N95- 70884

LOW COST BOOSTER AND HIGH PERFORMANCE ORBIT INJECTION PROPULSION EXTENDED ABSTRACT

R. L. Sackheim
TRW Space and Electronics Group

Introduction and Background

Space transportation is currently a major element of cost for communications satellite systems. For every dollar spent in manufacturing the satellite, somewhere between 1 and 3 dollars must be spent to launch the satellite into its initial operational orbit. This also makes the weight of the satellite a very critical cost factor because it is important to maximize the useful payload that is placed into orbit to maximize the return on the original investment. Most communications satellites in use today operate from geosynchronous orbit. Since most of the launch vehicles currently available (e.g., Delta, Atlas, Ariane, Long March, Titan, etc.) insert these satellites into a geosynchronous transfer orbit (GTO), an apogee kick propulsion system must be included on-board the satellite to provide the additional energy required to achieve the final operational geosynchronous orbit (GEO). The satellite apogee propulsion system (APS) using propulsion technologies that are available today is a major fraction of the cargo weight carried into GTO by the current family of launch vehicles. Additional propulsion capability must also be provided by the satellite if there are significant station keeping (maintaining longitude and latitude positioning) requirements for the communication mission to provide the specified earth coverage. It seems apparent then, that tremendous economic advantage for satellite communications systems can be gained from improvements in two key highly leveraged propulsion areas. The first and most important economic improvement can be achieved by significantly lowering the cost of todays launch vehicles. The second gain that would greatly benefit the communications satellite business position is to increase both the useful (payload) weight placed into orbit and the revenue generating lifetime of the satellite on-orbit.

The point of this paper is to first explain that these two goals can best be achieved by cost reduction and performance increasing advancements in rocket propulsion for both the launch vehicle and for the satellite on-board apogee insertion and on-orbit velocity control systems. Let us first deal with low cost propulsion leverage on low cost launch vehicles. It has been determined in previous studies that the rocket engines typically comprise 40 to 50% of current expendable launch vehicle (ELV) costs[1]. The next most expensive elements are the vehicle structure including the propellant tankage, followed by the pressurization and fluid feed systems. Because of the high leverage of the rocket engine cost on the launch vehicle cost, it was found in previously reported studies by McDonnell Douglas Aerospace (MDA)[1,2] and TRW that the most cost effective engine for ELVs would be a fundamentally low cost design that operated at low pressure (< 1000 psia); incorporated hardware elements specifically designed for low cost such as simple and inherently stable injectors with passively cooled thrust chambers; and that also relied upon a simple high pressure gas feed system[3]. However, it was later determined by MDA that for larger vehicles, a purely gas-pressurized feed system would tend to increase costs because of the weight and complexity of the high pressure propellant tanks and the very large gas pressurization feed system. A low cost alternative to heavy and complex pure gas pressure feed systems was found to be the use of simple low pressure, fluid film bearing turbopump assemblies that were stage mounted as part of the low cost vehicle design. A team of MDA, TRW and Allied Signal Aerospace was then formed to conduct some very preliminary design and development activities (on independent company IR&D funds) to establish and verify this low cost launch vehicle design concept.

For the orbit insertion and velocity control phases of the communications satellite mission the real pay off comes from the opposite end of the propulsion technology spectrum. Here, as illustrated in Figure 1, the real pay off comes from high performance that minimizes the on-board consumables to maximize the useful payload fraction in orbit. To this end, TRW is working to advance two key spacecraft propulsion technologies. These are advanced liquid apogee engines to increase specific impulse above 330 seconds and very high performance electric propulsion systems that, under the right circumstance, can drastically reduce the weight of propellant for both orbit raising to GEO and for subsequent on-orbit maneuvering.

To appreciate the discussion that follows, it is important to recognize that for a spacecraft integral apogee propulsion system, specific impulse (ISP) is a very important parameter in communications satellite design, because one second of ISP is worth about 10 to 14 lb of spacecraft weight reduction. Depending upon the specific satellite design, some commercial communications manufacturers have stated that each pound saved then will reduce initial satellite cost by about 10,000 to 20,000 dollars. On the other hand, to achieve low cost expendable launch vehicles, rocket propulsion performance is not a key driver, but it is critically important to reduce the cost of the most expensive vehicle hardware elements, namely the rocket engines, structure and fluid systems. The remainder of this paper will discuss these specific points in more detail.

Space Transportation Cost Influence Factors to Reduce Costs

The emphasis in the past to reduce expendable launch vehicle costs has been to reduce gross lift off weight (GLOW). The perception was that if the design team can minimize GLOW by maximizing performance, then the launch vehicle cost will be minimized by some significant number of dollars per pound of vehicle weight saved. Furthermore, as reported in Reference 1, if one examines the

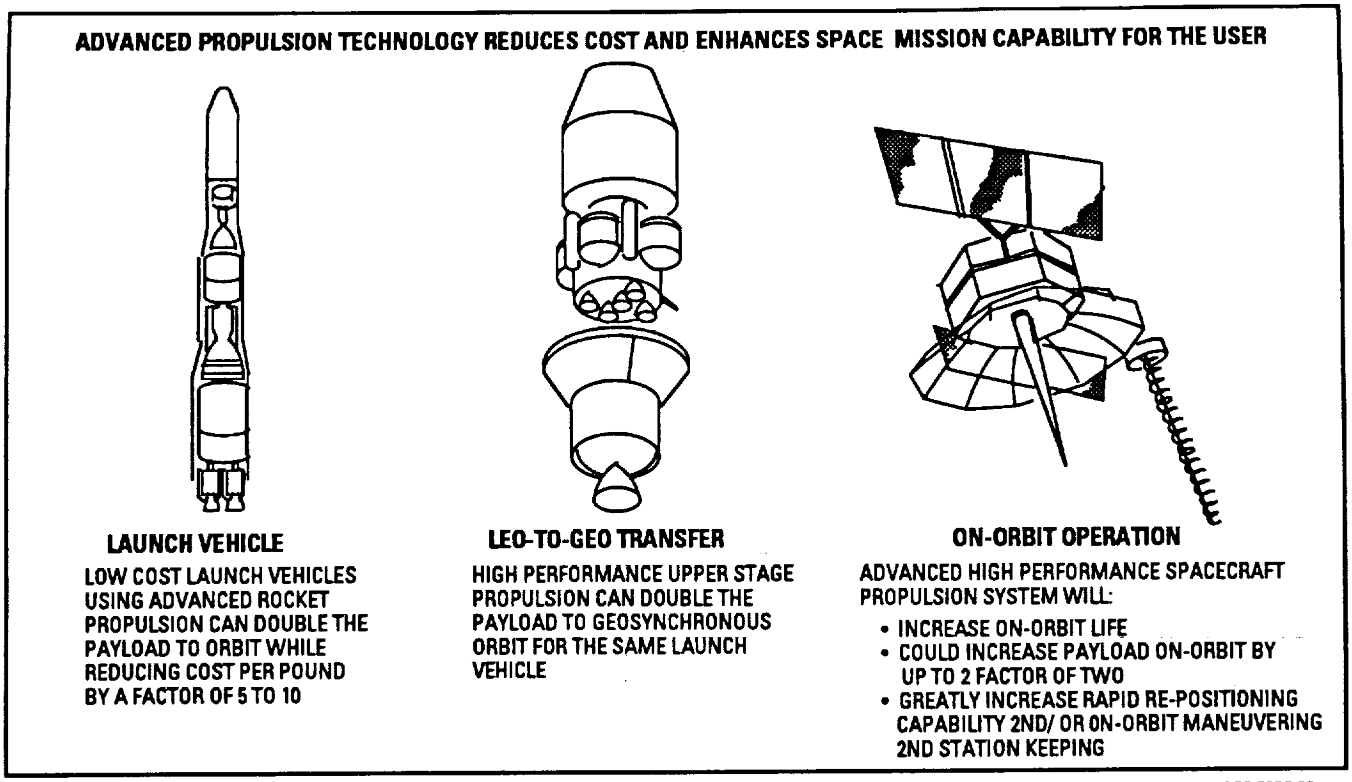


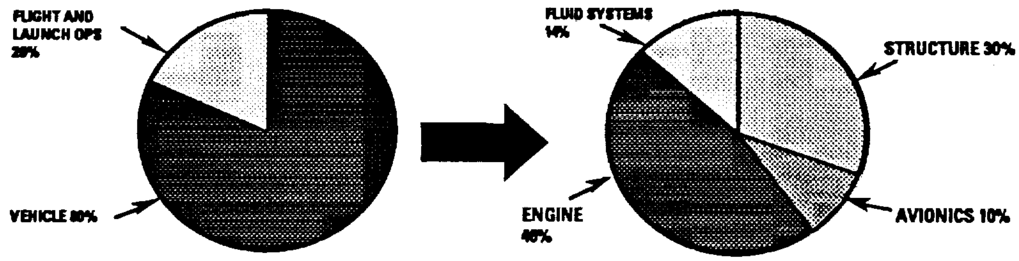
Figure 1. Integrated Rocket Propulsion Advancements for Efficient Space Transportation

total cost of a launch, it is apparent that the vehicle hardware is 80% of the cost while flight operations account for only 20% (Figure 2). This again would tend to substantiate the argument that minimum GLOW equals minimum launch vehicle cost. However, one has to only examine what makes up the vehicle cost to find out that half the cost is in the engine, a third of the cost the structure, and the remainder of the cost is the fluid systems and avionics. Of this grouping, only the structure at 30% has any direct cost relationship to its weight. Its cost per pound, however, can vary greatly depending on the type of structure employed. For example, isogrid structures are complex and cost about $400/lb while monocoque structures cost less than $100/lb. Vehicles designed with expensive structures place a premium on achieving maximum engine performance in order to reduce structural cost. Use of low cost structures, on the other hand, permit relaxed engine performance requirements. Thus, a vehicle designed with a simple low cost structure benefits not only from the reduced structural cost, but also from reduced engine costs.

Other vehicle components are sophisticated systems and there are many other factors that can drive up the cost. In the major contributor, the rocket engine, cost is driven mainly by chamber pressure and complexity. Very high pressure engines tend to have extremely complex cycles and mechanisms. The very high costs for these high pressure engines are related to the fact that they rely upon integral, very sophisticated turbopumps with complex power cycles such as expander or staged combustion, where one or both of the high pressure propellants is used in some form to regeneratively cool the combustion chambers. These high costs are not only driven by the many precision parts and components of the various subsystems, but are also caused by their interrelationship that adds to engine complexity and lowers reliability.

Shown in Figure 2 is a simple comparison of four LOX/LH_2 engines. There's the current state of the art design which is the reusable SSME that is recognized as an expensive and complex engine. The next most complex engine design concept is the STME which still operates at relatively high chamber pressure and utilizes a regeneratively cooled combustion chamber with high pressure integral turbopumps. The third most costly engine is the French Vulcain where the French did extended studies trying to minimize the cost of their engines. This engine design reduces the chamber operating pressure considerably and simplifies the combustion and cooling cycle. However, it still uses a regeneratively cooled combustion chamber. The fourth engine, which is TRW's ultra low cost design, goes to the other extreme. It operates at minimum chamber pressure and separates the turbopump from the engine so that it can function as an independent system and can be stage mounted. It has a very simple injector concept with a passive ablative cooled chamber so that it is a truly inexpensive, expendable engine. This design is estimated to be at least an order of magnitude less expensive than the other American engines and one-fifth the cost of the French engine. Also with the much simpler TRW engine and Allied Signal turbopumps, there is a significantly lower development and qualification cost.

There is some question as to why the ultra low cost engine has to be low pressure. One of the answers is that



Engine Type	TRW Engine (TRW Engine & ASE TPA)	STME	SSME	French Vulcain
• Chamber pressure • Power cycle • Injector • TCA cooling • Reusability	• 300 psi • Stage mounted boost pump • Simple single pintle injector • Ablative chamber • Expendable	• 2,250 psi • Gas generator and turbo pump • Complex multi-element injector • Regenerative chamber • Expendable	• 3,260 psi • Engine mounted turbopumps and staged combustion • Complex multi-element injector • Regenerative chamber • Reusable	• 1,470 psi • Engine mounted gas generator & turbopump • Complex multi-element injector • Regenerative chamber • Expendable
Manufacturing comparison (parts, operations, welds, etc.)	82	2565	7417	Unknown
Cost/unit, $M	2	>14	67	10
Development/qual cost	180 M	>1B	>3B	Unknown
Thrust $_{vac}$ (lb$_f$)	480,000	650,000	512,000	202,000

R1M 93.0226.03

Figure 2. Simple Engine = Low-Cost Reliable Propulsion = Low-Cost Reliable Launch Vehicle

the low pressure ratio enables a simplified turbopump design which is a major cost reduction factor. The low pressure operation also significantly lowers the heat flux to the thrust chamber throat which then allows the use of a castable ablative cooled combustion chamber which provides major reduction in engine costs. As shown in Figure 3, the most important design region for low cost engines is in the operating chamber pressure ranges from 300 to 1000 psi. The push to go to 1000 psi chamber pressure is from the upper stage application driven requirement of engine nozzle envelope. Current studies have shown the 300 psi chamber pressure is a cost optimum design condition for the first stage engines where nozzle exit diameter is usually not a driving factor. In the case of upper stage engines, the nozzle in many cases is truncated to fit in a given envelope and, therefore, some nozzle performance is lost. The overall combustion efficiency of these very low pressure engines is nearly the same as that of the high pressure engines. There is a very small increase in performance due to the pressure level. Most of the performance difference between the high pressure and the low pressure engines is in the fact that a higher area ratio nozzle can be packaged in a given envelope for the higher pressure engines. The low cost engines can be made to be reusable at most chamber pressures with the incorporation of internal cooling ducts or regenerative chamber technology. But both of these cooling techniques will significantly affect cost. The Allied Signal foil bearing pump and a TRW pintle injector assembly are already reusable as currently designed for the ultra low cost configuration.

Baseline MDA/TRW/Allied Signal Ultra Low Cost Launch Vehicle Design Concept Using Low Cost Propulsion

Based upon the results of recent joint in-house studies, the MDA/TRW/Allied Signal team has established an ultra low cost launch vehicle design concept. This concept consists of two stages; each using LO_2/LH_2 propellants, simple monocoque aluminum tanks and structure. A low cost TRW pintle-injector thrust chamber using passive ablative cooling is used for each stage. The thrust chambers for each stage are fed by Allied Signal foil bearing, turbopumps that are mounted on the stage structure and driven by a simple gas generator power cycle. For Delta-class payload capability, the first stage is powered by either a single 750 K lb thrust engine or two 400 K lb thrust engines. The second stage engine thrust is 50 to 60 K lb (vacuum). Increased payload capability can be provided by adding either solid or liquid propellant strap-on boosters to the core vehicle. The liquid strap-ons in this case, would be built from core vehicle components, giving a modular family of ultra low cost vehicles.

The TRW ablatively cooled pintle injector thrust chamber assembly is the key enabling technology making such an ultra low cost vehicle concept viable. The low chamber pressure (300 to 1000 psia) permits use of low cost, mold-in-place ablative materials and simplifies chamber design and manufacturing. This low cost passively cooled approach, however, results in propellants entering the chamber in a colder state than with the much more

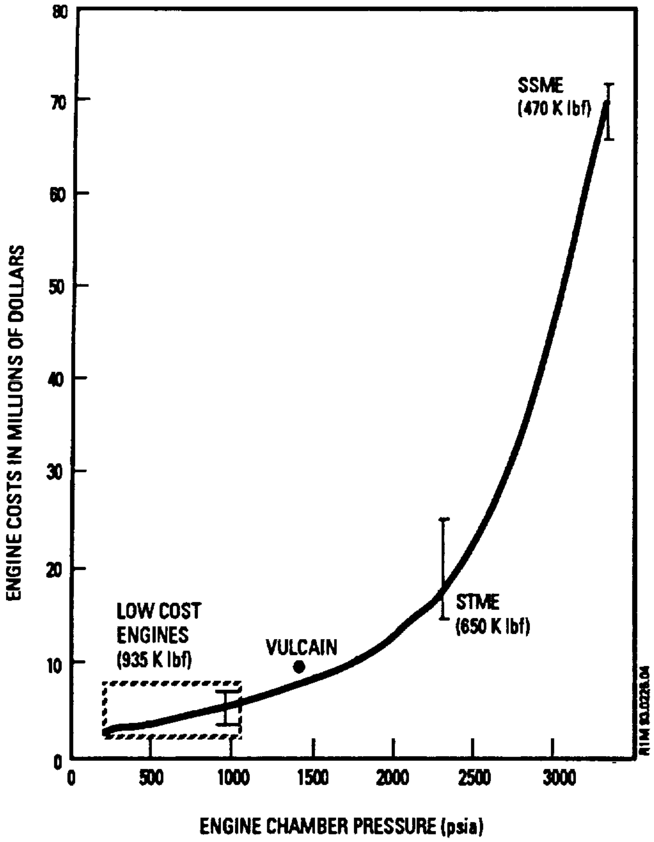
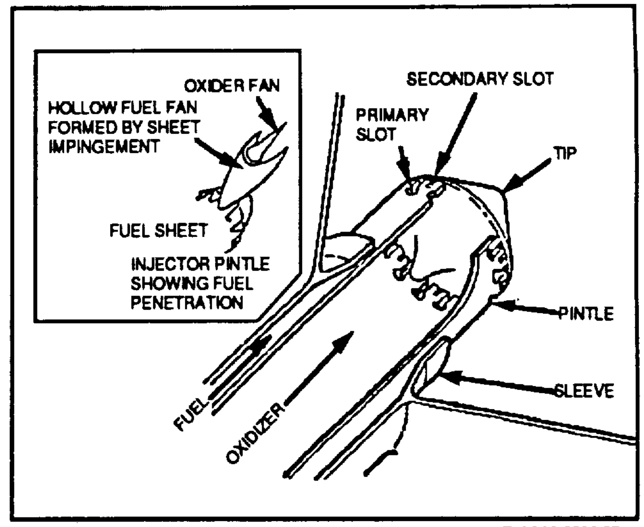


Figure 3. First Article Engine Costs

expensive regeneratively cooled chamber designs. In the case of LOX and LH_2 propellants, conventional injectors produce spontaneously unstable combustion at the LH_2 temperatures of interest. Use of the TRW pintle injector eliminates this problem, however, because of its inherently stable combustion characteristics.

This injector is a patented design exclusive to TRW rocket engines and has unique features that make the engine combustion characteristics different from those using other types of injector designs. Its many benefits include excellent combustion performance, efficient deep throttling, adaptability to low cost manufacturing, and high reliability. Approximately 200 pintle injector engines of various sizes and operating on a variety of propellants have been flown without a single in-flight failure. Also, in over thirty years of development, testing and production, TRW has never experienced combustion instability in any of its pintle injector engine designs. This has been true of engines operating over a range of thrust from 5 to 250,000 lb on earth-storable hypergolic propellants and a large number of smaller engines operating on a variety of propellants (21 combinations) in long duration-firing, pulsing (down to 2 msec) and deep throttling (as much as 19:1) modes. Operating chamber pressures have ranged from 10 to 3,500 psia.

The basic pintle injector concept is illustrated in Figure 4. It consists of a closed cylindrical element that projects into the combustion chamber and has ports machined into the cylindrical surface that allow the center propellant to flow radially into the chamber. The center propellant may be either oxidizer or fuel. The propellant port configurations typically range from discrete primary



R1M 93.0226.07

Figure 4. TRW Coaxial Pintle Injector Concept

and secondary jet slots to a continuous gap. Selection of a particular configuration is governed by a number of factors including the propellants to be used, the required combustion chamber wall thermal environment, desired combustion performance, and whether the injector is intended to operate in continuous flow, throttling, or pulsing modes.

The other propellant enters the chamber flowing axially along the exterior of the cylindrical element. Mixing of the propellants occurs where this axial-flowing cylindrical sheet meets the radial flow issuing from the central propellant slots.

The genesis of the pintle injector is traceable to the Apollo program. It provided a means to perform deep throttling, needed for a controlled descent to the lunar surface, while maintaining good stable combustion performance and mixture ratio control. Once Apollo got underway, TRW work on the pintle injector attracted NASA interest and resulted in its selection for the Lunar Module Descent Engine (LEMDE). LEMDE was an ablative-cooled, pressure-fed engine having a maximum thrust of 10,500 lb with a chamber pressure of 100 psia and a 10:1 throttling range operating on NTO/A-50 propellants. This engine proved to be very stable throughout the development, qualification and flight phases of the Apollo program. It successfully landed on the moon six times and saved the crew of Apollo 13.

In the mid 1970's, a fixed thrust variant of the LEMDE was produced and designated as the TR201. It flew 75 successful missions as the pressure-fed second-stage engine on the Delta launch vehicle. During the late 1960's and early 1970's, the basic LEMDE concept was scaled up to 250,000 lb thrust and operated on NTO/UDMH propellants. In addition, 50,000 lb thrust engines were operated on IRFNA/UDMH, LOX/RP-1 and LOX/Propane. Smaller engines having 3000 lb thrust were tested on FLOX/LCH_4, FLOX/GCH_4 and FLOX/(LC_2H_6 + LCH_4) propellants. In all cases, explosive disturbances purposely produced during tests, were well damped and no evidence of spontaneous instabilities were observed even under liquid/liquid injection conditions with cryogenic propellants.

In recent years, TRW pintle engines have also operated on gelled hypergolic propellants up to 8,000 lb thrust and LOX/LH_2 up to 16,400 lb thrust. No spontaneous instabilities have been observed in either case. In the LOX/LH_2 tests, both propellants were injected at near normal-boiling point conditions for which conventional injectors are spontaneously unstable. Again, explosively produced disturbances were found to be well damped in this case. This inherent stability characteristic of the TRW injector is a major cost reduction benefit in that typical TRW rocket engine design practice is not concerned with combustion instability as an issue. This approach is justified since no pintle engine has had to employ stability enhancing features, such as baffles or acoustically resonant chambers which must undergo protracted and expensive empirical characterization and verification test programs. Because of these inherent stability characteristics, TRW engines can operate in low cost regimes not possible with engines using other types of injectors.

Allied Signal foil bearing turbopumps are particularly attractive for this low cost launch application because of their simplicity, low cost and robustness. The foil bearing is a series of overlapping metal foils which provides a self-energized hydrodynamic fluid film bearing of the same fluid being pumped (Figure 5). This type of bearing has a number of advantages as compared to ball bearings or hydrostatic bearings. Foil bearing turbopumps are expected to cost much less to develop and manufacture and be more reliable than the types of pumps currently used in rocket engine applications.

Status of Low Cost Space Transportation Propulsion Advancements at TRW

In recent years, TRW has established an active program, in cooperation with McDonnell Douglas, Allied Signal and NASA, to develop ultra low cost pintle injector engines operating on LOX/LH_2 propellants. In 1991, a TRW engine with a sea level thrust of 16,400 lb was successfully demonstrated at the NASA Lewis Research Center (LeRC) under a NASA Space Act cooperative test agreement. This engine demonstrated that a pintle injector engine can operate stably with excellent combustion performance with LOX/LH_2 propellant injected at near normal boiling point temperatures, typical of conditions envisioned for the low cost vehicle application.

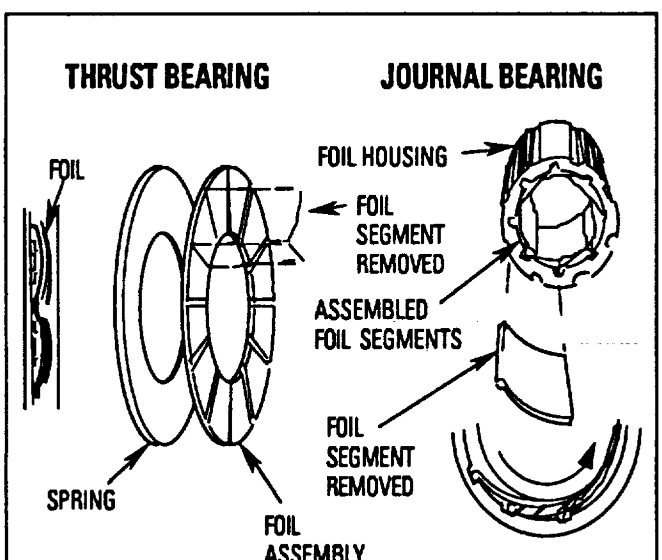


Figure 5. Allied Signal Foil Bearing Concept

Recently, a 40,000 lb sea level thrust (50,000 to 60,000 lb vacuum thrust) engine was, designed fabricated, and tested. This engine uses low cost molded-in ablative liners. An extensive series of tests have been sucessfully conducted at NASA LeRC. The results of these tests continue to demonstrate the technology required for an ultra low cost upper stage engine, as well as add to the data base for scaling the design up to much larger first stage engines.

With the successful completion of the 40,000 lb thrust engine tests at LeRC, TRW now plans to seek funding to scale the design up to 400,000 lb thrust. Fabrication and testing of this engine would follow, with the objective of demonstrating good combustion performance and stability in an engine size of interest for first stage applications.

High Performance Spacecraft Propulsion to Maximize Space Asset Payoff

Up to this point we have primarily focused on the economic impact of the earth to orbit launch phase of space transportation for communications satellites. The basic argument thus far has emphasized that launch providers must find realistic ways to drive the cost of their launch services way down to maintain the economic viability of space based communications systems. We have presented data that shows that the major cost driver for ELVs is the propulsion system with the majority of these costs coming from the rocket engines. The data presented in the preceding sections argues that the most effective (in fact the only way – if you believe history) way to reduce these costs is to design and build the lowest cost and least complex propulsion system consistent with acceptable reliability standards rather than to attempt to maximize performance. We will now change our focus to examine what factors influence the cost of the ELV cargo element itself to see if propulsion advancements can lower the cost of the fixed communications satellite asset on orbit.

Even if the launch vehicle cost could be driven way down, there is still plenty of room to increase the cost effectiveness of the cargo element launched into initial orbit. Depending upon where the earth-to-orbit launch vehicle injects its cargo, an additional velocity increment or ΔV (or orbit injection energy) will usually be required to achieve the operational orbit. In the case of GEO COMSATs, this additional energy usually provides for apogee circularization (or "apogee kick") and in some cases includes perigee raising augmentation energy. This ΔV energy can either be provided by an additional upper stage or by an integral propulsion system on board the satellite. The argument from this point forward now switches to maximizing the upper stage or on-board propulsion system performance to a level that is consistent with specific space system financial investments versus on-orbit revenue pay offs. The propulsion performance benefits will vary depending on the customer/user system concept and the specific contract. It should be noted, however, that in almost all cases there seems to be significant pay off from increases in space propulsion system performance (again consistent with the specific customer contract provisions and constraints).

Additional orbit transfer stage propulsion system performance benefits will vary with the stage size, its specific purpose and use and the total value of the injected space asset. In the case of the on-board integral propulsion system, however, the economic benefits of performance improvements will tend to keep increasing in one way or another as long as the non-recurring and recurring costs do not become completely unaffordable. This is because about 40 to 60% of the spacecraft weight will be used for some combination of final orbit injection velocity and on-orbit velocity and attitude control. Obviously, if this fraction of the spacecraft weight could be reduced, then more of the weight would be available for revenue generating payload or longer life on-orbit.

The two basic approaches to improving space propulsion performance are either increasing the efficiency of existing chemical systems or the use of high performance, high power electric propulsion systems. TRW as well as many other companies is working to develop both of these technologies to realize the increased payload economic advantages discussed above.

Status of High Performance Spacecraft Propulsions Systems at TRW

Spacecraft propulsion systems for most of the past three decades have relied upon limited use of solid apogee kick rocket motors and earth storable liquid propellants, principally hydrazine as a monopropellant and nitrogen tetroxide-amine fuels as bipropellants. As shown in Figure 6, the technology level for these propellants and the systems in which they are used has continually progressed and been upgraded as spacecraft missions have changed. The introduction of the dual mode (N_2O_4-N_2H_4) system concept by TRW and others represents one of the last significant earth-storable propulsion system improvements available. The dual mode system utilizes a N_2O_4-N_2H_4 bipropellant liquid apogee engine for apogee circularization and insertion and catalytic thrusters plus either (depending on the system requirements and constraints) electrothermally heated monopropellant hydrazine thrusters (EHT), or gas-gas injection, N_2H_4-N_2O_4 after burner thrusters, or higher power arcjets (if high power is available) for attitude control and stationkeeping. The hydrazine fuel for the main engine and attitude control subsystem (ACS) is also integrated into the same tank or tanks for additional system weight advantage. TRW has developed, qualified, and flown a 100-lbf thrust (100 psia) N_2O_4-N_2H_4 apogee engine demonstrating 314.6 lbf-sec/lbm ISP. TRW is presently developing an advanced dual mode N_2O_4-N_2H_4, liquid apogee engine in the 328 to 330 lbf-sec/lbm ISP range at nominal thrust chamber pressure levels. TRW has also recently demonstrated 318 sec ISP with an N_2O_4/MMH liquid apogee class engine. Other improvements can also be achieved using higher engine operating pressures because of the potential for higher thrust coefficient levels, the enabling use of higher temperature materials, the reduced length and volume of the engine envelope, and the potential engine weight savings. It is also clear that the use of higher pressure engines is a good method for meeting smaller satellite volume and length constraints. The net benefit of higher operating storable propellant engines should be the capability to achieve about 335 seconds ISP with smaller and lighter LAEs than are currently available. TRW is currently working under contract to NASA/Lewis Research Center to develop a higher operating pressure liquid apogee engine to also gain this additional spacecraft performance benefit. In summary, TRW is working, under contract to NASA and other spacecraft prime contractors, on a family of advanced, high performance spacecraft apogee and velocity control engines. These engine technology advancements will use three basic building blocks to evolve in a logical sequential fashion to the maximum achievable performance levels for storable chemical rocket engines. These are higher temperature capability materials (currently coated rhenium) for thrust chambers, higher operating pressures (about 300 to 500 psia as compared to current levels of about 100 psia) and the use of a higher energy space storable oxidizer (liquid oxygen). Incorporation of these advanced technologies will ultimately result in a spacecraft engine that will be capable of operating at or above 350 seconds of ISP. This engine will enable either increases in payload fractions of 15 to 20% or a like reduction in the overall spacecraft weight, relative to todays operational spacecraft integral propulsion systems. These improvements will, in turn, contribute to much more profitable communications satellite systems.

Finally, it must be pointed out that electric propulsion (EP) technology also offers tremendous performance benefits for spacecraft and space transportation systems. The high thrust efficiency of electric systems compared to chemical propulsion can significantly reduce the amount of propellant required for the same operations. In addition, the high power that is inherent in electric propulsion spacecraft will actually enhance or enable many operational mission concepts that up to now have been considered to be out of reach because of the cost of high power systems just for these missions (without the propulsion savings). Advances in critical EP related

Spacecraft Propulsion Systems technologies over the last three decades now enable the near term use of these systems for high performance, high payload fraction, communications satellites.

Advances in materials, microelectronics, and spacecraft design tools have contributed to the near term development of electric propulsion spacecraft. Additional new spacecraft technologies that are now becoming available include high power, radiation resistant solar arrays, high power distribution and control, qualified electric propulsion subsystems, lightweight radiation hardened avionics, advanced structural and thermal materials, and fully autonomous guidance and control for orbit raising and on-orbit control of high power, high performance communications satellites.

Electric propulsion systems will soon be flying on both flight demonstration and fully operational spacecraft. These systems will be capable of operation at power levels from

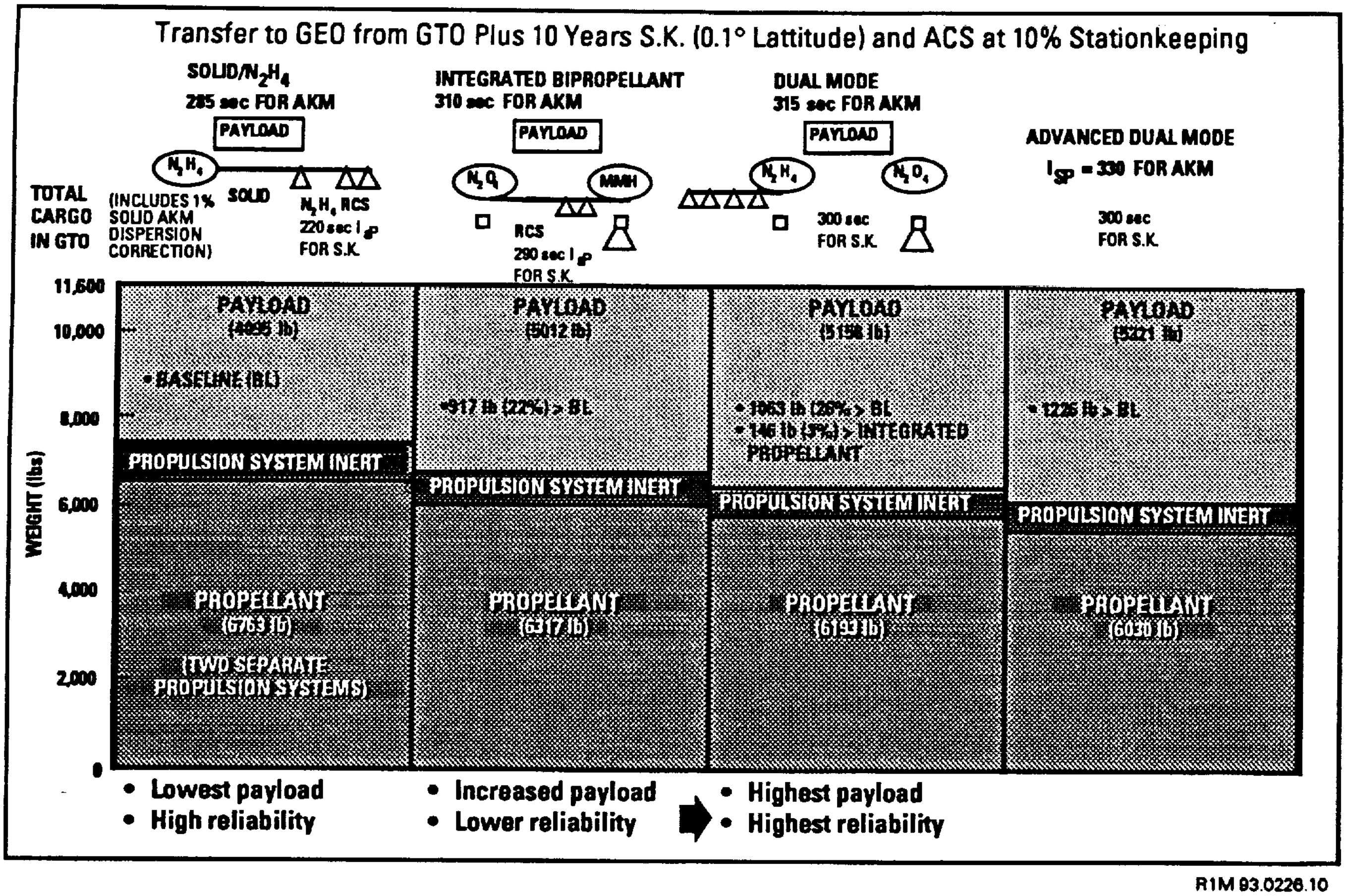


Figure 6. Comparison of the Evolutionary Performance Growth Spacecraft Propulsion Systems

several hundreds of watts to tens of kilowatts and will use either arcjets, ion thrusters or stationary plasma thrusters (SPTs). Specific impulse values will range from 500 seconds to 2000 to 3000 seconds, depending on the devices used. There is a drawback for some missions requiring very rapid "launch on demand" response, because it will take more time to reach the operational orbit using a low thrust electric propulsion orbit transfer system (typical trip times will take about six months from LEO to GEO, using 1,000 sec. ISP 20 to 30 KWe hydrogen arcjets). However a tremendous net savings could still be achieved in total communications system cost reductions. In simple terms, it has been shown that the use of an all electric propulsion orbit raising and on-orbit velocity control (positioning) system for high power communications satellites can result in almost twice the payload in operational orbit for about half the current or near term projected space transportation costs.[4]

Summary and Conclusions

This paper has presented information that clearly shows the influence of space transportation system performance and cost on the overall economics of space based communications systems. It has been pointed out that the space transportation system for communications satellites generally consists of three basic phases, which are: earth-to-orbit (launch vehicle); orbit raising to higher transfer orbits; and injection into, and maintenance in final operational orbit. Data has been presented to show that the major cost drivers for these three transportation phases are either the cost or the performance of the respective propulsion systems. The major point being made here is that the propulsion system economics must be viewed in two different ways. For the earth-to-orbit launch vehicle, low cost, simple, reliable and moderate performance propulsion system designs are far more cost effective than highly complex, ultra high performance designs. In fact, it is clearly shown that a major fallacy in past launch vehicle designs has resulted from repeated attempts to develop the highest performance, lightest weight rockets. This fallacy is a major reason for the relatively expensive launch vehicles that must be used for todays communications satellite systems. The only way to reduce the launch cost from the current $10,000 to $14,000 per pound to GTO level is to design a next generation of launchers that use a simple power cycle and lower operating pressure rocket engine with simple although somewhat heavier feed systems.

On the other hand, the relative cost to place any cargo into space will always remain high enough (even with the low cost innovations described herein) to demand the use of high performance spacecraft propulsion to maximize the fraction of cargo weight that is truly revenue generating, useful payload.

Therefore it is vitally important to develop the propulsion advancements described in this paper that will both dramatically, lower the cost of launch vehicles and maximize the useful payload fraction on-orbit for the required operational life times. The results of recent studies have been summarized to illustrate the specific economic advantages of using ultra low cost, simple propulsion technology for low cost launch vehicles in conjunction with high performance upper stage and spacecraft integral propulsion systems for maximum value satellite payloads on-orbit.

References

1. J. P. Henneberry, F. J. Stoddard, A. L. Gu, and S. T. Thelander, "Low Cost Expendable Launch Vehicles." AIAA Paper 92-3433 presented at the AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference and Exhibit, July 7 - 8, 1992, Nashville, Tennessee.

2. Carlson, C. R. and Simpson, J.S., "Low Cost ELV Technology Applicability to Spacelifters." AIAA Paper 93-4124 presented at the AIAA Space Programs and Technologies Conference and Exhibit, September 21 - 23, 1993, Huntsville, Alabama.

3. Fritz, D. E. and Sackheim, R. L., "Study of a Cost Optimized Pressure Fed Liquid Rocket Launch Vehicle," AIAA Paper No. 82-1108 presented at the AIAA/SAE/ASME 18th Joint Propulsion Conference, June 21 - 23, 1982, Cleveland, Ohio.

4. Sackheim, R. L. and Rosenthal, R., "Electric Propulsion: The Next Real Breakthrough in Space Transportation," IEPC-93-061, presented at the 23rd International Electric Propulsion Conference, September 13 - 16, 1993, Seattle, Washington.