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SOLAR BI-MODAL SYSTEM CONCEPT: MISSION APPLICATIONS, A PRELIMINARY ASSESSMENT

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Abstract

The current fleet of medium/heavy expendable launch vehicles (ELVs) and upper stages are expensive, inflexible, and non-responsive to the needs of the satellite designer/builder. These transportation systems confine satellite designers to a very narrow operational envelope. If a satellite exceeds its mass budget by even a few percent, mission planners must choose between eliminating instrumentation (reducing the spacecraft's capabilities) or launching on a larger/more expensive ELV. Many people have suggested the development of a new, less expensive ELV to reduce launch costs. While such a system may eventually repay its development cost, current budgets do not make this approach practical. A new upper stage based on chemical technology is also likely to be expensive, with little performance improvement. In order to significantly improve the cost effectiveness of launch assets, alternate propulsion technologies must be developed. The approach to electrical power system design should also be modified. Currently, a new power system is designed for each new satellite. Each of these new power systems must be thoroughly developed, tested, and integrated into the satellite. While this process has produced extremely reliable power systems, the approach is very costly. An alternate approach, currently under investigation, is the use of a single power system with a standard interface to serve all satellites within a specified power range. This standard power system may also incorporate the stationkeeping functions of the satellite, an approach which has been referred to as the "common bus". While cost reductions are possible in both the propulsion and power systems, numerous studies have shown that the combination of power and propulsion into a single system, the Bi-modal approach, may offer additional benefits as well. These Bi-modal systems use a single nuclear or solar energy source to serve both the power and propulsion sub-systems. This paper will provide a preliminary assessment of the application of a solar thermal Bi-modal system for orbit transfer and on-orbit management missions in terms of: dependability (reliability and graceful degradation), performance (capacity and quality), availability and responsiveness (orbit response times, flexibility, survivability and launch time), coverage (orbit implications), and resources (affordability, life cycle costs, and supportability).

INTRODUCTION

Historically, power and propulsion systems have evolved separately. Through years of evolution in the chemical propulsion and photovoltaic power industries, many commercial and defense aerospace companies have organized these functions into separate departments. The search for more efficient (higher specific impulse) propulsion systems has led to the investigation of both solar and nuclear thermal propulsion. Unlike chemical rockets which expend all of their energy when the propellant is depleted, solar and nuclear thermal systems can continue to produce energy long after the propellant is gone. This energy can therefore be harnessed to provide power for the spacecraft, eliminating the need for large photovoltaic arrays. While these Bi-modal systems seem quite worthy of detailed study, this effort requires the support and cooperation of both the power and propulsion communities.

Authors such as Robert Zubrin (1992) have described the many benefits of nuclear Bi-modal systems quite admirably. Many of these same benefits apply to solar Bi-modal systems as well. These systems differ in the manner in which they produce their energy, but both use heat as a source for the propellant

and power conversion systems. In the past, a great deal of money has been spent on the design and development of nuclear thermal propulsion, solar thermal propulsion, nuclear power generation, and solar power generation. However, only recently have funds been devoted to examining the Bi-modal approach. The Air Force Phillips Laboratory and the Department of Energy have been working together to assess Bi-modal system concepts and their benefits to the satellite community. This program has made significant progress with the limited resources which have been provided. However, there is still the difficult challenge of getting the spacecraft community to embrace the idea of a combined system. This requires a fundamental change in the way the government and aerospace companies have approached the design process.

We must also change the way we evaluate and compare systems because Bi-modal systems can perform three distinct missions (orbit transfer, stationkeeping, and electrical power). Traditional performance measures such as system mass and specific power cannot be directly applied at the systems level. For example, a 3 kWe Bi-modal system may be ten percent heavier than a 3 kWe photovoltaic system, but if the Bi-modal's propulsion system can deliver fifty percent more payload to orbit then the power system mass is irrelevant. To provide a fair evaluation, we must look at the mission payload (electronics) mass that can be placed in orbit at a given power level.

REFERENCE SOLAR BI-MODAL CONCEPT

In order to assess the application of a solar Bi-modal system to the orbit transfer and on-orbit management missions, a reference design is needed. The Babcock & Wilcox company has developed a solar Bi-modal concept which integrates propulsion, power, and energy storage into a single system. The concept uses parabolic solar concentrators to collect and focus thermal energy into an insulated central cavity containing a thermal energy storage material. The central cavity serves as the heat source for both the power and propulsion sub-systems, just as a reactor serves as the heat source for a nuclear Bi-modal system.

In the propulsion mode, propellant (hydrogen) is heated by passing it through the energy storage material. The hot gas is then expanded through a nozzle to produce thrust. To provide electrical power, the insulation is removed from around the cavity allowing the heat to radiate to a static power conversion sub-system, or coolant can be passed through the thermal energy storage material for a dynamic power conversion system. This is basically the same scheme as in a nuclear Bi-modal system.

RELIABILITY

While there is no way to determine the reliability of a system in the conceptual stage, there are design features which are inherently more reliable than others. The solar Bi-modal concept was developed with these features in mind. For example, a major concern with most solar thermal propulsion concepts is the use of very large inflatable concentrators. Even if they can be manufactured and deployed, there are still concerns about structural stability and the consequences of debris impact. Thermal energy storage significantly reduces the concentrator size which is necessary to transfer a given amount of energy to the propellant. This enables the use of either rigid or smaller inflatable concentrators. The reliability of rigid concentrators should be similar to that of deployable antennae.

Thermoelectric power conversion was selected as the baseline for this concept because of its demonstrated reliability on RTG power systems. Static power conversion systems are generally considered more reliable than systems with pumped loops and rotating machinery. Thermionic devices also use a static conversion process and offer greater efficiency and higher temperature capabilities than thermoelectric devices. For solar thermionics, the emitter is not in contact with the heat source, so reliability and lifetime should be significantly greater than for nuclear fueled thermionics (TFEs).

FLEXIBILITY

One of the most attractive features of the solar Bi-modal system is its flexibility. Figure 1 shows the mass which can be delivered to GEO on an Atlas IIAS as a function of orbit transfer time and propellant composition (assuming a 3 kWe power requirement). With the current approach, chemical propulsion and photovoltaic power, satellite designers must meet their mass limits or face significant penalties. For example, if a satellite misses its mass limit by five percent, the Air Force must either pay tens of millions of dollars for a larger ELV or reduce the capabilities of the satellite by removing some of the mission payload. With the solar Bi-modal concept, there is a third option. The Air Force can accept a slightly longer orbit transfer time. For many missions this is a much more desirable alternative.

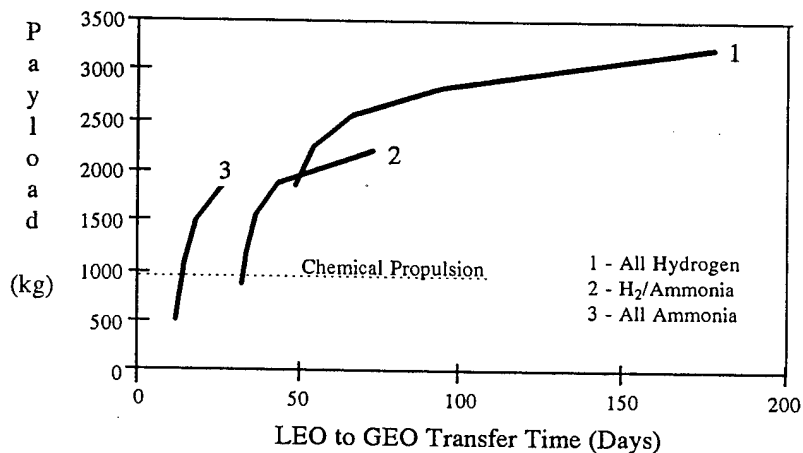


FIGURE 1. LEO to GEO Payload Mass versus Transfer Time on Atlas IIAS with Solar Bi-Modal.

Another trade which can be made by the mission planner is payload versus on-orbit propellant. The high Isp of the solar Bi-modal enables much more mass to be placed in GEO for a given ELV. This mass can be used by the Air Force for either payload or propellant. The additional propellant may be used for stationkeeping to extend mission life or can be used for on-orbit maneuvering to increase responsiveness to regional conflicts.

PERFORMANCE

Since a Bi-modal system performs the same functions as both the chemical propulsion and photovoltaic systems on current spacecraft it is incorrect to evaluate the system based on traditional factors such as mass and power conversion efficiency. For example, a 3 kWe Bi-modal system may be ten percent heavier than a 3 kWe photovoltaic system, but the higher specific impulse of the propulsion system may enable it to deliver fifty percent more mass to orbit. The greater system mass is more than made up for by propellant mass savings. A better scale of measurement is the amount of mission payload (electronics) that can be delivered to GEO for a given ELV and a fixed power requirement. Figure 2 shows the mission payload that can be delivered for each of the three medium and heavy lift ELVs in the current inventory. Tables 1 and 2 show the assumptions and key system parameters on which these analyses were based. The mass of the solar Bi-modal is heavier than the mass of conventional 3 kWe system in all cases, but the propellant mass savings provides a considerable increases in the mass available for mission hardware (electronics).

There are many solar thermal propulsion concepts which claim a higher specific impulse than the Bi-modal concept presented here; however, these concepts generally achieve this performance through higher risk technologies such as large inflatable concentrators and high temperature materials (3000 K). While our goal should certainly be to reach these promising levels of performance, near term systems

should be based on proven technology. It is more important that the first solar thermal propulsion system be practical and offer moderate performance improvements, rather than offer order of magnitude performance improvements at considerably higher risk.

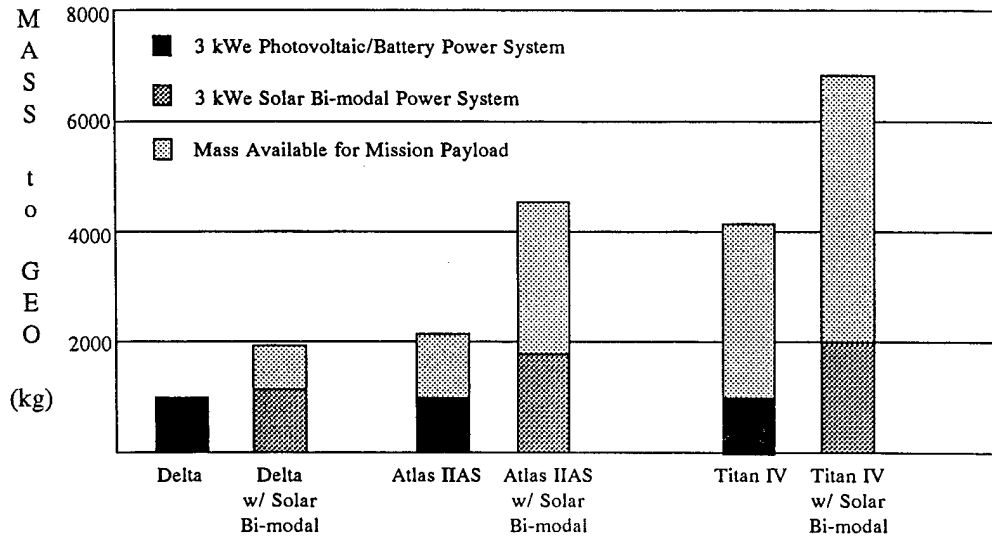


FIGURE 2. Payload Mass to GEO with Current ELVs and Satellite Power Requirement of 3 kWe.

TABLE 1. Mission Analysis Assumptions.

LEO to GEO transfer (28.5 degrees)
Perigee burns from LEO to GTO, Apogee burns to GEO
3 kWe power requirement
No gravity losses assumed (short burns)
Full electrical power required during eclipse.

TABLE 2. Key System Parameters for Analysis.

Electrical Conversion Eff. (%)	7.5
Thermal Energy Storage Material	Silicon
Receiver Operating Temp. (K)	1684
Thrust (lbf)	25-100
Propellant	LH ₂ /Ammonia
Specific Impulse (s)	680/350
Outlet Temperature (K)	1650 min.
Burn Time (min.)	7-10
Concentrator Area (m ²)	48
Concentration Ratio	5,000:1
Concentrator/Receiver Eff. (%)	70
Maximum Receiver Power (kWt)	40

STANDARDIZATION

The Air Force has shown considerable interest in the development of a standard power system (or family of systems). Such a system would free the satellite designer from having to develop and qualify a separate power system with each new satellite. This approach should be more cost effective and produce a more reliable system. Many have suggested that the stationkeeping function be included on these power systems, an approach termed the "common bus". A Bi-modal system would support the "common bus" approach very well, as the stationkeeping function could be integrated with the propulsion system. Both thermal propulsion and electric propulsion could be used for this function.

Each Bi-modal system would be developed at a specified power level and attach to the satellite via a standard interface. The satellite designer would then need only to design the payload instrumentation with the appropriate interface to hook to the Bi-modal system. This standardized approach should ease the manufacturing process and reduce overall system costs.

CONCLUSION

A solar Bi-modal concept has been developed which offers modest improvements over chemical propulsion/photovoltaic systems. This concept incorporates power, propulsion, and thermal storage into a single system which can be developed with near term technologies. The Bi-modal approach offers significant advantages to the users in terms of flexibility and responsiveness, allowing each mission planner to choose the system configuration that best supports his or her needs. The Bi-modal approach is compatible with the "common bus" architecture should the Air Force decide to employ it. The system design draws on technology developed by the Air Force and NASA in both current and previous programs to take advantage of the investments already made.

Acknowledgments

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