N92-11097

# HYBRID PROPULSION SYSTEMS FOR SPACE EXPLORATION MISSIONS

D.K. Darooka
General Electric Company
Astro Space Division

In the previous two presentations, you heard some very specific dual mode operations of the propulsion systems, which were referred to as hybrid systems. We felt that we should take a little broader look at the hybrid system, and give much broader top level characteristics of the various possibilities of combining the propulsion systems, and look at the constraints and the advantages.

Some information was presented on the NTP system in the previous two presentations, but since there was no information presented on the hybrid NEP system in the JPL conference, we want to provide a little additional basis for evaluation of the different concepts. I think it will be useful to see what the different technologies can bring, in terms of synergistic benefits, with respect to the other technologies, when you combine them together.

At the top of the chart (Figure 1) we have the chemical technology. Its' technology obviously is at hand, and it's a cliche to repeat the fact that it's limited in its performance by the specific impulse that it can provide. The next stage is a nuclear thermal, which has many advantages. First of all, it will improve upon the specific impulse problem that you have with the chemical system. It does have some negative aspects. It requires additional electrical power, and it has a requirement that no one has answered yet: how much hydrogen propellant you would need and how you would accommodate that and how much volume is associated with it. Then there is the question of our ability to ground test such a system.

Next there is a nuclear electric system, which has several positive points. The negative point obviously is the longer trip time, the associated long duration in the Van Allen Belt part of the orbit. So, since there are negative aspects with all of these systems, it benefits us to see if we can combine all these three and find the best hybrid system.

So we looked at all the possible combinations (Figure 2). First you can combine nuclear thermal with chemical, both being high thrust systems. You don't expect a tremendous amount of performance improvement there. Nevertheless, you will need some chemical propulsion for orbit capture, and definitely for altitude control, maneuvering and so forth, in addition to your NTP propulsion. Next is combining NEP with chemical. Again your performance could be limited depending on what your mass ratio requirement is, and then it could be limited in the chemical Isp that you can obtain in escaping Earth orbit. It also will be helpful, however, in achieving the orbit capture at Mars and on the

PRECEDING PAGE BLANK NOT FILMED

return trip.

The NTP/NTP is basically a dual mode operation which you heard described earlier, and it has several plus points. But it makes the system complex, so you lose one of the key benefits of simplicity, and then also you have to account for the associated structural fraction penalty -- this being a high thrust system. By NTP/NTP I mean that you operate in a dual mode to generate high thrust and low thrust with one reactor. It's a matter of nomenclature.

The next one is NTP/NEP or NEP/NTP depending on what your inclinations are. One could be beneficial to the other, combining the high and the low thrust operation. High thrust phase is used for rapid Earth departure and the low thrust phase is used for the rest of the trip to reduce the trip time. One immediate drawback here is that two independent reactor technologies are required.

Finally, to compensate for NTP/NTP I also have NEP/NEP, wherein you would use a combined high and low thrust operation, but the same single reactor. It retains the Isp benefits of NEP throughout the mission. You operate at high thrust during departure from Earth orbit and low thrust subsequently. This approach has a single reactor technology, and there are some constraints associated with it that will be discussed later.

Figure 3 is basically the high and low thrust profile mission, wherein you rapidly come out of Earth orbit using the high thrust and spiral in to Mars.

Figure 4 shows the impact of the thrust-to-weight ratio, for example, on the velocity requirement. You can see in the thrust-to-weight ratio that at lower orbits you pay additional penalty because of the Earth gravity. In addition to providing that additional Delta V, you also have lower acceleration, which results in longer trip time. On the right, going from LEO to GEO orbit you have Delta-V versus thrust-to-weight ratios. In the range to the left, the Delta-V requirement is nearly constant. However, as you increase thrust-to-weight ratio, you can reduce your trip time going from LEO to GEO. When you consider just going from the LEO to, let's say, outside the Van Allen Belt, you can significantly cut down the trip time.

Now, to look at some of the concepts that were generated combining the high and low thrust, consider the earlier SNAP concepts. You can consider this in many different ways. This could be a dual mode operation, wherein you have an NTP system combined with a nuclear electric power producing system. It's not for nuclear electric propulsion, but is combined with an electric generator to produce utility power. It could use the same reactor or it could use another reactor to produce power. For example, you can replace the power generation part with the SP-100 to deliver 50 kilowatts, or whatever the power requirement is to the crew module. That is another item that hasn't been discussed yet, but I think it is an important item in the NTP system, namely, how do you provide this power that would be needed for the crew during the multi-year time of their living on the spaceship. In another concept, high thrust NTP chemical propulsion system is combined with nuclear electric propulsion. After coming out of the Earth orbit, the high thrust part is ejected and the rest of the spacecraft goes on its trip to Mars. Figure 5 shows a combination of NTP and NEP. In this variation the nuclear electric propulsion part of the system is boosted by the high thrust NTP. After it has come out of the Earth orbit, the system is deployed as shown in the figure; spacecraft panels are extended and the high thrust part is ejected. The whole system can also be given an artificial gravity by rotating the spacecraft. In the variation shown in Figure 6, the high thrust part is achieved by chemical propulsion. Figure 7 is a little better picture of the same spacecraft showing a deployed configuration. In this case the high thrust system is not discarded, but is available throughout the mission.

Finally, you have an NEP/NEP configuration (Figure 8) wherein the same reactor is used to generate the high- and low-thrust propulsion, using the same electrical output. With this you have a single reactor, and you have a low thrust engine, for example, an ion propulsion engine, combined with high thrust MPD thrusters to provide a combination of thrusts.

There are several advantages of the system (Figure 9). It can significantly reduce the duration in the Van Allen Belt and it avoids the need for the crew rendezvous in the high Earth orbit if you can do the mission in a single spacecraft. There is significant reduction in the power level to achieve the trip time. I think this is an important factor in the NEP system, because it relates to system reliability, launch and assembly constraints, and it avoids the need for the development of two independent reactor technologies. It's better to have a single reactor that achieves the same goal.

We went through several preliminary analyses, which I will discuss in another session. But to summarize, one particular case using NEP/NEP for example, to go from NSO, nuclear safe orbit, to approximately 10,000 kilometers using 1200 Isp (Figure 10), you need about 28 days. Obviously this probably is not short enough, but you can trade that off against the power requirement, and also the amount of shielding that you will need.

At the moment we don't have any definition on the amount of shielding that we will need for the crew protection from solar flare, for example. It may turn out that the shielding requirement for the solar flare may overshadow the shielding requirement that you need for the Van Allen Belt, so this trip time may not be too far out.

Basically the bottom line here is that you need a total mass of 650 metric tons, and that compares very well with the reference design. Also, although there may be differences in the launch dates and trajectories, it is comparable with the 680 metric tons that you need for the NTR system (Figure 11).

So, looking at the features of the hybrid propulsion system that affect the SEI mission (Figure 12), it pays to follow the high thrust with a low thrust when the leftover Delta V that you have to work with after the high thrust is of the same order or greater than the high thrust Delta V. This definitely is the case when you are escaping the Van Allen Belt radiation. You are not escaping the entire Earth orbit but you are simply trying to get out of the Van Allen Belt. For comparable initial mass in Earth orbit, the NEP/NEP hybrid system can substantially cut down the Earth escape time. For comparable trip-time, the power requirement is substantially lower than for the pure NEP system. Alternatively, for the same power level, trip time can be shorter. As another important consideration, when you combine the high thrust and the low thrust system, the structural part of the spacecraft becomes very critical. Figure 13 shows the effect of structure fraction on payload fraction. It is seen that the payload fraction drops off rapidly as the structure fraction increases for a given Delta V. This is important in a purely high thrust system. You must design the spacecraft for the high thrust, which may have a very hefty structural requirement. So it's important to have a graceful structural integration between high and the low thrust requirements, for example, by not going at a wide range of Isp, but keeping it closer together. A high-thrust phase could then be available at any point in the trajectory to achieve mission resiliency.

Figure 14 summarizes the status and need for hybrid system technology. It is concluded that hybrid systems do offer many advantages, and I think they should be considered, should be looked at much more closely, and should be compared with the other innovative technologies that we are looking at.

## BIBLIOGRAPHY

D.K. Darooka
Hybrid Propulsion Systems for Space Exploration Missions


1. Borowski, S.K., M.W. Mulac, and O.F. Spurlock; "Performance Comparisons of Nuclear Thermal Rocket and Chemical Propulsion Systems for Piloted Missions to Phobos/Mars", IAF 89-027

2. Crouch, M.F. "Nuclear Space Propulsion", Astronuclear Press 1965

3. Kunz, K.E. "Orbit Transfer Propulsion and Large Space Systems", J. Spacecraft, Vol. 17, 1980.

4. LeGalley, D.P. and J.W. McKee edits. "Space Exploration", McGraw Hill Book Company, 1964.

## Propulsion System Technology

**Chemical**
- Technology In Hand
- Specific Impulse Limits Performance
- Large Amount of $LO_2$ and $LH_2$ Must be Transported and Stored or Manufactured at LEO

**Nuclear Thermal**
- NERVA ReactorTechnology Ground Tested In Early 70's
- Specific Impulse Double That of Chemical
- Requires Large Amount of $LH_2$ to be Transported To LEO
- Requires Additional Electrical Power Source
- Requires Technology Revitalization - Ability For Future Ground Testing To Be Established

**Nuclear Electric**
- Electric Propulsion Engine Development In Embryo Stages
- Space Reactor Power Technology Validation In Progress
- High Specific Impulse Promises Heavy Cargo Delivery Capability But Results In Longer Trip Time
- Long Duration Van Allen Belt Exposure
- Relatively Easier Storage and Transportation of Xenon Propellant
- Design Modulatiry/Resiliency to Meet Broad Range of Propulsion Requirements
- Commonality With Proposed Lunar Mission Requirements

**Hybrid**
- Development Paced as Above
- Potential to Overcome Shortcomings of Above

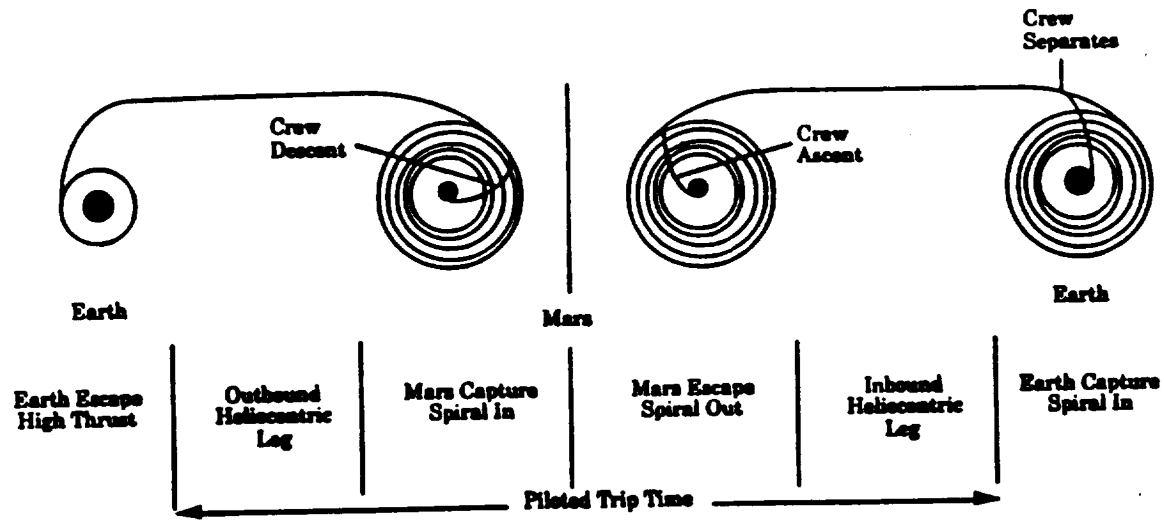
Figure 1

## Characteristics Of Hybrid Propulsion Systems

| | |
|---|---|
| NTP/Chemical | • Very Limited Performance Improvement Can Be Expected<br>• May Be Necessary For Short Burn Orbit Capture And Trim Control |
| NEP/Chemical | • Usefullness Depends On Mission Applications<br>- Limited By Chemical ISP And Required Mass Ratio<br>• Helpful In Orbit Capture |
| NTP/NTP | • Dual Mode Operation - Electric And Thermal<br>• Available Throughout Mission<br>• Substantially More Complex And Expensive |
| NTP/NEP or NEP/NTP | • Combined High/Low Thrust Operation<br>• High Thrust Phase Used For Rapid Earth Departure<br>• Low Thrust Phase Used During Otherwise Coasting Period<br>• Two Independent Reactor Technologies |
| NEP/NEP | • Combined High/Low Thrust Operation<br>• Retains Benefit Of NEP Throughout Mission<br>• Single Reactor Technology |

Figure 2

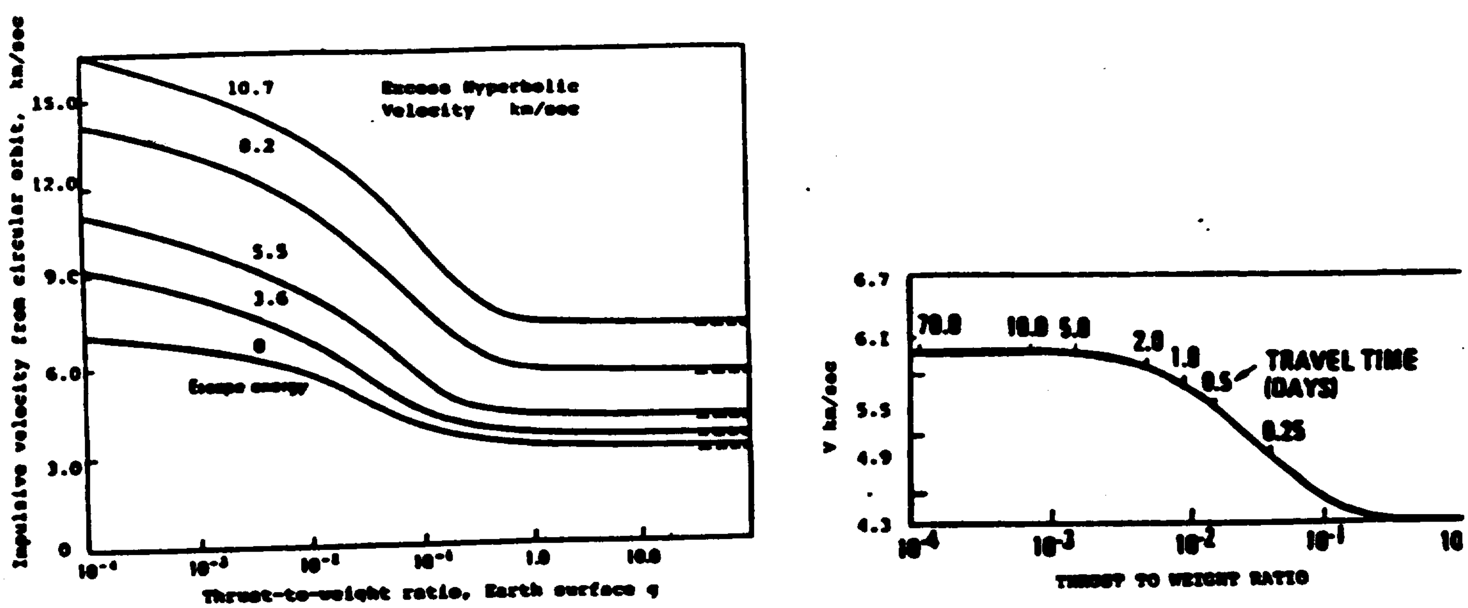
# Typical Combined High/Low Thrust Profile




HIGH THRUST STAGE JETTISONED AFTER TRANS-MARS INJECTION BURN
NEP SYSTEM USED FOR REST OF MISSION

Figure 3

## *Impact Of Thrust To Weight Ratio On Delta V Requirements*




ESCAPE FROM CIRCULAR ORBIT

LEO TO GEO ORBIT TRANSFER

*Higher Thrust To Weight Ratio Can Assist Near Earth Orbit Transfer And Escape*



Figure 4

## NTP/NEP CONFIGURATION WITH ARTIFICIAL GRAVITY

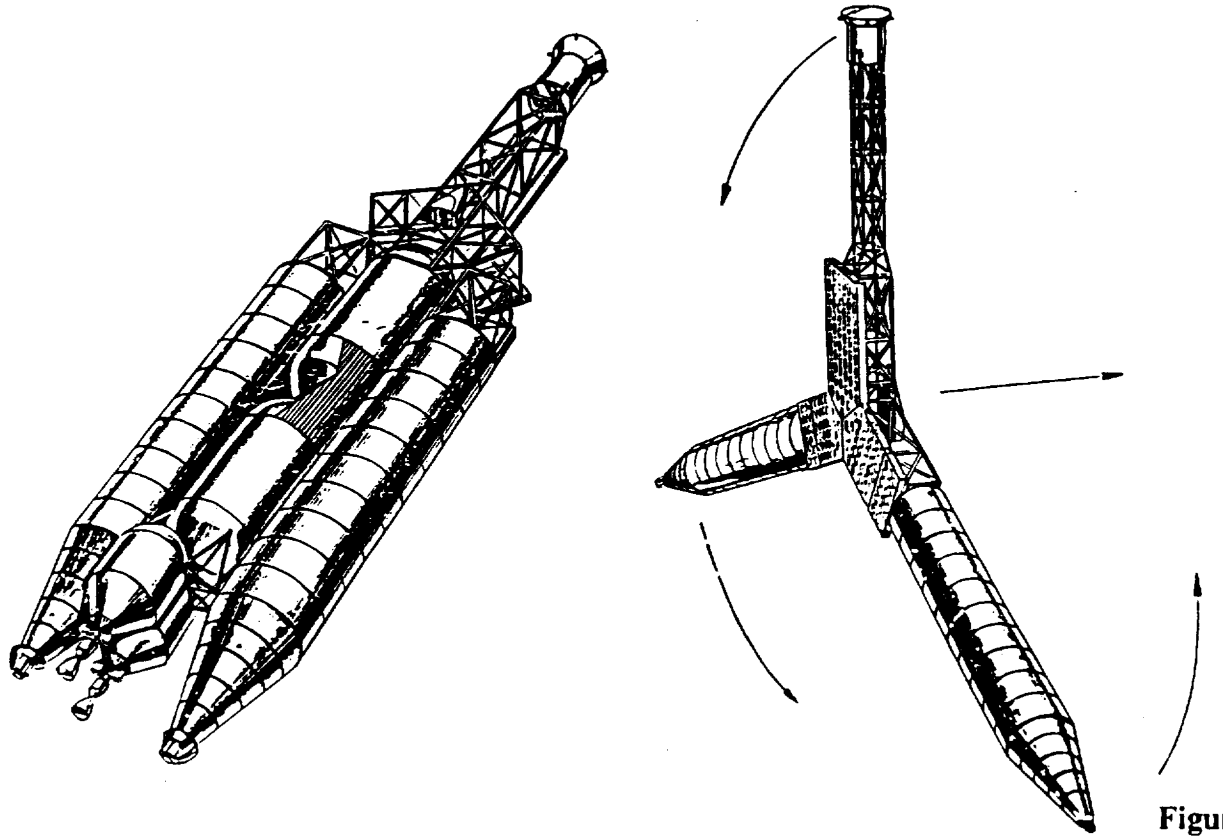


Figure 5

## A Conceptual Design of Hybrid NEP/Chemical Propulsion System

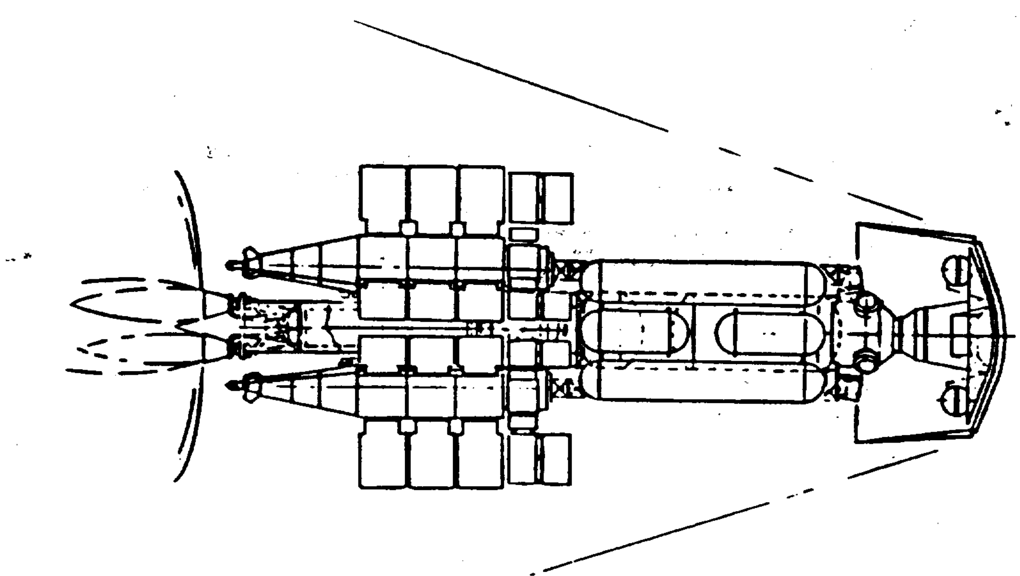


Figure 6

## A Conceptual Design of Hybrid NEP/Chemical Propulsion System

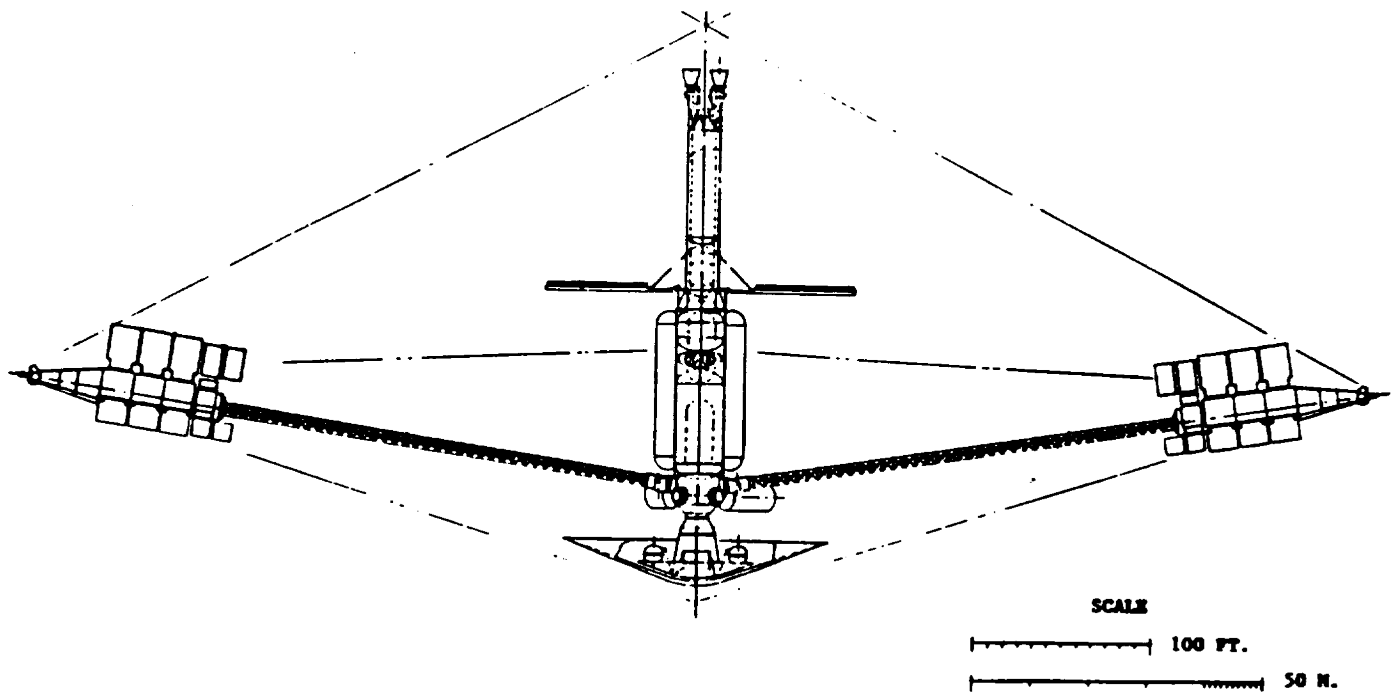



Figure 7

## A Concept Of Hybrid NEP/NEP System

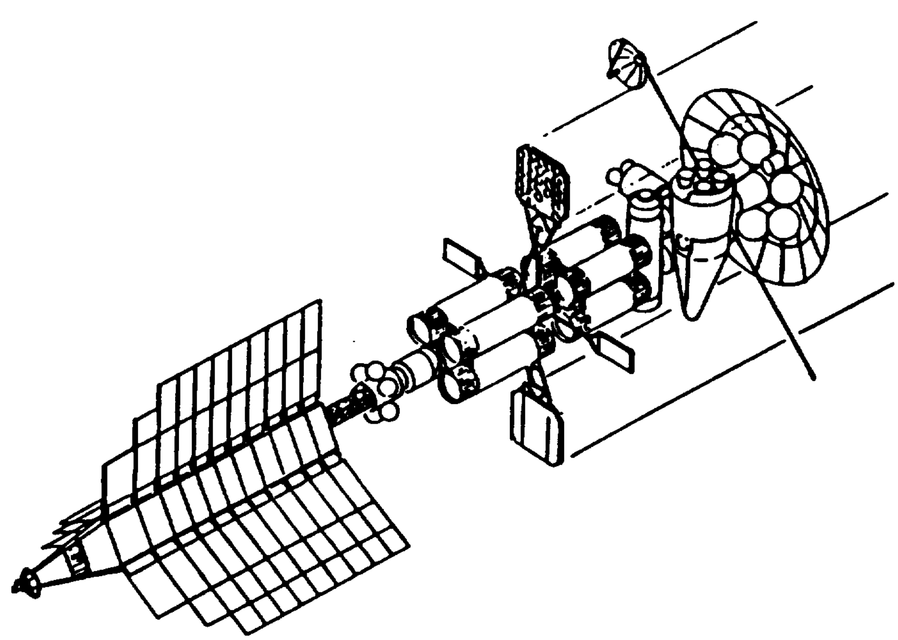


Figure 8

## Combined High/Low Thrust NEP System

- *Use ARC Jet/MPD Engines For Initial High Thrust Stage From NSO to 10000 km Orbit*
- *Use Ion Engines For The Remaining Low Thrust Leg Of The Journey To Mars*
- *Use Low Thrust Spiral And Crew Separation For Return Earth Capture*

*Advantages*

- *Significantly Reduce The Duration In Van Allen Belt*
- *Avoids Need For Crew Rendezvous In HEO*
- *Significant Reduction In Power Level To Achieve TripTime*
- *Lower Power Level - Essential To Meeting Overall System Reliability And Launch And Assembly Constraints*
- *Avoids Need For The Development Of Two Independent Reactor Technologies*

Figure 9

## Hybrid NEP/NEP System Characteristics

| *Trajectory Phase* | *Thruster* | *ISP(Sec)* | *One Way Trip Time (Days)* | *Power (MWe)* |
|---|---|---|---|---|
| NSO To ~ 10,000 km | Arc Jet/MPD(NH3) | 1200 | 28 | 10 |
| 10,000 km To Mars Orbit | ION (Xenon) | 5000 | 150 | 10 |

*Mass Estimate*

| | | |
|---|---|---|
| Delivered Payload Mass | Mt | 125 |
| NEPS (Dry) (Includes High And Low Thrust System) | Mt | 200 |
| High Thrust Propellant Mass | Mt | 175 |
| Low Thrust Propellant Mass (Two Way) | Mt | 150 |
| Total Mass | Mt | 650 |



Figure 10

## Performance Of Alternative Propulsion Systems

### Evolutionary Mars Exploration

| Propulsion System | IMLEO, t | | Percent of Chem/AB IMLEO | |
|---|---|---|---|---|
| | [a]2004 | [b]2011 | [a]2004 | [b]2011 |
| Chem/AB | 573 | 662 | 100 | 100 |
| Chem/AP | 3800 | 3141 | 663 | 475 |
| '72 NTR | 1133 | 933 | 198 | 141 |
| '89 NTR | 1031 | 857 | 180 | 129 |
| Advanced NTR | 787 | 680 | 137 | 103 |
| NTR/AB | 380 | 443 | 66 | 67 |

[a]2004: First Flight, Opposition-Class Mission
[b]2011: Fifth Flight, Conjunction-Class Mission

*Ref: Borowski S. K. et. al. Paper IAF-89-027*

Figure 11

## Features Of Hybrid Propulsion System Affecting SEI Missions

- *It Pays To Follow A High Thrust With A Low Thrust When Performing Fast Interplanetary Transfer When The Remaining $\Delta V$ Is Of The Same Order Or Greater Than The High Thrust $\Delta V$*
- *Such Is The Case When Escaping Most Severe Portion Of The Van Allen Belt*
- *For Comparable Total IMEO NEP/NEP Hybrid System Can Substantially Cut Down The Earth Escape Time*
- *For Comparable Trip Time Power Requirement Can Be Substantially Lower Than NEP System Alone*
- *Alternatively For The Same Power Level Trip Time Can Be Shorter*
- *Structural Requirements Can Be Gracefully Tailored Between High And Low Thrust Requirements*
- *High Thrust Phase Also Usable At Any Point In The Trajectory To Achieve Mission Resiliency*

Figure 12

## Effect Of Structure Fraction On Payload Fraction

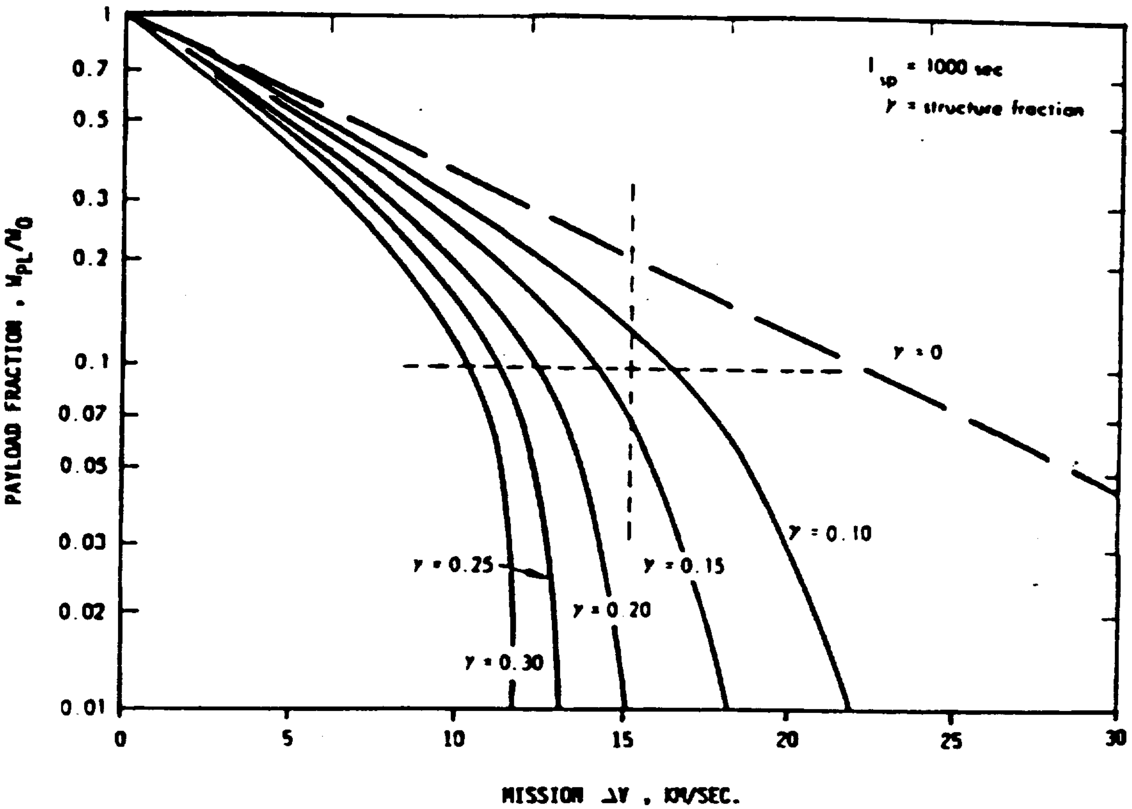



Figure 13

## NEP Hybrid System Technology Status And Needs

- *Conceptual Spacecraft Design Using Arc Jet As Active Load For 100-kWe SP-100 Has Been Studied In Detail For SDI-Missions*
- *MPD Thrusters More Suitable To Meet High Power Needs*
- *Shielding Requirements For The Crew Compartment Not Defined Yet*
- *Shielding For Solar Flare May Overshadow The Need For Short Duration Van Allen Exposure (Can Be Traded Against Power Needed)*
- *Spacecraft Concepts For Combined High And Low Thrusts Required*
- *Study Of Best Combinations And Optimization Needed*
- *Direct Comparison Required With Best NTP System*

- *Understanding Of Hybrid Systems Is Important To Evaluate System Flexibility To Meet Potential Requirements*
- *Hybrid High And Low Thrust NEP System Can Provide Cost Effective Way Of Meeting Requirements For Manned Mars Mission*

Figure 14