44	1.45
3800	3.03	2.22	1.39
4000	2.85	2.14	1.37

Velocity vs Semi-major Axis of Departure orbit for low thrust and escape in plane option

a (AU)	low thrust velocity	Vesc	Vtotal
	0	12.34	12.34
	8.73	8.73	17.45
	14.90	6.17	21.07
	20.37	3.90	24.27
5	22.13	2.76	25.39
10	24.35	2.25	26.61
30	25.08	1.95	27.03
50	25.58	1.75	27.32

Appendix C:

Radio Frequency Communications

Link Budget

RADIOFREQUENCY COMMUNICATIONS APPENDIX

The radiofrequency communication link equation may be written in terms of three major components: the transmitter, the channel and the receiver [Reference 1]. The transmitter element takes the power amplifier output and transmitter antenna gain into consideration. The channel component consists mainly of transmission loss terms, free space loss in particular. The receiver aspect entails receiver antenna gain and system noise losses. The link equation may be written as

$$(C/No) = (EIRP) - Lt + (Gr - (kT)) \quad (dB\text{-}Hz)$$

where

(C/No)	=	received carrier to noise energy density ratio (dB-Hz)
(EIRP)	=	transmitted effective isotropic radiated power (dBW)
Lt	=	total channel losses (dB)
Gr	=	receiver antenna gain (dB)
kT	=	effective receiver noise energy density (dB-Hz)

The transmitter term may be expressed as

$$(EIRP) = Pt - Ll + Gt \quad (dB)$$

where

Pt	=	transmitter power, or the power available to the individual crosslink channel
Ll	=	line and coupling losses
Gt	=	transmitter antenna gain

It was decided to eventually solve for transmitter power in terms of information bit rate. A frequency of 120 GHz (with a corresponding wavelength of 2.5 mm) was chosen for this system for four major reasons [Reference 2]:

1. This frequency gives greater advantage in link performance compared to lower frequencies.

2. This frequency is far away from planned terrestrial communication frequencies, so the probability of interference is reduced.

3. This frequency lies near the center of the band (105 - 130 GHz) allocated by the International Telecommunications Union for future intersatellite links.

4. It is assumed that this frequency can be achieved in the near future.

C.1

Assuming Ll = 2 dB, antenna diameter = 10 m, antenna efficiency = 0.6 and λ = 2.5 mm

$$Gt = 10 \log\frac{4\pi A\eta}{\lambda^2} = 80 \text{ dB}$$

Thus, (EIRP) = Pt - 2 dB + 80 dB = Pt + 78 dB

The most significant loss term is the free space loss, which is the loss, relative to the receiver, of signal energy due to the transmitted energy's geometric dispersion with distance. It may be written as

$$Lf = 20 \log\frac{4\pi r}{\lambda} \text{ (dB)}$$

where

r = distance between the transmitter and receiver

λ = transmission wavelength

Assuming r = 1 light-year, Lf = 394 dB.

Another loss is the antenna pointing and polarization loss, Lp. If the transmissions are circularly polarized, the polarization loss is negligible. But the pointing loss depends on antenna tracking accuracy. Assuming this loss equals 3 dB, and adding another 1 dB for miscellaneous implementation errors and degradations, Lt = 398 dB.

The receiver component of the link equation consists of two parts -- the receiver antenna gain and the system noise density. Since the same antenna will be used as both the transmitter and receiver, Gt = Gr = 80 dB. The system noise density equals the product of Boltzmann's constant, k = -228.6 dB-Hz/K, and the effective system noise temperature. This is given by

$$T = Ta + To (L - 1) + LTm + Tr$$

where

T = effective noise temperature

Ta = antenna noise temperature (5 K)

To = ambient cryogenic environment temperature (50 K)

L = loss in the microwave feed structure (1.02)

Tm = MASER noise temperature (11 K)

Tr = temperature due to subsequent units (1 K)

C.2

Substituting these values into the equation, $T = 18$ K. Therefore the receiver component of the link equation is

$$80 - (-228.6 + 18) = 290.6 \quad (\text{dB-Hz})$$

Substituting these values into the original link equation

$$(C/No) = (EIRP) - Lt + (Gr - (kT)) \quad (\text{dB-Hz})$$
$$(C/No) = (Pt + 78 - 398 + 290.6) \quad (\text{dB-Hz})$$
$$(C/No) = Pt - 29.4 \quad (\text{dB-Hz})$$

The carrier to noise ratio depends on the required energy per information bit to noise energy density ratio (Eb / No) which is needed to achieve a specific bit error probability. The relationship between (C/No) and (Eb/No) is

$$(C/No) = (Eb/No) + R + M$$

where
R = information bit rate (dB)
M = system link margin (assumed to be 2 dB)
The value of (Eb/No) depends on the required bit error probability and the modulation scheme that is used. For these calculations, it is assumed that the bit error probability will equal 10 e-5, and the modulation scheme will be BPSK (Binary Phase Shift Keying). Therefore, using Figure 1,

$$Pt - 29.4 = 9.5 + 2 + R$$
so
$$Pt = 40.9 + R$$

Therefore, assuming a bit rate of 100 bps,

$$Pt = 40.9 + 20 = 60.9 \text{ dB} = 1.23 \text{ MW}$$

Assuming a bit rate of 1000 bps,
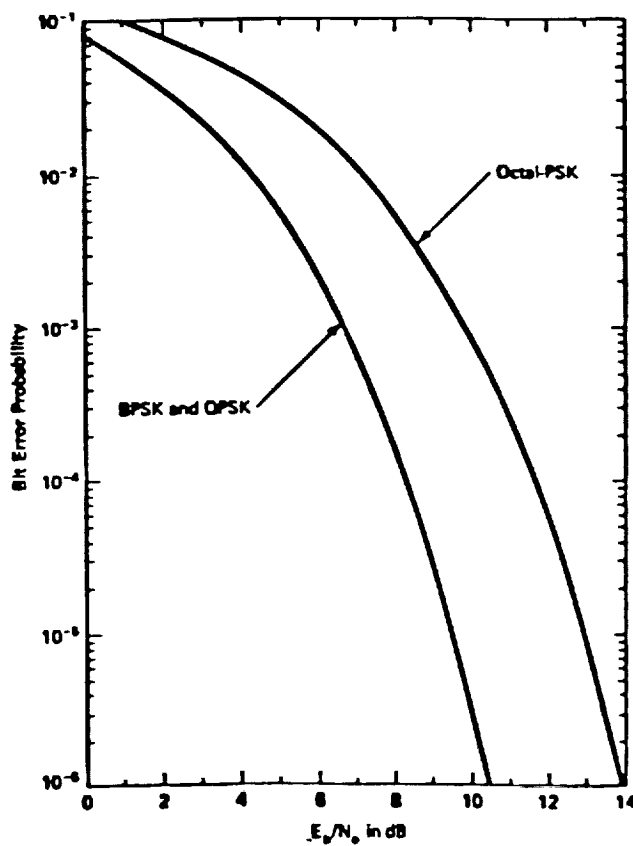
$$Pt = 40.9 + 30 = 70.9 \text{ dB} = 12.3 \text{ MW}$$

FIGURE 1 (ref. 1)

BIT ERROR PROBABILITY VS Eb / No PERFORMANCE OF COHERENT BPSK, OPSK, AND OCTAL-PSK

C.4

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1.   King, M.A., Jr. "A Brief Outline of an RF Crosslink System Design." Laser Satellite Communications. Ed. M. Katzman. Englewood Cliffs, NJ: Prentice - Hall, Inc. 1987. pp. 214 - 231.

2.   Rooney, K.J. "Interstellar Probes - A Communications Philosophy." Journal of the British Interplanetary Society, 31 (1978), 323 - 334.

Appendix D:

Laser Communications

Link Budget

LASER COMMUNICATIONS APPENDIX

Radiofrequency communication systems are limited by the thermal noise associated with the communications receiver, and their performance is evaluated after the received carrier-to-noise energy density ratio is specified. Thermal noise, however, is not a limiting factor for laser communications. In this case, the received background noise, in the form of light, is the primary limitation. The actual link performance depends on the individual values of both the signal and background noise strengths, and not just on their ratio. The following link budget applies only to direct detection systems, as opposed to heterodyne systems, which use photomultiplier tubes, or equivalent, detectors [Reference 1].

There are three steps in calculating the laser communication link budget:

1. Determine the number of detected signal photons per pulse at the detector.
2. Determine the number of detected background or noise generated photons per pulse position moduation slot at the detector.
3. Compare the number of detected signal photons per pulse with the number of detected noise photons per slot.

To determine the number of detected signal photons, the useable beamwidth must first be calculated using

$$\theta t = 1.5 \; \lambda \; / \; D = 1.35 \; \mu \, rad$$

where

θt = useable beamwidth (rad)

λ = optical wavelength = 0.9 μm

D = telescope diameter = 1 m

The footprint diameter at the receiving detector is evaluated by

IFOV = footprint diameter at the receiver

R = distance between the transmitter and receive

= 1 light-year

Since the diameter of the receiving telescope is much smaller than the footprint diameter, a reduction factor must be used.

$$RF = \frac{Da}{IFOV}^2 = 2.44 \times 10^{-18}$$

where
    RF = geometric signal level reduction factor
    Da = diameter of the receiver aperture = 20 m
The receiver power then equals the transmitted power multiplied by the reduction factor. The energy received per pulse is then calculated using

$$E/P = \frac{\text{power received}}{\text{bit rate} \times 8 \text{ bits per pulse}}$$

assuming a pulse position modulated word size of 256. Dividing the energy received per pulse by the energy per photon then yields the number of photons per pulse.

Other non-space losses must also be considered. Assuming 50% efficiencies for both transmit and receive optics, and 30% for the detector quantum efficiency, the total detected photon efficiency is 7.5%. Therefore,

Number of detected photons = 0.075 x number of photons per pulse

The second step toward solving the laser link budget is determining the number of background generated noise photons which are detected per pulse position modulated slot time. Table 1 shows the approximate count rates for a variety of both extended and point sources. In this calculation, it is assumed that the detectors will not have any source having the same magnitude as the Sun directly in their field of view for most of the time, but will generally have some fainter stars as a background against an incoming communication signal. Therefore, it is assumed that there will be 0.10 noise counts per slot.

The detected signal photons per pulse may then be compared with the detected noise photons per slot. From Figure 1, the number of detected photons required per pulse is 10.

Finally, the transmitted power requirement may now be calculated. With a margin of 2 dB,

Number of detected photons = 10 x 1.585 = 15.85
Number of photons per pulse = 15.85 / 0.075 = 211

Energy per pulse = 211 / (6.626 x 10^{-34} x 3 x 10^8 / 0.9 x 10^{-6})

= 4.67 x 10^{-17} joules

Extended Sources	# of noise counts/slot
Sun	10^5
Mercury	0.8
Venus	3.0
Earth (typical)	0.6
Mars	0.1
Jupiter	0.03
Saturn	0.01
Uranus	0.003
Neptune	0.001
Moon	0.2
Clear sky:	
Day	0.1
Moonlit night	1 E-7
Moonless night	1 E-8
Background noise outside the atmosphere	1 E-8

Point Sources	# of noise counts/slot
Zero magnitude star	6
6-th magnitude star	0.02
Pluto	3 E-5

TABLE 1   (ref. 1)

BACKGROUND NOISE COUNTS IN GROUND-BASED
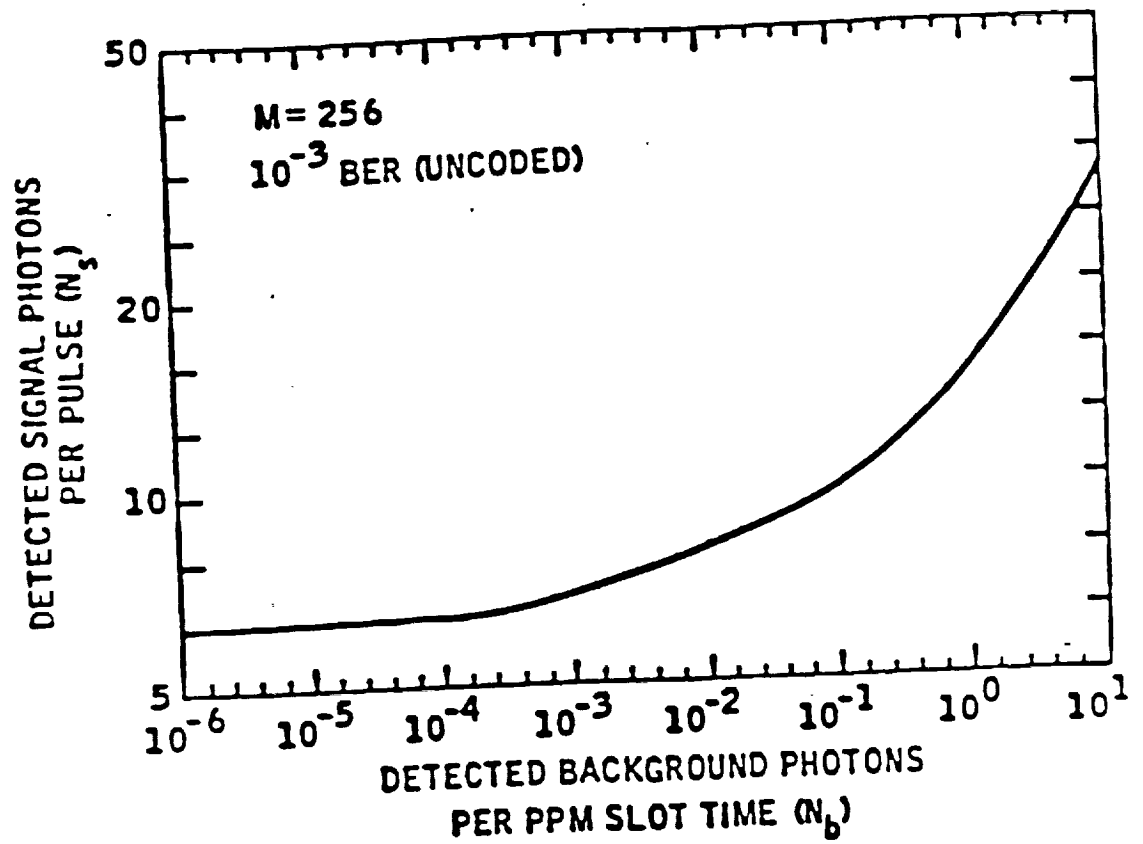OPTICAL COMMUNICATIONS

FIGURE 1 (ref. 1)

REQUIRED SIGNAL PULSE INTENSITY AT DETECTOR VS.
DETECTED BACKGROUND COUNT RATE

D.4

Assuming a bit rate of 100 bps,

$$\text{Power received} = 4.67 \times 10^{-17} \times 100 \text{ bps} \times 8 \text{ bpp} = 3.74 \times 10^{-14}$$
$$\text{Power transmitted} = 3.74 \times 10^{-13} / 2.44 \times 10^{-18} = 15.3 \text{ kW}$$

Assuming a bit rate of 1000 bps,

$$\text{Power received} = 4.67 \times 10^{-17} \times 1000 \text{ bps} \times 8 \text{ bpp} = 3.74 \times 10^{-13}$$
$$\text{Power transmitted} = 3.74 \times 10^{-13} / 2.44 \times 10^{-18} = 153 \text{ kW}$$

REFERENCES

1.   Lesh, J.R., et al. Design and Analysis of Optical Communication Links. JPL NPO - 17017 / 6536. January 1989.

Appendix E:

System Configuration

System Configuration

Nozzle

Reaction Chamber

Working Fluid Tanks

Nuclear Reactor

Sensor System