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RELIABILITY COMPARISON OF VARIOUS
NUCLEAR PROPULSION CONFIGURATIONS
FOR MARS MISSION

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Abstract

Currently, trade-offs are being made among the various propulsion systems being considered for the Space Exploration Initiative (SEI) missions. It is necessary to investigate the reliability aspects as well as the efficiency, mass savings and experience characteristics of the various configurations. Reliability is a very important factor for the SEI missions because of the long duration and because problems will be fixed onboard. The propulsion options that were reviewed consist of nuclear thermal propulsion (NTP), nuclear electric propulsion (NEP) and various configurations of each system. There were four configurations developed for comparison with the NTP as baselined in the Synthesis (1991): 1) NEP, 2) hybrid NEP/NTP, 3) hybrid with power beaming, and 4) NTP upper stage on the heavy lift launch vehicle (HLLV). The comparisons were based more or less on a qualitative review of complexity, stress levels and operations for each of the four configurations. Each configuration included a pressurized NEP and an NTP ascent stage propulsion system for the Mars mission.

INTRODUCTION

As indicated in the Synthesis Group Report nuclear thermal propulsion (NTP) for the Mars Transfer vehicle was selected on the basis of its substantially increased efficiency, safety, readiness, and its cost effectiveness in comparison to chemical propulsion. Reliability was only reviewed indirectly through safety, efficiency, etc. The intent of this paper is to extend the review of the various propulsion configurations that might be available for use on the SEI missions. Four configurations were developed. They include NEP, NTP/NEP hybrid, hybrid with laser power beaming, and finally using NTP as an upper stage on the HLLV.

A chemical propulsion comparison with NTP has been completed (Segna, 1991) and will not be repeated here. This comparison looked at those parameters such as complexity, stress levels, and operational difficulties that have a propensity of affecting reliability. Reliability as used in these comparisons relates to the ability to accomplish the mission and return the crew safely. While these parameters do not comprise a classic reliability study, they can be used effectively in the conceptual design phase when trade studies are being performed. It was the practice of Apollo and Shuttle program managers when selecting a propulsion system, that orbit mass and even cost was allowed to be compromised in order to enhance reliability. Obviously, a concept with more experience should have a high priority, however, systems with less experience but less complexity and with lower stress levels should also be considered. Higher reliability guided the decision to utilize storable, pressurized, and hypergolic propulsion systems for the Apollo space propulsion engine on the Command and Service Module, the descent and ascent engines on the Lunar Excursion Module, and the orbital maneuvering system on the Orbiter. These decisions were made even with a sacrifice in efficiency and mass savings that would have been afforded by the various cryogenic propulsion systems.

Importance of Propulsion System Reliability

For the Mars mission, there is probably no partial success for the main propulsion maneuvers. The propulsion maneuvers have to start on time and continue for the required duration. For instance, there is no practical backup to the Mars orbit insertion maneuver using an impulse maneuvering system. A free return, as was planned in the initial Apollo Missions in the event of a no-go at lunar orbit insertion, is not practical for Mars orbit insertion. The reason is that a short duration trip to Mars is necessary to minimize the galactic radiation effects and deconditioning during the lengthy, zero gravity period. The short duration trip times are not compatible with a free return because there is unreasonable excess velocity upon arriving at Mars. Even if free return, along with the longer trans Mars time were acceptable, the excessive duration for the return leg, two years or longer, is undesirable. In addition, proper operation of the propulsion system is required in other instances such as the trans-Earth injection maneuver.

leaving Mars and the braking maneuver just prior to entering the Earth's atmosphere. Even a partial burn in either situation could be a major problem. Therefore, a highly reliable propulsion system is imperative and will be a major factor in the final selection of the propulsion system.

Assumptions

This study makes the assumption that with increased complexity, stress levels and/or the operational requirements of a system, with all else equal, the less reliable that system becomes.

At the design phase, increased complexity and stress levels, in themselves, do not decrease reliability because designers can accommodate them. If NASA said, "design to 0.9999," that is what the designer would do, but in actuality the as-built and as-operated may have an entirely different reliability factor than that predicted from design. Many factors can compromise the predicted reliability such as how the organization makes decisions. How do they allow information to be communicated? How does the designer integrate changes made in one area to insure those changes do not affect other systems? Are the specifications right? How good is the suppliers' QA program? Is the fidelity of the test programs adequate? Is the training program complete, etc.?

Below are items that illustrate some of the consequences of these factors:

- The Challenger accident may be considered an organizational problem. The information "not to launch" was there, but was not communicated to the proper staff members. This case illustrates the point above, that complexity is not the whole story. The solid rocket booster is a simpler system than the SSME's and was expected to have a very high reliability -- after the fix it may be, but for that particular launch condition it was not. The problem could have been circumvented if the test program had been of higher fidelity, without compromising the predicted reliability. Simplifying the SRB would have circumvented the problem. This could have been accomplished by making the booster in one piece, thereby avoiding o-ring failure. An example of the reliability of a simple system is the RTG nuclear isotope power supply.
- On Apollo 13 the reason for the LOX tank explosion was traced to a checkout procedure problem. Procedures were misread and DC instead of AC voltage was applied to a circuit inside the oxygen tank overloading the circuit and causing it to short. When the circuit was energized in space the accident happened.
- The Hubble telescope didn't have high enough fidelity tests to see the error in the mirror grinding.
- Sometimes you get lucky. Apollo 8 POGO (propellant oscillations) was a design problem. While it was successful, if design margins hadn't added favorably, the thrust structure probably would have failed.

These examples are included to stress that if the system ignores good judgement, predicted reliability is worth no more than the paper the prediction was written on. Good judgement must prevail, and a thorough ground and flight test program must be conducted to screen any possible built-in problem(s).

So how is the comparison going to be valid relative to complexity? Simply, the more complex a system the higher probability that "Murphy" will cause a problem. Also, every part, component, and system has a finite time to failure. We may not know what that time is, but we can say that the probability of failure will increase with complexity. Again, the Challenger accident is a case in point. If the SRB had not been segmented, as mentioned above, there would not have been an o-ring to fail.

Equating increase in stresses on a system to lower reliability is not an easy relationship. One system can be designed for 1000 K and the other for 3000 K. As with complexity, either system can be designed to the same reliability. Let's look at factors where higher stresses might compromise reliability:

- Usually there is less experience at the higher stress level. Designers have to resort to using newer and more exotic materials as the stress levels are increased.
- The higher the system is stressed the greater the chance a failure will cause secondary damage. For example, failure of higher pressure systems creates higher speed projectiles; higher temperatures create more chemical reactivity, and higher temperatures increases heat transfer, likewise with higher voltage, etc.

- A specified safety factor for a higher stressed system usually has a higher penalty mass and/or cost than the same safety factor for a lower stressed system. Since mass and cost are always under scrutiny, it is a greater probability that the higher stressed system will have a lower safety factor thus the potential to be less reliable.

Chemical Vs. NTP Assumption

This comparison was previously completed under the same basis included in this paper. The result was the NTP has a very high potential for being more reliable than chemical, therefore, NTP as used in the Synthesis Report is the baseline for this study. Also, because of its higher reliability, NTP will be used in two other applications such as the ascent stage for Mars and a smaller version in conjunction with NEP in a hybrid mode. In addition, it was shown that a pressurized NTP is even simpler and is used in all the NTP configurations.

These configurations begin with the Synthesis Report NTP as the baseline. The first configuration developed for comparison replaced the NTP with a pressurized NEP and an NTP replaced the Mars ascent stage H₂ O₂ cryogenic propulsion system. Next, a relatively small NTP was added to the NEP configuration and is referred to as the hybrid followed by adding power beaming and finally adding pressurized NTP as the upper stage to the HLLV.

It did not appear that the NEP alone would be potentially more reliable than the NTP because of added complexity, so the hybrid and the power beaming were added for further analysis. The NTP upper stage was added separately and though not included in all the comparisons, but because of its much higher efficiency and simplicity it is considered for this review.

These four configurations are applied to a Mars mission and are summarized in Table 1. Each succeeding configuration builds on the previous configuration.

Comparison

The preceding configurations were then reviewed with respect to complexity, stress levels, and operations and then compared in Tables 2 through 5. Guidelines used for the comparisons are as follows:

- Each of the four configurations builds on the previous concepts.
- Benefits and adverse items will be listed compared to the previous concept. NTP will be considered the baseline and all the comparison items will be in the NEP column. For the NEP Plus Hybrid configuration, NEP will be the baseline and NEP Plus Hybrid will contain all the comparison items etc. This way the adverse items and the benefits are additive for each configuration change.
- Ascent stage will be NTP and pressurized (no propellant pumps). Also, reduces "g" build-up as propellants are used.
- NEP propellant tanks will be pressurized (some increase in mass but reduces complexity).
- Minor comparison items are ignored.

TABLE 1. Configuration Summary

MISSION PHASE	SYNTHESIS NTP	NEP	PLUS HYBRID	PLUS POWER BEAMING	PLUS HLLV PRESS. NTP UPPER STAGE
Basic Concept	Split/sprint	Same	Same	Same	Single mission
Launch	HLLV - 250MT	Same	Same	Same	HLLV - 350MT
LEO Ops					
unmanned	Assy for TMI	-Assy LEO -Spiral to escape	Same	-Dock components to OTVe & pwr/bm	NA
manned	Assy for TMI	-Assy. veh. & dock to OTVe -Crew board taxi	Same	-Dock components to OTVe & pwr/bm -Crew board taxi	Same
Staging					
unmanned	NA	NA	NA	-Beam OTV/veh. to L1 & assy.	NA
manned	NA	-OTV Spiral to L1 -Followed by crew taxi to L1	Same	-Beam OTV/veh to L1 & assy. -Followed by crew taxi to L1	Same
TMI					
unmanned	NTP	Spiral to escape	Same	Same	NA
manned	NTP	-Undock OTV -Taxi Dock -Crew xfer -Spiral escape	-Undock OTV -Taxi Dock -Crew xfer -Small NTP	Same	Same
Trans Mars	Coast	NEP	same	Same	Same
Mars Capture					
unmanned	NTP	Spiral to LMO	NEP spiral	Same	NA
manned	NTP	-Spiral to medium Mars orbit	-NEP braking -Small NTP capture HMO	Same	Same
Mars Orbital Operation					
unmanned	-Undock TEI propellant -Prepare for descent.	-Undock MTV/NEP & TEI propellant -Split NEP to be comm sat. -Prepare for des	-Same except -Spiral descent stage to LMO	-Same except -Split NEP to be comm & beam satellite -Beam OTV & des sig to LMO	NA
manned	-Dock w/MTV & TEI propellant -Prepare for descent.	-Dock w/MTV/NEP & TEI propellant -Prepare for des	-Des.to circ LMO with small NTP	Same	-Same except -Split redundant syst. to be comm & beam satellite.
Descent					
unmanned	-Descent by cryo	Same	Same	Same	NA
manned	-Descent by cryo	-Same except from medium orbit	-Same except from LMO	Same	Same
Surface Operation	-Short or long duration	Same	Same	-Same except surface power is beamed	Same
Ascent	-Ascent by cryo	-Same except to medium orbit by NTP (asc. stage)	-Same except to LMO	Same	Same
TEI	NTP from LMO	-NEP spiral to escape	Small NTP-2 burn	Same	Same
Trans Earth	Coast	NEP	Same	Same	Same
Earth Capture	Direct entry	-Same except from high L1 -Use taxi to return -Possible reuse	Same	Same	Same

TABLE 2. NEP SUMMARY

ADVERSE ITEMS	COMPLEXITY	BENEFITS
<ul style="list-style-type: none"> • Very large radiators • Much smaller engines but more of them • More lines and valving • High current lines • Requires separate launch for crew and taxi vehicle • Large propellant tank required on the NTP ascent stage • Requires jettison of NTP on ascent stage 	<ul style="list-style-type: none"> • Eliminates separate power supply • Smaller and/or fewer propellant tanks • Less radiation shielding requirements • Reduced structural requirements (less thrust) • Less precise reactor control mechanism • Eliminate need for separate comm sat. • Minimum storage requirements for photovoltaic power (standby or backup power) at L1 staging point • Reduces "g" loading due to propellant usage -- eliminates staging or wide range of throttling 	
STRESS LEVELS		
<ul style="list-style-type: none"> • Higher temperatures in engine • High electrical currents • Higher magnetic fields • Vehicle spends long time in Van Allen Belts • Increase radiation dosage from NTP ascent stage 	<ul style="list-style-type: none"> • Much lower thrust levels • Lower tank and engine pressures • Less propellant slosh • Lower temperature in reactor • Much lower pressure levels in reactor • Reduced level debris field • Reduced mission duration • Less galactic ray exposure • Less probability to solar flare • Minimum atomic oxygen • Reduces refrigeration requirements over straight NTP (less fuel mass) 	
OPERATIONS		
<ul style="list-style-type: none"> • Large radiator deployment • Greater radiator shadowing/thermal control operations • Continuous propulsion on-time operations • Spiral out to escape at mass adds >20 days 	<ul style="list-style-type: none"> • Minimum docking of propellant tanks • Larger launch windows from Earth and Mars • More abort capability • Reduced trip times • Longer Mars stay time for short duration stay missions • Less Mass in LEO less assy operations • Combining comm with MTV reduces number of separate satellites to manage • No nuclear operations near LEO • L1 staging reduces communication link complexity (reduces TDRS requirements) • No orbital decay • Back contamination can be accommodated at L1. Requires more time (~7 days longer + contamination clean up) • Further mass to LEO reduced by not carrying crew reentry vehicle to Mars and back 	

TABLE 3. NEP Plus Hybrid (Small NTP) Summary

ADVERSE ITEMS	COMPLEXITY	BENEFITS
<ul style="list-style-type: none"> • Adds complexity of another propulsion system NTP 	<ul style="list-style-type: none"> • The NTP would be non generic redundant propulsion system • Further reduction of mass to LEO 	

STRESS LEVEL	
	<ul style="list-style-type: none"> • Trip times further reduced • Further reduction in galactic ray and probability of solar flare exposure • Greatly reduced time in Van Allen Belts
OPERATIONS	
	<ul style="list-style-type: none"> • Less Mass in LEO further reduces assy operations • Mission duration further reduced • Two different types of propulsion systems to guard against generic problems

TABLE 4. NEP Plus Power Beaming Summary

ADVERSE ITEMS	COMPLEXITY	BENEFITS
<ul style="list-style-type: none"> • Adds power beaming transmitters and receivers • Adds large radiator • Requires power beaming to OTV from Earth and Moon • Precise control for power beaming acquisition and tracking 	<ul style="list-style-type: none"> • Further reduction of mass to LEO • Eliminates need for separate surface prime power • Redundancy is external to vehicle for some power and propulsion phases at Earth, Moon and Mars 	
STRESS LEVELS		
	<ul style="list-style-type: none"> • Trip times further reduced • Further reduction in galactic ray and probability of solar flare exposure 	
OPERATIONS		
<ul style="list-style-type: none"> • More radiator shadow/thermal control requirements 	<ul style="list-style-type: none"> • Less Mass in LEO further reduces assy operations • Wider launch windows at Earth and Mars • L1 staging with beaming enhances reusable crew taxi which could be common with Mars ascent stage • Commonality with lunar operations • Enhances robotic operations because line-of-sight coverage from synchronous orbit is almost half the globe. • Crew excursions are also enhanced 	

TABLE 5. Plus NTP Upper Stage HLLV Summary

ADVERSE ITEMS	COMPLEXITY	BENEFITS
	<ul style="list-style-type: none"> • Reduces total mass in orbit • Possible to reduce to single mission (non split/sprint) 	
STRESS LEVEL		
<ul style="list-style-type: none"> • If ocean launch salt water 	<ul style="list-style-type: none"> • Trip times further reduced • Further reduction in galactic ray and probability of solar flare exposure 	
OPERATIONS		

- May launch from ocean
- Public opinion against nuclear

- Less assembly requirements in orbit
- Wider launch windows at Earth and Mars
- Can vary launch latitude and azimuth if ocean launch
- Less stringent launch abort requirements
If ocean launch, non split/sprint capability if hybrid, power beam and L1 staging point used
- Non split/sprint, possible to use Mars excursion vehicle as life boat per Apollo 13
- Eliminates double missions (manned & unmanned) on succeeding launch opportunities

CONCLUSIONS

The NTP in a pressurized and somewhat reduced chamber pressure mode is a very simple propulsion system and has the potential of being very reliable. Replacing the cryogenic chemical ascent stage with an NTP system, using it in a hybrid mode with NEP and even as an upper stage of the launch vehicle, should increase the actual reliability of the Mars mission.

There are two major draw backs for the NEP configuration: very large radiators and long duration in the Van Allen belts for much of the spacecraft. To counter the drawbacks, there are many more benefits but of a lesser impact. Without a more detailed study, judging the potential reliability difference would be very subjective.

Adding the hybrid adds no measurable adverse items since a redundant propulsion system is required regardless. The different propulsion concepts are desirable and eliminate a generic problem making both propulsion systems inoperable. Power beaming does add complexity because of the transmitting antennas along with the large radiators needed to cool the antennas. However, the benefits of eliminating the surface prime, power equipment, the ability to be power rich, and to provide easily distributed power to exploring vehicles giving them unlimited range, will weigh heavily in the trade-off studies. The use of NTP for the upper stage of the HLLV may be precarious because of the public opinion against nuclear, but the reported (to the Synthesis Group) 60% increase in payload is extremely favorable. Also, the higher potential reliability over a cryogenic propulsion system, is most desirable. Especially since the Uranium 235 fuel is relatively safe (free of fission products and from transuranics) until the upper stage is started.

There are sufficient benefits when compared to adverse items that show NEP in a hybrid configuration with power beaming, should be included in the Mars technology trade-off studies. The added mission flexibility, power rich capability, and reduced trip times are very favorable. The blinders were on to take a qualitative look at the reliability comparison; therefore, the next effort should include the readiness level of the technology, the development schedule, and quantitative levels for both the adverse and benefit items. It is important to note the use of pressurized NTP for the hybrid and the Mars ascent stage propulsion systems and the use of L1 as the staging point for TEI and Mars return. It keeps from having to take the reentry vehicle to Mars and back; it also affords back contamination processing if required.

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